RESTRICTED

AP 3401

ROYAL AIR FORCE
MANUAL

CONTROL AND REPORTING
2

MINISTRY OF DEFENCE
January 1969

RESTRICTED

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ROYAL AIR FORCE
MANUAL

CONTROL AND REPORTING 2

By Command of the Defence Council

MINISTRY OF DEFEN

January 1969

CONTENTS

INTRODUCTORY NOTES

1. This publication forms the second part of the manual of control and reporting and commences at Chapter 20. Chapters 1 to 19 are contained in Control and Reporting 1, which is a companion document of higher security classification.

2. The first two digits of the paragraph numbers in this publication and its companion are those of the chapter number. Reference to a particular paragraph can therefore be made by quoting the paragraph number alone, thus avoiding the complexity of reference to the document title and chapter, section and paragraph number.

3. The ways and means of waging air warfare are continually evolving, and control and reporting is as much affected by such development as any other aspect of air operations. The co-operation of all readers is therefore requested in pointing out errors or omissions and suggesting amendments or additions to the contents. Proposals and comments should be made to:

The Officer Commanding
Air Defence Ground Environment Examining Board
RAF West Drayton
West Drayton
Middlesex

LIST OF ABBREVIATIONS

AA	Anti Aircraft
ABH	Angle Between Headings
AC	Alternating Current
ACC	Air Control Centre
ACE	Allied Command Europe
ADC	Air Defence Centre
ADF	Automatic Direction Finding
ADNC	Air Defence Notification Centre
ADOC	Air Defence Operations Centre
ADPS	Automatic Data Processing System
ADRS	Air Defence Radar Station
AEW	Airborne Early Warning
AFOR	Air Force Operations Room
AGC	Automatic Gain Control
AI	Airborne Interception
AID	Aeronautical Information Document
AM	Amplitude Modulated
AP	Auto Pilot
API	Air Position Indicator
ASP	Aircraft Servicing Platform
ATC	Air Traffic Control
ATCC	Air Traffic Control Centre
ATCRU	Air Traffic Control Radar Unit
BCP	Battery Command Post
BMEWS	Ballistic Missile Early Warning System
CAFSO	Command Air Formation Signals Officer
CAP	Combat Air Patrol
CATO	Civil Air Traffic Operations
CEW	Continental Early Warning
CENTO	Central Treaty Organization
CH	Chain Home
CHEL	Chain Home Extra Low
CHL	Chain Home Low
COP	Change-Over Panel
C & R	Control and Reporting
CRT	Cathode Ray Tube
CT	Command Trailer
CW	Continuous Wave
dB	Decibels
DC	Direct Current
DEL	Direct Exchange Line
DF	Direction Finding
DIP	Display Information Processor
DME	Distance Measuring Equipment
DPT	Data Processing Trailer
DTO	Data Take-Off
DVST	Direct View Storage Tube
EC	Emergency Circuit or Evaluation Centre
ECM	Electronic Countermeasures
ECCM	Electronic Counter-Countermeasures
EEA	Equivalent Echoing Area
EHT	Extra High Tension
EM	Electromagnetic
EMF	Electromotive Force
FCC	Flight Control Computer
FCE	Fire Control Equipment
FD	Flight Director
FIR	Flight Information Region
FLIP	Flight Information Publications
FM	Frequency Modulated
FTC	Fast Time Constant
FTLP	Final Turn Lead Pursuit
FU	Fire Units
FWC	Flight Watch Centre
GAR	General Assessment Report
GCA	Ground Controlled Approach
GCI	Ground Controlled Interception
GEOREF	World Geographical Reference System
GMT	Greenwich Mean Time
GSD	General Situation Display
GSM	General Situation Map
HF	High Frequency
HFR	Height Finding Radar
HPRP	High Power Reporting Post
HSA	High Speed Aerial
Hy AD	Heavy Air Defence
IAA	Initial Approach Angle
IAF	Interceptor Alert Force
IAGC	Instantaneous Automatic Gain Control
IAS	Indicated Airspeed
ICAN	International Commission for Air Navigation
ICAO	International Civil Aviation Organization
ICBM	Inter-Continental Ballistic Missile
IF	Intermediate Frequency
IFF	Identification Friend or Foe
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
IP	Identification of Position
IR	Interrogator Responder
IRBM	Intermediate Range Ballistic Missile
kHz	Kilohertz
LAA	Light Anti Aircraft
LCP	Launch Control Post

LF	Low Frequency
LFS	Light Fighter Sight
LLAD	Low Level Air Defence
LMT	Local Mean Time
LOS	Lamp Order Signal
LPD	Labelled Plan Display
LRD	Labelled Radar Display
Lt AD	Light Air Defence
M	Mach
MAR	Master Allocation Room
MATO	Military Air Traffic Operations
MCRU	Mobile Control and Reporting Unit (RAAF)
MF	Medium Frequency
MHz	Megahertz
MIP	Missile Impact Predictor
MRBM	Medium Range Ballistic Missile
MRD	Marked Radar Display
MRP	Mobile Reporting Post or Missile Repair Point
MRS	Master Radar Station
MTI	Moving Target Indication
MW	Megawatt
NATS	National Air Traffic Service
NATO	North Atlantic Treaty Organization
NEOC	Near East Operations Centre
NORAD	North American Air Defence
NRC	Nuclear Report Cell
ORP	Operations Readiness Platform
PAR	Precision Approach Radar
PBX	Private Branch Exchange
PD	Passive Detection or Potential Difference
PHI	Position and Homing Indicator
PHO	Parallel Head On
PI	Practice Interception
PLD	Pulse Length Discrimination
PPI	Plan Position Indicator
pps	Pulses per second
PRF	Pulse Repetition Frequency
PRFD	Pulse Repetition Frequency Discrimination
PUT	Prolonged Uninterrupted Trunk
PW	Private Wire
RAOC	Regional Air Operations Centre
RB	Rocket Battery
RCC	Rescue Co-ordination Centre
RF	Radio Frequency
ROC	Royal Observer Corps
RPDS	Radar Photographic Display System
RRE	Royal Radar Establishment
RT	Radio Telephony
SACEUR	Supreme Allied Commander Europe
SAM	Surface-to-Air Missiles
SARBE	Search and Rescue Beacon Equipment
SEATO	South East Asia Treaty Organization
SHAPE	Supreme Headquarters Allied Powers in Europe
SHOC	Supreme Headquarters Operations Centre
SIF	Selective Identification Feature
SOC	Sector Operations Centre
SRS	Satellite Radar Station
SSB	Single Sideband
SSR	Secondary Surveillance Radar
STCOC	Strike Command Operations Centre
STOL	Short Take-Off and Landing
SU	Signals Unit
Surv R	Surveillance Radar
TACAN	Tactical Aid for Control and Navigation
TAS	True Airspeed
TC	Tactical Control
TEV	Terminal Equipment Vehicle
TIR	Target Illuminating Radar
TPA	Track Production Area
UHF	Ultra High Frequency
UKADR	United Kingdom Air Defence Region
UKWMO	United Kingdom Warning and Monitoring Organization
VA	Vulnerable Area
VF	Voice Frequency
VFR	Visual Flight Rules
VHF	Very High Frequency
VISIDENT	Visual Identification
VMC	Visual Meteorological Conditions
VP	Vulnerable Point
VPD	Vertical Performance Diagram
VTOL	Vertical Take-Off and Landing
WT	Wireless Telegraphy

CHAPTER 20

ELECTRONIC FUNDAMENTALS

CONTENTS

BASIC ELECTRICITY AND MAGNETISM

The Structure of Matter

2001. Matter is that which occupies space and has weight. We can see matter all around us and we are aware that it can exist in three states: as a solid, liquid or gas. Although we cannot see the atmosphere it consists of a mixture of gases.

2002. Let us take a piece of matter, *eg* a drop of water, and see what happens when it is sub-divided into smaller and smaller portions. The drop is first cut in half, each half-droplet is halved and the process is continued indefinitely. The resulting smaller and smaller droplets will soon become invisible to the naked eye but we can continue the process of sub-division in imagination. A point will eventually be reached where the particles of water are of such a size that further sub-division will split them into the hydrogen and oxygen of which they are composed. These last minute water droplets are known as molecules and are the smallest particles of water which can exist as such and still behave chemically as water. If a water molecule could be magnified sufficiently it would be seen to consist of three smaller particles closely bound together. These three particles are three atoms, two of hydrogen and one of oxygen (Fig 20–1). Hydrogen and oxygen are known as elements, whereas water is a compound. Every material is built up from its molecules as there are different chemical substances. Every different molecule can be sub-divided into its constituent atoms. As we have seen, water is composed of only two different kinds of atom—hydrogen and oxygen—but many molecules are composed of several kinds of atom with perhaps several of each kind. Whilst there exists almost an infinite number of different molecules (*ie* different chemical compounds) there are only about 100 different atoms (*ie* different elements). Hydrogen and oxygen are of course examples of elements; others are iron, copper, silver, chlorine and carbon. Examples of compounds are water, salt and sugar.

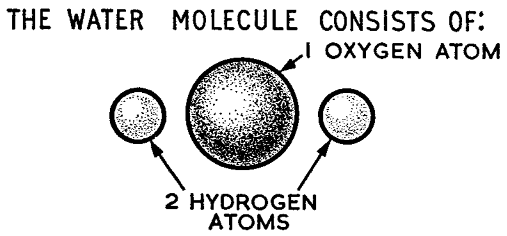


Fig 20–1 The Water Molecule

Atoms

2003. At one time it was thought that atoms were minute solid particles which could not be broken down further and which were the basic "bricks" from which substances were built up. We now know that atoms themselves are composed of even smaller particles. Let us take an atom of hydrogen as an example. A hydrogen atom is incredibly small—about 10^{-8} cm in diameter—but if it could be magnified sufficiently it would be seen to consist of a core or nucleus with an electron travelling round it in a roughly circular path or orbit, rather like a planet travelling round the sun (Fig 20–2). The nucleus has a positive quantity or charge of electricity and the electron an equal negative charge; thus the whole atom is electrically neutral. The atoms of other elements have more than one electron travelling round the nucleus; for example, the oxygen atom has eight electrons outside the nucleus, but the nucleus has eight positive charges on it which exactly neutralize the negative charges of the eight electrons. Thus any atom under normal conditions is electrically neutral. The particles carrying the positive charges are called protons. In addition to the protons the nucleus may also contain electrically neutral particles called neutrons; neutrons help to make up the atom to the correct weight. We see therefore that not only the atom but also the nucleus of the atom may be broken down into smaller particles of matter. Note that an electron always carries the same negative charge whatever atom it belongs to—and so does a proton with its positive charge.

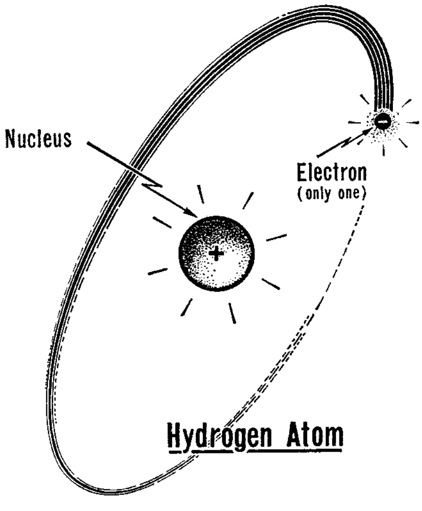


Fig 20–2 The Hydrogen Atom

Free Electrons

2004. In Fig 20-3 are shown simplified diagrams of the oxygen and copper atoms. The electrons in the oxygen atom travel round the nucleus in two orbits whereas those in the copper atom are in four orbits. Electrons in outer orbits are not so strongly attracted to the positive nucleus as those closer in and hence may readily be stripped from their orbits. An atom which has "lost" an electron in this way has lost one of its negative charges and is no longer neutral; it is called a positive ion (Fig 20-4). The electron stripped from its orbit may attach itself to a neighbouring atom in the material; this atom, having gained a negative charge, is no longer neutral and becomes a negative ion. In some materials (*eg* conductors) the electrons stripped from their orbits can wander at random among the atoms; these are free electrons; if they can be made to move in a particular general direction through the material they constitute an electric current.

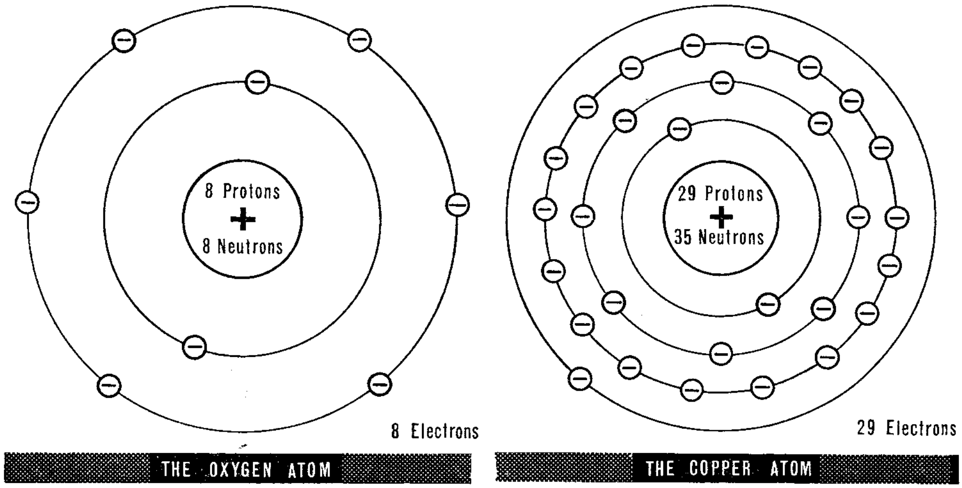


Fig 20-3 Oxygen and Copper Atoms

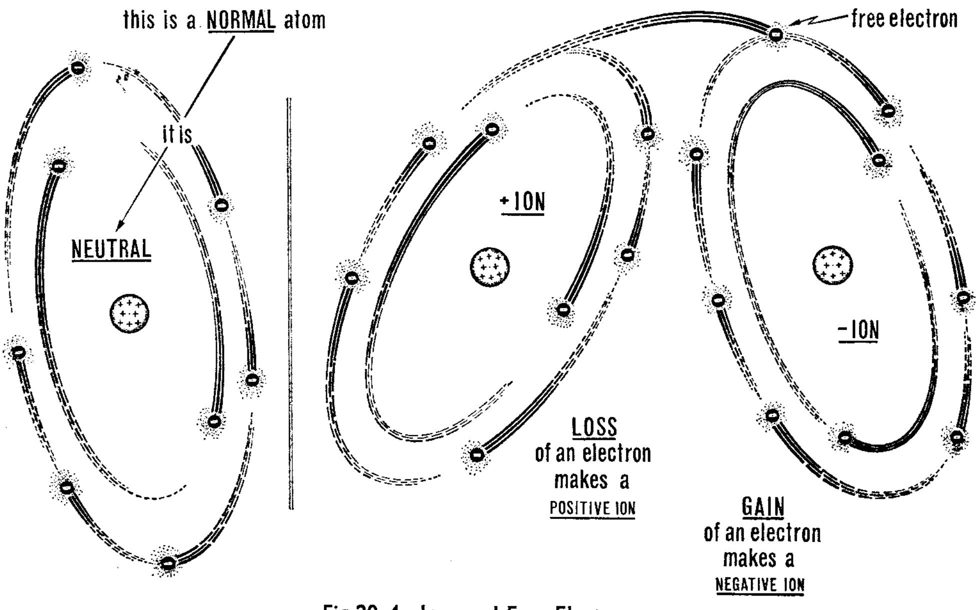


Fig 20-4 Ions and Free Electrons

Electronic Theory of Charge and Current

2005. Substances like wood, glass, rubber, porcelain, and plastics are called insulators because the electrons in them are quite strongly bound to their atoms, and they will carry a current only under protest. In fact there are materials with properties ranging the whole way from conductors to insulators, so that the difference between the two is one of degree. The measure of the difficulty with which a body will pass a current is called its resistance; this depends both on the size and shape of the body and the material of which it is made. A good conductor has a very low resistance, and a good insulator a very high one. A current loses energy in overcoming the resistance of a conductor, and this energy is converted into heat. The heating effect of the electric current is the basis of the electric lamp and the electric fire or heater.

2006. An electric current can also flow by the movement of ions, which, as explained earlier, are charged atoms or molecules. It is in this way that a current flows through water or solutions like the electrolyte in batteries; pure water is a very bad conductor, greatly improved by dissolving acids or salts in it, or even slight impurities. Though water or solutions cannot compare with metals as conductors, wetting with them is enough to spoil the insulating properties of any good insulator.

2007. Gases like air are not normally conductors, but they can be made to ionize and thus carry a current. This type of conduction is familiar in the spark or arc, the silent corona discharge from high-voltage points, and the gas-discharge tube used in advertisement signs and fluorescent lighting. The lower the pressure of the gas, the less is the electrical pressure or potential difference needed to make it ionize (though at extremely low pressure, what is called a hard vacuum, there will not be enough ions to carry a current).

2008. Analogy with the flow of water helps in communicating the idea of electricity. A conductor may be thought of as a pipe between two reservoirs, and electrons as water flowing from one reservoir to the other through the pipe. The water pressure at either end of the pipe will depend on the level of the water in the reservoir connected to the end in question. If the levels in the reservoirs are the same, no water will flow through the pipe. If the levels are different, water will flow from the higher to the lower as long as a difference in level remains, and its rate of flow will depend on the difference in level. The electrical level is called the electric potential, and the difference in level, which makes the current flow and governs the size of it, the potential difference. The force exerted by a battery or generator to drive a current through a conducting circuit is called its electromotive force or EMF, and this is analogous to the pressure developed by a water-pump. These three quantities are all measured in volts, and it is common to refer to them loosely as voltage, which just means something measured in volts. The power developed by an electric current, *ie* its rate of doing useful work such as heating, is proportional to the square of the voltage or the square of the current.

2009. Before the discovery of electrons, electric currents were conventionally assumed to flow from positive to negative. This convention became so firmly established that it has not been abandoned, even though the electrons clearly flow in the direction opposite to that postulated; when necessary, the flow of electrons from negative to positive is described as electron current, and the notional flow from positive to negative is distinguished as conventional current. A current need not be steady, but may vary in all sorts of ways in response to a varying potential difference. DC or direct current is the customary name for a steady current in one direction, and AC or alternating current is a current that regularly reverses its direction, oscillating in the harmonic (sine-wave) manner described in paras 2031–2050.

Electric and Magnetic Fields

2010. The force of attraction between two unlike charges is found to increase with the strength of the charges, to decrease with the distance between them, and (though it is affected by what is between them) to be exerted even in the highest vacuum.

2011. This is called action at a distance (gravitation is an example of the same sort of thing) and it may be described either in terms of imaginary elastic lines of force which tug at the charges or poles, as earlier mentioned, or by the idea of fields of force. Lines of force are easier to conceive and so are more immediately attractive, but they can explain only the simpler effects and are not discussed in this manual.

2012. An electric charge is said to create an electric field all around itself, and the measure of this field at any point is the force (of attraction or repulsion) that there would be on another charge (for uniformity's sake, a unit positive charge) if it were at that point. So an electric field may be thought of as a sort of invisible force present around an electric charge, which makes itself known by its effect on other charges. Like the force it gives rise to, the field has direction as well as magnitude, and so it is what is known as a vector; in fact it is sometimes called the electric vector. The fields produced at a point by several charges add together in the vector manner to give a resultant field, in the way that an object pulled by ropes in several different directions at once will move in the direction of the resultant pull; or stay still, as a properly guyed mast will, if the resultant is zero. A changing or moving charge (such as a current) will clearly produce a changing field. In the same way the idea of a magnetic field can be built up, by taking magnetic poles instead of electric charges.

2013. This account has barely mentioned the material surrounding the charges or poles, and has generally described what happens if there is no material at all, *ie* if they are in a vacuum. All materials are affected to some extent by electric and magnetic fields and in return affect fields acting in them, but this is unimportant for the present purpose and will not be discussed in detail. What is important is to remember that electric and magnetic fields can and do exist at any point of space quite independently of what matter is there; that is to say, the action of charges or poles at a distance is not carried by the atoms of whatever is round them, or by anything material.

2014. Since electrons are charged particles, an electric field will exert a force on them and cause them to move: thus, if a conductor is held in an electric field, the free electrons in it tend to move in the positive direction and redistribute themselves. More important, if the field is changing, the electrons in the conductor surge up and down, and a varying current is induced. This will later be recognized as the principle of the receiving aerial in radio.

Electromagnetic Effects

2015. A changing electric field generates a magnetic field and, conversely, a changing magnetic field generates an electric field. This has many interesting and useful consequences.

2016. A current flowing along a wire creates a magnetic field round the wire. If the wire is wound into a coil of many turns, making a solenoid, the magnetic field becomes concentrated inside the coil. If now a piece of soft iron, which gains and loses magnetism easily, is placed inside the coil, the iron is made a strong magnet (an electromagnet) as long as the current passes. By contrast, a magnet that does not depend on the continued stimulus of a current for its magnetism is called a permanent magnet.

2017. If a closed coil of wire is rotated between the poles of a fixed magnet, then, since the magnetic field of the magnet is stationary, the magnetic field relative to the coil itself will change. Hence a current will be induced in the coil, and by drawing off this current, the machine can be made to function as a generator or dynamo. Many improvements and variations can be made on this fundamental technique of converting mechanical work into electricity, and generators made in this way provide almost all the electricity used today.

2018. If the process is reversed, *ie* if a current is made to flow through a coil placed between the poles of a magnet, then the coil will generate a magnetic field that tends to push upon the poles of the magnet. The result of this, if the magnet is fixed and the coil free to turn, is that the coil will itself be pushed and will start to turn. If a commutator is used to reverse the direction of the current when the coil has turned over, it will go on turning, and the machine will function as an electric motor, by which electricity is converted into mechanical work.

Electrical Units of Measurement

2019. All the units used in electricity and magnetism (also in radio) are based on the centimetre-gram-second system, and use the standard prefixes for divisions and multiples:

a. Kilo-(k) means a thousand times ($\times 10^3$), and mega-(M) means a million times ($\times 10^6$); thus a kilovolt (kV) is one thousand volts, and a megawatt (MW) is one million watts.

b. Milli-(m) means a thousandth ($\times 10^{-3}$), and micro-(μ) means a millionth ($\times 10^{-6}$); thus a milliampere (mA) is one thousandth (0·001) of an ampere, and a microvolt (μV) is one millionth (0·000001) of a volt.

2020. The most common units are:

a. The volt (V), which is a unit of EMF and potential difference.

b. The ampere (A), which is a unit of current.

c. The ohm (Ω), which is a unit of resistance.

d. The watt (W), which is a unit of power or rate of working (1 watt = 1 joule per second).

e. The joule, which is a unit of energy.

2021. Another unit that is often used is the decibel (dB). This does not measure any physical quantity, but is used in comparing the ratio of two voltages or powers. The simplest way of making such a comparison is to state the ratio between the two powers in question; to say, for example, A is ten times as powerful as B. But the ratios that arise in this way are often very large numbers, and also they do not adequately represent the effect of the comparison on the human senses: for example, if there are three sounds A, B, and C, B 10 times as powerful as A, and C 100 times as powerful as A, then one might suppose C to be very much louder than either A or B; but in fact the ear perceives the same increase in loudness from B to C as from A to B.

2022. Put differently, this means that the senses work on a logarithmic scale of power, and a useful scale of comparison should do the same. The bel is defined to mean a tenfold increase of power, so that in the example given in para 2021, B is A plus 1 bel, and C is A plus 2 bels. The bel is inconveniently large for many purposes, and a tenth of it, the decibel, is used instead. Decibels are very widely used in radio for expressing power-level comparisons such as gains of amplifiers; the table may be helpful. It should be remembered that the decibel scale is a logarithmic one, so that decibel figures add when the corresponding power or voltage ratios are multiplied together.

2023–2030. (*Not allotted*).

ELECTROMAGNETIC WAVES

Oscillations

2031. All radio and radar depends on the properties of electromagnetic waves, and all waves are made up of harmonic, or sine-wave oscillations: so to understand radio one should first be familiar with harmonic oscillations and waves in general.

2032. A simple example is the behaviour of a mass swinging on a cord like a pendulum, or bobbing up and down on the end of a spring. Its motion is regular about a centre point: the mass speeds up as it approaches this point and slows down to a halt as it leaves it behind, reversing its direction of movement always at the same extreme points (if the damping effect of air resistance and friction is ignored); the same cycle of events is repeated time after time. If the motion were shown as a graph of displacement against time, it would be like the curve in Fig 20–5. This is a typical sine-curve; *ie* a curve of the form $x = A \sin mt$ (where x is the displacement, t the time, m and A constants); this

Difference in dB.	Power Ratio	Voltage Ratio	Difference in dB.	Power Ratio	Voltage Ratio
1	1·26	1·12	12	15·9	3·98
2	1·58	1·26	15	31·6	5·62
3	2·00	1·41	20	100	10·0
4	2·51	1·58	25	316	17·8
5	3·16	1·78	30	1,000	31·6
6	3·98	2·00	35	3,160	56·2
7	5·01	2·24	40	10,000	100
8	6·31	2·51	50	100,000	316
9	7·94	2·82	60	1,000,000	1,000
10	10·0	3·16			

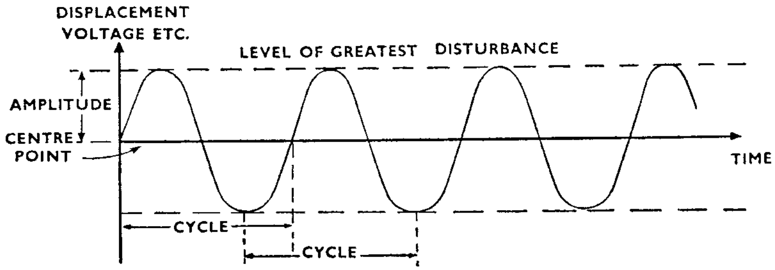


Fig 20–5 Simple Harmonic Motion

being the law or equation that describes the motion. The motion is the fundamental type of oscillation, and is called harmonic or sine-wave (sinusoidal). It is the pattern of many familiar phenomena; *eg* alternating current (AC) is a sinusoidal variation of current whose "centre point" is zero current.

2033. The following terms are in common use in referring to oscillations:

a. *Cycle.* A cycle is one complete oscillation: *eg* from one moment of passing through a given "point" to the next moment of passing through the same "point" in the same direction.

b. *Period.* The period of an oscillation is the time taken for one cycle.

c. *Frequency.* The frequency of an oscillation is the number of cycles that occur in a given time. It is usually measured in Hertz (Hz) or the multiples kHz (1,000 Hz) and MHz (1,000,000 Hz).

d. *Amplitude.* The amplitude of an oscillation is the greatest variation of displacement, current, *etc*, from the centre point or zero value.

e. *Phase.* The time-relationship of two oscillations at the same frequency and both going on at the same time is expressed as their difference in what is called phase. Two such oscillations are shown in Fig 20–6, where they can be seen to be always out of step by a fixed interval of time. This interval is quoted as a fraction of a cycle, counting the full cycle as 360° or 2π radians (the period of variation of the sine), and is called the phase difference. Two oscillations in step, with zero phase difference, are said to be in phase; if they are half a cycle out of step, with 180° phase difference, they are called exactly out of phase or in anti-phase. The oscillations in Fig 20–6 are about 90° (one quarter of a cycle) out of phase with one another. Clearly a phase difference of a whole cycle (360°) is exactly the same as zero phase difference, and all possible phase differences can be specified by amounts between 0° and 360°.

2034. So far only simple harmonic oscillations have been dealt with; but a very important theorem (Fourier's Theorem) shows that any oscillation at all, provided it is periodic (*ie* repeats itself regularly), can be built up by combining suitably chosen harmonic oscillations of different frequencies and amplitudes, and it will be clear that all the terms explained in para 2033 apply to any oscillation.

Waves

2035. The ripples spreading outwards on a pond from the fall of a stone are easily seen, experimented with and understood, so they are perhaps the most familiar kind of wave motion. Sound also, spreading out through the air from a source (a speaker's mouth or a musical instrument), is now generally known to be made up of waves. The simplest waves of all can be made by holding one end of a clothes-line that is supported at the other end but not taut, and moving it up and down: the motions of one's hand will pass along the line in the unmistakable form of a wave.

2036. What have these things in common as waves? The clothes-line waves move in one dimension, the ripples in two, while sound travels in all three dimensions of space; in the first two something material, string or water, is visibly displaced by the motion, while sound, as the eardrums will witness, is made up of variations in the pressure of the air. But in all three

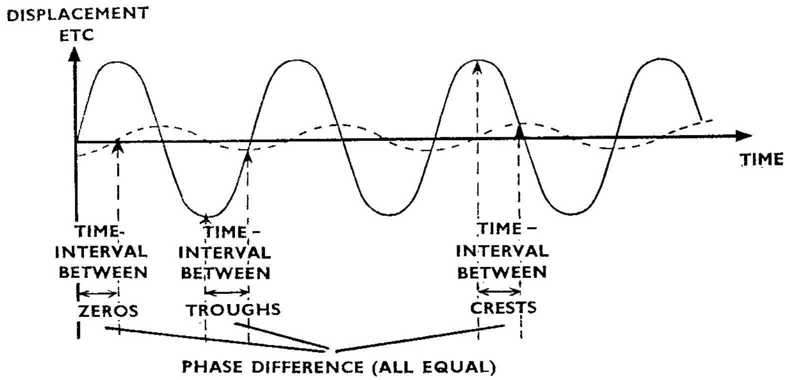


Fig 20–6 Phase Relations

it is a disturbance or pattern that moves, while the medium (string, water, or air) stays in its place, only agitated as the wave passes through it, as it were handing the movement on. This is the characteristic of wave motion, to transport energy without also transporting matter. One must not suppose that a material medium is essential to a wave; if the disturbance is in something that is independent of matter in producing its effects, such as an electric field, then clearly the wave needs no substantial medium.

2037. Imagining these waves to be steadily maintained from their sources by regular sinusoidal vibration, the reader will see that at each point affected by the wave there is a simple harmonic oscillation going on—each point of the string is moving up and down, each point of the pond's surface is rising and falling, the pressure of the air at each point is increasing and decreasing rhythmically. Also, the profile of the disturbance along a radius from the source appears as a sine-wave with crests and troughs, moving steadily forward through the medium (Fig 20–7). This is easier imagined than drawn, because its essence is change.

e. *Phase*. In para 2033 it was explained how the idea of phase is used to express the time-relationship between two oscillations at the same frequency. This idea can be used to compare the oscillations produced by one wave at two points or by two waves at one point, or for many similar purposes.

It can be shown that if the wave velocity is v, then

$$f\lambda = v$$

This simple relationship between frequency, wavelength, and wave velocity is of great practical importance.

2039. There is one important difference between sound and water-waves. In water-waves (also in clothes-line waves) the vibration is going on at right-angles to the direction in which the wave travels, while the vibrations of the particles of air in sound are actually along the line of travel and not sideways. So there are two kinds of waves: the transverse or sideways, where the oscillation is at right-angles to the line of advance, and the longitudinal where oscillation and motion are in the same direction.

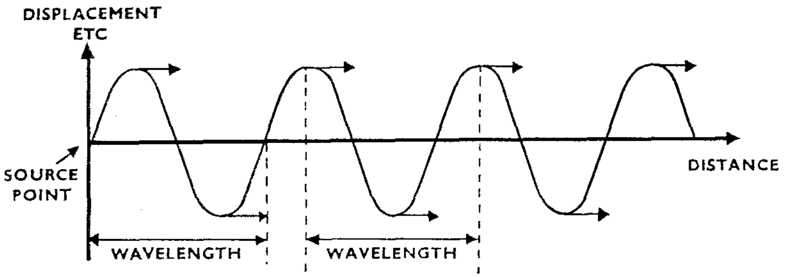


Fig 20–7 Wave Profile

2038. The following terms are in common use when discussing waves:

a. *Amplitude*. The amplitude of the wave is the greatest value of the disturbance.

b. *Wavelength*. The wavelength is the distance in which the wave profile repeats itself, *eg* the distance between crests. Its customary symbol is λ.

c. *Frequency*. The frequency is the number of waves passing any point in a given time, which is also the frequency of the harmonic oscillation at each point. The symbol for frequency is usually f.

d. *Velocity*. The velocity of the wave is the velocity or speed with which the profile moves forward.

Properties of Wave Motion

2040. **Reflection.** When a train of ripples on the surface of a pond reaches the edge, it sets off another train of ripples moving away from the edge; when a burst of sound strikes a wall, it returns as an echo; and even the waves that were made to travel along a clothes-line start to come back when they reach the far end which is fixed. This is reflection, a mode of behaviour common to all types of wave. When a wave strikes a surface obliquely, it is reflected obliquely so that the angles of incidence and reflection are equal, as shown in Fig 20–8. The reflections appear to come from an image of the source that is as far behind the surface as the source is in front of it. The reflection (of waves in two or three dimensions) from a small

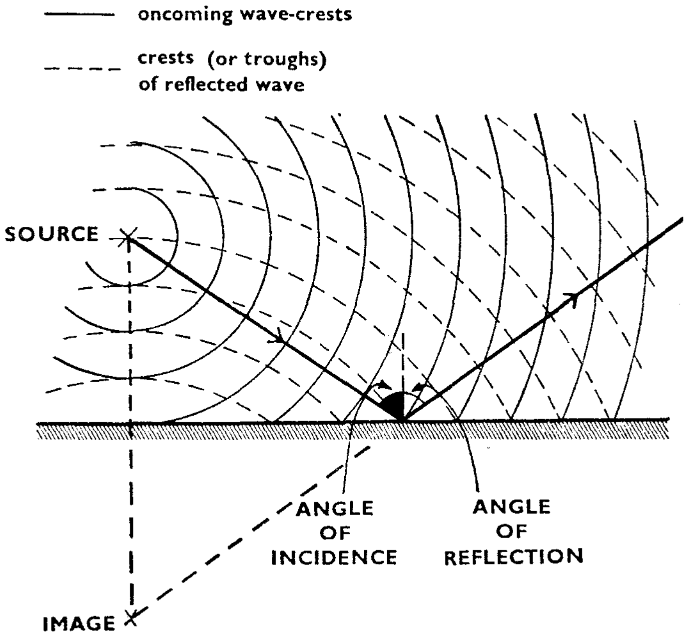


Fig 20–8 Reflection

object is in all directions, and is often known as scattering; smallness is judged by comparison with the wavelength of the waves, and an object much smaller than the wavelength scatters waves only very slightly. Reflections from the different parts of an object much larger than the wavelength tend to reinforce one another in some directions only, and so give the familiar impression of directional reflection.

2041. **Refraction.** The velocity of a wave depends on the medium in which it is travelling; if a wave moves from one medium into another so that its velocity changes, then, since its frequency cannot change, it must alter its wavelength according to the equation $f\lambda = v$ (*see* para 2038). It will be seen from Fig 20–9 (in which, for simplicity, plane waves are shown) that the change of wavelength means a change in the direction of the wave. This bending of a wave as it passes from one medium to another is called refraction. The wave is bent towards the normal (the line at right-angles to the surface) as it passes into a denser medium. Part of the wave is also reflected from the boundary instead of passing through, though in conditions like those shown in Fig 20–9 it is only a small part. A wave coming out of a dense medium into a lighter one gets bent away from the normal. At a certain critical angle of incidence the wave is bent so far that it glances along the boundary surface. Any wave arriving at a greater angle cannot get through, and has no choice but to be reflected; this is known as total internal reflection (Fig 20–10).

2042. **Diffraction.** So far it has been assumed that waves travel in straight lines; but it is common knowledge that something like a screen does not cast a sharp shadow for sound, and that although the sound is cut off immediately behind the screen it can be heard by moving back a short distance; that is, it spreads round. This spreading is a characteristic of all waves, and is called diffraction. It can very clearly be seen when ripples on a pond encounter an obstacle that they cannot move, and the instantaneous form of the resulting wave-crests is shown in Fig 20–11. The degree of this spreading effect is governed by the size of the obstacle compared with the wavelength: if it is large in proportion, it will seem to cast quite a sharp shadow; if it is about the same, a small fuzzy shadow like the one in Fig 20–11 will be cast; and if it is small in proportion there will be no shadow at all and it will have hardly any noticeable effect on the waves. Diffraction also makes it possible for waves to spread round corners and out of holes, but the extent of the spreading away from the straight-line path is always governed by the size of the wavelength. The shadow cast by an edge or small object is

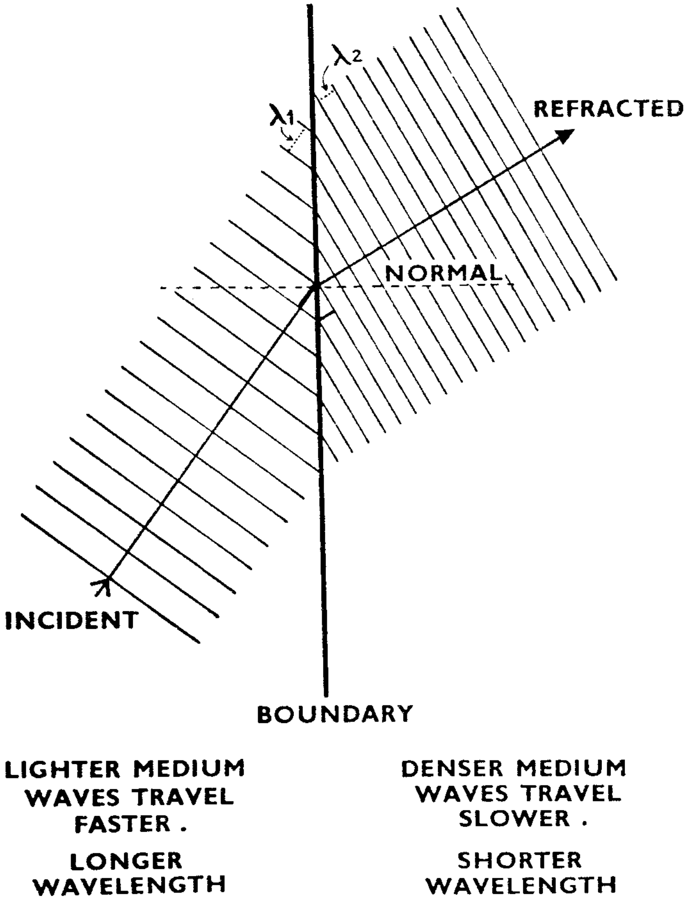


Fig 20–9 Refraction

also bordered or surrounded by a series of fringes or zones of varying disturbance. The spacing apart of these zones is governed by the size of the wavelength and they can be shown to be caused by diffraction: they are generally known as diffraction patterns.

2043. **Interference.** If two waves of the same sort are passing through the same region then they must combine, since the disturbance at any one point cannot be two things at the same time. The disturbance created by the two waves are added together algebraically: if they are in the same sense (say, both upwards) then they reinforce; if they are in opposite senses the total disturbance will be less than either component, and may be nothing at all. In this way, if the two waves have the same frequency (and wavelength, of course) an interference pattern will be formed of places of double disturbance separated by places of complete calm. What happens at any point is decided by the phase difference between the oscillations that the two waves produce at that point. If they are in phase they will reinforce, and if they are in antiphase they will cancel one another out. First let us consider two sources A and B that are in phase. A point equidistant from them receives crests from both at the same time, *ie* in phase. But a point that is a half-wavelength nearer to B than to A will be getting crests from A at the same time as troughs from B, *ie* in antiphase. So the phase difference at any point P is determined by the difference PA–PB between its distances from A and B, and this is called the path difference. It is possible to work out the shape of interference patterns, which are important in radar. Of course a pattern may be formed by the waves from any number of sources all of the same frequency; or even by a wave and its reflection from a surface, as if the source and image were interfering.

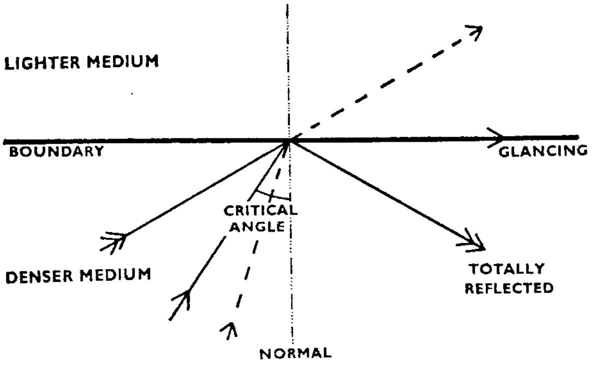


Fig 20–10 Total Internal Reflection

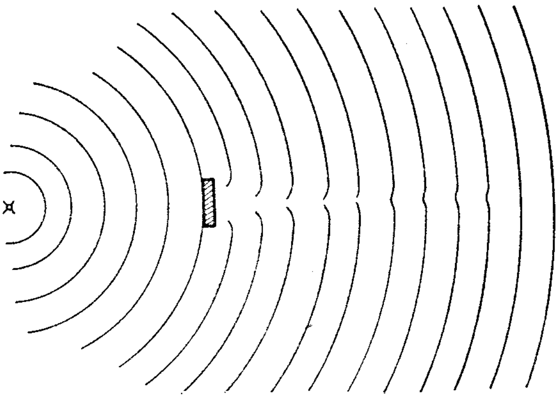


Fig 20–11 Diffraction: Form of Wave Crests

2044. **Polarization.** The waves on the clothes-line were thought of as up-and-down waves generated by moving the hand vertically. But side-to-side waves could be obtained by a sideways movement, and even combinations of the two by moving the free end of the line in a closed curve like a circle. Generally speaking, the direction in which transverse waves oscillate is open to choice, though it must be at right-angles to the direction in which the wave is travelling. If the oscillations are in one direction only, as in the first two examples above, the wave is plane polarized, and the plane containing the directions of oscillation and wave motion is called the plane of polarization. The third example, in which the free end of the line moves in a circle, is a combination of two oscillations of equal amplitude at right-angles to one another, and this wave would be called circularly polarized (left- or right-handed according as the rotation of the end makes a left- or right-handed screw along the direction of travel). Longitudinal waves cannot be polarized, since they have only one possible direction of oscillation; thus there is no such thing as polarized sound.

2045. **Absorption.** Sound waves get weaker the further away they are from their source, because the energy from each oscillation of the source is spread out over the surface of an expanding sphere as the wave advances. Clearly the amplitude of the wave is inversely proportional to the surface area of the sphere, and is thus inversely proportional to the square of its distance from the source. These waves also lose energy in overcoming the resistance, or friction, of the medium; hence, even when they flow along a channel or tube that prevents them from dispersing, they still weaken and die out at a distance. This loss of energy to the medium is called absorption; the energy normally being converted into heat.

2046. **Doppler Effect.** The velocity of waves is not usually affected by movement of their source; but if either or both of the source and observer are moving, so that the source is moving in relation to the observer, then the waves between them will be crowded up if they are closing together, or spread out if they are moving apart. The result of this is that the wavelength and frequency appear to the observer to be altered. This shifting of frequency is called the Doppler effect, and is familiar as the drop in pitch of the whistle of a railway engine or the exhaust of a motor car when either passes close by. The shift can be calculated, and is roughly proportional to the speed of the source relative to the observer. When a Doppler shift is very slight it may be more easily perceived as a change of phase than of frequency.

Electromagnetic Waves

2047. Let us imagine that a rapidly oscillating electric current is made to flow in a wire made of some conductor. It has been seen in para 2012 that such a changing current must give rise to changing electric and magnetic fields about the wire. Though the nature of the fields is not intuitively obvious, it can be found by mathematical deduction from the laws of electricity and magnetism, and it can also be confirmed by experiment that such oscillating fields spread outwards from their source instead of being localized; the manner of the spreading is by wave motion, as discussed earlier in these paragraphs.

2048. The waves are called electromagnetic waves (EM waves), since they are a disturbance

5513 C

FREQUENCY	WAVELENGTH (In free space)	BAND DESIGNATION	USES: COMMUNICATIONS	USES: RADAR
AL8 ~~Kc/s~~ KHz 3	100 Km	VLF (Very Low Frequency)	LONG-RANGE UNDERWATER ETC.	
30	10 Km	LF (Low Frequency)	LONG-RANGE SHIPS & BROADCAST	
300	(1,000 metres)	MF (Medium Frequency)	BROADCAST	
AL8 ~~Mc/s~~ MHz 3	100 metres	HF (High Frequency)	LONG-RANGE AIR-TO-GROUND & GROUND-TO-GROUND BROADCAST	
30	10 metres	VHF (Very High Frequency)	SHORT RANGE GROUND-TO-AIR & GROUND-TO-GROUND	
300	1 metre	UHF (Ultra High Frequency)	SHORT-RANGE GROUND-TO-AIR	~~L BAND~~ AL4
3,000	10 cm	MICROWAVES	BEAMED SHORT-RANGE RELAYS	~~S BAND~~ ~~C BAND~~ ~~X BAND~~ ~~J BAND~~ ~~K BAND~~ ~~Q BAND~~
30,000	1 cm			
300,000	1mm			
AL8 Hz ~~c/s~~ 3×10^{12}	0·1mm (100μ)	INFRA-RED RADIATION		
3×10^{13}	0·01mm (10μ)			
3×10^{14}	0·001mm (1μ or micron)	VISIBLE LIGHT		
3×10^{15}	10^{-7} metres (0·1μ, 1,000 Å)	ULTRA-VIOLET RADIATION		
3×10^{16}	10^{-8} metres (100 Å)			
3×10^{17}	10^{-9} metres (10 Å)	X-RAYS		
3×10^{18}	10^{-10} metres (1 Å or Ångström Unit)			
3×10^{19}	10^{-11} metres (0·1 Å)			
3×10^{20}	10^{-12} metres (0·01 Å)	GAMMA RAYS		
3×10^{21}	10^{-13} metres (0·001 Å)			

Fig 20–12 Spectrum of Electromagnetic Waves

of both electric and magnetic fields (it is impossible for either the electric field or the magnetic field to vary without the other of the two also varying). Electromagnetic waves in free space are transverse waves; they generate oscillating electric and magnetic fields in such a way that these two inter-linked oscillations at any point of space, are always at right-angles to one another, always in phase and always with their amplitudes in a constant proportion to one another. Since electric and magnetic fields can exist independently of matter, electromagnetic waves need no material medium to support them. The velocity of electromagnetic waves in free space is found both by calculation and by measurement to be 299,774 kilometres per second; for practical calculations it is usually taken as 300,000 kilometres (3×10^8 metres), 162,000 nautical miles, or 186,000 statute miles, per second, and it is given the symbol c. This speed is exactly the measured velocity of light in a vacuum.

2049. Before the discovery of electromagnetic waves, light had been thought to be a form of wave motion because it could be reflected and refracted and behaved like waves in many other ways. There were difficulties in this idea; light could obviously travel with great ease through a vacuum such as separates the earth from the sun and stars, yet no wave was then known that did not need a material medium to support it; and light appeared to travel in straight lines without diffraction, unlike the then familiar forms of wave motion. The second difficulty was removed when it was understood that the wavelengths of visible light were very small indeed (between 0·00004 and 0·00008 centimetres) and that diffraction and interference effects could only be produced with it on this small scale. It was eventually realized that the first of the two problems had arisen from too narrow a conception of wave motion. Uncertainty about the wave theory of light seemed to be cleared up by the existence of electromagnetic waves travelling at the velocity of light, since all the known facts would be explained by assuming that light was just an electromagnetic wave of very high frequency and small wavelength—and that is the basis of the present theory of light.

2050. A very wide range of electromagnetic waves is known and used: those with wavelengths less than a millimetre are usually considered as light, and those with wavelengths greater than a millimetre as radio waves. It should be clearly understood that there is no fundamental difference between light and radio waves; the outward distinction between them arises entirely from the great disparity between their usual wavelength ranges. A spectrum of electromagnetic waves is shown in Fig 20–12; it is drawn on a logarithmic scale of wavelength, and shows frequencies, uses, and the generally accepted names of the different frequency ranges. For all electromagnetic waves the frequency f in Hz and the wavelength λ in metres are related by:

$$f\lambda = c = 3 \times 10^8 \text{ metres/second.}$$

2051. Electromagnetic waves possess all the common properties of wave motion, and these are reviewed in the following sub-paras:

a. *Reflection.* Light and radio waves are reflected or scattered by objects or surfaces in the manner described in para 2040. The efficiency of reflection (the ratio of the amplitudes of reflected and incident waves) depends largely on the electrical conductivity of the surface; good conductors reflect strongly, while poor conductors reflect rather weakly except in total internal reflection. Reflection from a smooth surface is regular, according to the law explained in para 2040, and is called specular reflection: the reflection of light by a silvered mirror or polished surface is a familiar example. But if a surface has irregularities of a greater order of size than the wavelength, then it will reflect irregularly and tend to scatter the incident waves in all directions, as light falling on a sheet of blotting-paper is scattered.

b. *Refraction.* The velocity of electromagnetic waves depends on the medium in which they are travelling, and is always slightly less than c except in free space. On passing from one medium to another they are refracted as described in para 2041; the refraction of light on passing from air into glass or water is very familiar. Poorly conducting materials reflect a proportion of any electromagnetic waves falling on them, but in general refract the rest, which may then rapidly be absorbed. The refractive index of a medium is defined as the ratio:

$$\frac{\text{Velocity of electromagnetic waves in free space}}{\text{Velocity of electromagnetic waves in medium}}$$

This ratio can never be less than 1, but is very nearly equal to 1 for air. In general, the denser a transparent medium, the higher is its refractive index. When electromagnetic waves pass obliquely from one medium into another of lower refractive index, they are bent away from the normal (*ie* the direction at right-angles to the surface).

c. *Diffraction.* All electromagnetic waves show diffraction, but the size of the wavelength governs the scale of the effect: thus light travels in straight lines according to everyday experience, and specially designed experiments are needed to show up its spreading and diffraction patterns; while very long radio waves can spread out-of-the-straight round the earth's surface so as to give useful intensities tens or hundreds of miles beyond the horizon. Diffraction patterns are important in the study of detail by means of light or radio waves. This behaviour of light waves can in most familiar cases be explained by geometrical optics, which considers them simply as rays following straight-line paths: this hypothesis is not always so satisfactory for radio waves, and they must quite often be treated by wave theory.

d. *Interference.* The scale of magnitude of interference effects is also related to the wavelength, so that they are only of academic importance with light but of great practical importance with the waves used in radar.

e. *Polarization.* Since electromagnetic waves are transverse, they can be polarized. The custom in the United Kingdom is to define the plane of polarization as the one in which the electric field varies and the wave advances (in the United States it is defined as the one in which the magnetic field varies and the wave advances, which means a wave that is regarded in the United Kingdom as vertically polarized is regarded in the United States as horizontally polarized). Light is not normally plane polarized but can be made so by passing it through special materials such as the now familiar polaroid. Radio waves are normally plane polarized by the nature of their origin. The exact manner in which a plane polarized radio wave is reflected by a surface such as the ground or the sea depends on whether its polarization is parallel to the surface or not. Radio and light waves can also be circularly polarized: this is equivalent to combining two waves of equal amplitude, differing in phase by 90° and polarized in planes at right-angles to one another.

f. *Absorption.* Light is strongly absorbed by many materials (there are not many transparent solids), and the shorter radio waves are quite easily absorbed by some gases and most liquids and solids, but the longer radio waves are normally only very slightly absorbed by any non-conducting medium. As one would expect, when electromagnetic waves fall on a conductor they set up currents in it and cannot penetrate far before being damped out.

g. *Doppler Effect.* The apparent shift of frequency (or phase) when a source of light or radio waves is moving relative to the observer is now well known, and has been put to good use in radar and astronomy.

2052. Energy resides in any electric field, as shown by the work it can do by moving an electric charge such as an electron; and in a similar way a magnetic field possesses energy. The energy in an electromagnetic wave may be thought of as divided between the electric and magnetic fields, and is demonstrated in the heating effect produced by light (particularly infra-red) and the currents induced by radio waves. The energy flows outwards from the source of the waves with a velocity that can be shown to be the same as the velocity of the wave motion. The power of the source is the rate at which it gives out energy in the form of electromagnetic waves.

Propagation of Radio Waves

2053. So far we have not considered what effect the form of a conductor has on its ability to act as a source of EM waves when carrying an oscillating current. For practical purposes a specially shaped conductor, called an aerial (in the United States, an antenna), is needed for efficient radiation. Moreover, if radio waves fall upon such a conductor they will induce oscillating currents in it; thus it will serve either as a transmitting or a receiving aerial. Aerials used in radar are discussed in Chapter 21.

The Ionosphere and its Effects

2054. The atmosphere surrounding the earth is subjected to a bombardment of ultra-violet and cosmic rays emitted by the sun. The energy from these rays is absorbed by the atoms of gas in the atmosphere, and some of the orbiting electrons are displaced, forming positive ions and free electrons. Thus the gases are ionized and, due to the increased numbers of free electrons present, the conductivity is greatly increased compared with that of the normal gas. As the solar radiation penetrates deeper into the atmosphere so it becomes weaker, and ionization decreases; furthermore, since pressure of the gases increases nearer the earth, the electrons recombine with the positive ions to re-form neutral atoms. In the upper regions however, where radiation is more intense and atoms more widely spaced, ionization persists. The part of the atmosphere where ionization occurs is called the ionosphere. It extends from approximately 30 miles above the earth's surface to at least 250 miles. In this region there are several ionized layers. There are three main layers of ionization in the ionosphere, called the D, E and F layers in ascending order. They vary in degree of ionization and in effective height, according to the time of day or night, and season of the year. At times the F layer can be divided into two layers, F_1 and F_2. Because of the limited rate of recombination in the higher regions, a certain degree of ionization persists throughout the night, despite cessation of solar radiation. An indication of the heights of these layers for winter and summer, day and night is given in Fig 20–13 but it should be noted that the heights vary and are only approximate. During day time the ionosphere consists of the D, E, F_1 and F_2 layers whilst at night the D layer disappears and the F_1 and F_2 layers combine to form a single F layer. The degree of ionization and hence the conductivity of the E layer decreases at night. The layer is then referred to as the residual E layer.

2055. The ionosphere layers are not clear-cut like petrol on water, and radio waves are not abruptly reflected by them, but are gradually refracted along curved paths that may lead back to the earth's surface. The extent of this refraction depends on frequency, and as the frequency increases the wave must be more and more oblique to be bent back to the earth, until a critical frequency is reached (2 to 4 MHz for the E region, 20 to 40 ~~HHz~~ MHz for the F region) above which there can be no "reflection" by the layer. Frequencies above the critical pass through the ionosphere out into space. The bending of waves below the critical frequency is very much like reflection in many ways, and for practical purposes is treated as if it were reflection. But it must be remembered that in bending a wave the ionosphere also absorbs some of it, and this absorption may sometimes seriously weaken the transmission.

2056. Thus radio waves may reach their destination either directly or by reflection in the ionosphere. The direct transmission is called the ground wave and the reflected one the sky wave (Fig 20–14). The ground wave can travel some way beyond the straight-line optical horizon both by diffraction, which is more important for the longer wavelengths, and by refraction in the

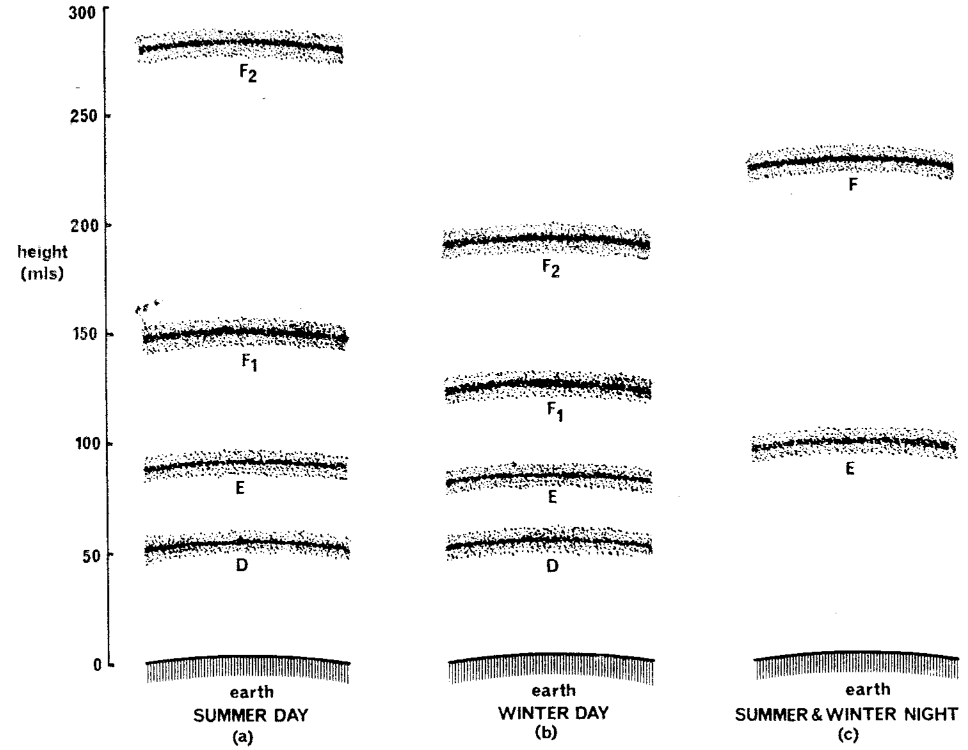


Fig 20–13 Ionization Layers

atmosphere (the density of air decreases with height, so waves are generally bent downwards), but it is obviously limited in extent; its farthest reach along the earth's surface is shown in Fig 20–14 as point A, which might be as far as 500 miles for a frequency of 30 kHz but is much less for the frequencies in common use. For any frequency there is a minimum angle of incidence at the ionosphere (α) below which waves are not reflected but pass through. This angle α varies seasonally and also from day to night and from night to day, and together with the height of the reflecting layer it fixes a nearest point that can be reached by the sky wave. This is shown as B in Fig 20–14, and the distance to it is called the skip distance. The region between A and B, where nothing is received by either ground or sky wave, is called the dead space.

2057. As the wavelength increases, so A becomes farther and B becomes nearer, and generally for MF and LF waves there is no dead space. Sky waves can be reflected from the earth up to the ionosphere again, and if the angle of incidence is right they can travel round the earth by rebounding between the two. Thus it is possible to receive at one point both ground wave and sky wave, or two sky waves that have come by different routes. Since these have not had the same distance to travel from their source, there will be a path difference (and hence a phase difference) between them, and this may lead them to cancel out partly or completely. This cancellation is the familiar fading, and it is not steady but varies with the constant shifting of the ionosphere, so that the strength of the received signal is continually varying and at times fades away completely.

2058. **Summary of Propagation Theory.** The following table summarizes the different means of propagation. This divides radio frequencies from 10 kHz to 300 MHz into five bands; the main features of propagation in each band are summarized under these band headings.

Band	Frequency	Wavelength
LF	10 kHz to 300 kHz	30,000m to 1,000m
MF	300 kHz to 3 MHz	1,000m to 100m
HF	3 MHz to 30 MHz	100m to 10m
VHF	30 MHz to 300 MHz	10m to 1m
UHF	Above 300 MHz	Below 1m

a. *LF Band.* This is the low frequency (LF) band and propagation by ground wave gives reliable and stable reception for ranges up to 1,000 miles. At these frequencies the ionized layer may be considered as an almost perfect reflecting surface and greatly increased ranges are obtained from a ray reflected between the lower edge of the ionosphere and the surface

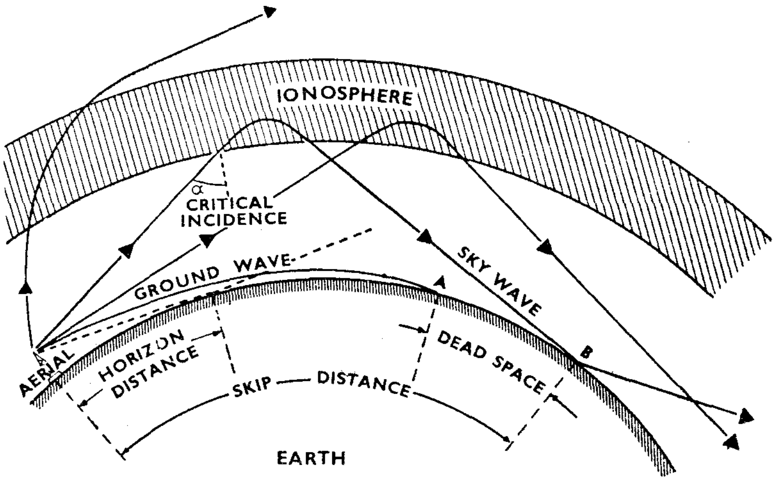


Fig 20–14 Propagation of Radio Waves

of the earth. Frequencies in the LF band are used for very high grade transoceanic telegraph communications and are practically free from fading. Communication in this band is subject to atmospheric interference caused by electrical discharges from clouds, and from man-made interference caused by unsuppressed electrical apparatus.

b. *MF Band.* This is the medium frequency (MF) band and provides high quality reception within a limited area. A station of medium power has a service radius of the order of 100 miles, the signal being provided by the ground wave. Beyond this is a zone of fading where signals are not normally received in daylight beyond about 150 miles from the transmitter over land, or 600 miles over water. During night time, when ionization is low, the sky wave is only slightly attenuated and reception (subject to severe fading) is possible up to 1,000 miles. The portion of the band between 1·5 MHz and 3 MHz is erratic and unsatisfactory for distant communication because of large losses in the ionosphere. Frequencies in this band are subject to the same type of interference that affects the LF band.

c. *HF Band.* The high frequency (HF) band is used for long distance communication. The sky wave is used, and frequencies are selected by means of prediction charts. The part of the band from 3 MHz to 6 MHz is used for communication within the limits of a continent,

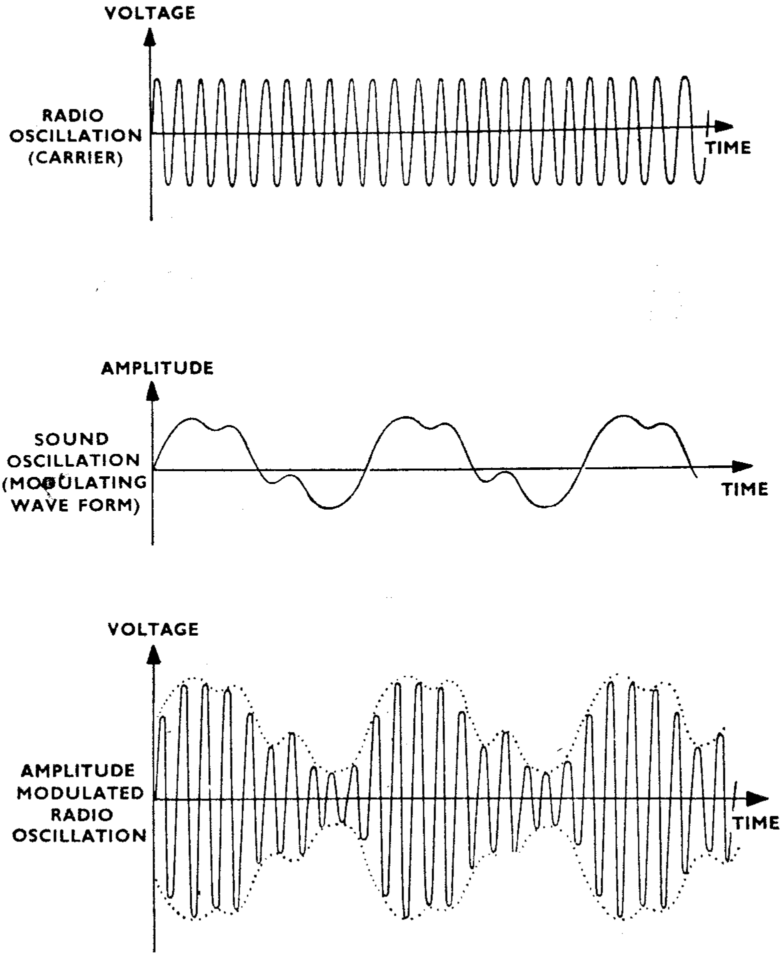


Fig 20-15 Amplitude Modulation

and above 6 MHz, by reason of the longer skip distances, for inter-continental communications. Short ranges inside the skip distance are covered by the ground wave. Atmospheric and man-made interference is not nearly so severe on frequencies in this band. However above 20 MHz, radiation from the sun and from nearby galaxies produces a "hissing" interference noise.

d. *VHF Band.* For frequencies above 30 MHz, the sky wave is not regularly returned to the ground, and the ground wave is rapidly attenuated. Communication is maintained within, or somewhat beyond the optical horizon, by means of the space wave. Short range reception within built up areas is possible, making this very high frequency (VHF) band usable for short range communication services, television and VHF broadcasting. Greatly increased line-of-sight ranges are obtained in communication between high flying aircraft and ground stations. Frequencies up to 60 MHz are used for ionospheric scatter propagation and ranges of the order of 1,000 miles are obtained.

e. *UHF Band.* Frequencies in the ultra high frequency (UHF) band provide line-of-sight reception between two stations, and are widely used for radar, navigational aids and landing aids. Both VHF and UHF bands are virtually free from atmospheric interference, but they are affected by solar and galatic interference. Above 500 MHz tropospheric scatter provides limited reception up to ranges of 400 miles.

Modulation

2059. Only unvaried radio waves (often known as CW—continuous wave) have been discussed so far, and these are, in themselves, uncommunicative; if they are to convey a message or be used in radar, a pattern must be imposed upon them. The imposition of a pattern on steady oscillations or waves is called modulation, and the method and manner of modulation is decided by the form in which intelligence is to be communicated, or the purpose of the radar system. The following methods of modulation are in common use:

a. *Keying.* The simplest way of sending a message by radio is to switch the transmitter on and off as one does with a signaller's lamp, using a code (almost always the Morse code) of long or short bursts for letters. The switching or keying is done with a Morse key, and the system is known as wireless telegraphy (WT).

b. *Amplitude Modulation.* Keying does not make it possible to transmit speech by means of radio waves, and to do this one must somehow take the pattern of the sound wave profile that is speech and impose it on the radio waves. The most obvious way of doing this is to make the amplitude of the radio waves vibrate in the same pattern as the sound (Fig 20–15 is an illustration of this, though it must be realized that in practice the sound and radio frequencies would be much more widely different). The transmission of speech by radio is called radio telephony (RT) and this method of doing it is called amplitude modulation (AM).

c. *Frequency Modulation.* Instead of varying the amplitude of the radio waves, one can vary their frequency in a pattern corresponding to that of the sound to be transmitted. This method is known as frequency modulation (FM).

d. *Pulse Modulation.* In radar a variety of keying is used in which a regular succession of short pulses of radio waves is sent out. This pulse modulation is discussed in Chapter 21, paras 2126–2129.

2060. All methods of modulation act to change a steady radio wave or oscillation into a more or less irregular one, and a modulated radio wave or oscillation must contain some components of frequencies different from the unmodulated frequency, because a single frequency means a steady wave or oscillation. The frequencies of these components are usually quite close to the unmodulated or carrier radio frequency, both above and below it; the components are thus said to be grouped in upper and lower sidebands. Sidebands may be of finite extent, as in amplitude modulation (*see* para 2061); or they may contain an infinite series of components which are smaller and smaller in amplitude the further they are from the carrier frequency (this is the form of the sidebands for frequency modulation and pulse modulation). The sidebands of a modulated oscillation are the frequencies that must be passed by a radio transmitter or receiver in order to reproduce the modulation faithfully. Many a radio circuit is designed to pass only a band of frequencies (called its bandwidth), and this must be wide enough to handle the sidebands of the modulation in use. Where the sidebands are finite in extent (as with AM), the bandwidth simply needs to include all their components: but no clearly defined bandwidth can be specified for handling an infinite series of sideband components and a compromise has to be made between the need for narrow-bandwidth circuits and the need for faithfulness of reproduction.

2061. If a carrier oscillation at frequency f is amplitude modulated at frequency F, the resulting oscillation can be shown to be exactly the same as that produced by adding to the carrier two oscillations of equal amplitude at frequencies $f + F$ and $f - F$ in a certain proportion. These two oscillations are the upper and lower sidebands of the amplitude modulation; *eg* if a wave or oscillation at 1 MHz is amplitude modulated at 10 kHz (0·01 MHz) then the sidebands are at 1·01 and 0·99 MHz. Thus the sidebands of an amplitude-modulated wave are two in number for each modulating frequency F, and they are spaced above and

(*Continued on next leaf*)

below it by an amount equal to F; the bandwidth of the modulation is 2F. The sidebands of AM RT are made up of such pairs of components, one pair for each frequency in the speech oscillation; and the bandwidth is twice the highest frequency in the speech.

2062–2064. (*Not allotted*).

THERMIONIC ELECTRONICS

Thermionic Emission

2065. The molecules in any form of matter (gas, liquid, or solid) are not at rest but constantly moving to and fro and colliding with one another, though the scale of this motion is too small to be seen with the unaided eye. The closeness of their packing determines whether the matter forms a solid, liquid, or gas; and their average velocity gives the temperature (which is proportional to the root mean square molecular velocity), for heat is just the form in which the energy of motion of the molecules is preceived. There is a temperature called the absolute zero (about −273°C) at which all molecules would be still, though this can never quite be reached; if a body is warmed up from a very low temperature the molecules in it gradually move faster and faster; and, as they force one another apart more and more violently the substance passes from solid to liquid and then from liquid to gas (or, sometimes direct from solid to gas), until at some stage the molecules themselves cannot hold together and they disintegrate into atoms.

2066. As a conductor is heated this molecular movement is passed on to the free electrons in it, and because they are so much lighter than the molecules they can escape from the surface long before the conductor turns to gas. This "boiling off" of electrons from a heated conductor is called thermionic emission. If the conductor is surrounded by a gas, such as air, then the electrons will quickly be captured by the gas molecules, ionizing them, and will not get far or last long as free electrons. But if the conductor is surrounded by a vacuum, so that the electrons are free to move as they please, they will be attracted by the residual positive charge that they have left behind them, and will hang round the conductor in a cloud which is called the space charge.

2067. If now another conductor is placed inside the vacuum and is made electrically positive to the heated one, then the electric field between the two will exert a pull on the negative electrons and draw them towards the positively charged conductor. If the potential difference between the two conductors is kept up, so that the heated one is continuously supplied with electrons to replace those it has lost by emission, then there will be a circulation of electrons, or in other words a current. But it is obvious that to reverse the situation (to make the heated conductor more positive than the unheated one) would not make a current flow in the opposite direction, since only the heated conductor can give off electrons. So this is a one-way device, or valve.

2068. The device described in para 2067 is the simplest type of thermionic valve, called a diode. The two conductors are called electrodes: the heated one or electron-emitter is the cathode and the unheated one (which must be positive with respect to the cathode, for a current to flow) is the anode. The cathode is sometimes in the form of a filament, self-heated by the passage of a current, or it may be a metal tube specially coated with compounds that improve its electron emission and heated by a separate filament inside. For all normal purposes the vacuum is maintained inside a glass envelope and is the hardest (*ie* has the lowest pressure) that can be obtained.

2069. The diode is an excellent one-way device or rectifier, and has many uses in radio, but it is incapable of amplifying; and without amplification wireless and radar would be nothing. A third electrode is needed for this purpose; it takes the form of a grid or wire mesh, which is mounted close to the cathode and made electrically negative to it so as to control the space charge or cloud of electrons round the cathode. If the grid is made negative enough, it can prevent any electrons passing through and reaching the anode, thus cutting off the current through the valve. If it is less negative than this, then by its effect on the electric field within the valve, it restricts and controls the flow of electrons. Quite small changes in the potential difference between grid and cathode (grid voltage) can produce proportionately large changes in the current through the valve; thus the valve can function as an amplifier. This three-electrode valve is the triode; many other more complicated valves are used with more than three electrodes, but they rely essentially on the principles given here.

Uses and Applications

2070. Thermionic valves are used in wireless and radar to generate and amplify oscillating voltages and currents. Circuits also contain resistances and such electrical devices for controlling the flow of oscillating currents as coils (inductances), transformers, and capacitors, and all the circuit components are connected where necessary by wires or printed circuits. At very high frequencies and wavelengths of only a few centimetres no attempt is made to construct wired circuits, and the electrical oscillations are handled as EM waves confined within waveguides or cavities, as described in Chapter 23.

2071. **Amplification.** The signal induced in a receiving aerial by radio waves from a transmitter hundreds or thousands of miles away are very small (usually measured in microvolts), and they must be boosted or amplified many times before they can be made to affect the senses and convey the information they carry. Valves are used to give this amplification, which is usually done in stages; for example, to amplify a signal to 100,000 or 10^5 of its original amplitude (and even higher amplification is used in radar) one might use five valves one after the other and each giving a multiplication of 10, or one might use two valves each multiplying by 100 followed by one multiplying by 10. The factor of multiplication given by an amplifier is called its gain, and is often quoted in decibels; in the above example the voltage gain of 10^5 (equivalent to a power gain of 10^{10}) would be an overall gain of 100 dB, and the stage gains proposed were either five steps of 20 dB or two steps of 40 dB and one of 20 dB. The reader will notice how stage gains measured in the logarithmic scale of decibels add together to give the overall gain. A broad distinction is drawn between amplifying at the audio frequencies (AF) up to 20 kHz, which are the frequencies of audible sound waves, and amplifying at the radio frequencies (RF) of the radio waves used. AF currents are produced by sound falling on a microphone, and when passed through a loudspeaker they reproduce the sound that they correspond to; they are used in RT to modulate the RF carrier (*see* paras 2601 and 2602) which is radiated into space. RF amplifiers usually amplify only a fairly narrow band of frequencies; since the sidebands of the modulation in use (AM, FM, pulse, *etc*) must be properly amplified in order to preserve the shape of the modulation, the extent of these sidebands must determine the bandwidth of an RF amplifier; and yet the bandwidth must also be kept small enough for signals on neighbouring frequencies to be rejected.

2072. **Oscillators.** A radio transmitter must have in it a source of RF oscillating current to be fed to its aerial, there to generate radio waves; a valve circuit designed as such a source is called an oscillator. An oscillator may either generate only a small voltage which is then amplified to gain the power needed for the transmission, or at the higher frequencies the oscillator may itself give all the required power. Oscillators may in fact be designed for any frequency less than about 300,000 MHz, even down to and below 1 Hz. An RF oscillator always contains a tuned circuit or its equivalent, which fixes the oscillation frequency. In the HF, VHF and UHF bands quartz crystals usually take the place of tuned circuits made out of coils and capacitors; their special electrical and mechanical properties make them behave like tuned circuits, and not only can they be cut very accurately to the required frequency but they have the stability that is needed to prevent communications on neighbouring frequencies from intruding on one another. Tuned circuits

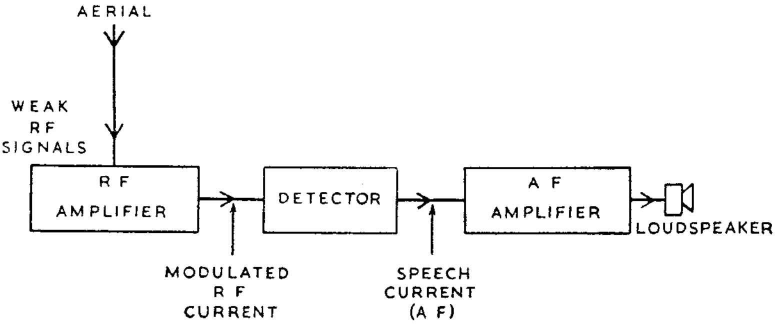


Fig 20–16 Simple Radio Receiver

are used however in frequency multiplier stages. The circuit selects the required harmonic (the 3rd harmonic would be three times the frequency of the original) by being tuned to that frequency. At extremely high frequencies (above about 1,000 MHz) the tuned circuits and valve may be combined—the magnetron is such a combination.

2073. **Detection.** When a modulated RF current has been picked up by a receiving aerial and amplified it is still not able to convey its meaning; it could not produce any sound if it were passed through a loudspeaker, because all its components have frequencies well above 20 kHz and are thus outside the audible range. A means is needed of recreating the original AF waveform that was used to modulate the radio wave, (*see* Fig 20–15) or, as it were, of reversing the process of modulation; this is called detection or demodulation. The essential working part of most detectors is a conductor that does not have the same resistance in both directions. Such a device is the diode in the form of a thermionic valve or a semi-conductor. Thus a simple receiver for RT might consist of an aerial, an RF amplifier, a detector, and finally an AF amplifier working into a loudspeaker (Fig 20–16).

Frequency Changing

2074. A receiver will have a large number of amplifying stages before detection due to the small signal received at the aerial. For a multichannel receiver (air to ground communication equipment for instance) it would be impossible to retune all of the stages simultaneously and for this reason, the superhetrodyne principle is used. The superhetrodyne receiver (Fig 20–17) uses a CW oscillator whose frequency is mode variable and whose value is dependent upon the frequency of the incoming signal. The incoming and oscillator frequencies are mixed and the difference (which is constant) is selected for further amplification. At most, only three circuits have to be tuned simultaneously, these being the RF amplifier, the mixer, and the local oscillator. The intermediate frequency ((IF) or difference frequency) displays all the characteristics of the modulated RF signal but due to its lower frequency particularly in a radar receiver, it is much more easily amplified. Example:

Incoming Frequency F_1 MHz	Local Oscillator F_2 Frequency MHz	Intermediate Frequency f MHz
300	340	40
298·1	338·1	40
3,000	3,040	40

Power Supplies

2075. Any valve circuit needs voltage to heat the cathode and a voltage to make the anode positive and drive the current through the valve (HT), together with various other bias voltages. On the ground, the power comes almost always from an AC supply (normally 230 volt 50 Hz for British equipment), and the necessary currents and voltages are derived from this supply by circuits using transformers and rectifiers; the AC for fixed installations in the United Kingdom is provided by self-contained generators or taken from the National Electricity Grid, while the AC for all transportable installations is provided by diesel-driven generators. In British fighter aeroplanes the power comes from the 27-volt DC general supply of the aircraft, either through a rotary transformer (a DC motor driving a DC generator) or through a motor alternator (a DC motor driving an AC generator) used with valve rectifier circuits. Mains electricity supplies vary occasionally in voltage, and if such variations would disturb the working of any circuit it is necessary to stabilize its power supply, *ie* to design the

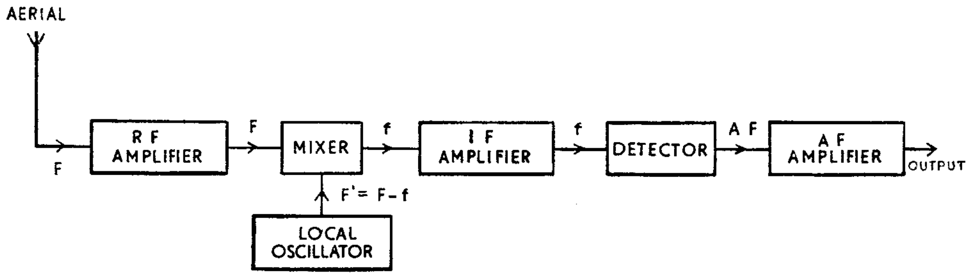


Fig 20–17 Superhetrodyne Receiver

supply circuits so that mains fluctuations do not alter their output. This can be done only for a few circuits, and variation has to be accepted in the rest if mains supplies are used.

Noise

2076. The output of any receiver contains all sorts of fluctuations or disturbances that are not related to the signals being received but tend to mask them. Such disturbances are known generally as noise (an extension of the familiar use of the word in connexion with sound): some noise is avoidable by careful siting and design, but there is always in a receiver output some unavoidable noise that cannot be reduced below a certain level. These two categories of noise are:

a. Avoidable noise which can be caused by man-made "static" (electrical disturbances from generators, ignition systems, *etc*), by bad contacts in the wiring of receiver circuits, or by the use of poor quality components. These sources of noise need no further mention.

b. Unavoidable noise may be external or internal: external noise may come from electrical disturbances such as thunderstorms in the lowest layers of the earth's atmosphere (this noise is known as static), or from more distant sources; while internal noise is generated in the components of the radio receiver. Static is important at frequencies up to 30 MHz, and may be propagated over great distances by sky-wave transmission. Quite large amounts of radio noise at frequencies between 15 and 100 MHz reach the earth from interstellar space, coming mainly in the plane of the Milky Way but also from the sun; this noise is similar to receiver noise in nature but more powerful at these frequencies. Above 100 MHz the only noise of importance is that generated in the receiver itself; this noise, rather than any restriction on the gain of amplifiers, sets a lower limit to the size of the signal that can usefully be received at such frequencies. Internal noise is described more fully in the following paragraphs.

2077. Receiver noise is made up of all the minute random electrical fluctuations that are always present in all the circuits and transmission paths of a radio receiver. The noise power generated by any component or circuit is evenly distributed over all radio frequencies, and thus the noise output of a receiver is proportional to its bandwidth B. Although the noise output is a continually fluctuating voltage, nevertheless it has, over any period of time, a predictable mean amplitude and delivers a predictable mean power. If fed to a loudspeaker or headset it produces a hissing sound, while on a Type A radar display it gives the trace an appearance sometimes described as "grass". The two main origins of the noise generated by a receiver are:

a. *Thermal Noise*. The molecules in any conductor are continually moving to and fro through very small distances, and their mean energy of motion increases with the temperature of the conductor. This motion is shared by the free electrons, and the consequent vibration of these electrons constitutes a continual minute fluctuating current in the conductor, which is called the thermal or Johnson noise. Thermal noise, which increases in power with increase in temperature, forms the irreducible minimum of noise present in the output of a receiver, and it is taken as the standard against which to compare all other forms of noise.

b. *Valve Noise*. The current through any valve in a radio receiver is carried by the movement of individual electrons from cathode to anode, and for this reason it cannot be quite continuous. The inevitable small irregularities or jerks in valve current constitute a form of noise known as shot effect or shot noise; the intensity of this noise depends on the state of the space charge in the valve, and thus on the conditions under which it is run. Another sort of noise, called partition noise, is caused by random electrons alighting on the positive grids of multi-electrode valves, and producing a noise voltage across the anode load in addition to shot noise.

2078. Any given receiver has a certain power output of noise, and if a signal after passing through the receiver is comparable in power to this noise output then it will be partly masked or blurred by the noise; while if it sinks at all far below noise level it will be lost. Hence the magnitude of a receiver's noise output sets the lower limit to the sensitivity of the receiver, *ie* to the power of signal that can be detected in the receiver output. The comparison between signal and noise is often expressed by the signal-to-noise ratio, which is defined as:

$$\text{S/N ratio} = \frac{\text{signal amplitude}}{\text{mean noise amplitude}}$$

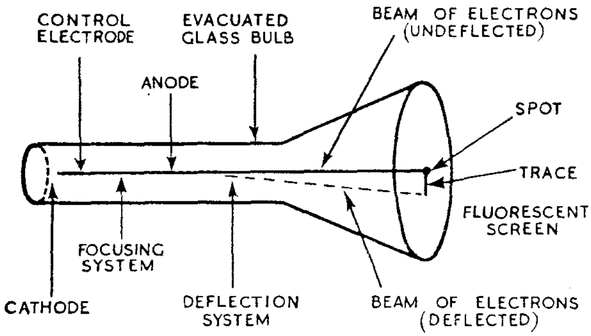


Fig 20–18 Layout of a Cathode Ray Tube

where amplitude may be either voltage, current or power. It is perhaps natural to think that there should be some threshold value of S/N ratio, which would be a dividing line between signals too small to be perceived and signals large enough to be distinguished from the background of noise; and it might seem that no signal could be perceived with a ratio less than 1:1 (*ie* the signal amplitude less than mean noise amplitude, which does not necessarily imply that the signal power is less than the mean noise power). But there can be no such clear-cut threshold ratio and one can only find or calculate values corresponding to given probabilities that an observer will pick out signals from noise. Even these values will depend on the nature of the signals, the method of presentation and the effective number of observations. If by some method of combining several successive observations it is possible to make use of the contrast between the randomness of the noise fluctuations and the comparative steadiness of the signal, then it may be possible to pick out a signal as far as 15 dB below noise. This problem is vitally important in radar, and is further discussed in Chapter 21, para 2134. When it is necessary to increase signal-to-noise ratios by cutting down the receiver noise output, the receiver bandwidth has to be made as small as it can be without seriously distorting the signals, and valve noise has to be reduced by using special low-noise valves and circuits; attention centres on the first few stages of the receiver, since the noise from them gets almost the full amplification of the receiver and thus provides almost all of the final noise output.

The Cathode Ray Tube (CRT)

2079. **Principles.** A cathode-ray tube (CRT) is a special type of thermionic valve in which a beam of electrons is made to strike a screen and produce a spot of light. The electron beam can be deflected by the action of electric or magnetic fields and can be made to follow very rapid changes of these fields, and, consequently, of the voltages or currents producing them; so that the CRT is a very useful means of displaying rapidly varying currents or signals. The essential parts of a CRT (Fig 20–18) are its cathode or electron gun, a control electrode or grid, a focusing system, an anode or accelerator, a deflexion system, and a glass bulb or envelope to enclose the whole in a vacuum, with its front forming a flat screen coated so that it glows wherever it is struck by the beam of electrons.

2080. **Cathode.** The cathode, which is the source of the electrons and is often called the electron gun (though this term may include the grid and focusing assembly), is usually a small nickel tube heated by a filament inside, closed at one end and coated there with substances that increase its electron emission.

2081. **Grid.** The control electrode is usually called the grid by analogy with the triode valve, though in fact it is not a wire mesh but a hollow nickel cylinder surrounding the cathode. It is kept negative to the cathode, and on the potential difference between them depends the number of electrons that get through and hence the brightness of the spot of light on the screen. Thus one can vary the brightness of the spot, and even black it out altogether, by varying the grid voltage (grid-cathode PD): the grid controls the electron stream just as the grid of a triode does.

2082. **Focusing System.** It is important to have a small and well-defined spot, so the beam of electrons must be focused in the way that a beam of light can be focused by a lens, to make all the electrons strike the screen in near enough the same place. A glass lens focuses by bending light rays, and a "lens" for focusing a beam of electrons consists of a suitably shaped electric or magnetic field, which exerts a force on the moving electrons and thus bends the beam. The focusing system is usually a set of coils of wire wound round the tube and carrying certain currents in order to create the necessary magnetic field. The focus can be varied by varying the current, and this gives the effect of moving the lens along the axis of the tube so that the beam can be brought into focus exactly on the screen.

2083. **Anode.** The anode, as in a diode or triode, is the electrode that is made positive to the cathode and creates the electric field that draws the electrons away from it. But the anode of a CRT is an accelerator more than a collector of electrons; it is at a higher potential than is usual for the anodes of ordinary thermionic valves. It is common to have a graphite coating on the inside of the envelope of the tube, between the deflexion system and the screen, and to keep this coating at a high potential in order to accelerate the electrons; in some tubes this coating may be the only anode. Since the brightness of the spot depends on the velocity of the electrons when they strike the screen, which in turn depends on the electric field used to move them, the greatest brightness that can be obtained with a given tube depends on the accelerating potential (or EHT) applied to the anode. This may vary from about 500 V for a small CRT to 15 kV for a tube with a very bright spot; 15 kV is normal for a modern 12-inch PPI tube.

2084. **Deflexion System.** By the action of electric or magnetic fields the electron beam can be deflected in any direction at right-angles to the axis of the tube, and this is the key to the usefulness of the CRT. If magnetic fields are used for deflexion they are generated by passing currents through coils that are wound on formers round the tube and are separate from it. The deflexion angle of the beam, and hence the distance moved by the spot on the screen, is proportional to the current through the deflector coils. This means that if a varying current is passed through the coils, then the movement of the spot on the screen will exactly reproduce the pattern in which the current is varying; *eg* if ordinary AC is used the spot will move to-and-fro in harmonic oscillation at presisely the same frequency as the AC. This ability of a CRT to trace the pattern of a varying current or voltage is the foundation of all radar displays and is further discussed in Chapter 21, paras 2186–2196.

2085. **Envelope and Screen.** A very hard vacuum (*ie* a very low pressure) is needed for the CRT to work efficiently, and the glass envelope must be extremely strong to withstand the external pressure on it. Since stray electric and magnetic fields generated by other circuits near the CRT might affect the electron beam and disturb its focus, the tube is usually shielded by being enclosed in an earthed cylinder of mumetal. The front of the envelope is made approximately flat and forms the screen on which the electron beam is displayed; it may be anything from 1 inch to 21 inches maximum tube dimension. It is coated on the inside with some special powder which gives out visible light when struck by electrons. The emission of light by a substance during electron bombardment is called fluorescence; but all the fluorescent coatings used in CRTs also emit light after the electron beam has been removed, and this is an entirely separate phenomenon, which is known as phosphorescence or afterglow. By choice of different coatings many different colours can be obtained, among them blue-violet, amber, green, and red, and the duration of afterglow (which decays exponentially from the moment bombardment ceases) may be made anything from a fraction of a microsecond to several minutes. The path followed by the spot when it is moved about the screen by deflecting voltages is called the trace; and the persistence of any point of the trace depends on the brightness of the spot when it passes that point as well as on the material used to coat the screen. It is possible to have two layers of coating, giving different colours, on top of one another, one with a short and the other with a long afterglow, so that by the use of colour filters one can distinguish between trace and afterglow. The fluorescent property of a coating may be destroyed by too much bombardment with electrons, and in spots where this has happened the screen will no longer respond to an electron beam by glowing, so that these spots or burns show as dark areas on the trace. Extreme burns appear as discoloration of the screen.

2086. **Varieties of CRT.** It has been explained that the focusing and deflexion can be by electric or magnetic fields, and in practice there are three combinations of these:

a. Electric focusing and deflexion.

b. Electric focusing and magnetic deflexion.

c. Magnetic focusing and deflexion.

The first combination is found in electrostatic tubes; the other two combinations in electromagnetic tubes. The use of an electric field consumes no power, and suitable deflecting voltages are easily generated without bulky and heavy circuits; but the deflector plates confine the beam, so making it hard to produce the large deflexions needed for a wide screen, and prevent the beam from being very thick in the neck of the tube, so making it hard to get a very bright spot. The use of a magnetic field makes it possible to produce a very bright, compact spot; it also simplifies construction, the magnetic focusing and deflexion assemblies being merely coils fitted over the tube; but the need to pass current through the coils wastes power and calls for cumbersome circuits to supply the current. The usual compromise for displays where a bright spot is important is electric focusing and magnetic deflexion.

2087. **Photographic Display of CRT.** It is sometimes desirable to present a CRT display on a very large scale, much larger than the greatest practicable size of screen, so that the display can simultaneously be studied by a large number of people. One method is to photograph the face of a normal sized CRT, develop the film in a very short space of time, and then at once project the negative optically (as if it were a lantern slide) onto a ground-glass or opaque screen. It has been made possible to develop the film in as little as 10 seconds, and to do the photographing, developing, and projection in a stepwise process; this gives a projected display that is renewed up to six times a minute and whose information is never more than 10 seconds old. Such a system magnifies the CRT display with very little loss of definition, but introduces a slight delay in presenting the information. Moreover by using colour film, together with a system of filters, and exposing the film to several CRT displays, it is possible to produce a coloured projected display which can contain far more information and is less confusing than a black and white display.

2088–2089. (*Not allotted*).

SEMICONDUCTOR ELECTRONICS

Introduction

2090. The valves described in paras 2065–2069 have several disadvantages: they are fragile; they require bulky power units to operate them; and they have a limited life as the cathode and heater deteriorate with age.

2091. Semiconductor devices, which differ from valves in both construction and operation, are being widely introduced to replace valves. Semiconductors have the advantages of:

a. Not requiring a vacuum or heated cathode.

b. Being much smaller and more robust.

c. Having an almost indefinite life if correctly used.

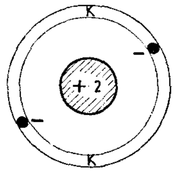
d. Requiring low voltages to operate them.

2092. There are many kinds of semiconductor material; germanium, silicon and selenium being the most common. Two of the most common semiconductor devices are the semiconductor diode and the transistor. The semiconductor diode can be likened to the diode valve, and the transistor to the triode valve.

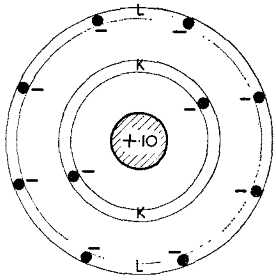
2093. A semiconductor is a solid material which is neither a good insulator nor a good conductor. Moreover, in contrast to normal metallic conductors, the semiconductor becomes a better insulator if its temperature is increased.

Atomic Structure of Semiconductors

2094. The behaviour of a material, chemically and electrically, depends on the disposition of the electrons in relation to the nucleus of the atom of the material. The electrons rotate round the nucleus in a definite and orderly manner. They can exist only in certain "shells" round the nucleus, and the number of electrons that each shell is capable of accommodating is fixed. Each shell is "filled" in order of atomic number, commencing at the innermost shell. Working outwards from the nucleus, the first (K) shell may contain one or two electrons but not more than two, so this shell is filled when the atom is helium which has two electrons. The second (L) shell, further away from the nucleus, may contain anything up to eight electrons and the first two shells are completely filled by the atom of atomic number 10, which is neon (Fig 20–19).



a. HELIUM ATOM



b. NEON ATOM

Fig 20–19 Atom Shell Structure

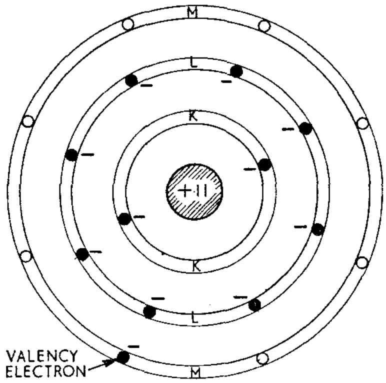
An atom which has just sufficient orbital electrons to fill completely one or more shells has no "free" electrons and is completely inert (*eg* the inert gases helium and neon). An inert gas is one which shows practically no tendency to combine with other elements. Further shells, of greater radii and having accommodation for a fixed number of electrons, exist for elements of high atomic number.

2095. For the great majority of elements, the number of electrons in the outermost shell is less than the maximum number that this shell is capable of accommodating. For example, the sodium atom (atomic number 11) has the K and L shells filled and has one "odd" electron in the M shell (Fig 20–20). The electron in the M shell is free to enter into external relationships with other atoms and because of this the sodium atom is extremely active. The electrons in an incomplete shell that tend to enter into external relationships are termed "valency electrons"; thus sodium has one valency electron. For many purposes the atom diagrams can be simplified by combining the filled shells with the nucleus and showing only the net electric charge inside a circle. Each of the electrons left over (the valency electrons) is represented by a minus sign outside the circle, the atom as a whole being electrically neutral. Fig 20–20b replaces the complete sodium atom diagram of Fig 20–20a in this notation. The semiconductors germanium and silicon may be represented as in Fig 20–20c, from which it is seen that there are four valency electrons.

2096. Fig 20–21 shows the diamond-shaped lattice structure of atom formation for germanium or silicon. The arrangement of atoms is such that each outer electron shares a space with an outer electron from a neighbouring atom. This common sharing of space creates a powerful bond between atoms and results in a hard stable structure.

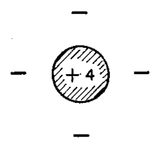
2097. In an ordinary conductor electric current is carried by free electrons which are loosely held by the nuclei of their atoms; an applied voltage, or heat, can detach the electrons and current flows. In germanium, heat or an applied voltage would have to overcome the powerful bonds between atoms in order to detach electrons. There are therefore few electrons in germanium at ordinary temperature and it is, in the pure state, a poor conductor.

2098. As the temperature rises, more bonds are broken and more free electrons are produced so that the material becomes a better conductor. Above about 80°C for germanium, and 200°C for silicon, the conductivity is good enough to upset the controlled use of these materials when they are used in semiconductor diodes or triodes.



a. SODIUM ATOM

b. SIMPLIFIED SODIUM ATOM



c. SIMPLIFIED GERMANIUM OR SILICON ATOM

Fig 20–20 Simplified Atom Diagrams

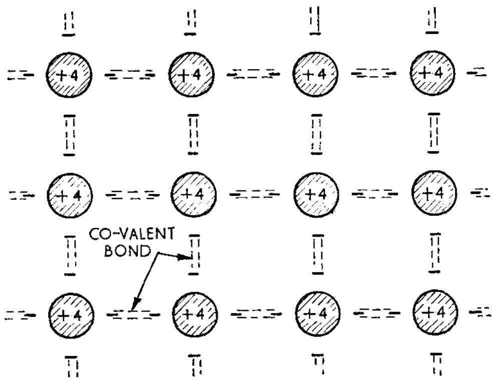


Fig 20–21 Germanium Crystal Lattice

Impurity Semiconductors

2099. The conductivity of pure germanium or silicon can be increased, without increasing its temperature, by adding a small amount of another element. The current flowing can then be strictly controlled. Antimony and arsenic have atoms with five outer electrons, and if a small quantity of either of these elements is added to the semiconductor its properties are altered considerably.

20100. The added element is called an impurity, and it is added in the proportion of about one part in a hundred million. Four of the outer electrons of the impurity form bonds with neighbouring germanium atoms, but the fifth becomes a "free-electron" (*see* Fig 20–22). The conductivity therefore improves when an impurity is added and an applied voltage will cause a current to flow due to the movement of these free electrons. A semiconductor modified in this way is called an impurity semiconductor and is said to be "doped". Because the current carriers are electrons which are negative charges the material is called an "n-type semiconductor".

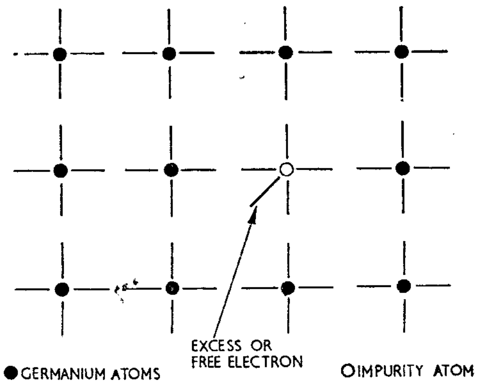


Fig 20–22 n-Type Semiconductor

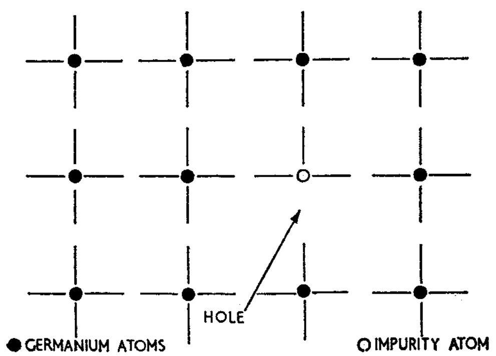


Fig 20–23 p-Type Semiconductor

20101. If an impurity element such as aluminium or indium, which has only three outer electrons is added, another type of doped semiconductor is produced. The impurity of atoms enter the crystal lattice structure and the three electrons form bonds with neighbouring atoms. There is, however, a gap or "hole" where the fourth electron should be (*see* Fig 20–23). If a nearby electron fills this gap, the bonds are completed, but the hole has moved to the atom which has supplied the electron. This process is going on all the time, and the holes can be thought of as moving at random through the material rather as free electrons do. A semiconductor which is doped so as to produce free holes which act as if they were a positive charge carrier is called a "p-type semiconductor". An applied voltage causes the holes to move as if they were positive charges moving towards the negative terminal of the battery (*see* Fig 20–24). In reality free electrons are moving the other way, filling up holes in the material, but it is more convenient to imagine that the current is carried by the holes.

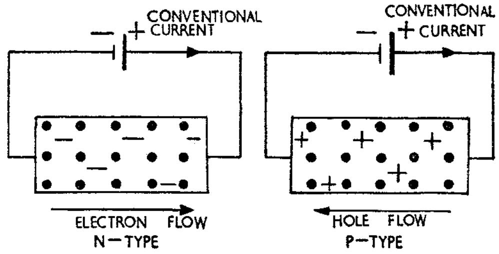


Fig 20–24 Direction of Current Flow

The p–n Junction Diode

20102. When two pieces of semiconductor, one n-type and the other p-type, are placed together to form a boundary or junction, we have a "junction diode". This has properties similar to those of a thermionic diode (*see* para 2070). The two halves have to be moulded together to form a continuous crystal lattice structure and the manufacturing process needed to produce this junction is quite complex (*see* Fig 20–25).

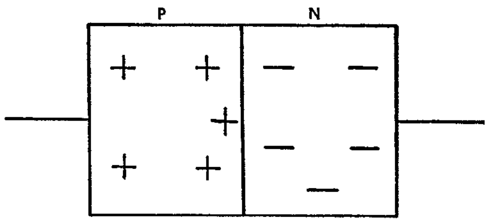


Fig 20–25 Junction Diode

When a p–n junction is formed it might be expected that electrons would flow from the n-type to the p-type and neutralize the holes, but this does not occur; each piece of material is originally electrically neutral, just as a piece of copper is neutral even though it contains millions of electrons. Some electrons drift or diffuse across the boundary into the p-type to become negatively charged and the n-type repels holes so that further movement of the charge carriers ceases.

20103. There is therefore, a "barrier" called a potential barrier, formed by the p–n junction which acts in the same way as would a battery connected as shown in Fig 20–26. The barrier prevents the flow of electrons and holes across the junction and so very little current can flow through the junction.

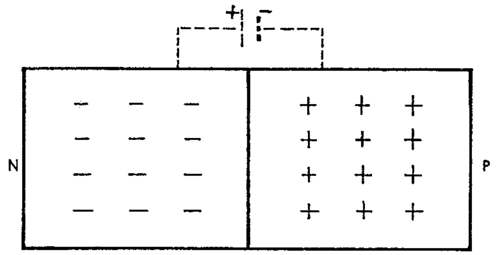


Fig 20–26 The p–n Junction

20104. If an actual battery is connected across the junction as shown in Fig 20–27a, it increases the barrier effect and little current flows. It can be imagined that electrons are attracted by the positive terminal away from the junction and holes are similarly attracted by the negative terminal.

20105. The effective resistance of the junction is very high, and the battery is said to be connected in the "reverse" or "back" direction, giving reverse or back bias to the junction. Because there are a few holes in the n-type, and a few electrons in the p-type materials caused by crystal defects and temperature, a very small current does flow, but it is only a few microamperes.

20106. If the battery is connected with the opposite polarity (*see* Fig 20–27b) electrons are attracted through the junction to the positive terminal and holes are attracted the other way. A large current therefore flows. Notice that electrons flowing in one direction and holes flowing in the other produce the same conventional current flow, which is in the direction of the holes.

20107. A very small forward voltage is sufficient to overcome the barrier potential and a voltage of 0·2 volts will allow several milliamperes to flow. The battery is now said to be connected in the "forward" direction and the junction is forward biased. The effective resistance of the junction is now fairly low.

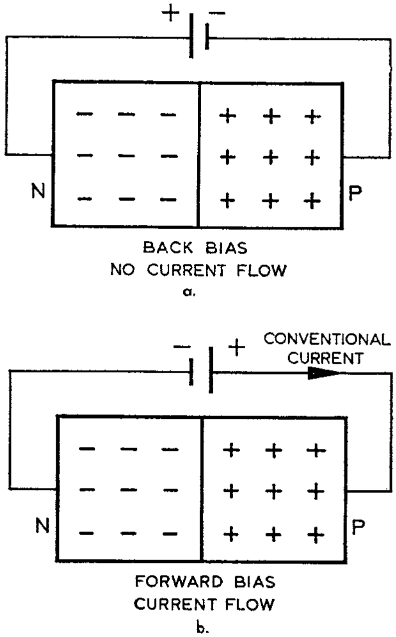


Fig 20–27 Forward and Back Bias

20108. The behaviour of the p–n junction is similar to that of the thermionic diode. It passes current easily when the voltage across it is of one polarity and allows almost none to flow when the applied voltage is of the opposite polarity. It can therefore be used as a rectifier in the same way as a thermionic diode.

20109. A p–n junction characteristic curve is shown in Fig 20–28. The portion of the curve A to B is the normal forward bias characteristic and is the useful operating region for a semiconductor rectifier. It is similar to that for a thermionic diode, the current being approximately proportional to the forward bias. With reverse bias (region B to C), there is a small "leakage" current which is usually considered constant over the working region of the diode,

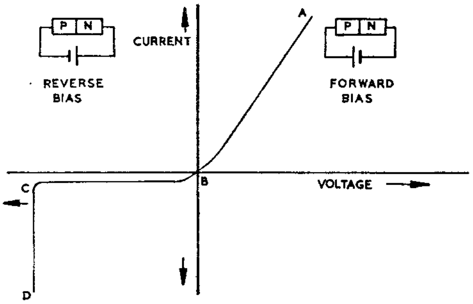


Fig 20–28 p–n Junction Characteristics

but which varies with temperature. For germanium, typical leakage currents are 10 microamperes at 25°C and 50 microamperes at 55°C. Portion C to D of the characteristic is known as the "zener" or "avalanche" region. When the reverse current reaches a particular value, perhaps 100 volts or more, the reverse current increases very sharply. This can result in complete breakdown of the diode caused by excessive heat caused by the very large current. Thus junction diodes used as rectifiers must not be operated with reverse voltages greater than the breakdown value.

20110. In some specially-designed diodes, known as zener or avalanche diodes, use is made of this part of the characteristic. They are often used as stabilizers or limiters; special precautions are taken to ensure that the device is not permanently destroyed but "recovers" when the reverse bias is removed.

Point-Contact Diodes

20111. Another type of semiconductor diode is known as the "point-contact" diode (*see* Fig 20–29). It is sometimes known as a crystal diode and is widely used in radar receivers.

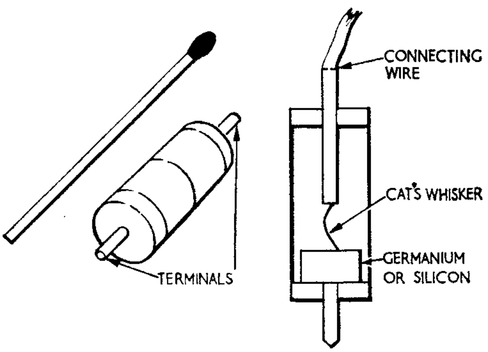


Fig 20–29 Point-Contact Diode

20112. In the point-contact type of diode, one side of the boundary is a semiconductor (p- or n-type) and the other is a wire. Although the metal does not have the same structure as a semiconductor, similar results are obtained with the metal junctions as with a p–n junction. A potential barrier is formed at the junction and current flows much more easily in one direction than in the other. Because of the structure of this diode the reverse voltage must not be allowed to exceed the breakdown value or the contact will burn out.

20113. In most types of point-contact diode the metal wire is tungsten, but in some the contact is gold. These are known as "gold bonded" diodes and have a slightly better performance than the normal point-contact diode. The point contact crystal diode is used a great deal in microwave equipment where it can handle small signal voltages of high frequency better than the junction type.

The Transistor

20114. It has been shown that a semiconductor diode consists of two pieces of impurity semiconductor, one n-type and one p-type, joined together to form a junction. If the diode is forward biased, current will flow in one direction only; if it is back biased so as to reinforce the potential barrier, no current flows.

20115. A transistor consists of three pieces of impurity semiconductor alloyed together, alternately p-type and n-type. There are therefore two p–n junctions in a transistor and the construction may be either p–n–p or n–p–n (*see* Fig 20–30).

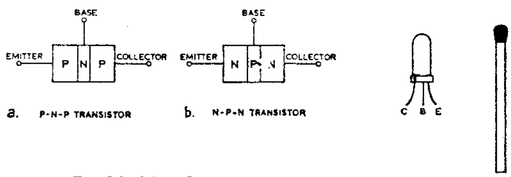


Fig 20–30 Construction of Transistors

20116. A p–n–p junction transistor has a thin piece of n-type semiconductor material sandwiched between two p-types. One of the p-types is the "emitter", the n-type is the "base" and the other p-type is the "collector". In the n–p–n transistor the p-type and n-type materials are interchanged. A non-rectifying contact is made to each of the three layers to provide leads.

20117. In a transistor the emitter corresponds roughly to the cathode; the base to the grid and the collector to the anode of a triode valve.

20118. Whichever type of transistor is used, the emitter-base junction is forward biased (positive battery terminal to the p-type material) and the base-collector junction is reverse-biased (positive battery terminal to the n-type material).

20119. **Action of a n–p–n Transistor.** The bias connections for a n–p–n transistor are shown in Fig 20–31. This type of transistor will be considered first since its action is nearer to that of a valve. A big difference, however, between transistor and valve action is that whereas the current through a valve is controlled by a *voltage* applied to its input circuit, a transistor is controlled by a *current* flowing in its input circuit. The reverse bias on the base-collector junction ensures that very few electrons from the n-type collector move to the base and that very few holes from the p-type base move to the collector. However the emitter-base junction is forward biased and electrons flow from the emitter through the junction into the base. Conventional current flows in the opposite direction. When electrons arrive in the base region they are attracted through the base-collector junction and produce a current in the collector circuit. A few electrons which enter the base are neutralized by holes in the base, but the base is very thin (about 0·5 mm across) and between 95 and 99% of the electrons from the emitter travel through to the collector. The remainder cause a small base current to flow. As the current through the emitter-base junction is varied, the collector current will also vary. Thus the collector current can be controlled by the base current.

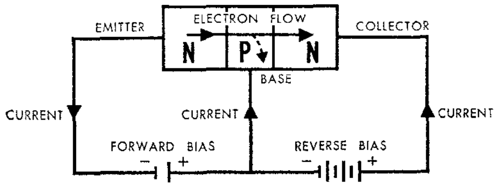


Fig 20–31 Action of a n–p–n Transistor

20120. **Action of a p–n–p Transistor.** The p–n–p transistor is the type more commonly used and the action of the emitter, base and collector is similar to that for a n–p–n transistor. The emitter-base junction is again forward biased and the base-collector junction is reverse biased. This time, however, since the emitter and collector are of p-type material, the battery polarities are reversed (*see* Fig 20–32). The major current-carriers are now holes, and these flow from the emitter into the base. The holes cross the narrow base region and are accepted by the negative collector. Some of the holes are neutralized by electrons in the base giving rise to a small base current. In order to reduce the number of holes lost in this way the collector-base junction is made much larger than the emitter-base junction, and because of this, emitter and collector leads cannot be interchanged. As with the n–p–n transistor, between 95 and 99% of the emitter current reaches the collector; by varying the base current the collector current varies.

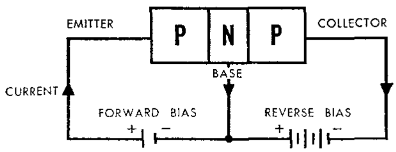


Fig 20–32 Action of a p–n–p Transistor

CHAPTER 21

FUNDAMENTALS OF RADAR

CONTENTS

DEVELOPMENT OF RADAR

Early Experiments

2101. Marconi successfully received wireless signals from across the Atlantic in 1901, and this gave rise to much speculation, since it was established that wireless waves travelled like light in more or less straight lines, yet they had clearly bent round the earth's surface. Scientists reached the conclusion that there must be layers of the earth's atmosphere able to reflect wireless waves, and they called them the ionosphere.

2102. Researches were made into the nature of the ionosphere, and about 1928 a technique was invented of sending off short bursts or pulses of radio waves and observing the well-defined echoes that came back from the layers of the ionosphere. When the pulses and their echoes were displayed on a cathode ray tube it was possible to measure the time taken between the transmission of a pulse and the reception of its echo, which was the time taken by the waves to reach the reflecting layer and return; hence the heights of the layers could be found, since the velocity of the waves was known.

2103. It occurred to Watson Watt of the National Physical Laboratory that the same method might be used for detecting aircraft, the metal parts of the aircraft taking the place of the reflecting layer, since it was well known that radio waves were reflected by metallic surfaces. In 1935 he suggested this to the Air Ministry, and an experiment was soon arranged which showed clearly that the radio waves reflected from an aircraft had enough energy in them to make the scheme a practical one.

RDF

2104. The demonstration mentioned in para 2103 suggested the idea of a chain of radio stations along the coast that would be able to detect aircraft out to some 50 miles and give far earlier warning of air attack than hitherto possible. Work was at once started, under the direction of Watson Watt at Orfordness, on the practical details of this scheme. The system was called RDF, which was a contraction of Radio Detection and Direction Finding, since it was foreseen that direction-finding methods could be used to give the bearing and even the height of a detected aircraft, though at first these possibilities received little attention.

2105. The researches were soon afterwards transferred to an experimental station at Bawdsey, and began to give practical results far exceeding the Air Staff's expectations. A chain of five stations was begun, and the system was tried out in the air exercises of 1936 and 1937; these trials provided valuable experience and criticism. Although improvements were constantly being made, it was recognized that RDF was unreliable and inaccurate; and the technique of measuring heights and bearings was still rudimentary. In spite of these shortcomings RDF was clearly of very great value to the air defences and capable of wide development, and the decision was made in 1937 to go ahead with a main chain of 20 RDF stations.

2106. This became known as Chain Home (CH) and the individual stations were called, for security's sake (RDF had not been made public), Air Ministry Experimental Stations (AMES) Type 1. By the outbreak of war in 1939, eighteen of these stations were operating, though none of them was yet in its final form. Many improvements had been made, and experience gained in the air exercises of 1938 and 1939 had laid the groundwork of a reporting system to make use of the information from RDF. The CH system was completed and extended during the first two years of the Second World War, and the great part it played in the Battle of Britain in 1940 is now widely known.

2107. For reasons that will presently be explained, it was not possible for CH stations to detect aircraft at low angles of elevation. An entirely new type of RDF had to be designed to provide warning of low-flying aircraft. Such a set, having little more than the basic principle in common with CH, had been developed by the Army at Bawdsey for the detection of ships from the shore. It worked at ten times the frequency used in CH and was altogether much less bulky and cumbersome. It was adopted by the Royal Air Force as Chain Home Low-Cover (CHL) or AMES Type 2, and installation began in the autumn of 1939.

Development and Applications

2108. When RDF was finally made public in 1941 it was called radio-location, and it later acquired the American name "radar" by which it is now universally known. Clearly, the principle of radar is a very general one, and the early-warning system that has been mentioned is only one of its many possible applications.

2109. A vast amount of research was done on radar during and after the war and as a result it has become possible to use still higher radio frequencies, corresponding to wavelengths of only a few centimetres; still shorter pulses; displays that are easier to interpret quickly; and many other improvements: all of which have helped to make radar more accurate and versatile. Among the uses to which radar has been put in the Royal Air Force are:

a. *Early Warning and Control.* A range of radars is used to provide early warning of air attack by aircraft and missiles, and to provide control facilities for defensive fighter aircraft and ground-to-air missile systems.

b. *Airborne Search.* Radar sets carried in aircraft are used for a variety of purposes including:

(1) *Airborne Interception (AI).* AI is used in interceptor aircraft to search for enemy aircraft and to provide data for computation of optimum approach paths and weapon delivery.

(2) *Aircraft to Surface Vessel (ASV).* ASV is used to search for ships or submarines which are partly above the surface.

(3) *Navigation and Offensive Weapon Delivery.* Radar is used to provide a display of the terrain in the vicinity of an aircraft which may be used as an aid to navigation or for offensive weapon delivery. In addition the radar data may be used by very low flying attack aircraft for automatic terrain avoidance.

(4) *Airborne Early Warning (AEW).* Search radars may be carried in aircraft to provide extended early warning and control facilities for air defence.

c. *Satellite Detection and Tracking.* Radar is used to detect earth satellites and to provide data on their orbit parameters.

d. *Identification.* Secondary Radar Systems are used as an aid to identification of aircraft and to provide beacon assistance to ground stations as an aid in tracking aircraft.

e. *Navigation Aids.* Radar is used by aircraft to provide navigation and airfield approach systems which may be either interpreted in the air or by ground controllers.

Not all of these applications of radar are of direct importance in control and reporting, and they will not all be described in this manual.

2110–2113. (*Not allotted*).

INTRODUCTION TO RADAR

Nature of Radar

2114. The word radar is a contraction of the phrase "radio detection and ranging", and is used to denote apparatus or techniques which use radio waves to locate, assess or control objects. In this section radar is considered primarily in connection with search and the associated problem of identification.

2115. The objects which a search radar is used to detect are generally called "targets". To locate a target by radar, it must be possible to detect radio waves coming from it, and there are two principal methods by which this can be done:

a. *Primary Radar.* A primary radar sends out radio waves, which are reflected or scattered by the targets on which they fall; it picks up the reflected waves that return to it, and from them it derives information about the position and nature of the targets. Because it needs no co-operation from the targets, this system is invaluable for giving warning of the approach of enemy aircraft. The reflections represent only a minute fraction of the radiated power, and it is necessary to have a very powerful transmitter.

b. *Secondary Radar.* A secondary radar also sends out radio waves, which can be picked up in the target by a radar receiver; this receiver is coupled to a transmitter so as to make it send out other radio waves, not necessarily at the same frequency, in reply to those that are received. The receiver of the secondary radar collects these secondary transmissions from the target and derives its information from them. The combined receiver-and-transmitter used in the target is known as a responder, though if it receives and transmits on different frequencies it may be called a transponder. This system can rarely be used to detect enemy aircraft, but is of great use in identifying friendly ones. The basics of primary and secondary radars are illustrated in Fig 21–1.

Search Radar Data

2116. In a control and reporting system the targets for search and identification radar are mainly aircraft, and as these move in three dimensions of space, so three measurements or co-ordinates are needed to specify their position completely at any instant of time. There are many systems of co-ordinates, but only two are commonly used in radar:

a. The first system uses the target's ground

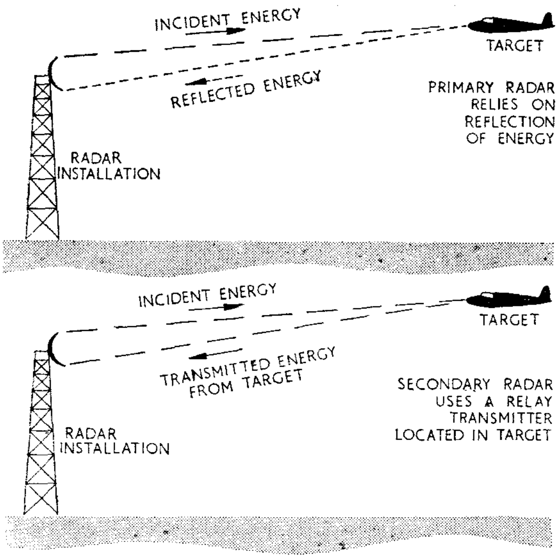
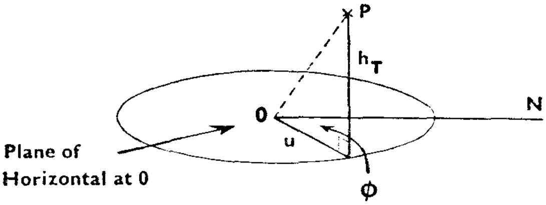
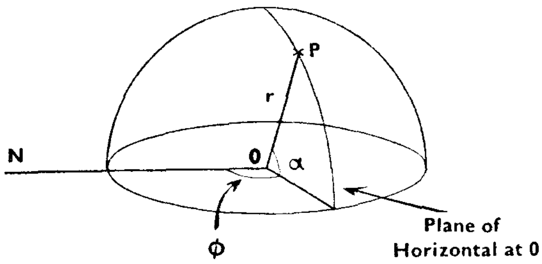


Fig 21-1 Primary and Secondary Radar



a Ground range, height and azimuth



b Slant range, elevation and azimuth

Fig 21-2 Co-ordinate Systems

range u, its azimuth or bearing ø from a fixed line (usually true North, sometimes magnetic North), and its height h_t above the radar, as shown in Fig 21–2a. But the height wanted is usually the height above sea level, and it is clear that, even when the height of the radar itself is allowed for, the height above sea level is greater than the height above the horizontal through the radar station, because of the curvature of the earth's surface. This difference is important at ranges greater than 50 miles and must be allowed for.

b. In the second system the target is fixed by giving its true or slant range r from the radar, its azimuth or bearing ϕ, and its elevation α above the horizontal, as shown in Fig 21–2b. Radar always measures slant range but is usually required to give its results as ground range; except at very short ranges the elevation of a target is usually so small that the two values of range hardly differ. The relation between the two systems is that $h_t = r \sin\alpha$ and $u = r \cos\alpha$, neglecting the earth's curvature. When α is small, $\sin\alpha$ is roughly equal to α measured in radians, and $\cos\alpha$ is nearly 1.

2117. Both these systems give ground position as a range and a bearing, and it is in such a form essentially that the information is obtained from a radar searching in azimuth. It may then be necessary to convert this position into other co-ordinates, such as Georef, if these are being used for reporting aircraft. Once a target has been located, its track and speed can very simply be estimated from measurements of its position at different times. Height-finding radar measures, essentially, range and elevation of targets; heights are deduced from these measurements.

2118. Information is also required concerning the nature of each target, *eg* its composition (*ie* number of aircraft, *etc*) and whether it is friendly or hostile. This information cannot be obtained as accurately as the position, but the form of the radar reflections can be made to give some idea of composition, while secondary radar systems can be used for identification.

Range Measurement

2119. All pulse search radar systems measure range by the echo principle. Echoes from the reflection of sound waves by hillsides, walls, or other hard objects are familiar to the reader, and he knows that the time between making a sound and hearing the echo increases with the distance of the reflecting surface. Let this distance be d feet and suppose that sound travels by the shortest or straight-line path at a velocity v feet per second. Then in travelling to the reflecting surface, being reflected, and returning to the source to strike the ear as an echo, the sound covers a distance of 2d feet; doing so must take 2d/v seconds, so that this must be the time that elapses between making the sound and hearing its echo. It should be noticed, however, that if the original sound is not sharp, but prolonged over this time, there can be no way of distinguishing between it and the echo.

2120. The echoes in radar are from the reflection of radio waves whose wavelengths are small compared with the ranges being measured, so that apart from the effects of refraction in the atmosphere they may be taken to travel in straight-line paths. Their velocity is c, the velocity of light (3×10^8 metres per second or 186,000 statute miles per second approximately); hence, by reasoning similar to that just employed, the time between transmission and echo from a target at range r is 2r/c seconds. This supposes that the transmitter and receiver are side by side, as they always are in a search radar. For a secondary radar the delay in triggering the responder must be added to the echo time worked out here, and has therefore to be subtracted when deducing the range.

2121. Hence, by measuring the time t, the range can be found; for if $t = 2r/c$, then $r = \frac{1}{2}ct$. From this relationship between t and r one finds that the echo time for a range of one statute mile is about 10·7 microseconds (μs) or millionths of a second (12·4 μs for one nautical mile), so that time measurement in radar cannot be by any ordinary kind of clock; it is in fact done electronically.

2122. Yet if the transmission of radio waves were continuous, or in only moderately short bursts, it would be impossible to distinguish between waves received direct from the transmitter and waves returned by reflection from an aircraft, since the beginning of one is separated from the beginning of the other by so very minute an interval of time. To achieve distinction it is necessary to send out very short pulses of radio waves, only a few microseconds long, these being the equivalent of the short sharp sound that gives a clear echo: this is the reason for using pulse radar. The received echo pulses can be compared with the transmitted pulses on a visual display, and the time between them measured. Pulses are sent out in rapid (regular) succession so as to obtain as much information as possible; the number of pulses in a given time is called the pulse recurrence frequency or PRF (n), which in practice may have any value from 10 to 5,000 pulses per second (pps). The duration of each pulse is called the pulse width (τ); it may in practice take any value from a fraction of a microsecond to as much as 30 microseconds.

Measurement of Bearing and Elevation

2123. The method just described will give the range of a target but no idea of its direction, and no such idea could be obtained if both transmitting and receiving aerials were omnidirectional, *ie* could not distinguish between one direction and another. To fix the target in space, once range has been measured, the angles of bearing and elevation must be found. For these angular measurements the radar's aerials must be given directional properties: such properties can be exploited by several techniques, the most important of which are:

a. *Searchlight Scan.* The transmitter and receiver aerials (or one aerial serving both purposes) are designed to give a narrow beam of radiation, and this beam is made to scan over the area to be searched in the manner of a searchlight, either simply in azimuth or elevation or in a complex pattern covering both angular co-ordinates. The display is arranged to show the direction of the beam at each instant; each target sends back echoes only when it is illuminated by the beam, and thus its angular position is clearly shown on the display. This is the radar system most widely used nowadays for measuring angles, and it can be made to give very accurate results.

b. *Signal Comparison.* The elevation of a target may be found by a method of signal comparison. This method makes use of several narrow beams in elevation which overlap and together illuminate a broad angle in elevation. The returns received in each beam vary according to the height and range of the target, and by comparing the signal strength of the returned echo in the different beams the height may be calculated. This method is explained in greater detail in paras 21107–21111.

c. *Estimation of Height from Performance Diagram.* A rough estimate of target height may be made by noting the range at which the target is first detected, and reading off from a performance diagram the height at which detection is normally made at the range of the target. This method can only give a very approximate target height but is a useful method if no height finding equipment is available.

d. *Automatic Following*. A radar can be so designed that once it is set onto a given target the aerial system automatically keeps itself pointing at the target and follows its movements in bearing and elevation. Both angular co-ordinates can then be measured continuously and with great accuracy (to within a few minutes of arc if necessary) from the inclination of the aerial.

e. *V-Beam Scan*. A radar is designed to radiate two fan-shaped beams inclined at different angles to the horizontal, which scan round in azimuth together. A given target will be illuminated by each of the two beams once in every scan rotation, at two separate positions of the aerial, and the interval of azimuth between these positions will depend on the target's angle of elevation. The display is arranged to show this interval, and the operator is given means for deducing target height from it. However this method is not well adapted to dealing with many closely-spaced targets.

2124. (*Not allotted*).

2125. Generally a search radar receives and displays echoes from not one but many targets at the same time, and it will be desirable to separate these echoes from one another. The closer together the targets are, the harder the echoes will be to separate. By analogy with optics, the distinguishing of the separate elements in a cluster of radar responses is called resolution, and this is a very important aspect of the capabilities and limitations of any radar. Limits to the resolution of a radar are imposed by several features of its design:

a. *Pulse Width*. Each echo pulse has a finite width roughly equal to the transmitter pulse width τ, which (from the formula in para 2121) is equivalent to a radar range of $\frac{1}{2}c\tau$ (in figures, 164 yards per microsecond of τ); if two targets are separated by less than this distance, and are illuminated simultaneously, they will give overlapping echoes that cannot be separated. The distance $\frac{1}{2}c\tau$ is always at least 30 wavelengths, and is often the practical limit to resolution in range.

b. *Beamwidth*. If two targets at the same range subtend between them at a searchlight radar an angle less than the beamwidth θ, then they will be illuminated simultaneously at some point of the scan, and so will present overlapping responses that cannot be distinguished one from the other. Hence the beamwidth is the limit of angular resolution for a searchlight radar. In the measurement of angle by signal comparison, all targets are simultaneously illuminated, and angular resolution of two targets at the same range is generally impossible.

c. *Display*. Even when the distance between two targets exceeds the above limits, so that their radar responses are separate in time and thus distinguishable, it may happen that the display is too coarse-grained to make the distinction; thus the resolution of a radar cannot be better than the resolution of its display.

Basic Requirements of a Pulse Radar System

2126. A primary radar installation must be able to detect targets at a distance, and provide information on the target's range, bearing and height. To be able to do this satisfactorily a pulse-modulated radar must have the units shown in Fig 21–3, *ie*:

a. *A Transmitter*. A transmitter must be capable of producing short-duration, high power pulses of RF energy at a given repetition frequency.

b. *An Aerial System*. An aerial system must produce a very narrow beam of RF energy which may be used for scanning.

c. *A Sensitive Receiver*. A sensitive receiver is required which is capable of receiving and amplifying the very weak signals so that they may be processed and displayed on an indicator or otherwise used.

d. *An Indicator*. An indicator, which is capable of measuring time intervals of only microseconds duration for range measurement, and which is connected to the aerial system for indication of the bearing and/or height of the target, is required. These basic requirements are discussed further in paras 2169–2172, 2188 and 21107–21111.

The Radar Transmitter

2127. Transmitter pulses are produced at a regularly recurring rate; the number of pulses produced each second being known as the pulse repetition frequency (PRF), measured in pulses per second (pps). The length of time for which the transmitter is switched on to give each pulse is known as the pulse width (sometimes called pulse length or pulse duration) and is measured in microseconds (μs).

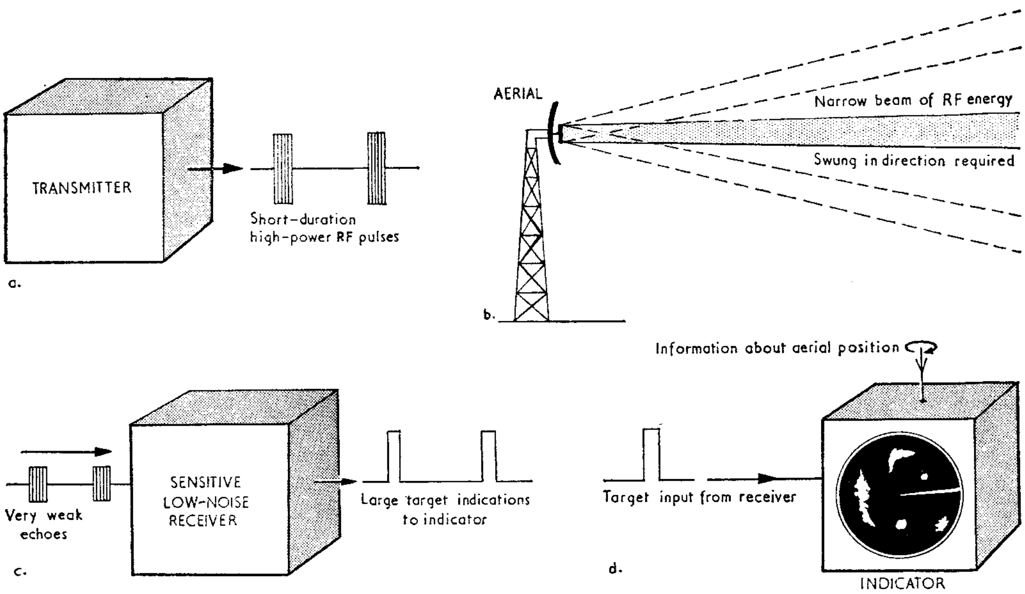


Fig 21–3 Basic Units of a Pulse-Modulated Primary Radar

2128. A radar transmitter operates at a very high frequency, and, for the duration of the pulse, produces a very high peak power output. Frequencies up to 30,000 MHz are common, and peak powers of 3 MW and more are used. The high powers are necessary to ensure adequate "illumination" of the target so that a good echo may be received. The need to use high frequencies is explained later. The system used to produce the high frequency, high power pulses of short duration at the required rate is illustrated in Fig 21–4. The main components are:

a. *Trigger Unit.* The trigger unit produces timing pulses which recur at precise intervals of time, and so determines the PRF of the equipment. The indicator timebase is synchronized with the transmitter pulses by applying "synchro pulses" from the trigger unit to the indicator timebase. This causes the trace to move across the screen of the CRT at the instant the transmitter fires each pulse.

b. *Modulator.* Because of the high rate of switching (many hundreds of pulses per second) and the very short time intervals being being used (a few microseconds at the most for the pulse duration) the transmitter operation cannot be controlled by normal switches or relays. The circuit which does this switching, and also provides the input power required by the oscillator, is the modulator. The modulator is an electronic circuit which is "triggered" by the output from the trigger unit and which produces a pulse whose duration is determined by the circuitry of the modulator. This pulse of controlled pulse width (or duration), recurring at the precise instants of time determined by the trigger unit, is used to switch the oscillator on and off.

c. *Oscillator.* The oscillator generates the high frequency oscillations at the high power required. It is switched on by the rising or leading edge of the pulse from the modulator, and is switched off by the falling or trailing edge of the pulse. The transmitter therefore produces a pulse of RF energy at the frequency of the oscillator. Special radar devices (*see* paras 21121–21128) are required to produce the very high frequencies at the high powers needed. It should be noted that although the pulse duration may be very short the frequency is sufficiently high to ensure that each pulse contains a large number of cycles of radio frequency (*see* Fig 21–5). For a frequency of 3,000 MHz and a pulse duration of 1 μs each pulse contains 3,000 cycles.

2129. Many factors have to be considered before the PRF and pulse width of a particular radar installation are decided, but typical figures are a PRF of 500 pulses per second and a pulse width of 1 μs. For the figures quoted the transmitter "fires" for only one millionth of a

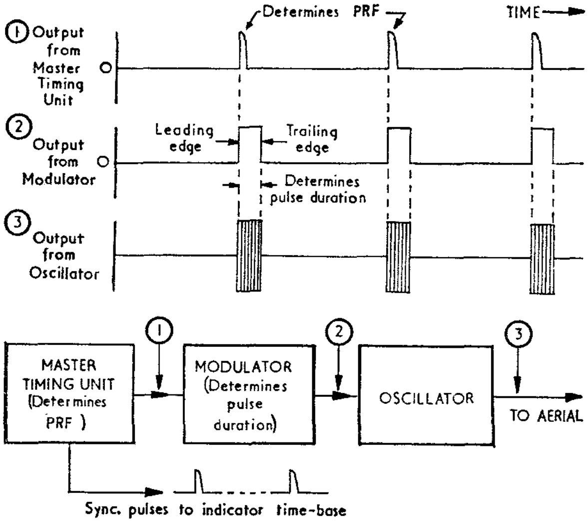


Fig 21–4 The Pulse-Modulated Transmitter

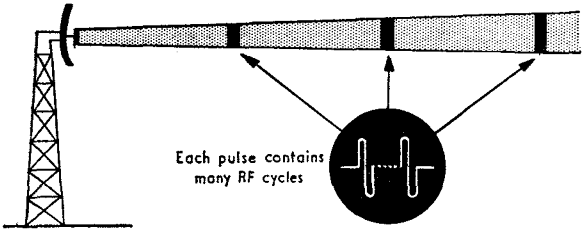


Fig 21–5 Radiated Pulses

second and is then off for $\frac{1}{500}$ second or 2,000 millionths of a second. To give an idea of what these figures really mean it is convenient to imagine them to be multiplied by one million as in Fig 21–6. This emphasizes that the transmitter fires for only a very short period of time, and the interval between each pulse is relatively long.

The Aerial System

2130. **Aerial.** To locate an object in space an aerial is required which is capable of producing a narrow beam of energy in one plane only (or in two planes at right angles) so that the high peak power output of the transmitter during each pulse may be concentrated to cover a small region of space so that accurate bearings in azimuth or elevation (or both) may be obtained. To produce such a beam some form of aerial array is required, and the higher the frequency the smaller are the aerial elements in the array. Centimetric radar uses frequencies in the band of 3,000 to 30,000 MHz. At these frequencies the aerial assemblies used for radiating a narrow beam are very similar to the structures used for focusing light rays. Typical of these is the parabolic reflector which may be compared with the headlight of a car (*see* Fig 21–7). Centimetric aerials are comparatively small, can produce narrow beams of RF energy and can be made to rotate or tilt fairly easily. Aerials are discussed at greater length in paras 2146–2171.

2131. **Scanning.** A radar beam must be capable of being swung in any required direction and the search for an object in a given volume of space must be carried out systematically to ensure that the whole volume is covered. To do this the aerial beam is made to "scan" the whole region which is to be investigated.

2132. **TR Switch.** Most pulse-modulated primary radars use an aerial that is common to both transmitter and receiver. This may be done because while the transmitter is working the receiver is not required, and while the receiver is working the transmitter is switched off. The transmitter can therefore be connected to the aerial for the duration of each pulse and the receiver connected during the interval between pulses. This is done by the transmit–receive (TR) switch, and the action is illustrated in Fig 21–8.

2133. **Output to Indicator.** Information on the angular position of the aerial is conveyed to a PPI for indication of bearing in azimuth, and information on the angle of tilt is conveyed to a height-range indicator (HRI) for indication of the elevation bearing.

Receiver

2134. The receiver amplifies the reflected pulses picked up by the aerial. After amplification the pulses are demodulated and the resultant pulses are applied to the indicator CRT for display of target information. The received echoes are very weak and may provide signals of a few millionths of a volt. However the input voltage required by the indicator in order to give a satisfactory display may be 10 volts or more. The receiver must therefore have high "gain". There is, however, a limitation to the amount of useful gain which can be obtained in practice. The main limitation is noise (*see* Chapter 20, paras 2076–2078). The noise level of a receiver has a marked effect on its performance, as noise may hide weak echoes from targets at long range. The noise generated by a receiver must therefore be the minimum possible. It is pointless having a high-gain receiver if it also has a high noise level; the noise is merely amplified further. One further point should be noted about receivers: to preserve the shape of the reflected pulse, the receiver circuits must have a wide bandwidth. This follows from the fact that a square or rectangular pulse contains a very wide band of frequencies which must be accepted by the receiver if distortion is to be avoided. A distorted pulse on the CRT display makes it difficult to determine range accurately.

The Indicator Unit

2135. An indicator is required to show the user the bearing, range and height of aircraft within the range of the radar. If only range is required a simple type A display (*see* Fig 21–9) is used. In the type A display the range is represented by the horizontal displacement of the target response from the trace origin, while the strength of the signal is represented by the vertical displacement of the trace. Where range and bearing are required a PPI display is usually used. Where height and range are needed a height-range indicator is employed, whilst if range, height and bearing are all required two CRTs, one a PPI and the other a RHI, are commonly used together. Alternatively a PPI only is used and relevant height information is extracted from a remote RHI position and displayed on a suitable numeric display.

2136. **Other Radar Displays.** A display can be designed to present almost any required information about a target in terms of range, bearing, height and elevation, or any two combinations of these. Fig 21–10 illustrates a few examples of additional displays in common use.

Schematic Diagram of a Basic Primary Radar

2137. In Fig 21–11 the various stages which have been discussed in paras 2126 to 2136 are linked together to form a block diagram of a basic primary radar system. The waveforms which would be seen if the various numbered points were connected to an oscilloscope are illustrated in Fig 21–12. The action of each "block" may be summarized as follows:

a. *Trigger Unit.* The trigger timing pulses produced by this unit control the PRF of the equipment and are applied to:

(1) The modulator, to trigger the transmitter operation at precise and regularly recurring instants of time.

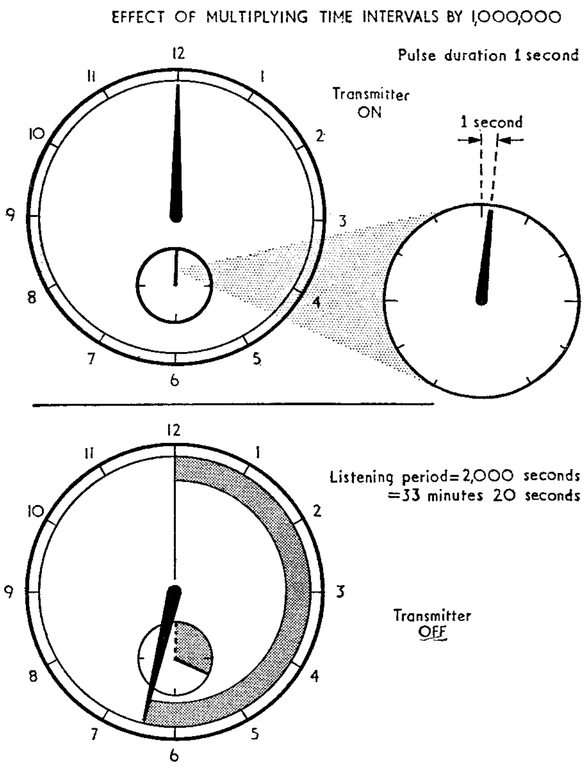


Fig 21–6 Time Intervals in Radar

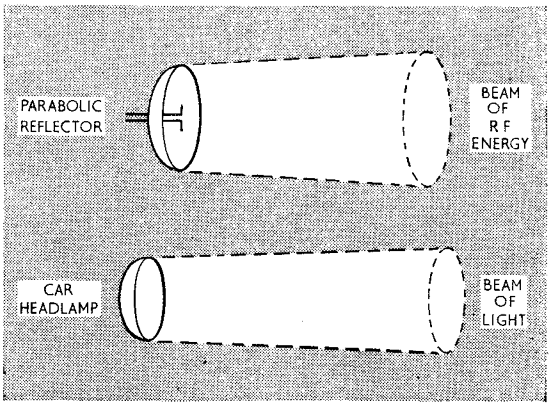


Fig 21–7 Concentration of Energy in a Beam

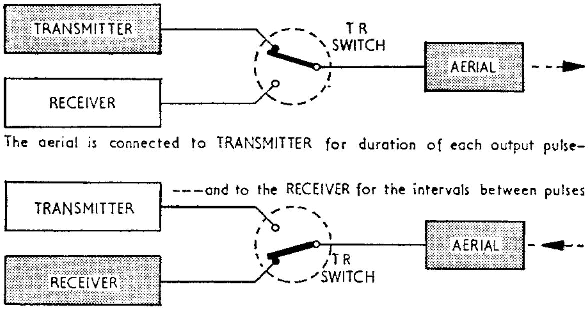


Fig 21–8 TR Switching

(2) The indicator timebase generator to synchronize the CRT trace with the transmitter operation.

b. *Modulator*. The modulator produces rectangular pulses of known pulse duration which switch the oscillator on and off.

c. *Oscillator*. The oscillator produces the very high frequency high power output pulses of short duration. The PRF is determined by the master timing unit and the pulse duration by the modulator.

d. *TR Switch*. The TR switch automatically connects the transmitter to the aerial for the duration of each output pulse, and connects the receiver to the aerial for the intervals between pulses.

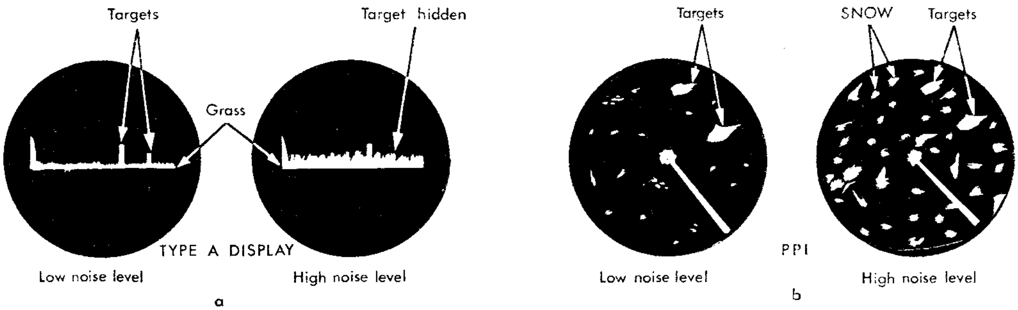


Fig 21–9 Type A Display and PPI Display

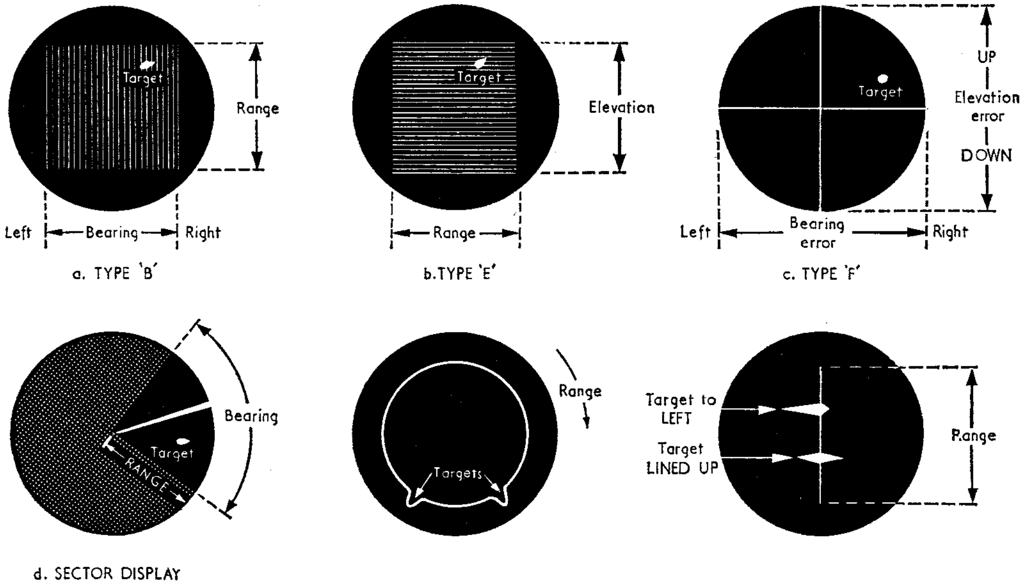


Fig 21–10 Other Common Radar Displays

e. *Aerial.* The aerial radiates the transmitter output in a narrow beam and picks up the reflected echoes for application to the receiver. The aerial may be moved for scanning, the movements being conveyed automatically to the indicator.

f. *Receiver.* The receiver amplifies the very weak echoes and presents them in a suitable form for display on a CRT.

g. *Indicator Timebase Generator.* The indicator timebase generator produces the range trace on the CRT screen. The sync pulses from the trigger unit ensure synchronization of indicator and transmitter operations.

h. *Indicator Display.* The indicator display presents the required target information in a suitable form.

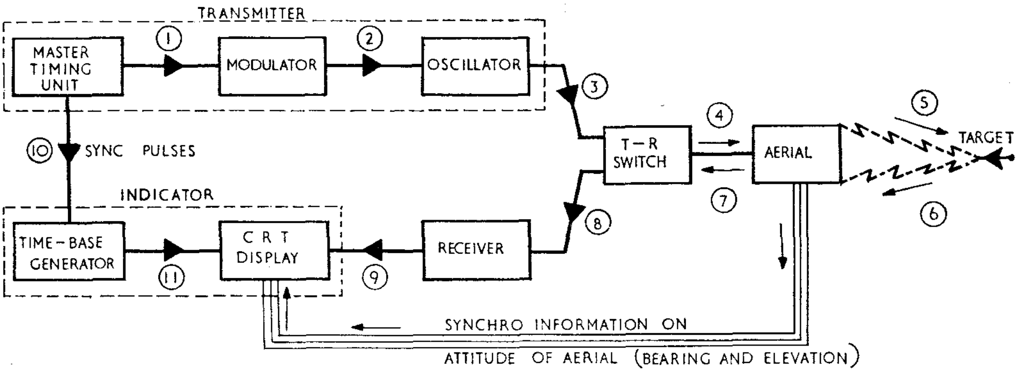


Fig 21–11 Basic Primary Radar Block Schematic Diagram

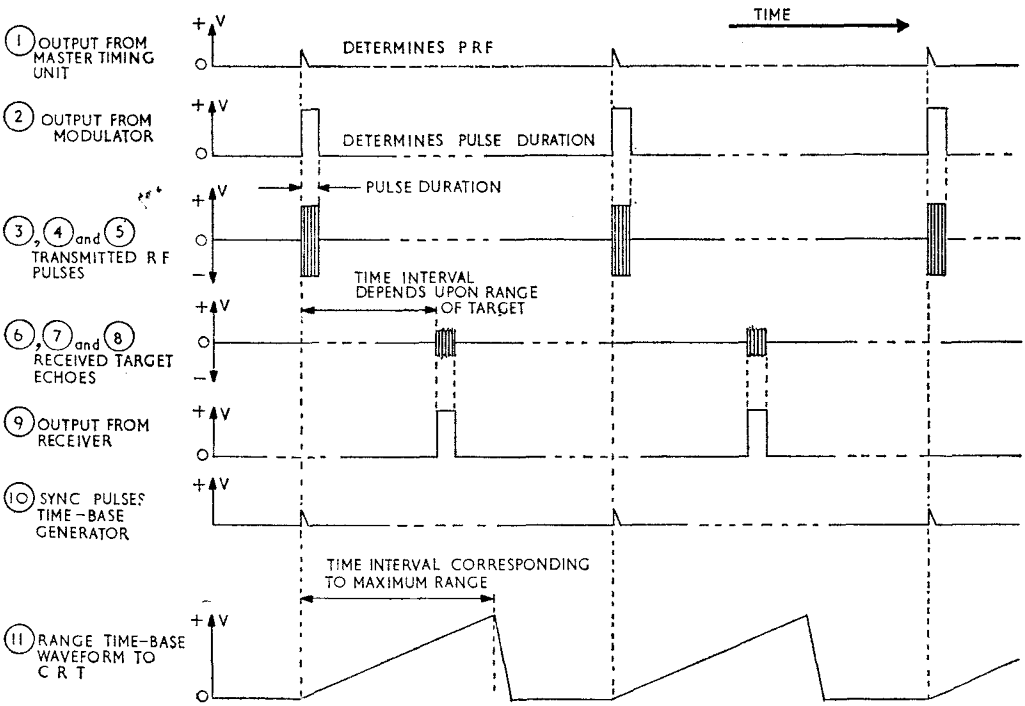


Fig 21–12 Waveforms at Various Points in a Primary Radar System

Secondary Radar Systems

2138. The pulse modulated primary radar system discussed so far relies on the reflection of the incident RF energy by the target. Instead of relying on reflections it would be possible to use the pulses received at the target from the primary radar to trigger a transmitter in the target aircraft. Such systems are known as secondary radar systems and can only be used when the target is friendly. When used in this manner the primary radar is known as the interrogator, and the secondary installation in the aircraft is called the transponder (transmitter-responder).

2139. One of the earliest applications of secondary radar was the identification equipment carried by friendly ships and aircraft in the Second World War, and known as IFF (identification friend or foe). In this system the primary radar on the ground is the interrogator and the ship or aircraft carries the transponder. When the transponder receives a signal of the correct frequency and pulse duration from the interrogator it automatically transmits coded pulses in reply and this response identifies the target as friendly on the ground radar PPI.

2140. Secondary radar may also be used as a navigation aid. In this role the interrogator is carried in the aircraft and the transponder is a radar beacon on the ground. The signals transmitted by the transponder when interrogated by the aircraft equipment are used by the aircraft to provide information on the range and bearing of the beacon. In this way the aircraft is provided with navigation or homing assistance. TACAN (*see* SD 727, Chapter 10) is an example of such an equipment.

2141. The operation of the secondary radar system is basically the same in the two cases mentioned above. The block diagram of a typical system is shown in Fig 21-13. Each pulse from the interrogator is picked up by the transponder aerial and passed to the receiver, where it is amplified and converted to a pulse. This pulse triggers the modulator which produces a waveform to switch the transponder transmitter on and off. A coding unit may be used to regulate the duration of the transmitter pulse, this pulse being radiated back to the interrogator where it is used to provide the required information about the target.

2142–2145. (*Not allotted*).

CENTIMETRIC RADAR AERIALS

Introduction

2146. One advantage of using centimetric wavelengths is that it is possible to build small aerials to give narrow beams. As the wavelength used gets shorter so the size of the aerial required to produce a given beamwidth decreases. For example, at 300 MHz (100 cm) an aerial of about 200 ft across would be required to produce a beamwidth of about 1°; at 10,000 MHz (3 cm) the same beamwidth is obtainable with a 6 ft aerial.

2147. With narrow beams accurate bearings in azimuth and elevation can be obtained and, because of the small size and light weight involved, rapid movement of the aerial is possible. Size and weight are particularly important considerations in airborne radars.

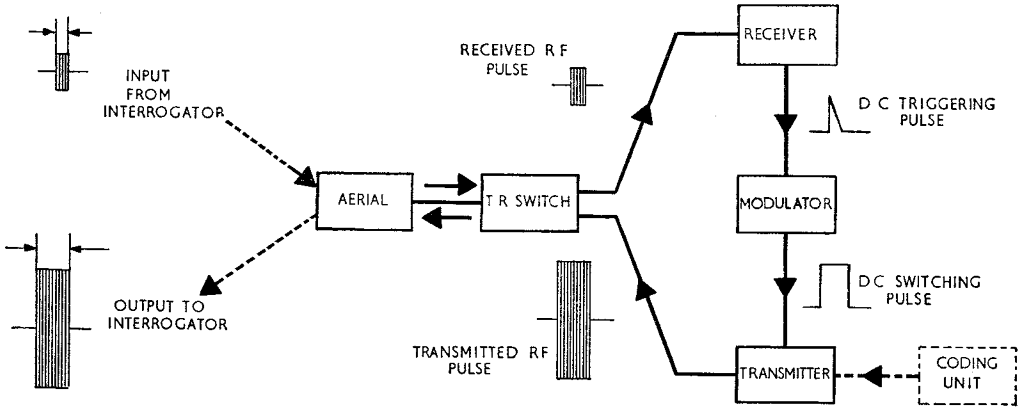


Fig 21–13 Block Schematic Diagram of a Secondary Radar Transponder

2148. It is possible to produce a narrow beam by radiating energy from an aerial into a reflector in much the same way as a searchlight beam is formed. At a given wavelength, the larger the reflector, the narrower will be the beam. This is the most common type of centimetric aerial and is known as a reflector aerial.

Aerial Parameters

2149. **Beamwidth.** The width of the radiated beam of a directional aerial is measured by the angle between the two points on the power radiation diagram where the power has fallen to half its maximum value (*ie* fallen by 3 dB).

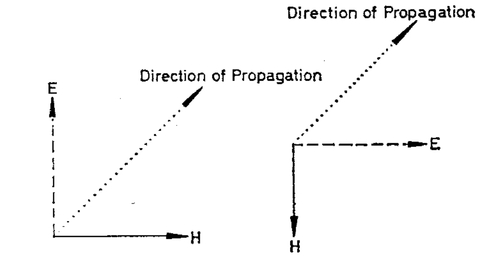
2150. **Gain.** The power gain of a directional aerial is the ratio of power radiated in the direction of maximum radiation to that radiated from a reference aerial (which may be an omnidirectional aerial or a simple dipole), both aerials being fed with the same current, *ie* the ratio:

$$\frac{\text{Maximum power radiated from the directional aerial}}{\text{Power radiated from the reference aerial}}$$

The gain is usually measured in dB.

2151. **Radiation Patterns.** By measuring the electric field strength in a certain plane around an aerial it is possible to plot a polar diagram for the aerial in that plane. Fig 21–14 shows a polar diagram for a typical centimetric aerial. On a narrow diagram it is difficult to measure the beamwidth and the plot is often made in cartesian co-ordinates as shown in Fig 21–14. From the cartesian radiation diagram the beamwidth can clearly be seen to be 5°. As well as the main lobe there are several side lobes. In centimetric radar aerials these must be kept as small as possible, for as well as wasting energy they can cause false indications.

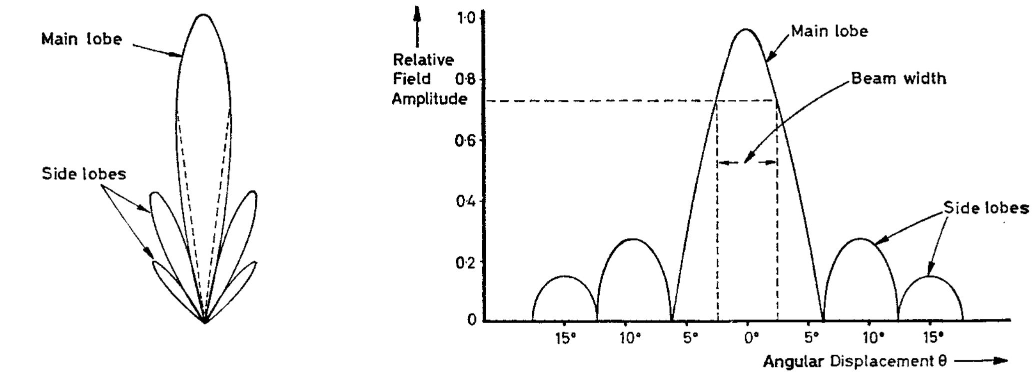
2152. **Polarization.** An electromagnetic wave radiated from an aerial consists of electric (E) and magnetic (M) fields are at right angles with each other and with the direction of propagation (*see* Fig 21–15). At some distance from the aerial



a. VERTICALLY POLARISED b. HORIZONTALLY POLARISED

Fig 21–15 The Plane Wave

the plane formed by the E (or H) vector and the direction of propagation is in a fixed direction and the wave is called a plane wave. The plane which contains the E vector and the direction of propagation is called the plane of polarization, and if this is vertical relative to the earth it is a vertically polarized wave, while if it is horizontal the wave is horizontally polarized, (*see* Fig 21–15). Most radars use horizontal or vertical polarization, but for some purposes (*eg* to obviate echoes due to rain) it is necessary to vary continuously the plane of polarization. This means that the E and H vectors, still at right angles to each other, rotate as the wave progresses. Circular polarization is an example of this type of polarization but elliptical or other types are possible. When the E vector rotates in a clockwise direction, viewed in the direction of



a. POLAR CO-ORDINATES b. CARTESIAN CO-ORDINATES

Fig 21–14 Radiation Patterns

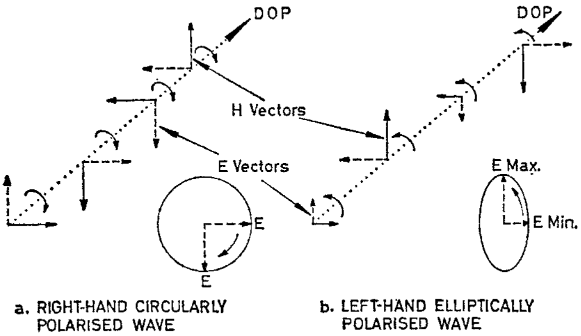


Fig 21–16 Circular and Elliptical Polarization

propagation, the wave is a clockwise, or right-hand polarized wave as in Fig 21–16a; if the E vector rotates in the opposite direction it is said to be an anti-clockwise or left hand polarized wave as in Fig 21–16b.

Parabolic Reflectors

2153. At centimetric wavelengths a specially-shaped metal reflector, similar in principle to a searchlight mirror, is used to produce a narrow beam. The parabolic reflector is the most widely used. In Fig 21–17a the section ABC is a cross-section of a parabolic reflector; point F is the focal point. If an aerial is placed at the focal point all energy radiated towards the reflector is reflected parallel to the axis BF. Furthermore, the path lengths F P_1 F_1, F P_2 F_2 *etc* are all equal. Thus rays radiated from F towards the paraboloid are reflected as parallel rays travelling in the same direction and arrive at XY in phase and therefore reinforce each other. A narrow beam in the direction of the arrow is thus formed by the reflector.

2154. Energy radiated from F directly towards XY without striking the reflector will not be in phase at XY and will produce diverging rays (*see* Fig 21–17b). This effect can be reduced by placing a small shield or sub-reflector behind the aerial as in Fig 21–17c.

2155. The larger the area of the opening (or aperture) AC, measured in wavelengths, the narrower will be the beam. The power gain of a parabolic reflector with an aperture diameter D is given approximately by $G = 6\left(\frac{D^2}{\lambda^2}\right)$, where λ is the wavelength of the radiated energy. D and λ must be in the same units.

Types of Parabolic Reflector

2156. To produce a pencil-shaped beam of circular cross-section a parabolic reflector (or "dish") with a circular aperture as shown in Fig 21–18 is used. The beam shape may be modified by cutting away parts of the paraboloid and making an "orange-peel" or truncated paraboloid as shown in Fig 21–19.

2157. The parabolic cylinder shown in Fig 21–20 is normally energized by a number of aerials placed along the broken line. The parabolic curvature causes narrowing of the beam in the vertical plane.

2158. The parabolic torus reflector shown in Fig 21–21 is formed by moving the parabola AB along the arc of a circle BC. The pencil-shaped beam formed by the reflector has fairly

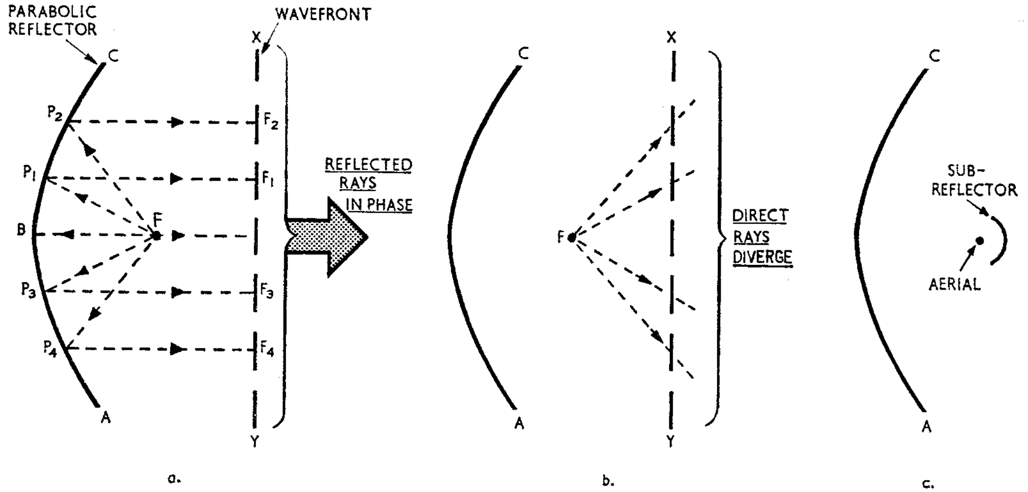


Fig 21–17 Principle of the Parabolic Reflector

small side-lobes. The torus reflector is normally used on ground radars where the reflector is stationary and scanning is achieved by moving the aerial feed.

2159. The above types of parabolic reflector may be constructed of metal or metallized plastic and for airborne use are usually solid. Large ground installation reflectors are normally of metal mesh to reduce weight and wind resistance.

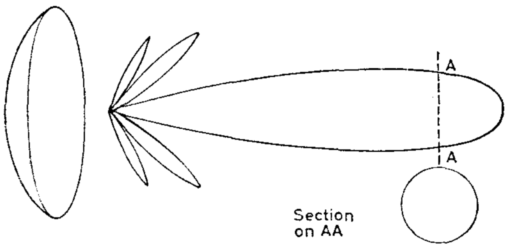


Fig 21–18 Paraboloid or Parabolic Dish

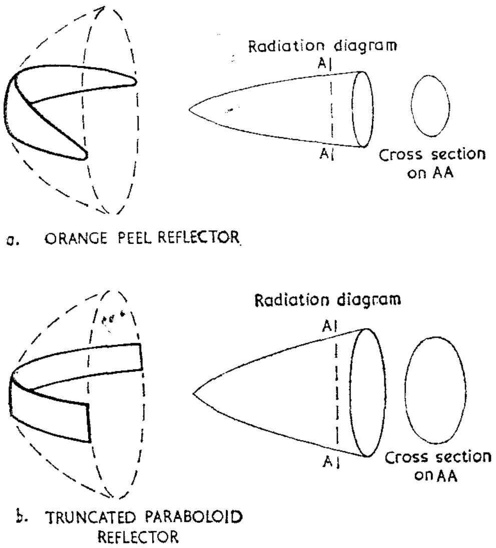


Fig 21–19 Types of Parabolic Reflector

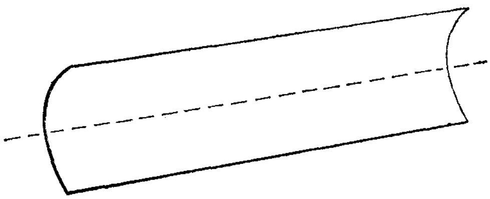


Fig 21–20 Parabolic Cylinder

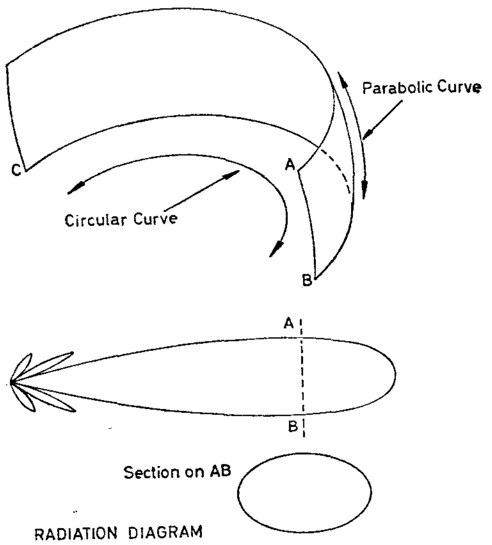


Fig 21–21 Parabolic Torus Reflector

Cosecant-Squared Reflectors

2160. The shape of the radiation pattern required from a radar aerial depends on the type of job the radar has to perform. Special beam shapes can be produced by using specially-shaped reflectors.

2161. An example is the cosecant squared (Cosec²) reflector used in some early warning and control radars so that similar targets at the same height but different angles of elevation return similar strength echoes. A cosecant-squared radiation pattern is shown in Fig 21–22.

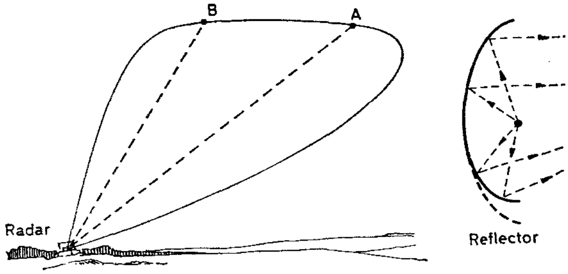


Fig 21–22 Cosecant-Squared Pattern

The lower portion of a parabolic reflector (it is usually a cylinder) is distorted so that some of the energy is reflected upwards instead of horizontally. Thus a target at A receives the same power from the radar as at B even though, because it is further from the radar installation, the energy is attenuated more. As the same aerial is used for receiving, constant illumination of the PPI results.

Methods of Feeding a Reflector

2162. **Horn Feed.** If a waveguide (*see* paras 21167–21171) is terminated by an open end (*see* Fig 21–23) energy is radiated from the waveguide into space. However if the termination is just a section through the waveguide as in Fig 21–23a, most of the energy is reflected back down the guide and harmful standing waves are produced in the waveguide. To overcome this difficulty the end of the waveguide is "flared" to form a horn as in Figs 21–23b and c, and maximum energy is radiated from the guide. The horn is also a directional radiator giving a fan shaped beam to radiate the reflector. By placing the horn at the focal point of a parabolic reflector a very narrow beam is radiated (*see* Fig 21–24). However the horn and its waveguide feed form an obstruction to the radiated beam. This distorts the radiation pattern and also the efficiency of the horn. This difficulty is overcome for ground search radars by offsetting the horn and placing it below the reflected radiation pattern.

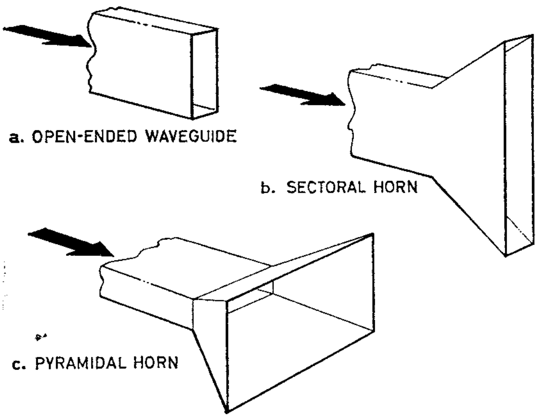


Fig 21–23 Waveguide Horn Radiators

2163. **Multi-Beam Reflector Aerials.** When a single reflector is fed with energy from several horn aerials mounted one above the other, a number of beams at different angles of elevation are formed. This type of aerial can be used to produce beams giving both high and low-angle coverage for a surveillance radar. By forming several beams, each beam requiring a separate horn, the aerial can be used as a height finder by using the principle of signal comparison (*see* paras 21107–21111). The outline of a "stacked horn" aerial in which four horns feed into a parabolic reflector is shown in Fig 21–25. The radiation diagram shows that four fixed beams at different angles of elevation are formed.

2164. **Moveable Feed Point Scanning.** Large ground radars are sometimes scanned by moving the position of the feed point and keeping the reflector stationary. This avoids the need to move a large metal reflector. By moving the feed point away from the focal point of a parabolic reflector, the direction in which the beam points is changed (*see* Fig 21–26), and the aerial scans over a limited sector. If the scanning angle is made too great the beam becomes distorted and the aerial gain falls.

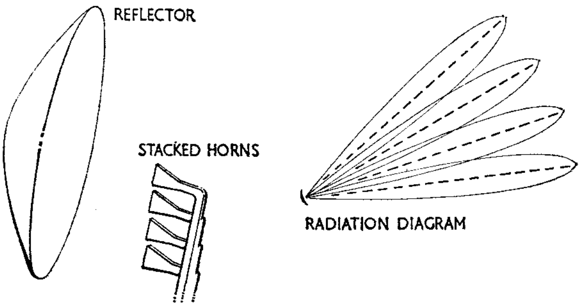


Fig 21–25 Stacked Horn Aerial

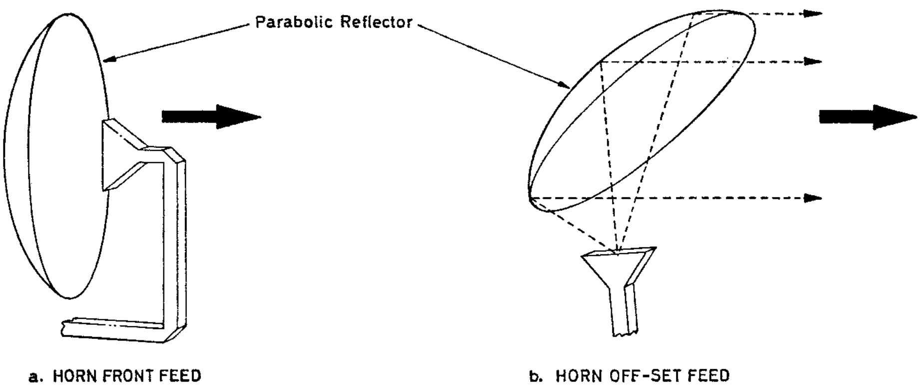


Fig 21–24 Types of Horn Feed

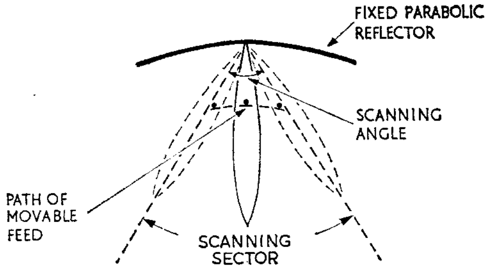


Fig 21–26 Movable Feed Point Scanning

2165. **Slotted Waveguide Arrays.** If a half-wavelength slot is cut in the narrow 'a' dimension of a waveguide (*see* paras 21167–21171) such that it interrupts the flow of wall current, it will act as an aerial. Slot 1 in Fig 21–27 is parallel to the wall current and therefore does not radiate. Slot 2 is slightly inclined and will radiate. As the angle of inclination is increased the percentage of power transferred from the waveguide to free space also increases. With an array of slots this angle is progressively increased to compensate for the reduction of energy in the guide so that each slot radiates equal energy. If the slots are placed at a distance equal to half of the wavelength of the RF in the guide ($\frac{1}{2}\lambda_g$), and inclined in the same direction, adjacent slots radiate in anti-phase and radiation at right angles to the array is zero. By alternating the slopes of adjacent slots as in Fig 21–27 the slots radiate in phase and a beam at 90° to the line of the energy is formed. The inclined slot array gives polarization in the same direction as the length of the waveguide.

2166. If slots are placed exactly at $\frac{1}{2}\lambda_g$ intervals, power may be lost due to the production of standing waves in the waveguide. However, by placing the slots at say $0{\cdot}55\lambda_g$ apart, the standing waves are obviated, and the array is termed non-resonant. But when the slots are placed $0{\cdot}55\lambda_g$ apart (Fig 21–28), the time taken for the RF in the waveguide to move from slot A to slot B is greater than the half-cycle time. Therefore the energy radiated from A will have reached P by the time the same wavefront is radiated at slot B. The two radiations therefore form part of a wavefront which is radiated not at right angles to the array, but at an angle to this direction. This angle is known as the "squint" angle.

Practical Slotted Waveguide Array

2167. The slotted waveguide array is normally used with parabolic or cosecant-squared reflectors to give the required beam shape. Fig 21–29 shows a typical arrangement for an S band (10 cm) ground radar. The horizontal non-resonant waveguide array has inclined slots cut in the narrow dimension facing into a cosecant squared reflector. The waveguide radiation produces a beam about 0·3° wide in the horizontal plane, while the reflector forms a consecant-squared pattern in the vertical plane.

2168. As shown in the insert of Fig 21–29 the waveguide array is enclosed in a channel, the top and bottom plates of which beam the radiation from the array so that the reflector is correctly illuminated. The front of the channel is fitted with a fibreglass window. The window is transparent to electromagnetic waves but makes the channel airtight so that dry air under pressure may be pumped through the waveguide to prevent corrosion, arcing or a corona discharge. The slots radiate about 90% of the total energy in the guide, the remainder being absorbed by a resistive dummy load at the end of the array remote from the transmitter input. The squint angle is about 4° and is compensated for by mounting the waveguide array such that the feed end is further from the reflector than the dummy load end. Horizontal polarization is used, but if vertical polarization is required, displaced slots cut in the broad dimension of the waveguide could be used.

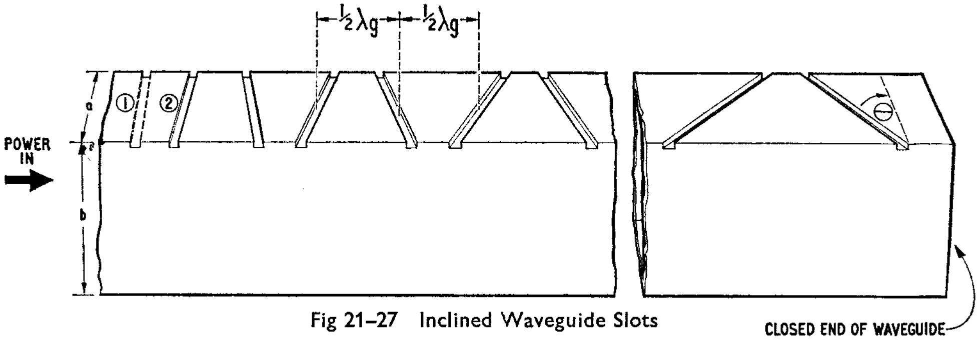


Fig 21–27 Inclined Waveguide Slots

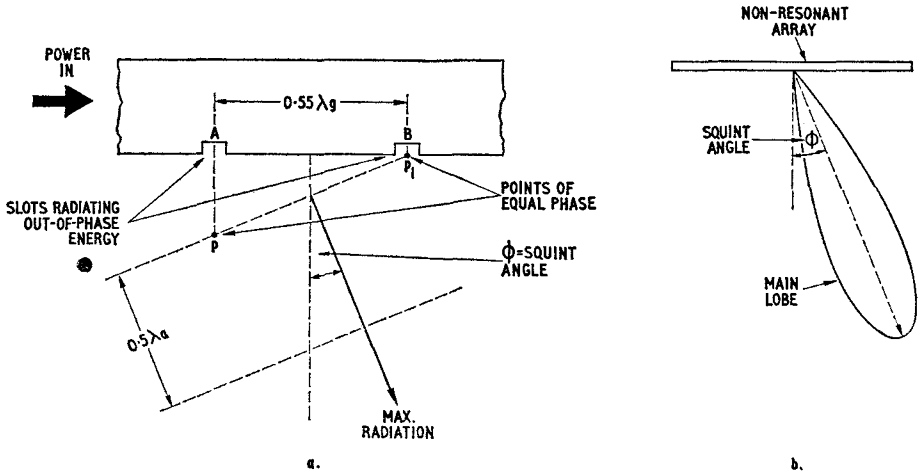


Fig 21–28 Non-Resonant Array

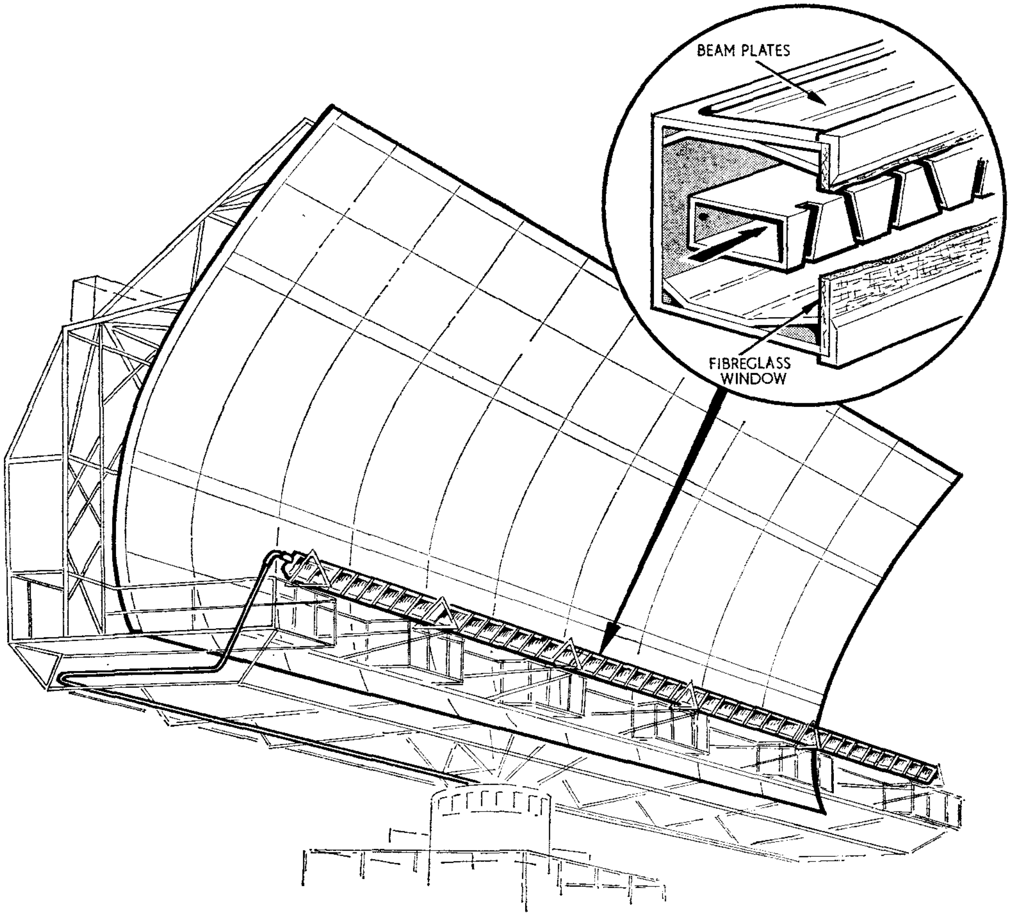


Fig 21–29 Typical Ground Radar Slotted Waveguide Array with Reflector

Application of Centimetric Aerials

2169. **Search in Azimuth.** A radar which is required to provide the bearing of a target needs an aerial which gives a narrow beam in the horizontal plane but wider in the vertical plane. At centimetric wavelengths a slotted waveguide array feeding into a cosecant-squared reflector will provide such a beam. The array gives a beam narrow in azimuth and the reflector shapes the vertical pattern so that targets at various angles of elevation can be detected. An airborne search radar for use as an aid to navigation and blind bombing and working in the X band would employ a similar aerial system but because of the shorter wavelength the assembly would be much smaller and lighter.

2170. **Height Finding Aerials.** The range and elevation of a target must be found to determine its height. A number of different types of aerial can be used for this purpose. Fig 21–30 shows an aerial which produces a beam narrow in elevation and wider in azimuth. The beam is usually directed onto the azimuth bearing of the target by information obtained from a surveillance radar. The aerial is then made to nod up and down so that the beam passes through the target. From the range and elevation angle so obtained the target height can be computed. Another method of height finding employs an aerial which produces a stack of narrow pencil-shaped beams at various fixed angles of elevation. The target response from each beam is fed

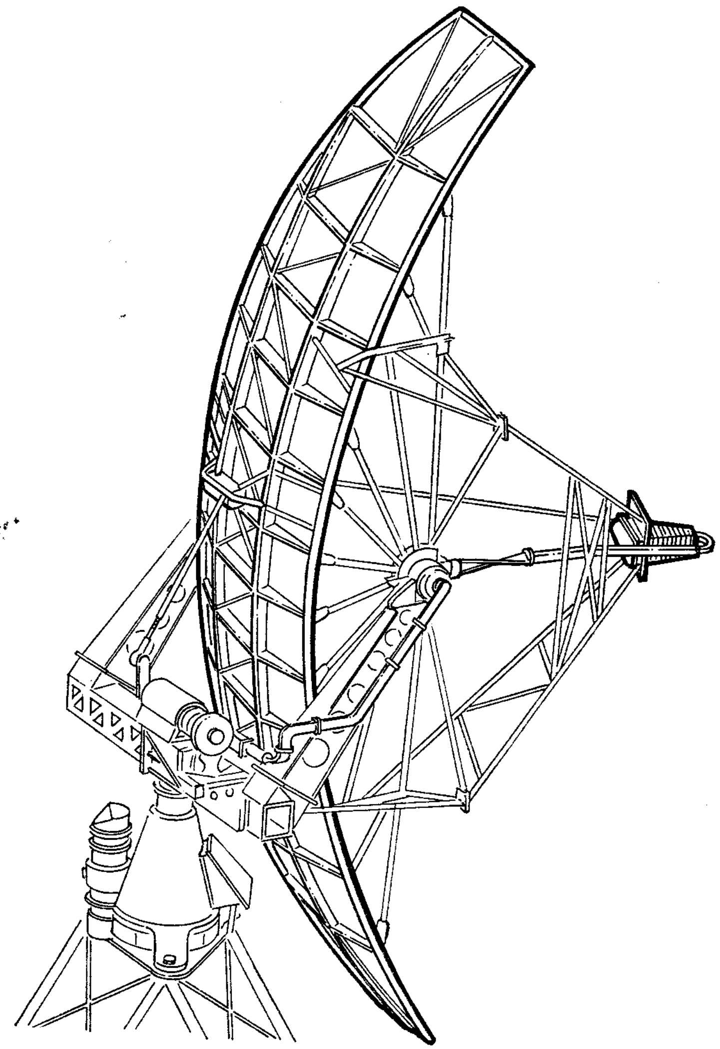


Fig 21–30 Height Finding Aerial

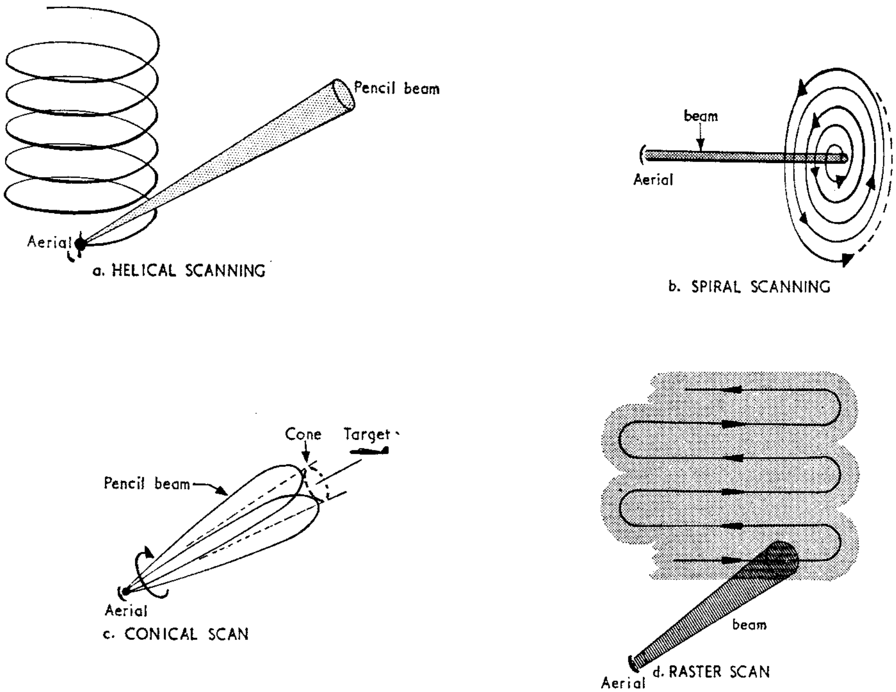


Fig 21–31 Pencil Beam Scanning Patterns

into a separate receiver and when the receiver outputs are compared an accurate indication of the target's elevation angle is obtained. This method is discussed further in paras 21107–21111.

2171. **Pencil-Shaped Beams.** A parabolic "dish" reflector may be used to form a pencil-shaped beam. Different types of parabolic reflector (for example the orange peel and truncated paraboloid reflectors) can be used to alter the shape of the beam. A beam narrow in both planes must be steered or scanned in order to search a required volume of space. The beam must follow a regular pattern in order that all the required space is searched. There are many types of scanning pattern, each suited to a particular task. Four common patterns are shown in Fig 21–31. Pencil-shaped beams can be moved by mounting the aerial and reflector on a platform which can be tilted and turned over the required angles of azimuth and elevation. In airborne radars the movement of the platform due to aircraft pitch and roll can be compensated for by gyroscopic stabilization. Scanning the beam may also be achieved by moving the aerial feed point and by mechanical or electronic beam steering methods.

2172. **Monopulse Radar.** Conical scanning requires information from at least four pulses to derive an error signal with which to position the aerial in both azimuth and elevation. If the amplitude of these pulses varies due to varying attitudes of the target or to intentional jamming, the accuracy of azimuth and elevation information is weakened. In a monopulse radar the angular measurements are made using one pulse only, and therefore these inaccuracies cannot occur. Two or more beams are formed simultaneously, and by comparing the relative phase or amplitude of the echo pulse received in each beam the angular position of the target can be determined from the information contained in a single pulse. Fig 21–32 shows an X band (3 cm) monopulse aerial used in an AI automatic tracking radar. The reflector, a double paraboloid, is fed from the rear by a four-way horn. This feed has four apertures, each pair of which is aligned with the focus of each paraboloid. The radiation pattern in elevation comprises two beams which cross. Thus if a target lies on the axis of the aerial, the amplitude of signals received at apertures 1 and 2 will be the same as that of signals received at 3 and 4. If the target lies off the vertical axis of the aerial there will be a difference in amplitude of signals received by the two pairs of apertures. The difference signal is used to align the aerial, in elevation, to the target. Azimuth bearing of the target is found by comparing the difference in phase

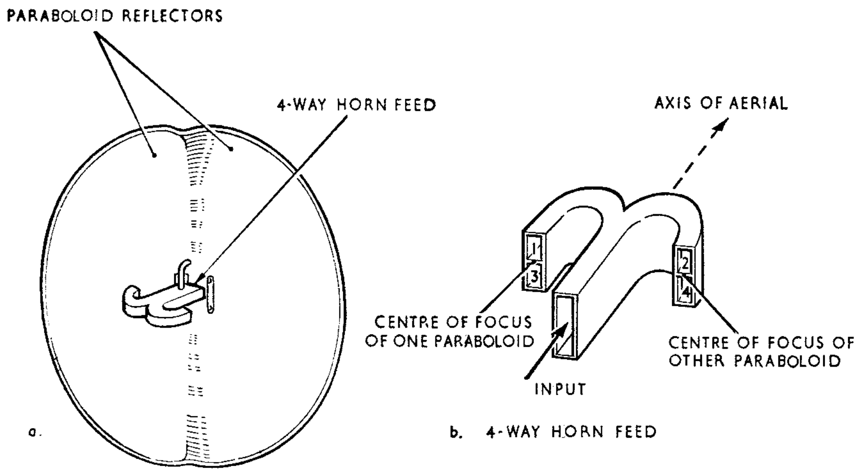


Fig 21–32 Monopulse Multi-Beam Aerial

between signals received by apertures 1 and 3, and 2 and 4. This difference is converted into a signal which aligns the aerial in azimuth.

2173–2185. (*Not allotted*).

RADAR DATA DISPLAYS

Introduction

2186. In modern air defence systems the information obtained from radars must be presented to the users in a way that can be interpreted easily. In addition to a "raw" radar display showing all radar targets, each user normally requires displays which will give detailed information about the targets with which he is personally concerned.

2187. To this end a variety of displays are available, including raw radar, synthetic radar, a mixture of raw radar and synthetic symbols, tabular, and closed circuit television. Thus an air defence position could contain the displays shown in Fig 21–33. In the following paragraphs each of the above displays will be considered briefly.

Synthetic Display

2188. In modern air defence systems radar information from primary and secondary radars concerning the range, azimuth angle, height and recognition category of a large number of aircraft may be fed, in digital form, into a computer. The range and azimuth angle, which together give the position of the aircraft, are changed into X and Y cartesian co-ordinates and corrected so that the aircraft position is relative to the control centre position. In this new form the positional data are passed to a digital store and up-dated on every aerial sweep. The computer calculates the aircraft track from successive positions, and this, together with height and identity data on each aircraft, is passed into another section of the computer store. The outputs from these stores are fed into a synthetic display. This is a normal type of PPI display fed with processed radar data. With a synthetic display the user can select for display those targets in which he is interested. This is done by operating switches which send demands for the required data to the computer. As well as the target responses displayed on the CRT screen each target may be marked with identification symbols and characters. The CRT has a dual fixed-coil deflexion system: one produces the radial scan synchronized to the rotating radar aerials; the other is an inter-trace deflexion system. This second deflexion system operates during the inter-trace period of the main scan (*see* Fig 21–34). These characters can be either in the form of "strobe markers", controlled by the display user, or groups of letters and numerals (known as "alpha-numeric" characters) originated by a character generator controlled by the computer. A simplified diagram showing the connections of equipment for inter-trace marking is given in Fig 21–35. The data concerning track, height or identity held in the computer store are fed to the character generator which produces currents to deflect the CRT beam and form the required character. Writing speeds of up to 50,000 characters per second are possible, each character being written in 20 μs by up to sixteen 1 μs

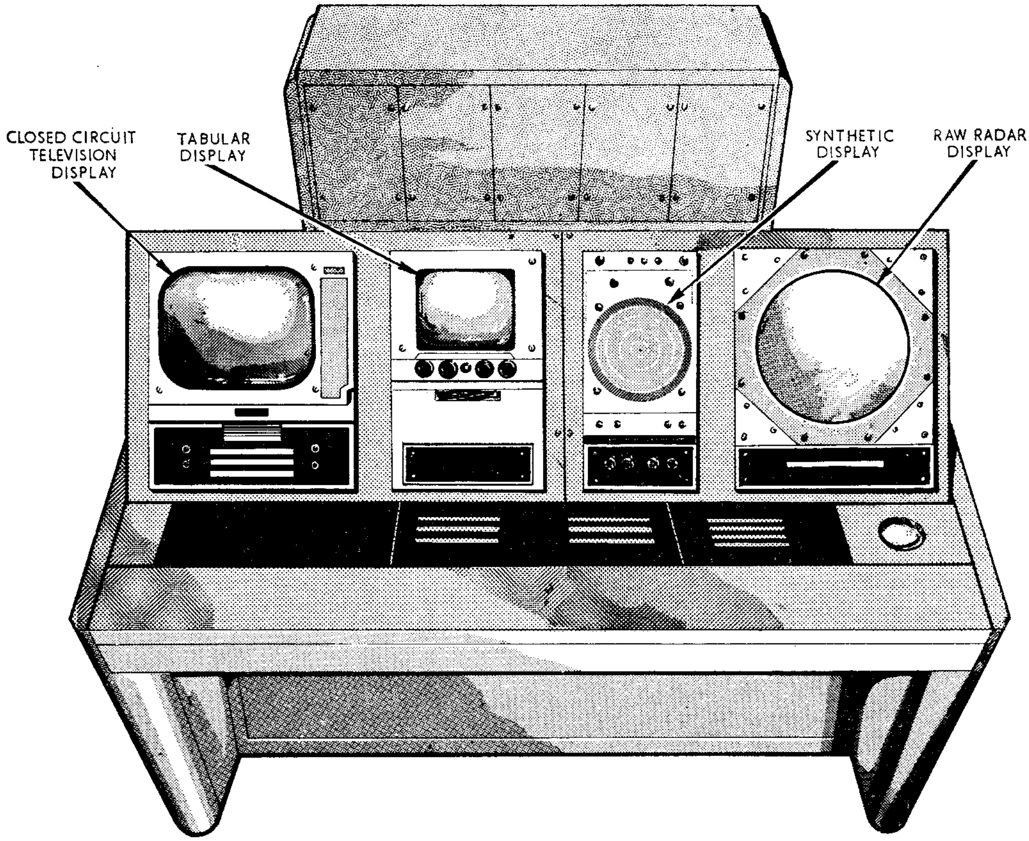


Fig 21–33 Typical Radar Display Console

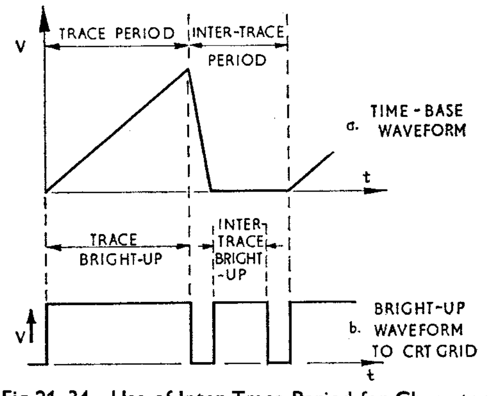


Fig 21–34 Use of Inter-Trace Period for Character Writing

deflections of the CRT beam. A display which consists entirely of synthetic information is generally known as a Labelled Plan Display (LPD), whilst a display consisting of raw radar responses with added labels or marks is termed a Marked Radar Display (MRD).

Tabular Displays

2189. A tabular display is one in which target information such as identity, height, track and estimated time of arrival at reporting points is written on the face of a CRT in alpha-numeric characters (*see* Fig 21–36). A tabular display is separate from the radar PPI display and does not contain target blips. The data employed may be derived from a digital computer or from a keyboard similar to that of a typewriter.

2190. In an automatic data processing system the information to be displayed is processed and passed to a digital store where it is kept up to date. The stored data are sequentially scanned and used to control an electronic character generator which provides the waveforms required to provide the characters on the display CRT. As the information is up-dated a single character on the display can be changed without altering the remaining characters.

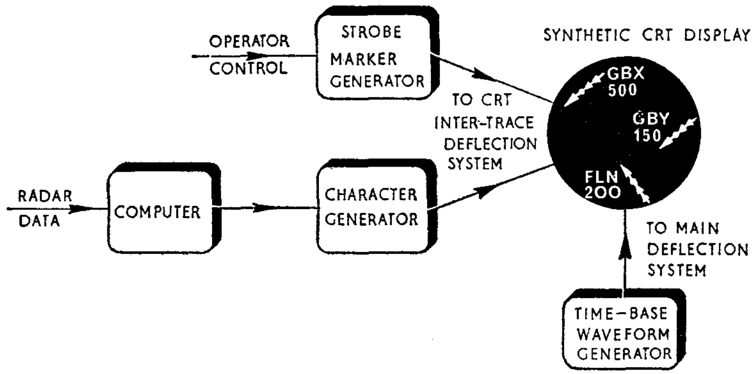


Fig 21–35 Arrangement for Production of a Synthetic Display

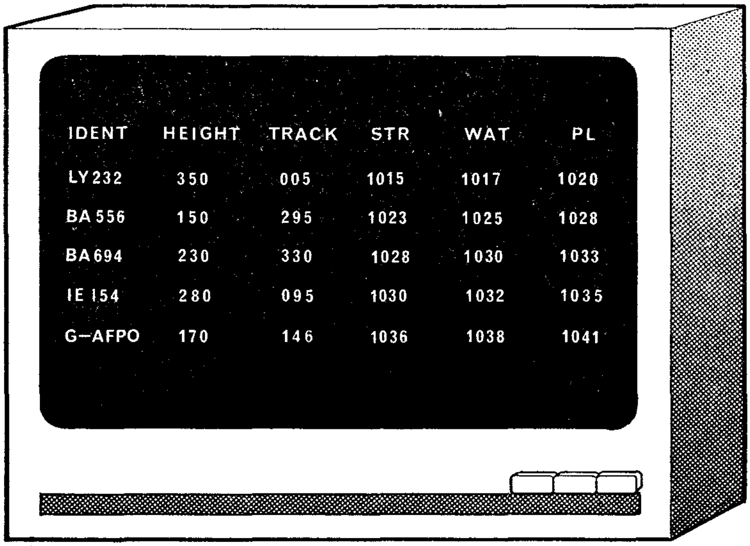


Fig 21–36 Typical Alpha-Numeric Tabular Display

2191. The information is displayed on a CRT screen as alpha-numeric characters in a series of horizontal lines. Each character is written by continuous movement of an electron beam through the intersections of a "modulated" matrix. The picture can be read in normal daylight at a distance of three feet.

2192. Typically, the equipment can write 50,000 characters per second, the CRT afterglow being such that a steady picture results. Several displays can be fed from one position and the user can select information on any target in which he is interested.

Video Maps

2193. Video maps provide a means of associating a radar PPI picture with geographical features such as cities, airfields, coastlines and mountains, and with reference systems such as the georef grid, reporting beacons and airways boundaries. The video map is mixed with the radar video echoes fed to the PPI CRT and appears as lines traced on the CRT screen. The display user can thus establish the position of a target with reference to important geographical and reference points.

2194. The map to be displayed is photographed and a photo-negative slide is obtained on which the coastline, airfields, airways boundaries, danger areas, reporting points *etc* are transparent. Fig 21–37 illustrates a slide which shows a coastline, airfields, airways boundaries and aircraft reporting points.

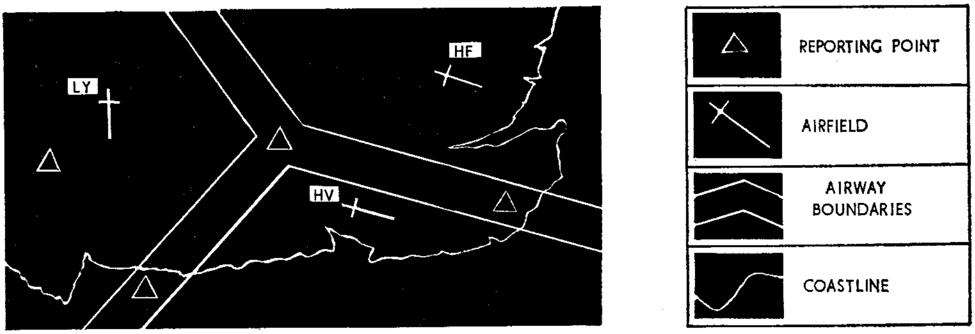


Fig 21–37 Photographic Slide for Video Map

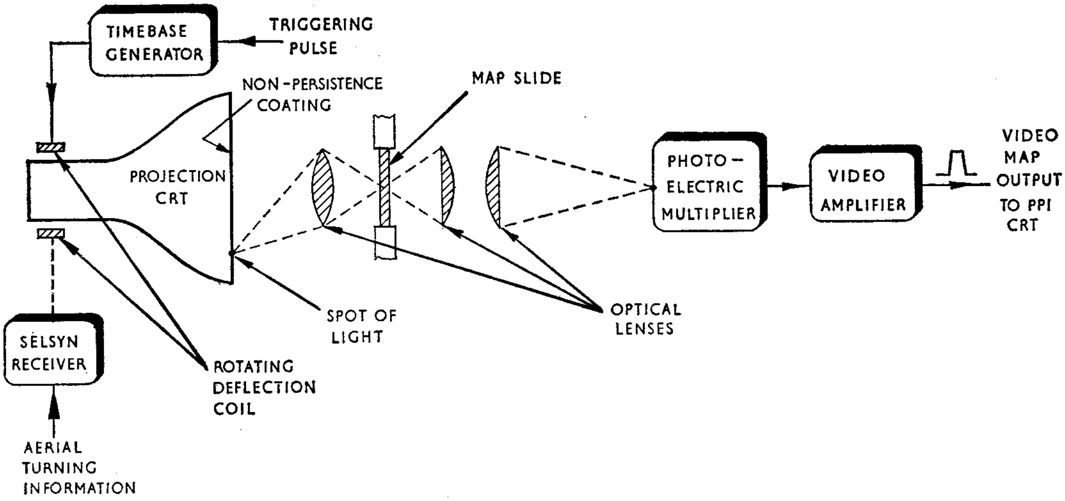


Fig 21–38 Outline of Equipment for Producing a Video Map

2195. The basic components of an equipment which produces a video map on the PPI screen from a map slide are shown in Fig 21–38. The projection CRT is a flat-faced tube giving a finely-focused spot of light. The screen is coated with a non-persistent luminous substance and the electromagnetic deflexion coil is rotated about the neck of the tube in synchronism with the aerial head. The timebase, triggered by the radar master timing pulse, is fed to the deflexion coil. Thus the spot of light on the projection CRT screen moves radially out from the centre of the CRT each time the radar transmits a pulse and moves round the face of the CRT in synchronism with the rotating aerial.

2196. A wide-angle optical lens focuses the spot of light on to the map slide on which the lines of information are transparent. The light which passes through the slide is then focused on to the light-sensitive cathode of a photo-electric multiplier which converts the pulses of light into electrical energy. The output consists of pulses of current of varying amplitude and duration. These are amplified and passed as constant amplitude pulses to the display PPI.

2197. The map slide is made from a master drawing and reduced to the required size when the negative is produced. The slide is mounted in a carrier which must be accurately positioned relative to the lens. Usually two range markers are marked on the plate at 20% and 80% of the maximum range and these are used in setting up the map picture against range markers on the PPI display.

Closed Circuit Television

2198. Closed circuit television monitor units are installed at some positions in modern air defence systems. A wide variety of information can be displayed on the units, as the information is originated by an operator who writes on an edge-lit perspex screen in chinagraph pencil. A television camera mounted behind each screen produces a high-definition picture of the written information which may be displayed at a number of monitor positions. The particular information screen display required by the user may be selected by push-buttons at the user position.

2199–21105. (*Not allotted*).

HEIGHT FINDING SYSTEMS

Introduction

21106. There are three basic height finding methods in use in ground environment systems of the Royal Air Force. The methods are known as beam comparison, V beam, and nodding aerial height finding. Each is described briefly in the following paragraphs together with their associated display read-out devices.

Beam Comparison

21107. The beam comparison method is used by some radars which radiate a number of narrow overlapping beams on the same azimuth but at different angles of elevation (*see* Fig 21–39). The beams may be produced by a single transmitter pulse feeding into separate radiating elements for each beam; by pulses from separate transmitters at different frequencies feeding into individual radiating elements; or by a combination of both. The radiating elements (normally horns) are placed one above the other and radiate into a focusing reflector, thus producing a radiation pattern covering a wide elevation angle and comprising narrow overlapping beams.

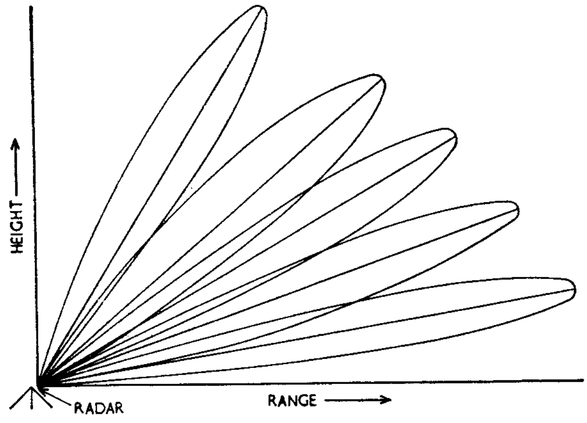


Fig 21–39 Multi-Beam Radar Receiver Radiation Pattern

21108. A target causes reflection of the radiated energy in the normal way and the signal received at each of the horns is fed through its own receiver circuit. A target which is at the centre of a beam will return a maximum signal to the horn which radiated that beam; signals returned to adjacent horns will be less than maximum. After processing, the individual signals for each beam are fed to a height finding computer which carries out a comparison of signal strengths in each beam, and by using the range of the target (found by the normal echo method), calculates the altitude of the target.

21109. Height information on a particular target may be requested by the operator by indicating or "gating" the target's return on the PPI display, or height information may be sought automatically by the system for each target response injected into it. The height calculated by the computer is displayed to display positions on a numeric read-out device.

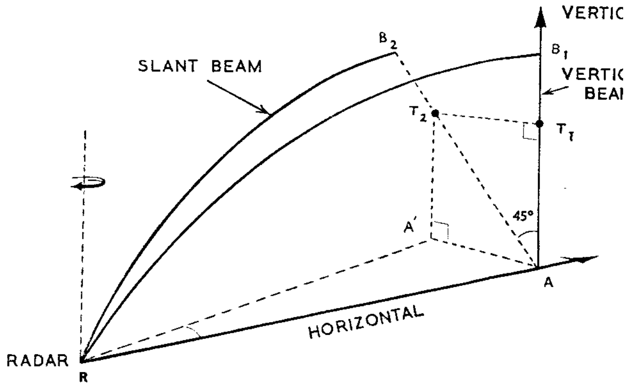


Fig 21–40 V Beam Principle of Height Finding

V Beam Heightfinding

21110. Another integral method of heightfinding (*ie* heightfinding combined with search and having the same range performance) is the V beam system. A V beam radar generates two fan-shaped beams (*see* Fig 21–40); one (the vertical beam RAB_1) is narrow in azimuth and usually cosecant-squared pattern in elevation; the other is the same shape but tilted at 45° to the vertical (RAB_2). The two beams form a V-shaped trough and intersect along the horizontal line RA. They rotate clockwise about the vertical axis of the radar at the same speed. Thus the vertical beam is the first to illuminate any given target, and then the slant beam illuminates it after the whole array has turned through a certain angle in azimuth. It is simpler, for the purposes of illustration, to reduce the radar with its beams to rest, and thus show the target apparently circling anticlockwise about the radar. In Fig 21–40:

T_1 represents the position of the target in the vertical beam.

T_2 represents the position of the target in the slant beam.

A and A^1 are ground projections of T_1 and T_2 respectively.

Thus the angle ARA^1 is the interval in azimuth between the two illuminations of the target. But this angle depends only on the elevation angle ART_1 of the target: The target's height AT_1 equals AA^1 (because $AA^1T_2T_1$ is a square, the diagonal angle T_1AT_2 being 45°) and this is easily shown to be $2RA \sin \frac{1}{2}ARA^1$, and so, given the ground range RA and the separation angle ARA^1, the target's height can at once be calculated. For targets at low elevation the two responses on a target (one from the vertical beam and the other from the slant) will be close together and may indeed overlap, making assessment of their separation difficult. To overcome this a fixed azimuth separation of the two beams in the ground plane is introduced (perhaps of 5°), so that the two responses are separated by 5° even if the target is at zero elevation; any separation due to the V beam would be added to this 5°.

21111. In modern data processing systems the operator merely "gates" each response on the PPI and a computer carries out the required calculation. The height is shown on suitable read-out display to those persons who require it.

Nodding Height Finders

21112. Nodding height finders have an aerial system which produces a "beaver tail" beam shape; narrow in azimuth (about 5°) and very narrow in elevation (about 1°). The aerial system is made to nod up and down (nutate) through an elevation angle of between about −1° and +33°. The whole array can be turned in azimuth so that the aerial is searching in the direction of the target. This action is initiated either by an operator "gating" a response on a PPI, or by a computer programme in an automatic data processing system.

21113. Once the array is searching on the correct azimuth the target is detected as the aerial nods through the elevation angle of the target. This angle is measured by the operator of a height range indicator which represents the movements of the aerial reflector. The operator bisects the target response with a "height line", produced electronically on the CRT. He then presses a button which causes the calculation of the target height to be carried out from the data available (the target elevation and range), and the height to be relayed automatically to the appropriate display position as a numeric read-out.

21114–21120. *(Not allotted)*.

FACTORS AFFECTING RADAR PERFORMANCE

Introduction

21121. Radar was introduced in paras 2114–2122 of this chapter, but the question of radar performance was not discussed. In the following paragraphs the following factors which affect pulse modulated radar performance are briefly examined:

a. Factors affecting maximum range.
b. The need for high powers.
c. The use of high frequencies.
d. The limitations of radar.
e. The effects of unwanted responses.
f. Discrimination between adjacent targets.
g. The relationship between PRF and pulse length.

Terms used in Pulse Radar

21122. Some of the terms used in pulse modulated radar have already been described in Chapter 20 and in paras 2126–2129 of this chapter. It is useful here to define these terms more precisely and show their relationship with other equally important terms.

21123. The waveforms shown in Fig 21–41 are "ideal", *ie* zero rise and decay times have been assumed. In practice however, each pulse is more rounded because it takes a finite time to rise and fall, but the ideal waveforms shown are adequate for the purposes of this section. Note that the axes used in Fig 21–41 are *power* against *time* although more usually the waveform refers to *voltage* and time.

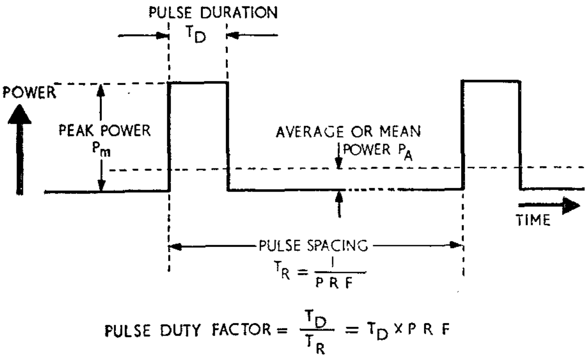


Fig 21–41 Terms Used in Pulse Radar

21124. **Pulse Repetition Frequency (PRF).** The PRF is the number of pulses occurring in one second. For a PRF of 500 pps the pulse spacing T_R is $\frac{1}{500}$ second or 2,000 microseconds (μs). The value of PRF normally lies between about 200 and 6,000 pps.

21125. **Pulse Duration (Pulse Length).** The pulse duration T_D is the length of time for which the transmitter is switched on to give each pulse. It normally lies between 0·1 and 10 μs.

21126. **Pulse Duty Factor.** The pulse duty factor (also known as the "duty cycle") is the ratio of the pulse duration T_D to the pulse spacing T_R. Since $T_R = \frac{1}{PRF}$, the pulse duty factor is also the product of pulse duration T_D and PRF. If the pulse duration is 1 μs and the PRF 500 pps, the pulse duty factor is $10^{-6} \times 500$, or $\frac{1}{2{,}000}$, which is usually read as 1 in 2,000. It means that there is one 1 μs pulse to every 2,000 μs. If each pulse were drawn with a width of one inch to represent the pulse duration of 1 μs the next pulse would occur 2,000 inches further along, *ie* approximately 55 yards away.

21127. **Peak and Average Values of Power.** It has been shown that the power output of the transmitted pulses should be as great as possible; but when power is developed in a circuit, heat is produced in the components. However, because the transmitter works in pulses, it is possible to develop a very high power in the circuit for the short duration of the pulses and, in the comparatively long resting time between pulses, the heat produced can be removed. If the transmitter uses a pulse duration of 1 μs and a PRF of 500 pps, in one hour of operation the transmitter is switched on for a total time of only 1·5 seconds. Although the peak power developed during each pulse may be very high, the mean power over a long period is quite low. The power rating of the components used in the transmitter circuit can therefore be much lower than might at first seem necessary.

21128. **Relationship Between Peak Power, Pulse Duration, PRF and Mean Power.** There is a very simple relationship between peak power, pulse duration, PRF and mean power. From Fig 21–42 it can be seen that the mean power is equal to the peak power multiplied by the product of pulse duration and PRF. Since pulse duration × PRF equals the pulse duty factor, the mean power P_A may be written as

P_A = Peak power P_M × duty factor.

Example: If a radar transmitter radiates a peak power of 1 MW with a pulse duration of 1 μs and a PRF of 1,000 pps the mean power is;

$$P_A = P_M \times T_D \times F_r$$
$$= 10^6 \times 10^{-6} \times 1{,}000$$
$$\therefore \quad P_A = 1 \text{ kW}$$

Thus a transmitter rated at 1 kW mean power can be used to produce 1 MW pulses if the pulse duty factor is $T_D f_r = \frac{1}{1{,}000}$

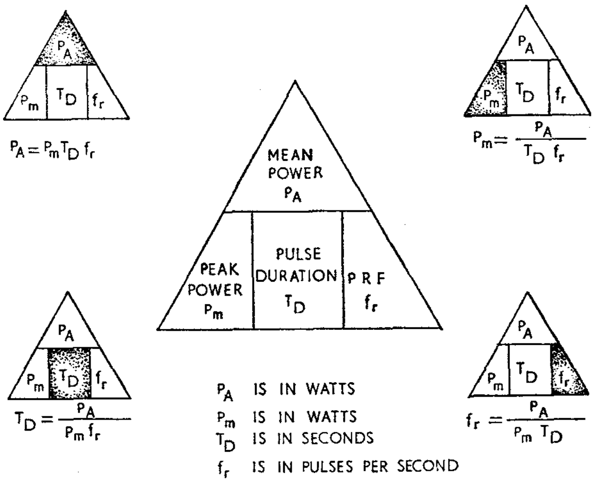


Fig 21–42 Relationship Between Peak Power, Pulse Duration, PRF and Mean Power

Factors Affecting Radar Operation

21129. Many factors affect the operation of a radar installation. Some of these factors are external to the radar set and affect all radars, *eg* reflections from unwanted objects and effects of external noise and jamming. Very little

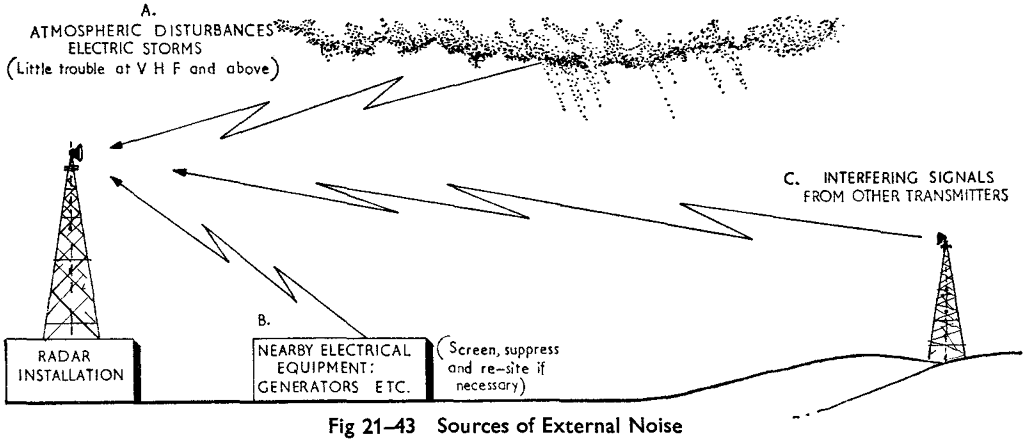


Fig 21-43 Sources of External Noise

control over such things is possible. Other factors controlling the performance of a radar are the result of deliberate decisions in design, *eg* the frequency of operation and the values of PRF and pulse duration. These are selected and adjusted to give specific results and thus intentionally limit the operation of the radar.

External Factors Affecting Performance

21130. The main external factors limiting the performance of a radar are:

a. Sources of external noise.

b. Reflections from unwanted objects.

c. The dimensions of the target.

d. The curvature of the earth's surface.

e. Atmospheric refraction.

f. Atmospheric absorption and scattering.

21131. **External Noise.** External noise may be caused by any of the factors illustrated in Fig 21-43. In some circumstances interfering signals from other transmitters may be the result of deliberate jamming of the radar by an enemy transmitter; this jamming technique is called Electronic Counter Measures (ECM) and uses a specialized radar.

21132. **Reflections from Unwanted Objects.** Unwanted objects must first be defined. Something which may cause an unwanted echo to one type of radar may be the wanted echo to another type. For example, clouds, built-up areas, hills and aircraft all produce radar echoes. For an early warning search radar the wanted echoes are those produced by aircraft or missiles. For meteorological radar, on the other hand, it is the cloud formations which produce the wanted echoes. For an air-to-surface weapon delivery radar the towns and hills produce the wanted echoes, *ie* a "radar map". In early warning search radar echoes produced by anything other than aircraft or missiles are unwanted and it is desirable to remove the unwanted "clutter" from the displays. Such clutter may be so pronounced, especially from objects near the ground radar, as to hide the wanted echoes completely. Fortunately modern radars have circuits which are largely able to eliminate clutter, and some of the techniques in common use are described in paras 21176–21191.

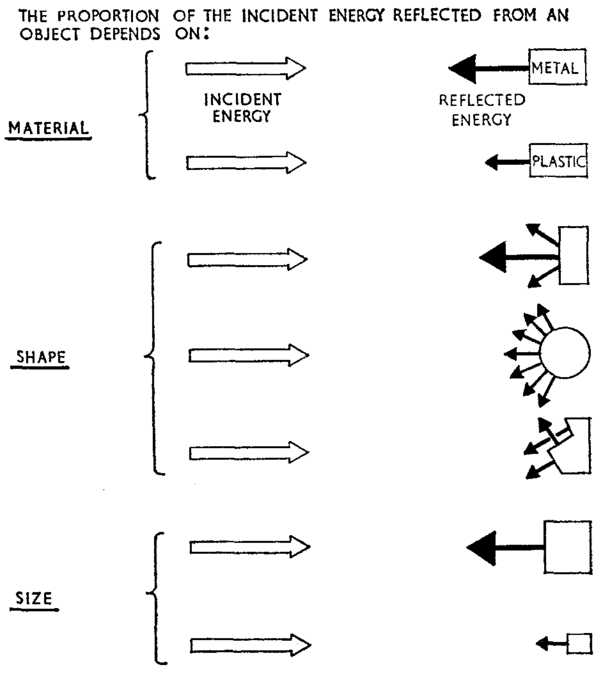


Fig 21-44 Characteristics of Targets

21133. **Dimensions of Targets.** All pulse modulated primary radars depend for their success upon the reflection of energy from objects which have been illuminated by a radar beam. All objects in the path of the beam will reflect energy to some extent. The amount reflected depends on the material of which the object is made, the shape of the object, and its size (*see* Fig 21–44). If two identical objects are placed at different distances from the radar the one nearer the radar reflects more energy. A metal object will reflect more energy than an object of the same size and shape made of wood or plastic. The better the conductor the greater is the reflection. The shape of the object will determine how the energy is reflected. If the object has a flat side facing the radar transmitter it will reflect more of the energy back towards the radar than an object of any other shape. Large objects will reflect more energy than small objects of the same material and shape at the same distance from the transmitter. However the object must be of a certain minimum size, in terms of the radiated energy, to produce a reasonable reflection of energy. Generally targets must be of a size greater than about a quarter of the wavelength being used before a detectable echo is received. Thus for the detection of small objects the radar wavelength must also be small; *ie* the frequency must be very high. This is one reason for the use of high frequencies in radar.

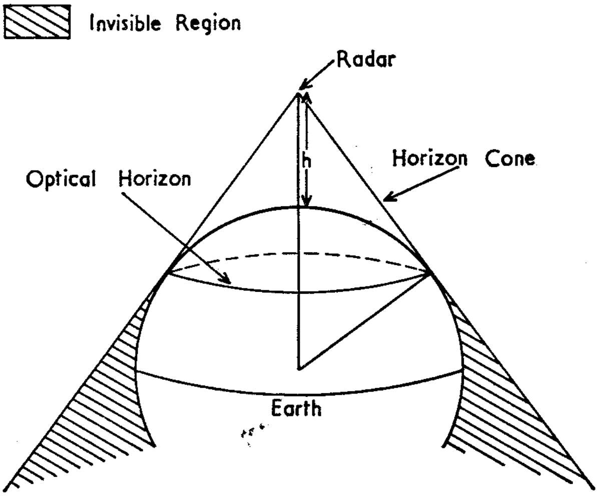


Fig 21–45 Optical Horizon

21134. **The Curvature of the Earth's Surface.** The curvature of the earth's surface imposes a limit on range obtainable by centimetric radars. If the earth is assumed to be a sphere (a good enough assumption for practical purposes), and if radar waves are assumed to travel in straight lines like light waves, it can be seen that objects below the optical horizon will be invisible (*see* Fig 21–45). It can be shown that the radius of the optical horizon is equal to about $\sqrt{1{\cdot}14h}$ nautical miles, where h is the height in feet of the radar above the regular surface of the earth. However radio waves, unlike light rays, do not travel in straight lines through the earth's atmosphere but follow a curved path because of refraction effects (*see* paras 2041 and 21135), so that the horizon for radar waves (the radar horizon) is somewhat greater than the optical horizon and is approximately equal to $\sqrt{1{\cdot}51h}$ nautical miles. The radar horizon radius is therefore the limiting range for the detection of targets at sea level, but targets above the earth's surface can obviously be detected at greater ranges. Since the radar horizon of a target above the surface of the earth is equal to $\sqrt{1{\cdot}51h_T}$ where h_T is the height in feet of the target, then

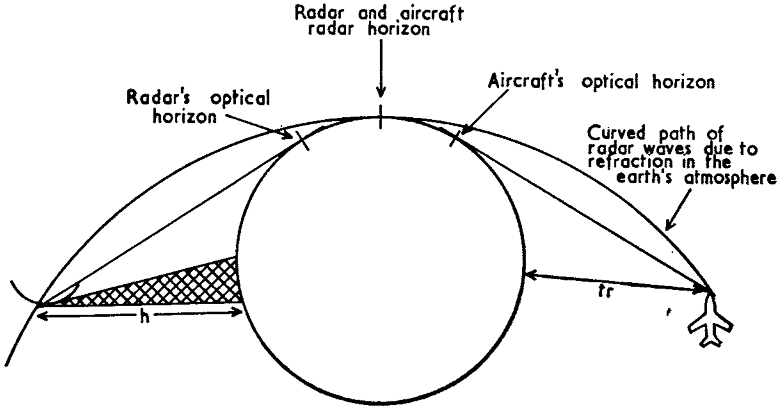


Fig 21–46 Radar Horizon

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the limiting range at which a radar at height h can "see" target at height h_T is $\sqrt{1 \cdot 51 h} + \sqrt{1 \cdot 51 h_T}$ (*see* Fig 21–46), when the radar energy just grazes the surface of the earth. The figures in the following table have been obtained by this method and are approximations of the range limit imposed by the radar horizon on centimetric radars.

Serial No	Height of Target (ft)	Height of Radar (ft)										
		0	20	50	100	200	300	400	500	600	700	800
1	0	0	5·5	8·7	12	17	21	25	28	30	33	35
2	20	5·5	11	14	18	23	27	30	33	35	38	40
3	50	8·7	14	17	21	26	30	33	36	39	41	43
4	100	12	18	21	25	30	34	37	40	42	45	47
5	200	17	23	26	30	35	39	42	45	48	50	52
6	500	28	33	36	40	45	49	52	55	58	60	62
7	1,000	39	44	47	51	56	60	63	66	69	71	73
8	1,500	48	53	56	60	65	69	72	75	78	80	82
9	2,000	55	60	63	67	72	76	79	82	85	87	89
10	5,000	87	92	95	99	104	108	111	114	117	119	123
11	10,000	123	129	132	135	140	144	148	151	153	156	158
12	15,000	151	157	160	163	168	172	176	179	181	184	186
13	20,000	174	180	183	186	191	195	199	202	204	207	209
14	30,000	213	219	222	225	230	234	238	241	243	246	248
15	40,000	246	252	255	258	263	267	271	274	276	279	281
16	50,000	274	280	283	286	291	295	299	302	304	307	309
17	60,000	301	307	310	313	318	322	326	329	331	334	336

21135. **Atmospheric Refraction and Super Refraction.** Refraction has already been discussed briefly in para 2041, and its effect of increasing radar range beyond the optical horizon was mentioned in the previous paragraph. Refraction occurs when waves pass between media of different densities. The density of the atmosphere generally decreases with height, and it is this characteristic which causes radar waves, radiated at angles up to about 20°, to follow a curved path which is roughly an arc of a circle (concave downwards) of radius four times that of the earth. Waves radiated at elevations greater than 20° are less curved, and a wave radiated vertically upwards is not refracted at all. However the density of the earth's atmosphere varies with temperature, pressure and humidity, and the amount of refraction therefore also varies. Under certain abnormal climatic conditions temperature can increase, and humidity decrease (thus causing an unusually high decrease of density) with height. When this occurs refraction may be abnormally high and a duct is formed between the earth's surface and a height of a hundred feet or so above the earth. This is called super-refraction, or anomalous propagation—sometimes abbreviated to "anaprop". At centimetric wavelengths radar waves may be trapped in the duct and ranges far in excess of the normal radar horizon are obtained. Adverse effects of this phenomenon are the decrease of normal high and medium cover, and echoes at false ranges from objects far in excess of the normal range of the radar. Weather conditions favourable for super refraction exist mainly in tropical and sub-tropical climates. In temperate climates the weather must be fine and settled for centimetric wavelengths to be affected.

21136. **Atmospheric Absorption and Scattering.** Radar waves of wavelength shorter than 30 cm may lose energy to the atmosphere in passing through it, and this loss may occur in two ways: by direct absorption in the gases of the atmosphere; and through absorption and scattering by condensed matter such as drops of water. The effects of direct absorption in the gases of the atmosphere is negligible in wavelengths down to 3 cm (X band) which is why wavelengths below this value can be used for radar detection only at very short ranges. The presence of condensed water in the atmosphere as fog or rain has an appreciable effect on the detection ranges of S band (10 cm) and X band (3 cm) radars. The attenuation rate varies with drop size and concentration and is illustrated in Fig 21–47. Relatively large drops of water such as are found in rain-giving clouds act as miniature radar targets and scatter radar energy as well as absorbing it. This contributes to the attenuation, but, perhaps more important, part of the scattered radiation returns to the radar and produces clutter on the display.

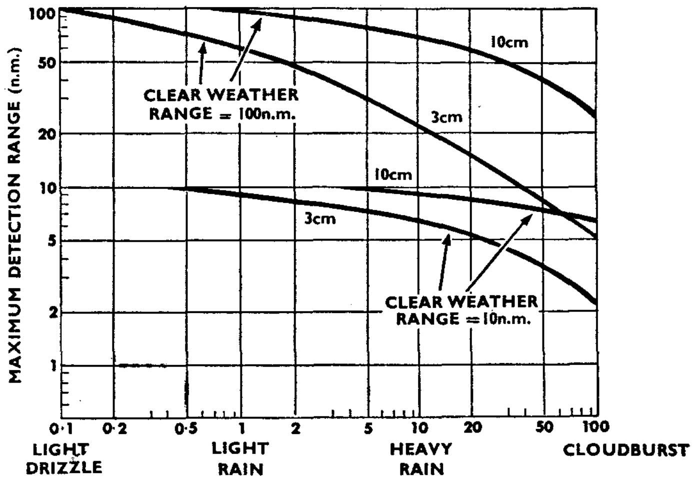

Fig 21–47 Effect of Precipitation on Maximum Detection Range

Design Factors Affecting Radar Performance

21137. The main factors in the design of a radar set which affect the performance of the radar are:

a. Transmitter power.

b. Receiver sensitivity and noise factor.

c. Frequency of operation.

d. Shape of radar beam and scanning methods used.

e. Pulse repetition frequency.

f. Pulse duration.

21138. **Transmitter Power.** Even with the most concentrated radar beam only a fraction of the energy of each radiated pulse strikes a target. At the target this fraction of the original energy is scattered, so that, in turn, only a fraction of the incident energy returns towards the receiving aerial. To compensate for this very inefficient reflecting process the greatest possible radiated power must be used. This is why peak powers of $2\frac{1}{2}$ MW or more are frequently used; but even with such high peak powers the power in the received echo is only of the order of milliwatts or even microwatts. In general the higher the radiated power the greater is the received echo power and hence the greater is the range (*see* Fig 21–48). However the increase in range obtained by increasing the radiated power

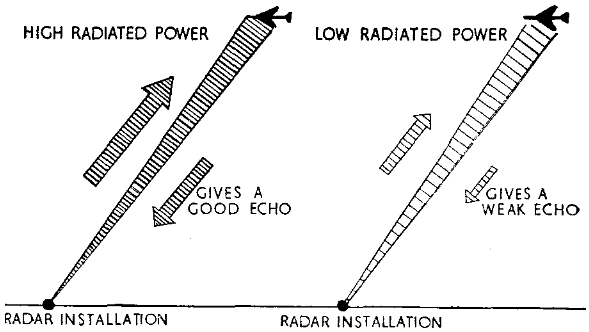

Fig 21–48 Effect of Transmitter Power on Received Signals

is very small. Even doubling the power only increases the range by 1·19 times. The power that the transmitter is designed to radiate depends on the job the radar has to do. Obviously a long-range search radar needs a very high peak power during the pulses. The power needed by an airfield approach radar, where the required range may be only a few miles, is very much less.

21139. Radar Sensitivity and Noise Factor. The main limitation on useful amplification in a radar receiver is the relationship between the amplitude of the wanted signal voltage and that of the noise voltage, *ie* the signal-to-noise ratio. If the input has a low signal-to-noise ratio the signal echo on the CRT may be "lost" among the noise indications. The input signal-to-noise ratio to a receiver is determined by external factors as previously noted, and it is, at the moment, the ultimate limitation on the reception of very weak echoes. In addition the receiver itself generates noise, and the receiver noise, when combined with the input noise, means that the output signal-to-noise ratio is lower than the input signal-to-noise ratio. The ratio of the signal-to-noise ratio at the input to that of the output is known as the "noise factor" of a receiver. It is a measure of the noise introduced by the receiver itself (*see* Fig 21–49). The design problem is to produce a receiver with as low a noise factor as possible. This is complicated by the fact that the receiver has to accept very narrow pulses and hence a wide band of frequencies. Wide bandwidths tend to increase the noise factor of a receiver. Thus the design of a receiver is a compromise between high sensitivity, wide bandwidth and low noise factor.

21140. Frequency of Operation. The frequencies used in radar are high for three main reasons (*see* Fig 21–50):

a. To obtain a good echo the radar wavelength must be less than four times the size of the target.

b. For good angular discrimination between adjacent targets, for accurate indication of bearing, and for adequate concentration of the radiated energy it is necessary to use aerials which produce a very narrow beam. This can be achieved much more easily at high frequencies.

c. High frequencies are needed to ensure an adequate number of RF cycles in each pulse.

The frequency chosen for a particular radar depends on the job it has to do. A high-resolution radar which is required to discriminate between targets very close together in bearing will use frequencies in the microwave region—in the band 3,000 to 30,000 MHz. For long range radars, where early warning is the criterion and accuracy of range and bearing of less importance,

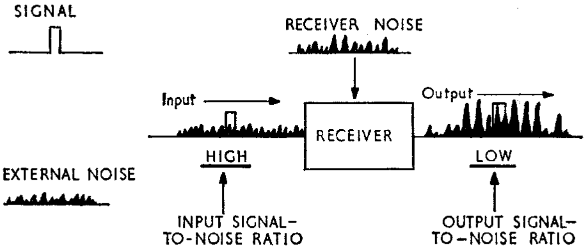

Fig 21–49 Receiver Noise Factor

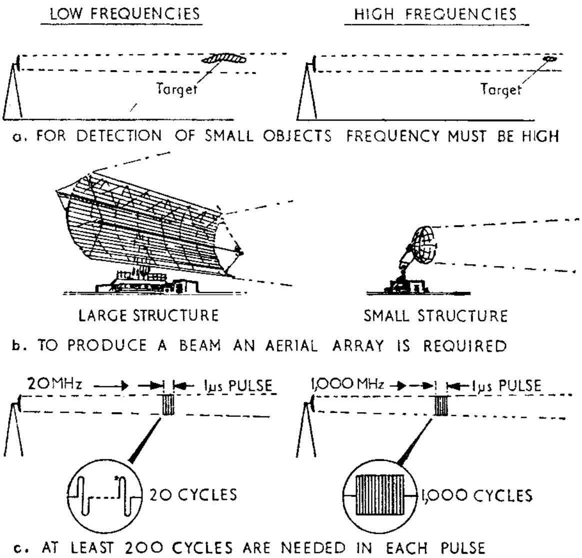

Fig 21–50 Need for High Frequencies in Radar

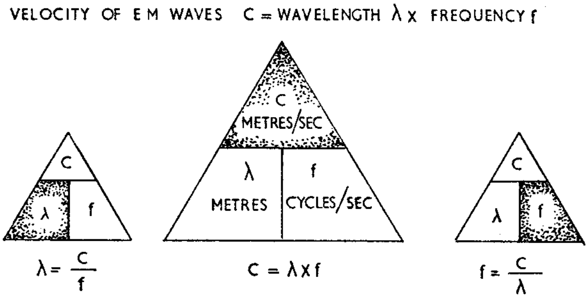

Fig 21–51 Relationship Between Frequency and Wavelength

the VHF band around 300 MHz could be used. The lower frequencies have the advantage of smaller atmospheric absorption at long ranges. In radar, the wavelength at which the equipment is operating is quoted as often as the frequency. The relationship between frequency f in cycles per second, velocity c of electromagnetic waves in miles per second, and wavelength λ in metres is illustrated in Fig 21–51. The most common frequencies used in radar, together with their corresponding wavelengths, are in bands as shown in the following table:

APPROVED LETTER BAND DESIGNATORS

	Band	Channel (1)
Letter	Frequency in MHz	Width MHz
A	0– 250	25
B	250– 500	25
C	500– 1000	50
D	1000– 2000	100
E	2000– 3000	100
F	3000– 4000	100
G	4000– 6000	200
H	6000– 8000	200
I	8000– 10000	200
J	10000– 20000	1000
K	20000– 40000	2000
L	40000– 60000	2000
M	60000–100000	4000

Notes:

(1) Each band is divided into ten numbered channels with width as shown, *eg* "A5" = 100–125 MHz; "H7" = 7200–7400 MHz.

(2) Exact frequency may be identified by defining the band, the channel (base or lowest frequency) and adding the MHz required, *eg* "D4 plus 15" = 1315 MHz.

(3) The frequency band limits above are exactly as agreed by NATO. For intra-UK use the upper limit should be read as "up to but not including". This will ensure that specific frequencies are included in one band only and not in two as above, *eg*:

Band A .. .. .. 0–249·999 MHz
Band B .. .. .. 250–499·999 MHz *etc.*

scan a given volume of sky may be too long for quick detection and tracking of a target. Very often other beam shapes and other scanning methods are used to determine quickly the required information about a target. One quick method of scanning involves the full rotation of a fan beam about a vertical axis (*see* Fig 21–52). Using a beam like this in conjunction with a PPI gives accurate determination of range and bearing in azimuth once every revolution of the aerial. No determination of elevation is directly possible. Fig 21–53 illustrates a "beaver tail

21141. **Shape of Radar Beam and Scanning Methods.** The need for narrow beams has already been noted. The shape of the beam will, however, depend upon the requirement of the radar. The "pencil beam" gives a high precision of angle measurement, but the time taken to beam". This beam, which is narrow in the vertical plane and somewhat broader in the horizontal (azimuth) plane, is "nodded" up and down between the scanning limits. It may be used in conjunction with a type B display or height-range indicator to give a quick and fairly

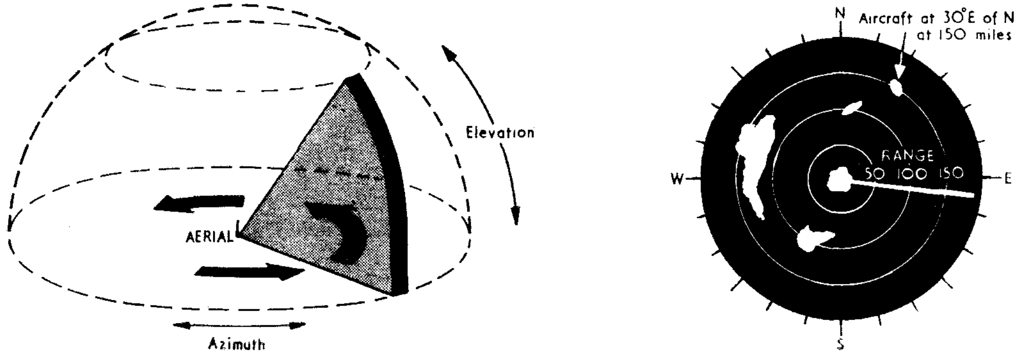

Fig 21–52 Use of a Fan Beam

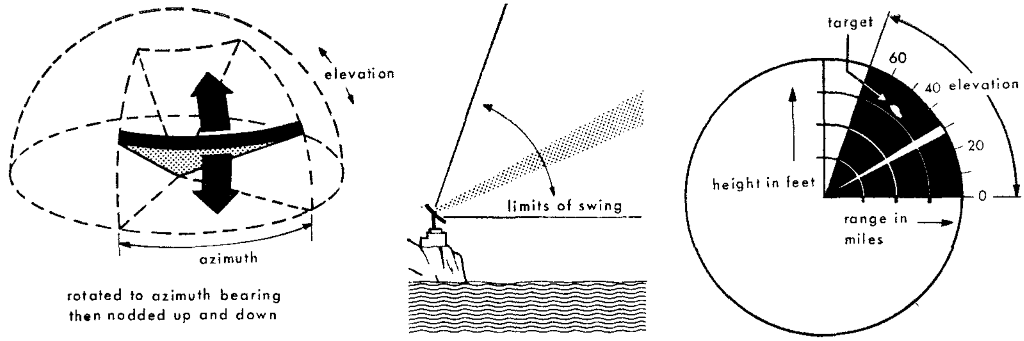

Fig 21–53 Use of a "Beaver Tail Beam"

accurate indication of the elevation of the target. Other beam shapes and scanning methods are described in paras 2146–2172.

21142. **Pulse Repetition Frequency (PRF).** The PRF selected for a particular radar depends on several factors; the most important are summarized below:

a. *Maximum Required Range.* Each pulse must be given time to travel to the most distant required target and return before the next pulse is transmitted otherwise there will be a risk of confusion on the display. If the maximum required range of a radar is 100 miles, the time taken for a pulse to travel to a target range 100 miles and return is $100 \times 10{\cdot}75 = 1075\ \mu s$. The transmitter must be quiescent for at least this time, *ie* the pulse spacing T_R must have a minimum value of $1075\ \mu s$. Since $\text{PRF} = \frac{1}{T_R}$, the maximum value of PFR is $\frac{10^6}{1075} = 930$ pps. If the PRF is adjusted to this maximum value, then any signals received from targets at a range *greater* than 100 miles would appear in the next pulse spacing period. Thus in Fig 21–54 target A, within the required range, is indicated on the CRT during every pulse spacing period. Target B, outside the required range, returns an echo every *alternate* period. The persistence of the CRT screen is normally sufficient to retain the indication of the target B all the time, and, to the operator, target B appears to be at a range of 40 miles. To avoid this, the pulse spacing is made very much longer than its minimum value of $1075\ \mu s$, *ie* the PRF is reduced well below 930 pps. The CRT timebase trace however is still adjusted for a sweep of $1075\ \mu s$. If a PRF of 200 pps is selected the result will be as shown in Fig 21–55. Any target beyond 100 miles range will return an echo after $1075\ \mu s$, when the timebase trace has been switched off, and so will produce no indications on the CRT. The same reasoning applies for any required radar range, but for smaller ranges the trace

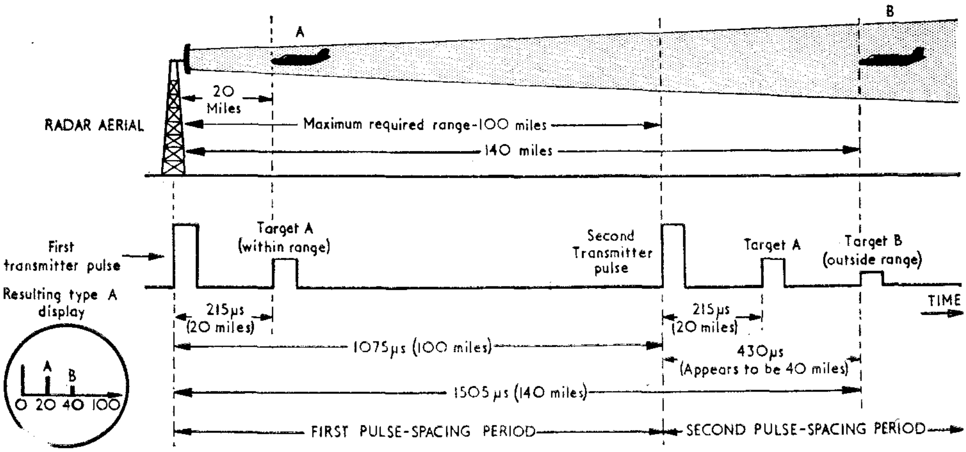

Fig 21–54 Indications from Targets Beyond the Required Range

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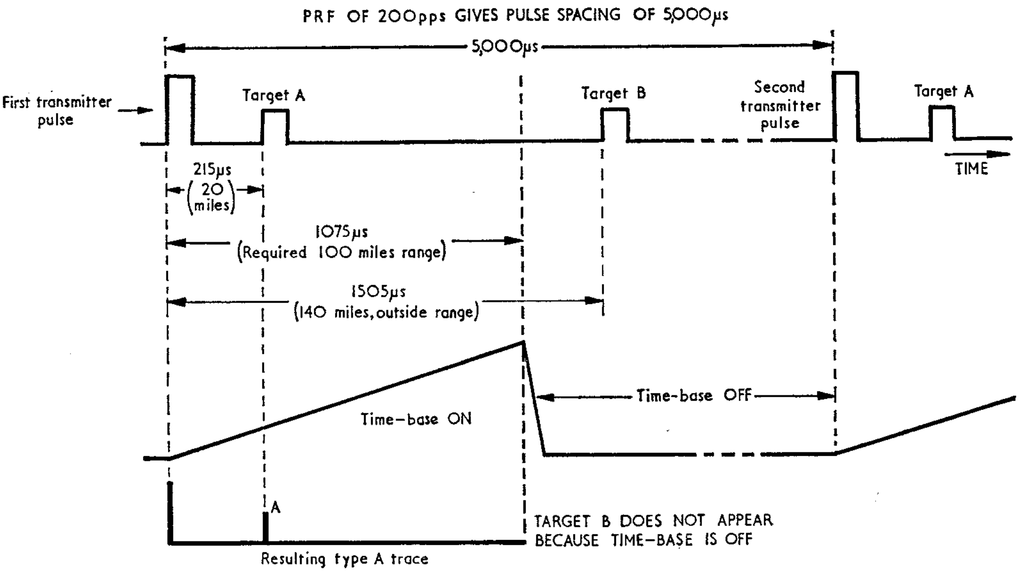


Fig 21–55 Adjustment of PRF and Timebase to Limit Indications to Required Range

intervals are less and the PRF may be increased. Thus the longer the required range the lower must be the PRF.

b. *Scanning Speed.* If the aerial scanning speed is high and the PRF is low some targets may be missed because, in the time interval between pulses, the aerial will have turned through a certain angle. Thus the higher the scanning speed the higher must be the PRF. Usually however, the PRF is decided by other factors and it is then the scanning speed which is adjusted to suit the selected PRF. The speed of scan is related to the PRF by the expression $f_r\theta$; where f_r is the PRF in pps, and θ is the half power (3 dB) beam width in degrees. For a beam width of 1° and a PRF of 500 pps the scanning speed must be less than $500 \times 1° = 500°$ per second or 1·4 rev/second or 84 rev/min. This ensures that at least one pulse per beam width is transmitted.

c. *Mean Power Available.* Given a certain available mean power and a required pulse duration, the PRF may have to be adjusted to produce an acceptable peak power output. This may be seen from the relationship given earlier:

$$\text{Peak power} = \frac{\text{Mean power}}{\text{PRF} \times \text{Pulse duration}}$$

If the mean power available is 1 kW and a pulse duration of 5 μs is required, then with a PRF of 2,000 pps the peak power during each pulse is $\frac{10^3}{2 \times 10^3 \times 5 \times 10^{-6}} = 100$ kW. If we require a larger peak power for the same values of mean power and pulse duration the PRF must be reduced. For a PRF of 200 pps the peak power output is now $\frac{10^3}{200 \times 5 \times 10^{-6}}$ = 1 MW. What has really been done in this case is adjustment of the pulse duty factor—the ratio of pulse duration to pulse spacing.

d. *Improved Definition.* The more pulses that are transmitted per second the more pictures are "painted" on the CRT per second. This means a brighter and clearer display and improved definitions. In addition the higher the PRF the more echoes that are received from any one target per second. This means more reports per second on the change in range and direction of a moving target.

From what has been said above it is clear that the PRF selected for a particular radar must be a compromise between several conflicting requirements (*see* Fig 21–56). Because of this, some radars have more than one value of PRF for different ranges.

21143. **Pulse Duration (Pulse Width).** The pulse duration selected for a particular radar depends upon several factors, the most important being summarized below:

a. *Minimum Range.* The time interval equivalent to one radar mile is 10·75 μs. Thus if a pulse duration of 10·75 μs is being used, any target at a range less than one mile will not be seen because the transmitter will still

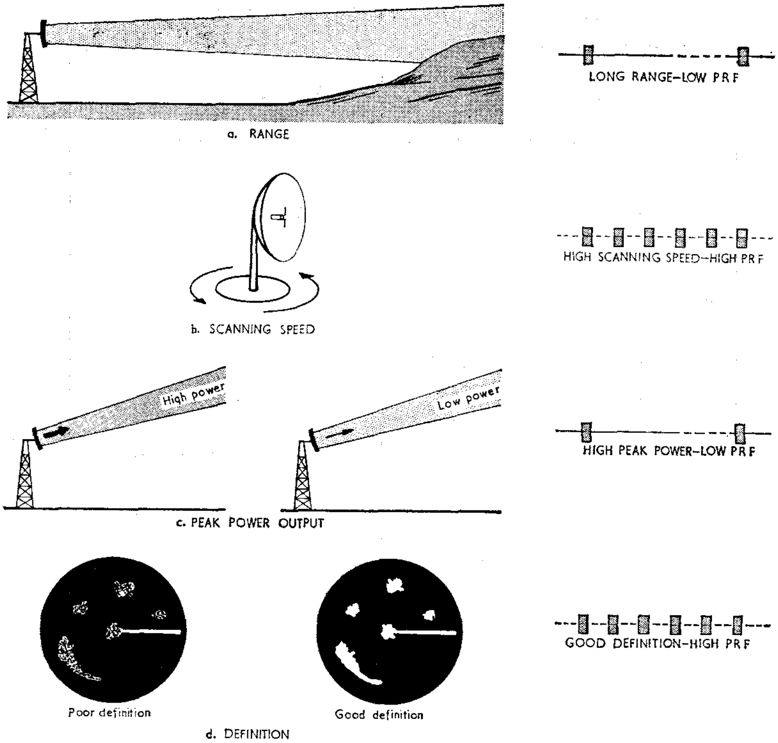


Fig 21–56 Factors Determining PRF

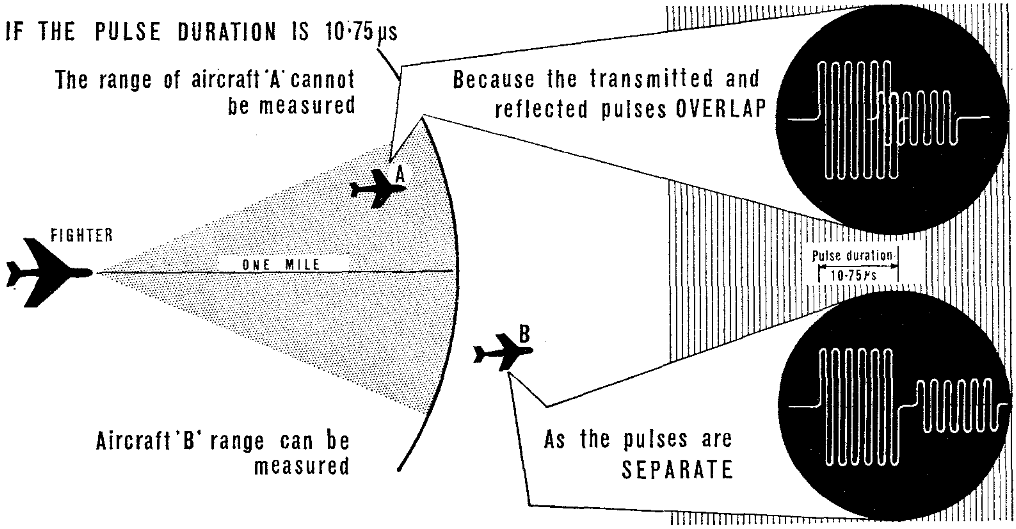


Fig 21–57 Effects of Using Long-Duration Pulses for Short Range Targets

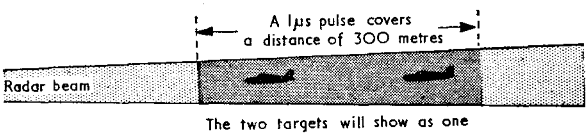


Fig 21–58 Range Discrimination of Targets

be firing when the target echo arrives back at the aerial. Since the aerial is still connected by the TR switch to the transmitter, the echo will not provide any input to the receiver (*see* Fig 21–57). Short duration pulses are needed for short-range working. There is an area surrounding any pulsed radar within which no targets can be detected. For long-range search radars this "blind" area is unimportant. However if the radar is an air-borne interception (AI) equipment carried in a fighter aircraft it is important that target echoes are displayed on the radar right up to the interception point. This may be only a few hundred feet. A pulse duration of 10·75 μs produces a blind area of one statute mile (5,280 ft). If interception down to 100 ft is required the pulse duration must not exceed $\frac{10{\cdot}75 \times 100}{5{,}280} = 0{\cdot}2$ μs. This is a typical value pulse duration for the low ranges of an air-borne interception radar.

b. *Target Discrimination in Range.* Since electromagnetic waves travel 300×10^6 metres in one second, a pulse of 1 μs will extend 300 metres along the direction of propagation. If there are two targets within that 300 metres they will be simultaneously "illuminated" by the pulse and may appear as a single echo at the receiver (*see* Fig 21–58). Short pulse durations are needed for good target discrimination in range in the same way that very narrow beams are needed for good discrimination in angle. To distinguish between two targets on the same bearing and elevation, but separated from each other in range by 100 ft, a pulse duration of less than 0·2 μs is needed (using the figures of the previous sub-paragraph).

c. *Frequency Used.* The lower the frequency the longer must be the pulse duration to ensure an adequate number of RF cycles in each pulse.

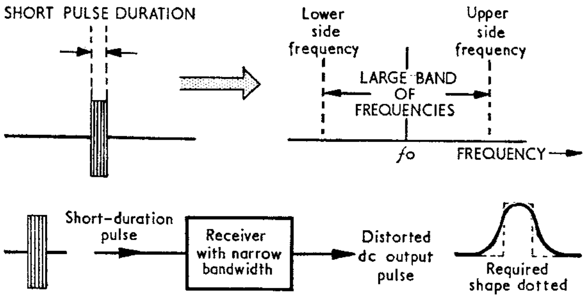


Fig 21–59 Pulse Duration and Receiver Bandwidth

d. *Mean Power Available.* Given a certain available mean power and a selected PRF the pulse duration may have to be adjusted to produce an acceptable peak power output. This may be seen from the relationship:

$$\text{Peak power} = \frac{\text{Mean power}}{\text{PRF} \times \text{Pulse duration}}$$

If the mean power available is 1 kW and the PRF is 5,000 pps, a pulse duration of 2 μs will produce a peak power of $\frac{10^3}{5 \times 10^3 \times 2 \times 10^{-6}}$ = 100 kW. By reducing the pulse duration to 1 μs (the other factors remaining constant) the peak power output increases to $\frac{10^3}{5 \times 10^3 \times 10^{-6}}$ = 200 kW. Again, it is really the pulse duty factor which is being adjusted.

e. *Receiver Bandwidth.* It has already been noted that the shorter the pulse duration the greater is the band of frequencies associated with the pulse and the greater must be the bandwidth of the receiver accepting such pulses. If the pulse duration is too short for the available receiver bandwidth, distortion and attenuation of the pulse result (*see* Fig 21–59). This leads to inaccuracies in range measurement. Thus where the receiver bandwidth has been limited for other reasons (*eg* reduction of noise) the pulse duration must not be made too short. Again, like the PRF, the value of pulse duration selected for a radar is a compromise between conflicting factors (*see* Fig 21–60). Because of this some radars have several values of pulse duration which may be selected as required.

21144–21150. (*Not allotted*).

RADAR DEVICES

Introduction

21151. Special radar devices are necessary to provide satisfactory oscillation and amplification of radio frequency (RF) energy at microwave frequencies (above 1,000 MHz) and to handle the RF energy produced. Three devices are commonly used for oscillation or amplification; the magnetron, the klystron and the travelling-wave tube. Transmit/receive (TR) switches and waveguides are used in handling the RF energy, and parametric amplifiers are used in some microwave receivers. These devices are described briefly and in simplified terms in the following paragraphs.

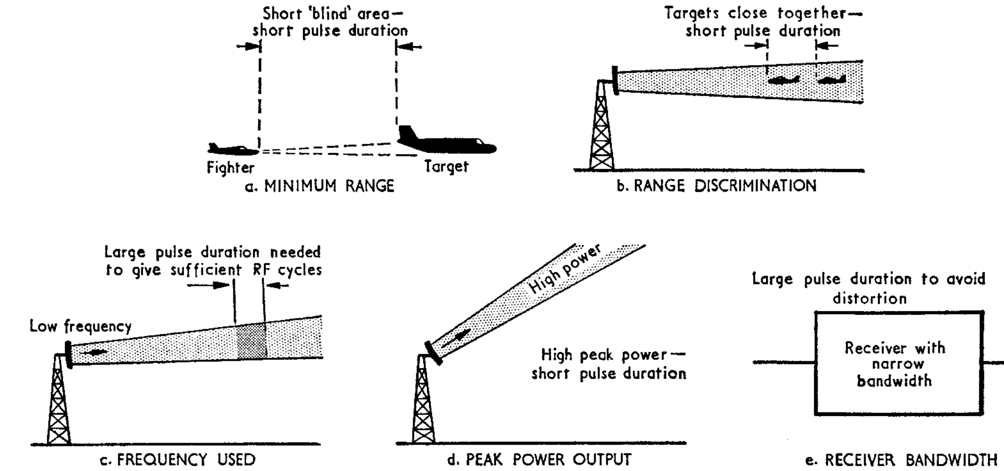


Fig 21–60 Factors Determining Pulse Duration

The Magnetron

21152. The magnetron is a high-power oscillator used primarily with pulse modulation, *eg* in radar transmitters. When so used it produces pulse power outputs ranging from about 40 kW to 3 MW or more at frequencies from 1,000 MHz upwards. The modern type is the multi-cavity magnetron. The multi-cavity magnetron consists essentially of a cylindrical oxide-coated cathode, placed symmetrically within a copper anode which has several (usually 8, 12 or 16) cylindrical cavities. Each cavity consists simply of a hole and a slot cut out of the copper block, the cavity being closed by two end plates. The basic construction is illustrated in Fig 21–61.

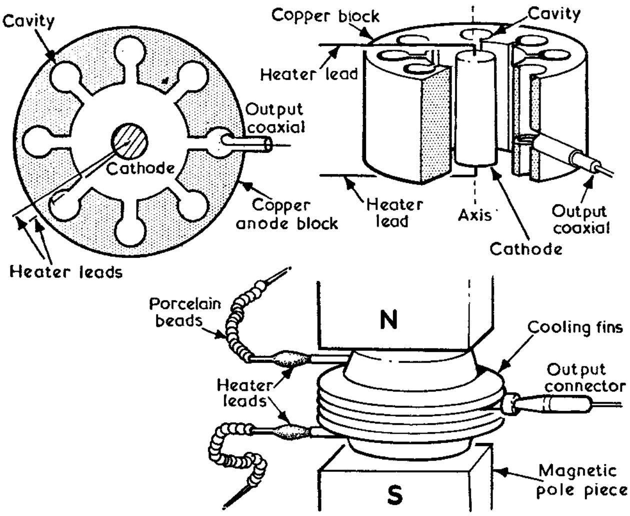


Fig 21–61 Multi-Cavity Magnetron Details

21153. The whole structure is evacuated, and the magnetron operates in a strong magnetic field parallel to the axis; this field is usually produced by a powerful permanent magnet. The size of the cavities determines the frequency of operation; the smaller the cavities, the higher the frequency. The anode block is normally earthed and the cathode is made negative with respect to earth by about 28 kV to provide the required anode-cathode voltage. Because of the high voltage, the cathode (heater) leads are well insulated.

21154. **Production of Oscillation.** In the absence of a magnetic field, but with a direct current voltage between anode block and cathode, electrons leaving the cathode travel in straight lines to the anode, as for path 1 in Fig 21–62. With a weak magnetic field, a force is exerted at right angles both to the lines of the magnetic field and to the direction of electron motion, and the path becomes curved, as for path 2. As the magnetic field increases in strength, the path becomes more curved until stage 3 is reached, when the electrons do not reach the anode at all, but return to the cathode. The minimum value of field required for this condition is called the cut-off field. In a magnetron the magnetic field exceeds the cut-off field. With this situation, imagine that RF oscillations are somehow produced in the cavities. Fig 21–63 shows the resulting RF field pattern at a given instant of time. Alternate parts of the block become positively and negatively charged, and the whole field pattern changes polarity at the frequency of the RF oscillations. Superimposed on this RF field is the static electric field

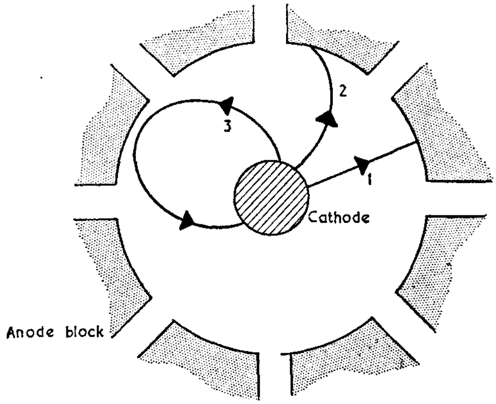


Fig 21–62 Electron Paths in Magnetic Field

produced by the anode-cathode voltage, and also the static magnetic field; these are not shown in Fig 21–63. The path of an electron is now modified by the RF field, and instead of the simple curved path mentioned earlier, a more complex path is travelled, such as path 1 in Fig 21–63. During its motion the electron interacts with the RF field and, if the frequency of oscillation is correct, the electron gives up energy to the RF field and so helps the maintenance of oscillations. Basically, the desired condition is that the electron travels from one gap in the anode block to the next, in about a half-period RF oscillation, so that it is always interacting with a field of the same polarity. When the electron gives energy to the RF field, the electron slows down. However, it is accelerated again by the static field so that the process

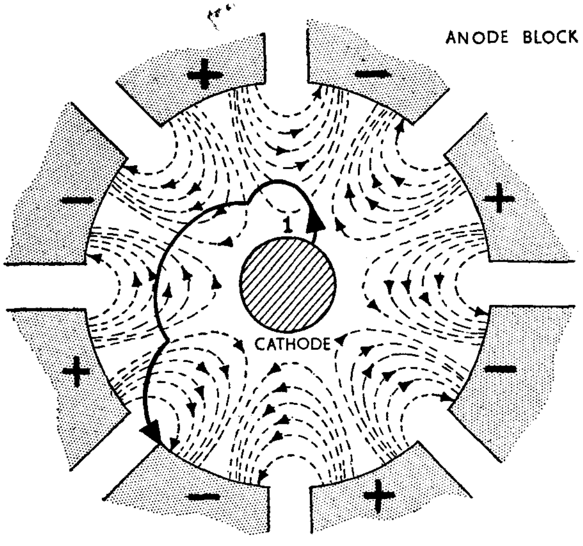


Fig 21–63 Electron Paths—Effect of RF Field

is one of conversion of direct current into RF electrical energy, as it is with all oscillators. Most electrons eventually strike the anode, perhaps after several revolutions, but a few never reach the anode and fall back into the cathode. This bombardment of the cathode is often enough to keep it at operating temperature without any heater current, once the action has commenced. In addition to the basic action described earlier, the electrons "bunch" and form "spokes" which travel round the cathode (*see* Fig 21–64). No mention has been made of how oscillations start in the first instance, but it may be assumed that random electron motions and the switching on of the direct current supply will "shock-excite" the cavities into oscillation.

21155. **Output Coupling.** The output can be taken from any one of the cavities, usually by a coupling loop placed in one of the cavities, or by a small section of waveguide (*see* Fig 21–65). The fields of the eight (or more) cavities link up in such a way that all contribute power to the output, and the magnetron is capable of providing megawatts of RF power in very short pulses.

21156. **Tuning.** In general, magnetrons are not easily tuneable. However, since the size of the cavities determines the main operating frequency, tuneable magnetrons can be manufactured. In one type, one end plate of the anode block is made in the form of a thin lid which can be depressed to change the frequency. Another type has metal rods which can be moved in and out of the cavities to change the effective volume of the cavities.

The Klystron

21157. The klystron was originally designed to generate a high frequency continuous wave (CW) of low power for use as a local oscillator in radar receivers. Later development produced a klystron amplifier for use at microwave frequencies as a radar transmitter device capable of producing CW at a power of 20 kW, or for producing high power pulses of RF energy for pulse modulated radars.

21158. **Reflex Klystron.** The reflex klystron, which can only be used as an oscillator, not as an amplifier, is commonly used as a local oscillator in radar receivers. Its useful frequency coverage is from about 2,000 MHz to 35,000 MHz, with output powers of the order of hundreds of milliwatts. A reflex klystron is illustrated in Fig 21–66 and the operating principle is shown in Fig 21–67. An electron stream is emitted by the cathode and attracted by the cavity anode because of the potential difference applied between them. The accelerating electron stream passes through the lips of the cavity and produces a minute oscillation which itself produces a minute oscillating electric field (E field) across the cavity lips. This oscillating field alternately accelerates and decelerates the electrons in the electron stream as they pass through the cavity, thus causing a slight "bunching" of electrons. The negative potential of the repeller causes the electron stream to be reflected back to the cavity, and by careful adjustment of the repeller potential, the electrons (which were initially accelerating and had passed beyond the cavity towards the repeller) can be made to arrive back at the cavity at the same time as the slower reflected electrons. Thus the cavity receives bunches of electrons at regular intervals. If the repeller potential is correctly applied the electron bunches can be made to arrive at the cavity when a retarding E field is present, and this causes energy to be given up by the stream into the cavity, thereby increasing its oscillating E field. This in turn increases the bunching effect on the electron stream and oscillations are sustained. The output is taken from the cavity either by a slot or a wire loop; the power taken depending on the slot dimensions or position of the loop. Adjustment of the frequency of the oscillations (tuning) is possible by variation of the repeller voltage and to a lesser extent by the cavity dimensions which are varied by means of one or more screws or "tuning slugs".

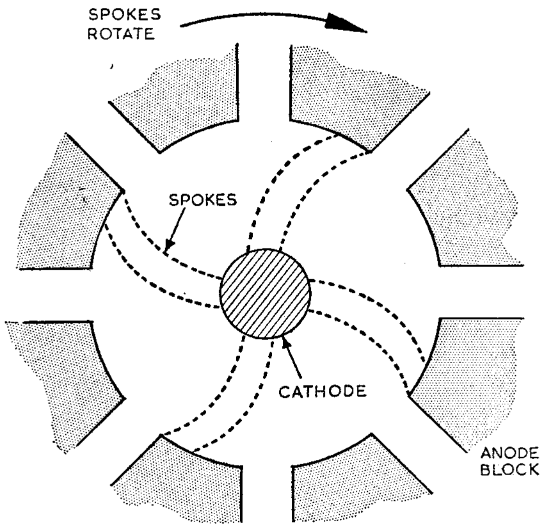


Fig 21–64 Velocity Modulation in a Magnetron

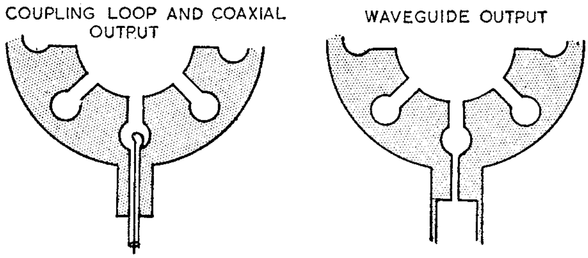


Fig 21–65 Output Coupling in Magnetron

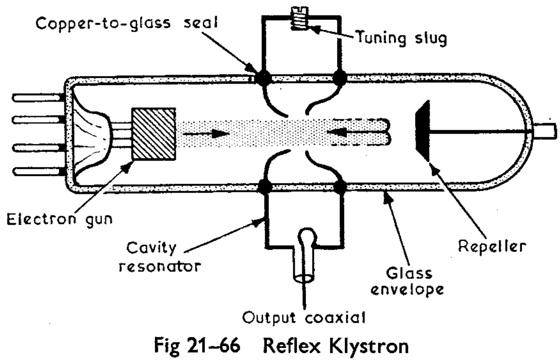


Fig 21–66 Reflex Klystron

21159. **The Multicavity Klystron.** The multicavity klystron can be made to produce either a CW signal or a burst of oscillations at high power. When used as the main valve in a transmitter the multicavity klystron has certain advantages over a magnetron (*see* para 21152). The principle of operation is similar to that for the reflex klystron described in para 21158, but in place of the repeller is placed a "collector", which serves to collect the electrons after they have passed through three or more cavities (each of which acts as a "buncher" in the manner described in para 21158). The last cavity before the collector is termed the "catcher" and it is given a positive potential with respect to the cathode and the earlier buncher cavities. The cathode is given a negative potential with respect to the cavities (*see* Fig 21–68). A small oscillatory signal is coupled into the first buncher. The resultant E field modulates the electron stream as it passes through. On reaching the second buncher, the modulated electron stream induces a large oscillatory field across the lips of the cavity which increases the bunching effect. This process is repeated at each buncher cavity, and when the electron stream reaches the catcher cavity similar action takes place. The amplified signal is taken from the catcher cavity either by a slot or loop coupling. If the klystron is being used as a CW generator, a small part of the output may be fed back as an input signal, thereby maintaining the oscillations. When used as an amplifier in pulse radar systems the input is generally taken from a gated crystal-controlled frequency multiplier circuit which results in greater frequency stability than is possible with a magnetron, and the ability to operate on a spot frequency. The disadvantages of the klystron are the necessary size and weight for a given power output and the emission of X-rays caused by the high velocity electron beam striking the collector.

The Travelling-Wave Tube

21160. Radar receivers are required to amplify signals of very small amplitudes to a useable level with the minimum addition of noise. All electric circuits produce noise, and the amount generated in the early stages of a receiver will determine the smallest signal which can usefully be amplified, *ie* the efficiency of the receiver.

21161. All radar receivers use the superheterodyne principle (*ie* the incoming high frequency signal is converted to a lower intermediate frequency by mixing with a local oscillator frequency before being fully amplified) to enable amplification to take place at lower, easier-to-use frequencies, and all must therefore use a local oscillator. The local oscillator signal appears in the earliest stages of amplification, and a device which can act as a local oscillator, while at the same time acting as an amplifier, and do so with very little production of noise, is extremely useful. Such a device is the travelling-wave tube.

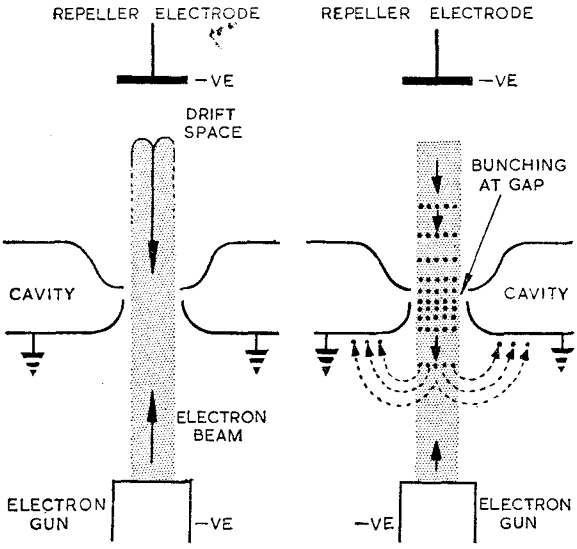


Fig 21–67 Principle of Reflex Klystron

21162. A travelling-wave tube consists of a long, evacuated glass tube with an electron gun (*see* para 2080) at one end and a target or collector at the other end (*see* Fig 21–69). In between a wire helix or spiral consisting of a single layer of turns is held by spacers so that its longitudinal axis is in line with the electron gun and collector. Surrounding the glass tube is a solenoid which produces a linear magnetic field to ensure that the electron beam does not diverge while passing along the axis of the helix.

21163. The small received signal from the radar TR system is fed to the input end of the helix. As the signal travels along the helix it produces an associated electromagnetic wave in the same way that a current flowing in a wire has electric and magnetic fields that travel with it. The wave travels in contact with the wire along the helix, and hence its speed along the axis of the tube is much less than its speed in the wire. A typical speed for the component along the axis is $\frac{1}{13}$ times the speed of light; this component is called the slow wave. The electrode voltages are adjusted such that the electron beam travels at a speed slightly greater than that of the slow wave, down the centre of the helix. The interaction between the slow wave and the electron beacon causes electron bunching (*see* para 21158). The bunches give up energy to the RF field associated with the signal which is therefore amplified as it goes along the tube. Because the electrons give up energy to the field all along the tube, there is no critical distance such as the bunching distance of the klystron. Neither is there a critical frequency, because the TWT has no cavity resonators. Therefore the TWT is a wide-band device, and the only limitations on the frequency it can handle is the difficulty in matching at the input and output terminals. By feeding part of the output back into the input at the correct amplitude and phase, the TWT can be used as a microwave oscillator. A TWT can also operate as a frequency changer by modulating the helix-cathode voltage. The TWT is a low-noise amplifier—much less noisy than the multicavity klystron.

The Parametric Amplifier

21164. In most conventional amplifying devices electrons transfer direct current energy obtained from a power supply to alternating current

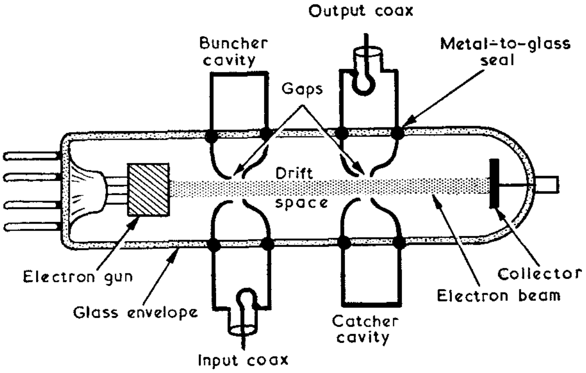


Fig 21–68 Double-Cavity Klystron

energy at the required frequency. In a "parametric" device the value of a circuit *parameter* such as resistance, inductance or capacitance is varied and used to transfer energy from an alternating current source (*eg* an oscillator) to energy at the desired frequency.

21165. Microwave parametric devices use the low-loss variable capacitance properties of a device called a "varactor", which is a semiconductor diode which has a variable capacitance. The parametric amplifier has a very low noise factor, mainly because it does not employ a "noisy" electron beam generated by a hot cathode. It is used as a signal frequency amplifier in a radar receiver to improve the receiver sensitivity and hence to increase the range of the radar. It is mounted between the TR cell and crystal mixer and is a "fail-safe" device, *ie* if the parametric amplifier ceases to operate the radar continues to function, although with a decrease in signal-to-noise ratio.

Masers

21166. The importance of a low noise factor in devices used as microwave amplifiers has already been stated. The signal-to-noise ratio of a radar receiver sets a limit to the maximum range of the radar and the trend has been towards microwave signal amplifiers which improve this ratio.

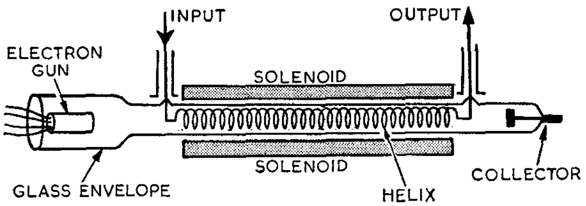


Fig 21–69 Travelling-Wave Tube

The low-noise travelling-wave tube and the parametric amplifier have given a considerable improvement in this direction.

21167. The "maser" is another type of microwave amplifier which has a very low noise factor. Its gain is similar to that of a parametric amplifier. The maser is at present used as a very low-noise signal frequency amplifier in ground equipments designed for satellite communication and in radio astronomy, but is likely to have wider applications.

Waveguides

21168. A waveguide is a hollow metal tube, rectangular or circular, through which energy is conveyed by means of electromagnetic waves which travel down it. Whenever a current flows in a wire or transmission line, electric and magnetic fields associated with this current are built up in the line. We usually think of the energy being "carried" by the current, but it is just as correct to think of it being carried by the electromagnetic wave associated with the current. In a waveguide we do not consider the current at all, but think of the energy being carried by the wave alone. Radio waves between a transmitting and receiving aerial carry energy in the same way. The difference is that in a waveguide, the waves are confined to the inside of a hollow metal tube instead of being allowed to spread through space; such waves are referred to as "guided" waves.

21169. If the properties of a rectangular waveguide are investigated, it is found that a waveguide of a certain cross-section size will only accept waves whose wavelength is less than a certain value called the "cut-off" wavelength. The cut-off wavelength is related to the dimensions of the waveguide and is, in fact, about twice the width of the broad side of the waveguide. From this it is seen that the longer the wavelength (and therefore the lower the frequency) the bigger is the waveguide required. For 10 cm waves (3,000 MHz) the standard waveguide is about 3 inches by 1 inch in cross section, for 3 cm waves (10,000 MHz) it is about 1 inch by ½ inch. For wavelengths greater than 10 cm (lower than 3,000 MHz), waveguides are too large and cumbersome to be of much practical value and co-axial cable, shielded twin-wire line, or twin open-wire feeders are used.

21170. RF energy can be launched into, or extracted from a waveguide in a number of ways (*see* Fig 21–70). A coupling loop and a

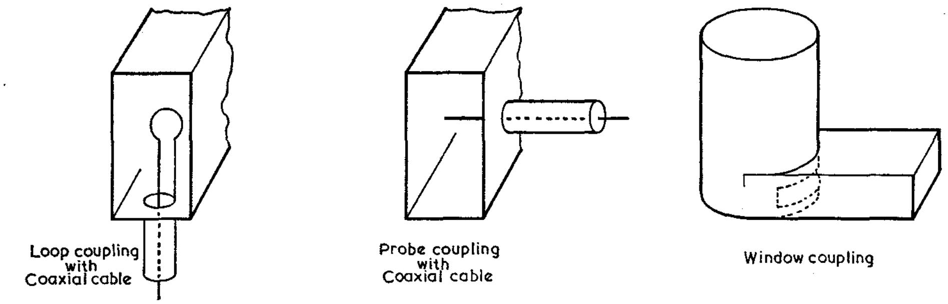


Fig 21–70 Coupling Methods with Waveguides

probe are common methods; a "window" may also be used to connect a waveguide to another hollow structure such as a cavity resonator.

21171. The pattern of the electric and magnetic fields in a waveguide which is carrying RF energy is quite complicated and the waveguide dimensions must be such that, for the wavelength of the RF energy being carried, the pattern fits correctly. There are a number of patterns that fit, corresponding to varies "modes"; each pattern has a different wavelength, although none can exceed the cut-off wavelength. By careful choice of waveguide dimensions the waveguide can be made to accept only one mode; this is desirable because unwanted modes cause waste of RF energy.

21172. A waveguide sealed off at both ends can have standing waves set up in it. Again, various modes are possible, corresponding to different resonant frequencies. The simplest type of sealed-off waveguide is a rectangular or cylindrical box, and this is the cavity resonator which forms the basis of the magnetron and klystron discussed earlier. A cavity resonator may therefore be considered as a short section of waveguide, completely enclosed, in which standing waves exist.

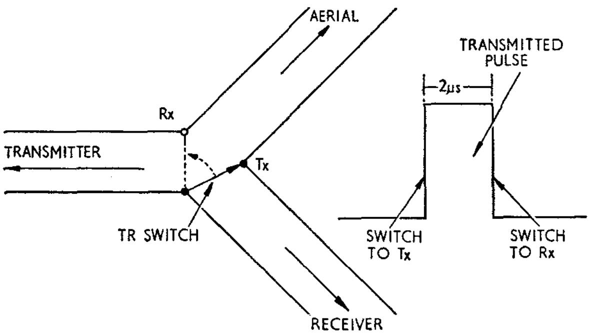


Fig 21–71 Principle of TR Switching

TR Switches

21173. If a common aerial is used in a radar system for transmission and reception a device is required to protect the receiver when the transmitter is fired, and to isolate the transmitter when signals are being received. Such a device is known as a transmit/receive (TR) switch. The principle of TR switching is illustrated in Fig 21–71. The TR switch must direct all the transmitter power to the aerial and all echo power to the receiver. In pulse radars the switching is done with gas-filled TR switches mounted in the waveguide and operated by a portion of the transmitter RF power. The requirements of such a switch are that it should switch rapidly from transmit to receive, allowing a minimum of power to pass to the receiver on transmit, and that its "recovery time" (*ie* the time it takes to switch the aerial to receiver) should be very short. An early form of TR switch was a simple spark gap and from this the more efficient "soft rhumbatron" and "multicavity" TR cells were developed.

21174–21175. (*Not allotted*).

REDUCTION OF CLUTTER

Introduction

21176. Clutter may be defined as confused unwanted echoes on a radar display. However, echoes which are unwanted on radar provided for one purpose may be wanted on another (*eg* cloud returns are unwanted on a search radar but wanted on a meteorological radar). These paragraphs are primarily concerned with methods of removing clutter from radars providing control and reporting facilities.

21177. It is often difficult to distinguish between noise and clutter. Both produce similar effects on the CRT display. However clutter is caused by transmissions from the radar itself, whereas noise is present at all times. Because of this, the appearance of clutter on the display will remain substantially the same from sweep to sweep, whilst that of noise will vary in a random manner.

21178. Where echoes from moving targets are of importance (as in control and reporting radars) clutter due to reflections from stationary objects can be considerably reduced by using moving target indication (MTI) radars. For a non-MTI radar, some reduction of weather clutter can be obtained by operating the radar at a low frequency, but for most control and reporting radars a high frequency is used for reasons explained in paras 2128–2129. Circular polarization helps in reducing weather clutter, and this technique is now used in many ground radars. These techniques and others in common use for the reduction of clutter in ground radars are described in the following paragraphs.

Fast Time Constant (FTC) Circuit

21179. Where clutter is of an "extended" nature, so that it fills a large area of the display, some reduction of the effect may be obtained by using an FTC circuit. To see the effect of this circuit, let us suppose that target echoes are being received from an aircraft under conditions of extended cloud clutter. The PPI presentation with the FTC circuit switched off may then be as shown in Fig 21–72a. The cloud produces a large clutter area which partly obscures the target echo. The cloud echo varies in amplitude and is weaker than the aircraft echo, but is of relatively long duration. Thus the early stages of the receiver have a short pulse (due to the aircraft) superimposed on a long pulse (due to the cloud). The FTC circuit is able to differentiate between the two types of response and the resultant PPI presentation with FTC in operation is shown in Fig 21–72b.

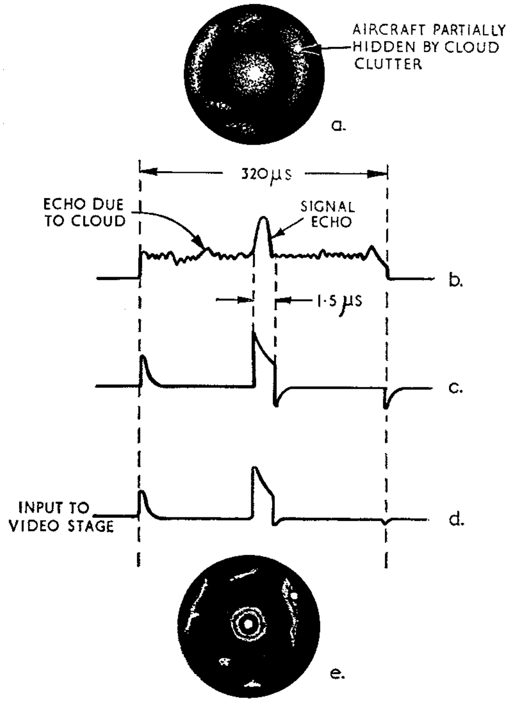


Fig 21–72 Effect of FTC Circuit

21180. Since the FTC circuit removes some of the desired signal energy as well as that due to clutter, the FTC is switched into the receiver only when needed. It is worth noting that the FTC circuit is successful in reducing all forms of "long pulse" interference which could take the form of a CW signal, either modulated or unmodulated.

Instantaneous Automatic Gain Control (IAGC) Circuit

21181. When the IAGC circuit is in use the gain of the receiver is immediately reduced when a long clutter pulse is received but it does not change on receipt of the short duration signal pulse. The echo pulse through the receiver therefore suffers little attenuation but extended clutter pulses are considerably reduced.

21182. Since modulated or unmodulated CW signals act in much the same way as long pulses, IAGC is also effective in reducing interference from such sources.

Swept Gain Circuit

21183. The strongest clutter echoes returned to a ground radar are from objects immediately surrounding the radar aerial. As the range from the radar increases, the clutter echoes become weaker. On a basic PPI display these effects produce a confused area at the centre of the screen, and if the ground clutter is strong enough it can saturate the receiver. The recovery time of the receiver is such that close-range targets are then missed. When the swept gain circuit is employed the gain of the receiver is progressively varied from a low value at short ranges to a high value at longer ranges. For targets at close range, when the echo return is strongest, the gain of the receiver is kept at a low value; and for long-range targets, when the echo is weaker, the gain of the receiver is adjusted to a high value. The rate at which the gain is made to vary with range can be adjusted by the operator to suit the conditions.

21184. This circuit may sometimes be referred to as anti-clutter gain control, or sensitivity time control (STC).

Logarithmic Receiver

21185. There are certain practical limitations to a swept gain system. The correct adjustment of the rate of change of gain depends on the clutter encountered and some skill is required in selecting the correct setting. If, in addition, the amount of clutter is not the same at all radar bearings, the swept gain setting must be a compromise. Hence ideal swept gain cannot be achieved. However the functions of an ideal swept gain system may be performed automatically by a receiver which has a response such that the output is the logarithm of the input, *ie* a logarithmic receiver. Such a receiver is as effective in reducing short-range clutter as a normal linear receiver which includes a perfectly adjusted swept gain circuit.

21186. A radar receiver giving a linear response to small input signals will usually saturate when the input voltage exceeds a few millivolts. Response to close-range clutter can therefore completely saturate the linear receiver. The result is that targets are lost, even though their echo may be stronger than that due to clutter. What is required is a receiver giving full amplification to small signals, without saturating on strong signals. The logarithmic receiver fulfils this function.

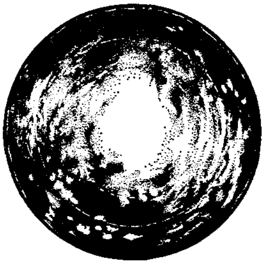
Clutter due to Weather Effects

21187. Reflections from fog, rain or snow particles are insignificant at the lower radar frequencies. However, since the amount of reflection from an object depends upon the size of the object in relation to the radar wavelength, at higher frequencies weather echoes may be strong enough to mask the desired target signals just as any unwanted clutter signal. It is clear therefore, that to prevent clutter due to weather effects the radar should be operated at a low frequency. However a ground control and reporting radar should provide accurate information and good angle discrimination both in azimuth and in elevation. This can be obtained easily only by the use of high frequency radars; 3,000 MHz (10 cm) is a typical frequency band. Thus while high frequencies are being used, some other means must be provided for reducing weather clutter.

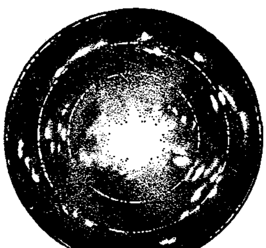
21188. Weather clutter is similar in many respects to ground or sea clutter and several of the techniques used to reduce other clutter echoes have some effect in reducing weather clutter. These techniques include the use of log receivers, swept gain, FTC, MTI radar (*see* para 21190) and circular polarization. In addition, if the radar operates with a narrow beamwidth and a narrow pulse duration the amount of weather clutter energy received back at the radar is reduced.

Circular Polarization

21189. One of the most common ways of reducing weather clutter is to use circularly polarized radiation. A circularly polarized wave incident on a spherical object, such as a raindrop, is reflected back to the radar as a circularly polarized wave with the opposite sense of rotation. Since the same aerial is used for both transmitting and receiving, the aerial is not responsive to the opposite sense of rotation and the echo energy due to raindrops and the like will not be accepted by the receiver. On the other hand, a complex target such as an aircraft is not a symmetrical reflector and it will return some energy with the correct polarization for reception. Thus circular polarization is of



a. LINEAR POLARIZATION



b. CIRCULAR POLARIZATION

Fig 21–73 Effect of Circular ~~Polrization~~ Polarisation

A28.

considerable value in reducing weather clutter. However it also reduces the required target echo energy so that arrangements are usually included in the radar to switch to linear polarization whenever weather conditions permit. A device termed "quarter wave plate" is normally used and is placed between the radiating source and the reflector. Fig 21–73 illustrates the effect of circular polarization in conditions of very heavy rain clutter.

Moving Target Indicator (MTI) Circuit

21190. The function of the MTI circuit in a radar receiver is to suppress returns from permanant echoes but at the same time permit the display of echoes from moving targets. Two systems are in use and are called non-coherent MTI and coherent MTI. Non-coherent MTI provides good cancellation of PEs and allows moving targets flying above PE areas to be seen, but this system has the disadvantage of cancelling moving returns in a clutter free area. For this reason non-coherent MTI has a limited use in areas of clutter only.

Angels

21191. Angels is the name given to a form of clutter caused mainly by reflections from birds and insects. For a ground-based radar sited on the coast clutter due to angels can be almost as great as that due to sea clutter because of the large number of seabirds. Although a bird has only a small cross-sectional area compared with that of an aircraft it can return a strong echo at short ranges. A bird at a range of 10 miles can return an echo as strong as that from an aircraft at 100 miles range. When birds travel in flocks the clutter caused on the display by angels can be severe. Fortunately, strong angel echoes occur only at short ranges so that swept gain or the use of a logarithmic receiver can reduce their effect.

21192–21195. (*Not allotted*).

INTERFERENCE AND JAMMING

Introduction

21196. In paras 21176–21191 the effects of clutter and its reduction were discussed. It will be remembered that clutter echoes are produced by the radar's own transmissions. Another class of unwanted signal that can enter the receiver is interference from nearby transmitters. This interference may be unintentional and originate from "friendly" communication or radar transmitters; or it may be intentional and originate from "hostile" electronic countermeasure (ECM) transmitters. In the following paragraphs both types of interference are briefly examined, and some of the steps that can be taken to reduce the effects are discussed.

Unintentional Interference

21197. In areas where there are many radar and communications transmitters, mutual interference between neighbouring installations can be severe. The interference may be CW, modulated CW or pulse. This section will mainly consider pulse interference such as might be caused by other radars.

21198. Mutual interference between radars may be reduced by operating neighbouring radars on different frequencies. However the band of frequencies occupied by a transmitted pulse is very wide. Thus, interference may be caused in a receiver whose operating frequency is quite different from that of the interfering transmitter.

21199. Special circuits which discriminate between the desired and the interfering signals may be included in some ground radars. Typical of such circuits are the pulse length discriminator (PLD) and the pulse recurrence frequency discriminator (PRFD).

21200. **Pulse Length Discriminator (PLD).** If the pulse length (or duration) of the interference differs from that of the desired signal, the difference in pulse lengths may be used as a means of discrimination between the two signals. The input pulse is applied to two circuits. In one circuit the pulse is delayed by a time equal to the pulse length of the desired signal. If the input pulse is the desired signal pulse, the trailing edge of the pulse will coincide with the leading edge of the delayed pulse. If the input pulse is not of the required duration the trailing edge of the input pulse and the leading edge of the input pulse will not coincide. A special circuit is able to check coincidence. Pulses of the incorrect length are rejected, thus preventing the interference from being amplified and displayed.

21201. **PRF Discriminator (PRFD).** PRFD uses a circuit which provides an output which is related to the number of pulses applied to the circuit in a given time. The circuit is made to give maximum output when the number of pulses per second is equal to the PRF of the radar; when the number of pulses per second is above or below that of the radar PRF the output of the circuit is very low. Thus this circuit is able to "select" signals of the required PRF and provide little output from interfering signals.

Other Methods of Reducing Interference

21202. Interference among radars located at the same station can be reduced if they are all operated on the same PRF and if they are synchronized to fire simultaneously. This is the method adopted at many RAF radar stations. The master timing unit generates a master triggering pulse which causes all radars on the site to operate simultaneously.

21203. Interfering signals over a wide band of frequencies can be reduced by subtracting the video output of the radar receiver from the output of an auxilliary receiver tuned to a different frequency. The output from the auxiliary receiver consists only of interference; that from the receiver consists of the desired signal plus the interference. By subtracting the video output from the two receivers, only the desired signal (plus noise) remains.

ECM and ECCM

21204. In war, a radar may be subjected to deliberate interference or "jamming" with the object of reducing the effectiveness of the radar. The methods used to produce jamming are called electronic countermeasures (ECM). To get sufficiently close to the radar which is being jammed the ECM equipment is usually carried in a jamming aircraft.

21205. To allow the radar to operate under conditions of jamming, the effects of interference must be counteracted. The techniques used to provide release from jamming are known as electronic counter-countermeasures (ECCM).

21206. There are two classes of ECM; those intended to cause confusion, and those intended to cause deception.

a. *Confusion ECM.* Confusion ECM masks the display of targets on the radar screen by producing effects similar to those produced by ground or sea clutter, but to a much greater extent. Effective confusion ECM completely obliterates the radar screen. Its effect can be partially off-set by good design of the radar receiver. A radar receiver is designed to have an optimum bandwidth at which the signal-to-noise ratio is a maximum, and a large amount of the jamming at frequencies outside that bandwidth is therefore rejected. Other points of good general design, which improve the noise factor of the receiver, are the use of low-noise receivers and careful screening.

b. *Deception ECM.* Deception ECM is designed to produce false echoes which appear on the radar screen as though they were real targets. Since deception echoes can be of about the same power as real echoes, the power output requirements of deception jammers are low. To combat deception ECM special techniques are required at the receiver.

21207. Both confusion and deception ECM may be produced by either passive devices or active devices. Passive devices do not radiate of their own accord; they merely re-radiate the incident radar pulse. Active devices contain a transmitter which radiates an interfering signal. There are therefore four possible ECM sources; passive confusion ECM; active confusion ECM; passive deception ECM and active deception ECM. Each of these is examined briefly in the following paragraphs.

21208. **Passive Confusion ECM.** One of the earliest forms of ECM used against radar was "window". Window consists of a mass of tinfoil strips, each strip acting as a reflector. If window is continuously released from a jamming aircraft it forms a "smoke screen" behind which following aircraft can fly undetected. On the screen of the ground radar, window produces a confused area of extended clutter within which real targets are difficult to detect. Since confusion ECM produced by window has an effect on the CRT screen similar to that produced by normal clutter it may be reduced by the methods considered earlier.

21209. **Active Confusion ECM.**

a. *Simple CW Jamming.* A simple method of jamming is for an ECM aircraft to transmit a CW signal at the frequency of the radar being jammed. Fortunately CW interference is easily suppressed by use of a fast time constant (FTC) circuit (*see* para 21179). Alternatively it can be reduced if the receiver employs instantaneous automatic gain control (IAGC) (*see* para 21181).

b. *Narrow-Band or "Spot" Noise Jamming.* A better method of jamming is to modulate the ECM transmitter with a noise signal. In spot jamming, the jammer radiates a noise-modulated signal at the frequency of the radar. The bandwidth of the radiated noise energy is sufficient only to cover the radar receiver bandwidth so that large amounts of noise power enter the receiver circuits. The intended effect is to cover the whole screen with clutter and make it impossible for the operator to detect targets. If the spot jammer power is large enough, the entire display can be swamped. The main ECCM take advantage of the fact that the spot jammer concentrates a large noise power over a narrow bandwidth. Thus, by changing the radar frequency, spot jamming may be avoided. To do this a tuneable radar is needed; the radar frequency must be changed rapidly so that the jammer does not have time to follow. An ideal arrangement would be to change the frequency from pulse to pulse. An auxiliary receiver could be used to monitor the whole band continuously and so provide information on which frequencies were free from jamming. Another effective ECCM is to reduce the side lobes of the radar aerial as much as possible. Maximum confusion will be produced if the noise jamming power is sufficient to enter the aerial side lobes. If the side lobes are reduced so that the jamming is picked up only by the main lobes the effect is considerably reduced (*see* Fig 21–74a). For a less efficient aerial, some jamming power enters by the side lobes; and for an aerial with large side lobes almost complete jamming results (*see* Fig 21–74b). Reduction of the side-lobes is important for another reason: Fig 21–74a shows the approximate bearing of the jammer; by triangulation with two or more similar radars the approximate position of the target (jammer) can be calculated.

c. *Wide-Band or "Barrage" Noise Jamming.* A wide-band jammer radiates noise over a wide band of frequencies. T

usually such that it covers the entire frequency range of a particular class of radar, *eg* a 10 cm radar. Hence the use of a tuneable radar is no defence against barrage jamming. One ECCM is to have several radars in different frequency bands, *eg* metric, L band and S band. This forces the ECM aircraft to carry more jammers than may be convenient. Although the barrage jammer is more effective than the spot jammer in many respects, it is less effective in one respect: since the available power of the barrage jammer is spaced over a very wide frequency range, the amount of noise power entering the receiver passband is less than that from a narrow-band spot jammer having the same output. Barrage jamming may be obtained by amplifying the noise output of a wide band receiver and using this to modulate the jammer transmitter.

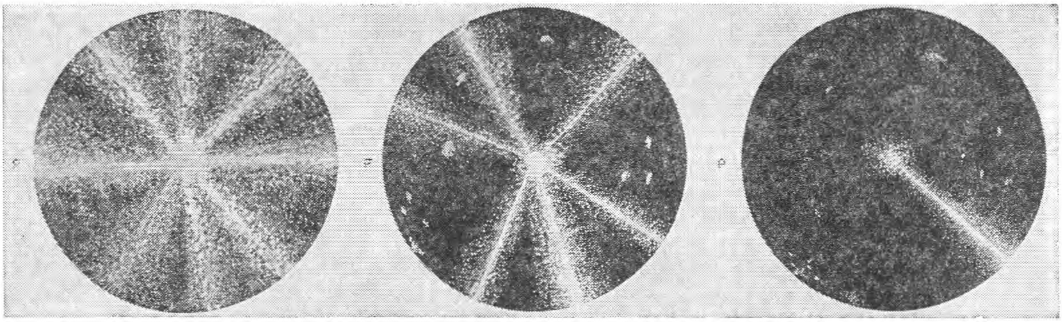


Fig 21–74 Importance of Reducing Aerial Side Lobes

Another type of barrage jammer uses a special valve called a carcinotron, which frequency-modulates noise to produce a random sweed in frequency. This is known as sweep-through or "sweep" jamming. To be effective as a wide-band jammer, the sweep in frequency must be large compared with the radar receiver bandwidth. Each time the carrier from the jammer sweeps through the receiver passband, a pulse is produced. The pulses are randomly spaced because the carrier sweep is random. For maximum confusion, the barrage jammer is adjusted in such a way that the time taken for the carrier to sweep through the receiver passband is equal to the time taken by the receiver to respond to an echo. A simple sweep-through jammer can simultaneously jam many different radars operating at different frequencies within a given band. Wide band jamming can be reduced by using a receiver with a

signing an aerial

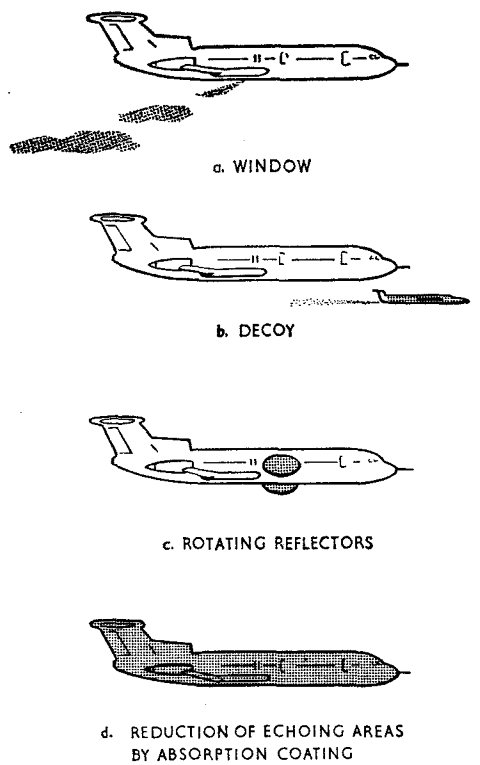


Fig 21–75 Passive Deception ECM Methods

with small side lobes. Where the side lobes are small, the position of the jamming aircraft can be plotted by triangulation using the main lobes from two or more ground radars. The other ECCM is to have several radars in different bands.

21210. **Passive Deception ECM.** Passive deception ECM methods are illustrated in Fig 21–75.

a. *Window.* The use of window to produce confusion ECM has been discussed. It can also be used to provide deception. If window is released from aircraft in a bundle, the bundle slowly separates and produces an echo at the ground radar similar to that produced by a large aircraft. The release of several bundles in succession produces deception by causing additional "targets" to be seen on the radar screen. The ECCM lies in the fact that window is quickly and easily recognized as not being a true target since it will only move with the wind. The necessary discrimination is performed either by an operator or by the use of MTI radar.

b. *Decoys.* A decoy is a small unmanned aircraft which can be launched from an attacking aircraft outside the range of the radar. When picked up by the ground radar, the decoy produces deception echoes. The decoy can be made to give an echo similar to that of a large aircraft by fitting it with reflectors. The remedy is to destroy every hostile target which is detected, including targets thought to be decoys.

c. *Rotating Reflectors.* Tracking radars which use a conical scan can be deceived by a rotating reflector mounted on the aircraft. If the reflector is rotating at the correct speed, it produces amplitude modulation of the echo signal returning to the radar receiver. This may be wrongly interpreted as a change of target position. The remedy here is to use the monopulse tracking system.

d. *Reduction of Radar Echoing Area.* The echoing area is the effective cross-section of a target as seen by the incident pulse from the radar. It can be reduced, thus deceiving the ground radar, by the use of radar-absorbing materials. However the use of such materials on aircraft imposes a performance penalty, and consequently the use of radar-absorbing materials is not widespread.

21211. **Active Deception ECM.**

a. *Repeater Jamming.* The jamming aircraft may carry a low-power transmitter which is triggered by the incident pulse from the ground radar. By delaying the received pulse and re-transmitting a slightly different pulse after a short time interval, false echoes are produced. The false echoes which appear on the ground radar will be at a different range and bearing from the real target.

b. *Transponder Repeater.* A transponder repeater plays back a stored replica of the received radar pulse shortly after the transponder has been triggered by the ground radar. By suitable arrangement of the circuit, the transponder can be silent when illuminated by the main radar beam, and made to respond only to side lobes. By doing this it creates false echoes which are greatly different in range and bearing from the true target.

c. *Range-Gate Stealer.* The range-gate stealer is a repeater jammer which causes a pulsed tracking radar to break its lock on a target. A tracking radar may use a pair of range gates, between which is the target, for automatic tracking. As the target moves, the range gates automatically move also to give automatic tracking in range. The range-gate stealer starts by transmitting a pulse in synchronism with the real echo, thus strengthening the real echo. If the stealer pulse is now slowly shifted in time, and is stronger than the true echo, the tracking radar will lock on to the false pulse and ignore the much weaker echo from the true target. The result is a completely false indication of the range of the target.

d. *Velocity-Gate Stealer*. CW radar may be used in the tracking role (*eg* in the Bloodhound Mk 2 SAM system). To deceive a CW radar which is relying on the Doppler shift in frequency to track a target, a repeater jammer may operate as a velocity-gate stealer. This transmits a signal which gives false information on the target speed; it may even indicate that the received echo is from a stationary target. Repeater-type jamming may be reduced by transmitting a pulse with a form of identification difficult for the jammer to imitate. The jammer can also be made ineffective if the ground radar switches to different values of pulse length or PRF or to a different polarization. The use of monopulse and aerials with small side lobes are also useful ECCM.

Summary

21212. The following table summarizes the various methods of ECM and ECCM discussed in this section:

	Confusion		Deception	
	ECM	ECCM	ECM	ECCM
PASSIVE	1. Window	1. Good receiver design; FTC and IAGC circuits	1. Window	1. MTI radar
			2. Decoys	2. Destroy all targets
			3. Rotating reflectors	3. Monopulse radar system
			4. Reduction of echoing area	4. Good receiver design
ACTIVE	1. CW jammer	1. Good receiver design; FTC and IAGC circuits	1. Repeater jammer	1. Use a pulse difficult to imitate; change pulse width, PRF or polarization; small aerial side lobes
	2. Spot noise jammer	2. Small bandwidth receiver; tuneable radar; small aerial side lobes	2. Transponder jammer	2. As for 1 above
	3. Barrage noise jammer	3. Small bandwidth receiver; several radars in different bands; small aerial side lobes	3. Range-gate stealer	3. Monopulse radar system
			4. Velocity-gate stealer	4. Monopulse radar system

21213–21220. (*Not allotted*).

CONTINUOUS WAVE (CW) RADAR

Introduction

21221. Pulse radars radiate short pulses of energy which are reflected by the target. The reflected echoes are detected by the receiver. By measuring the time required for a pulse to travel to the target and the echo to return to the receiver the range of the target can be determined. Continuous wave (CW) radars however do not transmit pulses of RF energy but transmit continuously and obtain information on targets by examining the nature of the CW signal reflected by the target. There are two basic forms of CW radar; frequency-modulated CW, and CW Doppler.

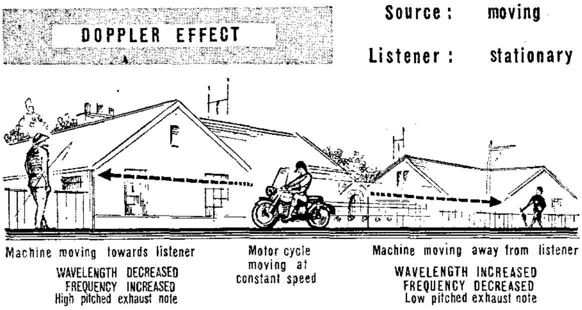


Fig 21–76 Doppler Effect with Sound Waves

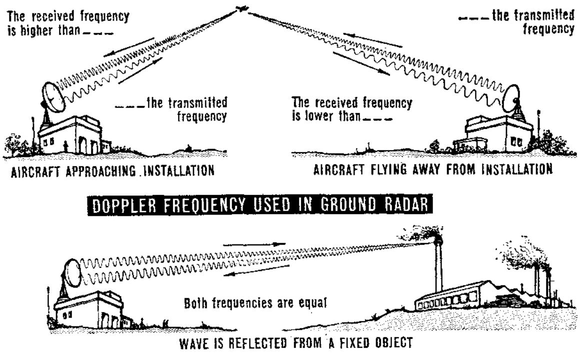


Fig 21–77 Doppler Effect with Radio Waves

The Doppler Effect

21222. An effect known as the Doppler effect can be observed frequently in everyday life in connection with sound waves. If a person is standing still and a motor cycle approaches, the note produced by the engine exhaust appears to change as the machine passes. This is illustrated in Fig 21–76. This phenomenon is known as the Doppler effect, and it occurs with radio waves as well as with sound waves. As a target approaches a radar aerial the frequency of the signal reflected by the target is higher than that of the transmitted signal. Conversely, if a target is moving directly away from the aerial the frequency of the reflected signal is lower than that of the transmitted signal. For stationary targets there is no change in the frequency of the reflected signal (*see* Fig 21–77). If the transmitted frequency is f_t, and the new frequency to which it is changed by the Doppler effect is f_r, the difference between these two frequencies is known as the Doppler shift $f_d = f_t - f_r$.

21223. The magnitude of the Doppler shift is related to the velocity of a target in a straight line between the target and the aerial. A high value of the Doppler shift indicates a high target velocity. If the target is approaching the aerial the received frequency is higher than the original transmitted frequency by the amount of the Doppler shift, *ie* $f_r = f_t + f_d$. If the target is moving away the received frequency is lower, *ie* $f_r = f_t - f_d$. The relationship between a target's velocity and the Doppler shift, provided the target is approaching or receding in a straight line from the radar aerial, is given by the expression:

$$f_d = \frac{2\,v}{c} f_t \quad \text{where}$$

f_d = Doppler shift in c/s.
f_t = transmitted frequency in c/s.
v = velocity of target in mph.
c = velocity of radio waves in mph.

for example, if the transmitted frequency (f_t) is 1,860 MHz and the velocity of a target (v) directly approaching the aerial is 360 mph, then Doppler shift (f_d) ≏

$$\frac{2 \times 360}{186{,}000 \times 60 \times 60} \times 1860 \times 10^6 = 2 \text{ kHz.}$$

This means that the frequency of the received signal f_r is $f_t + f_d$ = 1,860 MHz + 2 kHz. If the target had been moving away in a direct line at 360 mph the frequency of the received signal would have been $f_r = f_t - f_d$ = 1,860 MHz − 2 kHz. In practice it is the velocity of the target which is required, so the calculation is made from knowing the values of the transmitted frequency, the Doppler frequency and the speed of radio waves. Knowing the relationship it is simple to convert any difference in frequency between the received signal and the transmitted signal into the relative velocity of the target.

21224. So far it has been assumed that the target is moving in a direct line either towards or away from the radar aerial. If the target is not moving along such a path, the difference in frequency which Doppler effect causes is less. From Fig 21–78 it can be seen that the important factor is the "radial velocity", *ie* that component of the target's speed which is in a direct line with the aerial. When the target is not moving along a radial line the radial velocity is less than the actual velocity. In fact if the target is moving at right angles across a radial line its radial velocity is zero. It is only the radial velocity which can be measured by the Doppler effect.

Use of the Doppler Effect in Ground Radar

21225. With pulse-modulated ground radar equipment reflections from large fixed objects cause "permanent echoes" on the indicator, and

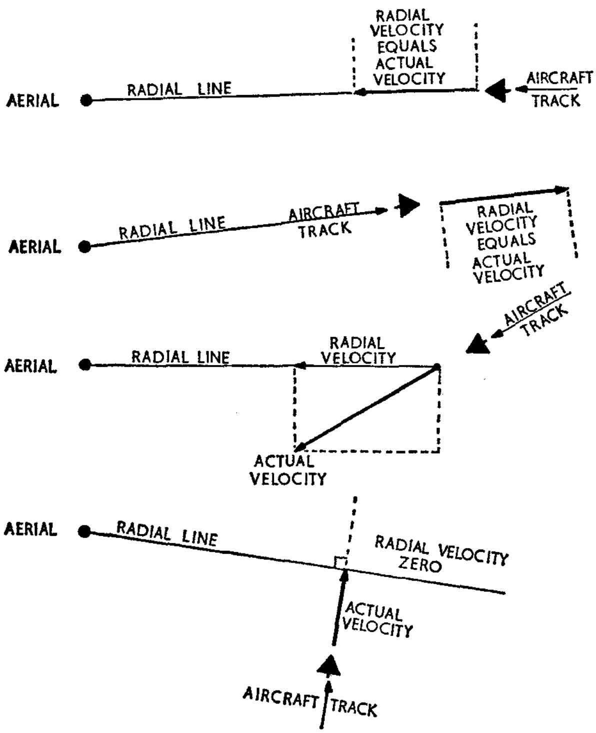


Fig 21–78 Radial Velocity

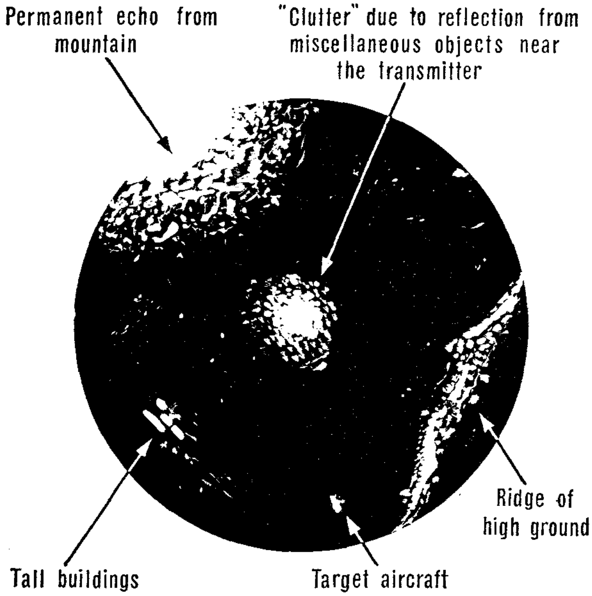


Fig 21–79 Echoes from Unwanted Objects in Pulsed Radar

random reflections from small objects close to the radar cause "clutter" at the centre of the PPI (*see* Fig 21–79). For most applications the receiver should ignore reflections from fixed objects and respond only to moving targets. This can be achieved by using the Doppler effect because a Doppler frequency shift is produced only by the radial velocity of a *moving* target. For a stationary object the reflected signal has the same frequency as the transmitted signal.

21226. Fig 21–80 illustrates a typical arrangement for the indication of a moving target. The frequency f_r of the reflected signal differs from that of the transmitted signal f_t by the Doppler shift f_d. The reflected signal is mixed with the output of a local oscillator to produce an intermediate frequency signal ($f_{if} \pm f_d$) where f_{if} is the intermediate frequency. This signal is amplified and fed to a discriminator whose output is either a positive-going or a negative-going direct current voltage depending on whether the frequency of the reflected signal is above or below that of the transmitter. It should be remembered that the frequency of the reflected signal increases if the target is approaching and decreases if it is flying away from the radar. Thus the sign of the discriminator output indicates whether the target is approaching or moving away. The magnitude of the discriminator output depends on the frequency deviation of the reflected signal in relation to the transmitter frequency, and this in turn is proportional to the target's radial velocity.

21227. An installation using CW Doppler radar is able to provide the following information about a target:

a. The presence of a moving target by the production of a Doppler frequency (unless the radial velocity is zero).

b. The bearing and elevation of the target by using a narrow beam.

c. The radial velocity of the target by measuring the Doppler shift.

d. The direction of travel of the target by the sign of the Doppler shift.

It should be noted that CW Doppler does not measure the range of a target. For this either a pulse-modulated radar or a frequency-modulated CW radar (FMCW) radar is used.

Use of the Doppler Effect in Airborne Radar

21228. If the radar transmitter is located in an aircraft the signals reflected from the ground ahead of the aircraft will also be subject to the

Doppler effect. Use is made of this property in aircraft navigation. To navigate accurately one important factor which must be known by the navigator is the ground speed of the aircraft. This may be quite different from the airspeed (*see* para 2961).

21229. Since the ground ahead of the aircraft is being illuminated by the radar beam from the airborne transmitter it will reflect energy back towards the aircraft. The aircraft is always moving towards the apparent source of radiation and so the received frequency f_r is higher than the transmitted frequency f_t by the Doppler shift f_d. The Doppler shift is determined by the radial velocity of the aircraft and is given by the expression $f_d \doteqdot \frac{2v}{c} f_t$. Special circuits in the receiver automatically measure the Doppler shift and the receiver output can be displayed on a simple meter calibrated in knots. A practical equipment which uses this system transmits not one, but four radar beams at different points around the aircraft. The information which is received from all four points on the ground is used to eliminate errors which would otherwise arise when the aircraft is climbing, diving or banking. The four beams also enable the drift of the aircraft to be calculated. A typical meter display is illustrated in Fig 21–81.

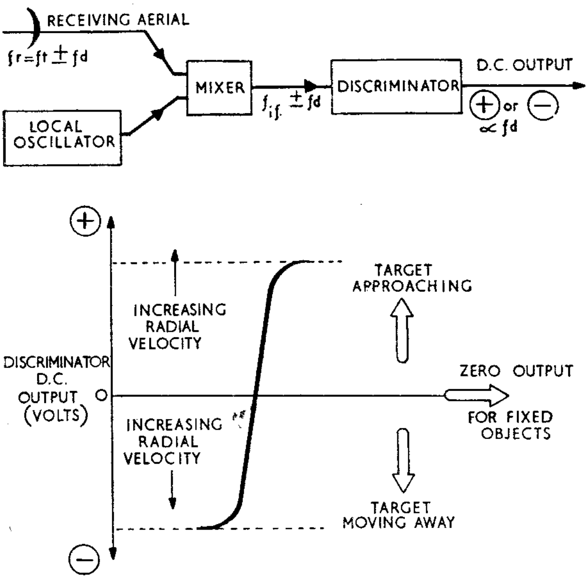
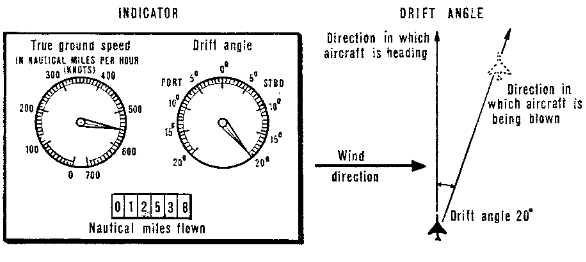


Fig 21–80 Indication of Moving Targets



DOPPLER PRINCIPLE IN AIRBORNE RADAR

Fig 21–81 Doppler Airborne Navigation Display System

Frequency-Modulated CW Radar

21230. In a frequency-modulated transmitter the carrier frequency is caused to change at a *rate* determined by the frequency of the modulation signal and by an *amount* determined by the amplitude of the modulating signal. The transmitter works continuously and produces a constant-amplitude CW signal whose frequency is varied by the modulating signal.

21231. Suppose that the frequency of a frequency-modulated transmitter is caused to deviate at a constant rate by using a "sawtooth" waveform as the modulating signal (*see* Fig 21–82). At point A the carrier frequency is, say, 1,000 MHz. At point B, 800 μs later, the frequency is, say, 1,400 MHz. Since the change in frequency is linear it is possible to say that the transmitter frequency is changing by 400 MHz every 800 μs. Assuming that the output frequency is changing as above and that at a given instant of time it is 1,200 MHz the wave of this frequency is radiated and is reflected by a target to be picked up by the receiver aerial. The wave takes a definite time to travel over this path so that when it arrives back at the radar the transmitter frequency has in the meantime changed to, say, 1,280 MHz. A portion of the transmitter output is fed directly to the receiver where it combines with the reflected input to produce a "difference" frequency, in this case 80 MHz. The greater the range of the target the greater is the difference in frequency between the direct and the reflected inputs. This difference frequency is automatically measured in discriminator circuits in the receiver, the output from which can operate a suitable meter to indicate range.

21232. Since the transmitter frequency is changing linearly by 400 MHz every 800 μs, a change of 80 MHz in the transmitter frequency represents a time interval of:

$$\frac{800}{400} \times 80 = 160\,\mu s.$$

Doppler effect. Use is made of this property in aircraft navigation. To navigate accurately one important factor which must be known by the navigator is the ground speed of the aircraft. This may be quite different from the airspeed (*see* para 2961).

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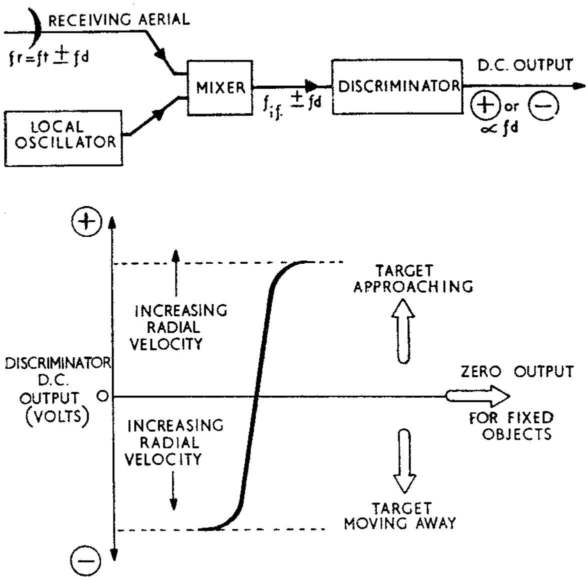
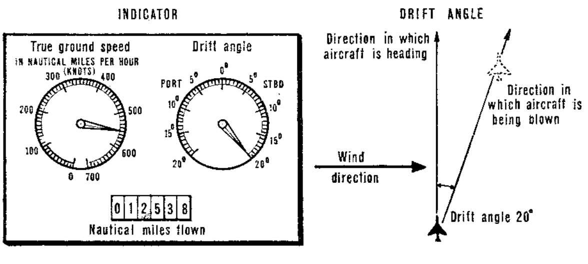


Fig 21–80 Indication of Moving Targets



DOPPLER PRINCIPLE IN AIRBORNE RADAR

Fig 21–81 Doppler Airborne Navigation Display System

Frequency-Modulated CW Radar

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$$\frac{800}{400} \times 80 = 160\,\mu s.$$

Although in the example above, the *peak* power radiated by the pulsed radar is 1,000 times greater than that radiated by the CW radar, the *average* power is the same for both. For the CW radar the duty factor is unity (transmitter operating continuously) so that peak power equals average power. For the pulsed radar:

Average power
$= \text{Peak power} \times \text{pulse duration} \times \text{PRF}$
$= 2 \times 10^6 \times 1 \times 10^{-6} \times 10^3$

Average power
$= 2\ \text{kW} =$ That of the CW radar.

The CW radar has the advantage that it is not subject to the very high peak powers of pulsed radar. There is, therefore, less danger of electrical breakdown in the CW radar. In addition no high power modulator stage is required.

21239. **Minimum Range.** A pulsed radar has a certain minimum range whose value depends mainly upon the pulse duration of the transmitter. At ranges less than the minimum range, a pulse radar is "blind" because the echo is received back at the radar while the transmitter is still firing. In CW Doppler radar however, the transmitter and receiver both operate continuously so that, in theory, the CW system can operate down to zero range. In practice, very small minimum ranges are possible.

21240. **Discrimination Between Moving and Stationary Objects.** In a conventional pulsed radar there is no easy way of distinguishing between moving and stationary objects. The result is that wanted moving targets are often obscured by returns from unwanted stationary objects (clutter), especially at short ranges and low angles of elevation. In a CW system, the received signal from a moving target is shifted in frequency from the transmitted frequency by the Doppler shift. Reflections from stationary objects produce no Doppler shift. It is therefore possible for CW radar to distinguish between moving and stationary objects by measuring any Doppler shift. Ground clutter can therefore be rejected to allow targets to be seen down to low ranges. Slow-moving clutter signals, such as those from clouds, can also be eliminated by selecting only the higher Doppler frequency shifts. Targets are normally tracked in CW radar by tracking the Doppler shift produced by the target's radial velocity. The rate of change of Doppler shift is normally slow enough to allow a velocity tracking gate to follow the target. If, however, the target drops window, the rate of change of the Doppler return from the window will be too rapid for the velocity tracking gate to follow. Therefore CW tracking radars are much less prone to the effects of window jamming than are pulsed radars.

21241. **Inability to Determine Range with Pure CW Radar.** The greatest limitation of the pure CW radar is its inability to determine the range of the target. To measure range, some sort of "mark" must be applied to the transmission to indicate the instant of transmission. The elapsed time between making this mark and the return of the received echo then gives a measure of the range to the target. This is done in pulsed radar, where the mark is the transmitted pulse. The sharper the mark, *ie* the narrower the pulse in pulsed radar, the greater is the accuracy of the elapsed-time measurement, and hence range measurement. However "marks" can be imposed on CW radar transmissions by frequency-modulating the RF carrier, thus enabling range to be determined. Frequency-modulated CW radar can therefore provide range information.

CHAPTER 22

RAF AIR DEFENCE RADARS

CONTENTS

RADAR TYPE 80 MKS 1, 2A and 3

Introduction

2201. The radar Type 80 is a long-range E/F band search radar designed for static installation. Installation of this type of radar began in 1955 for the second stage of the Rotor C and R Plan and was completed by 1957. Concise details of the Type 80 are given in Annex A and the radar is illustrated in Fig 22–1. The Mks 1 and 2A differ only slightly in the construction of the aerial framework: Mk 3 has a square framework capable of supporting two reflectors back-to-back, a different type of turning gear, and a higher-power magnetron. All three marks give similar operational facilities and performance and will therefore be described together in the following paragraphs.

Function

2202. The Type 80 is a long-range, medium power, surveillance and control, primary radar.

Deployment

2203. A Type 80 Mk 1 is installed at Buchan, a Mk 2a at Saxa Vord, and a Mk 3 is also installed at Bishops Court, which is an Air Traffic Control Radar Unit.

Transmitter System

2204. The transmitter uses a magnetron which has a peak power output of 1 MW for the Mks 1 and 2A and $2\frac{1}{2}$ MW for the Mk 3. The transmitter pulses are normally 5 μs wide, but adjustment to 2 μs is possible. A PRF of between 250 and 270 pps is normally used, but may sometimes be within the limits 235 to 300 pps. The magnetron may be one of several in the E/F band of frequencies.

Aerial System

2205. The aerial system of the Type 80 has a 75 ft × 25 ft reflector with a vertical cross section which produces a Cosec^2 radiation pattern (*see* Fig 22–2b) mounted on a 25 ft

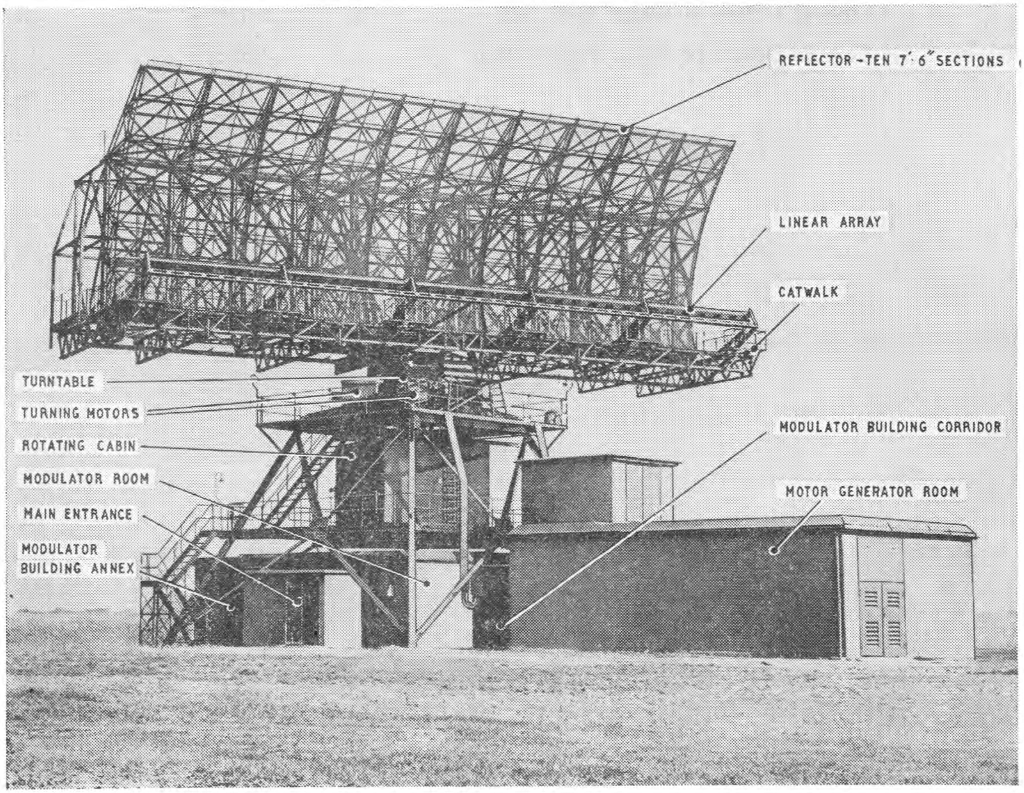

Fig 22–1 Radar Type 80

gantry. The reflector surface consists of a grid of horizontal rods and vertical slats. The aerial is fed by a linear slotted waveguide which is pressurized to prevent arcing due to the high power transmitted.

2206. The whole aerial is mounted on a turntable, below which is a rotating cabin which contains part of the transmitter/receiver. Power to rotate the whole assembly is provided by four electric motors (two in some Mk 1, 2 and 2A installations). The number of motors actually used at any time in the four-motor installation is varied according to wind speed and aerial rotation speed. The aerial may be rotated at up to 6 rev/min, but the normal turning speed is 4 rev/min. Electrical connections to the rotating cabin are provided by slip rings. The vertical coverage provided by the reflector can be varied by adjustment of portions of the waveguide feed relative to the reflector and by alteration of the angle of tilt of the reflector. However these adjustments are limited and difficult to effect, and are consequently normally made when the radar is installed.

Receiver System

2207. Two receiver outputs are provided: linear and logarithmic. The logarithmic receiver is effective against cloud, sea, permanent echo, or anaprop clutter, but overall performance is reduced because of the loss of the weakest signals due to the increased noise amplification.

Signal Processing

2208. The video output of the receiver channels is fed to the radar office and thence to the various display consoles. A continuous check of radiated mean power is possible, and the spectrum of the magnetron output can be analyzed to ensure that the radar is operating at peak efficiency.

Coverage

2209. Typical vertical coverage of the Type 80 is shown in Fig 22–2b. A Canberra size target of $15M^2$ at 40,000 ft should have a 90% probability of paint at about 200nm.

Siting

2210. A high site is desirable for cover at low altitudes and cliff sites have mostly been used.

2211–2214. (*Not allotted*).

RADAR TYPE TPS–34

Introduction

2215. The TPS–34 is an American-made lightweight air-transportable tactical radar which provides three-dimensional coverage, using the V beam principle to give an integral height-finding capability. The TPS–34 can be used in both fixed and air-transportable systems; in the latter case the radar is dismantled on to pallets for the airlift and can be rapidly re-assembled at the destination. The radar is illustrated in Fig 22–3, concise details are at Annex B to this Chapter and a typical coverage diagram is shown at Fig 22–2a.

Function

2216. The TPS–34 is a high power long-range primary radar used for surveillance and control. It is used tactically to provide control and reporting facilities at unprepared locations at short notice.

Radome

2217. An inflatable radome covers the whole aerial. The radome is 50 ft in diameter, 47 ft high, and is made up from eight sections of double-walled neophrene-coated nylon fabric held up by internal air pressure. The air pressure is maintained at about two-thirds lb per square inch by a motor-driven inflator; additional inflators provide increased air pressure to keep the dome rigid during high winds by pressurizing the complete interior rather than just the walls. The radome is capable of withstanding steady-state winds up to 60 mph and gusts up to 90 mph. Mounted in the roof joints of the radome are hoists which are used during the erection of the aerial and depend on the rigidity of the radome for support.

Principles of Operation

2218. The TPS–34 is a D band radar which uses a V beam aerial comprising two separate reflectors, one superimposed on the other. Each reflector is fed by its own transmitter and radiates its own sheet beam. One sheet is vertical; the other is inclined at 45° to the vertical. Both vertical and slant beams are simultaneously radiated and are rotated by the aerial to provide V beam space coverage. The vertical sheet provides the primary search function: the slant beam may be used to supplement it, and is used in conjunction with it for height finding.

2219. As the aerial rotates, the vertical sheet beam strikes the target. The return signals are

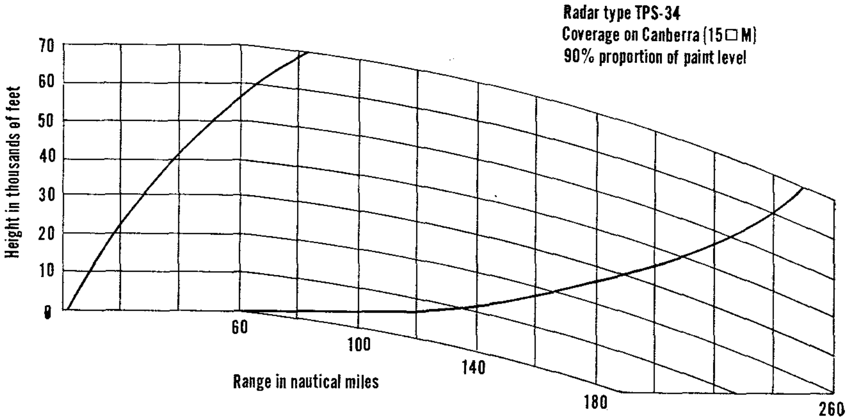

Fig 22–2a. Radar TPS–34—Typical Coverage Diagram.

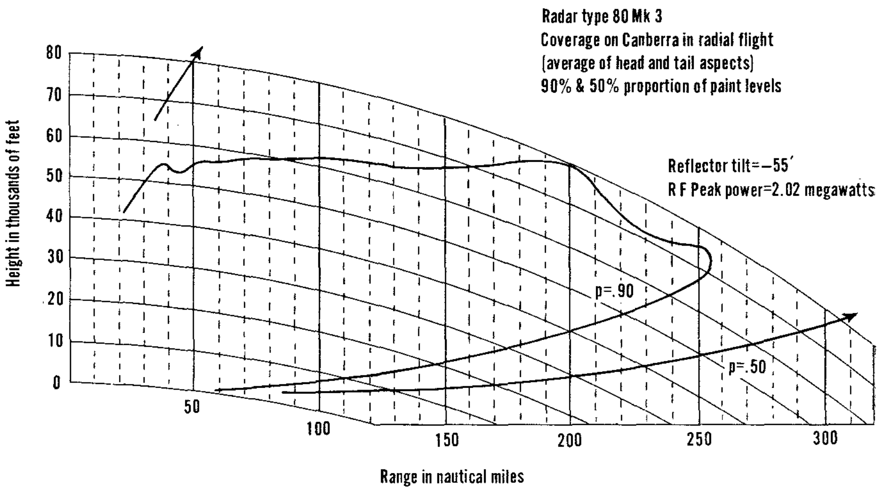

Fig 22–2b. Radar Type 80—Typical Coverage Diagram.

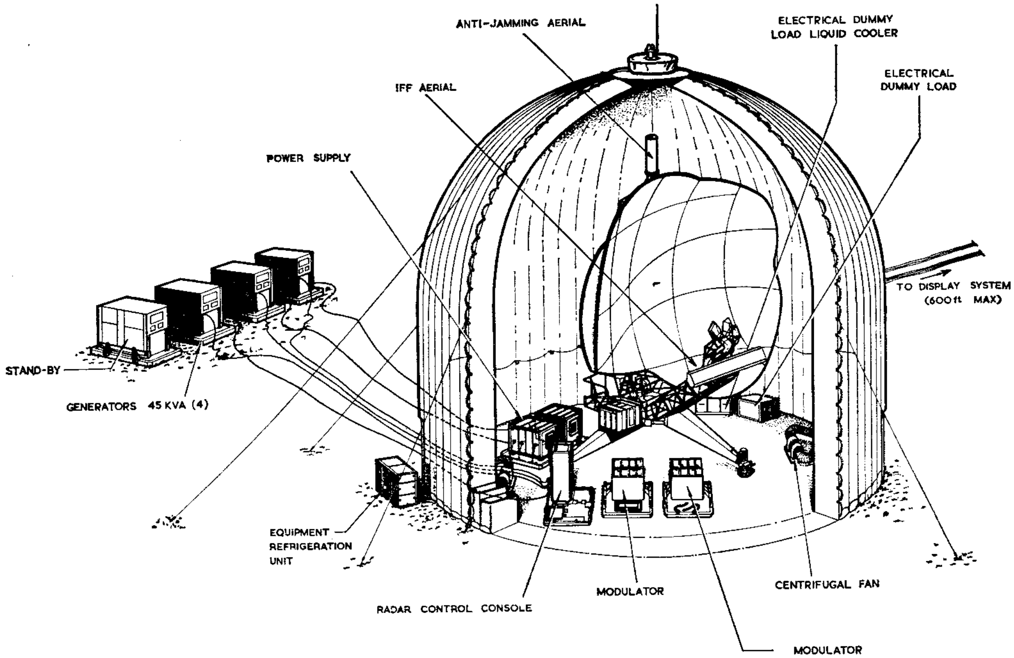

Fig 22–3 Radar Type TPS–34

used to display target azimuth and range information. As the aerial continues to rotate the slant beam intercepts the target and the angle of rotation between the striking of the vertical and slant beams is measured. This angle, together with target range, gives enough data for the height of the target to be calculated. The data is fed to an automatic height computer which executes the necessary calculation and feeds the height display system.

2220. In the event of jamming or interference various ECCM circuits can be employed to minimize the adverse effects. Performance monitoring equipment is built into the radar to ensure an optimum level of operation.

2221. The TPS-34 can conveniently be considered as comprising five functional components augmented by a sixth. These components are described in the following paragraphs.

Transmitting System

2222. Two transmitters (one for the vertical sheet and the other for the slant sheet) are housed in the radome. High power RF pulses are generated by the transmitters at a PRF of 295 pps and fed into the waveguide system. A radar control console is included for monitoring and controlling the radar.

Microwave Transmission and Aerial System

2223. The transmission and aerial system are contained in the radome. The aerial is mounted on a three-legged pedestal which carries cables and hoses to supply power and coolant to the transmitter amplifier and waveguide systems (which rotate with the aerial) through a rotating joint and slip rings. The aerial is driven by an electric motor through a gearbox.

2224. The aerial reflector is of a double-wall fibreglass construction with polarization-sensitive gratings on the surface, and is assembled from 22 separate segments. The reflector is radiated by two feed horns, one for the slant sheet and the other for the vertical. Electrical separation is achieved by polarizing the beams to match the gratings, the vertical beam being horizontally polarized and the slant beam vertically. The reflector also collects the energy returned from targets and focuses it on the appropriate vertical or slant feed horn depending on its polarization.

2225. A subsidiary drum-shaped aerial is mounted on top of the main reflector and is used to counteract enemy jamming in the side and back lobes of the main aerial.

2226. An IFF Mk 10 (SIF) aerial is mounted on the feed horn support structure of the main aerial and is aligned with the vertical beam. An AN TPX–28 IFF Mk 10 (SIF) interrogator provides active and passive SIF.

2227. The aerial assembly rotates in a clockwise direction (viewed from above) at 6 rev/min.

2228. The transmitters use magnetrons in two separate parts of the D band of frequencies (1,250–1,350 MHz). A normal separation of about 65 MHz is maintained between the two beams. The pulse width is about 6μs and the PRF about 295 pps. The magnetrons give a peak power of 4 MW or better.

Receiver System

2229. The receiver system accepts the returned target signals, processes them to reduce various forms of interference, and distributes them to the altitude computer and to the various user displays.

Signal Processing

2230. Signal processing is controlled from radar processing console. The processes which are available to reduce the effects of clutter and jamming include:

a. Side lobe interference suppression (SLIS).

b. Side lobe blanking.

c. Log fast-time constant (Log FTC)

d. Dickie fix.

e. Polarization cancellation.

f. Jammer amplitude versus azimuth (JAVA).

g. Automatic video noise level (AVNL).

h. Automatic gain control.

j. Non-coherent MTI.

Altitude Computer

2231. The altitude computer automatically computes the altitudes of targets selected and injected into the computer by an operator. This part of the system uses British equipment.

Auxiliary Systems

2232. The auxiliary systems comprise test equipment, the radome, a tool kit, spares, the IFF Mk 10 (SIF) equipment and power supplies.

Siting Considerations

2233. The best site for a TPS–34 installation is a flat surface in surroundings free from obstructions which could cause permanent echo returns of such strength that the MTI is unable to eliminate them. Considerations affecting the siting of the equipment when used in the transportable role are:

a. The radome site should be level (to within five degrees maximum slope).

b. The site should be at least 600 ft by 150 ft in size.

c. The site should be well drained and free from protrusions likely to damage the floor of the radome.

(d) **A radiation hazard to personnel exists from exposure to the beams at heights comparable with the centre of the aerial aperture. With the aerial head rotating a potential hazard exists within a distance of 11 metres.”**

2234–2240. (*Not allotted*).

RADAR TYPE S259

Introduction

2241. The S259 radar system is a medium power, lightweight, tactical D-band radar. It is readily air transportable and can be deployed to its selected operational site by helicopter. The radar is designed to carry out an azimuth search role and has no height finding capability. Three basic units form the system: the display cabin, the transmitter cabin and the transportation pallet. Each unit is fitted with lifting slings

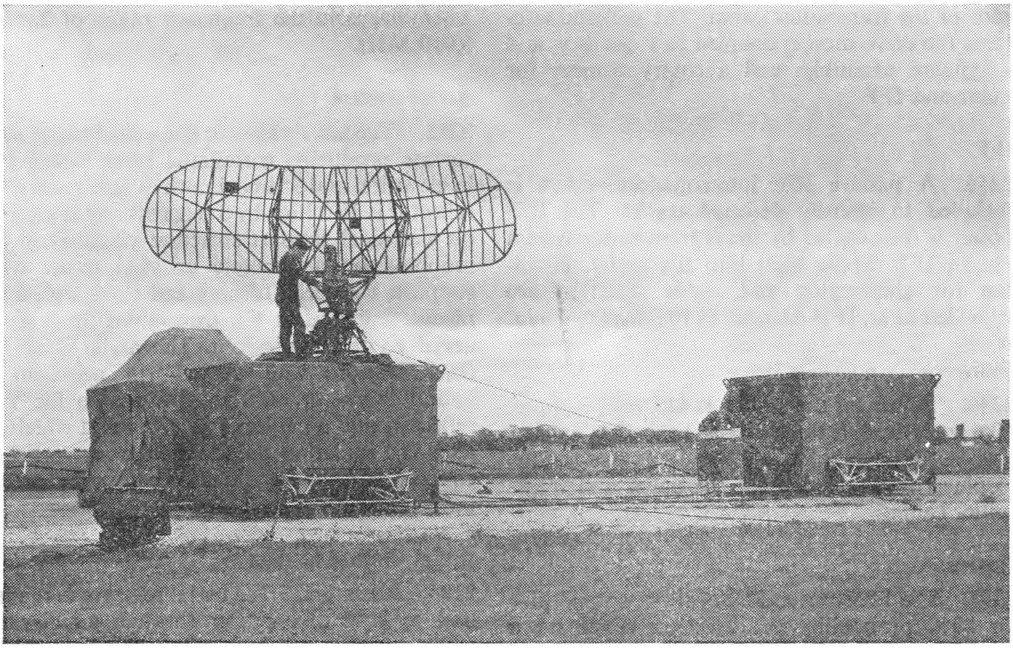

Fig 22–4 Radar Type S259

for hoisting when the system is being transported by helicopter. One set of four-wheeled running gear is provided to facilitate manoeuvrability of these units for on-site deployment and loading onto transport. Concise details of the radar are at Annex C and Fig 22–4 illustrates the erected radar system.

Function

2242. The S259 fulfils three main functions:

a. Early warning during the initial stages of an emergency, when a comprehensive control and surveillance radar is not available.

b. Extension of early warning cover in support of other ground radars by forward deployment.

c. Provision of standby facilities should the primary radar be off the air.

The D band transmitter/receiver is of solid-state design incorporating a parametric amplifier and is housed in the transmitter cabin. Control of the transmitter is normally from a remote control panel in the display cabin. To facilitate easy testing and local monitoring of the transmitter functions, a performance monitor is built into the transmitter. The transmitter cabin is 7 ft high, 8 ft 6 in wide and 10 ft long.

Displays

2243. The display cabin, 6 ft 6 in high, 8 ft 6 in wide and 10 ft long, is the operators cabin and houses a signal processor, which provides video and MTI processing and clutter elimination. The processor also provides the accurate trigger pulse for the transmitter and can be at a set interpulse period or at a selected stagger. Range scales of 32, 64, 128 or 256 data miles can be selected on the 12 inch PPI displays located at the two operating positions in the display cabin.

Aerial System

2244. Operation of the aerial is via a servo system linked to the PPI displays and has an adjustable rotation in continuous mode of up to 15 rpm. The aerial reflector divides for transportation into three sections; a centre section and two end sections. When the aerial reflector sections are assembled, with the aerial support and feedhorn, they form a modified parabolic reflecting surface capable of transmitting a horizontal beamwidth of 3·8° and a vertical beamwidth of 10°. The vertical pattern of the aerial can be adjusted between −2° and +5°. The reflector is supported on the aerial pedestal which is mounted on the roof of the transmitter cabin. The pedestal contains the drive motor, coupled to a gearbox and a synchro assembly, and a rotary coupler for radar and IFF.

IFF

2245. A passive IFF interrogation system is included to identify detected tracks. The IFF power is transmitted by the rf transmitter system via an IFF dipole built into the aerial. Facilities for challenging and mode selection are provided at an IFF decoder in the display cabin.

Power

2246. Power for the system is 415 volt, 3-phase, 50 Hz derived from a diesel generator source. Two separate supplies are required; one for the display cabin and one for the pallet and transmitter cabin.

Coverage

2247. The S259, set at 3° elevation, should give an 80% probability of detection range on a Canberra type target (15M^2) at 40,000 ft of 130 nm.

2248–2281. (Not allotted).

RADAR TYPE HF 200

Introduction

2282. The radar Type HF 200 is a medium power nodding height finder made by Plessey Ltd. It is a long range E/F band primary radar used in fixed installations both in the UK and overseas. The radar is illustrated in Fig 22–5 and its concise details are listed at Annex D to this Chapter.

Function

2283. The HF 200 is used in the UK and overseas to find heights on aircraft at long, medium or short ranges which have been detected by a surveillance radar.

Transmitter System

2284. The transmitter used in the HF 200 is a conventional E/F band magnetron transmitter, giving a peak power output of 2½ MW and using a pulse width of about 5 μs at a PRF of about 250 pps. The magnetron which feeds the aerial via a pressurized transmitter/receiver waveguide assembly, is in the frequency range of 2,800 to 3,010 MHz.

Aerial System

2285. The aerial reflector has a double-curvature surface producing a radiated beam which is ¾° in elevation and 3° in azimuth at 3dB points. The reflector is 35 ft high by 8 ft across and is mounted on a conical support structure which is in turn mounted on a concrete or steel tower which supports the aerial turning and elevating mechanisms, and houses the transmitter/receiver and aerial control equipment. The aerial is nodded (in elevation) and slewed (in azimuth) by hydraulic power. A horn waveguide feeds the reflector, and a device is incorporated which can alter the radiation polarization from vertical to circular to reduce the clutter caused by precipitation returns.

Aerial Control System

2286. **Elevation.** The aerial reflector is made to nod by hydraulic power through an elevation angle which has a lower limit fixed at –3° and an upper limit which may have one of four values. The upper limit of the nod depends on the range of the target in the following way:

a. +33° for targets up to 50 nm range.

b. +18° for targets between 50 nm and 100 nm range.

c. +9° for targets between 100 nm and 160 nm range.

d. +6° for targets over 160 nm range.

By restricting the upper nod limit in relation to range a greater number of elevation scans per minute can be made, thus increasing the speed of detection and utilization of the aerial.

2287. **Azimuth.** The aerial is slewed in azimuth automatically or by the action of the azication PPI operator (one Type HF 200 aerial may be shared by several PPI operators) who uses a control to place a marker on the target response on the PPI. This action causes the aerial to slew on to the required bearing at a maximum acceleration of 43° per second up to a maximum turning speed of 6 rev/min.

Receiver System

2288. Two main receiver channels are provided and both may use either vertical or circular polarization. The two channels are:

a. Linear (to which instantaneous automatic gain control (IAGC) may be applied).

b. Logarithmic.

A fast time constant (FTC) and a swept gain processing circuit can be applied to either linear or logarithmic output.

Coverage

2289. The coverage of the HF 200 is illustrated in Fig 22–7.

Data Rate

2290. The maximum slewing rate is 6 rev/min, and the nodding rate (over the maximum angle of 36°) is 20 scans per minute. Over 9° the rate is 56 sweeps per minute. This makes possible a maximum data rate of approximately 15 sequential height readings per minute or 8 priority readings per minute.

Height Finding Accuracy

2291. At a range of 150 nm the height accuracy should be about ± 1,000 ft, but relative height error should be about ± 500 ft at the same range.

2292–2297. (*Not allotted*).

RADAR TYPE FPS–6

Introduction

2298. The radar Type FPS–6 is a medium power nodding height finder of American origin which has been in service for some years and which now incorporates many British components. It is a long range E band primary radar used in some fixed installations in the UK. The radar is illustrated in Fig 22–6 and its concise details are listed at Annex E to this Chapter.

Function

2299. The FPS–6 is used in the UK to find heights on long, medium and short range targets which have been detected by a search radar.

Transmitter System

22100. The FPS–6 transmitter is a British made conventional magnetron type giving a peak power output of 2½ MW at a PRF of 250 or 270 pps, using a pulse width of 4·7 μs.

(*continued on next leaf*)

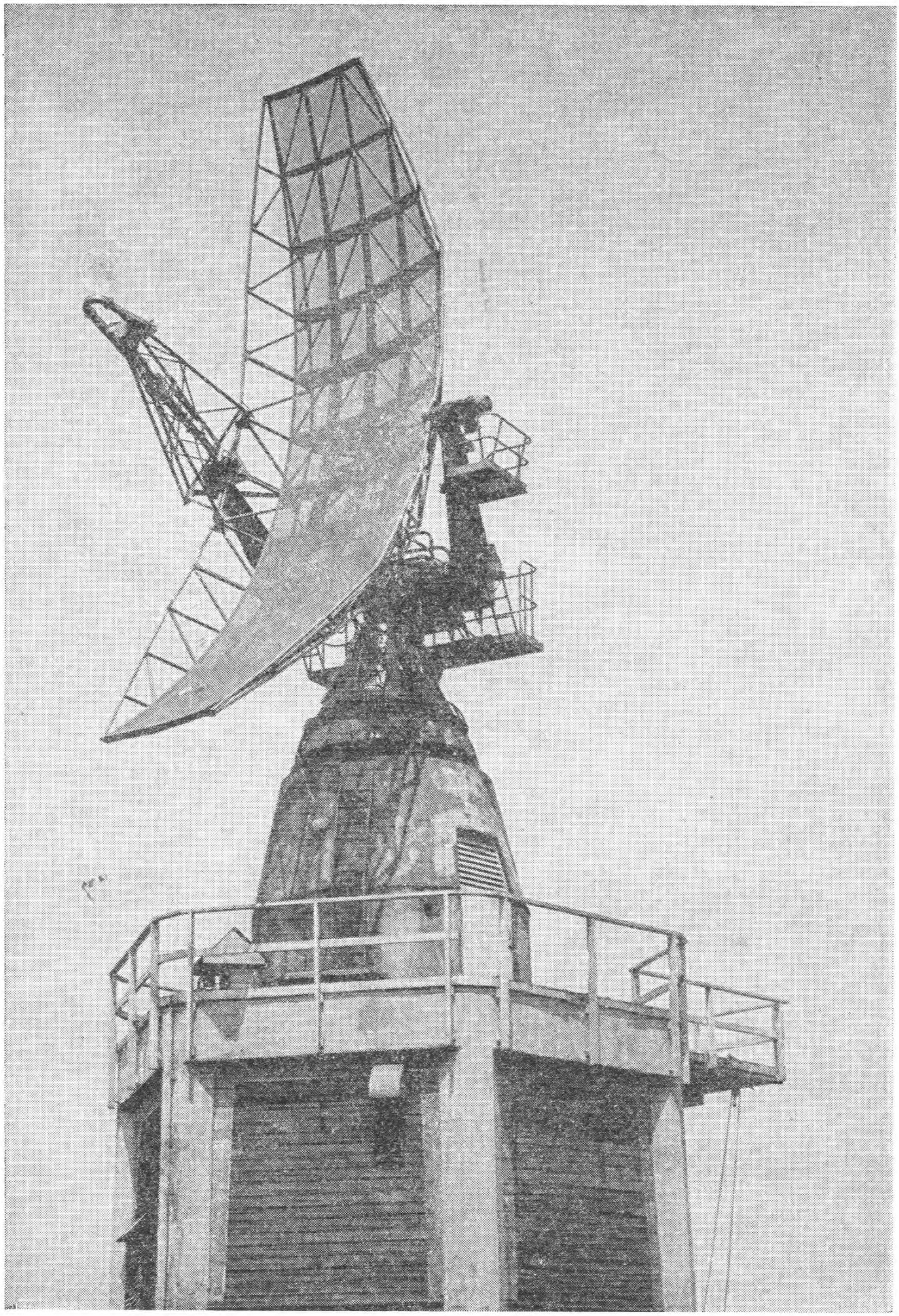

Fig 22–15 Radar Type HF 200

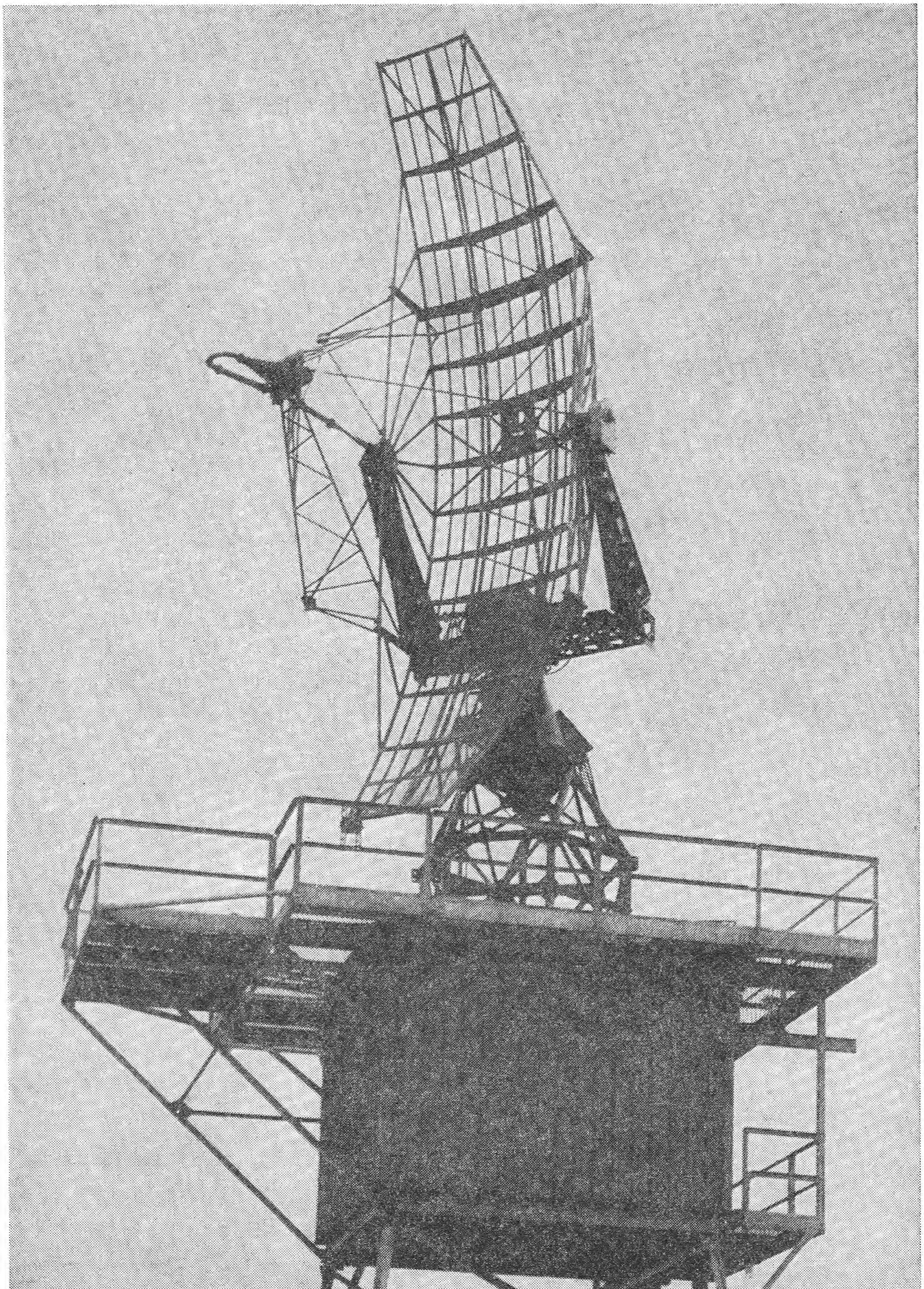

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Fig 22–26 Radar Type FPS–6

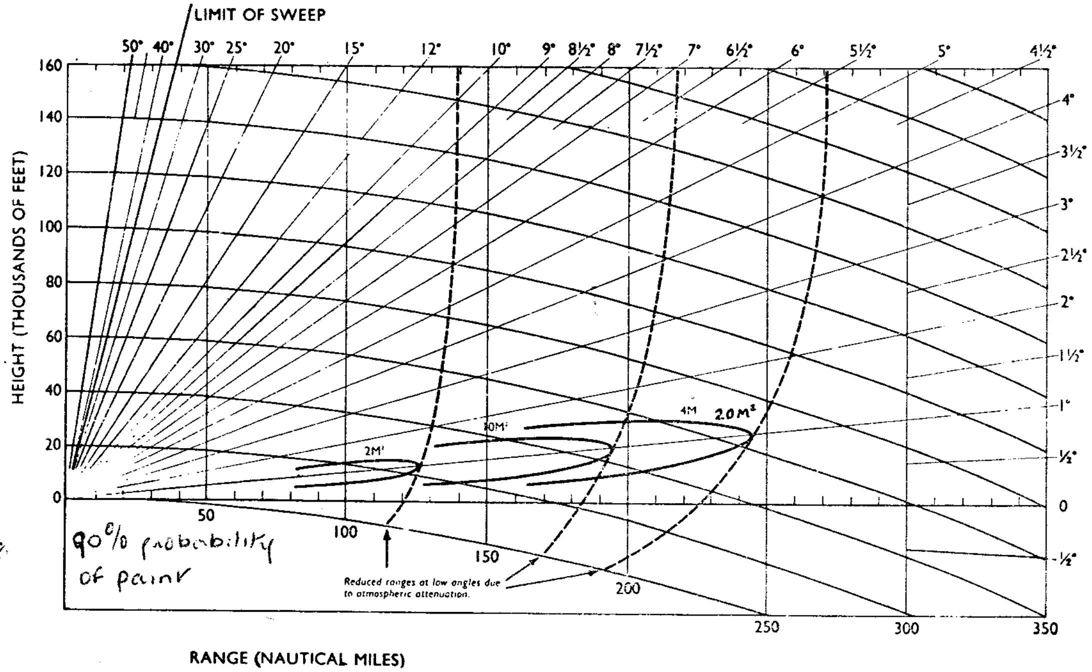


Fig 22-7 Coverage of Radar Type HF 200

Aerial System

22101. The aerial of the FPS–6 is very similar to that of the Type HF 200 (*see* para 2285) but is mounted on a rectangular steel lattice tower, the top half of which is enclosed to house the transmitter and aerial control equipment. The aerial radiates a beam which is 0·85° in elevation and 3·2° in azimuth at 3 dB points. The radiation is vertically polarized.

Aerial Control System

22102. **Elevation.** The aerial is made to nod, by an electro-mechanical system through an angle of −2° to +32°. The nod rate can be selected by the height reader to be either 20 or 30 sweeps per minute.

22103. **Azimuth.** The aerial is azicated on to the target bearing by the action of the height reader in placing a marker on the target response on the PPI display.

Receiver System

22104. The receiver has a single output to which fast time constant (FTC), swept gain, and automatic noise limitations can be applied to reduce the effects of clutter and jamming and to maintain the gain at the optimum level under varying noise conditions.

Coverage

22105. The coverage of the FPS–6 approximates to that of the HF 200, which is illustrated in Fig 22-7.

RADAR TYPE UPS–1

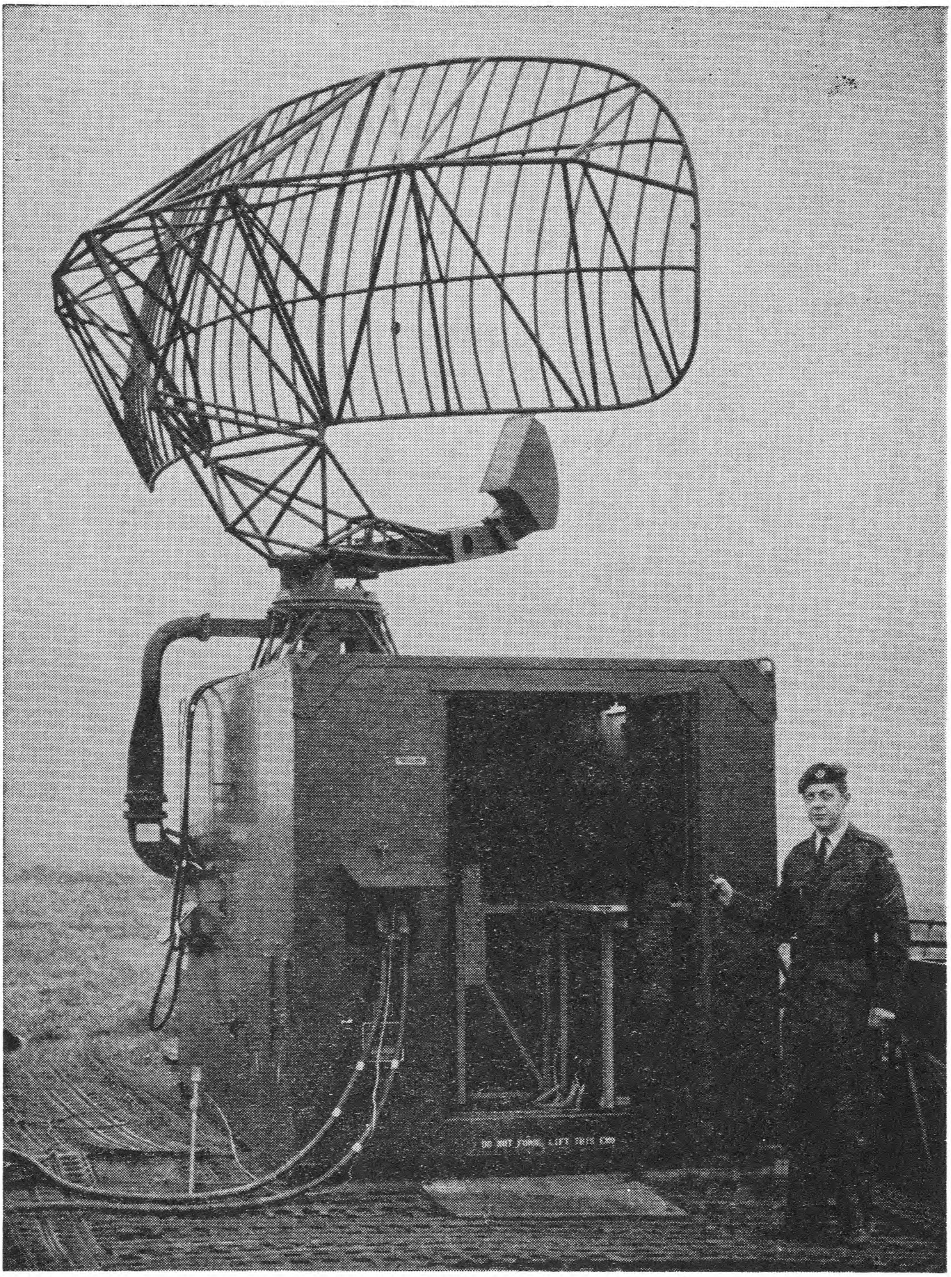


Fig 22-~~9~~ 8 Radar Type UPS–1

AL8

RADAR TYPE UPS–1

Introduction

22106. The UPS–1 is an American-made ultra-lightweight assault radar without a height finding capability. It is readily air-transportable and can be deployed to diverse sites by helicopter. It is of rugged construction and uses integral containers for packing components during deployment. The radar can be re-assembled in a short time by a small number of men. Concise details of the radar are at Annex F, and Fig 22-8 illustrates the radar when erected.

Functions

22107. The UPS–1 fulfils three main functions:

a. Early warning during early stages of an emergency, when a comprehensive control and surveillance radar is not available.

b. Extension of early warning on aircraft at high or low altitude, in support of other ground radars by forward deployment.

c. Provision of standby facilities should the main radar be off the air.

Transmitter

22108. A cabin approximately 7 ft high by 12 ft long by 7 ft wide houses all the electronic equipment, provides operations accommodation and supports the aerial and its turning gear on the roof. Except for the display console the electronic units are mounted at one end of the cabin and separated from the operations area by sliding doors which eliminate any radiation hazard and reduce the noise level.

22109. The transmitter uses a magnetron in the D band. The actual frequency used is tuneable in the range 1,250 to 1,350 MHz by a single knob control. The pulse length is 1.4 μs when the 20, 40 or 80 nm display ranges are used, but when the 275 nm scale is used the pulse length is increased to 4.2 μs. The PRF is similarly adjusted, being 800 pps for the three shorter ranges and 267 pps for the 275 nm scale.

22110. One of two interchangeable aerials may be used; they are known as the Type 1 and the Type 2:

a. *Type* 1. The Type 1 produces a beam with a horizontal beamwidth of 3·8° and a vertical coverage of 10°.

b. *Type* 2. The Type 2 produces a beam with horizontal beamwidth of 3·7° and a vertical coverage of 11°, but in addition provides a Cosec² radiation pattern in the vertical plane between 9° and 42° from the horizon.

The vertical pattern of both aerials can be varied by adjusting the reflector between −2° and +5° from the horizontal. The Type 2 reflector is 1 ft higher than the Type 1, being 16 ft long by 6 ft high. Both reflectors have rounded ends and are parabolic (Type 1) or Cosec² (Type 2) in vertical section. Both the reflectors are parabolic in horizontal section.

22111. The reflector is radiated by a horn waveguide, and the whole assembly is mounted on the roof of the cabin. The aerial can turn at speeds up to 15 rev/min, but 4 rev/min is the recommended speed for air defence operations. The turning gear is a self-contained assembly and is electrically powered.

Receiver System

22112. The receiver output, which may be enhanced by use of a parametric amplifier, is fed to a single display unit which contains a 10-inch PPI and a 3-inch A-scope.
The display unit can be removed up to a distance of 50 ft to a remote operating position. A different display system altogether may be used where the UPS–1 is operating as a standby radar in a semi-static state.

Signal Processing

22113. An effective coherent MTI is provided on the 20, 40 and 80 nm range scales, and the outer range of the MTI can be adjusted to suit conditions. Other anti-clutter and anti-jamming devices include swept gain (American designation: sensitivity time control), fast time constant and interference blanking.

Coverage

22114. The UPS–1 gives an 80% probability of detection on a Canberra at 40,000 ft at a range of 210 nm, using the parametric amplifier and Cosec² aerial. Without the parametric amplifier the equivalent range is reduced to about 110 nm.

22115 – 22120. (*Not allotted*).

CONCISE DETAILS OF RADAR TYPE 80

1. **Class of Equipment.** The Type 80 is a long range fixed radar operating in the E/F band of frequencies.

2. **Purpose of Equipment.** Long and medium range control and surveillance.

3. **Frequency.** One of several frequencies in the E/F band from 2,850 to 3,050 MHz.

4. **Coverage.**

a. *Azimuth.* 0° to 360° on continuous rotation.

b. *Elevation.* Cosec^2 radiation pattern from 0° to about 30°.

5. **Range Performance.** *See* Fig 22–2b. 90% probability of paint on Canberra-sized target at about 200 nm at 40,000 ft.

6. **Discrimination.** The Type 80 should discriminate between two targets one mile apart at 150 nm.

7. **Aerial Characteristics.**

a. *Polarization.* Horizontal.

b. *Beam Shape.* In elevation Cosec^2; in azimuth 0·3° at 3 dB points.

8. **Aerial Reflector.** 75 ft long by 25 ft high, of distorted parabolic section, producing Cosec^2 radiation pattern. Mounted on 25 ft gantry.

9. **Aerial Feed.** Slotted waveguide.

10. **Scanning Rates.** Normally 4 rev/min, but up to 6 rev/min possible.

11. **Transmitter.**

a. *Type.* Magnetron.

b. *Pulse Width.* 5 (normal) or 2 μs.

c. *PRF.* 235 to 300 pps.

d. *Peak Power Output.* ~~1 MW (Mks 1, 1A, and 2),~~ 2½ MW (Mk 3).

12. **Receiver.** Two output channels: linear and logarithmic.

CONCISE DETAILS OF RADAR TYPE TPS-34

1. **Class of Equipment.** The TPS–34 is a high-power, air-transportable surveillance and control radar operating in the D band of frequencies. It has integral height-finding using the V beam principle and several anti-jamming and anti-clutter facilities are available.

2. **Purpose of Equipment.** The TPS–34 is used by the RAF for control and surveillance in tactical deployments at short notice to unprepared sites.

3. **Frequencies.** Overall 1,250 to 1,350 MHz (D band).

 a. *Vertical Beam*—Tuneable in the D band range.

 b. *Slant Beam*—Tuneable in the D band range.

4. **Coverage.**

 a. *Azimuth.* 0° to 360° in continuous scan.

 b. *Elevation.*

  (1) 0° to 45° for detection.

  (2) 0° to 30° for height finding.

5. **Range Performance.** A 90% probability of paint on a 15 square metre target at 210 nm at 40,000 ft. Height finding capability to 240 nm.

6. **Radar Accuracy.**

 a. *Range.* ± 1%.

 b. *Azimuth.* 1° ± 0·3°.

 c. *Elevation:*

  (1) ± 2,500 ft at 125 nm at 45,000 ft.

  (2) ± 3,500 ft at 125 nm to 200 nm at 45,000 ft.

7. **Discrimination.**

 a. *Range.* 0·5 nm.

 b. *Azimuth.* 1·6°.

8. **Aerial Characteristics.**

 a. *Polarization.*

  (1) Vertical beam—horizontal.

  (2) Slant beam—vertical.

 b. *Horizontal Beam Width.*

  (1) Vertical beam—1·6°.

  (2) Slant beam—2·3°.

9. **Aerial Reflector.** Double-walled, fibreglass, shaped, reflector with dual reflecting surfaces sensitive to polarized radiation, giving two separate beams. Assembled from 22 component sections.

10. **Aerial Feed.** Two separate horns are used:

 a. Horizontal-polarization-sensitive for vertical beam.

 b. Vertical-polarization-sensitive for slant beam.

11. **Scanning Rate.** Clockwise (viewed from above) at 6 rev/min.

12. **Transmitters.** Two transmitters are used, one for the vertical beam and one for the slant beam.

 a. *Type.* Magnetron.

 b. *Pulse Width.* 6 μs.

 c. *PRF.* 292 pps.

 d. *Peak Power.* 4 MW or better.

CONCISE DETAILS OF RADAR TYPE S259

1. **Class of Equipment.** The S259 is a ruggedly constructed air transportable D band radar with no height finding capability.

2. **Purpose of Equipment.** The S259 is used by the RAF for control and surveillance as follows:

   a. Extension of early warning and control capacity during an emergency by forward deployment.

   b. Standby facilities for a primary radar.

3. **Frequency.** D band, 23 cm, tuneable in the range 1,250 to 1,380 MHz.

4. **Coverage.**

   a. *Azimuth.* 0° to 360° using continuous rotation.

   b. *Elevation.* 0° to 10°, variable by tilting the aerial between the limits of —2° to +5° relative to the horizontal.

5. **Aerial Characteristics.**

   a. *Polarization.* Horizontal.

   b. *Beam Widths.* 3·8° horizontal, 10° vertical.

   c. *Side Lobes.* 26 dB horizontal, 20dB vertical.

6. **Aerial Reflector.** 16 ft by 4 ft 9in, parabolic in vertical section.

7. **Aerial Feed.** Horn wave-guide.

8. **Scanning Rate.** 0–15 rev/min: 4–6 rev/min normally selected for air defence use.

9. **Transmitter.**

   a. *Pulse Width.* 5μs.

   b. *PRF.* 285·5–291 pps dependent upon frequency.

   c. *Peak Power.* 2 MW.

10. **Receiver.** Three processed receiver outputs:

   a. MTI.

   b. Log/PLD.

   c. Fully processed receiver band width. 500 KHz.

11. **Display.** Two 12in PPI displays.

12. **IFF.** AN–TPX 47 interrogator (transmitter cabin) (IFF decoder 7117 (display cabin):

   a. *Frequency.* 1,030 MHz (transmission), 1,090 MHz (reception).

   b. *Band Width.* 8 MHz.

   c. *Power.* 1–2 kW.

CONCISE DETAILS OF RADAR TYPE HF 200

1. **Class of Equipment.** Long range, medium power, fixed, nodding height finder operating in the E/F band.

2. **Purpose of Equipment.** Heightfinding on aircraft at long, medium or short range in the UK and overseas.

3. **Frequency.** A frequency in the range 2,800–3,010 MHz (E/F band).

4. **Coverage.**

a. *Azimuth.* 0° to 360° by slewing at a maximum rate of 6 rev/min.

b. *Elevation.*

(1) —3° to +33° at 20 scans/minute to a range of 50 nm.

(2) —3° to +18° at about 44 scans/minute from 50 to 100 nm range.

(3)—3° to +9° at about 50 scans/minute from 100 to 150 nm range.

(4) —3° to +6° at 56 scans/minute at a range of over 160 nm.

5. **Range Performance.** About 210 nm on a 15 square metre target at 40,000 feet with a 90% probability of paint.

6. **Discrimination.** 1nm at 150 nm in range, 12,000 ft at 150 nm in elevation.

7. **Aerial Characteristics.**

a. *Polarization.* Vertical or circular.

b. *Beam Shape.*

(1) Horizontal beamwidth 3° at 3 dB points.

(2) Vertical beamwidth ¾° at 3 dB points.

8. **Aerial Reflector.** Double curvature, 35 ft high by 8 ft wide.

9. **Aerial Feed.** Horn waveguide.

10. **Transmitter.**

a. *Type.* Magnetron.

b. *Pulse Width.* 5 μs.

c. *PRF.* 200–250 pps.

d. *Peak Power Output.* 2½ MW.

11. **Receiver.** Two output channels: linear and logarithmic.

12. **Signal Processing.** Vertical or circular polarization, fast time constant (FTC) and swept gain. Instantaneous automatic gain control (IAGC) on linear channel.

13. **Accuracy.** ± 1,000 ft at 150 nm, but about ± 500 ft for relative heights at the same range.

CONCISE DETAILS OF RADAR TYPE FPS-6

1. **Class of Equipment.** The FPS–6 is a long range, medium power, fixed nodding height finder operating in the E band.

2. **Purpose of Equipment.** Provision of heights on aircraft at long, medium and short range.

3. **Frequency.** E band, in the range 2,700–2,900 MHz.

4. **Coverage.**
   a. *Azimuth.* 0° to 360°.
   b. *Elevation.* −2° to +32°.

5. **Aerial Characteristics.**
   a. *Polarization.* Vertical.
   b. *Beam Shape.*
      (1) Horizontal beamwidth 3·2° at 3 dB points.
      (2) Vertical beamwidth 0·85° at 3 dB points.

6. **Aerial Reflector.** Double curvature, 30ft by 7½ ft.

7. **Aerial Feed.** Horn waveguide.

8. **Transmitter.**
   a. *Type.* Magnetron.
   b. *Pulse Width.* 4·7 μs.
   c. *PRF.* 250 to 270 pps.
   d. *Peak Power Output.* 2½ MW.

9. **Receiver.** Single output channel.

10. **Signal Processing.** The following signal processing circuits are available:
   a. Fast time constant (FTC)—to reduce clutter and jamming effects.
   b. Swept gain—to give more even returns from short and long range targets.
   c. Automatic noise limiting—to maintain the gain at the optimum level under varying noise conditions.

CONCISE DETAILS OF RADAR TYPE UPS–1

1. **Class of Equipment.** The UPS–1 is a ruggedly constructed, highly portable, air transportable D band radar with no height finding capability.

2. **Purpose of Equipment.** To provide:

a. Early warning during early stages of an emergency.

b. Extension of early warning cover by forward deployment.

c. Standby facilities for a main radar.

3. **Frequency.** D band, tuneable in the range 1,250 to 1,350 MHz.

4. **Coverage.**

a. *Azimuth* 0°–360° using continuous rotation.

b. *Elevation.*

(1) Using Type 1 aerial reflector—0° to 10°.

(2) Using Type 2 aerial reflector—0° to 11°, with Cosec^2 pattern radiation between 9° and 42°.

The coverage in elevation is variable by tilting the aerials between the limits of −2° to +5° relative to the horizontal.

5. **Range Performance.**

a. 210 nm on a Canberra-type target at 40,000 ft using a Type 2 aerial and parametric amplifier.

b. 110 nm on a Canberra-type target at 40,000 ft using a Type 2 aerial but without the parametric amplifier.

6. **Aerial Characteristics.**

a. *Polarization.* Horizontal.

b. *Beam Shape.*

(1) Type 1 Aerial—3·8° in azimuth, 10° in elevation.

(2) Type 2 Aerial—3·7° in azimuth, 42° in elevation.

7. **Aerial Reflectors.**

a. *Type* 1. 16 ft by 4 ft 9 ins, parabolic in vertical section.

b. *Type* 2. 16 ft by 6 ft, distorted parabolic in vertical section to give Cosec^2 coverage.

8. **Aerial Feed.** Horn waveguide.

9. **Scanning Rate.** 0−15 rev/min; 4 rev/min recommended for air defence use.

10. **Transmitter.**

a. *Type.* Magnetron.

b. *Pulse Width.*

(1) 1·4 μs on range scales 20, 40 and 80 nm (MTI useable).

(2) 4·2 μs on 275 nm range scale (MTI inoperative).

c. *PRF.*

(1) 800 pps on range scales 20, 40 and 80 nm (pulse width 1·4 μs).

(2) 267 pps on range scale 275 nm (pulse width 4·2 μs).

d. *Peak Power.* 1 MW.

11. **Receiver Outputs.**

a. *Linear.* Bandwith matches pulse width according to range scale selected.

b. *MTI.* On range scales 20–40 and 80 nm. Range to which MTI is effective adjustable within range 0–80 nm. Coherent MTI.

c. *Swept Gain.* (American terminology: sensitivity time control.)

d. *Fast Time Constant.*

12. *Display.* Using American console, one 10-inch PPI and one 3-inch A scope per console. Console can be remoted up to 50 ft from aerial.

13. **Range Resolution.** 0·5 nm at 20 nm.

14. **Azimuth Resolution.** 4° at 50 nm range.

15. **Azimuth Accuracy.** 1°.

CHAPTER 23

RADAR DISPLAYS AND ASSOCIATED EQUIPMENT

CONTENTS

CONSOLE TYPE 64

Introduction

2301. Console 64 is a general-purpose fixed coil PPI console used to give an accurate and stable display of information derived from radars in static installations; the information reaches the console through the radar office. It was the standard PPI installed in UK radar stations prior to the introduction of the GL–161 and SLEWC systems. A general view of the console is given in Fig 23–1. The CRT indicating unit, with a control panel beside it, is mounted sloping back at the most comfortable viewing angle, and beneath it is a desk with a row of controls mounted in a well. The CRT has a screen 12 inches in diameter, with an afterglow of about one minute in complete darkness. The control panel carries those controls needing only infrequent adjustment by the operator, and in normal use is concealed behind a hinged cover. Focus and brilliance are pre-set and not accessible to the operator; the high stability of the display does away with the need for frequent readjustment of the controls. Several different control desks may be fitted to the console. The type depends upon the facilities available at the station, but various desks appropriate to the following applications are available:

a. *Plotting.* This desk carries only basic facilities.

b. *Interception Control.* This desk carries extra line keys and RT control.

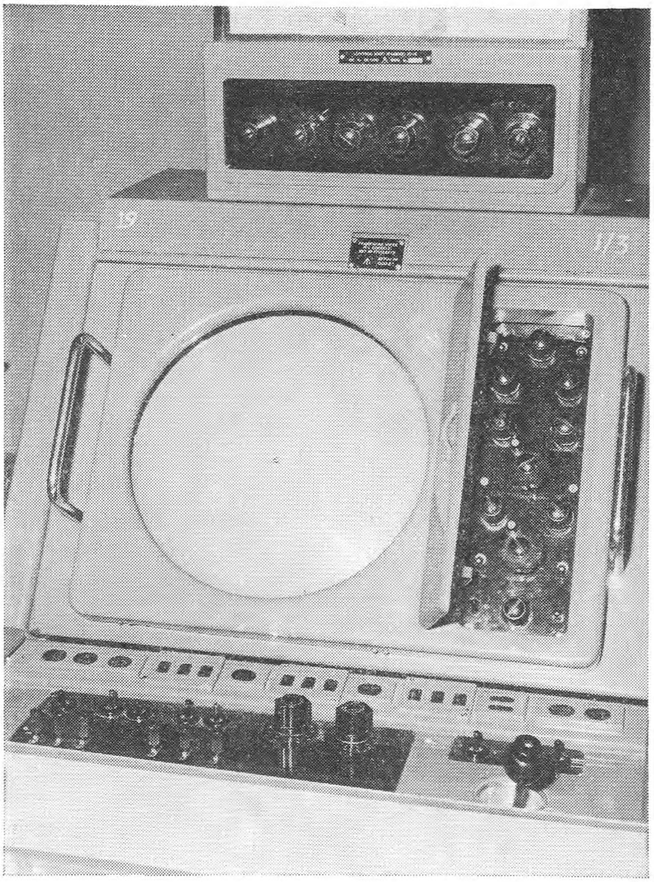


Fig 23–1 Console Type 64

c. *Azication.* This desk gives control over an associated height-finder and provides azication marker facilities.

d. *Height-Finding.* The PPI presentation may be replaced by a height/range display to enable heights to be obtained using an associated nodding height finder.

All controls used by the operator can be illuminated for ease of adjustment in the dark.

Operational Features

2302. The main operational features common to all Consoles 64 used as PPIs are:

a. *Selection of Radar Information.* The operator can select for display the information (radar signals, scan rotation, *etc*) from any of the azimuth-search radars on a site; the radars need not work at the same PRF or be synchronized in rotation.

b. *Range Timebase.* The duration of the normal range timebase supplies from the radar office at 250 pps corresponds to 240 nm, while that of the long-range timebase at 250 pps is 320 nm but in the latter case the first 40 nm is blank. The full timebase sweep is rarely seen on the display, only part of the scanned area being selected by trace expansion and off-centring. Those parts of the trace that go off the screen are automatically blanked out.

c. *Trace Expansion.* There are four degrees of trace expansion corresponding to screen diameters of 320, 240, 160, and 80 nm, which, if the scan origin is at the screen centre, give maximum displayed ranges of 160, 120, 80 and 40 nm.

d. *Off-Centring.* The scan origin may be displaced to any point in a square centred on the screen centre, whose sides are the equivalent of 400 nm in length. This enables any part of the scanned area to be displayed at any degree of expansion.

e. *Range Markers.* Range markers can be displayed as range rings superimposed on the radar signals at any required intensity. There is a choice between 5-mile and 10-mile markers, and the 40-mile markers are emphasized for ease in reading.

f. *Video Map.* As an alternative to range markers, the video map output can be superimposed on the radar signals at any required intensity on a PPI display giving a reference grid independent of trace expansion and off-centring. There is a choice between two maps.

h. *IFF.* The PPI console has facilities for IFF Mk 10 mode selection and challenging, and displays the IFF signals alone or together with primary radar signals.

2303. Additional facilities are provided for the RHI application and PPI application depending on the type of station at which the consoles are installed.

Control Panel

2304. The control panel is to the right hand of the CRT face, and carries controls that may need occasional adjustments by the operator (as opposed to those on the control desk, which may be in continual use). These controls are:

a. *Anti-Clutter.* This switch enables the video gain to be reduced over about the first twenty miles of the trace, so as to cut out the obscuring effect of ground clutter.

b. *Radar Signals.* This is the radar video gain control.

c. *Video Map.* This control varies the brightness of the video map when it is displayed on the PPI.

d. *Strobe Markers.* This control varies the brightness of the azication marker and range strobe (or the ring strobe) when they are displayed on the PPI.

e. *Range Strobe.* This control varies the brightness of the range strobe relative to the other markers.

f. *IFF.* This is a video gain control for the IFF signals.

g. *Range Rings.* This control varies the brightness of the range rings (range markers) when they are displayed on the PPI.

h. *Off-Centre Controls.* These two controls shift the scan origin in relation to the screen centre—OFF CENTRE VERTICAL in northings, and OFF CENTRE HORIZONTAL in eastings. Each can give up to ±200 nm in shift.

i. *Range.* This switch has four positions marked 80, 160, 240 and 320 miles, corresponding to the four degrees of trace expansion.

j. *Screen and Dial Lights.* These two switches control the edge lighting of the mask over the CRT and of the control panel.

k. *HT On.* This switch controls the bringing on of power supplies, and is normally left on, the main switch on the control desk being used to turn the console on and off.

l. *HT Reset.* This button is connected with the safety circuit of the console: if for any reason this circuit operates and automatically switches off the console, power may be restored by pressing the reset button; but the console will again switch itself off when the button is released, unless the fault has cleared itself. The reset button should rarely be used by the operator, and must never be held down for longer than five seconds.

Control Desks

2305. There are several different control desks for the various applications of the console, all built on the same framework and clipping on to the front of the console in the same way. They all carry the following fundamental controls:

a. *Main Switch.* This switch is marked ON, and is the main power switch for the console. Associated with it are two indicator lamps, a red (valve heater supplies) and a green (HT). The red lamp should light at once when the console is switched on, and the green lamp should light within a minute of this to indicate that the console is ready for use.

b. *Radar Head.* This switch has nine or more positions for selecting information from the various search radar receivers. More than one position may be allotted to a given radar; *eg* Type 80 linear and logarithmic signals on different positions. A special position is used to bring the long-range timebase into use (with Type 80 signals) on some reporting displays where intertrace markers are not needed.

c. *Video Map/Range Rings.* A change-over key marked VM–RR offers a choice of video map or range rings on the display; the centre position of the key is neutral, giving no calibration of either sort. Beside this key is one marked FINE-COARSE; this offers the choice between 5-mile and 10-mile range rings, or between two video maps, displaying different information.

d. *IFF.* There are at least two three-position IFF keys on most PPI consoles; one with positions marked RADAR ONLY, IFF ONLY, and RADAR + IFF; and the other with positions marked MODE 1, MODE 2, and MODE 3.

Operation

2306. The Type 64 console has many operational applications; local setting up procedures should be used for setting up the console.

2307–2309. (*Not allotted*).

CONSOLE 4476

2310. Console 4476 is a large-scale fixed-coil PPI display unit designed for use by more than one operator. It can accommodate four operators each with his communications panel, and otherwise gives facilities closely similar to those of Console 64 (except that the extent of trace expansion is less). The CRT is mounted with its 21-inch screen horizontal beneath an amber mask in the centre of an octagonal desk covered with a detachable plastic top. Round the desk top at the operating positions are four identical recessed panels, originally intended for controlling communications and inter-console marking. The rest of the controls are mounted on vertical panels facing the operators and immediately beneath the desk apron. The console is very similar in operation to Console 64. Local procedures should be used for setting up the console.

2311–2321. (*Not allotted*).

RADAR RECORDING EQUIPMENT 1497

2322. Radar Recording Equipment 1497, generally known as the radar recorder, is designed for the photographic recording and playback of a single radar video signal channel from an azimuth-search radar for display on the PPIs of static stations (and in special training installations). It does not record signals from height-finding radars, or IFF responses. Any recorder can play back a photographic record from any other recorder no matter what its location, but in using records from other sites it is important to make sure that the display calibration (video map, *etc*) refers to the correct origin.

2323. When recording, the trainer takes the required video signals from the radar office amplifiers (or Head and PRF unit), synchronizing pulses from the master trigger rack, and a selsyn rotation drive (with automatic-aligning signals) from the chosen radar. A linear time-base is used on a 3½-inch recording CRT, either 120 or 240 nm in range, and the video signals are applied (after limiting) as intensity-modulation to this CRT in such a way that the noise is not shown. The trace is photographed through a lens onto a special 35 mm cine film, which is moved past the lens assembly at a rate of three inches per aerial rotation (*ie* 1 ft/min at 4 rev/min) by a motor coupled to the aerial's selsyn drive. A North marker, showing as a line across the film when the aerial passes through North, is recorded at the beginning to establish the orientation. Timing pips from a clock are recorded on the edge of the film at two-second intervals. The film spool contains 400 feet of film, which is enough for about six hours running at 4 rev/min. The setting-up of the CRT brilliance is of critical importance, and a senstitive photometer is provided for this; a microscope attachment is also included for focusing. Video map signals can be recorded on the film together with radar signals if required, at any ratio of intensity, but they are then irremovable by the PPI operator (which is unrealistic).

2324. The processing of the high-contrast film has to be very carefully controlled, but once it is complete any number of positives may be printed, and kept as permanent records to be played back as often as wished. On play back the trainer can run by itself, as required for a station with no radars operating, generating its own trigger pulses and rotation drive to rotating coil consoles; or it may accept both of these from outside when it has to fit into an operational station. The output from the photo-electric cell, which is the played-back radar video without noise, is amplified and also mixed with a suitable proportion of artificially generated noise. The two-second time markers are read off the film by a combination of lamp and photo-electric cell, and made to work a counter; another counter beside this is driven directly by two-second pulses from the clock, and the readings of the two can be visually compared by an operator to keep a check on the accuracy of playback timing.

2325. A patching rack allows great flexibility in the application of the trainers, but there are some limitations. First of all, it is essential for the control trainer to be synchronized in rotation with the source of its background display, hence the control trainer can be used with recorded signals only if the recorder takes a rotation drive from an aerial head or is patched through on a radar head channel. Also, the control trainer can have only one external video input (that is mixed in with the synthetic signals as background), and so cannot be patched into two signal channels from different radar receivers. Substitution of recorded for raw radar signals by the switch units of the trainer-patching rack does not affect the time-bases and other information supplied to the consoles; hence it is essential that the recorder should receive a rotation drive either from the radar head for which it is substituted, or a least from one rotating in synchronism. This also means that one recorder cannot be patched in at once to signal channels from two radars not rotating in synchronism.

MULLARD TRAINER 2292/3

Introduction

2326. Trainer 2292 or 2293 is a control trainer designed to generate synthetic controlled tracks for display on the PPI consoles of static radar stations (and also in special training installations). It has facilities for the generation of synthetic IFF responses and jamming signals, but it does not give signals for height-range displays.

2327. The basic unit of the trainer consists of two racks, generating four tracks, and associated with four pilot control units (located in a training room). The trainer may be extended to give eight or twelve tracks by the addition of

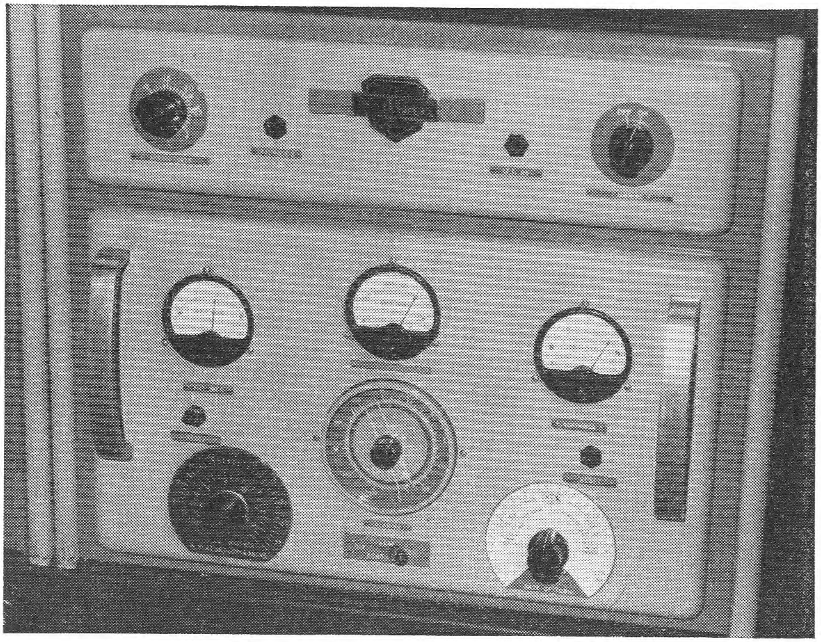


Fig 23–2 Mullard Pilot Control Unit

one or two racks and four or eight pilot control units. The control trainer is normally operated with a radar or radar recorder to give a back-ground display (by themselves the synthetic signals do not look convincing) and the chosen background video signals are fed into the trainer to be mixed with synthetic tracks.

Operational Features

2328. Each track can simulate an aeroplane moving at any speed between 100 and 1,500 knots, making any required turns at rates up to $1\frac{1}{2}$ in steps of $\frac{1}{8}$, for a period of flight up to six hours. A steady wind at any speed up to 150 knots in any direction can be imposed on all the tracks; the wind cannot vary from place to place or be applied to individual tracks only. No altitude is attached to the tracks.

2329. Each track has the following characteristics:

a. Its range from the simulated radar can vary between three and 200 nm.

b. Beamwidth can be preset to any value between $\frac{1}{2}$° and 15° (the signal gating can be adjusted so that the edges of the response tail off realistically).

c. Pulse width is between 2 μs and 10 μs.

d. Accuracy (with no simulated wind) as follows:

(1) Aircraft speed set to ±5%, held to ±3%.

(2) Heading set to ±4°, held to ±2°.

(3) Change of aircraft speed set to ±10 knots.

(4) Change of heading set within ±2°.

2330. The trainer supplies synthetic video signals mixed with a background from a radar or recorder. It is normally run in conjunction with a radar or recorder, from which it takes an aerial rotation drive, also deriving pulses from the master trigger rack; but for testing it can be run independently of other sources of signals, generating its own trigger pulses (at 250 or 500 pps), 10-mile range markers, and aerial rotation drive (variable between 3 and 12 rev/min).

Controls

2331. The main operational controls of the trainer are mounted on the Pilot Control Unit 4646 (*see* Fig 23-2). One such unit is provided for each synthetic track, to be manipulated by an operator on instructions over the telephone (simulating R/T) from a controller. The unit has the following controls and indicators:

a. *Aircraft Speed*. A calibrated control that varies the TAS between 100 and 1,500 knots.

b. *Rate of Turn*. A control that varies the rate of change of heading from zero to rate $1\frac{1}{2}$ in steps of $\frac{1}{8}$, both to right and to left. The times for a complete 360° turn (subject to ±10 per cent setting error) are:

Rate of Turn	*Time through* 360° (*sec*)
$\frac{1}{4}$	480
$\frac{1}{2}$	240
1	120
$1\frac{1}{2}$	80

c. *Heading*. A knob with parallel bars used to indicate the heading attained by operation of the rate-of-turn control. The compass cursor calibrated in 2° steps over the full range of 360°, is used as a track control and for initial setting.

d. *Northings and Eastings*. Two meters graduated from −200 to +200 data miles in steps of 10 data miles, showing the instantaneous ground position of the track in northings and eastings relative to some fixed point (usually the location of the simulated radar).

e. *Ground Range*. A meter graduated from 0 to 200 data miles in steps of 5 data miles, showing the instantaneous ground range of the track from the simulated radar.

f. *Reset*. Two switches that enable the operator to reset the track position quickly to any point within the operational 200-mile radius. When the northing switch is pressed, the track is rapidly driven up to +200 data miles in northings, then disappears, reappears at −200 data miles and again drives north, this sequence being repeated until the switch is released. The operator should let go the switch when the required position has been reached (as indicated on the northing meter). The easting reset switch operates similarly.

g. *Echo Pulse*. A three-position switch affecting the amplitude of the synthetic signals and giving either strong paints, weak paints, or no paints at all on the display. It can be used (in conjunction with the ground range meter) to simulate roughly the cover of a control radar.

2332. There is also, in one of the trainer racks, a Control Unit 4655 that has the following two controls affecting all tracks:

a. *Wind Speed*. A control varying the speed of the simulated wind applied to the tracks. It is calibrated in steps of 10 knots up to 150 knots.

b. *Wind Direction*. A control varying the heading of the simulated wind. It is calibrated in steps of 10°, over the full 360° range. This unit also has a full set of track controls for use in testing the trainer.

2333-2339. (*Not allotted*).

GL 161 RADAR DISPLAY CONSOLES

Introduction

2340. Three types of console are in use with GL 161 System 2 at No 1 Air Control Centre:

a. 21 in labelled radar display (LRD).

b. 12 in labelled radar display.

c. 12 in electronic data display (EDD).

~~In addition, System 6 at a radar station overseas has height range indication consoles (HRI) for use with the HF 200 height finders~~. Each type of display uses a separate cathode ray tube. An operating position consists of a 12 in LRD with its associated EDD if the function of that position requires it. Every console carries the necessary control panels to carry out its functions. However, slight variations do exist in the controls on these panels between different LRDs and the different Systems.

Labelled Radar Display

2341. The labelled radar display is a normal PPI tube which also shows computer symbology to display:

a. *Track Numbers*. Every radar response which is being tracked by the system is allocated a two-figure track number by the computer. The track number is displayed over the radar response.

b. *Identification*. The selected identity for an aircraft is shown as a letter which appears in front of the track number.

c. *System Heights*. The aircraft height is shown as a two digit number alternately with the identification letter and track number.

d. *Crash Heights*. Crash heights are discrete heights obtained on any aircraft, as distinct from system heights measured as a function of the tracking programme. Crash heights are displayed concurrently with the identification letter and track number and are shown as three digit numbers.

e. *Rolling Ball Markers* (*RBM*). Rolling ball markers are displayed as a circle of constant size regardless of the range scale selected.

f. *Airfield Markers*. The four airfields programmed into the system are shown as diamonds which appear on fighter interception LRDs only.

g. *Interception Data*. The Tactical Offset Point (TOP) for any selected interception is shown as a square, with the predicted kill point as a cross, on fighter interception LRDs only.

Console Control Panels

2342. The 12 in LRD console controls and the HRI controls are each housed in two control panels, at the side of the viewing unit and in a box across the top of the console. The 21 in LRD console controls are mounted on similar panels remote from, yet convenient to, the console. The controls for the EDD are fitted directly on the facia of the viewing unit.

2343. **Console Controls — Side Panel — 21 in LRD, 12 in LRD and HRI.** Fig. ~~23-6~~ 23-3 shows the layout of the controls on the side panel of the viewing unit of the 21 in console. The function of the various controls is as follows:

a. *Focus* — controls the focus of the CRT.

b. *Panel Lights* — controls the brilliance of the lights on the control panel.

c. *Lights Plotting* — controls the brilliance of the lights on the horizontal plotting surface over and around the tube face.

d. *Video* 1 — controls the gain of video channel 1.

e. *Video* 2 — controls the gain of video channel 2.

f. *Auxiliary Video* — controls the gain of the video map, the 10° angle markers and the SIF gate.

g. *IFF* — controls the gain of the IFF.

h. 10*m* — controls the gain of the 10 mile range rings.

j. 50*m* — controls the gain of the 50 mile range rings.

k. *Radar Brilliance* — controls the brilliance of the radar time base.

l. *Limiter* — this control is designed to reduce clutter when operating at short range by cutting down the overall signal strength of responses.

The two rows of controls on the lower panel are push button. The top row of these switches set the console to "Off", "Standby" and "On" respectively, while the lower buttons select ranges of 32, 64, 128 or 256 miles as required.

2344. The side panels for the 12 in LRD and the HRI vary in the following respects:

a. The top four rotary switches on the 12 in LRD control the:

(1) Panel lights.

(2) Focus.

(3) X Centre — to off-centre the trace in the horizontal direction.

(4) Y Centre — to off-centre the trace in the vertical direction.

b. The top eight rotary switches on the HRI control the:

(1) Lights.

(2) Focus.

(3) X Centre.

(4) Y Centre.

(5) Lin — to control the gain of the linear HF 200 video.

(6) Log — to control the gain of the logarithmic HF 200 video.

(7) Elevation marks — to control the gain of the elevation marks.

(8) Video 4 — to control the gain of video channel 4 (this channel is not use at present).

Figs ~~23-7~~ 23-4 and ~~23-8~~ 23-5 show the varying switches on the 12 in LRD and the HRI respectively.

2345. **System 2 Radar Controls — Upper Panel.** ~~The upper Radar Control Panel also differs between System 2, System 6~~ and the HRI consoles in System 6. Fig ~~23-9~~ 23-6 shows the layout of the controls on the radar control panel associated with the LRD consoles in System 2. The function of the various controls is as follows:

a. *Channel Selectors* 1 *and* 2 — these are push-button controls which are used to select which channel of display drive equipment is used.

b. *Video Selector* — this is a seven-position rotary switch used to select the type of video required. The video selected is displayed on channels 1 and 2. The videos which may be selected are as follows:

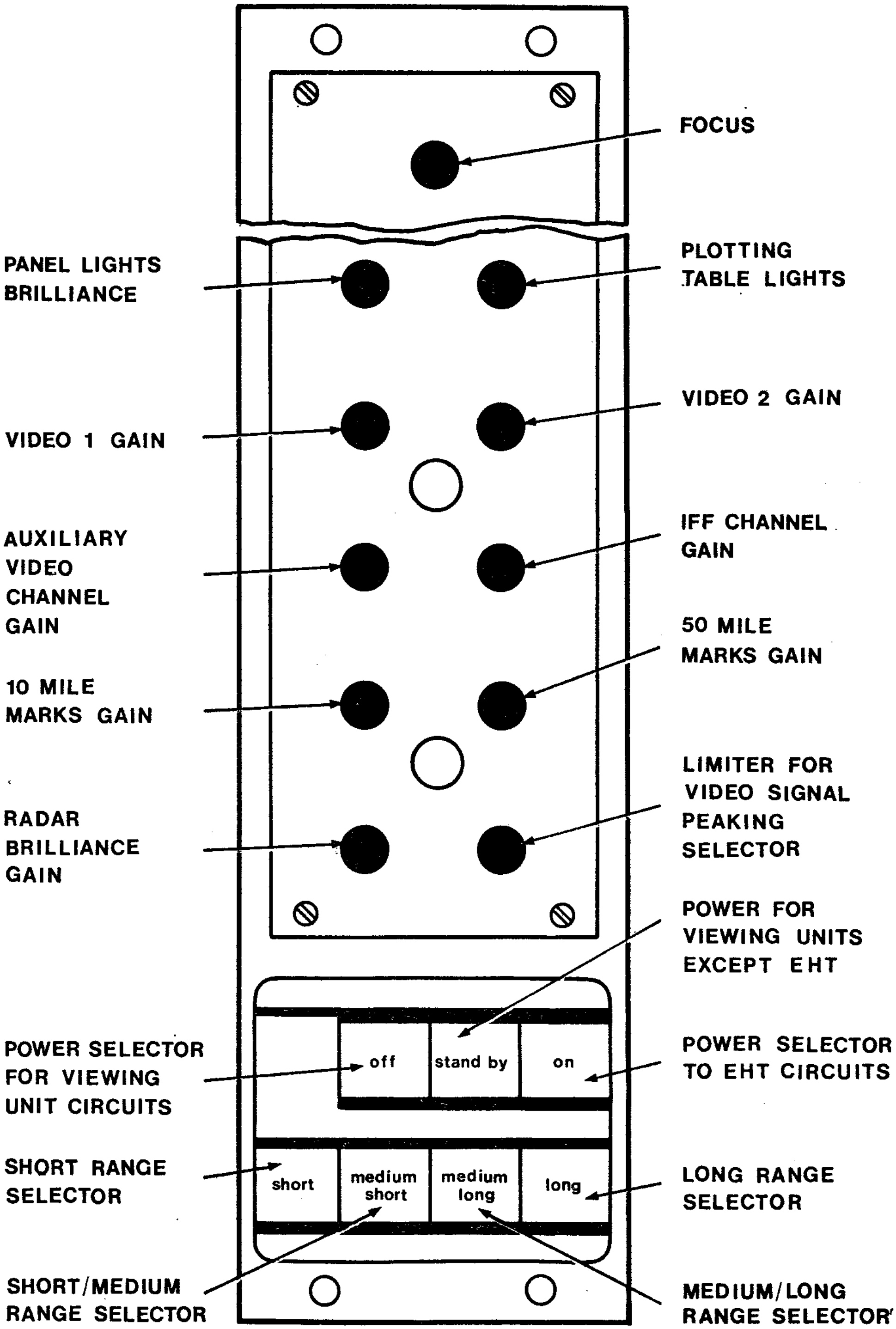
(1) *VS* — Vertical and slant beam video from the TPS–34 radar.

(2) *V+S* — Vertical and slant video additively mixed.

(3) *V* — Vertical video only, but brief slant may be obtained by pressing the BRIEF SLANT push-button.

(4) *S* — Slant video only.

(5) Various anti-jamming circuits may be selected.



AL 8 Fig ~~23-6~~ 23-3 21 in Viewing Unit Control Panel Type 11211A

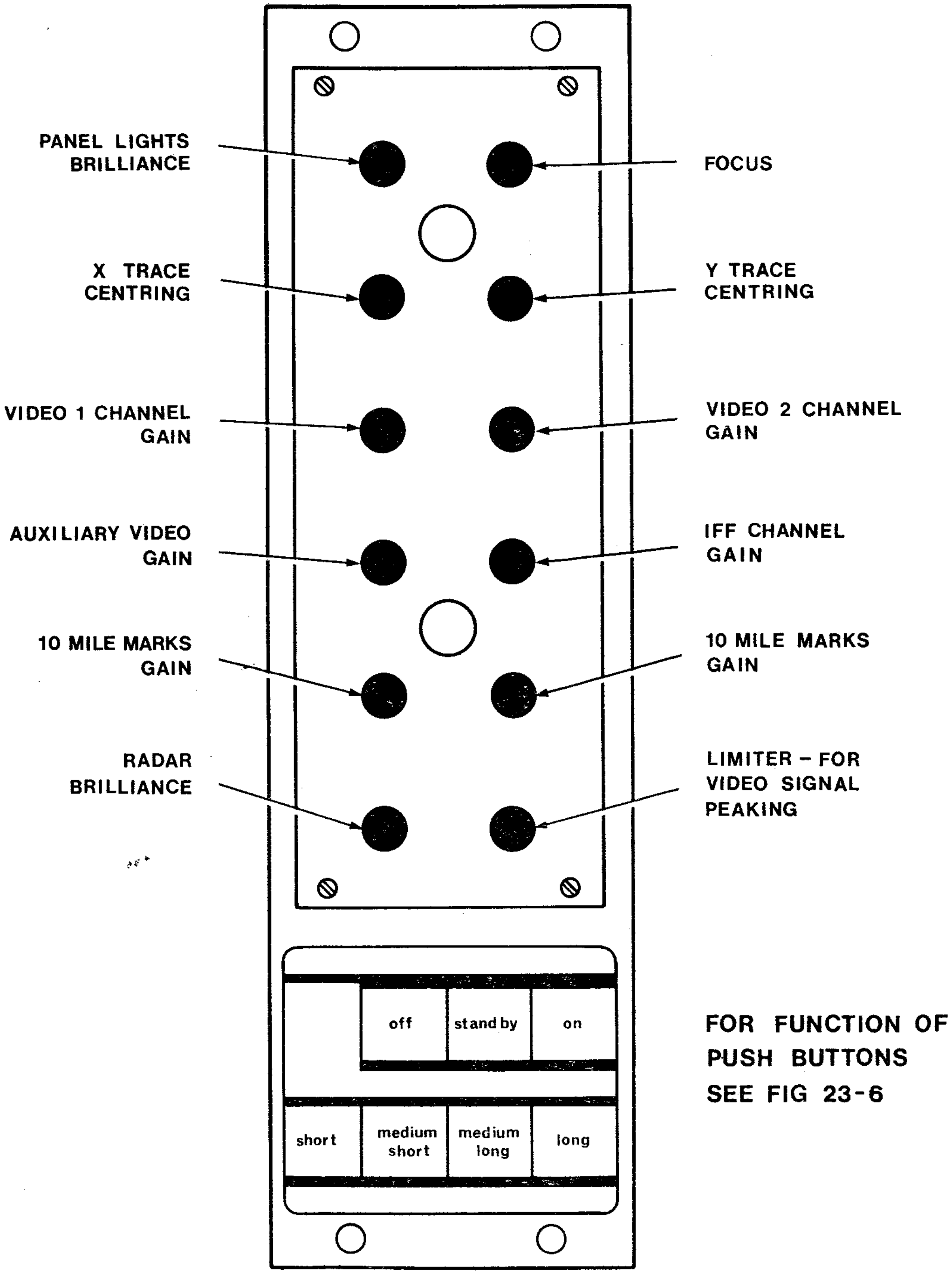


Fig ~~23-7~~ 23-4 12 in LRD Viewing Unit Control Panel

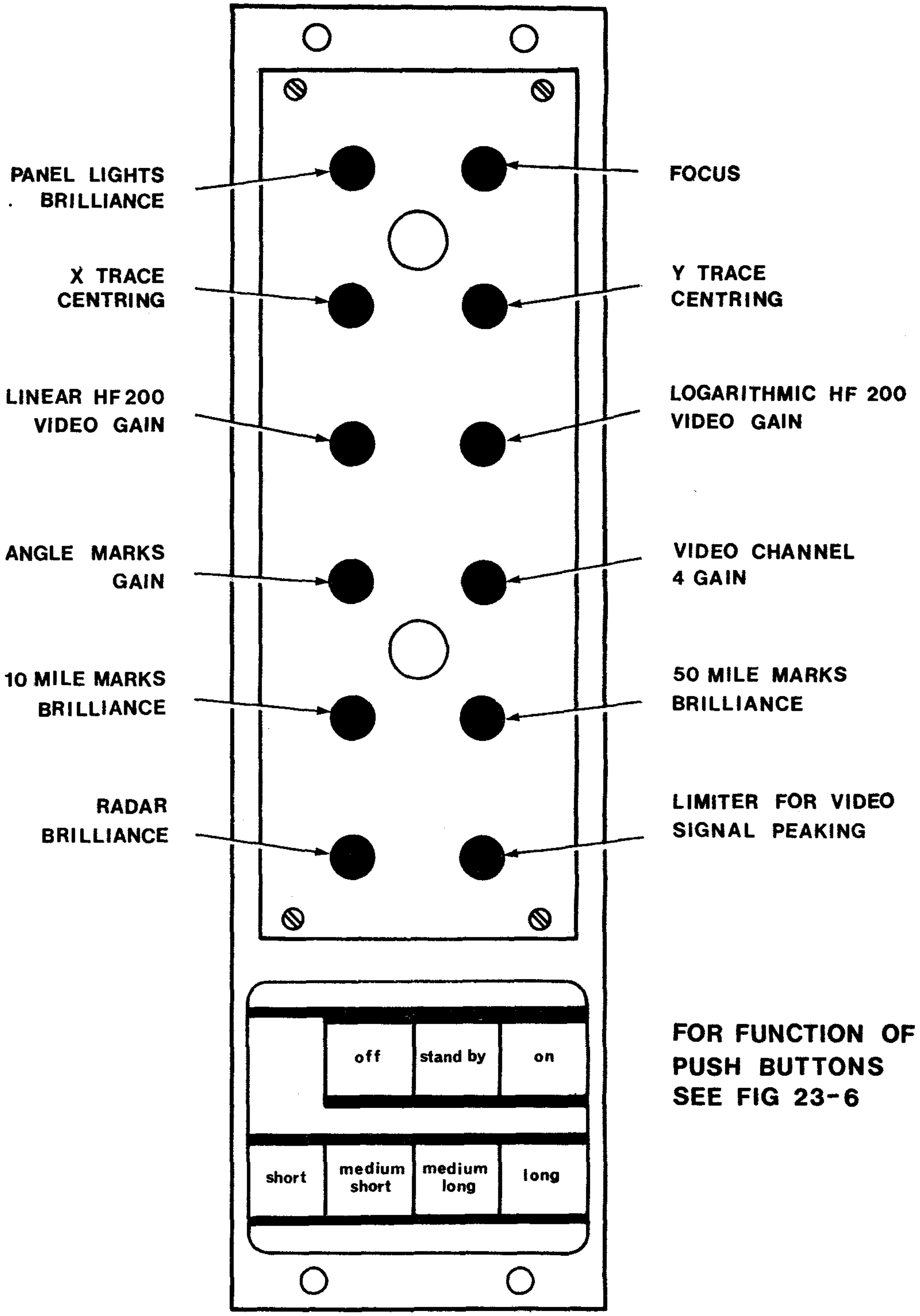


Fig ~~23-8~~ 23-5 Heightfinders Viewing Unit Control Panel
23-~~16~~ 12 AL8.

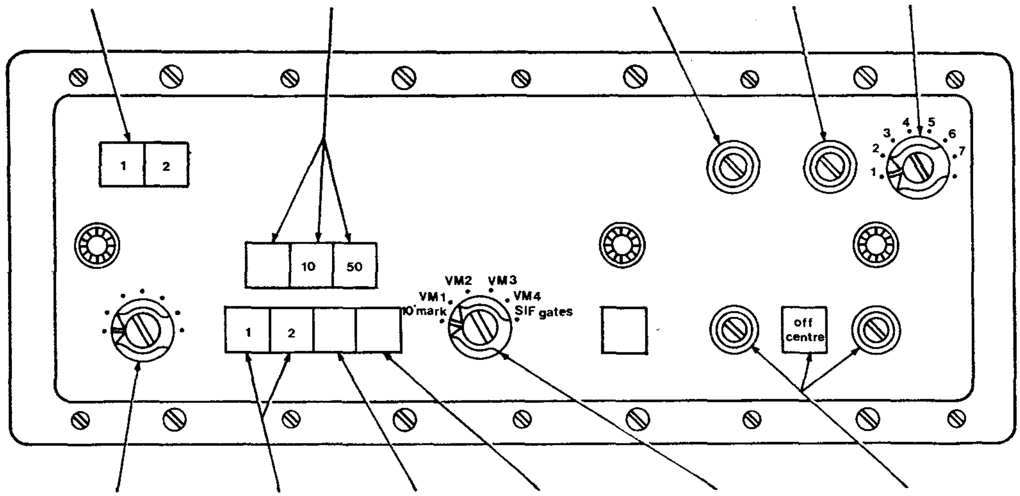


Fig 23–6 LRD Radar Control Panel (System 2)

c. *Video* 1 — this is a push-button which, when depressed, switches on the No 1 video channel.

d. *Video* 2 — similar to that for Video 1.

e. *IFF* — as above but for IFF video.

f. *Aux Video* — as above but for the auxiliary video.

g. *Aux Video Selector* — this is a six-position rotary switch which selects the type of video fed to the auxiliary channel. Its various positions are as follows:

(1) 10 *Marks* — this provides 10° angle marks on the CRT.

(2) *VM* 1, 2, 3, 4 — these four positions give a choice of four video map presentations.

(3) *SIF Gate* — this displays the SIF gate when an active decode is selected.

h. *Range, Marks Off,* 10*m*, 50*m* — these three push-buttons are used to switch off all range rings, or to select either 10 mile or 50 mile marks.

j. *Symbol Brilliance* — this controls the brilliance of the RBM on the CRT.

k. *Character Brilliance* — this controls the brilliance of the characters on the CRT.

l. *Off-Centre,* X and Y — the off-centre control is a push-button switch which, when operated, allows the picture to be off-centred by use of the associated X and Y rotary controls.

m. *Panel Lights* — this is an eight position dimmer switch which controls the degree o illumination of the panel lights.

2346. (*Not allotted*).

2347. **HRI Radar Controls — Upper Panel.** The layout of the controls on the Height-Range Indicator control panel is shown at Fig 23–7. Apart from the range mark switches which perform the function as already described, the

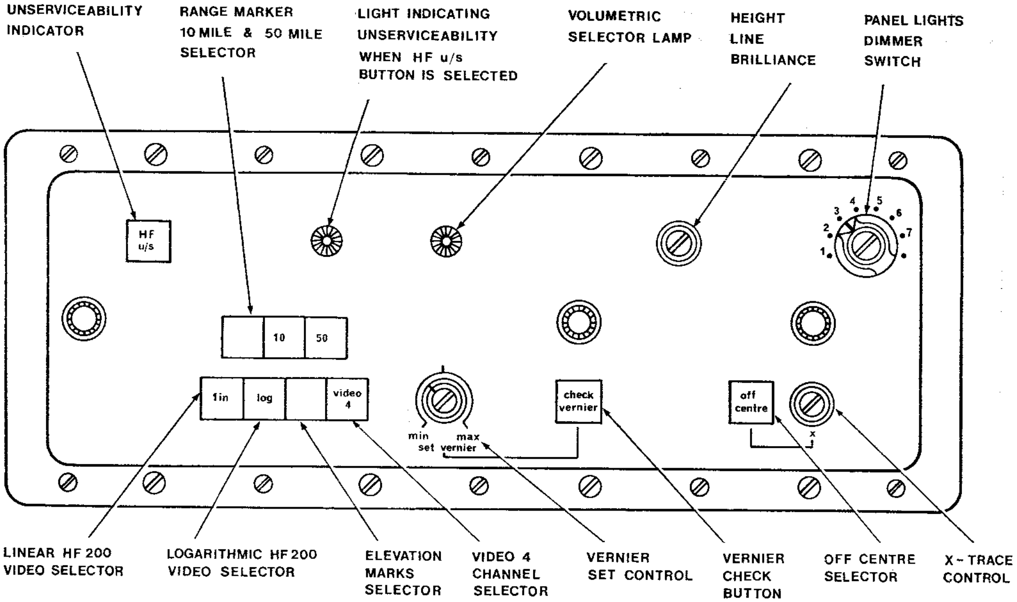


Fig 23–7 Height-finders Radar Control Panel (System 2)

functions of the other switches on the panel are as follows:

a. *HF U/S* — a push-button switch by means of which the operator indicates to the data handling system that his heightfinder radar is unserviceable. This prevents the data handling system from sending further azication data to that heightfinder.

b. *Unserviceable* — this lamp lights when the HF U/S switch is depressed.

c. *Line Brilliance* — controls the brilliance of the height line on the display.

d. *Panel Lights* — an eight-position rotary switch for controlling the intensity of the panel lights.

c. *Range Marks* — Off, 10m, 50m.

f. *Vid* 1 — a push-button switch which, when depressed, switches on the No 1 video channel.

g. *Video Selector* — a seven-position rotary switch which selects the type of video fed to the No. 1 video channel. The seven positions are as follows:

(1) *Off*.

(2) *Lin* — to select the linear video.

(3) *Log* — to select the logarithmic video.

(4) *IAGC* — to select instantaneous automatic gain control video.

(5) *DF* — to select Dickie Fix video.

(6) *QDF* — to select quantized Dickie Fix video.

(7) *CCM* — to select counter countermeasure video.

h. *Check Vernier* — a push-button switch used to check the accuracy of the zero of the height line. Depressing the button sets the height line to its zero position.

j. *Set Vernier* — a control to adjust the height line to coincide with the zero angle mark.

k. *Off Centre and X* — the off centre push-button switch, when depressed, allows the picture to be off centred by the X control.

Keyboard Units

2348. The keyboard units enable the console operator to activate a data processing programme associated with the data handling system. By pressing a certain sequence of keys the operator is able to send information to, or demand information from, the data handling system. A standard keyboard unit is fitted to the front of all operational consoles though certain keys on the keyboard may be "blanked out" where they are not required for that particular position. There are ten numeral keys, twenty function keys (*eg* "Identify", "Transfer", "Fuel", *etc*, mounted in five rows of four), an "Enter" and "Erase" key, an "Error" lamp and a six position light control switch.

2349. Further details may be found in the following documents:

a. GL 161 System 2 CD 115B-0503-1A.

~~b. GL 161 System 6 CD 115B-0503-1B.~~

2350-2354. (*Not allotted*).

SLEWC RADAR DISPLAY CONSOLES

Introduction

2355. The basic SLEWC console unit contains a labelled radar display (LRD), an SIF panel, a communications panel and a horizontal desk panel (*see* Fig 23-13). The desk panel contains the PPI controls, a keyboard and a Rolling Ball. Various equipment is added to the basic unit to give the facilities required at a specific position. The console provides for the presentation of both raw and synthetic radar information. The display unit utilizes a 12-inch diameter CRT and is fully transistorized. The operator positions equipped with this console unit are as follows:

a. Reporting.

b. Manual Interception Control.

c. ADP Interception Control and SAM Control.

d. Executives (MC, CC(F), CC(S), DC).

Except for the utilization of a 16-inch diameter CRT the consoles used by the Fighter Marshal are similar in construction to those here described and the functions of the controls apply equally.

Labelled Radar Display

2356. The main operational features common to all SLEWC consoles are located on the facia of the radar display and on the horizontal desk panel. The front facing of the LRD carries the following controls:

a. A push button switch to control mains supply to the console.

b. A push button switch to select centre blanking of the CRT trace for anti-clutter purposes.

c. Finger-tip control discs situated at the four corners of the screen, to vary the intensity of the:

(1) Radar video.

(2) Range marks/Video map, as selected.

(3) Secondary radar trace.

(4) Displayed computer symbology.

(5) Console screen edge lighting.

The horizontal desk panel carries the following controls:

d. *Selection of Radar Information*. By the use of the Head Select switch the operator can select for display the information from

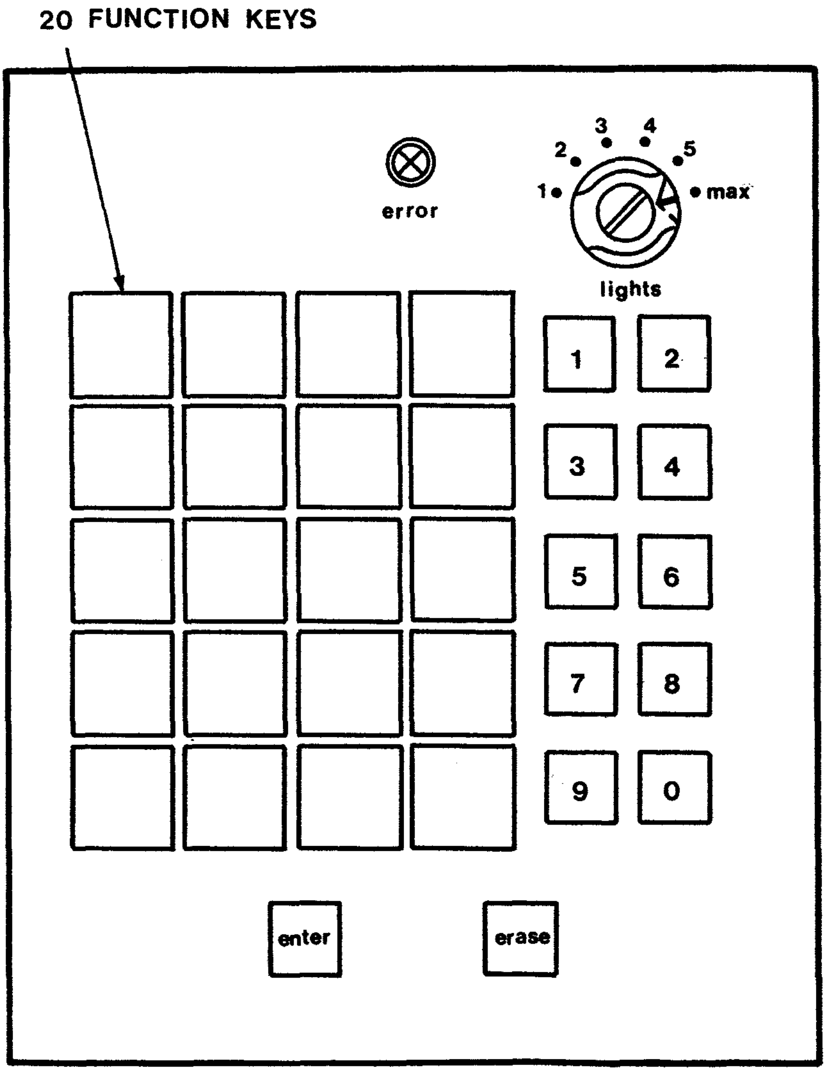


Fig ~~23-12~~ 23-8 Keyboard Unit Layout

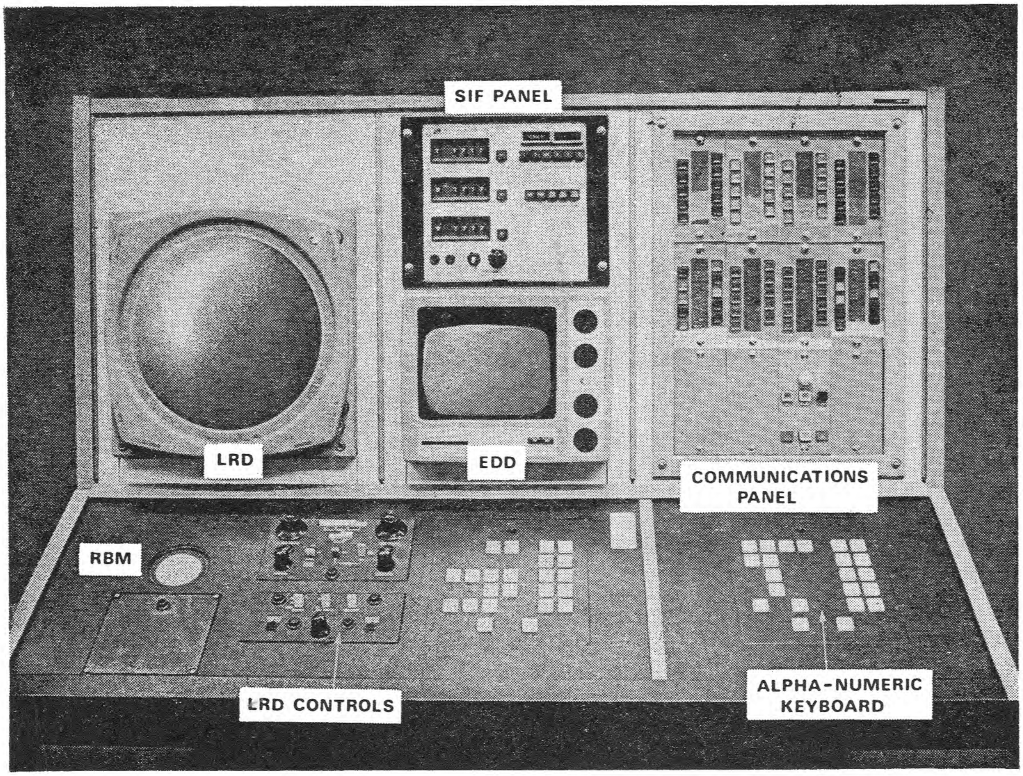


Fig 23-13 SLEWC Console Unit

up to six individual radar presentations, as available.

e. *Range Selection.* By the use of the Range control the operator can select for display ranges of 40, 80, 120 and 160 data miles per tube radius, giving a maximum range with off-centre of 320 data miles. However, computer limitations prevent modified rate aided tracking being used in excess of 256 data miles.

f. *Radar/Simulator Selection.* A three-position switch allows the following selections to be made:

(1) Radar video only.

(2) Radar plus simulated video.

(3) Simulated video only.

A further two-position switch allows the video to be switched off without interrupting the mains supply to the console. The CC(F) 1 has a further facility in that the simulated IFF/SIF responses on all the displays in the system can be inhibited. This enables any IFF/SIF responses remaining to be positively identified as "live".

g. *Off Centring.* By selection of a push button the origin of the radar scan can be recentred to the centre of the CRT, or off-centred by the use of the X and Y controls.

h. *Range Marks.* A Fine/Off/Coarse switch allows the display of range rings at 5 or 10 mile intervals with emphasis on each 40 mile ring, or range rings off altogether.

Exercise Preparation

2369. The preparation of an exercise is the most difficult and time consuming stage of NESS simulation. All the environmental data has to be prepared, checked and punched on to paper tape. Then the flight plans for all the background tracks must be calculated and plotted. All velocity and height changes must conform to the specified performance data or else they will be rejected by the computer. When all the pre-planning is complete, the tracks are punched on to paper-tape and checked in the computer. The exercise is then ready for running.

Exercise Running

2370. When required, the paper-tape outputs from the preparation state are entered into the computer and the exercise started. Background tracks, jamming, SSR returns, *etc* will automatically appear at the times and positions specified during the exercise preparation. When interceptions are called for, simulated interceptors are "scrambled", fly out using normal ATC procedures, and are then controlled by the fighter controller and manoeuvred by a simulator "pilot" (voice console operator (VCO)) who has his own keyboard and tabular display (maximum of four interceptors per VCO). AI radar contacts, target identity, aircraft emergencies, combat results, *etc*, can be preprogrammed and are displayed to the VCO for relaying to the controller. Recovery procedures to any of four specified airfields can be computer controlled, and random emergencies and airborne malfunctions can be injected by the exercise "controller" who also has his own keyboard and tabular display.

Exercise Recording and Analysis

2371. When completed, (the maximum running time of an average exercise is approximately 3 hours) it is possible to re-run the exercise showing, in addition to the background tracks, the flight paths taken by the interceptors. This re-run can either be at normal speed or as an accelerated version of the original exercise. During an exercise a mass of information is output by the computer which can later be analysed for evaluation purposes. This information covers such areas as tracking efficiency, operator reaction times, operator loading, interception profile requests, *etc*.

2372–2375. (*Not allotted*).

AIR DEFENCE DATA CENTRE DISPLAYS

Introduction

2376. Three types of display are in use at the ADDC:

a. Marked Radar Display (MRD).

b. Labelled Plan Display (LPD).

c. Electronic Data Display (EDD).

Marked Radar Display

2377. The MRD is a plan position indicator displaying raw radar, video maps and certain marking facilities. It uses a 12″ CRT with an afterglow of 1·5 minutes set into a standard console:

a. *Radar Heads.* Upon selection, information from any one of up to 13 search heads may be displayed at any one time.

b. *Video Maps.* Any combination of 4 video maps, with or without 10 data mile range rings, can be selected.

c. *Video Selection.* For any radar either 2 or 4 video selections are available, according to type as follows:

(1) Radars type 85 video 1–4.

(2) Radar type 84, 80 and civil radars video 1–2.

d. *Range Rings.* Ten data mile range rings with a bright-up at every 40 data miles.

e. *Off Centring.* The MRD can be off centred to any one of 4096 off centre points; these points are at the bottom left hand corners of each eight mile square of graticule.

f. *Range Expansion.* The following range expansions are available:

(1) 64 data miles diameter.

(2) 128 data miles diameter.

(3) 160 data miles diameter.

(4) 320 data miles diameter.

2378. **Marked Radar Display Marks.** System generated marks displayed on the MRD are divided into 2 types: Fast marks and Slow marks. Fast marks are generated by the central computer system eight times a second and appear to be a permanent display. The following are fast marks:

a. *Rolling Ball Mark (RBM).* This appears on the MRD as a ring and is used by the:

(1) Operator to communicate a plan position to the Radar Data Processing System (RDPS).

(2) RDPS to communicate a predicted plan position to the operator.

b. *Call Down Marks:*

(1) *Track Plot.* A dot indicating the latest stored position of a UK extracted track.

(2) *Early Warning Plot.* A dot indicating the latest stored position of a called down EW track.

(3) *Zero Velocity Plot.* A dot indicating a stationary position of operational interest.

(4) *Flight Plan.* A pointer indicating the proposed route of an aircraft according to its in system flight plan.

2379. The following are Slow marks and are generated once every four seconds and appear as flashing marks:

a. *Initiator's Mark.* Appears as a dot and marks the last plotted position of an 'in system' track.

b. *Handover Mark.* A dot modified with a South pointing tail indicating a track available for takeover.

c. *Retention Mark.* A dot modified with an East pointing tail and indicates a track not to be cancelled.

The Passive Detection Mark is a small system generated circle indicating on each trace sweep the plan position of a jamming source.

Labelled Plan Display

2380. The LPD is a system generated electronic digital picture of all tracks in the Radar Data Processing System (RDPS). It uses a 12″ CRT set into a standard console; data displayed is updated every five seconds:

a. *Playout Rate.* The playout rates are as follows:

(1) Track position data is played out eight times a second; however, in the event of one control computer failing it is reduced to four times a second.

(2) A complete set of digital maps is played out every 2·018 seconds, but only those selected by the operator are displayed.

b. *Range Selection.* The following ranges scales are available:

(1) 800 data miles diameter.

(2) 400 data miles diameter.

(3) 320 data miles diameter.

(4) 160 data miles diameter.

c. *Off Centring.* Any one of 100 standard off centring points may be selected.

d. *Digital Maps.* There are eight digital maps available, from which an operator may select a combination of any two for simultaneous display. Maps are played out individually in the sequence one to 8 giving a 'wipe out' effect from north to south.

2381. **Marks.** The following marks are generated by the system for display on the LPD:

a. *Labels.* Data relevant to in system tracks can be displayed on the LPD as 'Labels'. There are four labels applicable to each track:

(1) *Label 1*: Recognition category and track reference.

(2) *Label 2*: Height information.

(3) *Label 3*: Special track interest and secondary radar.

(4) *Label 4*: Tactical information.

Each label consists of three characters, the centre of the label indicates track position. Only one label may be viewed at any one time and the label selection applies to all tracks displayed.

b. *Velocity Tails.* A tail extending back from the present track position indicating aircraft tracks and ground speed.

c. *Dots.* Tails may be suppressed and aircraft position indicated by dots.

d. *Pointers.* Pointers are displayed to indicate selected flight plan paths.

e. *Zero Velocity Plots.* ZVPs are played out on all LPDs as a label and are displayed regardless of any other display selection made.

2382. **Track Display Selection.** Tracks held 'in system' appear basically as dots with velocity tails. Subject to label and category selections, labels replace the dots:

a. *Tracks by Source.* A key facility controls the display of all tracks on the LPD:

(1) *Key Up.* Only UK extracted tracks and ZVPs are seen as labels.

(2) *Key Centre.* All tracks and ZVPs are seen as labels.

(3) *Key Down.* Only EW tracks and ZVPs are seen as labels.

This is the primary LPD selection following which additional selections may be made by recognition category and status selection.

b. *Tracks by Recognition Category.* This secondary selection, which is achieved through the alphanumeric keyboard, permits the simultaneous display of all tracks of up to three recognition categories subject to the primary (tracks by source) selection.

c. *Status Selection.* There are two key facilities for selecting the display of certain labels by 'status'. Within the limits imposed by primary and secondary selections and subject also to the restricted LPD facility, the following options are available:

(1) *Interceptors by Status:*

(a) Committed interceptors.

(b) All interceptors.

(c) Uncommitted interceptors.

(2) *HUX by Status:*

(a) Allocated HUX.

(b) All HUX.

(c) Unallocated HUX.

d. *Display Restrictions.* Operating the push key REST LPD causes the system to preset as 'labels' only those tracks called down on the associated Electronic Data Display. All other selections are reduced to 'Dot' and 'Tail'.

Electronic Data Display

2383. The Electronic Data Display (EDD), with its associated Alpha-Numeric (A/N) keyboard, is the method of communication between the operators and the Radar Data Processing System (RDPS). Information supplied by the RDPS can be displayed on the EDD, and data to be fed into the RDPS by an operator is first written on the

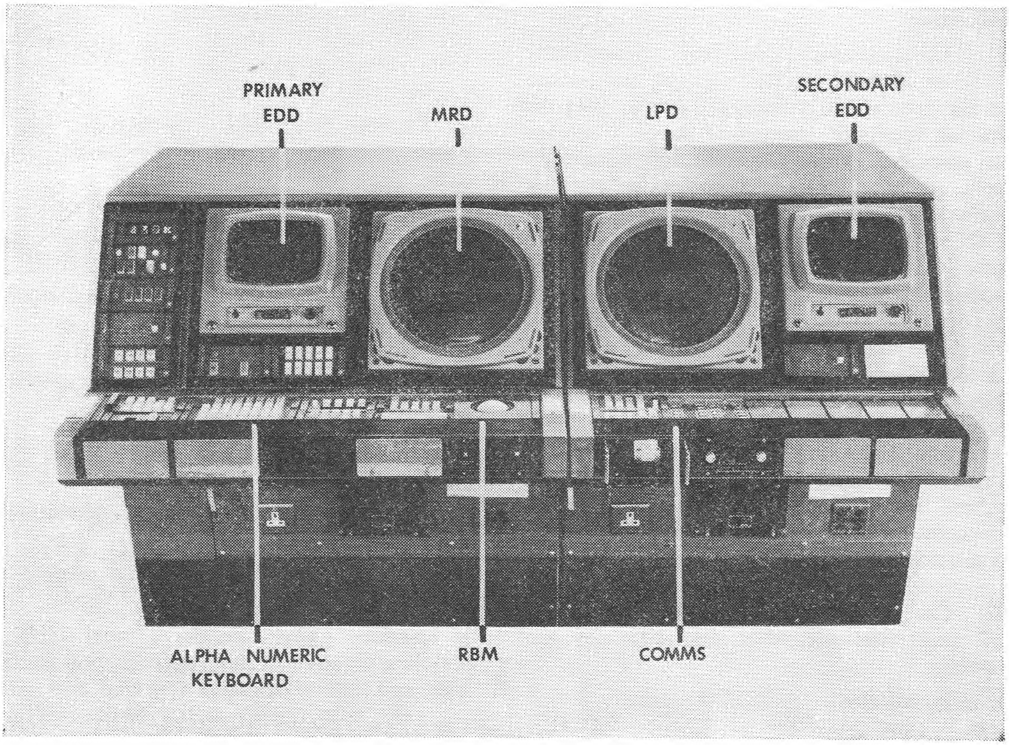


Fig 23–10 ADDC Console Suite

EDD using the A/N keyboard prior to injection.

2384. **Method of Display.** Data called down from the store is displayed on the EDD in a variety of formats under fixed headings depending upon the particular requirements of the operator.

2385. **EDD Format.** The EDD format has a total capacity of twelve rows each containing 61 character spaces. The format is divided up into two areas as follows:

a. *Operational Data Area.* This represents the upper area of the EDD (rows 1–9) and contains operational data common to all positions.

b. *Positional Information Area.* This represents the lower area of the EDD (rows 10–12) and contains data of interest only to the operational position.

2386–2390. (*Not allotted*).

THE WEST DRAYTON SIMULATOR

Introduction

2391. The simulator at West Drayton, originally called Simulator M (or SIM M) was designed to meet the operational training requirements of the Linesman/Mediator control system. Together with associated Voice Consoles and communications, it now meets the controller training requirements of the Air Defence Data Centre (ADDC); the London Air Traffic Control Centre (Military) (LATCC (MIL)), and the School of Fighter Control (S of FC). It provides very realistic radar 'pictures' and sufficient controllable and background aircraft to enable both air defence and air traffic operational procedures to be exercised at varying degrees of intensity. It can faithfully reproduce the performance and display characteristics of all RAF search radars currently in use. The simulator can, therefore, also be used for the trial and evaluation of new control procedures and techniques before they are accepted into service.

2392. The simulator is based on the Elliott 502/2 real time computer and provides the following:

a. *Control Area.* A 1024 dm square digital area is simulated from sea level to 96,000 ft in which 128 specified reference points (e.g. airway reference points, airfields, recovery points) are available and variable wind velocities may be simulated.

b. *Controllable Tracks.* For air defence a total of 64 fully controllable tracks and up to 275 predetermined background tracks can be displayed (the actual number of displayed background tracks depends on the number of controllable tracks in use).

c. *Aircraft performances.* Up to 16 aircraft performance sets may be used in any one exercise, which comprise:

(1) Minimum, normal and maximum speeds.

(2) Normal and maximum rates of climb.

(3) Fuel load and consumption rates.

(4) Acceleration rates.

(5) Normal and maximum rates of descent.

(6) Normal and maximum rates of turn for subsonic and supersonic speeds.

(7) Ceiling height.

(8) Radar echo area.

d. *Simulation of Primary Radars.* Up to four radars for Air Defence and three radars for Air Traffic are available together with a wide variety of parameters, signal processing facilities and jamming effects.

e. *Clutter Simulation.* Permanent ground echoes and weather returns may be displayed as required.

f. *Secondary Radar Simulation.* Tracks may be specified to transpond SR modes and codes, display emergency codes and IP, and select standby. The information is provided on the EDDs but not on PPI scopes.

g. *Other Simulated Facilities.* Airfield Wing Operations and aircraft emergencies can also be incorporated.

Operating Positions

2393. The associated operating positions are:

a. *Simulator Exercise Controller* (1) from which overall supervision of the exercise is carried out.

b. *Special Voice Consoles* (2) provided to simulate external ground agencies and scrambler, and initiate or cancel special events.

c. *Voice Consoles* (10) from which operators act as 'pilots' by acknowledging controllers messages and relaying appropriate instructions to the computer through alfa numeric and function keys.

d. *Voice Positions* (8). Operators at these positions provide simulated information from all appropriate outside agencies which have no automatic data links with the unit.

Exercises

2394. **Interceptions.** If the rules of interception are applied, realistic contact and kill messages are relayed to the controller from the aircraft whilst weapon and fuel expenditure is also correctly reflected.

2395. **Exercise Duration.** Exercise running times vary; air defence exercises are of two hours duration, or arranged in phases which are up to two hours long whilst air traffic exercises can be up to 75 minutes in length. Facilities exist which enable exercises to be 'frozen' and restarted at will in addition to varying running speeds which allow the simulator to synchronise with simulators at other units.

2396–23100. (*Not allotted*).

SETTING UP PROCEDURE—DISPLAY CONSOLE TYPE 64

a. Check all desk controls vertical except Radar ON.

b. Check air system to console is active.

c. Set rotating controls (except off-centre) to zero.

d. Check that HT and Head Combination switches are off.

e. Set Range selection control to 80 nm.

f. Turn off-centre controls fully anti-clockwise, then turn clockwise five complete revolutions.

g. Check console ON/OFF to ON, check Green light.

h. Check screen and panel lights and DIM/BRIGHT switch.

j. Switch on HT, check Red light.

k. Select designated Radar Head and Video (No trace).

l. Select range rings, turn up range ring COARSE.

m. Centre range rings—no ripple, circular, coarse/fine focus and working on all range settings.

n. Turn up Radar Signals to correct level.

p. Switch in Anti-clutter.

q. Switch off range rings at control desk.

r. Select Video Map, adjust to correct level of intensity, check Video Map/Sector grid overlays correctly and accurately, check equal intensity.

s. Switch off Anti-clutter, check trace origin.

t. Select ELR on Head Select. Select 320 nm, select Range Rings, check 120 nm marker 'T's on video map correspond with 120 nm range ring. Switch in Anti-clutter and select video map.

u. Select IFF ON, turn IFF control clockwise to adjust gain.

v. Select MIX position, check IFF through all modes whilst displaying ALL SIGS/ALL CODES.

w. Check console communications.

CHAPTER 24

SECONDARY RADAR SYSTEMS

CONTENTS

Introduction

2401. One difficulty in air defence is the recognition of the friendly or hostile nature of an aircraft track observed on radar. In the second world war a system was developed for distinguishing friend from foe called Identification Friend or Foe (IFF) which was based on secondary radar principles.

2402. Primary radar depends on the reflection of radio waves, secondary radar (SR), however, depends on the transmission of radio waves from a piece of equipment called a transponder carried in an aircraft. The transponder is activated by an interrogatory signal transmitted from the ground equipment and not only receives the interrogation but replies to it. The ground aerial equipment for SR is often mounted on the aerial of a primary search radar, but may be located separately on its own turning gear. Correlation equipment between primary and secondary radar enables SR responses to be displayed on the user's display console, or to be stored with the appropriate track data within an ADP system.

2403. Current SR uses the D frequency band employing 1030 MHz for ground equipment and 1090 MHz for airborne transponders.

2404. SR is used extensively in the control of military and civil air traffic and the two systems employed by the RAF are known as IFF Mk 10 (SIF) and Secondary Surveillance Radar (SSR). No attempt is made in this chapter to describe the operating procedures for SR; these are fully covered in the appropriate UK and NATO manuals.

IFF Mk 10 Selective Identification Feature (SIF)

2405. Basic IFF was only able to provide a simple unique response to each interrogation but IFF Mk 10 (SIF) achieves a degree of flexibility through electronic coding. The length of the SR pulse is varied to produce three modes of operation and by means of differing interrogator pulse timings and multi pulse transponder replies it is possible to sub-divide the SIF modes into a number of discrete codes. This selective identification feature does not, however, provide positive identification friend from foe nor does it contain any inherent security unless a system of rapidly changing code allocation is used.

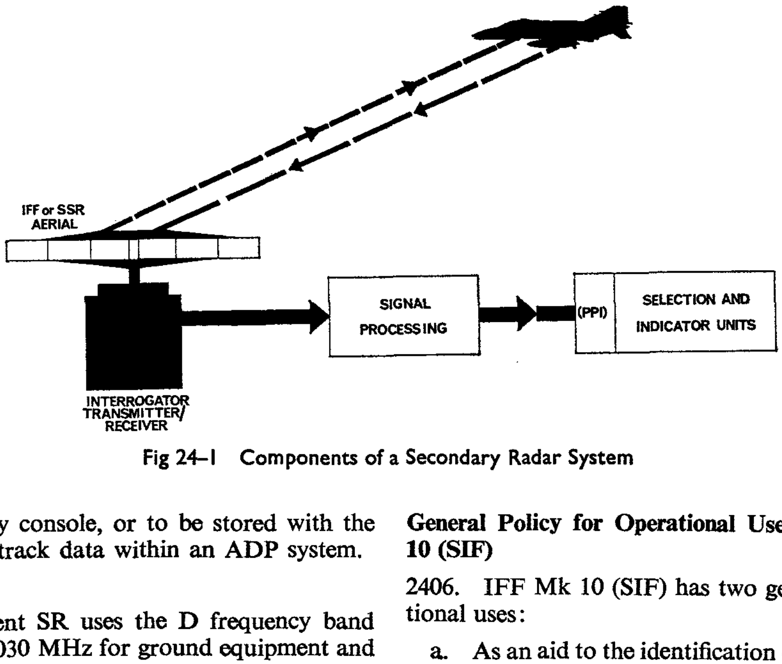


Fig 24-1 Components of a Secondary Radar System

General Policy for Operational Use of IFF Mk 10 (SIF)

2406. IFF Mk 10 (SIF) has two general operational uses:

a. As an aid to the identification of an aircraft individually or by function.

b. As a beacon to assist in the tracking of aircraft with a low reflectivity to ranges in excess of the primary radars normal capability.

Modes of Operation

2407. The following uses for the modes of operation of IFF Mk 10 (SIF) has been agreed for worldwide employment:

a. *Mode 1.* Tracking and beacon assistance in the control of friendly aircraft and general identification.

b. *Mode 2.* Tactical operations and the identification of aircraft by airframe.

c. *Mode 3.* Air traffic control and co-ordination, and tactical/functional operations.

Transponders

2408. The transponders in aircraft fitted with SIF are equipped with coders that provide replies to the following interrogations:

a. *Mode 1.* 32 codes designated 00–73 which can be changed manually by the aircrew. Mode 1 interrogations will elicit only Mode 1 replies.

b. *Mode 2.* 400 codes, from a possible 4096 (designated 0000–7777) are currently used in RAF systems. Generally the code selection cannot be altered in flight and is pre-set on the ground. Mode 2 replies will be transmitted only when the Mode 2 switch on the transponder control unit is set to the Mode 2 position.

c. *Mode 3.* 64 codes designated 00–77 are available and can be selected manually by aircrew. Mode 3 transponder replies will only be transmitted when the Mode 3 switch on the transponder is selected 'on'. Mode 3 is the common military/civil mode and some codes have been allocated for special purposes; code 76 is used by aircraft experiencing radio failure, and code 77 is used by aircraft in distress (for civil aircraft outside the UK FIR only).

2409. The transponder also provides two additional functions as follows:

a. *Emergency.* The emergency function is used when an aircraft is in distress or orbiting survivors or as prescribed in local orders. When the emergency function is activated, easily recognised responses of three or four bars or bloomer pulses (depending on the permutation of console settings and equipment in use) will be seen on all displays.

b. *Identify Position.* The IP function provides rapid and short term display of a two bar response for individual identification and is available on all modes. As with emergency replies, the IP breaks through the system and will be displayed on all consoles either as a one or two bar response, depending on console SR settings.

2410. The appearance of SR responses is shown in Fig 24–2.

Relationship between SIF Interrogations and Replies

2411. The following table shows the relationship between SIF interrogations and replies:

Serial No	Mode	IR Interrogation	Transponder Reply
1	1	3 microseconds	One of 32 codes
2	2	5 microseconds	One of 4,096 codes (only 400 in use)
3	3	8 microseconds	One of 64 codes

Pulse Train Formation

2412. Formation of Numbers 0 to 7 from a block of up to three pulses. The numbers 0 to 7 can be formed from a block of up to three pulses in the following manner:

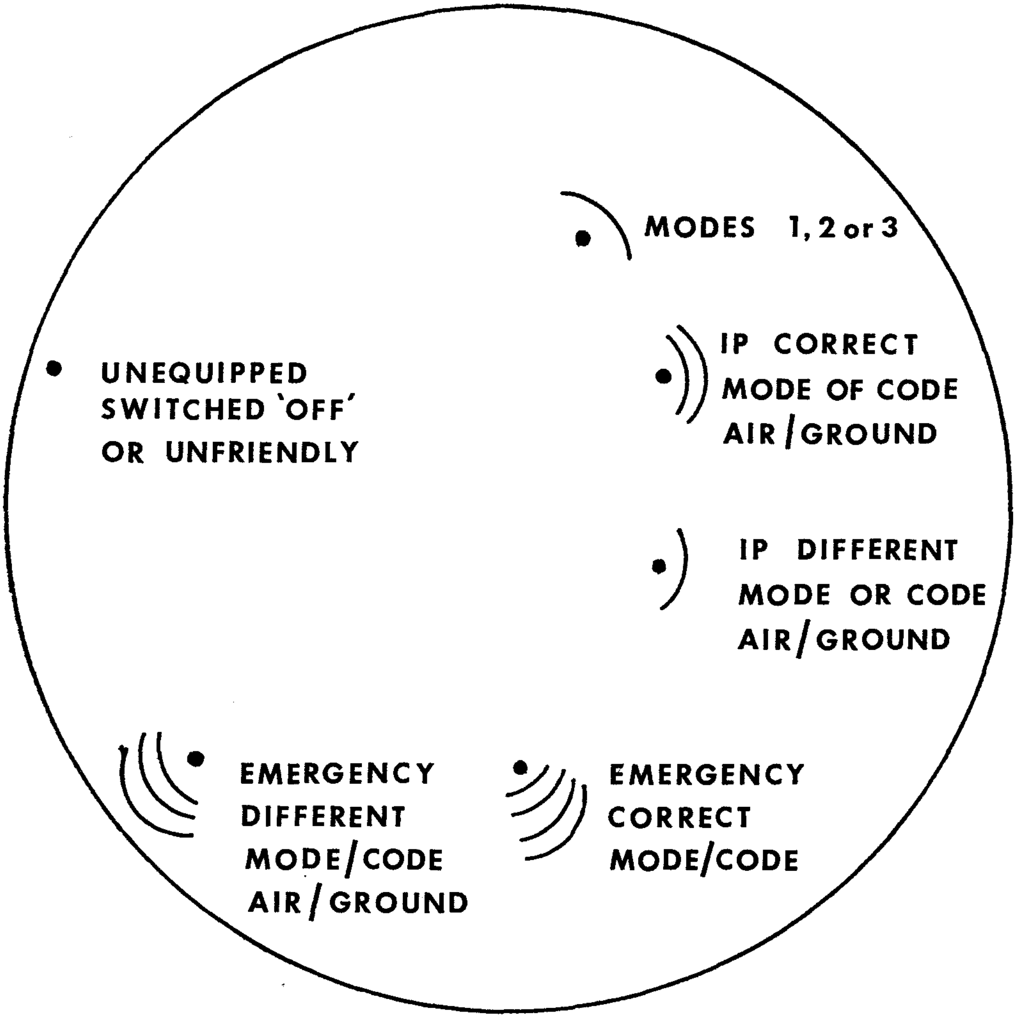
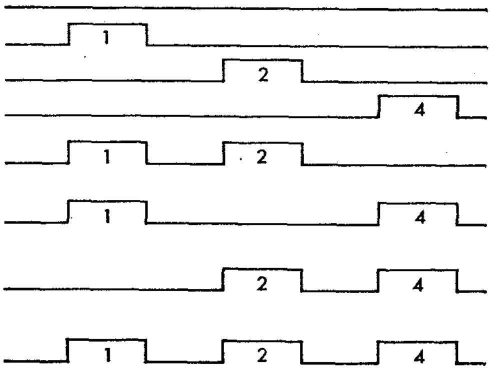


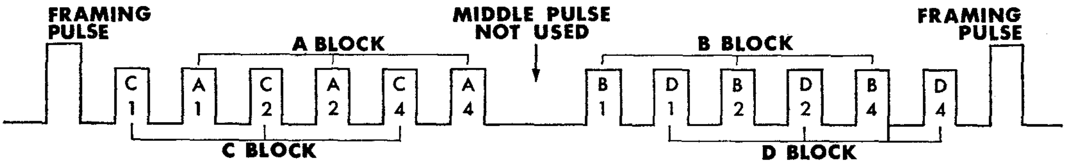
Fig 24–2 Appearance of SR Responses



No pulse	Number 0
1 pulse in first space	Number 1
1 pulse in second space	Number 2
1 pulse in third space	Number 4
1 pulse in first space + 1 pulse in second space = 1 + 2 = 3	Number 3
1 pulse in first space + 1 pulse in third space = 1 + 4 = 5	Number 5
1 pulse in second space + 1 pulse in third space = 2 + 4 = 6	Number 6
1 pulse in first space + 1 pulse in second space + 1 pulse in third space = 1 + 2 + 4 = 7	Number 7

2413. **Complete Pulse Train.** A complete pulse train may consist of up to 13 pulses, but the seventh, the middle one, is never used. There are therefore 12 usable pulses, which are divided into four blocks of three pulses. This arrangement gives the possibility of a code of four numbers, each in the range 0 to 7 inclusive. The four blocks, termed A, B, C and D are formed as follows:

2416. **Mode 3 Pulse Train.** Mode 3 codes use Blocks A and B. Mode 3 codes, therefore, consist of two numbers, each in the range 0 to 7 (eight numbers). There are eight ways of choosing the first number and eight of the second, making a total of 8 × 8 = 64 possible choices of Mode 3 code.



2414. **Mode 1 Pulse Train.** Mode 1 codes use five information pulses; three in Block A and two in Block B. The three pulses in Block A give the possibility of any number in the range 0 to 7 (eight numbers), and the two in Block B give the possibility of any number in the range 0 to 3 (four numbers). There are therefore eight ways of choosing the first number and four ways of choosing the second, thus making a total choice of 8 × 4 = 32 codes possible in Mode 1.

2415. **Mode 2 Pulse Train.** Mode 2 uses all four blocks, so Mode 2 codes consist of four numbers, each in the range 0 to 7 (eight numbers). There are therefore eight ways of choosing the first number of the code, eight of choosing the second, eight of the third and eight of the fourth, thus making a total of 8 × 8 × 8 × 8 = 4096 possible codes available for Mode 2. However, in RAF systems only 400 are used.

Ground Unit Decoding

2417. **Active and Passive Decoding.** Two types of decoding are possible—active and passive. Their characteristics are as follows:

a. *Passive Decoding.* Passive decoding takes place when the controls on a console are set to receive specific individual or groups of codes; other unwanted codes are eliminated from the display. This form of decoding can answer the questions:

(1) Where are the aircraft using a particular mode?

(2) Where are the aircraft using a particular code?

b. *Active Decoding.* Active decoding takes place when an individual response is selected on a PPI by a gate strobe controlled by a joy stick or a rolling ball control. The coded transmission from the aircraft in the gate is analysed, decoded, its degree of correctness assessed, and the answer displayed in numerical form. Active decoding answers the question: what is the code of an aricraft at a particular PPI position?

SECONDARY SURVEILLANCE RADAR

2418. **Introduction.** The IFF Mk 10 system has been used as the basis for development of a secondary radar system to meet the requirements of the International Civil Aviation Organization. The resultant system, which has been agreed by ICAO for use by civil aviation, is termed Secondary Surveillance Radar (SSR). Future RAF SR equipments will conform to ICAO policy.

2419. **Characteristics.** The system operates on the same frequencies as IFF Mk 10 (SIF) and provides coded responses in 4 modes:

a. *Mode A.* Civil/military identification, 4096 codes numbered 0000–7777.

b. *Mode B.* Civil identification, 4096 codes numbered 0000–7777.

c. *Mode C.* Automatic altitude read out, 1278 codes available.

d. *Mode D.* Future system expansion.

R/T PHRASEOLOGY FOR USE WITH SECONDARY RADAR

2420. The following is a list of R/T phrases and their meaning used in connection with the operation of secondary radar:

Phrase	*Meaning*
"SQUAWK"...	...Operate the transponder as instructed.
"SQUAWK STANDBY"	...Turn IFF master control to the "STANDBY" position, retaining present mode and codes.
"SQUAWK NORMAL"	...Turn IFF Master control to "NORMAL" position.
"SQUAWK MAYDAY"	...Turn IFF master control to "EMERGENCY".
"SQUAWK IDENT"	...Operate "I/P" key (SIF/BASIC) or "IDENT" button (SSR) retaining present mode and codes.
"SQUAWK ONE CODE ( )" ...	...Turn IFF master control to "NORMAL" and Mode 1 code controls to designated setting.
"SQUAWK THREE CODE ( )"	...Turn on the IFF Mode 3 switch (and turn Mode 3 code controls to designated setting)
"SQUAWK TWO"...	...Turn on IFF Mode 2 switch.
"SQUAWKING ( ) CODE ( )"...	...Showing IFF on mode stated (and SIF on code indicated).
"STOP SQUAWK THREE" ...	...Switch off Mode 3.
"STOP SQUAWK"...	...Switch off transponder.
"TRANSPONDER"	...IFF Mk 10 (SIF) or ICAO/SSR transponder.
"TRANSPONDER TANGO" ...	...IFF Mk 10 (Basic) transponder, without coding possibility.
"TRANSPONDER SIERRA" ...	...IFF Mk 10 (SIF) transponder.
"TRANSPONDER INDIA" ...	...ICAO/SSR transponder.
"WHICH TRANSPONDER" ...	...Report which type of transponder fitted.
"SQUAWK SQUARE"	...Aircraft addressed is to set SIF control unit controls for Modes 1 and 3 to "00" code.

IFF MK 10 (SIF) AND SSR

IFF MK 10 (SIF)		SSR	
Tracking Beacon Assist General Ident	MODE 1 INTERROGATION 3 MS 32 CODES		
Tactical Ident	MODE 2 INTERROGATION 5 MS 400 out of 4096 CODES		
Assist Air Traffic Control Tactical	MODE 3 INTERROGATION 8 MS 64 CODES	MODE A INTERROGATION 8 MS 4096 CODES	CIVIL
		MODE B INTERROGATION 17 MS 4096 CODES	CIVIL
		MODE C INTERROGATION 21 MS 1278 CODES	AUTOMATIC ALTITUDE READOUT
		MODE D INTERROGATION 25 MS 4096	FUTURE SYSTEM EXPANSION

Note: With the integration of SSR at most Air Defence Radar Units, Mode 3 combined with Mode A gives a total choice of 4096 codes for display.

CHAPTER 25

COMMUNICATIONS

CONTENTS

PRINCIPLES OF COMMUNICATIONS

The Need for Communications

2501. The most general meaning of communications is the imparting or exchange of intelligence—which here includes information and orders—by any means, though it is not usually taken to include direct word of mouth. A control and reporting system is constructed around its means of communication, and to understand them one must first of all realize what categories of intelligence they are required to carry. These are:

a. *Orders.* An air defence commander has to be able to pass his orders to aircraft, control and reporting units, and other forces under his control on the ground, and an interception controller has to be able to pass orders to aircraft in flight.

b. *Reporting.* Reporting units must be able to pass their information to operations rooms.

c. *Order-of-Battle.* Accurate up-to-date information must constantly be before an air defence commander concerning the state of all the fighting forces under his control.

d. *Briefing.* Before an interception, both pilot and controller must receive up-to-date information about the enemy, the state of the battle, and the weather.

e. *Debriefing.* After any engagement, combat reports must be passed from squadrons and control units to higher authority.

f. *Liaison.* Individuals at units and formations must also be able to exchange information and discuss matters that do not directly fall under any of the headings above.

2502. Different means of communication are needed to meet these different purposes. Most of them call for two-way communication, but for a few, no return path is necessary. The qualities looked for in choosing a means of communication are:

a. *Speed of Communication.* For most purposes in control and reporting, speed is essential, and every second counts. Other requirements have to take second place.

b. *Security.* The intelligence transmitted should be secure from interception by the enemy, but the value of such interception often depends on how much time is left to make use of the information gained, and if an order or operational message refers to something that will happen too soon for the enemy to act on the information, then the risk of interception may be disregarded—the best security for such a message is the speed of its communication. High security is obtained by using codes or ciphers, but their use may cause delay.

c. *Reliability.* Communication should be intelligible and available at all times despite natural or enemy interference.

d. *Flexibility.* A communications system must be chosen to bridge the gap between the given end-points, mobile if necessary, without unreasonable cost or complication. Enough channels should be available for all needs.

2503. The communications links needed in control and reporting can be grouped as follows:

a. *Ground-to-Ground.* Required for reporting, order-of-battle information, debriefing, ground liaison, and some of the orders and briefing.

b. *Ground-to-Air.* Required for orders and briefing to airborne aircraft, liaison with them, and position fixing.

c. *Air-to-Air.* Required for control of airborne formations by their leaders. Since the problems are only very slightly different from those of ground-to-air, they will not be discussed separately.

2504. (*Not allotted*).

Means of Communication

2505. Means of communication may be divided into:

a. *Radio* (*Wireless*). The conveyance of intelligence as modulation on radio waves, which travel independently of any medium.

b. *Line.* The conveyance of intelligence by fluctuating current flowing through conducting circuits, usually wires or lines.

c. *Visual.* The conveyance of intelligence by light waves received by sight. This means has too short a range to be used in control and reporting.

d. *Message-Carrying.* The conveyance of intelligence as the written word. This is too slow to have any use in reporting or in the immediate control of the tactical battle.

2506. Only radio and line communications will be discussed in this manual. They may carry the following types of communication:

a. *Speech* (*Telephony*). Telephony is the direct transmission of the equivalent of the spoken word—known on radio circuits as radio telephony (RT). It is the fastest form of communication between individuals, but does not lend itself very conveniently to enciphering or recording. However it can be disguised without losing its speed by scrambling.

b. *Telegraphy.* Telegraphy is the transmission of words by a code of signals; examples are the Morse code, used for wireless telegraphy (WT), and the five-unit code, used with teleprinters. Time is inevitably lost in the encoding and decoding, but a permanent record is normally made.

c. *Automatic Data-Transmission.* The transmission of information not in words but in a special code of electrical impulses which reproduces the information directly upon a display. Where the restricted scope of the information lends itself to this sort of coding (as in reporting and order-of-battle information), an automatic system can be faster and more reliable than any other, because it does without the human element. An automatic means of transmitting information and orders directly from a control station *via* a computer to the pilot has been developed. This gives a visual presentation in the cockpit. An automatic system for transmitting order-of-battle information is being developed. The transmission of radar information by radar links is discussed elsewhere in this manual.

2507. Radio communications (even beamed relays) can easily be intercepted, and are by nature completely insecure; interception of line communications is less easy, since a would-be interceptor must get at the actual line circuit in use, but lines are rarely considered safe (even when they run through defended territory) for traffic graded above RESTRICTED. Security can be given to the communications only by encoding or enciphering the traffic. Teleprinter traffic in a fixed system can be made secure without any loss of time by automatic "on-line" ciphering devices, whose use is limited mainly by their cost; but this equipment is unsuitable for mobile air forces, which must use either machine or book ciphers at the cost of some delay to the traffic.

2508. Radio and line both carry their messages at roughly the velocity of light, and thus the information spends very little time in transit between any two points on the earth's surface. Time may, however, be lost in translating information from the form in which it is presented (speech or writing) into a form suitable for radio or line transmission (cipher or signalling code), and in re-translating at the receiving end; it is the speed of this process of translation, human or mechanical, that determines the speed of communication. Telephony requires no such translation, and is therefore a very fast though usually insecure method of communication.

2509. The patterns of varying current into which both speech and telegraphy are converted, are built up of oscillations at many different frequencies within a certain band of frequencies. To transmit intelligence in either form one has therefore to design a link to handle the appropriate frequency-band; in radio communication this introduces the question of the modulation sidebands and the bandwidth of the circuits to pass them. In line communication it is simply a matter of designing a line to carry the required frequency band without loss; but in radio, each channel of communication must be a small band of frequencies in the spectrum of radio waves, large enough to accommodate the sidebands and yet not overlapping the band of any other channel; hence there is only a limited number of channels available in each range of frequencies. The spectrum of radio frequencies has to be divided so as to allow channels not only for military communications but also for sound broadcasting, television, police-car and taxi control, commercial uses, amateurs, radio navigation aids, radar, and many other purposes. The government of each nation allocates frequencies to be used for these various purposes over its own territory, subject to international agreement—in the United Kingdom the final authority on frequency allocation is the Ministry of Posts and Telecommunications.

2510. Radio communication is liable to natural interference by static and fading, which can be overcome by careful choice of frequency, and to jamming, which can be countered. Though line communication is not troubled by either of these, it can easily be broken by enemy action in bombing, shelling, or line-cutting.

2511. The choice between radio and line is most often made on the ground of flexibility. As already mentioned, line communication has advantages in security, reliability, and the number of channels it can provide: but it is either impracticable or very costly in many applications, such as across large stretches of water, over enemy-held or inaccessible territory, in communication with aircraft, and in tactical air force operations with rapid redeployment. For such purposes radio must be used, with or without safeguards, according to the nature of the traffic. Ground communications between fixed or semi-permanent units within a defended territory are generally handled by line, though radio may be held available as a standby.

2512–2514. (*Not allotted*).

Security in Communication

2515. The security of the intelligence transmitted by radio or line can be sought either by safeguarding the physical channel of communication or by enciphering the intelligence, or by both these means if possible:

a. *Physical Security*. Radio transmissions cannot be made secure from interception, and lines have only limited physical security. Line circuits are officially classified for their security, which is determined by their vulnerability to interception. The signals staff should always be consulted if there is any doubt about the security of a landline.

b. *Cipher Security*. Ciphers are not ordinarily used for the operational traffic of a static control and reporting system.

2516. If a message has to be passed which is of higher security classification than that of the available line or radio circuits, it should be given the proper cipher protection. A commander, at his discretion, may authorize the transmission of traffic up to SECRET without safeguard, if he considers that the need for speed outweighs the risk of interception: but careless transmission of classified matter without the proper safeguards has been a fruitful source of information for enemies. TOP SECRET traffic must always be enciphered. Full instructions for communications security are given in ACP 122.

2517. Communications may also disclose to any enemy information other than that which they carry. Such disclosure is most serious with radio because it is so easy to intercept radio transmissions. The positions of radio transmitters can be found by direction-finding, and much valuable order-of-battle information can be pieced together by studying the flow of traffic, the callsigns and frequencies used, and the nature of the messages. There is no complete defence against this sort of interception; but strict RT or WT discipline helps to restrict the intelligence which can be gained. The following errors are most useful to the enemy:

a. Compromise or confusion of callsigns or channel letters.

b. Premature breaking of radio silence, and unauthorized or unessential transmissions.

c. Transmitting indistinctly or too fast so that repetitions have to be given.

d. Use of special or personal procedure which may identify an individual or unit.

e. Compromise of code and cipher systems.

2518. The above errors also help the enemy to mislead and spread confusion by putting out fake transmissions, which have the best chance of working when RT discipline is lax. Authentication systems of challenge and reply code words are used to guard against enemy fake transmissions: but they are often made optional, because of the delay and increased risk of compromise if every transmission has to be challenged and authenticated.

2519–2520. (*Not allotted*).

LINE COMMUNICATIONS

Nature of Line Signals

2521. Radio and line communications differ in the means of conveying electrical vibrations from place to place: in radio this is achieved by modulating a carrier radio wave which is radiated freely into space and may be picked up anywhere within range. In line communication, electrical vibrations are carried either as they are, or modified in some way, along conducting paths (*ie* two wires or "pair") which are generally known as line circuits. Lines are essentially a point-to-point means of communication.

2522. Every sound in speech can be built up as a mixture of a large number of oscillations at different frequencies. In other words, each sound has a frequency spectrum; it may range from as low as 100 hertz up to about 15 kHz, which is the highest note that most people can hear. This is a wide band and not easy to reproduce in full, but it is found that the section of the spectrum between 300 Hz and 3 kHz is all that is needed to make speech intelligible and retain those individual traits of voice by which people may be recognized. Frequencies in this range are therefore called speech frequencies.

2523. The first essential in telephony, therefore, is to have devices to convert the sound oscillations of speech into their electrical equivalent and *vice versa*. These devices are the microphone and the loudspeaker or telephone receiver. The most usual type of loudspeaker consists of a coil of wire suspended between the poles of a magnet and attached to a diaphragm; when speech currents are passed through the coil it oscillates and makes the diaphragm generate sound waves. Some microphones use this principle in reverse by making the sound vibrate a coil in the field of a magnet, so that speech currents are induced in the coil; these are called electromagnetic microphones, and are the type mainly used in aircraft. Carbon microphones, the other important type, consist of a box of lightly packed carbon granules through which a battery drives a current; one side of this box is a flexible diaphragm, and when sound falls on this it vibrates in sympathy, thus varying the pressure on the carbon granules; the resistance of these varies with the pressure packing them together, and so the current through the microphone oscillates in the pattern of the sound. For convenience a microphone and a receiver are often mounted together in a hand microphone-telephone (HMT).

2524. Morse code is transmitted by one single frequency (usually 1 kHz) being switched off and on. The characters of the Morse code are of many different lengths, and this irregularity makes it difficult to design a machine to encode and decode Morse automatically. Present-day automatic signalling systems, therefore, use instead the five-unit or Murray code, in which every letter, figure, and sign is made up of a block of five pulses each of the same width (usually 20 milliseconds on British circuits only), and during each of these pulses the signalling equipment can be in one of two states, commonly described as "mark" or "space" (*eg* A is MARK MARK SPACE SPACE SPACE, B is MARK SPACE SPACE MARK MARK, and so on).

2525. A teleprinter has two main parts: a transmitter with a typewriter keyboard which generates the correct five-unit code signal for each letter, giving a positive 80-volt pulse on mark and nothing, or a negative 80-volt pulse, on space (such signals are called DC pulses); and a receiver which accepts five-unit DC pulse signals and prints the correct letter for each. Before each signal an extra pulse ("space") is sent to denote its beginning (in case it begins with a space), and after each signal a "mark" is sent to denote the end of that character. The number of possible combinations of five in this way is 32 (*ie* 2^5), and so, in order to get figures and other signals as well as letters, one of the five-units characters is called FIGURES and is arranged to shift the printing mechanism of the teleprinter receiver as in a typewriter to bring a second type-case into action. DC pulses are not easily amplified, and for long-distance signalling they are converted into tones—audio-frequency oscillating currents—either so that mark corresponds to tone and space to no tone, or with two tones at different frequencies, one for mark and one for space; tones can be amplified as easily as speech currents.

Line Circuits

2526. The simplest kind of line circuit is a pair of wires, most usually known as a line pair or just a pair, stretching between two points and carrying speech currents or telegraphy signals in either direction. A "pair" of wires is required to make an electrical circuit. A pair may be made of heavy copper wire and be supported by poles above the ground, or may run underground in multi-core cables or under the sea in heavily armoured and protected cable, or indoors it may be in twin flex similar to that used in domestic wiring. In any or all of these forms, the simple line pair is the foundation of all short-distance or local circuits and of internal wiring.

2527. Over a long distance, however, the signals may lose so much of their strength in the resistance of the wires that they must be amplified before they can be used at the far end. All long lines have amplifiers called repeaters spaced regularly along them; since amplification is needed in both directions it is not possible to use a single pair for both go and return (that would give a closed path through two amplifiers and instability similar to acoustic feedback) and a long-distance circuit must consist of two pairs, one for each direction. This is known as four-wire working.

2528. It is possible to convey several signalling tones at different frequencies along the same line pair and separate them at the far end with filters (circuits accepting only narrow bands of frequencies); thus a line pair capable of carrying speech currents, with frequencies from 300 Hz to 3 kHz, can be made instead to carry at least six quite separate channels of telegraphy (a system called voice frequency (VF) telegraphy).

Many line pairs can be made to carry frequencies much higher than 3 kHz, and several speech circuits may be fitted in on one such pair by making use of a sort of frequency-changing: *eg* mixing the currents of one speech channel with a 3 kHz tone would raise all their frequencies by 3 kHz to give a band from 3 to 6 kHz, which could be put on the same line as another ordinary speech channel from 0–3 kHz; the higher frequency band could be separated out at the far end by filters and converted back to speech. Also a gap can be made in the frequency spectrum of a speech channel, wide enough to take two tones for telegraphy (which can be filtered out when wanted for use), but not wide enough to affect the quality of the speech; this enables an ordinary speech circuit to carry two telegraphy channels as well, one in either direction, and is called speech plus duplex. The reader will see that, by means such as these, a simple line pair may be made to carry a great deal more than one conversation or one teleprinter channel. The number of channels possible depends largely on the upper limit to the frequencies that the line can efficiently carry. This limit can be raised to about 60 kHz for some types of line pair, by special construction; or coaxial lines may be used. A coaxial line can be made to pass frequencies up to several MHz, and hence can carry several hundred channels—but it is so costly to install and needs repeaters so closely spaced that its use is justified only on the largest trunk routes.

2529. Line circuits are usually built up in sections from the sort of links that have been described. To get the right level of output at the far end of a circuit constructed in this manner clearly needs very careful adjustment of the gain of the various repeaters on the way; this can be done exactly for a line that always has the same two terminations, but only very roughly for lines connected to an exchange. For both telephony and telegraphy, countries are covered by networks of multiple point-to-point links, which are terminated at trunk centres and smaller centres on distribution frames. Circuits are made up by cross-connexions on the frames with wires called jumpers, and are classified according to their function and the type of signals they carry.

2530. Jumpering on distribution frames is not a satisfactory way of making cross-connexions that often have to be altered in the ordinary course of operations; for this purpose the lines may instead be brought out from the frame room to jacks (sockets) on a panel—often called a change-over panel (COP)—and the connexions made on this panel with patching leads having a plug at each end to fit the jacks.

2531–2534. (*Not allotted*).

CHANGE OVER PANELS (COPs)

Responsibility for Operating the COP

2535. A COP enables re-routing or "patching" as it is commonly called, of communications within operations rooms. Correct use of the COP is therefore vital and only competent and fully trained personnel should be allowed to operate it. The persons responsible for operating the COPs at the various C&R units are detailed in the appropriate ~~C&R Procedure Instructions~~s. local Order Books A>

Telephone Circuits on a COP

2536. The following telephone circuits are normally wired to a COP.

a. *Internal Circuits.*
 (1) All keyboard key positions.
 (2) All telephone jack positions.

b. *External Circuits.*
 (1) All external operations circuits.

Facilities Available on a COP

2537. The following main facilities are available on a COP.

a. Monitoring for supervision, line checking and ringing tests.

b. Patching of circuits (internal line to internal line, internal line to external line or external line to internal line).

c. Coupling several circuits together ("bunching").

d. Increasing amplifications of coupled circuits by using conference amplifiers if bunching causes a reduction in signal strength.

KEYBOARDS

2538. It is frequently necessary for C&R personnel to be able to speak without delay to a number of persons at a variety of external agencies or internal positions. Some form of switchboard is required for this purpose, and a keyboard is normally used. The keyboard has a number of lines (which may be local or external) terminated on it, and by operating keys the user can switch his own telephone handset or headset to any one of the lines. On some keyboards keys are provided for interconnecting lines. A calling or ringing key is also provided which causes a lamp to light, a bell to ring or a buzzer to sound at the receiver end of the circuit to attract attention. More than one handset or headset may be used with certain types of keyboard, thus allowing several individuals to listen in or speak on the line. Several lines connected to one keyboard may also be put in parallel by throwing all their keys; thus allowing a speaker to broadcast orders or information to a number of destinations simultaneously.

2539. Telephone communications are insecure, but it is possible to reduce the security risk by making the speech unintelligible unless special equipment is used. This technique is known as "scrambling".

LANDLINE ORGANIZATION

Provision and Maintenance

2540. In peace and war, all lines and terminal line equipment for the Royal Air Force in the United Kingdom are provided and maintained by the Post Office Corporation. All save quite minor facilities must be approved, and are normally ordered, by the Ministry of Defence. Post Office engineers are established at units and formations according to the amount of line equipment there is to be maintained: a large centre may have a resident engineer, while a smaller unit will have only a part-time service for routine maintenance work, with an engineer on call at two or three hours' notice to repair faults on operational equipment (though establishments would be increased in wartime).

2541. Line communications for tactical air forces and all commands abroad, in both peace and war, are provided for the Royal Air Force by the Army. The Royal Air Force often has some responsibility for provision and maintenance of terminal equipment however. Units of the Royal Corps of Signals, called Air Formation Signal regiments, are established under the operational control of the Royal Air Force to install and maintain all line circuits which are entirely or largely used by the Royal Air Force: common-user or trunk circuits are dealt with by regiments of the Royal Corps of Signals under the control of the parent army formation, which may employ civil authorities to do the work if it is convenient. A chief air formation signal officer (CAFSO) is established at each RAF headquarters abroad and is responsible to the air commander for the operational aspect of the air formation signals work in the command.

Telephone Organization

2542. The public telephone system operated by the Post Office in the United Kingdom is constructed round a number of regional trunk switching centres which are connected to one another by large numbers of speech circuits called trunk lines. To each of the trunk centres are connected all the exchange switchboards for its area, and every telephone subscriber has a line to his local exchange, called a direct exchange line (DEL). A subscriber may also have a trunk subscriber circuit direct to his regional trunk switching centre for convenience in making trunk calls. An RAF station usually has a private branch (PBX) connected to DELs, and usually by subscriber circuits as well, to the PO system. Trunk subscriber circuits may also be provided to operational keyboards.

2543. The Royal Air Force also has its own telephone system connecting units and formations in the United Kingdom, composed of circuits rented from the Post Office which are called private wires (PWs). The administrative telephone network is built, like the PO system, round a number of terminal trunk centres and follows the normal channels of command down to station and unit PBXs. Operational circuits are usually between fixed end-points, with no intervening switchboards, and they follow the channels of operational control. PW circuits cannot ordinarily be connected to the public system; but they are routed through the distribution frames of PO centres, just as are circuits of the public system, and on this account cannot be considered more secure. They are identified most commonly by their PO numbering (*eg* PW 12345 for a circuit covering more than one region, or PW/HC 4321 for a circuit entirely within a region identified by HC), but they also have Ministry of Defence circuit numbers.

2544. An operational telephone link between two units may be wanted only occasionally, or even on one occasion only for some special operation. It would be wasteful to rent a PW for such a purpose, since the PO regulations normally require lines to be hired for at least one year; but there are two ways of obtaining the result without extravagance, and these are:

a. *EC Line.* A link which is required in wartime only, or for occasional exercises, may be provided as an emergency circuit (EC). This is a form of PW in which the sections of circuit between PO centres are available to the public system or other users except when the link is needed by the renter. It is to be established at the outbreak of war, after a delay varying with the requirement but not less than 36 hours. It can be set up for an exercise at 10 days notice. Such a circuit requires Ministry of Defence approval as for a PW.

b. *PUT Call.* A link which is needed continuously for several hours, but not on repeated occasions, may be set up as prolonged uninterrupted trunk (PUT) call over the public system. Such a call is routed through the DELs or trunk subscriber circuits of the stations and the PO switchboards, but is held immune from interruption. It is for this purpose that trunk subscriber circuits may be provided to operational keyboards. Authority for PUT calls can be given by the headquarters of the controlling formation, and they are set up by arrangement between the local signals officer and the supervisor of the local Post Office exchange or trunk centre.

Telebriefing

2545. While PW telephone circuits are provided from master radar stations to the wing operations rooms of fighter airfields, it may be desirable for the master controller or his staff to be in communication with pilots of aircraft waiting on the operational readiness platforms. This could be done by radio, but that would overload already crowded UHF and VHF channels and unnecessarily sacrifice security; and so a system called telebriefing (earlier known as telescramble) has been introduced, in which the pilots' headsets and microphones are connected to a landline through long wander-leads that can be plugged into aircraft on the operational readiness platform. All these leads are wired in parallel, and are connected through a special amplifier to a line in parallel with the line to the wing operations centre so that each pilot can receive orders and information direct from the executive operations centre. When the telebriefing socket is connected, the pilot's microphone and headset are disconnected from his UHF or VHF set and connected to the line; a press-to-speak button is fitted in the cockpit of each aircraft, so that a pilot may speak on the line. When aircraft move off the platform, the telebriefing sockets are pulled out automatically.

2546. In each command abroad there is a unified inter-service telephone system with some lines provided specially for the Royal Air Force, and the facilities are generally similar to those of the PW network in the United Kingdom.

Teleprinter Organization

2547. The Royal Air Force operates a world-wide teleprinter network using both line and radio links and does not ordinarily use the public telegraph service. This main communications system uses complicated high speed signalling devices which handle the messages as perforations on paper tape, and is called the tape relay system; a detailed description of it would be out of place in this manual.

2548. Teleprinters for operational use in an air defence system are sometimes provided on straightforward point-to-point circuits, *eg* between master radar stations and air traffic control centres. The teleprinter PWs at an operations centre are usually terminated on a teleprinter switchboard connected to a teleprinter, and through the switchboard it is possible to broadcast a message to any or all of the terminal stations.

2549–2550. (*Not allotted*).

GROUND-TO-AIR RADIO COMMUNICATION

Choice of Frequency

2551. The choice of a working radio frequency or band of frequencies for radio communication must clearly depend on the point-to-point range required; since it is only by diffraction, ionospheric reflection, or forward scatter that radio waves can consistently be propagated beyond the radio horizon and the extent of these phenomena varies with the radio frequency. But both the extent of natural interference and the number of communication channels also vary with radio frequency, and must be considered in choosing a working frequency. In ground-to-air communications for control, one is concerned with fighter aircraft often at ranges up to 200 miles. The need for speed and direct contact with the pilot makes RT or data link essential, and natural interference must be eliminated because there is no time during an interception to ask for repeat transmissions.

2552. **Range.** The ground-wave transmission is limited to the radio horizon at frequencies above about 50 MHz (at lower frequencies there is appreciable diffraction round the earth's surface). Any greater range must be obtained by ionospheric reflection and for waves with a frequency above about 30 MHz this is possible only in freak conditions. No use can be made of forward scatter propagation in ground-to-air communication, because the techniques demand fixed endpoints. Control systems always use frequencies in the VHF and UHF bands (100 MHz and upwards) for communication with aircraft, because of advantages described below; propagation at such frequencies is by nearly straight-line paths, curved only slightly by atmospheric refraction. The problems of cover raised by the straight-line path limitation are discussed in para 2576.

2553. **Natural Interference.** Communication may be disturbed by fading which makes the signal fluctuate in strength or even disappear completely. This is a result of ionospheric reflection, and is eliminated by using frequencies above 50 MHz. The other important form of natural interference is static, the name given to irregular EM waves radiated from electrical disturbances such as lightning discharges; the frequency spectrum of these waves extends to about 70 or 80 MHz, and in receivers working on frequencies lower than this they give crackling noises, which are often loud enough to interfere seriously with communication. Both fading and static are avoided by using frequencies in the VHF and UHF bands, and this is the chief reason for not using lower frequencies for fighter direction.

2554. **Number of Channels.** In para 2509 it was explained that the spacing between frequencies of adjacent channels must not be less than the width of the sidebands corresponding to the modulation being carried. Speech contains frequencies up to about 15 kHz but is perfectly intelligible provided its components from 300 Hz to 3 kHz are transmitted. Hence the bandwidth necessary for clarity in an amplitude-modulated RT transmission is 6 kHz (twice the greatest frequency of modulation); the international channel spacing for broadcast stations in the LF, MF and HF bands is 9 kHz. But to use such a spacing one must be able to build receivers with an IF bandwidth less than 9 kHz, since receivers with greater bandwidth will not be able to separate two transmissions on adjacent channels; at high radio frequencies such bandwidths are not practicable and it is receiver design rather than width of the sidebands that determines the channel spacing. It is difficult to make an IF amplifier with a bandwidth less than about $\frac{1}{200}$ of the value of the IF, and for communications it has generally been considered unwise to use a single IF less than about $\frac{1}{10}$ of the radio frequency (because of second-channel or image-frequency interference —*see* AP 1093); so that the channel spacing cannot normally be finer than about $\frac{1}{3000}$ of the radio frequency, *eg* about 50 kHz at 150 MHz, without using two or more IF frequencies. Frequency-modulated transmissions generally occupy much wider bands than amplitude-modulated, often about 200 kHz. The reader will see that there can be only a limited number of channels in any range of frequencies, and that to obtain more channels one has either to overcome great difficulties in receiver design or turn to higher radio frequencies.

Choice of Modulation

2555. Several systems of modulation have been used for conveying RT. The simplest one, which is in general use throughout the Royal Air Force, is amplitude modulation. Frequency modulation is used in some other allied services (the Army for tactical operations); it can offer the advantages over amplitude modulation of clearer speech with better signal-to-noise ratio—consequently greater range within optical limits for a given transmitter power—and also a clear-cut selection of the stronger of two stations working on the same channel (known as the capture effect). Its disadvantages are the greater bandwidth needed (about 200 kHz), which reduces the number of channels possible, and greater difficulty in servicing the receivers.

VHF Band

2556. The band 100 to 156 MHz was allocated for British aeronautical communications, both civil and military; this range of frequencies is called the VHF band, and was once used for all ground-to-air communications with British fighter aircraft. The VHF band has been superseded by the UHF band although some aircraft (but not operational fighters) are still using VHF. In all, about 460 VHF channels were available, of which the Royal Air Force was allotted about 330 (about 40 of these shared with the Royal Navy). These 330 frequencies had to be shared between all users in each theatre; *eg* the peacetime allocation to No 11(F) Group was only about 150 frequencies for all purposes, including airfield control, navigation aids and training as well as fighter direction. The small number of frequencies available in the VHF band did not give enough channels for a fully efficient air defence communications system and the UHF band (*see* para 2561) was therefore adopted for operational ground-to-air communications.

2557–2560. (*Not allotted*).

UHF Band

2561. As mentioned in para 2556 the UHF band (225 to 399·99 MHz) has been brought into service for operational ground-to-air communications. The channel spacing is 50 or 100 kHz, and so the band contains some 1,750 (or 3,500) channel frequencies. These must be shared between all three Services and about 70 of them are needed for various navigation aids. About 800 channels are at present allotted for air force use, and about 200 more are shared with the other Services. The channels are not exclusively given to the Royal Air Force, but are for use by the aircraft of all the NATO powers. To provide enough channels it will still be necessary to double-up on frequencies but wide geographical separation standards have been agreed. For fighter direction channels there is a clear radius of 300 nautical miles around each ground station, which implies a minimum separation of 600 nautical miles between ground stations on a common frequency: 10 per cent is deducted from this for each 100 kHz difference between channel frequencies, so that, for example, two stations on frequencies differing by 100 kHz must be 540 nautical miles apart (the separation for 200 kHz difference being 480 nautical miles and so on up to 600 kHz difference—above that, no limit is prescribed). There are corresponding but smaller separations for airfield approach and for local control channels. It will now be understood that the UHF band is an inexhaustible reserve of operational channels.

a. Vertical polarization is used for communication in the UHF band. There are two main reasons for this choice:

(1) *Ground Reflection.* The gaps in the radiation pattern due to interference from ground reflections are less deep with vertical than with horizontal polarization, and thus there is less danger of their causing a fade of communication at certain points of space.

(2) *Aerial Construction.* It is much easier to make an aerial horizontally omni-directional, as is needed both on the ground and in the air, if the polarization is vertical —the basic construction is simply a vertical rod. Except in short-range work, it is usual for the ground transmitter to radiate more power than the airborne (often about 10 times as much). This is because the airborne receiver, working under far worse conditions than the ground receiver is in practice less sensitive than it; and also the airborne set cannot be large and heavy enough to generate more than about 5 to 10 watts, while there is no such stringent limitation on the ground transmitter.

UHF transmitter and receivers are crystal-controlled, but all those used in fighter direction are so designed that they can be set to any of the channels by using combinations of a small number of internal crystals and without the need of a crystal specific to the channel; the pilot of an aircraft has only 18 preselected channels available to him in flight with the other channels on manual selection. The transmitter frequencies are held stable within ± 7 kHz.

b. Communication in the UHF band is free from static and fading (*see* para 2553) and is thus very reliable. With all but very strong signals the background of receiver noise is noticeable as a continuous hissing or rushing sound. UHF receivers are fitted with muting circuits which cut their gain right down when no signal is being received, so as to relieve the annoyance of a continual noise background between transmissions; they are also fitted with automatic gain control (AGC)—sometimes called automatic volume control (AVC) —which reduces the gain as the signal strength increases, so as to give an almost even output level for all signals above a certain strength.

2562. In spite of the choice of vertical polarization, communication in the UHF band may be seriously affected by interference from waves reflected by the ground. This effect is discussed in more detail elsewhere in this manual, being more familiar to the reader in its radar application. It is rarely noticeable in VHF communication (though of course it is present), but comes into greater prominence at higher frequencies for reasons explained below. It has been shown that the radiation pattern of an aerial mounted h feet above the ground consists of a number of lobes and gaps; the gaps are generally directions of minimum but not zero field strength, their depth depending on the nature of the ground (land or sea), the radio frequency and the direction of polarization. An aircraft flying away from the aerial will cross the gaps one after another, so that a pattern of maxima and sharp minima will be superimposed on the steady decrease of signal strength with range. The automatic gain control of the receiver will smooth out most of these variations so that they are not heard; but the farthest minimum, arising from the first gap above the horizontal (roughly at elevation $\alpha = 94\lambda/h$), may bring the signal strength down so low that there is a fade-out of communication. This does not ordinarily happen with VHF, but the smaller wave-lengths of the UHF band mean a correspondingly lower first gap and greater likelihood of a fade, particularly over sea at great altitudes; the time taken by a 600-knot aircraft to pass through such a fade may be as much as a minute. Several measures can be taken to avoid this serious loss of communication:

a. *Decrease of Aerial Height.* The lower the aerial, the higher the first interference gap—thus it is desirable to mount the aerial fairly near the ground. But with decrease in aerial height the line-of-sight ranges to low-flying aircraft decrease appreciably, and screening by nearby buildings and trees become more extensive: the aerial height must in practice be a compromise, and cannot normally be less than about 40 feet.

b. *Vertical Beaming.* The signal strength from aircraft at low elevations, where fades may occur, can be boosted by using an aerial with vertical beaming, but this beaming must not be so powerful as to endanger communication with aircraft at higher elevations.

c. *Height Diversity.* A method can be used that is analogous to simple radar gap-filling: two aerials are mounted on the same tower at different heights, each connected to a separate receiver, and the receivers are connected in such a way that at any instant the operator hears only the greater of the two signals.

Fading of communication can also arise from screening of the aircraft aerial, as discussed in para 2580.

Microwave Bands

2563. It is very unlikely that any band of frequencies higher than UHF will be generally used for ground-to-air communications; not only technical difficulties but also the cost and complication of re-equipment would oppose such an idea. The great directivity obtainable with microwaves makes them well suited to special methods of communication devised to counter jamming. The object of such methods is to direct a microwave beam on to the friendly aircraft by radar, and then apply to the pulses some form of modulation that can be converted back to speech by a simple receiver in the aircraft. No such system is in service with the Royal Air Force.

Ground Installations

2564. Ground VHF equipment is not in general use for fighter direction and will not therefore be described.

2565–2566. (*Not allotted*).

2567. VHF ground aerials are normally vertical wide-band dipoles built in cage shape, which are mounted in static installations on 90-ft wooden towers and in mobile installations on 50-ft guyed tubular-steel masts. A wooden tower can carry up to eight dipoles, but a guyed steel mast holds only two. UHF ground aerials are generally less easily recognizable as dipoles, though they work in a similar manner and are also broad-banded. There are two main types: the equivalent of a single vertical dipole with a broad vertical radiation pattern, for short-range use, and a stack of four vertical cage dipoles arranged to give a beam with 5 dB gain at 6° elevation, for long-range working (*see* para 2562)—this is a large and cumbersome array. They are generally mounted at about 40 feet on existing towers. VHF and UHF aerials can serve either for transmission or for reception. Coaxial feeders are used between the aerials and the transmitters or receivers, and the design of the aerials makes both matching and radiation reasonably even over the band in question. One aerial must be used for each transmitter, and one for each receiver. Separate transmitter and receiver towers are used, and the transmitting and receiving sites should be at least a quarter of a mile apart.

2568. It is desirable to place VHF and UHF aerial masts away from any large buildings or radar aerials and on the highest ground in the neighbourhood; so the transmitters and receivers, which must be close to their aerials, are operated by remote control through land lines. The speech currents from the controller's microphone are carried by a line pair to the transmitter, and the same pair can be made to carry a keying voltage which switches on the transmitter when the "transmit" key is pressed. The speech currents and noise that form the output of the receiver are carried to the operations building by another line pair, and may then be amplified again and distributed to loudspeakers or headsets for controllers' and monitoring positions. Thus two line pairs are used for each channel, and at each controller's or monitoring position it is possible to select any one of the channels in use; for each channel a transmitter and receiver are continuously available. The British UHF equipment offers the remote selection of any one of 12 pre-set channels for each transmitter and receiver; it would not be practical to bring the channel-selection switches out to each console, and they are usually placed together in a position near the master controller so that a central control of channel allocation can be maintained.

2569. In spite of the spacing between the transmitter and receiver aerials each receiver will pick up a very strong signal from the corresponding transmitter when it is switched on, and if the loudspeaker and microphone are at all close to one another any slight vibration from the receiver will be passed through the microphone, modulate the transmitter, be picked up by the receiver in amplified form and pass round the closed circuit being amplified more and more in a snowball effect. This will cause a high-pitched howl or whistle which may be loud enough to drown all communication—a condition called acoustic feedback. To avoid it a device is usually provided to cut down the gain of each receiver channel whenever the corresponding TRANSMIT key is pressed. If there is no such device, the feedback must be removed by careful adjustment of the receiver channel gain and the positions of microphone and loudspeaker.

2570. Receivers can usually be left unattended, since they are very stable, but transmitters should be manned. It must be possible for mechanics to control the transmitters locally when tuning and making adjustments, and each transmitter has a LOCAL-REMOTE switch which allows keying and modulation to be performed either by the mechanic on the site (LOCAL) or in the way described in para 2568 (REMOTE). The output of the transmitter and receiver can be monitored locally without interrupting remote working.

2571. Power for VHF and UHF ground transmitters and receivers is normally obtained from the main electricity supply in static installations, and from diesel-driven alternators (AC generators) in mobile installations. Such alternators are also often provided at static installations, as a standby against mains failure. Many diesel alternators now have automatic starting devices, and can be brought into use on full load in less than a minute, though they are not entirely stable for the first hour: hand starting normally takes rather longer.

Aircraft Installations

2572. VHF equipments are not generally installed in fighter aircraft and will therefore not be described.

2573. **UHF.** Aircraft UHF sets are combined transmitter-receivers. The set installed in British aircraft is the ARC–52 set whose power output is about 20W. Eighteen channels can be pre-set in less than five minutes (while the aircraft is on the ground, but without removing the UHF set) to any of the channels in the UHF band without need of any external crystals. An aircraft installation contains one such UHF set with one or two broadband aerials; the pilot has a control unit with a switch enabling him to select any one of the 18 pre-set channels (plus a guard channel of 243 MHz, the international emergency channel) with not more than six seconds' delay, or a twentieth "manual" which can be rapidly set in the air to any channel in the UHF band by adjusting four dials. AGC and muting are provided, also the means for transmitting a steady tone modulation (MCW), which is useful in obtaining a fix. The pre-set channels are numbered from 1 to 18 and G, and the channel numbers are used to identify the frequency over the RT. The channel spacing on this equipment is 100 kHz. A second receiver in this equipment is always listening out on the guard frequency.

Combined UHF/VHF

2574. Combined UHF and VHF transmitter receivers are also in use in some fighter aircraft, these are:

a. *PTR*175. Similar to the ARC–52 set in that there are 18 pre-selected channels plus the guard channel, with a twentieth "manual" position whereby any channel can be selected by setting four dials. The frequency coverage is 117·5 to 135·95 MHz (VHF) and 225 to 399·95 MHz (UHF) channel spacing 50 kHz.

b. *PTR*177. Similar to the PTR174 except that the guard receiver is removed and data link facilities used in its place.

Data Link

2575. Due to the increase in speed of modern aircraft and the additional operational complexity, the current methods of air control based on human decisions and radio-communication, are becoming impracticably slow. This is particularly true in the case of high speed fighter aircraft where time margins are becoming so small that interceptions using radio-telephony control may eventually become almost impossible. The UHF data link is a communication system whereby information and commands are transmitted direct from the radar computers to the aircraft being controlled. The function of the link is to control the flight path of the aircraft in such a way as to bring it within the airborne radar lock-on range of an assigned target in the minimum of time and at a suitable position for attack. This flight path is calculated by the interception computer from information supplied by the ground radar system. The computer feeds complete messages to the data link equipment; these messages contain information to be passed to the aircraft where they are displayed visually on the flight instruments and the airborne radar.

Cover

2576. Radar cover is discussed elsewhere in this manual: VHF and UHF communications use wavelengths within the range considered there, and hence they are essentially subject to the same limitations. In applying the conclusions of the text, however, one must remember that a communications link is one-way, involving no reflection; the received signal power at a range r is proportional to $1/_r{}^2$ and not to $1/_r{}^4$, that is to say it falls off far less rapidly with increase of range than in primary radar. Immediate consequences of this are that adequate vertical coverage can usually be obtained with a simple dipole aerial having little gain, that large transmitter power is not needed (except for countering jamming), and that the gaps caused by interference from ground reflections do not generally cause loss of communication (*see* para 2563 for the exceptions to this). But straight-line propagation affects VHF and UHF communications almost exactly as it affects radar, by imposing limitations on the range attainable and by leading to screening. Apart from straight-line limitations, which are discussed below, it may generally be taken that reliable communication ranges up to about 200 nm are practicable on VHF; with the higher powers and improved design of UHF equipment one may count on ranges up to about 250 nm. Greater ranges than these are rarely practicable along a line of sight.

2577. The theory of the radio horizon is explained elsewhere in this manual, and it is shown that with normal atmospheric refraction the maximum possible range between a ground aerial at height h feet and aircraft at height h_t feet is given by:

$$\sqrt{2h} + \sqrt{2h} \quad \text{statute miles}$$
$$\text{or } \sqrt{1{\cdot}51h} + \sqrt{1{\cdot}51h} \quad \text{nautical miles}$$

The table below gives as an example, the figures of greatest possible ranges from an aerial on a 90-ft tower sited on level ground:

Aircraft Altitude (ft)	*Maximum Possible* Range (nm)
0	12
50	20
100	24
200	29
500	39
1,000	50
2,000	67
5,000	98
10,000	134
20,000	185
40,000	258
60,000	313

Maximum ranges vary with changes in the weather. Beyond the quoted maximum ranges (*ie* in the diffraction zone) the signal power falls off very rapidly indeed, and even a tenfold increase in transmitter output will hardly increase the range by more than a mile or so. The reader will realize that some extra cover, particularly valuable in the control of low-flying aircraft, can be had by choosing a VHF or UHF site on high ground; this is an advantage that should always be used. In the absence of high ground it may be possible to use higher aerial towers, or an additional site nearer the region where cover is needed, with remote control through longer landlines than usual or through a microwave radio relay. Such an installation is called a forward relay.

2578. Absorption of radio waves by heavy rain-clouds may cut down the strength of VHF or UHF signals, but only very rarely does it interfere at all with communications. Ranges may be extended beyond the normal radio horizon by anomalous propagation; this phenomenon is more likely at the higher frequencies, but is rare in temperate climates, where it is unusual for a duct to be formed that would be deep enough to trap such waves. A freak condition of the ionospheric E layer, called sporadic E, may cause it to reflect VHF radio waves, and sky-wave transmission then becomes possible, giving ranges far beyond the normal; but this is very rare for frequencies over 100 MHz. Abnormally high communication ranges may also be given by tropospheric scatter, but scatter-propagation signals are usually too weak to be detected by ordinary receivers.

2579. Buildings and other large objects near VHF and UHF aerials cast shadows in the radiation, since they are not transparent to radio waves and the diffraction round their corners is not very marked (the wavelengths ranging from 2½ to 10 feet). Thus unless the aerials are sited well away from all such obstructions they may be partly screened in some directions. If the aerial masts are not higher than all the surrounding ground, hills may give a similar screening. It is important to remember this when siting VHF aerials, and still more important with UHF aerials since screening is more complete at the higher frequencies.

2580. The radiation pattern of an aircraft VHF or UHF aerial should be omni-directional, but it is always distorted to some extent by interference from reflections off the metal skin of the aircraft. It is also possible in some positions of the aircraft for its wing or fuselage to screen its aerial from the ground aerial. Both these effects cause a variation of signal strength with aircraft attitude, though this may only occasionally be noticeable at VHF. The effect is generally more severe at UHF and some aircraft must have two UHF aerials in different positions on the airframe, which cannot be energized both at once but are selected by the pilot to give the best result when screening is suspected.

2581–2584. (*Not allotted*).

GROUND-TO-GROUND RADIO COMMUNICATION

Choice of Frequency

2585. Ground-to-ground radio communications are used by C&R systems only in:

a. Tactical operations.

b. Standby for lines.

c. Micro-wave data links.

Ranges up to several hundred miles may be needed. Because of its speed RT is preferable for most operational traffic; but some messages, such as combat reports, may be satisfactorily sent by telegraphy.

2586. The VHF and UHF techniques already described are reliable but give only short ground ranges; other methods of propagation are needed for long-range work. These are the following alternatives:

a. *Diffraction and Ionospheric Reflection.* Radio waves at frequencies below about 30 MHz can be reflected by the ionosphere, and the resulting sky-wave transmissions can give ground ranges up to thousands of miles; the diffracted ground-wave transmission gives useful ranges beyond the radio horizon, increasing with decrease of frequency. These forms of propagation have hitherto been relied upon for long-distance radio links, and the operating frequencies have been in the HF band (3 to 30 MHz, 10 to 100 metres; often called the short-wave band). Longer waves than these have not been used because of the scarcity of channels in the lower frequency-bands.

b. *Forward Scatter.* Long-distance HF links are subject to deep fading and diurnal variation through changes in the ionosphere, and are not very reliable; while their useful bandwidths are generally not great enough for them to carry RT. It has been proved that reliable beyond-horizon radio links of ample bandwidth can be established by using the forward-scatter propagation of radio waves at frequencies greater than 25 MHz, and such techniques will be applied to fixed long-distance communications. They are not suitable for tactical use, because of the bulk of the terminal equipment and the complication of the setting-up. Forward scatter links are not proof against jamming or interception, but their directivity makes them more secure than HF links.

c. *Micro-Wave Links.* These are links whereby high-gain dish-shaped aerials are used pointing directly at one another with the distance between these aerials being anything up to 70 miles. There can be a series of these links to form a long distance chain. The frequencies used for these links are in the micro-wave band (3,900 to 4,200 MHz and 4,400 to 4,800 MHz) and they can carry either RT or telegraphy. Some of these links may carry as many as 240 channels. Although such a link appears secure from interception the signals can in fact be usefully picked up by a sensitive receiver as far as 50 miles behind the transmitter aerial.

HF Communication

2587. Because of the variation in the height and the nature of the layers of the ionosphere from day to night, the skip distance for each frequency varies greatly over the 24 hours, and for a link between any given two points there is a maximum usable frequency (MUF) varying with the time of day. It is general to have two frequencies for each channel of communication, a day and a night frequency.

2588. HF radio communications are also much afflicted with fading at all points that can be reached by the sky-wave—most severely near the edge of the dead space, where a slight change in the ionosphere may make the waves completely miss the receiving aerial. Fading may show itself as continual change in signal strength, slow or rapid, while in magnetic storms (usually associated with strong sun-spot activity) signals may fade out entirely for several hours. Fading may sometimes affect only very narrow bands of frequencies, which may fall within the modulation sidebands of a transmission, and it then gives distortion of RT which is often so severe as to make speech quite unintelligible—this is called selective fading. Because fading depends on the difference in length between two or more transmission paths, it is never the same at all places; and if two or more receiving aerials are used, spaced at about half a mile apart, then there will very often be a usable signal from at least one of them; the automatic selection of the strongest of a number of such signals is called diversity reception and is one standard method of combating fading, though not always practicable. Fading can also be very effectively countered by the use of single-sideband modulation (*see* para 2594) which makes long-distance HF RT quite reliable.

2589. Static (*see* para 2553) affects communications on HF and since it is propagated both by ground-wave and sky-wave it can disturb reception thousands of miles from its point of origin. Like noise it is distributed over a wide range of frequencies, though not so regularly, and its effect on radio reception can therefore be reduced by narrowing the bandwidth of the receiver. Thus weak telegraphy signals are easier to make out than weak RT, partly because they occupy a smaller band of frequencies and the receiver can use a smaller bandwidth.

Forward Scatter

2590. Ionospheric scatter of radio waves at frequencies in the range 25 to 60 MHz can be used over paths between about 500 and 1,200 miles in length. A high-power transmission is radiated from a beamed aerial aligned so that its main lobe is directed towards a point in the E layer about 280,000 feet (46 nm) above the mid-point of the great circle path. The receiving aerials (generally two for diversity, about 20 wavelengths apart) are similar and directed to the same point. Low-noise receivers are used, but at these frequencies the output noise level is largely determined by cosmic noise. The signals are normally 40 to 80 dB weaker than those that would be received at an equal distance by a line-of-sight path, and are subject to multi-path fading at rates between $\frac{1}{3}$ hertz and 10 hertz (largely cancelled out by the diversity reception); there are frequent irregular bursts of very intense signal associated with meteors, and several effects associated with auroral activity and abnormal states of the ionosphere. The level of the received signals does vary throughout the day and with the season, but never "drops out" catastrophically; hence it is possible to set up a reliable continuous link. Ionospheric scatter links will generally have bandwidths not greater than about 20 kHz and be used for multi-channel; they are also capable of carrying high-quality RT.

2591. Tropospheric scatter links have been proved and operated over paths up to about 400 miles at 4,000 MHz. The technique is rather similar to that for ionospheric scatter, though here the high-gain aerials are directed to a common mid-point in the troposphere, cosmic noise is not important, and meteor effects are uncommon. If large enough transmitter power and aerial gain are available, a tropospheric link can have a bandwidth up to 10 MHz and be very reliable; it may be used for carrying a large number of speech or telegraphy channels, or could possibly serve for a radar link—television pictures of excellent quality have been received by a link nearly 200 miles long.

Telegraph Communication Systems

2592. The simplest telegraphy system is CW Morse. When this is produced by hand keying, it requires only quite simple equipment and is thus very flexible for tactical use, though calling for skilled operators. Practical operating speeds, however, cannot be much greater than 20 words a minute; hence it is rather a slow means of communication and allows only a low traffic capacity. Machines have been used to produce high-speed Morse; they remove the disadvantages associated with hand keying but have less flexibility, being no more flexible but rather more complicated than five-unit teleprinter machines, and are no longer used in the Royal Air Force.

2593. The five-unit code mark-and-space signals generated by a teleprinter (*see* para 2525) can be modulated on radio waves in several different ways to give a radio teleprinter system. This is now the standard for long-distance ground-to-ground communication in the Royal Air Force throughout the world. It has a great traffic capacity, can be made most reliable, and needs only moderately skilled operators; but the terminal equipment is rather heavy and complicated, and may not be very suitable for tactical use.

RT Communications Systems

2594. HF RT must be carried by amplitude modulation, since there is no room for the wide sidebands of frequency modulation. A simple amplitude-modulated wave consists of an unmodulated carrier wave plus two sidebands, one on either side. A large proportion of the output power is in the carrier frequency, which carries no information at all. All the information could be conveyed by transmitting the sidebands only (or even just one of them, since they are equally spaced about the carrier) provided there were some means of re-creating the carrier in strength at the receiver. This would give a more efficient use of the power that the transmitter can generate, and if only one sideband were used it would halve the bandwidth of the transmission. Circuits have been designed to make this extraction and re-creation of carrier and sideband possible, and systems using the principle are called independent-side-band (ISB) and single-sideband (SSB). SSB can be obtained with quite simple equipment, and gives vastly greater signal-to-noise ratios and freedom from fading on HF than the normal amplitude modulation. It has been shown to give reliable and clear RT at distances greater than 500 miles.

CHAPTER 26

AIR DEFENCE AIRCRAFT AND THEIR EQUIPMENT

CONTENTS

INTRODUCTION

2601. This chapter contains restricted information on the operation of certain Air Defence aircraft and details of their equipment. Further details of some of the above aircraft and equipment may be found in Control and Reporting 1.

FIGHTER OPERATIONS

2602. **Performance Requirements.** Four aspects of performance in which the defensive fighter should excel are:

a. *Ceiling*. The fighter should be capable of intercepting at all altitudes from sea level up to the maximum operating altitude of likely targets.

b. *Rate of Climb*. A fighter scrambled to intercept an enemy raid must be able to gain sufficient altitude to launch an attack before the enemy aircraft reach the point of weapon release for their free fall bombs or stand-off air-to-surface missiles. This requirement and the delay between the initial detection of an enemy raid and the scrambling of fighters impose a need for the fighter to have a very high rate of climb. A high rate of climb means that:

(1) Targets can be intercepted earlier, thus giving more time to assess the threat.

(2) Pilots have a better chance of attaining a position from which they can recognize an unidentified aircraft ("visident") and if proved hostile, to gain an advantageous position. The latter is of particular importance in fighter versus fighter tactics and if armament is restricted to guns or free-flight aircraft rockets.

c. *Speed*. The greater the speed advantage of the fighter over the target, the greater will be the distance at which the target is intercepted, and more time will be available to correct errors or for countering evasive action. Speed superiority is especially important for fighters armed with guns or free-flight aircraft rockets, where the maximum firing ranges are small. Speed advantage is not quite so important for fighters armed with guided air-to-air missiles. Such fighters have more flexibility because the missiles normally have a high speed advantage, greater range, and can be launched from a wider variety of attack positions.

d. *Manoeuvrability*. Ideally a fighter should have a constant radius of turn at all altitudes, and this radius should be as small as possible. In practice however the radius of turn varies with altitude and speed. Good manoeuvrability is needed to enable the fighter to:

(1) Correct errors quickly without loss of performance.

(2) Counter target evasion.

(3) Evade successfully from enemy fighter or SAM attacks.

NAVIGATION SYSTEMS

2603. Fighter aircraft are fitted with one or more of the following navigation systems:

a. Inertial Navigation.

b. TACAN.

c. Distance Measuring Equipment (DME).

d. Radio Compass/ADF.

In addition, Violet Picture (*see* para 2610) is fitted to many interceptor aircraft and can be used to provide navigation information.

Inertial Navigation Systems (INS)

2604. INS are the newest development in the field of navigation aids. A stable platform, comprising sensitive accelerometers, is kept horizontal to a high degree of accuracy. The accelerometers measure an aircraft's acceleration using integrators; velocity, and then (using a further integrator) distance can be calculated. The aircraft is then provided with the information required to compute its position continuously. Furthermore accurate velocities are available with which to calculate release conditions for weapon delivery. Because a stable platform is required to compute the accelerations made in the INS, the aircraft has a very accurate attitude reference as well.

TACAN (Tactical Aid for Control and Navigation)

2605. TACAN is a navigation aid which provides the airborne user with easily interpreted information giving the bearing and distance of the aircraft from a transponder beacon on the ground, on a ship, or in another aircraft. It can also provide bearing and distance from an offset position which has been selected and whose range and bearing from the TACAN beacon are known. It involves the use of a ground or ship-borne responder beacon and of an interrogator-receiver, with associated display equipment in the aircraft, working at a frequency of about 1,000 MHz. The transmissions from the beacon are pulse modulated in such a way that the aircraft interrogator can measure both the bearing and the distance of the beacon, and display them on conventional meters or feed the information to an integrated navigation display. Ranges up to 200 nm can be displayed. Range accuracy is $\pm 0{\cdot}25$nm $+0{\cdot}2$ per cent of range at distances above 5 nm and 5 per cent of range below 5 nm. Bearing accuracy is $\pm$ (1 +tan a°), where a is the elevation of the aircraft relative to the beacon. The beacon has a maximum capacity of about 100 aircraft at one time for range information, but bearings are always obtainable within range since the aircraft equipment does not have to interrogate for these.

DME (Distance Measuring Equipment)

2606. DME indicates the sight-line distance of the fighter from a selected ground beacon. and, if the beacon signal is strong enough, an indication of which way to turn to home onto the beacon. A fix can be obtained by:

a. Ranges from two separate beacons.

b. Range from a beacon and an RT DF bearing.

c. Range from a beacon and a radio compass bearing.

2607. DME involves the use of a radar transmitter/receiver set in the aircraft together with time measuring equipment, and an indicator (Rebecca 7 or 8). The aircraft transmitter sends out a pulse on the frequency of the selected ground beacon (Eureka 7). This pulse triggers off a response from the ground beacon on a different frequency which is received by the aircraft equipment. The time interval between transmission by the aircraft and receipt of the triggered-off response is measured and displayed to the pilot on a dial as a range in nautical miles. With Eureka Mk 7/Rebecca Mk 7 or 8 equipment, ranges up to 200 nm should be obtainable provided the aircraft is above 25,000 feet. Accuracy is ± 2 per cent of range. The set in each aircraft will operate with most Eureka beacons no matter where they are located geographically. DME can, of course, be used as a landing approach aid.

Radio Compass

2608. A radio compass is carried in some fighter aircraft. It provides an automatic indication of the relative bearing of the transmitter of any radio signal received in the range 200–1,700 kHz and simultaneous aural presentation of the RT or CW signal. With low-powered MF beacons the range of the equipment is about 60 nm. This range increases with the power output of the transmitter. Ranges of over 200 nm can be obtained from high-power broadcast stations. On powerful broadcast stations the probable accuracy is $\pm 1°$ by day or $\pm 2°$ by night up to a range of 150 nm. With low-powered MF beacons the accuracy is about $\pm 2\frac{1}{2}°$. Radio compasses can be made unreliable by enemy jamming. Approach and let-down to an airfield is possible using radio compass as landing approach aid.

2609. **Automatic Direction Finding (ADF).** ADF is akin to a radio compass, but uses an interceptor's normal UHF receiver to provide bearing indications of UHF transmitters.

Violet Picture

2610. Violet Picture is a homing equipment used in conjunction with an interceptor's UHF transmitter/receiver set to provide homing indications which are displayed on the ILS indicator. The frequency range of the equipment is 225–400 MHz. It operates only on spot frequencies as selected on the aircraft's transmitter/receiver, but will accept CW, RT and noise jamming signals. Violet Picture may be used in the following roles:

a. As an air-to-air homing facility between aircraft on the same frequency.

b. To enable an aircraft to home onto a ground UHF transmitter.

c. To enable an interceptor to home onto a target which is jamming on a known UHF frequency.

d. To enable an aircraft to home onto a search and rescue beacon equipment (SARBE) in air sea rescue operations.

The equipment gives homing indications left or right of the interceptor's fore-and-aft centre line. No range information can be obtained from the equipment, but an indication is given when the aircraft is directly above or below the homing transmitter, and the elevation of a target relative to the interceptor is also indicated.

LANDING APPROACH AIDS

Instrument Landing System

2611. Most fighter aircraft are fitted with the Instrument Landing System (ILS). Two refinements of the basic ILS, Zero Reader or Auto/ILS, may also be fitted. The ground equipment consists of:

a. *Runway Localizer*. This is a transmitter situated at the up-wind end of the runway that "beams" two overlapping field patterns, one each side of the runway. The line of equal signal intensity, where the two beams overlap, can be taken as the extended centre-line of the runway, and can be received between 17 and 25 miles from the runway when approaching the airfield. The signals received in the aircraft are used to actuate a vertical ammeter needle and show the pilot his position in azimuth relative to the centre-line of the runway.

b. *Glide Path Transmitter*. In the same way as the localizer is beamed in the horizontal plane, so the glide path transmitter is beamed in the inclined vertical plane, and the signal of equal intensity denotes the glide path. This can be received up to 10 miles from the airfield, and actuates a horizontal ammeter needle to show the pilot his position relative to the set glide path angle.

c. *Marker Beacons*. To provide range check points, two ground transmitters or master beacons radiate narrow vertical beams which indicate to the pilot, by means of a flashing light on the instrument panel or aurally in his headphones, his distance from the runway. The outer marker, normally situated 5 miles from the touch-down, gives two low-pitched dashes per second, and the middle marker, normally situated about 1,000 yards from touchdown, gives high-pitched dots and dashes.

~~The ILS approach is described in Chap 27, para 2766.~~

2612. The Zero Reader coupled with ILS reduces instrument flying fatigue by eliminating the mental processes of co-ordinating information from several separate sources. It indicates to the pilot whether to turn, climb, or descend to maintain a set flight path, whereas the "raw" ILS only tells the pilot where he is in relation to a desired flight path.

2613. Auto/ILS is a further refinement and, with little or no action on the part of the pilot the system will fly the aircraft virtually to the break-off height. The auto-pilot uses information received from the ILS system to control the aircraft.

Airborne Radar Approaches

2614. The AI equipment in the modern fighter can assist in making an approach to the runway. If special radar reflectors are set up at the ends of the runway the approach can be a very accurate one. This means that the fighter can land at an airfield in poor weather conditions without any outside control assistance, other than that required to ensure adequate spacing between aircraft. The Phantom, with a short range, expanded scale radar mode, is especially well equipped in this respect.

Ground Controlled Approach (GCA)

2615. Interceptor fighters frequently make use of GCA as a landing approach aid. No extra equipment is required in the aircraft for a GCA as all interpretation is carried out on the ground and the pilot is directed by the ground controller through normal RT messages. ~~GCA is described more fully in Chap 27, para 2767.~~

AIRCRAFT

Lightning F Mk 2A

2616. The Lightning F Mk 2A is a twin-engined supersonic single-seat fighter currently operated by the RAF in Germany.

2617. **Performance.**

a. *Fuel.* 10,608 lb of fuel are carried giving a maximum sortie length of 85 minutes. Ultimately, endurance depends on speed and duration of attacks and range operated from recovery base. The aircraft can be fitted with an air-to-air refuelling probe.

b. *Scrambling.* Telebrief is fitted and a fully armed aircraft from wheels rolling can reach 25,000 ft in 2 mins, 55 secs without reheat (using 1,500 lb of fuel) or in 2 mins, 6 secs with reheat (using 1,948 lb of fuel). Full climb data is given in the Lightning F Mk 2 Operating Data Manual.

c. *Airborne.* The maximum speed with or without missiles is 1.7M/650 kt—whichever is reached first (with probe 625 kt) and the minimum practical operating speed 220 kt. The ceiling is 56,000 ft as dictated by the pilot's breathing apparatus. The tactical height for most medium and high level attacks is 25,000 ft and reheat accelerating data for that level is given below:

Speed Mach No	1·0	1·1	1·2	1·3	1·4	1·5
Time secs	15	30	55	80	110	150
Distance nm	2	4	9	15	22	32

Note: At 25,000 ft
650 kts = 1.44M

Table 1. Reheat Acceleration (Initial Speed ·9M at ICAO temperature).

d. At low level the Mk 2A is very fast in accelerating, taking only 30 seconds to accelerate from 300 to 600 kt (air temp 10°C) at 5,000 ft. Endurance speed is 225 kt but the ideal speed for tactical CAPs, giving good acceleration without too much fuel consumption, is 300 kt.

e. Full acceleration data is given in the Lightning F Mk 2 Operating Data Manual.

2618. **Weapons System**

a. *Radar.* AI 23 is fitted providing pick-up ranges varying from 20–28 nm at high level, to 5 nm or less at low level.

b. *PAS.* The Pilot Attack Sight, which is a gyro weapon sight, works either in conjunction with the AI radar or manually, and gives ranging and breakaway indications.

c. *Armament.* There are two alternative fits:

(1) Two Firestreak AAMs and two 30mm Aden cannon.

(2) Two 30mm Aden cannon plus two further 30mm Aden cannon in place of the missile pack.

2619. Details of the Aden gun and Firestreak missile are given in paras 2643–2654.

2620. **Radio and Navigational Equipment**

a. *UHF Installation.* Two UHF R/T sets are available, the first giving manual selection of 1750 UHF channels and the second, for emergency and test purposes providing only two channels, 243·0 MHz and 243·8 MHz.

b. *ILS.* Standard ILS is fitted.

c. *TACAN.* TACAN coupled with the offset computer enables a selected homing point to be set in.

d. *Violet Picture.* The VP homer provides indications on the navigation display for homing onto UHF transmissions.

e. *IFF Mk* 10 (*SIF*) *and IFF/SSR.*

Lightning F Mk 3

2621. The Lightning F Mk 3 is a twin-engined supersonic single-seat fighter currently operated by the RAF in the UK.

2622. **Performance**

a. *Fuel.* 7,728 lb of fuel are carried giving a maximum subsonic sortie length of 50

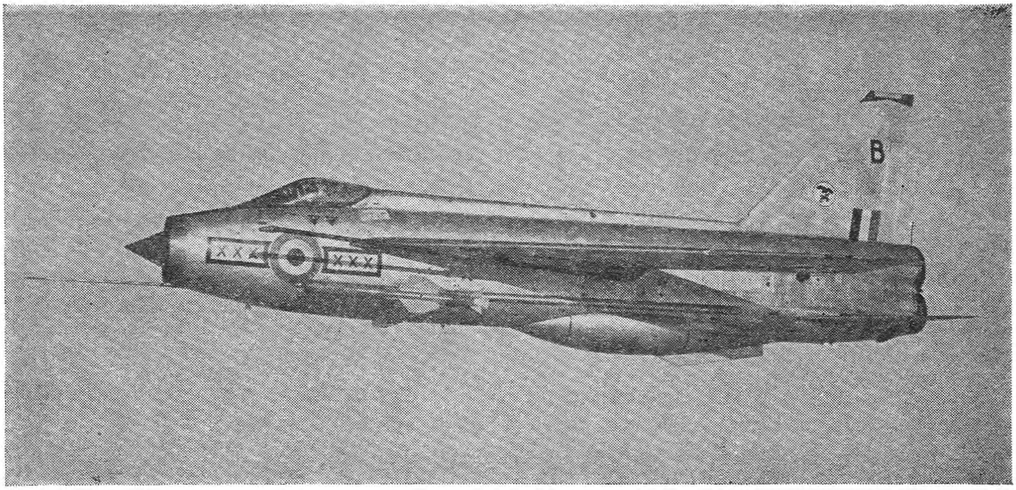


Fig 26-1 Lightning F Mk 3 Aircraft

minutes. Ultimately, endurance depends on speed and duration of attacks and range operated from recovery base. The aircraft can be fitted with an air-to-air refuelling probe.

b. *Scrambling*. Telebrief is fitted and a fully armed aircraft from wheels rolling can reach 25,000 ft in 2 mins, 30 secs without reheat (using 1,300 lb of fuel) or in 1 min, 45 secs with reheat (using 1,680 lb of fuel). Full climb data is given in the Lightning F Mk 3 Operating Data Manual.

Speed Mach No	1·0	1·1	1·2	1·3	1·4	1·5
Time secs	15	24	45	60	72	85
Distance nm	2	5	8	11	14	18

Note: At 25,000 ft 650 kt = 1.44M

Table 2. Reheat Acceleration (Initial Speed ·9M at ICAO temperature).

c. *Airborne*. The maximum speed with or without missiles is 2·0M/650 kt—whichever is reached first, (625 kt with probe), and the minimum practical operating speed is 220 kt. The ceiling is 56,000 ft as dictated by the pilot's breathing apparatus. The tactical height for most medium and high level attacks is 25,000 ft and reheat accelerating data for that level is given below:

d. At low level the Mk 3 is very fast in accelerating, taking only 29 seconds to accelerate from 300 to 600 kt (air temp 10°C) at 5,000 ft.

e. Full acceleration data is given in the Lightning F Mk 3 Operating Data Manual.

2623. **Weapons System**

a. *Radar*. AI 23B is fitted providing pick-up ranges varying between 25 and 40 miles at high level depending on conditions and between 5 miles or less at low level. Details are given in paras 2655–2658.

b. *LFS*. The Light Fighter Sight works with the AI or visually and provides an aiming mark and range. Details are given in paras 2659–2662.

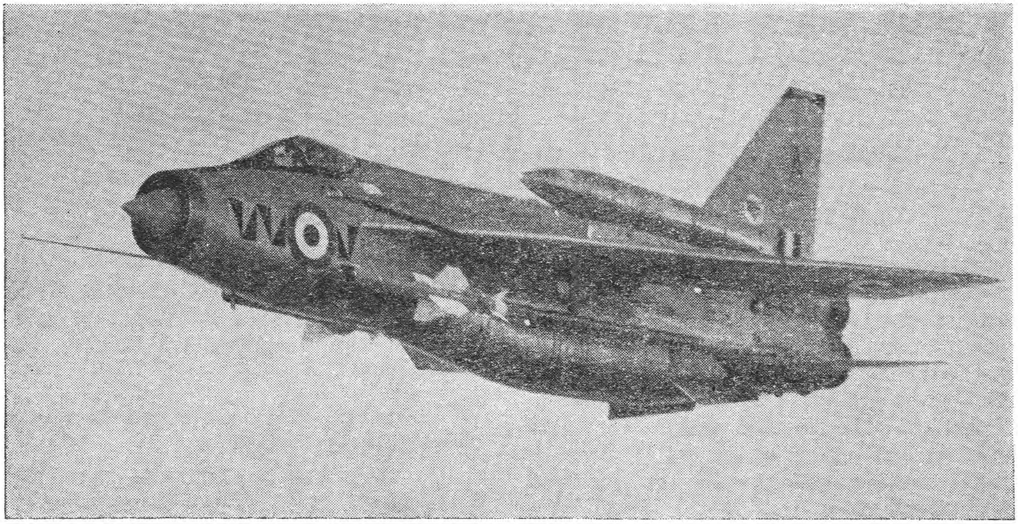


Fig 26-2 Lightning F Mk 6 Aircraft

c. *Armament*. Either two Firestreak or two Red Top missiles may be carried.
Concise details of these two types of missile can be found in paras 2649–2654 and Control and Reporting 1 (SD727), paras 1037–1041 respectively.

2624. **Radio and Navigational Equipment**

a. *VHF/UHF Installation*. Two sets are available, the first giving manual selection of 370 VHF or 3,500 UHF channels and the second, for emergency and test purposes giving only two channels 243·0 MHz and 243·8 MHz.

b. *ILS*. ILS is fitted.

c. *TACAN*. TACAN coupled with the offset computer enables a selected homing point to be set in.

d. *Violet Picture*. The VP homer provides indications on the navigation display for use in homing on to UHF transmissions.

e. *IFF Mk* 10 (*SIF*) *and IFF* (*SSR*) is fitted.

Lightning F Mk 6

2625. The Lightning F Mk 6 is a twin-engined supersonic single-seat fighter currently operated by the RAF in Cyprus and the UK. It carries more fuel than the F Mk 3 resulting in longer supersonic endurance and extended patrol time.

2626. **Performance.**

a. *Fuel*. The F Mk 6 has several fuel configurations as follows:

(1) For combat, guns mounted–10,008 lb.

(2) For combat, guns not mounted–10,608 lb.

(3) For ferrying–10,608 lb plus two jettisonable overwing tanks (OWT) each containing 2,080 lb–total 14,768 lb.

b. On combat sorties the maximum endurance is 85 minutes although this would ultimately depend on speed and duration of attacks and range operated from base.

c. Maximum ferry range at 36,000 ft at ·9M (ICAO) for a fully armed aircraft is 1,600 nm.

d. The aircraft can be fitted with an air-to-air refuelling probe.

e. *Scrambling*. Telebrief is fitted and a fully armed aircraft from wheels rolling can reach 25,000 ft in 2 mins, 54 secs without reheat (using 1,580 lb of fuel) or in 1 min, 54 secs with reheat (using 1,930 lb of fuel). Full climb data is given in the Lightning F Mk 6 Operating Data Manual.

Speed Mach No	1·0	1·1	1·2	1·3	1·4	1·5
Time secs	20	36	55	82	100	125
Distance nm	2	6	10	14	20	25

Note: At 25,000 ft
650 kt = 1.44M

Table 3. Reheat Acceleration (Initial Speed ·9M at ICAO temperature).

f. *Airborne*. The maximum speed with or without missiles is 2·0M/650 kt whichever is reached first (with probe 625 kt, with OWTs ·95M/475 kt). The minimum practical operating speed is 220 kt. Operating ceiling as dictated by the pilot's breathing apparatus is 56,000 ft. The tactical height for most medium and high level attacks is 25,000 ft and reheat accelerating data for that level is displayed above.

g. At low level the Mk 6 is fast in accelerating taking only 36 seconds to accelerate from 300 kt to 600 kt (air temp 10°C) at 5,000 ft. CAP speed is similar to the F Mk 2A and F Mk 3.

h. Full acceleration data is given in the Lightning F Mk 6 Operating Data Manual.

2627. **Weapons System**

a. AI 23C radar and LFS are fitted. Details may be found in paras 2655–2659 and in Control and Reporting 1 (SD 727), paras 1064–1066.

b. *Armament*. Various weapon fits are possible as shown below:

(1) Two Red Top and two 30mm Aden cannon.

(2) Two Firestreak and two 30mm Aden cannon.

(3) Two Red Top only.

(4) Two Firestreak only.

c. Concise details of the Aden cannon, Firestreak and Red Top missiles are in paras 2643–2654 and in Control and Reporting 1 (SD 727) at paras 1037–1041.

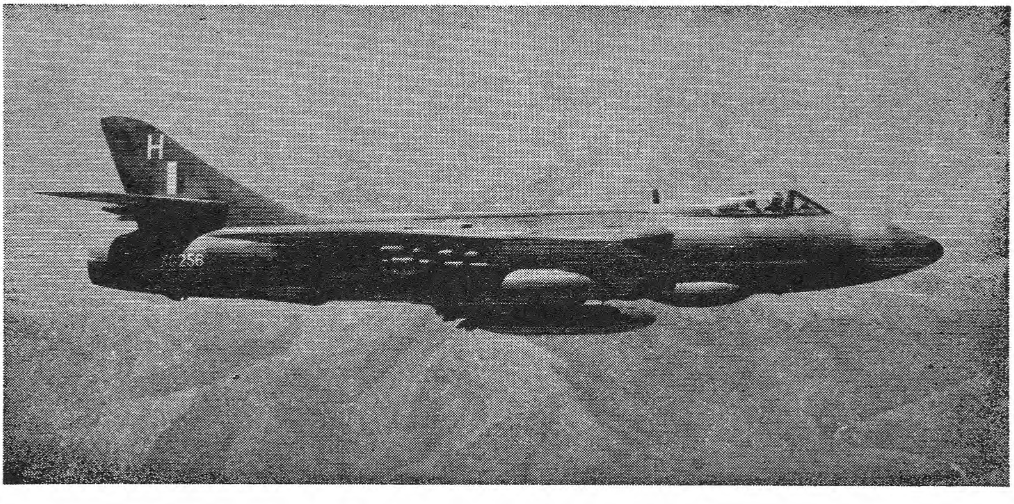


Fig 26-3 Hunter F Mk 9 Aircraft

2628. **Radio and Navigational Equipment.** The same equipment is fitted as to the F Mk 3. In addition, a radio compass may be fitted in the ferry role.

Hunter F Mks 6 and 9

2629. The Hunter is a single-seat day fighter ground attack aircraft.

2630. **Performance**

a. *Fuel*.

(1) *Mk* 6. Internal 3,018 lb; four 100 gallon drop tanks 3,080 lb. Total 6,098 lb. The full load detailed above gives 65–70 minutes endurance depending on height.

(2) *Mk* 9. Internal 3,018 lb; four 230 gallon drop tanks 3,542 lb; two 100 gallon drop tanks 1,540 lb. Total 8,100 lb. The full load detailed above gives 120–145 minutes endurance depending on height.

b. *Scrambling*. Telebrief is fitted. Times to height are given below. Normal climbing speed is 370 kt/·8M.

	10,000 ft		30,000 ft	
	Time (mins)	Distance (nm)	Time (mins)	Distance (nm)
Mk 6, two drop tanks	2½	10	6	40
Mk 9, four drop tanks	3	10	9	60

Table 4. Climb Performance

c. *Airborne*. Limiting IAS is 620 kt converting. At a CAP height of 10,000 ft cruise speed is 300 kt and maximum speed is ·86M. At 30,000 ft the figures are ·8M cruise and ·88M maximum. Full performance data is available in the Hunter Operating Data Manual.

2631. **Weapons System.**

a. A radar ranging gunsight is fitted providing a visual aiming mark for the pilot.

b. Four 30mm Aden cannon are fitted. Details of the Aden cannon are given in paras 2643–2648.

2632. **Radio and Navigational Aids.**

a. *Mk* 6.

(1) Two-channel UHF radio.

(2) DME.

(3) IFF Mk 10 (SIF).

b. *Mk* 9.

(1) Two-channel UHF/VHF radio.

(2) DME.

(3) Radio compass.

(4) IFF Mk 10 (SIF).

2633. **Handling Characteristics.** The Hunter is renowned for its good handling qualities but like most other aircraft it is delicate to handle at height. Turns in the climb should be done as low as possible so as not to degrade the climbing performance above FL 250. Aircraft fitted with four tanks are best employed at low levels because of the Mach limitations and handling characteristics.

Canberra B Mk 2 and T Mk 19

2634. These are variants of a twin-engined light bomber currently employed in the UK for target facilities.

2635. **Canberra B Mk 2.** Accommodation is provided for a crew of three seated in ejection seats; a Rumbold seat, which folds into the starboard wall is available for use by a fourth crew member. There is a prone position in the nose which may be used for observation and map reading.

2636. **Canberra T Mk 19.** Two crew are carried on ejection seats with one passenger on the Rumbold seat. The main difference between the two types is the modified nose of the T19 which was redesigned to accept the AI

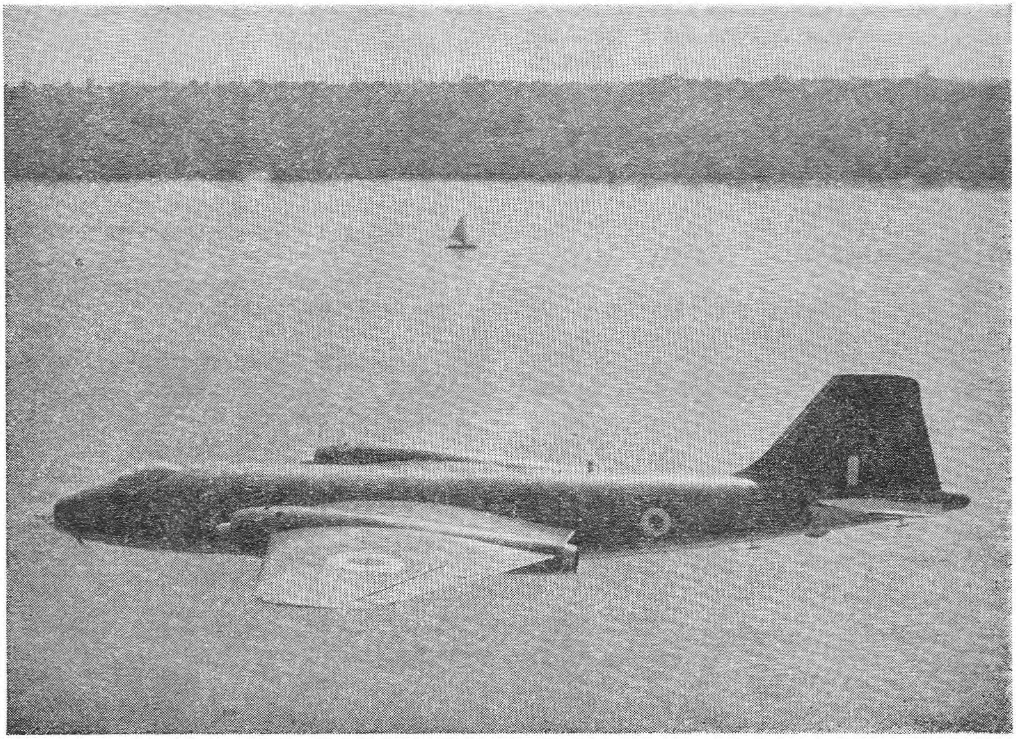


Fig 26-4 Canberra Aircraft

Mk 17A radar when the aircraft was used to train navigators at No 228 (Javelin) OCU in 1964/65. The radar has now been removed and the nose filled with concrete to maintain the centre of gravity.

2637. **Performance.**

a. *Fuel.*

(1) The B2 in normal configuration (internal plus tips) carries 14,920 lb. A bomb-bay tank is available with a further 2,344 lb.

(2) The T19 (internal only) carries 11,016 lb.

b. The T19 is more economical on fuel than the B2 although the normal sortie length for both is similar. For an aircraft on tow at medium level, 80 nm from base, sortie length is approximately 2 hours which would allow about 1½ hours actually on task.

c. **Scrambling.** Climb is normally at 300 kt/·72M; to reach a tow height of 35,000 ft the B2 takes 15½ mins covering 77½ miles, and the T19 11 mins covering 55 miles. Full data is in the Canberra Operating Data Manual.

d. **Airborne.** At 35,000 ft normal cruise is at ·72M. Operational ceiling is 48,000 ft AMSL. Both marks are highly manoeuvreable and it is sufficient to say that the Canberra can turn inside a Lightning at any height up to the operational ceiling.

2638. **Weapons Systems.** No weapons are carried by either the B Mk 2 or T Mk 19.

2639. **Radio and Navigation Aids.**

a. *B Mk 2*

(1) Radio – VHF/UHF on 3,500 UHF and 370 VHF channels. Guard is preselected in the main set and a standby

UHF set provides guard plus one other frequency.

(2) Air Position Indicator with Air Mileage Unit.

(3) ADF.

(4) TACAN.

(5) IFF Mk 10/SIF SSR.

b. *T Mk* 19

(1) Radio – VHF/UHF 18 preset frequencies, 1,750 manually selected frequencies plus one guard channel.

(2) TACAN.

(3) IFF Mk 10/SIF SSR.

Miscellaneous Aircraft

2640. **Lightning F Mk 1/1A.** The F Mk 1 was the original service mark of Lightning. There are still some in service for use as high speed targets, although their AI radar has been removed and the only armament remaining is two 30mm Aden cannons. Additionally the F Mk 1A is fitted with an air-to-air refuelling probe.

2641. **Lightning T Mk 4.** The T Mk 4 is the twin seat trainer version of the F Mk 1. It is not used operationally.

2642. **Lightning T Mk 5.** The T Mk 5 is the twin seat trainer version of the F Mk 3 it can carry two Firestreak or two Red Top missiles, a probe can be fitted and as such the aircraft can be considered fully operational.

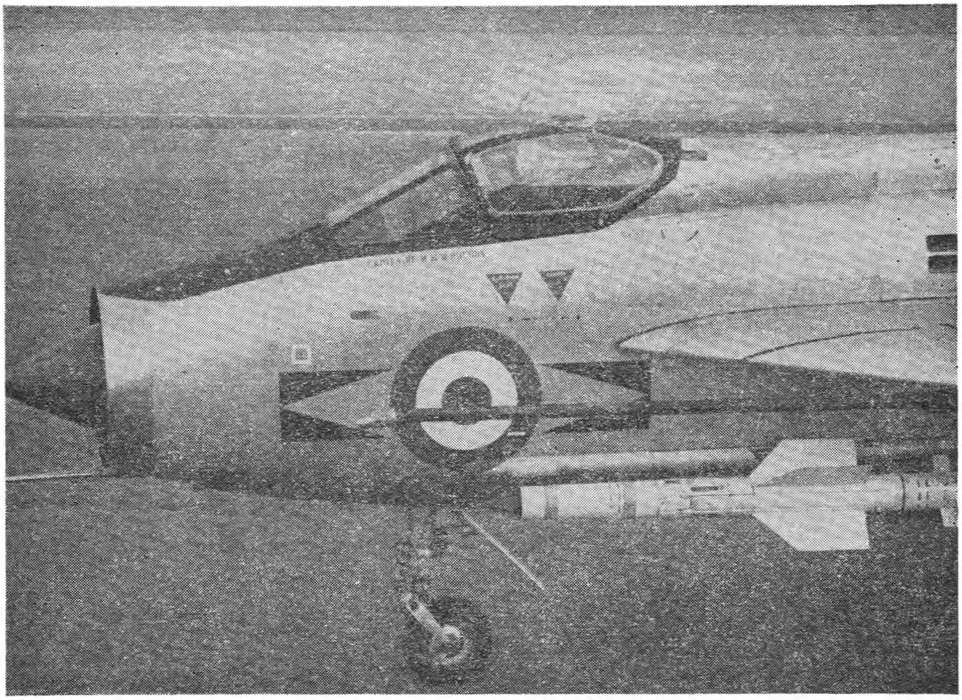


Fig 26-5 Firestreak Missile on Lightning F Mk 3

WEAPONS

Aden Cannon

2643. **Description.** The Aden gun is an automatic machine gun of 30mm calibre with a rate of fire of 1,200–1,400 rounds a minute. It is carried by Lightnings Mk 1/1A, 2A and 6 and the Hunter F6/9. 120 rounds are carried per gun giving 5 to 6 seconds firing time.

2644. **Warhead.** The ammunition is filled with high explosive and is fitted with contact fusing. After firing the shells are armed automatically by the action of the spinning of the shell.

2645. **Range.** The guns maximum effective range is 800 yards, but the ideal is 500 yards.

2646. **Most Suitable Type of Attack.** The best type of attack for the Aden gun is 180° × 10 mile approach, the fighter to finalize in the astern cone of the target, with overtake.

2647 to 2648. (*Not allotted*).

Firestreak

2649. **Description.** Firestreak is a passive homing air-to-air missile designed to operate from sea level to 55,000 feet within ± 10,000 feet of the target. It can be launched at fighter speeds between ·6M to 1·7 M, (with a minimum of 300 kt and 300 feet) and is carried by the Lightnings F2A, F3, F6, T5.

2650. **Warhead.** The warhead is detonated by either a proximity or contact fuse and is self destroying 12 seconds after launch. The casing contains approximately 17 lb of high explosive and the outer case is of a fragmentation design.

2651. **Guidance.** Guidance is based on infrared homing on to jet pipes and hot exhaust. The system is sensitive to sun and clouds and if possible this should be considered when setting-up attacks. After arming, the system fulfils three functions:

a. Pre-launch – search for and detect a target.

b. Pre-launch – indicate target seen to pilot.

c. Post-launch – guide missile to target.

2652. **Ranges.** Firing brackets for different levels are given below.

a. 5,000 feet – ¾ mile to 1¼ miles.

b. 25,000 feet – ¾ mile to 1¾ miles.

c. 35,000 feet – ¾ mile to 1¾ miles.

d. High target supersonic – 1¼ miles to 2¼ miles.

2653. **Most Suitable Type of Attack.** Final approach on a target must be from the stern quarter with the fighter possessing 50–100 kt (low level) or ·2M overtake. Rollout should be in a 20° cone astern the target at 2 to 3 nm, on the target's heading.

2654. (*Not allotted*)

AIRBORNE RADAR AND ATTACK SYSTEMS

AI 23 B/C

2655. The AI 23 B/C is an I-band radar and analogue computer system which, by means of a CRT (B scope) display, enables a pilot to carry out attacks. The system is able to calculate and display an approach course to a position suitable for firing the selected weapon and also indicates when to fire. Pick-up ranges vary from 25–40 nm at high level (depending on target size) to 5 nm or less at low level. Certain extra facilities are provided by the AI 23 C modification. Details of these can be found at para 1064 of Control and Reporting 1 (SD 727).

2656. During an attack the system works in several phases as follows:

a. *Search Phase*. The radar searches for the target in a given sector ahead of the fighter:

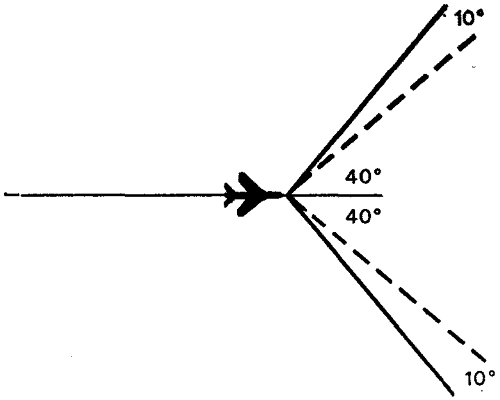
(1) *Azimuth*. Automatic scan through 100° in azimuth.
Targets are increasingly difficult to detect beyond 40° either side of scan and therefore controllers should try to keep targets well within the AI scan whenever possible.

(2) *Elevation*. The scan pattern can be manually directed upwards through 25° and downwards through 10°, relative to the terrestial horizontal, within the ±30° scanner limits:

(3) *Elevation Scan Patterns.* One, two or four bar scans may be selected by the pilot, offering varying degrees of vertical coverage. The pilot is able to select range scales 0–10 nm, 0–40 nm or 20–60 nm but 0–40 nm is normally used. Fig 26–8 shows the B-scope presentation in the search phase.

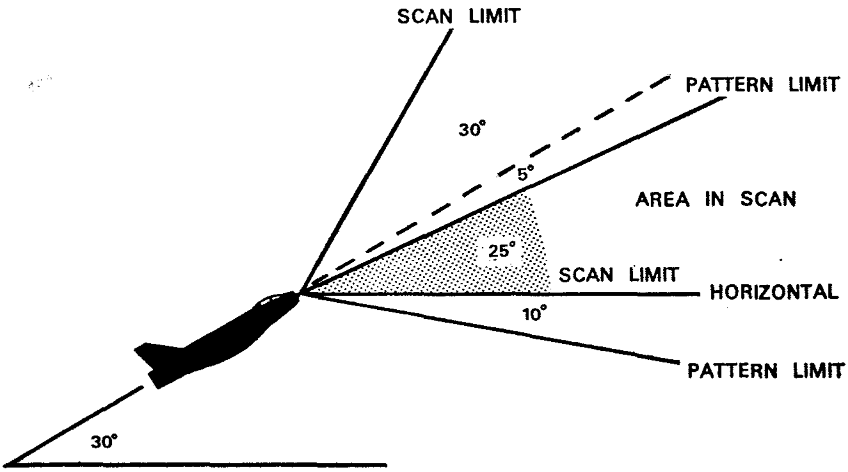
From this initial presentation the pilot is able to calculate approximately the target's heading and height, but not it's speed.

b. *Acquisition Phase.* The pilot marks the target with the acquisition marker and selects "Acquire". The scan pattern now becomes single bar (5·5°) within ±5° of the marker in azimuth. The pilot can now control the 10° scan ±50° in azimuth as well as +25° to −10° in elevation. The object of this phase is to highlight the target with a radar pencil beam so that the pilot can select the Track Phase. Fig. 26–9 shows the B-scope presentation in the acquisition phase.



AZIMUTH PATTERN - AUTOMATIC SCAN THRU 100°

Fig 26-6 Azimuth Scan Pattern (AI 23B)



ELEVATION PATTERN

Fig 26-7 Scan Pattern with Aircraft in 30° Climb

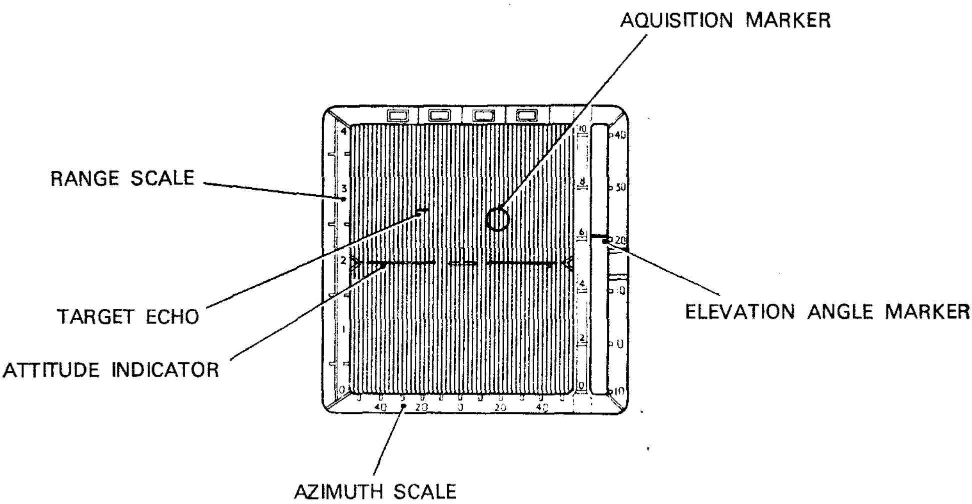


Fig 26-8 B Scope Presentation During Search

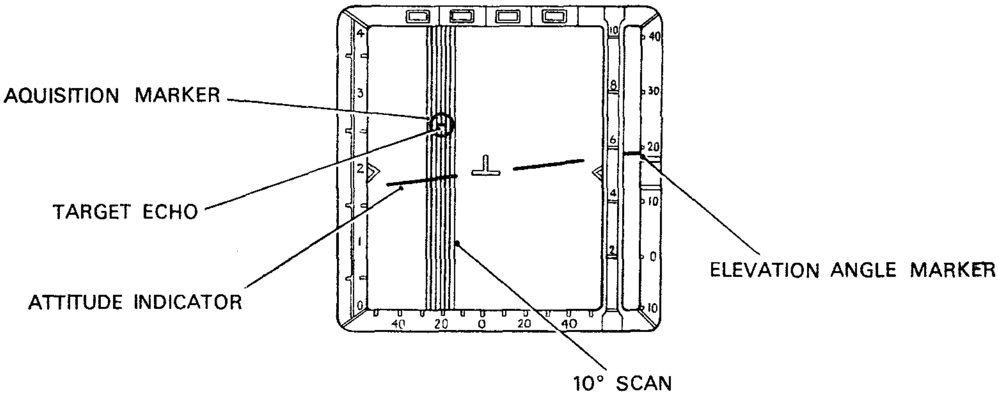


Fig 26-9 B Scope Presentation During Acquisition

c. *Track Phase.* Upon selecting Track, attack information is displayed to the pilot as follows:

(1) Steering signals – by dot and reference circle.

(2) Angle off and range of target – by tracking strobe.

(3) Scanner elevation (from which target height can be calculated).

(4) Closing speed or angle between courses – by the time circle.

(5) When to fire – by the time circle.

(6) Breakaway.

d. *Breakaway.* When the fighter is inside minimum missile release range, the time and reference circles are replaced by a large cross, telling the pilot to break off the attack whether he has completed it or not.

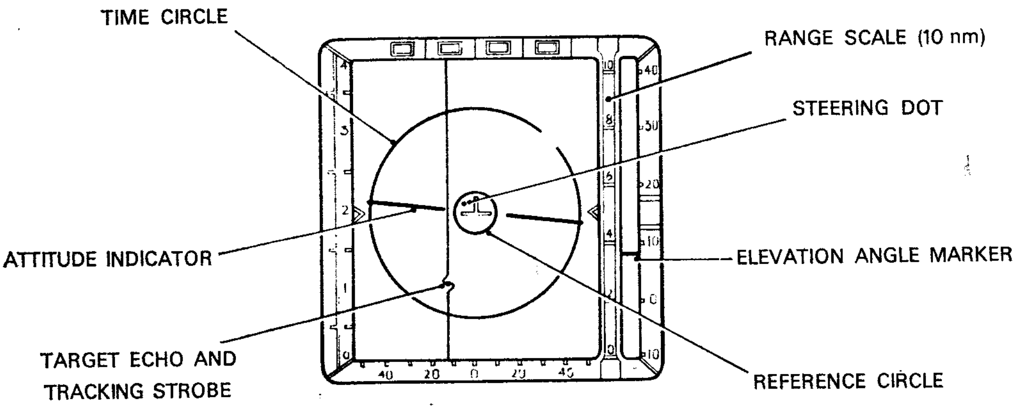


Fig 26-10 B Scope Presentation During Track

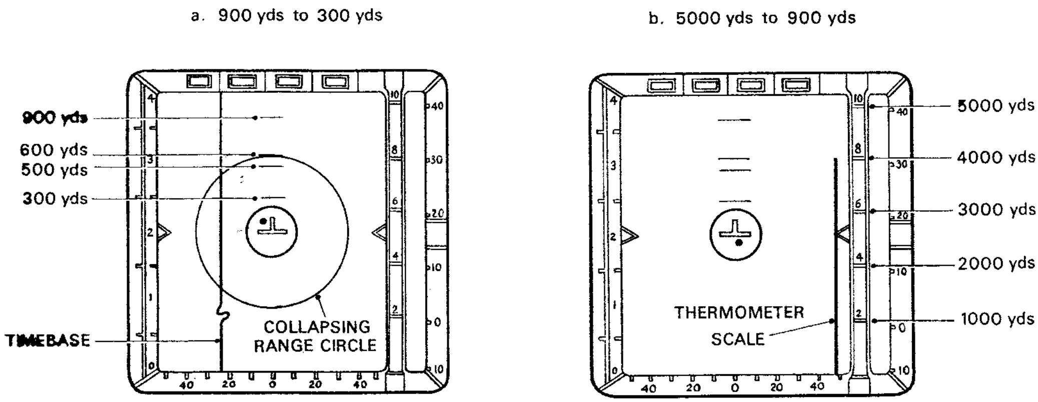


Fig 26-11 B Scope Presentations in the Visident Mode

e. *Visident Mode*. Visident mode permits the pilot to make a controlled approach to the target from 5,000 yards down to 300 yards. Weapons may be fired in this mode. There are two B-scope presentations as shown in Fig 26–11.

E/F Band Homer

2657. The system also provides E/F band homing in the jammed environment. The azimuth of the E/F band jammer is displayed and the computer calculates the quickest approach course. This is fed to the aircraft navigational system. Successful homing can be carried out from ranges of 100–150 nm depending on the height and power of the jammer.

Radar Ranging

2658. The AI radar may be used in conjunction with the LFS to carry out visual air-to-air attacks. The AI radar supplies an in-range signal to the LFS at a range appropriate to the armanent in use.

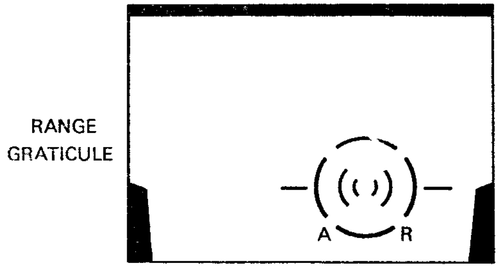
Light Fighter Sight (LFS)

2659. The LFS acts as a standby for the AI 23 B/C and in combat or visual attacks provides an aiming mark. If the pilot knows the target wingspan it also indicates the range. It can be used in conjunction with the AI for gun and missile attacks, in which mode the AI searches for the target and provides an "in-range" signal for the weapon selected. Indication that one or both of the missiles has acquired the target is also displayed. With the AI radar unserviceable, or in a visual attack with guns or missiles, the LFS acts as a gyro prediction sight, and it provides a missile sight line to aim on if the attack is to be carried out with missiles. The LFS is fitted to the following marks of Lightning:

a. F Mk 3

b. T Mk 5

c. F Mk 6



A indicates ACQUISITION R indicates IN RANGE

LIGHT FIGHTER SIGHT - PILOTS PRESENTATION

Fig 26-12 Light Fighter Sight

2660–2675. (*Not allotted*).

PERFORMANCE CHARACTERISTICS

2676. Some brief notes are now given about the characteristic behaviour of modern fighters, but only those points which are relevant to the controller's work are mentioned.

Taxying

2677. Modern fighters use approximately 400 lb of fuel for start-up and taxying, the amount varying with the distance to taxy to the runway. The greatest saving of fuel is made by starting up on the Operational Readiness Platform (ORP), but, time permitting, it is simpler to allow the extra few minutes for taxying and operate from the Aircraft Servicing Platform (ASP). Most fighters have a free-castoring nose-wheel and are steered by differential braking on the main wheels, but steerable nose-wheels are now being fitted, the Phantom being a case in point.

Starting Up

2678. Jet engines are started by a starter turbine which is spun at high speed by gases from a starter fuel called AVPIN. Combustion of the starter fuel is initiated either by a small electrically fired cartridge or high frequency igniter plugs.

Take-Off and Climb

2679. Jet engines need no warm-up or run-up time after starting, allowing immediate take-off, but some time may be necessary for inertial navigation systems to become effective. After take-off the aircraft is held down to allow it to accelerate to its best climbing speed: this indicated speed is maintained at full power until the best climbing Mach number is reached.

2680. The rate of climb decreases as height increases, due to the decreased thrust produced by a jet engine as the air density decreases. This can be offset by the use of reheat if necessary, but an aircraft such as the Lightning or Phantom can even accelerate to supersonic flight without the use of reheat whilst still climbing. Rate of climb at any height is very much dependent upon air temperature: the warmer the air, the slower the climb. Above-average air temperatures on a climb are usually associated with a high tropopause, and so a slower climb. The tropopause is higher in the latitudes near to the Equator and lower towards the poles; a slower climb can therefore be expected in tropical latitudes than in temperate ones.

2681. Although reheat can be used to boost the thrust of the engine, it involves a fuel consumption penalty, and its use must be governed by such considerations as the time available to climb to height.

Accelerations

2682. The best acceleration performance is found near the tropopause, and interceptors normally accelerate at this level.

Manoeuvrability

2683. The steady increase in the size of an aeroplane's turning radius with increase in altitude has already been mentioned. In general, manoeuvrability deteriorates with increasing altitude. At any given altitude an increase in speed normally brings with it an increase in the minimum turning radius.

Range and Endurance

2684. No fighter carries much fuel reserve because added weight costs something in performance. Consequently a main considera-tion influencing pilots' and controllers' tactical decisions is whether a fighter will have enough fuel left on completion of its mission to return to a suitable airfield and land safely. The fuel must always be of great concern to pilots and controllers.

2685. The range and endurance of a jet air-craft vary according to power and, above all, altitude. Low-altitude operation is costly in fuel, and it is best, depending on how much fuel is available, to climb to altitude. When flying for range, the aim is to get the maximum distance for the minimum fuel, and this can only be achieved at high altitude (*eg* 36,000 feet for Lightning F Mk 3). When flying for endurance the aim is to use the minimum fuel per unit time: this also is normally done at high altitude (*eg* 30,000 feet for Lightning F Mk 3), but a smaller distance will be covered than when flying for range as the speed will be lower.

2686. The two usual ways of extending a fighter's range of endurance are:

a. Fitting jettisonable external fuel tanks.

b. In-flight refuelling.

2687. **External Fuel Tanks.** The fuel capacity of fighters can be increased by fitting external fuel tanks and, although they are jettisonable, this is only justified in operations or exercises. However, when multiple external tanks are fitted, a significant increase in ferry range is possible if tanks are jettisoned when empty.

2688. **In-Flight Refuelling.** Many fighters, besides carrying external tanks are also fitted for in-flight refuelling, enabling them to take on fuel from special tanker aircraft (*see* Fig 26–13). This can greatly extend the ferry range of a fighter and so make possible the rapid reinforcement of distant bases, but with each of the two basic techniques used—"Accom-panied" and "Rendezvous"—there are draw-backs. Difficulties common to both techniques are the vulnerability of the tanker aircraft to enemy attack and refuelling in turbulence or cloud.

2689. **"Accompanied" Technique.** When using the "Accompanied" technique the fighters and their tanker aircraft fly together in loose for-mation along the route. The number of fighter aircraft per tanker will depend upon the distance to be flown, since the tanker aircraft has only a set amount of fuel available to the fighters. Taking into account the time taken for a fighter to refuel and the need for the fighters and/or tanker aircraft to be able to divert to a suitable airfield should the necessity arise, each fighter is allotted a set time at which to refuel which presumes a minimum fuel state. One drawback with this technique is the difference in performance between the fighter and tanker, resulting in differing best speeds and heights at which to fly for maximum range. The fighter would usually prefer to fly higher and faster than the tanker aircraft. However, ease of navigation for the fighters may warrant the use of this technique.

2690. **"Rendezvous" Technique.** Using the "Rendezvous" technique the fighters meet up with the tanker aircraft. This technique allows much greater flexibility for the fighters *en route*, allows both fighter and tanker to fly at their best speed and height for maximum range and requires a reduced number of tanker aircraft thus permitting a greater number of fighter aircraft to be ferried in a shorter time. The greatest difficulty with this technique is to join up the fighters and the tanker aircraft outside areas of radar cover. The fighters' AI could be used but cannot be guaranteed to remain

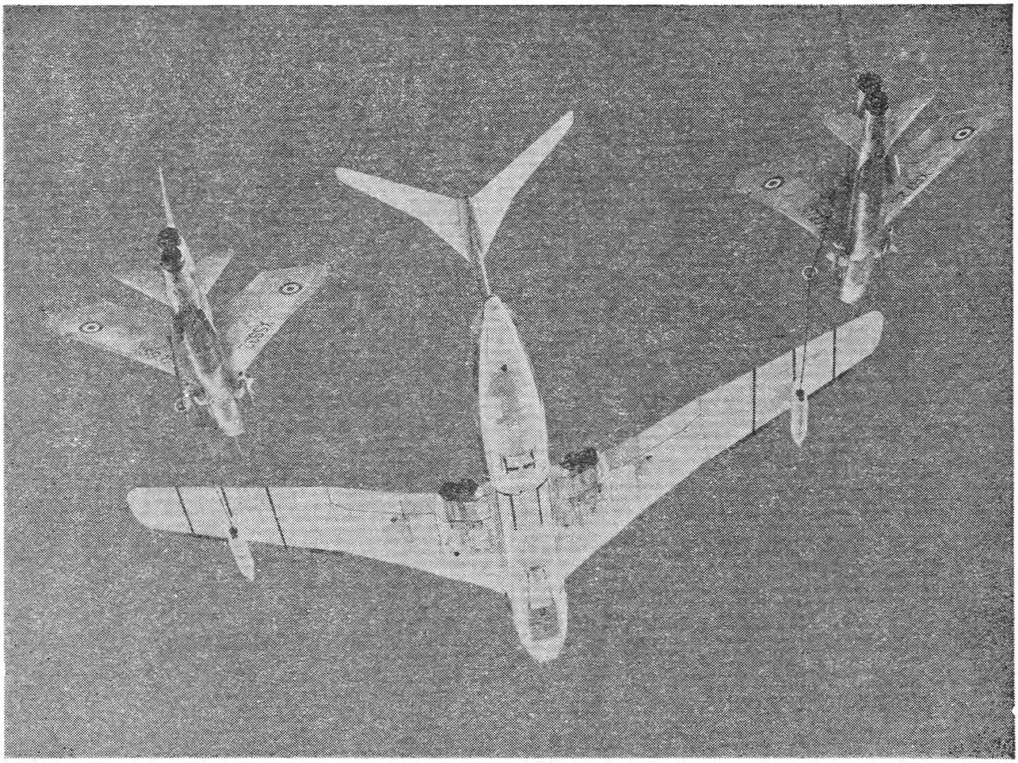


Fig 26–13 Victor Tanker Aircraft Refuelling Two Lightning Aircraft

serviceable and must therefore be regarded as a secondary aid. Fighter/tanker aircraft RT position reports would be very liable to enemy interference, and undesirable from the point of view of security. Techniques have now been developed which use a reliable rendezvous aid such as airborne TACAN or Violet Picture, thus allowing this technique to be commonly used. Reinforcement fighters may use a combination of the accompanied and rendezvous techniques.

Descent and Landing

2691. Jet fighters, being aerodynamically clean aircraft, must use airbrakes when descending quickly from high altitude, to prevent an unacceptable increase in airspeed with increasing angle of descent. However, if a slow descent over a long distance is permissible airbrakes need not be used.

2692. Most fighters, especially when carrying external fuel tanks, are designed to take-off at a weight appreciably above that at which they could be landed safely. The excess weight is normally dissipated early in the flight by the consumption of fuel by the engines. If the fighter is required to land soon after take-off, fuel must either be used up or, if provision is made for it, jettisoned, in order to reduce the aircraft weight below the permissible maximum for the type of landing. If the aircraft is also carrying a full weapon load a considerable proportion of the fuel may need to be consumed or jettisoned unless the weapon load can be released. A tail parachute for braking the aircraft on landing helps to reduce the severity of this problem, as does the arrester hooks fitted on aircraft like the Phantom, provided the ground arrester gear is available.

PHANTOM FG 1 and FGR 2

(*See Chapter* 10, *Control and Reporting* 1)

LIGHTNING F Mk 2A

1. **General Description.** The Lightning F Mk 2A is a single seat supersonic interceptor fighter powered by two Avon Mk 211 axial-flow gas turbine engines each developing approximately 11,750 lb static thrust at sea level and approximately 15,000 lb with full reheat. The aircraft may be fitted with a flight refuelling probe. The F Mk 2A is operated by the RAF in Germany.

2. **Armament.** The following weapons fit are possible:

a. Two Firestreaks and two 30 mm Aden cannon.

b. Two 30 mm Aden cannon in the upper nose and additionally an interchangeable armament pack of two 30 mm Aden cannon fitted to the underside of the fuselage.

3. **Fuel.**

a. *Main and Leading Edge:* 2 × 325 gallons (2 × 2,600 lb)

b. *Flap:* 2 × 33 gallons (2 × 264 lb)

c. *Ventral:* 610 gallons (4880 lb) carried in a non-jettisonable tank.

d. *Total:* (AVTUR @ 8·0 lb/gall) 1326 gallons (10,608 lb)

4. **Radar.** The AI 23–H/I band radar is fitted, giving normal pick-up ranges up to 25 nm.

5. **Performance.**

a. *Sortie Length.* Depends on attack speed and duration of combat speed. Where attack speed is subsonic and is made at or near the tropopause sortie duration would normally be up to 85 minutes, allowing 2,400 lb fuel for recovery.

b. *Ceiling.* The aircraft should not be flown above 60,000 feet.

c. *Maximum Speed.* Clean aircraft, or with ventral tank and/or missiles, 1·7M or 650 kts, whichever is attained first.

d. *Climb* (Cold power climb at 450 knots/0·87M with 2 Firestreaks under ICAN conditions at 39,000 lb take-off weight). The following figures, taken from the Lightning Operating Data Manual, include the fuel used from start-up and distance covered and time taken during the ground level acceleration to climbing speed from wheels rolling:

	Climb to (Ft × 1000)	Fuel Used (1b)	Distance (nm)	Time (min/sec)
From Sea Level to	10	1180	10	1·50
	36	1766	32	4·24

e. *Endurance Speed (two engine cruise)*

Altitude (Ft × 1000)	Speed (kts)	Fuel Used (lb/min)
2	250	90·5
10	250	75
30	0·7M	60
36	0·85M	60

6. **Radio and Navigational Equipment.**

a. *UHF Installation*. The installation provides normal R/T communication. Two sets are provided for R/T; one for normal use which allows 1,750 UHF channels to be selected, the other set is for standby use and has only two channel selections, normally 243 MHz and 243·8MHz (used for test purposes).

b. *Telebriefing*. Standard fit.

c. *ILS*. Standard ILS equipment is fitted, the presentation being shown on the navigation display of the Integrated Flight Information System.

d. *TACAN with Offset Computer*. The TACAN offset computer on the UHF control panel enables a selected homing point from a beacon to be set in.

e. *Violet Picture*. The normal UHF receiver may be used in conjunction with the ILS localizer indicator on the navigation display to provide homing directions onto UHF transmissions.

f. *IFF Mk* 10 *(SIF) and IFF/SSR.*

LIGHTNING F Mk 3

1. **General Description.** The Lightning F Mk 3 is a single seat supersonic interceptor fighter powered by two Avon Mk 301 or Mk 302 axial-flow gas turbine engines with variable reheat. The Avon Mk 301 develops approximately 12,300 lb static thrust at sea level (approximately 15,900 lb with full reheat) and the Mk 302 develops 12,600 lb (16,300 lb with full reheat). The aircraft may be fitted with a flight refuelling probe.

2. **Armament.** The weapons system uses one of two interchangeable packs fitted to the underside of the fuselage:

a. Two Red Top missiles } mounted externally
b. Two Firestreak missiles }

3. **Fuel**

a. *Main and leading edge* 2× 320 gallons (2× 2560 lb)

b. *Flap:* 2× 33 gallons (2× 264 lb)

c. *Ventral:* 250 gallons (2,000 lb) carried in a jettisonable tank.

d. *Total* (AVTUR @ 8·0 lb/gall) 966 gallons (7,728 lb)

4. **Radar.** The AI 23B H/I band radar is fitted, giving normal pick-up ranges up to 60 nms. Further details of the AI 23B radar are to be found at Annex J and in AP 101B–1003,5 & 6–15B.

5. **Performance.**

a. *Sortie Length.* Depends on attack speed and duration of combat speed. Where attack speed is subsonic and is made at or near the tropopause sortie duration would normally be up to 50 minutes, allowing 2,400 lb fuel for recovery.

b. *Ceiling.* The aircraft should not be flown above 60,000 feet.

c. *Maximum Speed.* Clean aircraft, or with ventral tank and/or missiles, 2·0M or 650 knots, whichever is attained first.

d. *Climb* (cold power climb at 450 kts/0·87M with ventral tank, two Red Top missiles under ICAN conditions). The following figures, taken from the Lightning Operating Data Manual, include the fuel used from start-up and distance covered and time taken during the ground level acceleration to climbing speed from wheels rolling:

	Climb to (ft× 1000)	Fuel Used (lb)	Distance (nm)	Time (min/sec)
From Sea Level to	10	1000	8	1·36
	36	1535	27	3·51

e. *Endurance Speed*

Altitude (ft× 1000)	Endurance Speed	Fuel Used (lb/min)
2	230kt	100
10	235kt	88
30	0·70M	64
36	0·85M	65

6. **Radio and Navigational Equipment**

a. *V/UHF Installation.* The installation provides normal R/T communication. Two sets are provided for R/T; one for normal use which allows 1,750 UHF channels to be selected, the other set is for standby use and has only two channel selections, normally 243 MHz and 243·8 MHz (used for test purposes). A modification has introduced a V/UHF installation with which any one of 370 VHF channels (117·5 MHz to 135·95 MHz) or 3,500 UHF channels (225 MHz to 339·95 MHz) may be manually selected.

b. *Telebriefing.* Standard fit.

c. *ILS.* Standard ILS equipment is fitted, the presentation being shown on the navigation display of the Integrated Flight Information System.

d. *TACAN with Offset Computer.* The TACAN offset computer on the UHF control panel enables a selected homing point from a beacon to be set in.

e. *Violet Picture.* The normal UHF receiver may be used in conjunction with the ILS localizer indicator on the navigation display to provide homing directions onto UHF transmissions.

f. *IFF Mk 10 (SIF) and IFF/SSR.*

LIGHTNING F Mk 6

1. **General Description.** The Lightning F Mk 6 is basically an extended version of the F Mk 3 and, as such, has the same type of power unit. In the ferrying role two jettisonable overwing fuel tanks may be carried. The aircraft may be fitted with a flight refuelling probe and an airfield arrester hook.

2. **Armament.** The weapons system consists of any of the following interchangeable packs:

a. Two Red Top missiles.

b. Two Firestreak missiles.

c. Ventral fuel/two 30 mm Aden cannon, and/or either a or b.

3. **Fuel.**

a. *Main and Leading Edge:* 2 × 325 gallons (2 × 2,600 lb)

b. *Flap:* 2 × 33 gallons (2 × 264 lb)

c. *Ventral:* (non-jettisonable) 610 gallons (4,880 lb)
But when a ventral tank with guns is fitted, ventral fuel is reduced to 535 gallons.

d. *Overwing:* 2 × 260 gallons (2 × 2,080 lb) carried in two jettisonable tanks.

e. *Total:* (AVTUR @ 8·0 lb/gall) 1,326 gallons (10,608 lb) for combat sorties.

f. *Total:* 1,846 gallons (14,768 lb) for ferry sorties.

4. **Radar.** The AI 23B H/I band radar is fitted. *See* Annex J for further details and AP 101B–1003,5 & 6–15B.

5. **Performance.**

a. *Sortie Length.* Sortie length depends on attack speed and the duration of combat speed. Where attack speed is subsonic and is made at or near the tropopause sortie duration would normally be up to 85 minutes, allowing 2,400 lb fuel for recovery.

b. *Ceiling.* The aircraft should not be flown above 60,000 feet.

c. *Maximum Speed.* Maximum speed limitations are:

(1) 2·0M/650 knots, whichever is first attained.

(2) 0·95M/475 knots, whichever is first attained, when fitted with overwing tanks.

d. *Climb* (cold power climb at 450 knots/0·87M with ventral tank, two missiles, under ICAN conditions). The following figures, taken from the Lightning Operating Data Manual, include the fuel used from start-up and distance covered and time taken during the ground level acceleration to climbing speed from wheels rolling:

	Climb to (ft × 1000)	Fuel Used (lb)	Distance (nm)	Time (min/secs)
From Sea Level to	10	1220	9	1·42
	36	1850	33	4·30

e. *Endurance Speed*

Altitude (ft × 1000)	Endurance Speed	Fuel Used lb/min
5	350 kts	100
10	400 kts	88
30	0·85M	64
36	0·88M	65

6. **Radio and Navigational Equipment.** The Lightning F Mk 6 is fitted with the same radio and navigational equipment as the F Mk 3. In addition, when used in the ferry role, a radio compass may be fitted.

VICTOR K Mk 1A AND 2

(*See Chapter* 10, *Control and Reporting* 1)

SHACKLETON AEW Mk 2

(*See Chapter* 10, *Control and Reporting* 1)

CANBERRA B MK 2 AND T MK 19

1. The Canberra is a twin engined light bomber currently employed in the UK for target facilities.

2. **B Mk 2.** Accommodation is provided for a crew of three seated in ejection seats; a Rumbold seat, which folds into the starboard wall is available for use by a fourth crew member. There is a prone position in the nose which may be used for observation and map reading.

3. **T Mk 19.** Two crew are carried on ejection seats with one passenger on the Rumbold seat. The main difference between the two types is the modified nose of the T19 which was redesigned to accept the AI Mk 17A radar when the aircraft was used to train navigators at No 228 (Javelin) OCU in 1964/5. The radar has now been removed and the nose filled with concrete to maintain the centre of gravity.

4. **Weapons System.** No weapons are carried.

5. **Performance.**

a. *Fuel*

(1) B Mk 2 in normal configuration (internal plus tips) carries 14920 lb. A bomb-bay tank is available with a further 2344 lb.

(2) T Mk 19 (internal only) carries 11016 lb. The T Mk 19 is more economical on fuel than the B Mk 2. However the normal sortie length for both is similar and for an aircraft on tow at medium level 80 nm from base this is approximately 2 hours. This would allow about 1½ hours on task.

b. *Scrambling.* Climb is normally at 300 kts/·72M and to reach a tow height of 35,000 ft the B Mk 2 takes 15½ minutes covering 77½ miles and the T Mk 19 11 minutes covering 55 miles. Full data is in the Canberra ODM.

c. *Airborne.* At 35,000 ft normal cruise is at ·72M. Operational ceiling is 48,000 ft AMSL. Both marks are highly manoeuvrable and it is sufficient to say that the Canberra can turn inside a Lightning at any height up to the operational ceiling.

6. **Radio and Navigation Aids.**

a. *B Mk 2.*

(1) Radio—VHF/UHF on 3500 UHF and 370 VHF channels. Guard is preset in the main set and a standby UHF set provides guard plus one other frequency.

(2) Air Position Indicator with Air Mileage Unit.

(3) ADF.

(4) TACAN.

(5) IFF Mk 10/SIF SSR.

b. *T Mk 19.*

(1) Radio—VHF/UHF 18 preset frequencies, 1750 manually selected frequencies plus one guard channel.

(2) TACAN.

(3) IFF Mk 10/SIF SSR.

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HUNTER F Mk 6, F(GA) Mk 9, FR Mk 10, T Mk 7 AND 7A

1. **General Description.** Several different versions of the Hunter may be encountered in the air defence environment. Basically the Hunter is a single seat aircraft powered by the Avon series axial flow gas turbine. The aircraft has no flight refuelling capability. The Mks 6, 9 and 10 are powered by the Avon 203/207 series developing about 10,000 lb of static thrust at sea level while the Mk 7/7A is powered by the 112 series developing 7,575 lb of static thrust at sea level.

2. **Armament.** The Mk 6 and 9 carry four 30 mm Aden guns under the nose of the aircraft. The Mk 10 has four 30 mm Aden guns in a removable pre-armed package in the underside of the front fuselage while the Mk 7 carries one Aden gun beneath the front starboard fuselage. The Mk 7A carries no guns.

3. **Fuel.** The Mks 6, 9 and 10 carry internal fuel and wing tanks on inboard and outboard stations. Two 100 gallon tanks can be carried outboard and a choice of 2 × 100 gall or 2 × 230 gall tanks inboard.

	galls	lb	
Internal	392	3136	
Wing drop tanks			
2× 100 gall	200	1600	
2× 230 gall	460	3680	
Total fuel	1052	8416	(of AVTUR @ 8·0 lb/gall)

The Mks 7 and 7A carry only 100 gall wing tanks in addition to the internal fuel:

	galls	lb	
Internal	414	3312	
Wing drop tanks			
2× 100 gall	200	1600, or,	
4× 100 gall	400	3200	
Total fuel	814	6512	(of AVTUR @ 8·0 lb/gall).

4. **Radar.** All the above marks of this aircraft carry radar ranging for the gunsight except the Mk 10 and 7A.

5. **Performance.**

a. *Sortie Length.* Depends upon altitude, speed and fuel carried. The Mk 9 with usable fuel of 6,160 lb at 30,000 ft, speed 250 kts, would have an endurance of two and a half hours; at 40,000 ft slightly less.

b. *Maximum Speed.* The maximum speed attainable in level flight with a clean aircraft is 620 kts/0·94M. The aircraft will reach sonic speed in a 30° to 40° dive but this may not be commenced below 25,000 ft because of the height loss during recovery. With wing tanks the maximum speed is 620 kts or 0·84M increasing with height to 0·88M if the tanks are carried outboard.

c. *Climb* (climb at 370 kt/0·80M with maximum loading of wing tanks). The following figures, taken from the Mk 9 Pilots Notes, include the fuel used from the time of start-up, and the time from wheels rolling:

	Climb to (ft × 1000)	Fuel Used (lb)	Distance (nm)	Time (min/sec)
From Sea Level to	10	580	10	2
	36	1280	75	9·30

d. *Endurance Speed*

Altitude (ft × 1000)	Endurance Speed (kts)	Fuel Used (lb/min)
2	250	65
10	250	56
30	250	40
36	0·79M	39

6. **Radio and Navigational Equipment.**

a. *UHF.* All marks.

b. *DME.* Mks 6, 9 and 7.

c. *TACAN and ILS.* Mk 7A.

d. *Radio Compass.* Mks 6, 9, 10 and 7.

e. *Telebrief.* All marks.

f. *IFF(SIF).* Mks 6, 9, 10 and 7A.

g. *Green Salad.* Mk 6 and 7.

h. *Integrated Flight Instrument System (IFIS).* Mk 7A, as a training aircraft for Lightning pilots.

AI Mk 23B RADAR

AI Mk 23B and Fire Control System

1. The Lightning F Mk 3 and F Mk 6 are equipped with an automatic fire control system, which derives its information largely from the AI 23B airborne interception equipment. In the event of failure of the AI 23B radar, visual aiming and manual firing of weapons may be carried out using a simple gyro sight, known as the Light Fighter Sight (LFS).

2. AI 23B is an H/I band radar, designed to search and lock on to the target and provide steering signals from its own computer to a head-down display. These signals deflect a steering dot away from a centre reference circle as a measure of any error between the actual path being flown and the desired approach in both elevation and azimuth. The equipment also computes and displays firing brackets and provides signals necessary to fire the weapons.

3. **Radar.** The radar operates in three modes: search, acquisition and track. The scanner is roll stabilized up to 110° and is stabilized in pitch within a lock angle limit of ±30° to the aircraft's weapon line. The azimuth lock angle limit is ±50°. The display is basically a B scope having range scales of 20–60 miles, 0–40 miles, 0–10 miles and, in the visident mode, 0–1,500 yards. The azimuth coverage is ±50°. Scanner elevation above the horizontal is displayed to the right of the B scope with a scale of −10° to +40°. The AI scan patterns and display presentations are shown in Figs a to k.

4. **Search.** In the search mode the scanner searches ±50° in azimuth, at a rate of 1 cycle every 2 seconds with either a single bar, two bar or four bar elevation scan giving a beamwidth at 3 dB points of 5½°, 9° or 16½° respectively. The centre of the scan can be controlled to move up to +25° or −10° from the horizontal, measured by the aircraft master reference gyro.

5. **Acquistion.** In order to spotlight the target the azimuth scan is reduced to a steerable sector of 10° which can be moved up to 50° either side. In elevation the scan is reduced to single bar and has limits of −10° to +25° relative to the horizontal.

6. **Track.** When the target has been spotlighted, the track mode is selected and the radar is locked in range and bearing. It is capable of holding lock up to the lock angle limits of ±50° in azimuth and ±30° relative to the aircraft axis in elevation. When the radar is locked, information is sent to the computer giving target bearing the rate of change of sight line angle in azimuth and elevation together with target range and rate of change of range (range rate).

7. **Radar Computer.** The radar computer operates in conjunction with the Flight Control System to provide steering and weapon firing instructions which enable the pilot to carry out an approach appropriate to the weapon in use and the speed and altitude of the target. The steering equations and firing bracket equations are dependent on:

a. The Master Armament Switch selection —either guided weapons or rocket battery.

b. Computer Switch setting.

c. Fighter height.

d. Whether the target is above or below the fighter.

For any computer switch setting a particular sequence in each programme is followed in azimuth and elevation.

8. **Date Link Signals.** AI 23B is capable of displaying certain information and instructions transmitted by a digital data link. A circle is generated on the B scope to indicate target range and relative bearing; height difference between fighter and target is displayed to the right of the B scope. The instructions either to "engage" or "interrogate" a target are displayed in the form of "E" and "I" lights, and "breakaway" is indicated by a cross on the B scope.

9. **E/F Band Homer Facilities.** The AI 23B system includes a separate E/F band receiver to enable the pilot to home on to E/F band jamming signals. The jamming is displayed across the bottom of the B scope in the form of "grass', and the bearing of the jammer is indicated by the maximum amplitude of the grass. When the

amplitude of the jamming signals is too great to be controlled by the gain control (normally when within about 10 miles of the jammer), the pilot reverts to the normal E/F band AI 23B display to complete the interception.

10. **Radar Ranging.** The AI may be used in conjunction with the light fighter sight to allow visual air-to-air attacks. The AI supplies an "in range" signal to the LFS at a range appropriate to the armament in use.

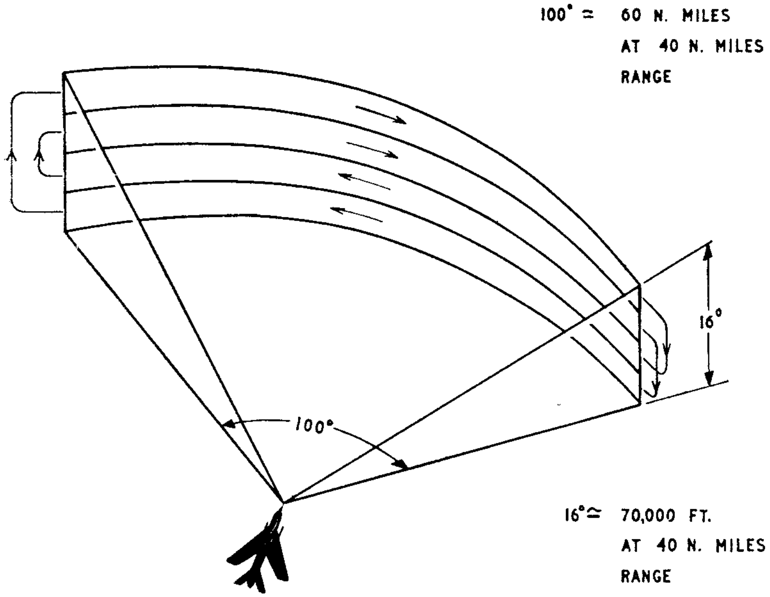
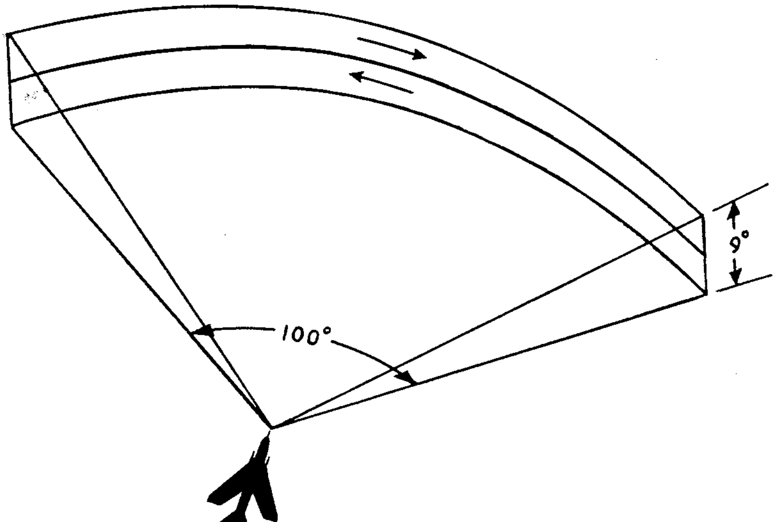
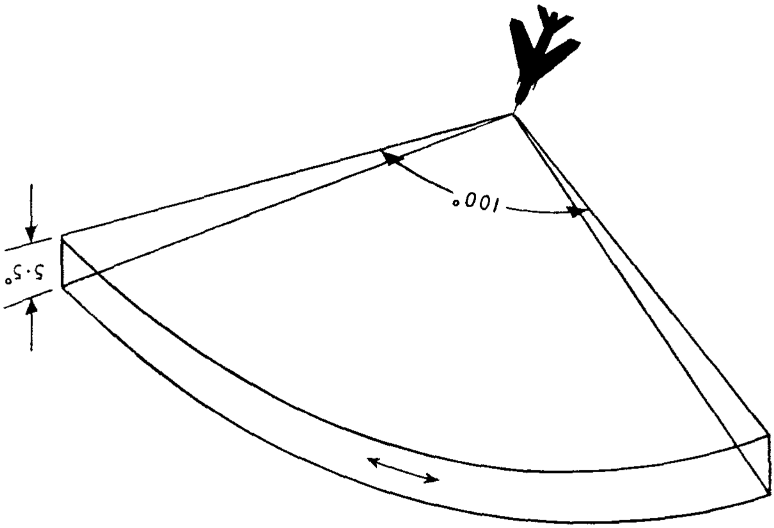


Fig a. Search Phase (1)—Four Bar.

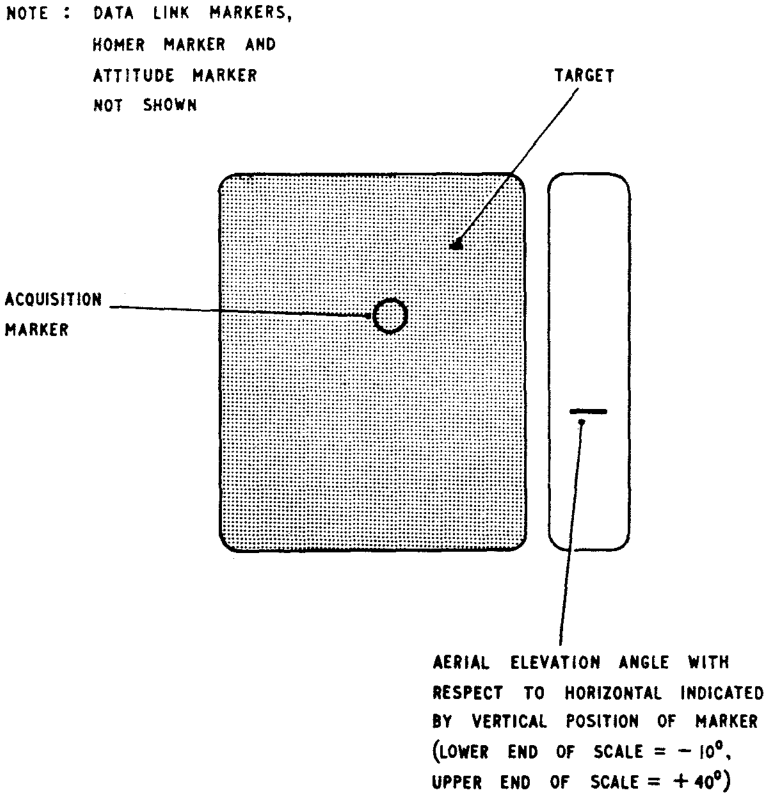
IN ALL CASES MEAN ANGLE IN ELEVATION OF PATTERN IS MANUALLY CONTROLLED BETWEEN +25° AND -10°



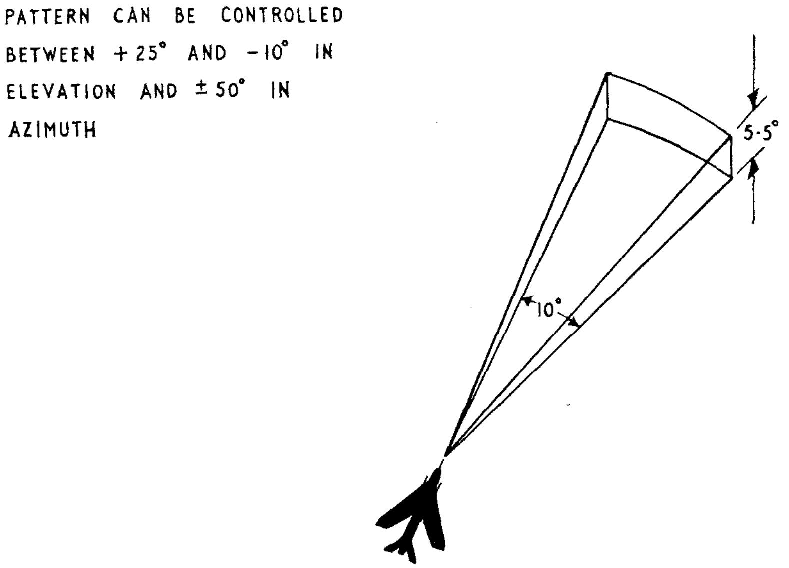
b. Search Phase (1)—Two Bar.



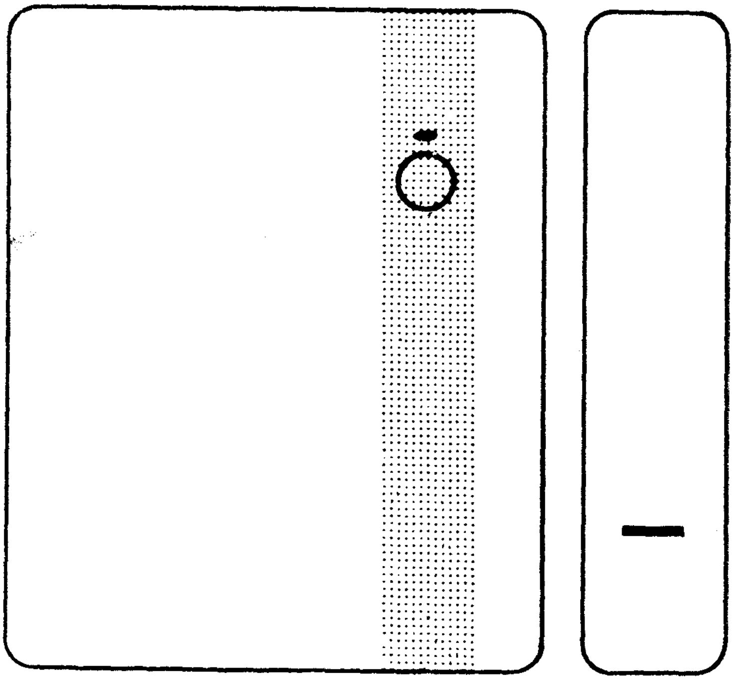
c. Search Phase (1)—Single Bar.



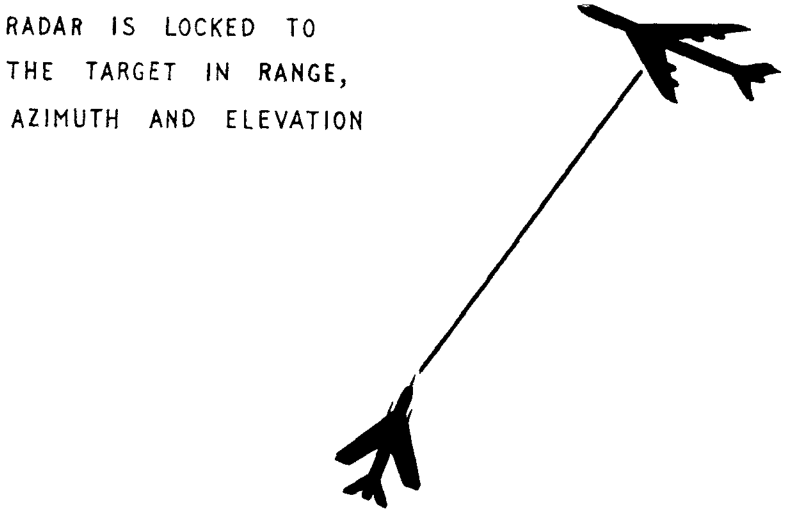
d. Search Phase (2).



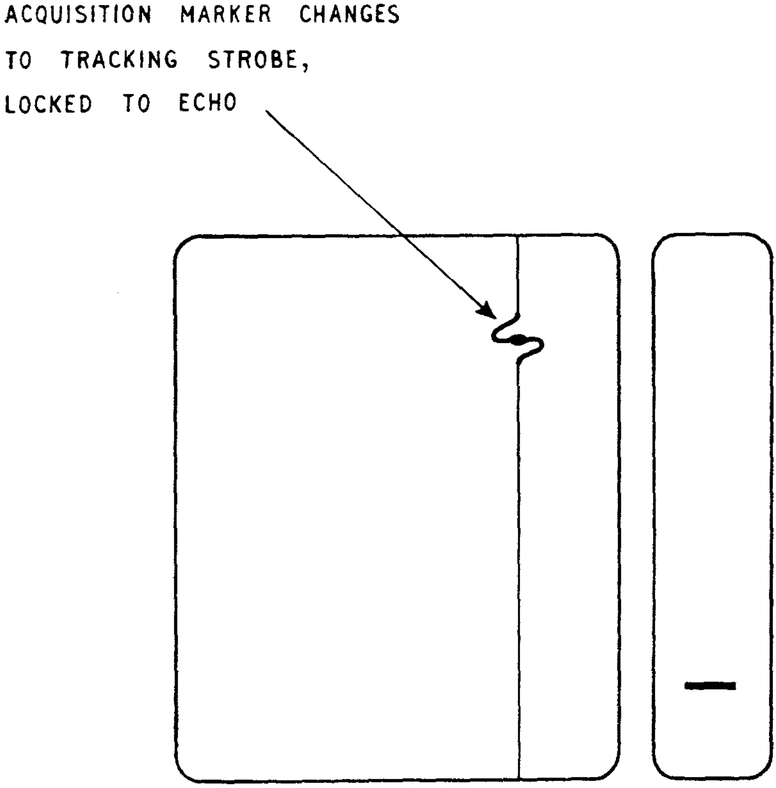
e. Acquisition Phase (1).



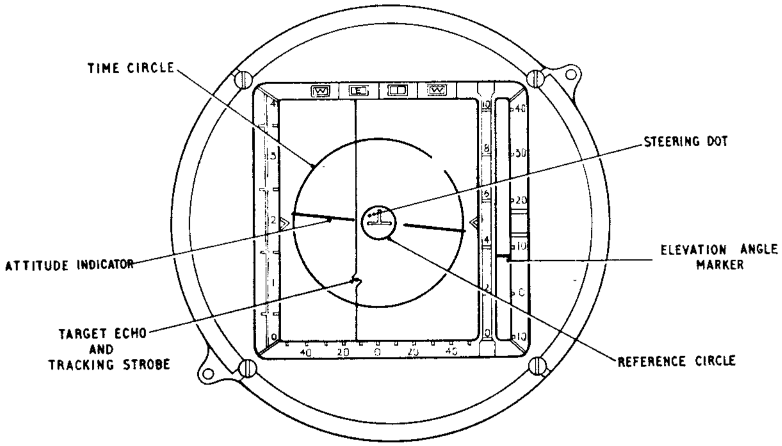
f. Acquisition Phase (2).



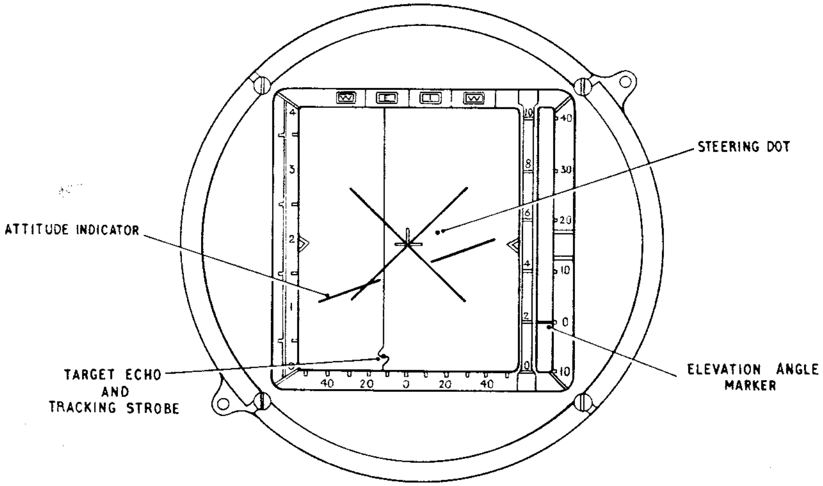
g. Track Phase (1).



h. Track Phase (2).



j. Initial Display During Track.



k. Display at Breakaway.

CHAPTER 27

AIR TRAFFIC CONTROL

CONTENTS

INTRODUCTION

Introduction

2701. Control and Reporting is inevitably closely concerned with Air Traffic Control: the reporting organization requires aircraft movement information for recognition; and fighters operate in airspace subject to air traffic control regulations. A brief outline of the air traffic organization and its responsibilities, and some of the regulations, procedures and services provided by Air Traffic Control (ATC) authorities are therefore given in the following chapter.

ATC POLICY

2702. **RAF Policy.** The policy is that it shall provide, in time of peace and war, aeronautical facilities and a ground organization which will:

a. Enable pilots of RAF aircraft to operate safely with tactical freedom in all weather conditions. The objectives are:

(1) To prevent collisions between aircraft in the air, or in the manoeuvring area between aircraft and obstructions.

(2) To expedite and maintain an orderly flow of air traffic.

b. Provide a flight information service.

c. Alert emergency services and initiate search and rescue activity when required.

d. Meet the requirements of the air defence organization for the notification of aircraft movements.

2703–2706. (*Not allotted*).

AIR TRAFFIC CONTROL ORGANIZATION AND RESPONSIBILITIES

Organization in the UK

2707. Within the UK the responsible authority for air traffic control is the National Air Traffic Service (NATS). The NATS is a twin-ministry department which is headed by a controller who is responsible directly to both the Ministry of Defence and the Department of Trade and Industry. The Headquarters of the NATS is in London and is staffed by both military and civil personnel. A Joint Field Headquarters is established at RAF Uxbridge, near London. The Joint Field Headquarters, which is directed by Headquarters NATS, has two components; Civil Air Traffic Operations (CATO) and Military Air Traffic Operations (MATO). Headquarters MATO has the status of a group headquarters, and is commanded by an air commodore. HQ MATO is operationally responsible to HQ NATS, and is responsible to HQ Strike Command for administrative and technical matters. ATC units are Air Traffic Control Centres (ATCCs), Joint Air Traffic Control Radar Units (JATCRUs) and Air Traffic Control Radar Units (ATCRUs). A diagram showing the organization of the NATS is at Fig 27–1.

Organization Overseas

2708. The Department of Trade and Industry, the Ministry of Defence and the Foreign and Commonwealth Office have agreed that they will provide, on an integrated basis in Commonwealth and British-influenced territories, the aeronautical facilities required for the safe movement of RAF aircraft, British civil aircraft, and some foreign aircraft. One authority, RAF or civil, is responsible for the provision and operation of any organization or facility. In areas abroad, certain British ATCCs, in addition to their normal responsibilities, maintain a watch over, and provide a flight information and alerting service for, RAF aircraft flying within RAF areas of responsibility. The part of the ATCC which undertakes these tasks is known as a Flight Watch Centre (FWC).

Responsibilities

2709. **NATS.** The NATS is responsible for:

a. Air Traffic Control policy and planning in the UK.

b. The operational direction of MATO and CATO.

c. Formulating operational requirements.

d. The execution of agreed policies and procedures for the UK Flight Information Regions (FIRs).

e. The air traffic control service provided by the UK over the North Atlantic.

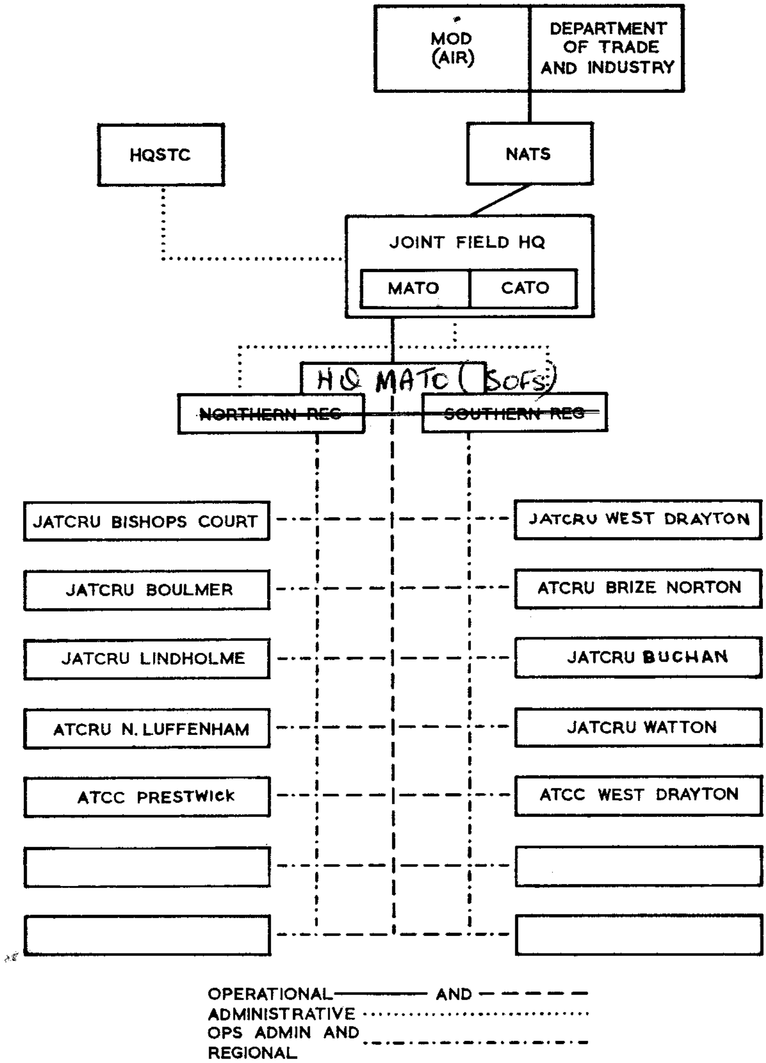


Fig 27–1 Organization of NATS

2710. **Ministry of Defence (Director of Control (Operations)).** All RAF air traffic control overseas, and airfield control matters at service airfields, are the responsibility of the Director of Control (Operations) at the Ministry of Defence.

2711. **MATO.** The AOC MATO is responsible to the controller NATS for:

a. The organization and provision of such common air traffic control and allied services as are necessary under policies notified by the controller NATS, for military aircraft in the UK FIRs.

b. Acting as the co-ordinating authority in all matters concerning the efficient use of airspace by military aircraft, and negotiation of solutions to problems caused by conflicting interests.

c. Co-operation with the Director, CATO in implementing NATS policy on matters affecting the control of military and civil aircraft jointly.

The AOC MATO is not concerned with ATC services at airfield level, as they are the responsibility of individual RAF commands. He is however, responsible for the resolution of local military air traffic problems.

2712. *(Not allotted)*.

2713. **Division of Airspace.** The UK airspace is divided into Flight Information Regions (FIRs) comprising all airspace below FL 245 and Upper Information Regions (UIRs) at, and above, this level.

2714. **Flight/Upper Information Regions (FIRs/UIRs).** A Flight Information Region is an airspace of defined dimensions within which an Air Traffic Control Centre (ATCC) is responsible for providing Flight Information Services (FIS) and initiating measures for search and rescue.

2715. **ATCCs in the UK.** The airspace above the UK is divided into 2 FIRs namely London and Scottish, which are under the jurisdiction of the ATCCs at West Drayton and Prestwick respectively. Prestwick ATCC is also jointly responsible with Shannon for the oceanic control area over the north Atlantic. The ATCCs are manned by RAF and Civil Aviation Authority (CAA) ATC staffs and their responsibilities are:

a. The control of aircraft flying in controlled airspace within its region.

b. The maintenance of up to date weather information within its region, together with pressure values, transition levels, and other information required to ensure the safe and expeditious operation of aircraft.

c. Provision of emergency and position fixing services to aircraft on the UHF international aeronautical emergency frequencies.

d. Provision of a Flight Information Service.

e. Arrangement and control of diversions of military aircraft.

f. Tracing overdue aircraft and initiation of search and rescue action as necessary.

g. Provision of an aeronautical information service and, in the case of West Drayton ATCC, a master aeronautical information service.

h. Operation of the Air Defence Notification Centre (ADNC) to provide the information required by the air defence organisation on the movement of friendly aircraft.

j. Operation of a signals centre for the receipt and dispatch of aeronautical information and airmove messages.

To fulfil the above responsibilities an ATCC is divided into the following main sections:

a. Operations/Control Rooms.

b. Distress and Diversion Section (D and D).

c. Aeronautical Information Section (AIS). The only military AIS is at West Drayton and it contains two sub-sections:

(1) Low flying section.

(2) Range co-ordination section.

d. Flight Information Service (FIS).

e. Meteorological Section.

f. Signals Section.

g. ADNC/Air Defence Movements Section (ADMS).

Flight Watch Centres

2716. To provide an operational control and management service for military aircraft on transit flights abroad, a Flight Watch System, operated by Flight Watch Centres, has been established to cover the Eastabout route between UK and the Far East. Communication is maintained on HF (Single Side Band and Double Side Band) Radio Telephony. Details of the boundaries of the Flight Watch Areas and services provided are given in the Planning Document. While the Flight Watch System is intended primarily for operational control and management, FWCs can be used for the following air traffic control purposes:

a. Diversion control and advice to aircraft.

b. Meteorological information.

c. Relay of ATC messages to nominated agents.

d. The alerting of search and rescue services in accordance with local instructions.

Communications with the Flight Watch System in no way supersedes national or foreign air traffic control requirements.

ATCRUs and JATCRUs

2717. JATCRUs and ATCRUs are similar units and are sometimes referred to collectively as Area Radar Units. The difference between them is that JATCRUs also have a civil control cell for providing radar services to civil aircraft within their area. ATCRUs are established to provide radar services within their respective areas. Selected portions of Upper Airspace between FL 245 and FL 660, have been designated as mandatory Radar Service Areas (MRSAs). Within MRSAs some areas have been set aside for training purposes and are known as Military Training Areas (MTAs).

2718. The ATCRUs and the military elements of JATCRUs are responsible for providing some or all of the following services in the given order of importance:

a. *Emergency Assistance.* Close liaison is maintained with the D & D section at ATCCs and a watch is kept for emergency IFF/SIF transmissions.

b. *Upper Airspace Service.* This is provided for both military and civil aircraft in MRSAs. Aircraft entering a MRSA must call the relevant ATCRU five minutes before entering the area unless entering by prior arrangement.

c. *Airways Crossing Service.* This assists aircraft which are unable to comply with instrument flight rules (IFR) in controlled airspace and facilitates airways crossing for military aircraft.

d. *Centralised Approach Control (CAC).* This is a recovery service given to selected airfields and includes a climb-out procedure.

e. *Middle and Lower Airspace Service.* This is an advisory service for aircraft operating outside controlled airspace below FL 245.

f. *Special Tasks.* Surveillance or control tasks as detailed by HQ MATO.

2719. **Radar Service Classifications.** The following degrees of radar service may be given:

a. *Radar Control.* Pilots are given mandatory instructions to ensure prescribed separation is maintained, together with details of conflicting traffic. No change of heading or flight level is to be made without the prior approval of the controller.

b. *Radar Advisory Service.* The pilot is informed of the bearing, distance and height (if known) of conflicting traffic together with the recommended avoiding action.

c. *Limited Service.* The radar controller may prefix the above types of service with the word 'Limited' (*eg* Limited Control). This indicates to the pilot that prescribed separation may not be maintained due to one of the following factors (never used in Controlled Airspace):

(1) The aircraft is close to the limits of the radar cover.

(2) Proximity of weather or ground returns.

(3) Radar performance is suspect.

(4) High traffic density.

d. *Procedural Service.* This is applicable to an MRSA only when the aircraft cannot be seen on primary radar; procedural separation from known aircraft may be given.

2720. **Airfield Air Traffic Control.** At RAF airfields air traffic control is divided into two distinct functions as follows:

a. *Aerodrome Control.* This control is necessary to reduce the risk of accidents occurring at, or in the vicinity of, aerodromes and it is responsible for:

(1) Control of all traffic (aircraft, vehicles and pedestrians) in the manoeuvring area of the aerodrome.

(2) Control of aircraft taking off and landing, or flying within the vicinity of an aerodrome, provided that flying is being conducted under VMC.

(3) Maintaining close liaison with Approach Control, including radar, in assuming responsibility for incoming aircraft and the handing over control of outgoing aircraft.

(4) The initiating of crash action where applicable.

(5) Making regular inspections of the aerodrome manoeuvring area and lighting, and informing pilots of any irregularity.

b. *Approach Control.* This function is operationally responsible for:

(1) Sequencing and separation of aircraft from known traffic.

(2) Military Air Traffic Zone (MATZ) control in IMC.

(3) En-route navigational assistance.

(4) Assistance to aircraft in emergency.

(5) Acting as a link between the operating authority and the aircraft captain.

2721. **Co-ordination Cells.** A co-ordination System has been devised to disseminate traffic information between Air Traffic and Air Defence Radar Units (ADRUs) utilising the North Sea airspace.

2722. **Facilities.** The facilities which are available are:

a. *Co-ordination Area.* A designated Co-ordination Area above FL 249.

b. *Control Positions.* Control positions are allocated at both the Air Traffic and Air Defence Radar Units for the system. At the ATCRUs this position is known as the Filter Position and at the ADRUs it is referred to as the Co-ordination Cell (Defence Co-ordination Cell (DEFCOC) at Neatishead and Joint Co-ordination Cell (JCOC) at Boulmer).

c. *Secondary Radar (SR) System.* Full use of the Mode 3A facility enables the controlling agency and control position of aircraft to be easily identified.

d. *Communications.* An extensive communications network exists between the Co-ordination Cells, Filter Positions, Air Traffic and Air Defence Control positions to facilitate the rapid exchange of information between all agencies.

2723. **Co-ordination System.** Together with prescribed separation standards and laid down procedures the co-ordination system aims at improving flight safety in the North Sea airspace.

2724. (*Not allotted*).

AIR TRAFFIC CONTROL REGULATIONS AND PROCEDURES

General

2725. The MOD has decided that the RAF will conform to the 'Rules of the Air'. It has also agreed that the RAF will conform to the International Civil Aviation Organization (ICAO) 'standards' and 'recommended practices' provided they do not conflict with military requirements.

2726. **Captains of Aircraft.** Captains of aircraft are responsible for everything that happens to their aircraft during flight. To facilitate this, the captain of an aircraft is normally granted absolute authority over all occupants irrespective of rank.

2727. **Rules of the Air.** Rules of the Air which are of concern to C & R personnel are as follows:

a. When two aircraft are on converging paths, the aircraft which has the other on its right is to give way.

b. When two aircraft are approaching head on each is to turn to the right.

c. An aircraft overtaking another is to turn to the right and keep clear until all danger of collision is past. (An aircraft is said to be overtaking another if it is approaching from the rear at an angle of less than 70° from the fore-and-aft axis of the aircraft in front).

d. An aircraft must not carry out any aerobatic manoeuvres:

(1) Over built up areas, towns or assemblies of people.

(2) Within controlled airspace, except with the consent of the appropriate authority.

e. Aircraft are considered to be low flying when at a height above ground or water level of less than:

(1) 500 ft in the case of helicopters.

(2) 2,000 ft for other aircraft.

The Quadrantal and Semi-Circular Systems

2728. The Separation Systems are designed to reduce the risk of collision between aircraft flying *en route* outside controlled airspace. The systems entail aircraft maintaining flight levels appropriate to their magnetic track, with the altimeter sub-scale set to the standard pressure setting of 1013·2 mbs. Pressure intervals equivalent to 500 ft separate adjacent compass quadrants up to FL 250; 1,000 ft from FL 250 but below FL 290; 2,000 ft intervals at or above FL 290. The systems are illustrated at Fig 27–2.

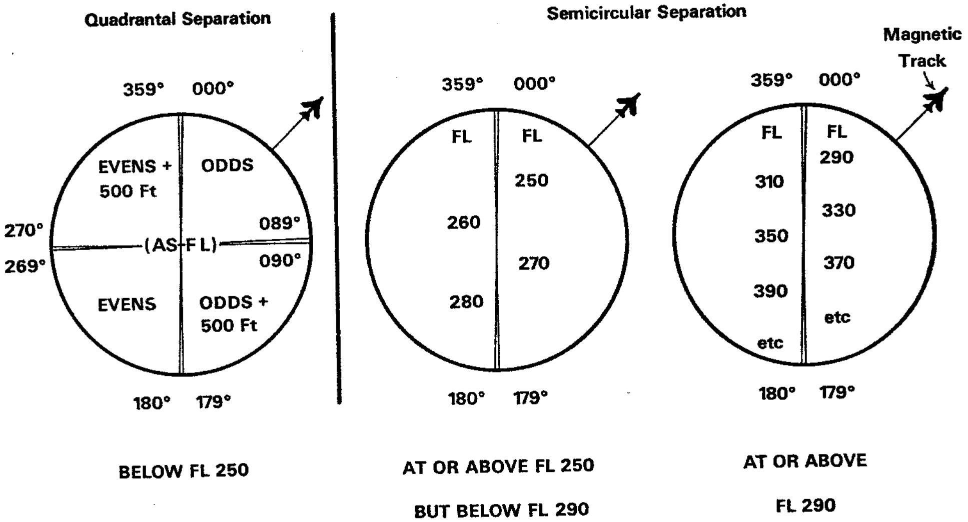


Fig 27–2 The Quadrantal and Semi-Circular Separation Systems

2729. The separation system does not apply:

a. In controlled airspace (unless so directed).

b. Below 3,000 ft in the United Kingdom FIRs.

c. To flights carried out under constant radar surveillance.

d. In the case of special flights and exercises.

Visual and Instrument Flight Rules

2730. **Visual and Instrument Meteorological Conditions (VMC and IMC).** VMC and IMC refer to the weather encountered during flight and not to the rules under which the flight is to be conducted. The responsibility for deciding 'in-flight' weather conditions rests with the pilot.

2731. **Visual Meteorological Conditions (VMC).** Conditions for VMC when above 3,000 ft are as follows:

a. One nautical mile (nm) horizontally clear of cloud.

b. 1,000 ft vertically clear of cloud.

c. In-flight visibility of at least 9km (5 nm).

If the weather satisfies these conditions the pilot is in VMC. If the weather is below these conditions, the pilot is in IMC.

2732. **Visual Flight Rules (VFR).** When in VMC and flying VFR the captain of an aircraft is to comply with the Rules of the Air and—if above 3,000 ft in the United Kingdom FIRs—with the Quadrantal and Semi-Circular Separation Systems (unless otherwise directed). Except within the traffic patterns of aerodromes or in zones around aerodromes where special conditions may require it, or controlled airspace permanently notified as IFR, or in MRSAs he is not subject to air traffic control.

2733. **Instrument Flight Rules (IFR).** In the UK a pilot must fly in accordance with IFR:

a. When in IMC.

b. By night in controlled airspace, irrespective of weather conditions. Night commences 30 minutes after sunset and continues until 30 minutes before sunrise.

c. At all times in certain promulgated airspaces which include:

(1) All UK airways.

(2) North Atlantic controlled airspaces.

(3) London, Manchester and Gatwick control zones etc.

2734. The Instrument Flight Rules are as follows:

a. For a flight in controlled airspace:

(1) A flight plan must be submitted to the ATC authority.

(2) Clearance must be obtained from the appropriate ATC authority.

(3) Pilot must have a valid instrument rating.

(4) The aircraft must carry appropriate radio equipment.

(5) The aircraft must carry specified navigational aids.

(6) The flight must be conducted in accordance with ATC clearance and instructions.

b. For a flight outside controlled airspace:

(1) When flying above 3,000 ft AMSL, cruising flight levels in accordance with the quadrantal/semi circular separation system based on the standard altimeter setting of 1013.2 mbs are mandatory unless flying in accordance with ATC instructions, or on a notified holding pattern; the separation system is advisory under VFR.

(2) At or below 3,000 ft AMSL, IFR flight is not permitted unless specially cleared, or when landing or taking off.

Special VFR Flight

2735. Special VFR flight is designed to enable pilots to fly into or out of controlled zones when for some reason they are unable to comply with IFR, because they have no instrument rating or the aircraft lacks navigational equipment. Separate regulations exist for each control zone but in each case:

a. A flight plan is not always necessary, although when one is not submitted separate notification must be given to the destination airfield.

b. Special zone clearance must be obtained.

c. ATC instructions must be followed.

d. Normal rules of the air still apply.

e. The pilot must be able to determine his flight path and keep clear of obstructions.

2736. (*Not allotted*).

Definitions

2737. The definitions of some of the terms frequently used in describing ATC procedures are given in the following paragraphs.

2738. **Airway**—A control area or specified portion thereof established in the form of a corridor marked with radio navigational aids.

2739. **Altitude**—The vertical distance of a level, a point or an object considered as a point, measured from mean sea level.

2740. **Controlled Airspace**—An airspace of defined dimensions within which air traffic control service is provided. A schematic diagram showing a combination of controlled airspaces is at Fig 27-3.

2741. **Control Zone**—A controlled airspace extending upwards from the surface of the earth.

2742. **Control Area**—A controlled airspace extending upwards from a specified height.

2743. **Terminal Control Area**—A portion of a control area normally situated at the confluence of airways in the vicinity of one or more major airfields.

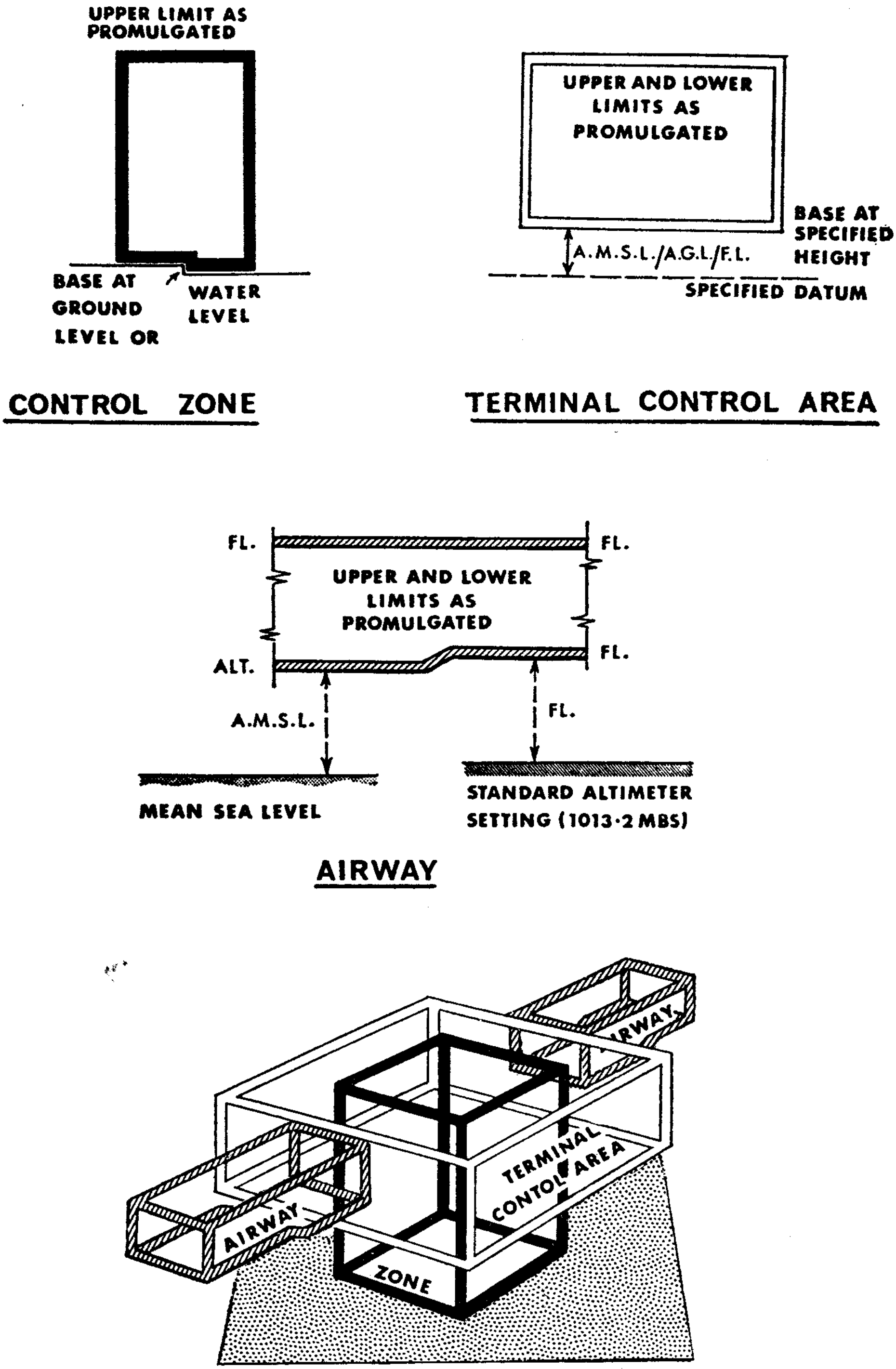
2744. **Flight Information Region (FIR)**—An airspace of defined dimensions within which a flight information service and an alerting service are provided.

2745. **Flight Level**—A layer of constant atmospheric pressure above a pressure datum of 1013.2 mbs (SAS). Flight levels are numbered at 500 feet intervals, *eg* 5,000 feet—FL 50; 5,500 feet—FL 55.

2746. **Flight Plan**—Specified information provided to air traffic service units relative to the intended flight of an aircraft.

2747. **Height**—The vertical distance of a point, or object considered as a point, from a specified datum.

2748. **Transition Altitude**—The altitude in the vicinity of an airfield, at and below which the vertical position of an aircraft is controlled by reference to altitude. It is normally 3,000 feet in the UK, exceptions being London, Scottish, Manchester and Gatwick TCAs where it is 4,000 feet or more. Aircraft climbing through the transition altitude will change altimeter setting to SAS.



SCHEMATIC DIAGRAM SHOWING COMBINATION OF CONTROLLED AIRSPACES

Fig 27–3 Controlled Airspaces

2749. **Transition Level**—The first Flight Level above Transition Altitude. Transition level can be calculated, or obtained from the flight level graph (Flight Information Handbooks) using the airfield QNH.

2750. **Transition Layer**—The airspace between the Transition Altitude and the Transition Level is known as the Transition Layer. The depth of this varies between 0 and 500 feet.

2751–2756. (*Not allotted*).

THE ALTIMETER

2757. **Introduction**

a. The Altimeter is an aircraft instrument which is basically a barometer measuring atmospheric pressure. This is indicated on the instrument as a measurement in feet or metres.

b. The pressure for any level or datum may be set on an altimeter sub-scale, and the instrument will then measure the vertical distance above that level.

c. Atmospheric pressure decreases as vertical distance increases (a change of 1 millibar (mb) is roughly equivalent to 30 feet).

Pressure Settings

2758. The pressure settings used by military aircraft are:

a. *QFE*—the barometric pressure at airfield level. When set on an aircraft altimeter, the HEIGHT of the aircraft above airfield level will be indicated. When the aircraft is on the airfield, the altimeter will read zero.

b. *QNH*—the barometric pressure measured at airfield level and adjusted to Mean Sea Level (MSL). When set on the aircraft altimeter it indicates the ALTITUDE of the aircraft above AMSL.

c. *Regional Pressure Setting* (*RPS*)—this is the lowest forecast QNH for a particular region; it is forecast one hour ahead and valid for one hour. The UK is divided into 14 Altimeter Setting Regions (ASRs) which are shown on En-Route Charts. RPS is used as a datum to indicate scale altitude for transit flying below 3,000 feet.

d. *Standard Altimeter Setting* (*SAS*) (1013.2 mbs : 29.92 mm) when set on the aircraft altimeter, SAS gives the FLIGHT LEVEL of an aircraft and is used for flight above the Transition Level.

2759. **Altimeter Setting Procedures.** These are as follows:

a. *Take off and initial climb.* The pilot sets QFE.

b. *Flight at or below 3,000 feet.* Within the airfield vicinity QNH can be used but on leaving the circuit the pilot changes to RPS.

c. *Flight above 3,000 feet.* On passing through the transition altitude, normally 3,000 feet, the pilot changes the altimeter setting to SAS.

2760–2761. (*Not allotted*).

DIVERSIONS

2762. Diversion is the act of flying to an airfield other than that originally intended for the purpose of landing. This applies whether the decision is the pilot's or the ground authority's.

Reasons for Diversions

2763.

a. Aircraft unserviceable or short of fuel.

b. Hazardous weather en-route or below the pilots instrument limit at the destination airfield.

c. Destination airfield unusable (failure of essential ground installation, obstruction *etc*).

d. Operational or administrative reason.

Categories of Diversions

2764. An aircraft diversion may be originated by the aircraft operating authority, air traffic control or the aircraft captain. An officer originating a diversion is to ensure that the captain is informed of the grade and reasons for the diversion, (*eg* weather, administrative requirements *etc*):

a. *Grade 1 Diversion.* Mandatory—originated only by the operating authority but may be passed by ATC. The pilot is to inform the operating authority if he cannot comply, giving reasons.

b. *Grade 2 Diversion.* Advisory—originated by the operating authority or ATC. When originated by an air traffic controller he is first

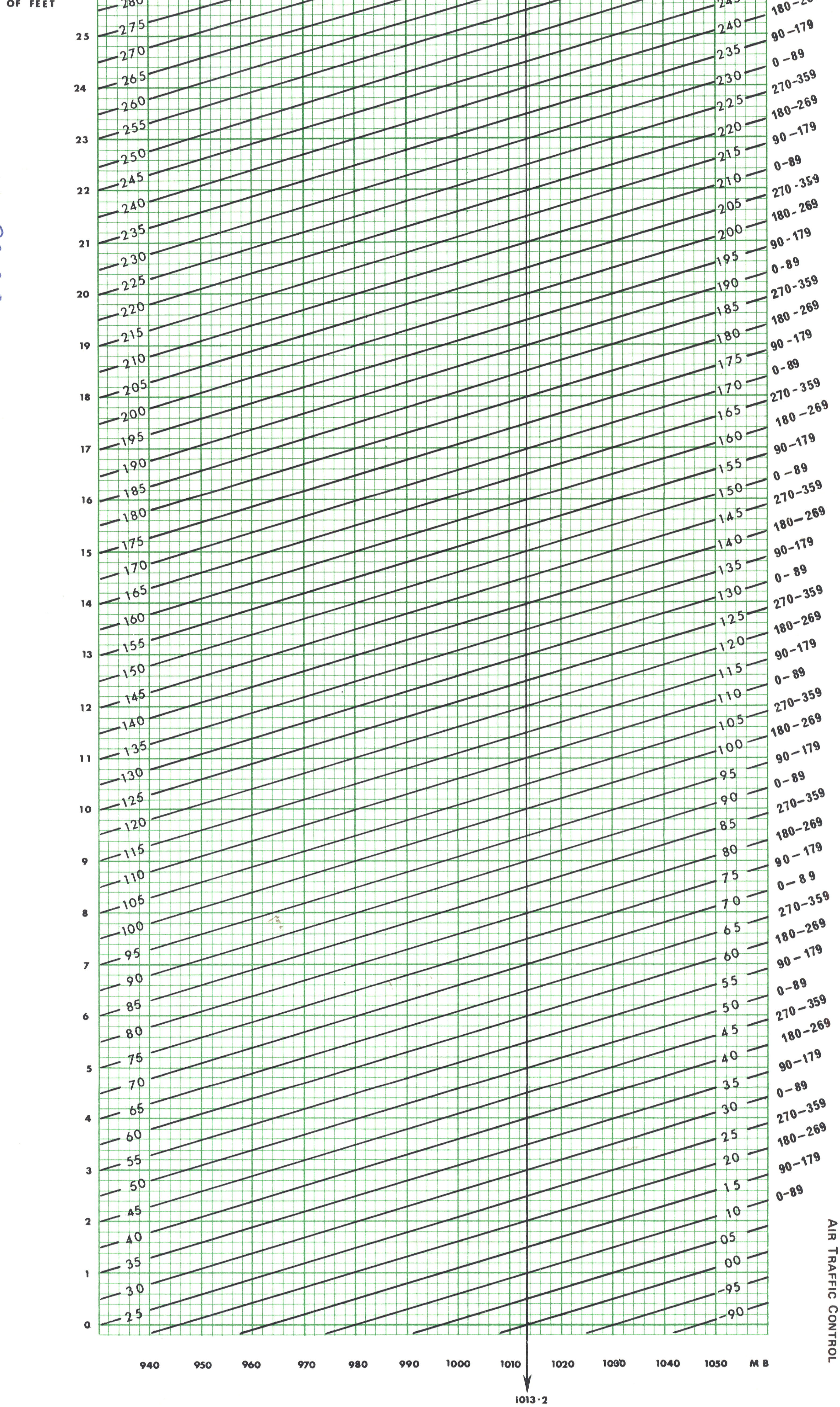


Fig 27-4

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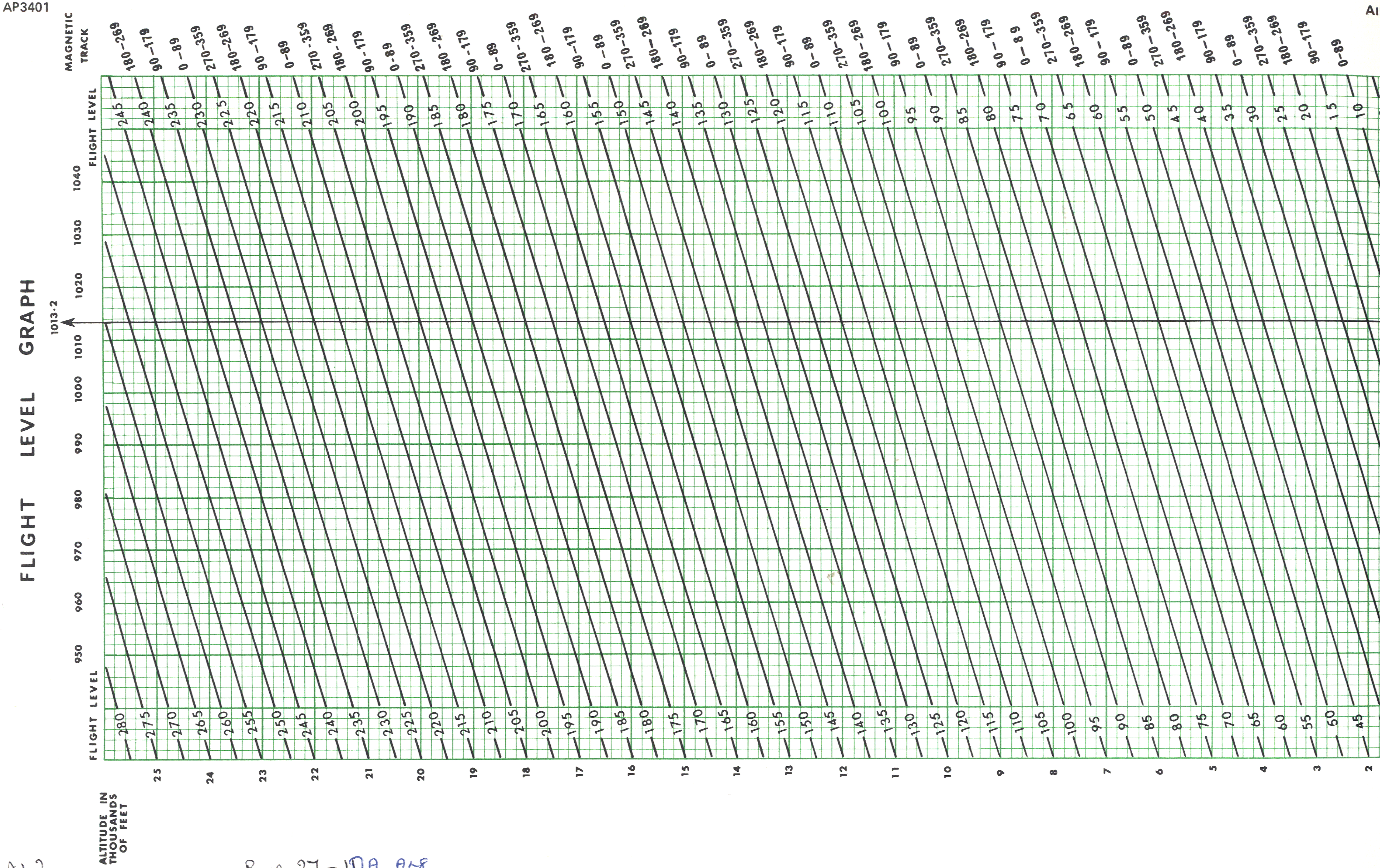

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to obtain the approval of the operating authority or inform him as soon as possible.

Note 1. Self Diversion. (Aircraft Captains Decision). When the captain of an aircraft requests a diversion, the diversion does not have a category.

Note 2. In the case of a military aircraft operating outside the jurisdiction of its own operating authority, or where the authority is not functioning, the operating authority is the Station Commander or his deputy at the destination airfield.

2765. **Supersonic Flights.** In the United Kingdom, supersonic flights are to be made over the sea. Aircraft heading directly out to sea may accelerate to supersonic speed when at least 10 nm out to sea and along a line of flight at least 20 degrees divergent from the mean line of the coast; the angle of dive is not to exceed the minimum necessary. Supersonic flights with the aircraft pointing towards the land, turning or flying parallel to the coast are to take place at least 35 nm from the nearest coastline.

2766–2769. (*Not allotted*).

EMERGENCY PROCEDURES

2770. **Introduction.** Within the UK FIRs, the RAF is responsible for providing an emergency organization for civil and military aircraft. Complete UHF coverage of the UK UHF international aeronautical distress frequency is generally obtained at 5,000 feet and above. An automatic direction finding system enables fixes to be obtained on aircraft calling on the aeronautical distress frequencies. Overseas the coverage of RAF areas of responsibility is not as complete as in the UK and therefore different procedures are adopted.

2771. **Emergency Frequencies**

a. (UHF R/T) 243·0 MHz International military distress/Emergency frequency.

b. (VHF R/T) 121·5 MHz International Aeronautical Emergency frequency.

c. (W/T) 500 KHz Internation Emergency frequency.

2772. **States of Emergency.** The RAF recognizes two states of emergency which are defined in the following table:

SERIAL NO	STATE	WHEN USED
1	URGENCY	Aircraft is in danger and in urgent need of assistance with the aid of which the danger may be overcome, eg, aircraft lost, fuel shortage, partial engine failure.
2	DISTRESS	Aircraft is threatened by serious and imminent danger and the crew is in need of immediate assistance, eg, ditching, crash-landing or abandoning aircraft.

2773. **Emergency Communication Procedures.** When an aircraft is in a state of emergency, the pilot should use the appropriate R/T procedure as follows:

SERIAL NO	STATE	R/T PRO-WORDS
1	URGENCY	"PAN, PAN, PAN, Aircraft callsign"
2	DISTRESS	"MAYDAY, MAYDAY, MAYDAY, Aircraft callsign (three times)"

Note: When making an Urgency or Distress call the IFF should be switched to emergency.

The text of the message should include as much of the following information as time permits:

a. Estimated position and time.

b. Heading (true) and airspeed (indicated).

c. Flight level or altitude.

d. Type of aircraft.

e. Nature of emergency and assistance required.

f. Intention of the captain.

g. Endurance remaining.

h. Any further information.

j. Aircraft callsign.

The pilot will transmit as much of this information as possible and add any further information he thinks may be of assistance.

2774. **Cancellation.** Should the emergency condition cease to exist, it is the responsibility of the pilot to immediately transmit a message on all frequencies used cancelling the original call.

2775. **Organization (UK):**

a. Both military ATCCs and all master airfields maintain a continuous listening watch on 243·0 and 121·5 MHz.

b. Certain additional (co-opted) airfields, chosen for their geographical position will, if alerted by an ATCC during operating hours, maintain a listening watch until stood down.

c. Additional emergency lines with emergency ringing are provided for telephone communications at all these airfields.

d. ATCCs (Distress and Diversion Sections) are responsible for plotting, co-ordinating and directing all emergency actions within their FIRs.

e. ATCRUs will provide assistance at the request of the ATCC or other stations.

2776. **R/T Triangulation System.** There are two methods of fixing an aircraft position by triangulation:

a. *Auto Triangulation.* Automatic triangulation is available on 243·0 MHz at Prestwick and West Drayton. This system incorporates a number of forward relay sites equipped with Tx/Rx and Commutated Antenna Direction Finders (CADF), which monitor 243·0 MHz. Bearings received are automatically passed by landlines to the appropriate ATCC where they appear as traces on a vertical screen display. The point of intersection of three or more traces provides a fix, indicating the aircraft's position and lasts for as long as the pilot transmits. This position is also pin-pointed on the screen by an assistant controller operating a 'light gun'. Generally the lower limit for fixing a position is 5,000 feet in the London FIR and 8,500 feet in the Scottish FIR.

b. *Manual Triangulation.* When a manual system has to be used, the bearings taken from CADF on VHF D/F equipments at Master or Co-opted airfields are passed by direct telephone line to the ATCC (D & D) where they are plotted manually to provide a fix.

Loss of R/T Procedure

2777. If a pilot has R/T unserviceability and is lost, he can switch his IFF/SIF to emergency and then fly a triangular pattern of tracks with sides of one minute's duration if he is flying at speeds greater than 300 knots (2 minutes for speeds less than 300 knots). If the pattern is right handed it indicates that the aircraft R/T transmitter is u/s; if left handed it indicates that both R/T transmitter and receiver are u/s. In addition, the pilot can indicate unserviceable R/T by setting Mode 3 Code 76 on his IFF Mk 10 (SIF) equipment. The ground radar authority observing this procedure should simultaneously:

a. Endeavour to contact the aircraft, passing instructions if the aircraft receiver is serviceable and the aircraft is seen to be complying with instructions.

b. Report the incident to the appropriate agency for obtaining the immediate assistance of a 'shepherd' aircraft.

c. Inform the appropriate air traffic control authority of the position, and if possible, the altitude of the aircraft in order to clear the path of the aircraft and thus avoid risks of collisions.

Speechless Procedures

2778. The failure of a pilot's microphone does not prevent him from making contact with ground stations. When the R/T transmitter button is pressed a carrier wave is radiated even though the pilot is unable to transmit speech. By initiating 4 short carrier wave transmissions thus indicating a speechless condition, the pilot can converse with the controller by using the following code:

a. 4 clicks . . . . .representing the letter H in morse, and signifying a request for homing.

b. 1 click . . . . . meaning YES or acknowledgement.

c. 2 clicks . . . . . meaning NO.

d. 3 clicks . . . . . meaning SAY AGAIN.

e. The letter X in morse (dash dot dot dash — . . —) meaning "I have an additional emergency".

By using the above code the pilot can reply to any questions from the controller which are suitably phrased so that they may be answered by a "Yes" or "No".

Royal Flights

2779. A "Royal Flight" is the movement of an aircraft carrying one or more of the undermentioned members of the Royal Family:

HM The Queen	HRH Princess Anne
HM Queen Elizabeth The Queen Mother	HRH Prince Andrew
	HRH Prince Edward
HRH Prince Philip	HRH Princess Margaret
HRH The Prince of Wales	

Certain flights by Heads of Foreign States, within the UK, can be classed as Royal Flights, as directed by MOD.

Royal Flight by Fixed Wing Aircraft

2780. Whenever possible, Royal Flights are to be conducted within existing controlled airspace. When this is not possible, and in order to provide separation from other flights, temporary controlled airspace will be established for Royal Flights within the UK. This airspace, known as Purple Airspace, is established in the form of Airways along the route, Control Zones and Areas of airfield of departure and destination.

Definitions

2781. **Purple Airspace.** This is temporary controlled airspace, established for the protection of Royal Flights in fixed wing aircraft, in which additional rules for air traffic and compulsory IFR apply at all times and in all weathers. Purple Airspace is not normally provided for Royal Flights in helicopters.

2782. **Purple Control Zone.** This is a temporarily controlled airspace, established at airfields not within an existing control zone at, or from, which a Royal Flight is due to arrive or depart.

Note. (1) Purple Control Zones are established around airfields of departure and arrival normally for periods of 15 minutes before until 30 minutes after ETD and ETA respectively.

(2) In permanent Control Zones appropriate sectors are classified as Purple Control Zones.

(3) Purple Control Zones have a radius of 10 nm centred on the airfield, and extend from ground level to a notified flight level.

2783. **Purple Airway.** This is a temporarily controlled airspace, in the form of an airway along the route of a Royal Flight.

Note. (1) Purple Airways are established with a width of 5 nm on either side of a stated centre line, for a period of 15 minutes before the Royal Flight is scheduled to enter the airway until 30 minutes after it is scheduled to leave the airway.

(2) When a Royal Flight is made on an existing airway, the appropriate height bands become Purple Airways.

(3) The vertical extent of purple airways and/or height bands will be notified by NOTAM.

(4) The controlling authority for purple airways are the ATCCs in whose FIR the airway is established.

(5) Purple Airways established for flights of more than one hour may be sectorized and may be established 15 minutes before ETA at the beginning of a sector, until 30 minutes after ETA at the end of a sector.

Control of Air Traffic within Purple Airspace

2784. At present, aircraft in a controlled airspace are only under positive Air Traffic Control when flying IMC or in an airway. However, it is essential that aircraft using controlled airspace when a Royal Flight is passing through it are under positive control irrespective of the weather conditions. To this end, when a Royal Flight is planned to pass through existing or temporarily controlled airspace, the airspace is subject to certain regulations which effectively ensure that all aircraft captains must file a flight plan and that all flights must be conducted under ATC clearance.

Use of Distress Frequencies

2785. No practice emergency calls are to be made on the distress frequencies during the period starting 15 minutes before ETD of a Royal Flight and until 30 minutes after ETA at destination.

Royal Flight Callsigns

2786. The following callsigns are used:

a. Whenever a Royal passenger, listed in para 2779, is being carried the R/T callsign "Kitty Hawk" followed by a single digit from 1 to 9 is used.

b. Whenever Prince Philip, Duke of Edinburgh is at the controls the callsign "Rainbow" will be used.

c. Whenever the Prince of Wales is at the controls the callsign "Unicorn" will be used.

d. The R/T callsign "Kitty" followed by a single digit will be used for all other flights by Queen's Flight aircraft including VIP and positioning flights.

e. For flights in other RAF aircraft, normal flight callsigns are used.

AERONAUTICAL INFORMATION DOCUMENTS SERVICE

Function

2787. This service is responsible for the publication and distribution of up to date unclassified aeronautical information through the medium of Flight Information Publications (FLIPS).

2788. The area of responsibility covered by FLIPS is the British Isles and North Atlantic, Europe (including Scandinavia) and the Mediterranean, Africa and South East Asia to 132°E.

2789. FLIPS are designed for the use of aircrew and, therefore, must be logical in layout and content, of minimal size and number, and up to date. The documents are described in the following paragraphs.

2790. **The Planning Document (PD).** The planning document is published to meet the requirements of advance and pre-flight planning and include the following sections:

a. *Section 1* (*White*)—General information, Index and Gazette.

b. *Section 2* (*Light Blue*)—ICAO Procedures and Flight Planning.

c. *Section 3* (*Red*)—Airspace Reservations.

d. *Section 4* (*Dark Blue*)—ATC National Procedures.

e. *Section 5* (*Yellow*)—Airfield Runway and Obstruction Data.

2791. **The En-route Supplement (ERS).** There are 3 ERSs published relating to the British Isles and North Atlantic (PINK), Europe and Mediterranean (GREEN), Africa and Southern Asia, including the Middle East (BROWN) containing the following information:

a. Airfield facilities.

b. LCN/LCG table.

c. Flight Watch Centres.

d. Identification Letters of airfields/navigation aids.

e. Safeguard systems (UK).

f. ATCRU details and coverage.

g. Emergency Fixer Service Coverage.

h. Airmiss and position reporting procedures.

2792. Other documents designed more for aircrew use include:

a. Flight Information Handbook.

b. En-route charts (ERC).

c. Terminal Approach Procedure Charts (TAPC).

d. Airfield Arrival and Departure Procedures books.

2793–2795. (*Not allotted*).

NOTAMS

2796. **Definition.** A notice, containing information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations.

2797. **Class of NOTAM.** NOTAMS are classed according to their terms of urgency:

a. *NOTAM Class I.* Coded information which is distributed quickly through the teleprinter network.

b. *NOTAM Class II.* Information distributed by postal means which will ensure adequate notice to the addressees.

Class of NOTAM	Time Factor	Method of Dispatch
Class I	Facility change immediate or taking place within 72 hours.	Signal
Class II	Facility change with over 72-hours notice.	By post

2798. **Distribution of NOTAMS.** The distribution of designated NOTAMS is the responsbility of the Aeronautical Information Service. It should be noted that undesignated NOTAMS are not distributed; they are retained at the ATCC for information. The distribution of designated NOTAMS is covered by:

a. Unit flight planning requirements.

b. Telecommunications available to the air traffic control service.

2799. **NOTAM Code.** The NOTAM code is provided to enable the coding of information regarding the establishment, condition or change of radio aids, airfield and lighting facilities, dangers to aircraft in flight, or search and rescue facilities. Encoding facilitates the dissemination of NOTAMS by reducing the transmission time over telecommunications channels and eliminates translation. All NOTAM code groups contain a total of five letters. The first letter of the group is always the letter Q to indicate that it is a code abbreviation for use in the composition of NOTAMS. Five-letter NOTAM code groups are formed in the following manner:

a. *First Letter.* The letter Q.

b. *Second and Third Letters.* The appropriate combination of two letters selected from the "Second and Third Letters" section of the code to identify the facility, service or danger to aircraft in flight being reported upon. It should be noted that the second letter has been restricted to A, E, I, O, or U.

c. *Fourth and Fifth Letters.* The appropriate combination of two letters selected from the "Fourth and Fifth Letters" section of the code to denote the status of operation of the facility, service or danger to aircraft in flight reported upon. It should be noted that the fourth letter has been restricted to A, E, I, O or U.

The first five-letter NOTAM code group in any NOTAM text is in all cases to be immediately preceded by the full name of the location of the particular facility, service or danger to aircraft in flight being reported upon except that, in cases where an ICAO place name abbreviation has been assigned, this shall be used to identify the geographical location.

Example:

1	2 3 4	5	6
EGXC	QEEOS	Jul 210800	Jul 240800

7
Calibration

Meaning:

The GCA at Coningsby will be out of service from 0800 hours GMT on July 21st until 0800 hours GMT on July 24th for calibration.

Explanation:

1. ICAO location indicator of Coningsby.
2. The letter Q identifying a five-letter code group as a NOTAM code group.
3. Second and third letters identifying GCA.
4. Fourth and fifth letters denoting "out of service from ....(date/time) until..........................(date/time)".
5. Date/time group completing the first blank in signification of the fourth and fifth letters "OS".
6. Date/time group completing the second blank in signification of the fourth and fifth letters "OS".
7. Plain language statement completing the third blank in signification of the fourth and fifth letter "OS".

In those significations where the expression "on.............. kHz (or MHz)" appears, the figure groups used alone will indicate the frequency in kilohertz. To express a frequency in megahertz the figures group is immediately followed by the abbreviation "HZ". Details of the composition of NOTAM code groups are contained in Flight Information Publication, Supplementary Data 1.

THE UK R/T FLIGHT INFORMATION SERVICE

27100. The R/T Flight Information Service has been established to enable military aircraft fitted with UHF R/T to obtain aeronautical information whilst in flight. This service operates from 0800 to 2359 hours Monday to Friday (except public holidays) from London and Scottish ATCCs and provides the following services:

a. Alerting service—notification to the appropriate organization of aircraft in need of Search and Rescue assistance.

b. Airfield states and serviceability changes.

c. Actual and forecast weather conditions at airfields, en-route weather information, meteorological warnings, RPSs for all UK Altimeter Setting Regions.

d. Relaying of position reports, passing of aircraft movement messages etc. *FIS* acts as a link between aircraft and airfields.

CHAPTER 28

SEARCH AND RESCUE

Introduction

2801. Full details of British Search and Rescue facilities are given in the British Supplement No 1 to NATO publication ATP-10 (B)-I—Search and Rescue. The purpose of this chapter is to give a brief outline of the facilities for those concerned with Control and Reporting.

2802. The search and rescue organization in the UK has the following broad functions:

a. To provide location and rescue facilities for military and civil aircraft within the UK area of responsibility.

b. To provide assistance to shipping in distress.

c. To provide assistance in instances of civil distress or life saving.

Search and rescue facilities in the UK are provided under joint RN/RAF organization and are based on the use of service and civil facilities co-ordinated and directed by Rescue Co-ordination Centres (RCCs). Broadly speaking the RAF is responsible for air search, the dropping of survival equipment, helicopter rescue at sea and mountain rescue on land; the Royal Navy is responsible for rescue by ships at sea. Help from all available military and civil resources may however be enlisted. The ability to help implies responsibility to help in the way directed by the co-ordinating authority.

2803. In commands abroad, search and rescue is the responsibility of the air commanders working in close association with naval and other authorities concerned. British search and rescue organizations abroad observe the same basic principles that underlie the search and rescue organization of the UK and resemble it as closely as local circumstances permit. The UK organization can therefore serve as an all-embracing example, and as such has been selected for description in this chapter.

Search and Rescue Organization of the UK

2804. Search and rescue activities in the UK and its surrounding areas are directed from Rescue Co-ordination Centres (RCCs) at Edinburgh and Plymouth respectively. Where an incident occurs on the boundary between two areas, mutually agreed action is taken by the RCC which is better placed to do so.

2805. A basic principle of search and rescue operation is that action should be taken at once by the authority first aware of an incident. Thus a station commander who receives a signal from an aircraft to say that it is being forced to come down in the sea-approaches to his own station, is justified in dispatching any search aircraft at his disposal without waiting for instructions from the RCC. He must, however, quickly inform the appropriate RCC of the incident and the action he has taken; all subsequent search and rescue activities will be controlled by the RCC. He must also inform the appropriate air traffic control centre.

2806. The RCCs have at their disposal aircraft from all the flying commands in the country, Royal Air Force marine craft, and can call upon aircraft and ships of the Royal Navy and aircraft of the United States Air Force; RAF mountain rescue teams are available on land. Helicopter facilities are provided by the RAF and RN to cover the United Kingdom and surrounding coastal waters (*see* Fig 28–1). Additional aid is often provided by local civilian boat owners. As soon as an incident occurs, the most suitable available craft is dispatched, irrespective of the command to which it belongs; thereafter the search is planned to make the very best use of all the resources that can be called upon. Help from the lifeboats of the Royal National Lifeboat Institution can be requested and a broadcast to shipping may be made, requesting that they keep a lookout, or if the approximate position of survivors is known, attempt a rescue.

2807. When survivors or wreckage are located, rescue may be attempted by surface craft, helicopters or amphibians. Rescue craft can use radar or radio to home on to a search aircraft that has found, and is circling, the crew or remains of a crashed aircraft.

2808. Strike Command does much of its flying over the sea and has a particular interest in the search and rescue organization. It is able to make great use of the principle that action must be taken at once by the authority that first learns of an incident. Its fighters are almost always under radar control when airborne and it usually has other fighters ready for instant take-off, or aircraft already in the air, which can render assistance.

Alerting of the Search and Rescue System by C & R Authorities

2809. When an interception controller becomes aware that an aircraft under his control or surveillance is going down in the sea, he must:

a. Determine the position of the aircraft with the greatest possible accuracy.

b. Pass the pilot any useful information, *eg* his position in relation to the coast, and whether he can profitably glide towards it before abandoning aircraft.

c. Tell his chief controller at once what has happened, and afterwards keep him fully informed of developments.

d. Give every possible help to the pilot of any accompanying aircraft that may be with the distressed aircraft.

2810. When a chief controller is informed by an interception controller that an aircraft under his control has, or is about to come down in the sea, he should immediately notify the master controller or control executive. The master controller would in turn inform the appropriate RCC and ATCC, either direct or through the diversion centre, whichever is the quicker. The master controller would also endeavour to dispatch an aircraft to the scene of the ditching to orbit the position until a helicopter or surface

craft arrived. The C & R system with its comprehensive radar and communications systems is often able to take control of the rescue forces, under the direction of the RCC. ~~Aircraft engaged on search and rescue operations set Mode 3 Code 27 on their IFF Mk 10 (SIF) equipments, and should therefore be readily detectable by defence radar stations within range.~~

Signalling of Distress by a Pilot

2811. A pilot has generally three ways of attracting attention when he is in distress:

a. By RT, using the standard emergency RT calls (*see* para 2813).

b. By switching his IFF/SIF to distress.

c. If his RT is unserviceable and he is above cloud and unable to descend safely, a pilot can indicate his distress by flying a triangular pattern of tracks with sides of one minute's duration if he is flying at speeds greater than 300 knots (two minutes for less than 300 knots). If the pattern is right-handed it indicates that the aircraft RT transmitter is u/s; when it is left-handed it indicates that both RT transmitter and receiver are u/s. In addition, the pilot can indicate unserviceable RT by setting Mode 3 Code 76 on his IFF Mk 10 (SIF) equipment. Immediately these patterns are recognized by a radar observer the master controller should be informed. He will then arrange for an aircraft to be directed to join up with the orbiting aircraft and lead it down to an airfield.

2812. Having ditched and boarded his dinghy, a pilot can attract the attention of searching aircraft by using his personal search-and-rescue beacon (SARBE), or by making visual signals with pyrotechnics and with the mirror provided in the survival pack. At night, pyrotechnics should be conserved and used in accordance with Night Search Techniques.

2813. Two degrees of emergency in the air are recognized, each having its own appropriate form of R/T signal for help:

a. PAN. A pilot who is in danger and urgently needs help (*eg* if he is lost, short of fuel, or experiencing partial engine failure) should transmit an urgency signal in which the normal call and message are preceded by a threefold repetition of the word PAN.

b. MAYDAY. A pilot who is threatened by imminent disaster (*eg* he is ditching, crash landing, or abandoning his aircraft) should transmit a distress signal consisting of a threefold repetition of the word MAYDAY (a corruption of the French "m'aidez"), followed by a threefold repetition of his call-sign, and then any brief explanation he has time to give.

2814. Pilots normally first make their emergency known over the R/T channel they are already using, and when their emergency amounts to urgency or distress they then usually change to the International Aeronautical Emergency Channel (243·0 MHz) for all further communication. However, if a fighter pilot meets an emergency under close control he is probably well advised to stay in communication with his controller, who knows where the pilot is on radar. The controller will, in any case, carry out the actions detailed in para 2809 and the chief controller the actions in para 2810.

(AL 5, Jun 73)

CHAPTER 29

ELEMENTS OF AIR NAVIGATION AND ALLIED SUBJECTS

CONTENTS

POSITION

Form of the Earth

2901. Although the Earth is not quite a true sphere (being slightly flattened at the poles) it may be regarded as such for the purposes of this chapter. The earth rotates about a constant axis passing through its centre. The two points at which this axis meet the surface of the Earth are called the poles.

2902. The intersection of any plane with the surface of a sphere is always a circle. If the plane passes through the centre of the sphere it forms a circle on the surface which is called a great circle; if it does not, the circle is called a small circle (*see* Fig 29–1).

one such great circle, unless the two points are diametrically opposite.

2904. Certain lines which can be imagined to lie on the Earth's surface are important, and are defined as follows:

a. *Equator*. The equator is the great circle whose plane is perpendicular to the axis of rotation of the Earth.

b. *Meridian.* A meridian is a semi-great circle joining the poles; only one meridian passes through a point of the earth except at the poles.

c. *Parallel of Latitude.* A parallel of latitude is a small circle whose plane is parallel to that of the equator.

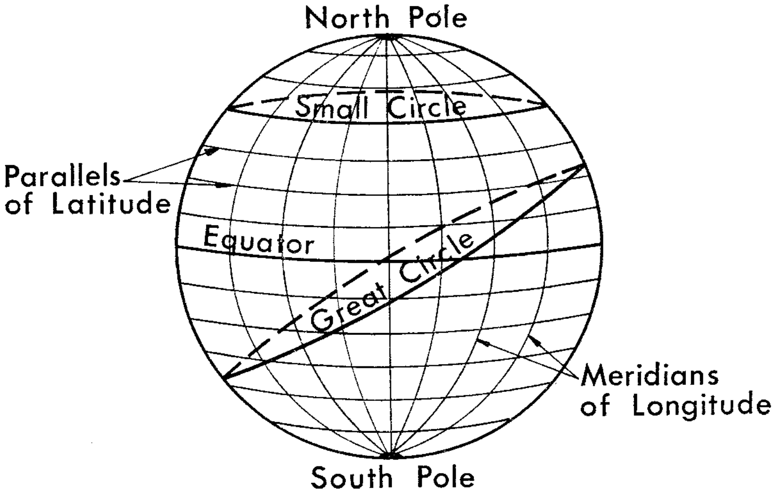

Fig 29–1 Great Circles and Small Circles

2903. The shortest superficial distance between two points on a sphere is by the lesser arc of the great circle passing through them. There is only

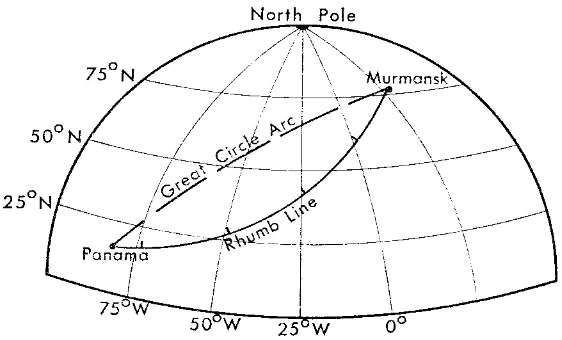

Fig 29–2 Rhumb Lines

d. *Rhumb Line.* A rhumb line is a line on the surface of the Earth which meets all meridians at the same angle (*see* Fig 29–2).

Direction

2905. **East and West.** East is defined as the direction in which the Earth is rotating. This direction is anti-clockwise to an observer looking down on the North Pole. West is the direction opposite to East.

2906. **North and South.** The North Pole is the pole which is on the left of an observer facing East, and the South Pole is the one on his right. North is the direction in which an observer would have to travel to reach the North Pole, and is at right angles to the East–West direction. The directions North, South, East and West, are known as "cardinal" directions.

2907. **Measurement of Direction.** The datum for measurement of direction is the meridian through the position from which the measurement is to be made. The meridian is the North–South line, and, by convention, direction is measured clockwise from North to the nearest degree, *ie* from 000° to 360°. The measurement is always expressed as a three figure group; thus East, which is 90° from North, is written 090° and West 270°.

2908. **True, Magnetic and Compass Directions.** Directions measured from the North Geographical Pole are called "True" (T) directions. However for centuries man has determined direction by using the magnetic compass. A magnetic compass points not to the True North Pole but to the North Magnetic Pole, which wanders very slowly around the North Geographic Pole. Directions measured relative to the direction of the North Magnetic Pole are "Magnetic" (M) directions. A magnetic compass in an aircraft is inevitably somewhere near metal components and electrical circuits which create magnetic fields. These disturb the compass needle and may cause it to point slightly away from magnetic north. Directions measured on a particular compass are known as "Compass" (C) directions. Three standards are therefore used in navigation for measurement of direction: True (°T), Magnetic (°M) and Compass (°C).

2909. **Variation.** The angular difference between True North and Magnetic North (and therefore true directions and magnetic directions) is called "Variation". Variation varies from place-to-place, and is termed Easterly or Westerly according to whether the North Magnetic Pole lies to the East or to the West of the North Geographical Pole when measured from a particular place. In addition to varying from place-to-place, variation also alters from year-to-year at each location, because the North Magnetic Pole wanders slowly about the North Geographical Pole. Variation is usually indicated on maps by lines drawn through places which have the same variation at any one time. These lines are called "isogonals". The isogonals are usually dated and the rate and direction of change of variation is indicated.

2910. **Deviation.** The angular difference between Magnetic North and Compass North, for any particular compass in a particular situation is called "Deviation". Deviation is Easterly or Westerly according to whether the compass needle points to East or West of the Magnetic Pole. It is important to realize that the deviation of a compass varies with the heading of the aircraft in which it is installed. To illustrate the various ways of quoting direction, consider an aeroplane heading North-~~West~~ East over a place where the variation is 10° East, and whose compass on that heading has a deviation of 3° West. The heading of this aeroplane can be specified as 045° (T), 035° (M), or 038° (C). The following rhyme helps to derive magnetic headings from compass headings, and *vice versa*:

> *Deviation East, compass least;*
> *Deviation West, compass best.*

Similarly, to derive true headings from magnetic headings, and *vice versa*, remember that:

> *Variation East, magnetic least;*
> *Variation West, magnetic best.*

Distance on the Earth Surface

2911. **Units of Measurement.** Distance on the earth's surface may be measured in kilometres, statute miles or nautical miles. In addition "data miles" are sometimes used in connection with measurement of range by radars. Definitions of these units are as follows:

a. *Kilometre.* A kilometre is the length of $\frac{1}{10000}$th part of the average distance between the equator and either pole. It is equivalent to 3,280 ft.

b. *Statute Mile.* A statute mile is 5,280 ft in length and is a purely arbitrary unit of measurement having little significance in the context of control and reporting.

c. *Nautical Mile.* A nautical mile is defined as the length of the arc of a great circle which subtends an angle of one minute (1/60th of a degree) at the centre of the earth. Thus the number of nautical miles in the arc of any great circle equals the number of minutes subtended by that arc at the centre of the earth. Thus if the angle subtended by two places on the earth's surface is measured and the angle converted to minutes, the resultant figure will be the distance between the places on the surface of the earth, measured in nautical miles. For example, in Fig 29–3, if two places A and B subtend an angle at the earth's surface of 40° 20′ the distance between them is 2,420 nautical miles (2,420 minutes = 40° 21′). However, the earth is not truely spherical, and the actual length of a nautical mile is not constant but varies with latitude.

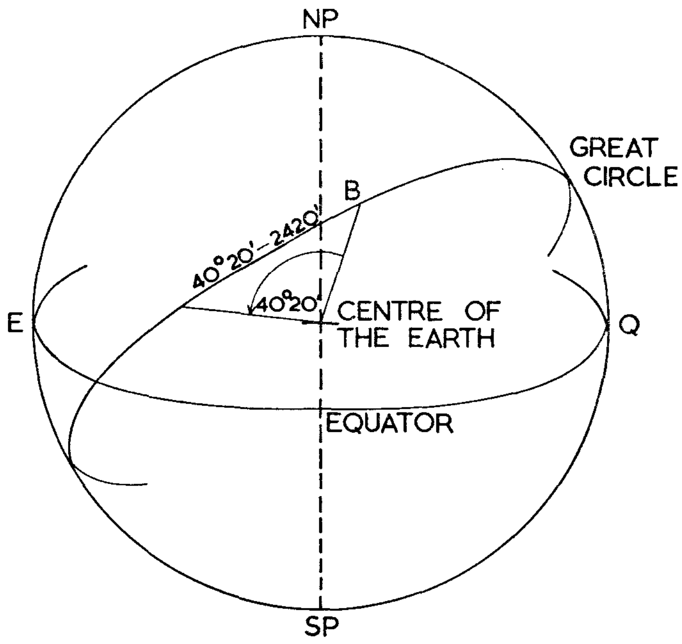

Fig 29–3 Angular Distance

But for practical purposes the length of a nautical mile is taken to be 6,080 ft, which is its average length, and errors arising from this approximation are generally negligible.

d. *Data Mile*. A data mile is 6,000 ft. It is used as it is a convenient round number of feet and approximates to a nautical mile.

Latitude and Longitude

2912. Meridians and parallels of latitude compose a reference system by which a position anywhere on the earth can conveniently be specified. The meridians when so used are known as lines of longitude, and the parallels as lines of latitude. A network of the two is called a graticule.

2913. The meridian passing through Greenwich in England is usually chosen as the prime meridian and is said to be of longitude 0°. The longitude of any other meridian is its angular distance, at the centre of the earth, east or west of the prime meridian.

2914. The latitude of the Equator is usually regarded as 0°, and the latitude of any other parallel is measured as its angular distance, at the centre of the earth, North or South of the Equator.

2915. Hence any place on the earth can be uniquely identified by its latitude and longitude. By convention, latitude is always quoted before longitude, so that it is unnecessary to introduce the words "latitude" and "longitude" when specifying a position. For example, the position of a place situated in latitude 51 degrees 5 minutes 17 seconds North and longitude 1 degree 37 minutes 48 seconds West is written either as 51°05′17″N, 01°37′48″W or, even more simply, as 510517N 013748W. (It is customary in this connexion to prefix all quantities less than 10 by "0", *ie* "01°", not "1°".)

Georef

2916. Georef (an abbreviation of World Geographical Reference System) is a reference graticule, based on latitude and longitude, which is used extensively in allied air defence systems. It has the advantage of being simple, speedy, unambiguous and capable of worldwide use. Moreover it is suitable for use in RT or telephone messages and can be coded easily for security purposes.

2917. The Georef System divides the surface of the earth into quadrangles of specific dimensions in terms of degrees and minutes of latitude and longitude. Each quadrangle is then identified by a simple, systematic code, using letters and numbers.

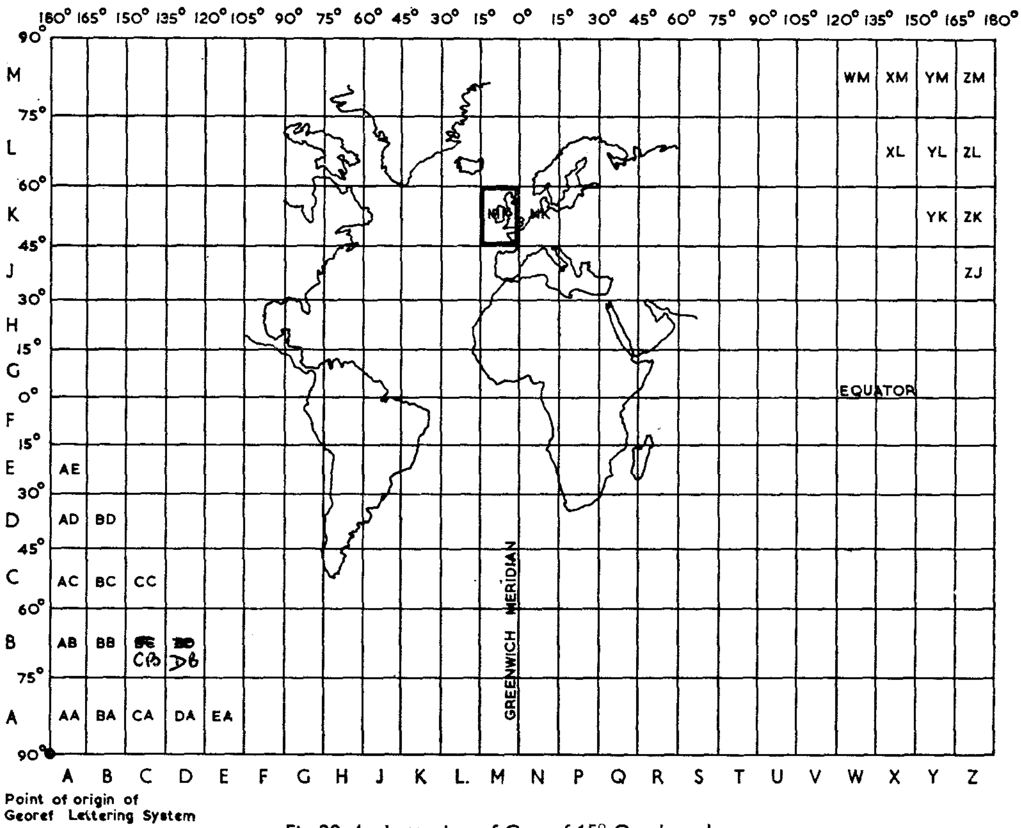

Fig 29–4 Lettering of Georef 15° Quadrangles

2918. The following facts should be borne in mind when considering georef:

a. There are 360° of longitude:
   (1) 180° East of the Greenwich Meridian.
   (2) 180° West of the Greenwich Meridian.

b. There are 180° of latitude:
   (1) 90° North of the Equator.
   (2) 90° South of the Equator.

c. There are sixty minutes (60′) in one degree (1°).

2919. The first division of the Earth's surface is into 24 zones of longitude, each 15° wide, which are lettered A to Z inclusive (omitting I and O), commencing eastwards from the 180° meridian. A corresponding division is made of the Earth's surface into 12 bands of latitude, each 15° wide, which are lettered A to M inclusive (omitting I). In this case, the lettering commences northwards from the South Pole. The earth is therefore divided into 288 (24 × 12) quadrangles, of 15° sides, each of which is identified by a unique combination of two letters. The first letter is always that of the zone of longitude (or easting) and the second that of the band of latitude (or northing). In this respect the system differs from that of latitude and longitude in which the latitude is always given first.

2920. Thus Wiltshire is in the 15° quadrangle MK (*see* Fig 29–4).

2921. Each 15° quadrangle is now sub-divided into 15 1° zones of longitude and bands of latitude, lettered A to Q inclusive (omitting I and O), commencing eastwards and northwards respectively from the south-west corner of the 15° quadrangle. Thus the 15° quadrangles are sub-divided into 225 (15 × 15) 1° quadrangles each being identified by means of four letters. The first two letters identify the 15° quadrangle, the third letter the 1° zone of longitude (easting) and the fourth letter the 1° band of latitude (northing).

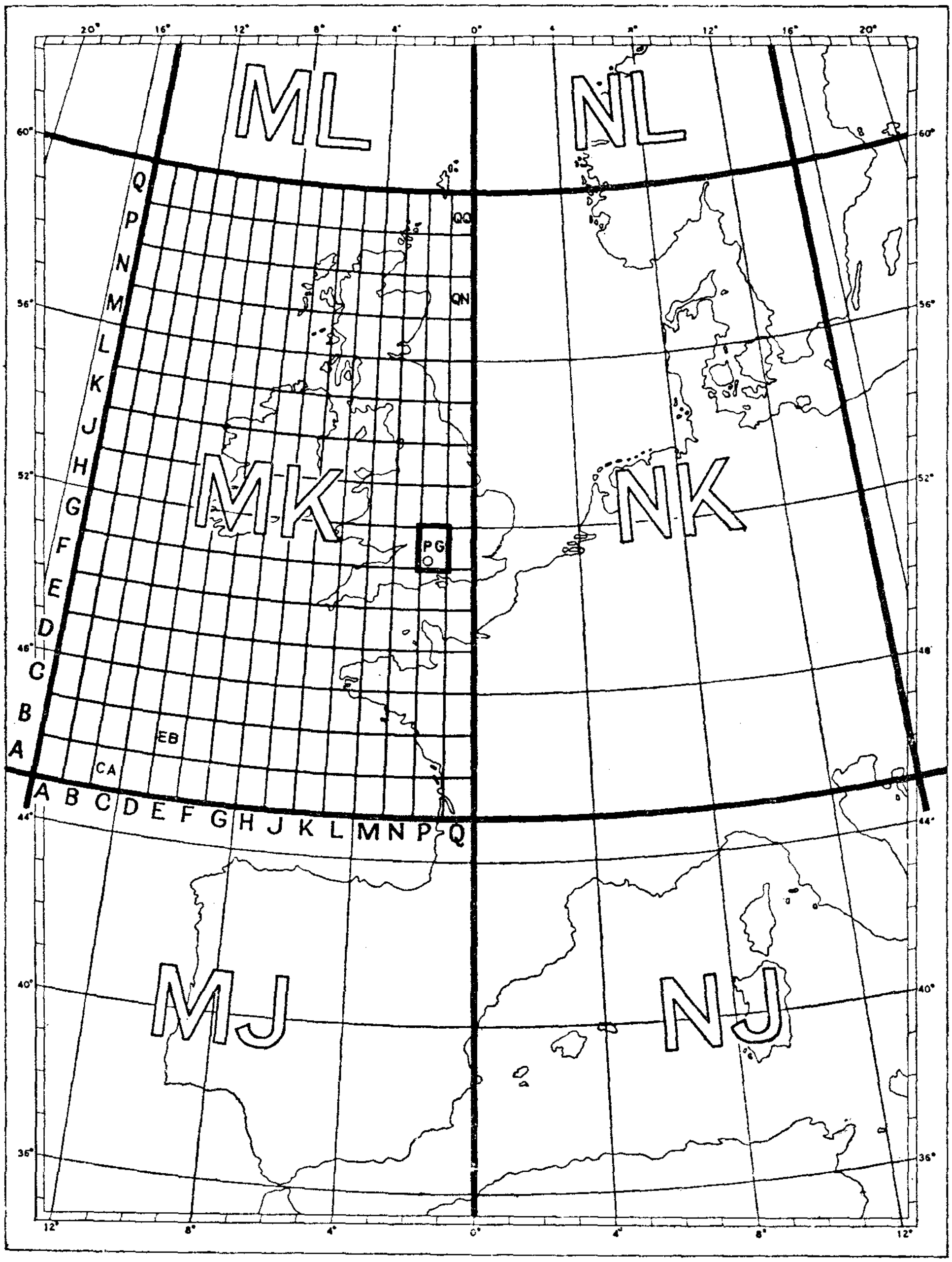

Fig 29–5 Division of 15° Quadrangles

2922. Salisbury, in the county of Wiltshire, therefore lies in the 1° quadrangle MKPG (*see* Fig 29–5).

2923. The 1° quadrangles are now further subdivided into 60 zones of longitude and bands of latitude (each 1′ of arc). The 1′ zones of longitude are numbered (from 00 to 60 inclusive) eastwards from the south-west corner of the one-degree quadrangle, whilst the 1′ bands of latitude are numbered similarly northwards.

2924. The reference number of any point can now be given, to an accuracy of one minute of

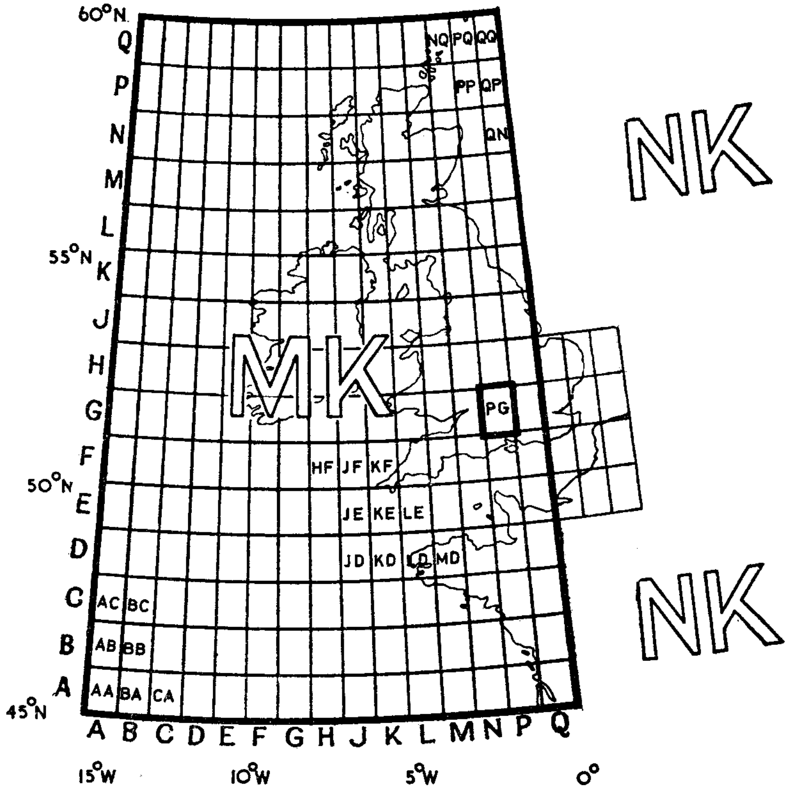

Fig 29–6 Lettering of Georef 1° Quadrangles

arc (or one nautical mile), by quoting four letters and four numbers. The four letters denote the 1° quadrangle, the first two numbers the easting, and the remaining two numbers the northing, of the position within the 1° quadrangle. If the number of minutes of easting or northing is less than ten, the first numeral is always 0. Thus the reference of Salisbury Cathedral (51° 04′ N, 01° 48′ W) is MKPG 1204 (*see* Fig 29–6).

2925. Occasions may arise (very infrequently in relation to Air Defence) when it is necessary to define a position to an accuracy greater than one minute. The Georef system can be expanded to allow such references to be given. Greater accuracy is obtained by measurement of the required position within the quadrangle having sides of one minute, in terms of units of $\frac{1}{10}$th of a minute (or 6 seconds). The reference is again measured from south west corner of the one-minute quadrangle and measured first eastwards and then northwards in units of $\frac{1}{10}$th minute. The accuracy of the position thus defined is within about 608 ft. The reference now has six numbers instead of four, and the position of the spire of Salisbury Cathedral is given by MK PG 122039. A further refinement to give an accuracy within about 61 ft is obtained by measuring the easting and northing of the required position, within the one-minute quadrangle, in units of $\frac{1}{100}$th of a minute. The reference then has eight numbers, and for the Salisbury Cathedral spire would be MK PG 12250386. The first four figures would represent the easting, and the second four the northing of the required position.

2926. On local operations where the risk of ambiguity with a neighbouring 15° quadrangle is unlikely, the first two letters of the reference may be dropped. The reference of Salisbury Cathedral would then become PG 1204 instead of MKPG 1204. Georef positions may be further abbreviated by using two letters (denoting the 1° quadrangle) together with two figures (denoting the 10′ quadrangle). For example, MKPG 10 becomes PG 10. This abbreviation may be used if no chance of confusion between 15° quadrangles exists.

which is called tertiary quadrang

Tactical Grid

2927. A position reference system called Tactical Grid is used in air defence operations by the Royal Navy and NATO navies. This system is described in the Manual of Joint Warfare, Volume 6 (JSP 6).

Other Methods of Specifying Position

2928. Three methods other than use of a grid system are commonly used to indicate position in air defence operations. These are:

a. By place name, *eg* over Hull.

b. Bearing and distance from a named datum point or place, *eg* Position 216°, Spurn Point 35, meaning that the position is on a bearing of 216° (T) from Spurn Point at a distance of 35 nautical miles.

c. Magnetic bearing and distance to a specified datum (usually a TACAN beacon (*see* SD 727, para 1033)) *eg* TACAN Weathersfield 270,80 would indicate a position from which a heading of 270°(M) would have to be maintained for 80 miles to reach the Weathersfield TACAN beacon. It should be noted that TACAN beacons are often remote from the airfield from which they derive their names, and positions given by this method are often related to the beacon and not the airfield.

2929–2930. (*Not allotted*).

TIME

The Apparent Solar Day

2931. The Earth rotates at an even pace on its axis in a direction which is anti-clockwise when viewed from above the North Pole. By itself, this motion would give an observer on the Earth an impression that the Sun revolved around the Earth from east to west. The Earth also moves however, at a much slower rate of revolution, in an anti-clockwise orbit (as viewed from above the "north pole" of the Sun) completing a circuit once a year. This results in the apparent movement of the Sun to the observer being retarded, whilst remaining from east to west. The time taken for one apparent full revolution of the Sun is called an apparent solar day.

The Mean Solar Day

2932. It would be inconvenient to keep apparent solar time since the length of the day is continually changing. Instead, an imaginary sun, called the "mean" sun, is assumed to circle the Earth in the plane of the Equator, keeping a constant speed throughout the year and completing the same number of circuits in a year as the real Sun appears to make. The interval between two successive crossings of a meridian by the mean sun is called a mean solar day.

Local Mean Time (LMT)

2933. The mean sun, therefore, traces its imaginary path by moving through an angle of $\frac{360}{24}$ degrees of longitude in every hour of mean time, *ie* 15 degrees of longitude. At any instant of absolute time, observers on different meridians experience mean times which vary by up to 24 hours, at a rate of four minutes of mean time for every one degree change of longitude. The mean time current at a particular meridian is called the local mean time (LMT).

Greenwich Mean Time (GMT)

2934. It is convenient to be able to refer to a common time in different places on the earth, and the local mean time for Greenwich in London (Greenwich Mean Time (GMT)) has been accepted as the international standard. GMT can be derived from the zone time by (for zones prefixed '+') adding to, or (for zones prefixed '−') subtracting from, the zone time a number of hours equal to the zone number as shown in the table below.

International Date Line

2935. The LMT advances by one hour from GMT for every 15° of longitude that is crossed in an easterly direction from Greenwich, *ie* one hour must be added to GMT to obtain the LMT. Similarly the LMT is one hour further behind GMT for every 15° of longitude crossed in a westerly direction, *ie* one hour must be subtracted from GMT to obtain LMT. Let us assume that it is 1400 hrs GMT on Monday. At a place of longitude 165°E the LMT will be $\frac{165}{15}$ = 11 hours ahead of GMT, or 1400 hrs + 11 hours = 2500 hrs = 0100 hrs LMT on Tuesday. At a place of longitude 165°W the LMT will be $\frac{165}{15}$ = 11 hours behind GMT, or 1400 hrs −11 hours = 0300 hrs LMT on Monday. Similarly at a place of longitude 179°E the LMT would be 0156 hrs on Tuesday and at 179°W the LMT would be 0204 hrs on Monday. Taking the extreme example, at a longitude of 180°E or 180°W (the same longitude), the time would be either 0200 hrs on Monday, or 0200 hrs on Tuesday, depending on whether the time was measured eastwards or westwards from Greenwich. A line has therefore been agreed internationally as being the transition longitude when the day, and therefore the date, changes. This line follows the 180° meridian except where it deviates to take account of international boundaries, and is known as the International Date Line.

Zone Time

2936. If every place kept its own local mean time, there would be confusion even in small countries. It has therefore been agreed internationally that the earth be divided into time zones so that defined areas can keep a standard time. There are 25 zones (bands of longitude), 23 of which are 15° wide, and two of which are only 7½° wide (*see* Fig 29–7). The central meridians of each of the 15° zones are spaced at intervals of 15°, starting from the Greenwich Meridian. The 7½° zones are on either side of the 180° meridian. The Greenwich Meridian is the central meridian of zone 0 which extends from 7½°W to 7½°E. The zones on either side of zone 0 are numbered consecutively from 1 to 12, and prefixed – or + according to whether they are respectively east or west of Greenwich.

2937. In RAF communications a suffix letter is added to local mean times to indicate the zone to which the time relates. The letter Z denotes Zone 0 time (*ie* GMT), and the letters A to M (omitting J) denote zone –1 time to zone –12 time respectively. Similarly, the letters N to Y refer to zone +1 to zone +12 time. The two 7½° zones are lettered M and Y and are zones –12 and +12 respectively. The International Date Line falls between these two zones. Zone boundary lines frequently deviate slightly to accommodate national boundaries. For times mid-way between two zones both letters are used. For example, in Singapore, GH are the suffix letters used to indicate that the local mean time is 7½ hours ahead of GMT: 1000Z is 1730GH.

2938. GMT (suffix Z) is always used for communications between one zone and another, and for all messages originated in the UK. Commands abroad may use local time for communications in the same zone, but GMT is used for all messages that include any address in the UK. All UK armed forces communication centres throughout the world use GMT (Zone 0) to record the handling of signals traffic, irrespective of the zone times used by the originator.

Serial No	Zone Boundary	To Obtain GMT From Zone Time	To Obtain Zone Time From GMT	Zone Time Suffix
1	7½°W to 7½°E	0	0	Z
2	7½°E to 22½°E	–1	+1	A
3	22½°E to 37½°E	–2	+2	B
4	37½°E to 52½°E	–3	+3	C
5	52½°E to 67½°E	–4	+4	D
6	67½°E to 82½°E	–5	+5	E
7	82½°E to 97½°E	–6	+6	F
8	97½°E to 112½°E	–7	+7	G
9	112½°E to 127½°E	–8	+8	H
10	127½°E to 142½°E	–9	+9	I
11	142½°E to 157½°E	–10	+10	K
12	157½°E to 172½°E	–11	+11	L
13	172½°E to 180°E	–12	+12	M
14	7½°W to 22½°W	+1	–1	N
15	22½°W to 37½°W	+2	–2	O
16	37½°W to 52½°W	+3	–3	P
17	52½°W to 67½°W	+4	–4	Q
18	67½°W to 82½°W	+5	–5	R
19	82½°W to 97½°W	+6	–6	S
20	97½°W to 112½°W	+7	–7	T
21	112½°W to 127½°W	+8	–8	U
22	127½°W to 142½°W	+9	–9	V
23	142½°W to 157½°W	+10	–10	W
24	157½°W to 172½°W	+11	–11	X
25	172½°W to 180°W	+12	–12	Y

2939. *(Not allotted)*.

Sunrise, Sunset and Twilight

2940. If there was no refraction of light-rays through the earth's atmosphere, sunrise and sunset would occur when the centre of the sun was at the horizontal to an observer. To the spectator at sea level, however, the centre of the sun appears to be well above the visible horizon when it is, in fact, horizontal, and the visible sunrise or sunset occurs when the sun's centre is really about one degree below the horizontal.

2941. Instead of there being a sudden transition from darkness to light and from light to darkness at sunrise and sunset, reflection and scattering of light-rays by the atmosphere cause the transition to be gradual. The period of change is called "twilight". It is usful to define the beginning of morning twilight, and the end of evening twilight, so as to be able to indicate how much light there will be (ignoring the effect of weather) just before sunrise and just after sunset. Three phases of twilight are recognized, and these are explained in the following table.

Serial No	Phenomenon	Begins (am) or Ends (pm) with Depression of Sun	Significance to Observer (Ignoring Weather)
1	Sunrise, Sunset	1°	Sun just visible
2	Civil Twilight	6°	Sea horizon can be clearly seen. Work possible without artificial light
3	Nautical Twilight	12°	Sea horizon cannot be clearly seen. Artificial light needed
4	Astronomical Twilight	18°	Absolute darkness is experienced when depression more than 18°

Those concerned with air defence should not forget that, for a pilot in the air, sunset always occurs later, and sunrise earlier, than for an observer on the ground below.

2942. *(Not allotted)*.

MAPS AND CHARTS

Projections

2943. A map or a chart portrays either a part or the whole of the spherical surface of the earth as a flat representation. The surface of a sphere cannot, however, be flattened without distortion of one kind or another. The aim in cartography is, therefore, to arrange the inevitable distortion so that in certain chosen respects the user of the map is given a true impression of the area represented. The cartographer may perhaps truthfully reproduce the shapes of land masses, or show the areas of the different land masses in correct relative proportion, or represent great circles as straight lines and so on. The retention of one kind of accuracy necessitates the rejection of another; however, some general purpose maps are a compromise between different requirements. Map making is based on the principle of projection.

2944. The idea of projection can be most readily understood by imagining the geographical features of the earth to be engraved on the surface of a transparent globe. If a point source of light is placed within the globe, an image of the engraving would be cast on to an adjacent or surrounding screen. The projected image of the area to be mapped is termed a "projection" of the original globe.

2945. The source of light can be placed in various positions within the globe or, where a map of only part of the earth is required, outside the globe; and the surface upon which the map is projected can be placed in different positions and at different angles in relation to the globe: it can even be wrapped cylindrically or conically around the globe. The selection of one of these many possible configurations will depend upon which characteristics are required to be truly represented in the map.

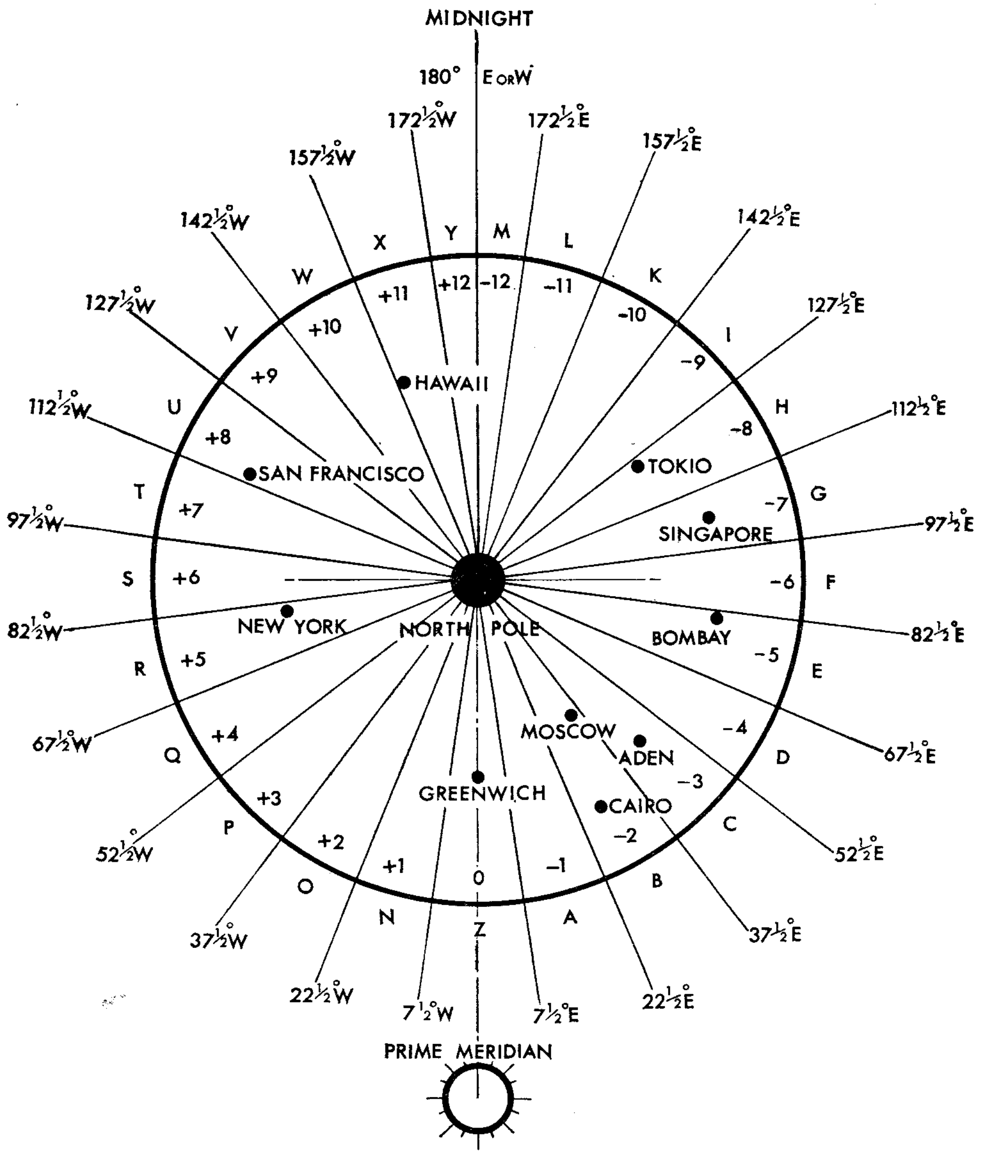

Fig 29–7 Zone Times

2946. A cylindrical projection can be derived by projecting the globe, from a light source at its centre, upon a sheet of paper wrapped cylindrically around it and either touching it at the equator or cutting it at two parallels of latitude (*see* Fig 29–8). A conical projection can be derived by projecting from an internal point on to a cone of paper fitted over the globe or intersecting it. A zenithal projection can be derived by projecting on to a flat surface that touches or cuts the globe. In practice however, maps are constructed mathematically, and such construction may be the exact equivalent of the process of physical projection already described or it may be distorted to achieve certain desired properties. Thus Mercator's projection, which is most commonly used for plotting purposes by air navigators, is derived from the cylindrical projection by adjusting the spacing of the parallels of latitude so that the scale towards the poles along the meridian at any point is increased in the same ratio as is the scale along the parallel intersecting that point; hence all angles are preserved, and the scale at any point is constant in all directions, although it changes from point to point. Areas in high latitudes are greatly exaggerated.

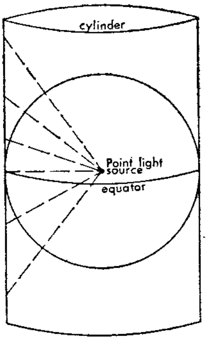

Fig 29–8 A Cylindrical Projection

2947. It is clearly desirable that any outline map used on a radar PPI display should have constant scale in all directions. No projection can provide this with complete accuracy, but some projections are more accurate than others. The projection used for PPI displays in the Royal Air Force is Lambert's Conical Orthomorphic.

2948. **Lambert's Conical Orthomorphic Projection.** Lambert's Conical Orthomorphic projection possesses the following properties:

a. With graticules of a small range of latitude the scale errors are small and the map may be regarded as constant scale.

b. Angles are correctly represented.

c. A straight line on the projection closely approximates to a great circle.

d. A rhumb line is a curve, concave to the nearer pole.

2949. **Mercator's Projection.** Except in polar regions, navigators of ships and aircraft normally use charts based on Mercator's projection. The great advantage of this projection is that aircraft tracks are usually rhumb lines which are represented as straight lines. The scale is however, greatly distorted in the north/south direction increasing steadily towards the poles. It is therefore necessary to use a measure for distance which varies in the same way, and this is provided by the latitude sub-divisions shown on the map.

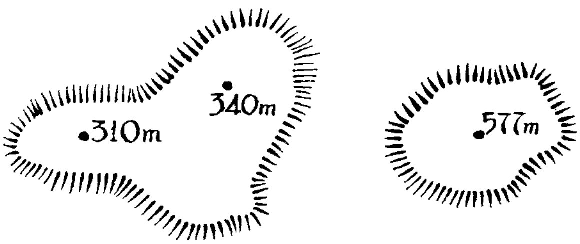

Fig 29–9 Spot Heights and ~~Contours~~ Hachures.

Presentation of Distance

2950. The scale of a map may be expressed in any of the following ways:

a. *Representative Fraction.* This expresses the ratio of one unit length on the map to the corresponding number of equal units that it actually represents. Thus 1/500,000 means that one inch on the map represents 500,000 inches on the earth.

b. *Graduated Scale Line.* This is usually provided and reproduces pictorially the actual length on the map that corresponds to the indicated distance on the earth.

c. *Statement in Words.* This simply states the actual scale in units of length, *eg* $\frac{1}{4}$ inch = 1 mile.

Presentation of Relief

2951. Elevation may be shown on maps in the following ways:

a. Spot heights.

b. Contours lines.

c. Layer tints.

d. Hachures.

e. Hill shading.

2952. **Spot Heights.** On some maps a spot marks the position of the highest ground in a locality, and the height in feet or metres of that spot is printed close to it. Similarly the height of airfields may be printed close to the dot or other symbol representing the position of the airfield (*see* Fig ~~29-9~~ 29-10)

2953. **Contours.** Contours are lines joining places of equal height above a selected datum level (usually mean sea level). The interval between successive contours depends on the scale of the map but is uniform on any one map. The height level of each contour is printed at some point along its length, and may be in either feet or metres. Care should be taken to check the height unit used. (see Fig 29-10)

2954. **Layer Tints.** Contours are often emphasized by tinting the area between each pair of adjacent contours. The shades of colour chosen for this purpose normally become deeper with increase of height. This system, known as layer tinting, enables an impression of the relief of an area to be gained at a glance. Layer tints may also be referred to as elevation tints, altitude tints, or hypsometric tinting.

2955. **Hachures.** Hachures are short tapered lines drawn on a map radiating from peaks and high ground. They show slopes and give a rough impression of relief, but are inexact and seldom used (*see* Fig ~~29–10~~). 29-9)

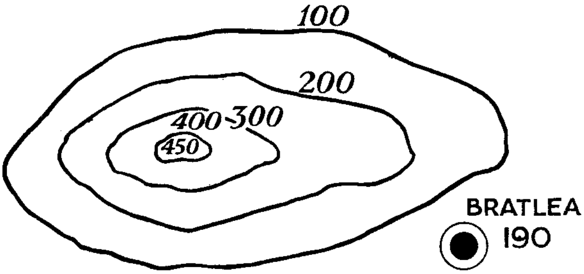

Fig 29–10 ~~Hachures and Spot Heights~~ Spot Height and Contours.

2956. **Hill Shading.** Hill shading is the effect produced by assuming that a bright light is shining across the map so that shadows are cast by high ground. The shadows produced however, may obliterate other detail on the map, and this method is rarely used.

TERMINOLOGY

Introduction

2957. Those concerned with control and reporting should be conversant with the precise meaning of certain terms used in air navigation. These are explained in the following paragraphs.

Speed

2958. **Indicated Airspeed (IAS).** IAS is defined as the airspeed of an aircraft as indicated to the pilot by an instrument called the airspeed indicator (ASI) which compares the pressure of the air in its movement past the aircraft (the "dynamic" air pressure) with the pressure of the same air on a body not moving against it (the "static" air pressure). The resultant IAS, is subject to errors resulting from local variations in the airflow round the aircraft ("position error"), the mechanical shortcomings of the instrument itself ("instrument error"), and, most pronounced of all, changes in the density of air at different heights and temperatures.

2959. **Rectified Airspeed (RAS).** The speed derived by correcting the IAS for position and instrument errors is called the rectified airspeed. A correction card, displayed in every aircraft, enables the pilot readily to convert IAS to RAS.

2960. **True Airspeed (TAS).** The speed derived by correcting the RAS for height, pressure, and temperature variations is called the true airspeed.

2961. **Ground Speed.** The ground speed of an aircraft is the speed at which it travels relative to the earth below. Ground speed generally differs in value from TAS because of wind effects.

2962. **Mach Number.** It is customary to refer to the speed of a high-speed aircraft by using its Indicated Mach Number (IMN), which is for practical purposes the same as its Mach number since machmeter readings are not subject to the same errors as airspeed indicators. The Mach number of an object is its speed relative to the local speed of sound. For example, if an aircraft's true air speed is 550 knots and the local speed of sound is 660 knots, then:

$$\text{The aircraft's Mach No} = \frac{\text{True Air Speed}}{\text{Local Speed of Sound}} = \frac{550}{660} = 0{\cdot}83$$

The speed of sound in air varies with temperature, decreasing as the temperature decreases. In temperate latitudes, it is about 660 knots at sea level, dropping, to about 570 knots at the tropopause. An aircraft flying at a true airspeed of 550 knots near ground level, where the speed of sound is 660 knots, has a Mach number of $\frac{550}{660} = 0{\cdot}83$, but an aircraft flying at the same true airspeed at 36,000 ft, where the speed of sound is 570 knots, would have a Mach number of $\frac{550}{570} = 0{\cdot}96$.

Direction

2963. **Heading.** The direction in which the longitudinal axis of an aircraft points is called its heading.

2964. **Track.** The direction in which an aircraft moves over the earth is called its track. An aircraft's track only coincides with its heading if it is not blown sideways by the wind.

2965. **Drift.** The angular difference between the heading and the track of an aircraft is known as its drift. Drift is measured in degrees to port or starboard of the aircraft's heading.

2966. **Wind Direction.** The direction from which the wind is blowing is called the wind direction.

2967. **Velocity.** Speed is defined as the rate of change of position, but a velocity is the rate of change of position in a given direction. Thus to say "The velocity of the aircraft is 220 knots" is to misuse the word "velocity"; it would be correct to say either, "The speed of the aircraft is 220 knots" or, "The velocity of the aircraft is 040 degrees at 220 knots".

Altitude, Height and Elevation

2968. **Altitude.** Altitude is the term normally used to describe the vertical distance of a level, a point, or an object considered as a point, measured from mean sea level.

2969. **Height.** Height is the vertical distance of a fixed point above ground level or some specified datum other than mean sea level. For the purposes of this definition an aircraft may be considered as a fixed point.

2970. **Elevation.** Elevation is the vertical distance of a point or a level, on or affixed to the surface of the earth, measured from mean sea level.

2971. **Barometric Altimeter.** Altitude is usually registered in an aircraft by a form of aneroid barometer known as an altimeter. This instrument is calibrated in terms of altitude instead of units of pressure, and uses the principle that pressure decreases with altitude. Unfortunately, both the pressure at any datum level and the rate of fall of pressure with increase in altitude differ from time to time and from place to place. The altimeter reading must therefore be corrected for the difference between datum level pressure at the aircraft's position, and some agreed standard value. It must also be corrected for the variation of air temperature at the aircraft's altitude, from the temperature value assumed in calibrating the instrument. The former correction is the more important since a decrease in pressure of one millibar increases the altitude indication by about 30 ft. The correction is made by adjusting a setting knob on the altimeter to show the current pressure at the chosen datum level on a sub-scale. However, the pilot can only do this with complete accuracy for one position at any one time. The temperature correction is of less importance and is made with the aid of a height computer.

2972. **Indicated and True Altitude.** The altitude registered by a barometric altimeter is called the indicated altitude. When the indicated altitude is corrected for any difference between the datum pressure set on the sub-scale by the pilot and the actual mean sea level pressure, and also for variations of air temperature drop from standard, it is known as the true altitude.

2973. **Absolute Altitude.** An absolute altitude is the height of an aircraft directly above the surface of the earth or terrain over which it is flying. Both the indicated and true altitudes obtained from the barometric altimeter are altitudes above theoretical datum levels, not actual altitudes above the ground. Many aircraft are therefore fitted with radio altimeters in addition to their normal (barometric) altimeters. The radio altimeter indicates with great precision the absolute altitude of an aircraft above the ground. This is of great assistance when an aircraft is flying at low altitudes over undulating ground.

2974. **Radio Altimeters.** The radio altimeter records height without reference to pressure. There are two types in common use, one depending upon a pulse radar system and the other on frequency modulation. Both types indicate the height above the earth's surface when flying over the sea or level ground. The pulse radar type, often referred to simply as "the altimeter", measures height over a range of 1,000 to 50,000 ft. Its error in the absolute measurement is within ± 100 ft, but changes of height at a fairly constant level are measurable to within about ± 30 ft. The frequency modulation type, sometimes referred to as the "radio altimeter", covers the height range from zero to about 5,000 ft; the error of this instrument is proportional to height and may amount to $\pm 3\%$. Both types are needed if the whole range of height is to be covered.

2975. **Altimeter Calibration.** The barometric altimeter is calibrated in accordance with the International Commission for Air Navigation (ICAN) Law. The ICAN Law assumes conditions which approximate to the average actual conditions over the whole of the world. These conditions, known as the international standard atmosphere, are: a sea level pressure of 1013·2mb, a sea level temperature of 15°C and a temperature lapse rate of 1·98°C per 1,000 ft up to a height of 36,900 ft, above which the temperature remains constant. The ICAN calibrated altimeter will indicate height correctly only when the actual atmospheric conditions are identical with those laid down by the ICAN Law.

CHAPTER 30

WEATHER

CONTENTS

INTRODUCTION

3001. Modern fighter aircraft are designed to operate in all types of weather, but air defence operations can nevertheless be affected greatly by weather conditions. Air defence personnel are not expected to be able to observe or predict the weather (except by passing reports of precipitation echoes observed on radar displays), but they must be able to understand the reports and forecasts provided by meteorologists in order to have a clear idea of the conditions in which aircraft under their control may have to operate. This chapter is intended only to introduce the study and terminology of weather phenomena, and readers are advised to study AP 3307, Elementary Meteorology for Aircrew, for a more complete coverage of the subject.

REPORTS AND FORECASTS

Difference between Reports and Forecasts

3002. The terms weather report and weather forecast are often confused, and air defence personnel should ensure that the terms are used correctly. A report describes weather that has been, or is being, actually experienced at a stated time and place; a forecast is a prediction of what the weather will probably be like at a stated place at some future time. Clearly, a pilot could be dangerously misled by a confusion of these terms.

Actuals

3003. A report of the current weather at a place is often referred to as an "actual".

Synoptic Charts

3004. The weather actuals over a large area are often displayed by marking symbols on a map. The result, which shows a synopsis of the pattern of the weather over many places at one time, is called a synoptic chart.

THE ATMOSPHERE

General

3005. The atmosphere is the gaseous envelope surrounding the Earth. It is composed mainly of a mixture of nitrogen and oxygen in the proportion of four to one, but also contains a small but very variable amount of invisible water vapour. This water vapour content is very important in the study of weather, for clouds, rain, fog or snow can only form as a result of the water vapour changing into water droplets or ice crystals. The atmosphere also contains microscopic particles of smoke and other matter which are held in suspension mainly near the surface. There is no top to the atmosphere—it merely becomes extremely thin at great heights, but even at a height of 200 miles there is enough air to make meteors white hot by friction, and so make them visible at night as shooting stars. The atmosphere and its characteristics are illustrated in Fig 30–1.

Layers of the Atmosphere

3006. The atmosphere may be divided into various layers according to their characteristics. The layers of importance to the controller are the troposphere and the stratosphere.

3007. **The Troposphere.** The troposphere consists of the lower layers of the atmosphere which are characterized by generally decreasing air temperature with increasing height. It is in this region that almost all precipitation and clouds are confined. Its depth varies significantly with latitude, being about 54,000 ft at the equator, about 35,000 ft at 50° latitude and about 28,000 ft at the poles. Its upper boundary is the tropopause (*see* Fig 30–1).

3008. **The Stratosphere.** The stratosphere is that region of the atmosphere lying above the troposphere in which the air temperature is relatively uniform or increases with increasing height (*see* Fig 30–1). Its upper boundary is at a height of about 30 miles (roughly 150,000 ft) where the air pressure is about 1 mb.

3009. **Higher Layers.** In the higher layers above the stratosphere different names are given for different purposes. If temperature structure is the criterion, the higher layers are divided into the mesosphere and the thermosphere. The terms ozonosphere, chemosphere and ionosphere are used of regions in which specific processes occur.

3010. (*Not allotted*).

PRESSURE

Atmospheric Pressure and Density

3011. **Pressure.** If a vertical tube extending to the top of the atmosphere was placed over one square inch of the earth's surface at sea level, the air in the tube would weigh about $14\frac{1}{2}$ lb, or

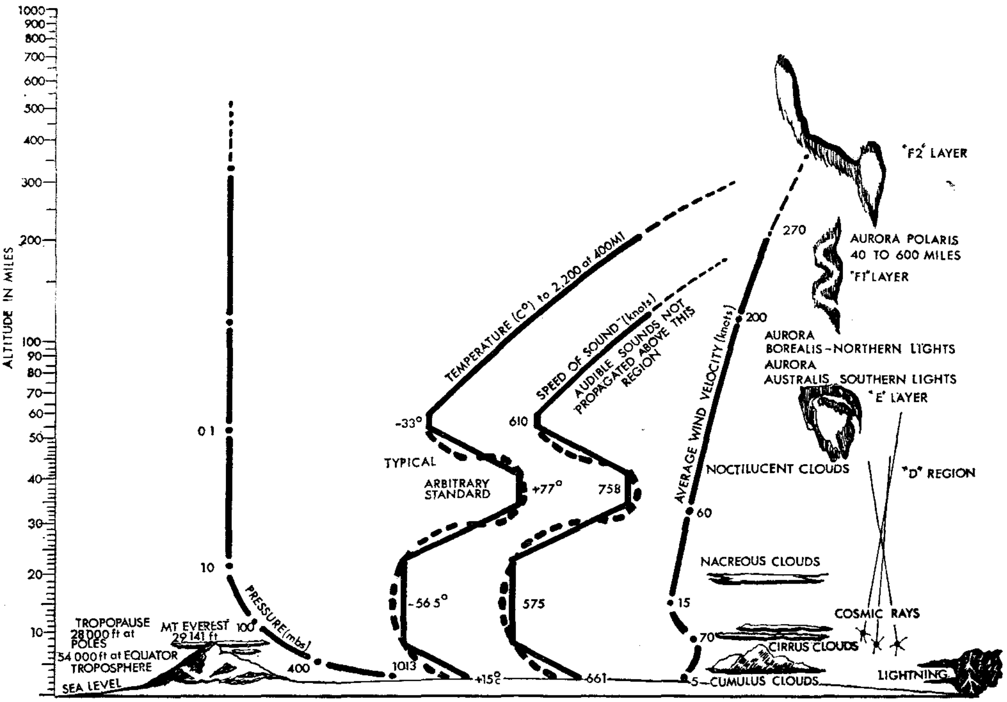

Fig 30–1 The Atmosphere and its Characteristics

if the tube covered 1 sq ft the air would weigh nearly a ton. Atmospheric pressure is the force per unit area exerted by the atmosphere on any surface in contact with it. This force varies slightly from day to day and from place to place. For meteorological purposes pressure is measured in millibars (mbs). A millibar is defined as a pressure of 1,000 dynes per square centimetre. At sea level in Western Europe pressure varies between about 950 and 1,045 mbs.

3012. **Density.** Thin, rarified air at great heights in the atmosphere is lighter than air near the ground—its density is less. Air density is defined as the mass of unit volume of air. Air density depends on three variables; pressure, temperature and altitude.

3013. **Dependence on Pressure.** Imagine a hollow tin cube with 1-ft sides and a small hole in the top. The greater the atmospheric pressure, the more air will be forced through the hole into the box, and the greater will become the mass of air within, *ie* the air density. If the atmospheric pressure is reduced, air will pass outwards through the hole, and the density will fall. Air density is thus proportional to atmospheric pressure.

3014. **Dependence on Temperature.** If the box is heated the air inside will expand and some will escape through the hole. The higher the temperature, the less the air density becomes. Conversely, if the box is cooled its contents will contract, more air will be drawn in, and so the density increases. The lower the temperature, the greater the air density; in fact, air density is inversely proportional to absolute temperature.

3015. **Dependence on Altitude.** As one climbs into the atmosphere, air pressure decreases, because there is a lesser weight of air above. So air density, which is proportional to the pressure, also gets less with increasing altitude. But the temperature of the air usually decreases with increasing height. By itself, this would lead to an increase of density with height, but the decrease of pressure has much the greater effect, so that air density decreases upwards.

3016. **Variation of Air Pressure with Altitude and Temperature.**

a. *Altitude.* Pressure decreases with height, but the rate at which it decreases is not constant. Near the ground, pressure decreases by 1 mb for a climb of about 30 ft, while at 20,000 ft a climb of about 50 ft would be

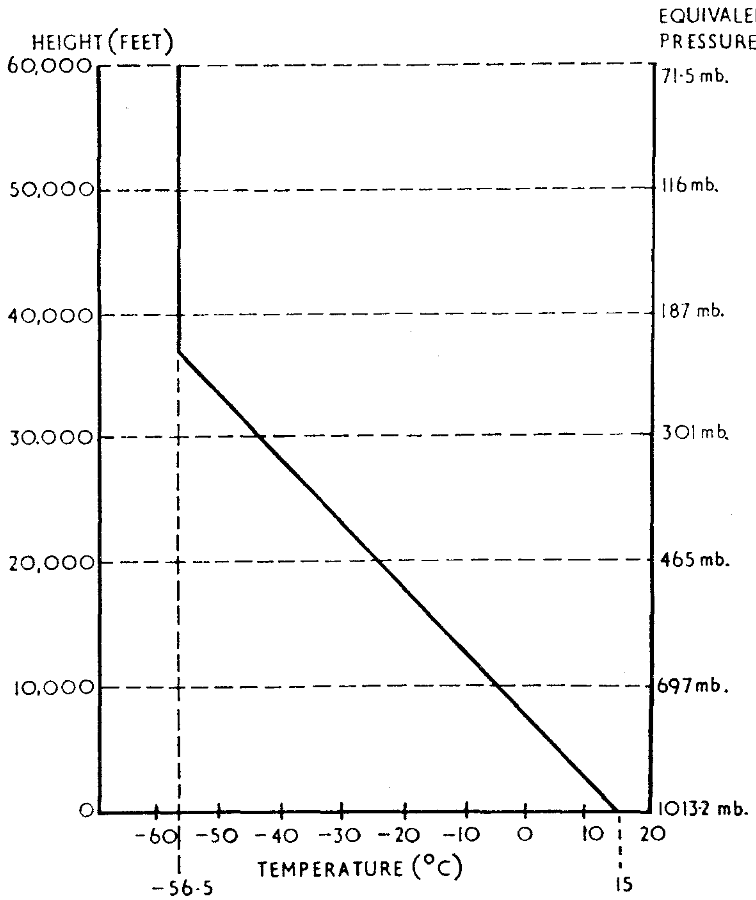

Fig 30–2 The International Standard Atmosphere

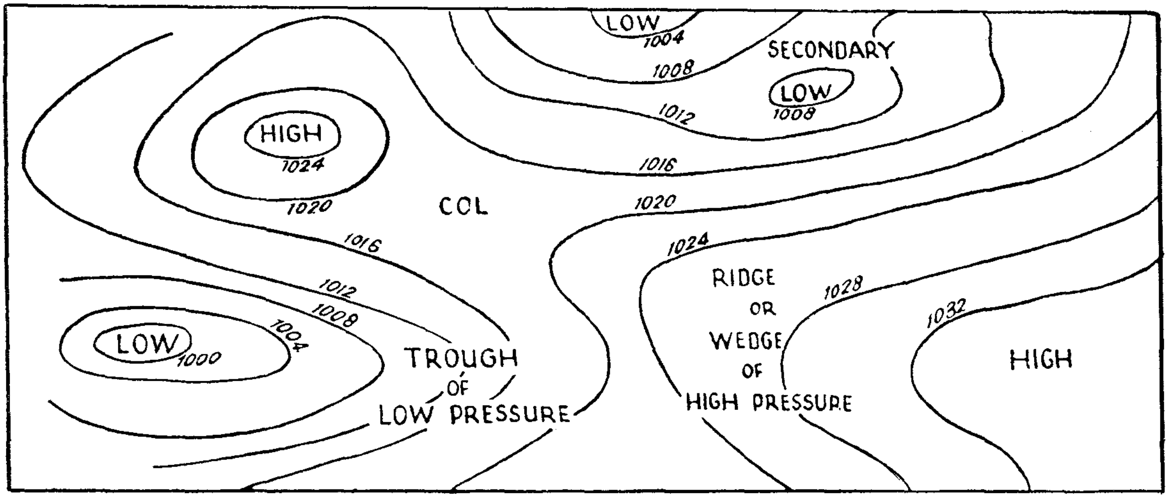

Fig 30–3 Types of Isobar Systems

necessary to give the same drop in pressure. These figures are only approximate, however, as the pressure also depends on temperature.

b. *Temperature.* Since cold air is denser than warm air the fall in pressure resulting from a climb of 1,000 ft in cold air will be greater than a similar climb in warm air. The rate of decrease of pressure with altitude is therefore greater in cold air than in warm air.

The ICAN Atmosphere

3017. A world-wide standard of values of the main variables in the atmosphere is required so that a common starting point exists for calibration of instruments and for meteorological criteria. The International Commission for Air Navigation (ICAN) has therefore specified an International Standard Atmosphere (ISA) which is defined as follows:

a. At sea level the pressure is 1013·2 mbs at 15°C.

b. Up to 11 km (about 36,000 ft) temperature decreases by 6·5°C per kilometre (about 1°C per 500 ft).

c. Above 11 km the temperature is constant at −56·5°C.

The International Standard Atmosphere is illustrated graphically at Fig 30–2.

Significance of Changes of Atmospheric Pressure and Density

3018. The performance of an aircraft depends on air density. Where air density is low because of high temperatures (as in the Middle and Far East) an aircraft will, for example, climb at a slower rate than in the UK, and will need a longer take-off run to become airborne.

Isobars on the Weather Map

3019. **Significance.** An isobar is a line joining points having the same barometric pressure at the same level. (The level used by the British Meteorological Service is mean sea level.) When isobars are plotted on a map they readily show the horizontal pressure differences which provide the force which moves air over the Earth's surface and so produces wind and weather changes. The pressure distribution shown by plotting isobars is therefore of great importance in the study of meteorology.

3020. **Types of Pressure Distribution.** Isobars often make up certain well-defined patterns to which special names have been given (*see* Fig 30–3). The main patterns are as follows:

a. *Depression.* A depression or "low", is a region of relatively low pressure shown by more or less circular and concentric isobars enclosing the centre where pressure is lowest. The size of the depression may be from a few hundred yards in a tornado; some hundreds of miles in a tropical revolving storm (when the term cyclone, typhoon or hurricane may be used); to more than a thousand miles in some of the largest depressions of middle latitudes.

b. *Secondary Depression.* A secondary depression is a small depression, within the area covered by a larger or "primary" depression, and appears rather as a satellite.

c. *Trough of Low Pressure.* A trough of low pressure is indicated by a protrusion of isobars from a low pressure area such that the pressure is lower in the centre of the trough than at either side. The isobars in a trough sometimes bend sharply forming a V shape.

d. *Anticyclone.* An anticyclone, or "high", is a region of relatively high pressure shown by more or less circular isobars enclosing the centre of highest pressure. The isobars are generally further apart than in a depression, especially near the centre.

e. *Ridge of High Pressure.* A ridge or wedge of high pressure is the converse of a trough, and is indicated by isobars extending outwards from a high so that the pressure is higher along the axis of the ridge than on either side. The isobars are never V-shaped but always rounded at a ridge.

f. *Col.* A col corresponds to a "saddle-back" on a geographical contour map, and is the neutral region between two highs or two lows.

3021. **The Significance of Pressure Systems.** The various types of isobaric configurations described above are generally associated with particular types of weather; their recognition and development are therefore a considerable aid to forecasting.

3022. **Pressure Gradients.** The distance between isobars on a weather map is a measure of the horizontal gradient of pressure. Since wind speed depends on the pressure gradient, the distance between isobars gives an immediate indication of the wind speed.

3023–3025. (*Not allotted*).

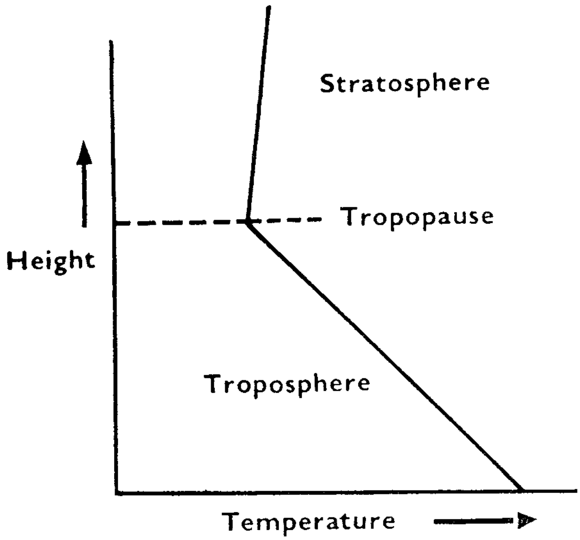

Fig 30–4 The Troposphere, Tropopause and Stratosphere

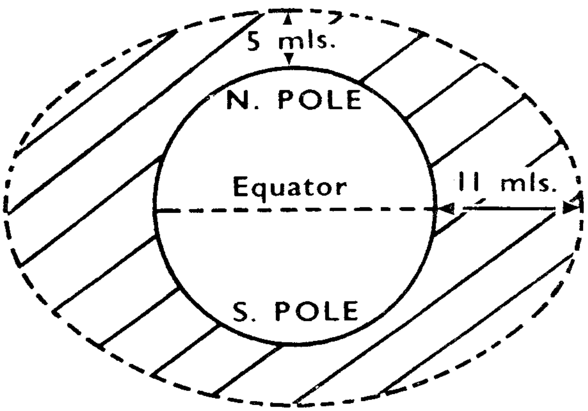

Fig 30–5 The Tropopause

TEMPERATURE

3026. **How the Atmosphere is Heated.** The atmosphere is heated by conduction, convection, and by absorption of energy radiated from the earth by water vapour. The atmosphere is warmed from *below* rather than by direct solar radiation from above.

3027. **Vertical Distribution of Temperature.** Since the atmosphere is heated from below one would expect the temperature of the air near the ground to be greater than at higher levels, and this is in fact the case—air temperatures fall with height up to a height of about five miles near the poles and ten miles at the equator. The part of the atmosphere below these levels, where temperature usually decreases upwards, is called the troposphere. Most weather phenomena are confined to the troposphere.

3028. **Temperature in the Stratosphere.** Above the troposphere is an atmospheric layer known as the stratosphere in which the temperature remains fairly constant or even increases with altitude and in which the air is sometimes very dry (*see* Fig 30–4).

3029. **The Tropopause.** The tropopause is the name given to the boundary between the troposphere and the stratosphere (*see* Fig 30–5). As shown in Fig 30–5, the average height of the tropopause decreases from about 11 miles at the equator to about 5 miles at the poles. However large variations in the height of the tropopause occur from day to day; these variations are related to the development and movement of pressure systems shown on synoptic charts.

3030. **Lapse Rate.** The rate of decrease of temperature with height is called the lapse rate. The average lapse rate in the atmosphere is about 2°C per 1,000 ft, but considerable variations occur.

3031. **Inversions.** Sometimes atmospheric layers exist in which temperature increases with height instead of *vice-versa.* This condition is known as an inversion. The tropopause is generally associated with a temperature inversion. Inversions based at ground level and extending through a shallow surface layer of air can have important effects on radio and radar performance and are discussed in Chapters 20 and 21.

3032–3033. (*Not allotted*).

HUMIDITY

3034. Water may be present in the atmosphere as an invisible gas, as water droplets (cloud or rain) or as ice (hail, snow, or certain types of cloud). In meteorology the term humidity refers only to the *invisible* gas or vapour which may be mixed with the dry air of the atmosphere. Given a quantity of dry air at a certain temperature, there is a definite limit to the amount of water vapour that it can be made to hold. When it holds the maximum amount, it is said to be saturated. The saturation content increases

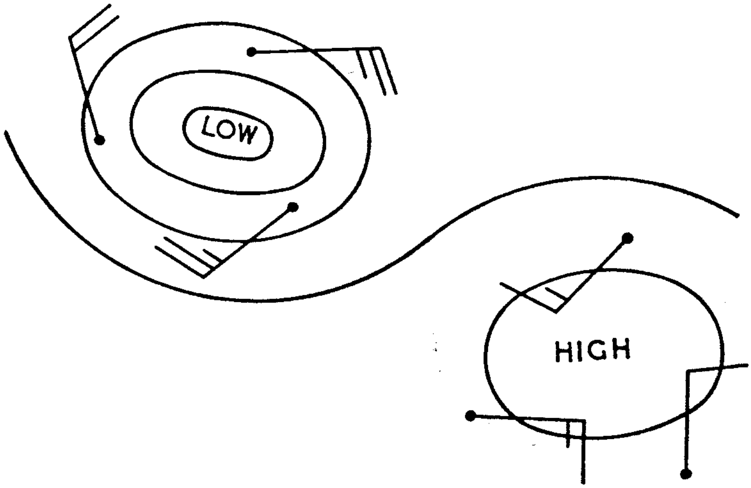

Fig 30–6 Circulation of Wind—Northern Hemisphere

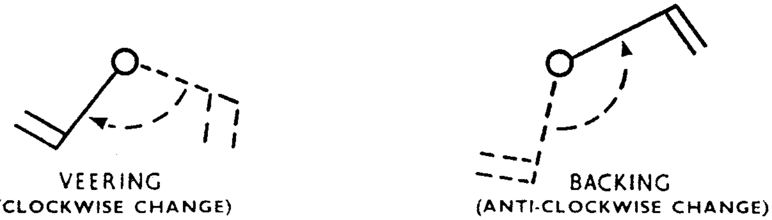

Fig 30–7 Veering and Backing

with temperature; in other words, warm air can hold more vapour than cold air. If, therefore, moist but unsaturated air is progressively cooled, it will ultimately reach a temperature at which it becomes saturated; moreover, any further cooling must cause some of the moisture to be precipitated in a liquid or solid form (for example as a cloud, fog, dew or hoar frost). The saturation temperature is called the *dew point*.

3035. The term used in meteorology to express the degree of saturation of air is relative humidity, which is defined as the percentage ratio of the amount of water vapour actually present in the particular sample of air to the amount which would be required to saturate it at that temperature.

WIND

Description of Wind

3036. In order to define wind precisely we need to know the speed and direction of the air motion. Wind speed is expressed in knots, and wind direction either in points of the compass or in degrees from true north. The direction given is always that *from* which the wind is blowing. For example an east wind, or a wind direction of 090°, means that the wind is blowing from east to west.

Buys Ballot's Law

3037. In the northern hemisphere winds tend to blow clockwise around a high pressure area and anti-clockwise around a low pressure area (*see* Fig 30–6). This rule is known as Buys Ballot's Law, which may be remembered in the following form, "If you stand with your back to the wind, lower pressure lies to your left in the northern hemisphere, but to your right in the southern hemisphere".

Veering and Backing

3038. Veering and backing are terms used to describe changes of wind direction. The wind *veers* when the direction changes clockwise, *eg* from south-east to south-west, and *backs* when the direction changes anti-clockwise (*see* Fig 30–7).

Gusts, Squalls and Gales

3039. Wind usually varies continuously in both speed and direction about average values. Gusts are comparatively sudden but brief increases in wind speed, often associated with rapid fluctuations in wind direction. Gusts affect the smoothness of an aircraft in flight and are of significance particularly to light aircraft on landing or take-off. A squall is a blast of wind which sets in suddenly, lasts for some minutes and then dies away. A squall is never due entirely to the effect of the local terrain, but is usually associated with some other weather feature such as a rapidly moving cold front or a thunderstorm. A gale is said to occur when the surface wind has a mean speed of 34 knots or more, or is gusting to 43 knots or over. Warnings of their likely onset are issued by the Meteorological Office.

Land and Sea Breezes

3040. In coastal regions sunshine makes the land appreciably hotter than the bordering seas, with the result that local sea breezes may be caused by cooler air flowing in from the sea to replace heated air rising overland. At night air over the land tends to become cooler than that over the sea, which results in a land breeze setting in after darkness, blowing from land to sea.

Jet Streams

3041. A jet stream is a strong narrow current of air, generally near the tropopause, characterized by strong vertical and lateral wind sheers. It is arbitrarily defined as having a minimum speed of 60 knots at every point along its axis. A jet stream is typically a few thousands of miles in length, a few hundreds of miles in width, but only a few miles (perhaps as little as two miles) in depth. The wind sheer as one moves away from the jet axis in the horizontal may be of the order of 2–5 knots per 1,000 ft. The wind sheer as one climbs or descends through a jet is usually even greater—of the order of 5–10 knots per 1,000 ft. There is increasing evidence that clear air turbulence may at times be associated with these regions of exceptional wind sheer. A cross-section of a typical jet stream is at Fig 30–8.

3042. Two main types of jet stream are recognized: the polar front (westerly), and the subtropical (westerly). The polar front jet stream is highly variable in position from day to day over a wide range of temperate latitudes, and as a result is masked on mean seasonal wind charts. In contrast the subtropical jet stream is relatively constant in position in a given season and is a prominent feature of mean seasonal wind charts.

Note: The figure shows, by means of the numbered black lines, the speed of the wind at right angles to the plane of the paper (towards the reader, assuming this to be the northern hemisphere). It should be noted that horizontal and vertical scales are different—the area enclosed by the 100 kt line appears to have about the same height and width; in reality it is only about 2 miles deep but is 200 miles wide.

3043. **Jet Streams over Britain.** Some of the main features of typical jet streams in the vicinity of the British Isles are summarized below:

a. Wind speeds in and near the jet streams are higher in winter than in summer, with an average maximum of 150 knots at about 31,000 ft in winter, but only 125 to 130 knots at about 33,000 ft in summer. In general the greater the temperature contrast between the warm and cold air masses, the greater the speed of the jet. Over Britain the greatest speed so far recorded is 202 knots, but from May to September the maximum wind rarely exceeds 150 knots.

b. Jet streams over Britain occur at any season, but are about twice as frequent in winter as in summer.

c. Apart from the motion of the winds at high speeds along the jet stream, the whole system normally moves rather slowly sideways over any given area at a speed of about 10 to 20 knots roughly at right angles to the long axis of the jet. Thus a typical jet stream affecting the west of Britain usually moves across to the east in one or two days, although jets sometimes persist for over a week. It is quite possible for one jet to affect the Shetland Islands while another affects the Scillies. Occasionally a jet moves by extending the head-down-stream or by retracting the tail.

d. Jet streams from a westerly point predominate over Britain, varying mainly between SSW and NNW. Easterly jet streams are very rare.

3044. **Significance of Jet Streams in Fighter Control.** The drift and ground speed of an aircraft under control can alter markedly over a small distance when a jet stream is encountered, and knowledge of the presence and effects of jet streams are therefore important to fighter controllers.

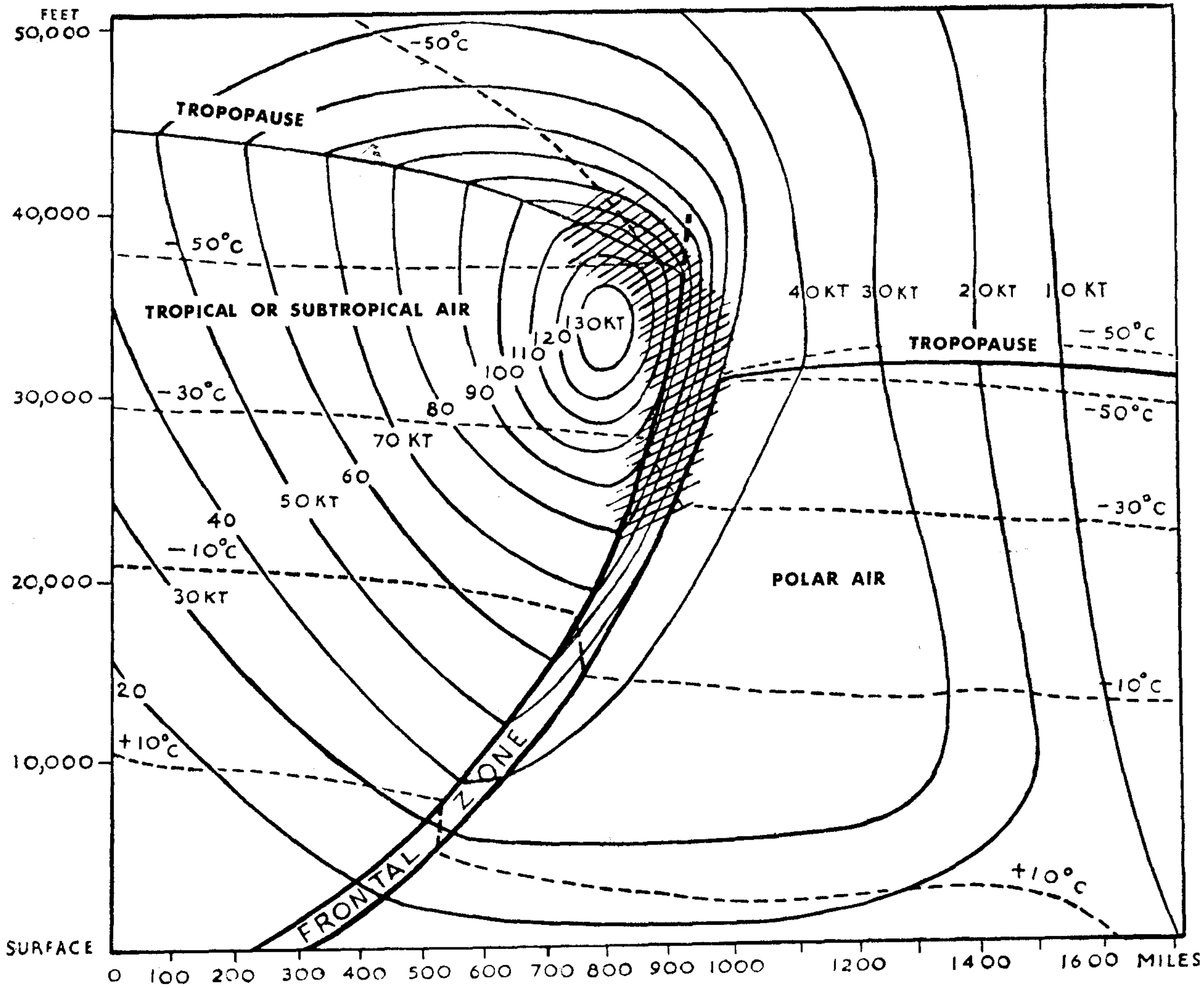

Fig 30–8 Vertical Cross-Section of a Jet Stream

3045. **Clear Air Turbulence.** Bumpy flying conditions may occur at high altitudes in clear air, well away from surface effects or thunderstorms. The higher the speed of the aircraft, the more marked is the effect. Over England clear air turbulence has occurred between 15,000 ft and 48,000 ft, but usually occurs between 7,000 ft below the tropopause to 3,000 ft above it. The layer is normally only about 500 ft deep, so it can often be avoided by small changes in altitude. In severe turbulence aircraft have occasionally suffered slight structural damage; pilots tend to be lifted from their seats, and observation of instrument panels becomes difficult. Slight clear air turbulence is encountered in about 50% of flights of $1\frac{1}{2}$ hrs duration at 40,000 ft over Southern England. Most cases of severe clear air turbulence occur near jet streams and the most favourable regions are indicated by the shaded area in Fig 30–8. It will be seen that the phenomenon is most likely to occur on the cold low-pressure side of the jet stream, and also just above the jet axis. However jet streams do not always produce clear air turbulence, and clear air turbulence can occur when there is no jet stream near.

3046–3047. (*Not allotted*).

CLOUDS AND PRECIPITATION

Clouds

3048. **Cloud Amounts.** Cloud amounts are reported in "oktas", or the number of eighths of the sky covered by cloud. An okta is easily estimated if one imagines the sky cut into four equal quadrants each quadrant, of course, being two oktas.

3049. **Classification of Clouds.** As a first step clouds may be divided into two fundamental classes: heap and layer clouds.

a. *Heap Clouds.* As shown in Fig 30–19, these clouds consist of isolated heaps or towers with marked vertical development. Large isolated clouds are sometimes 30,000 ft or more in vertical thickness and about the same in horizontal diameter, but heap clouds also occur in long narrow belts of almost continuous cloud. Well developed heap clouds are associated with changeable weather, and showers may occur locally, sometimes accompanied by thunderstorms, severe turbulence, and strong vertical currents.

b. *Layer Clouds.* Layer clouds form a fairly level sheet, often covering a wide area. The vertical thickness of layers may vary from a few tens of feet to several thousand feet. Such clouds usually give smoother flying conditions and less changeable weather than heap clouds. Since layer clouds are frequently split into filaments or rounded masses, a more detailed classification is necessary for general use.

3050. **International Cloud Classification.** Similar forms of cloud occur over most of the world, and an international classification has been agreed by all countries as shown in the following table:

Serial No	Family	Classes (General)	Abbreviation	Limits of Height Within Which Cloud Normally Lies		
				Polar Regions (ft)	Temperate Regions (ft)	Tropical Regions (ft)
1	High Cloud	Cirrus Cirrostratus Cirrocumulus	Ci Cs Cc	10,000 to 25,000	16,500 to 45,000	20,000 to 60,000
2	Medium Cloud	Altocumulus Altostratus	Ac As	6,500 to 13,000	6,500 to 23,000	6,500 to 25,000
3	Low Cloud	Nimbostratus Stratus Stratocumulus	Ns St Sc	Surface to 6,500	Surface to 6,500	Surface to 6,500
4	Heap Cloud (clouds of vertical development)	Cumulus Cumulonimbus	Cu Cb	Near Surface to 25,000	Near Surface to 45,000	Near Surface to 60,000

Note: Nimbostratus often extends into medium cloud levels and merges with altostratus.

Photo by: Fundacio Concepcio Rabell, Barcelona.

Fig 30–9 Hooked Cirrus

Photo by: Mr. G. C. A. Clarke

Photo by: Mr. G. A. Clarke

Fig 30–11 Cirrocumulus

Photo by: Mr. G. A. Clarke

Photo by: Mr. G. A. Clarke

Fig 30–13 Altostratus

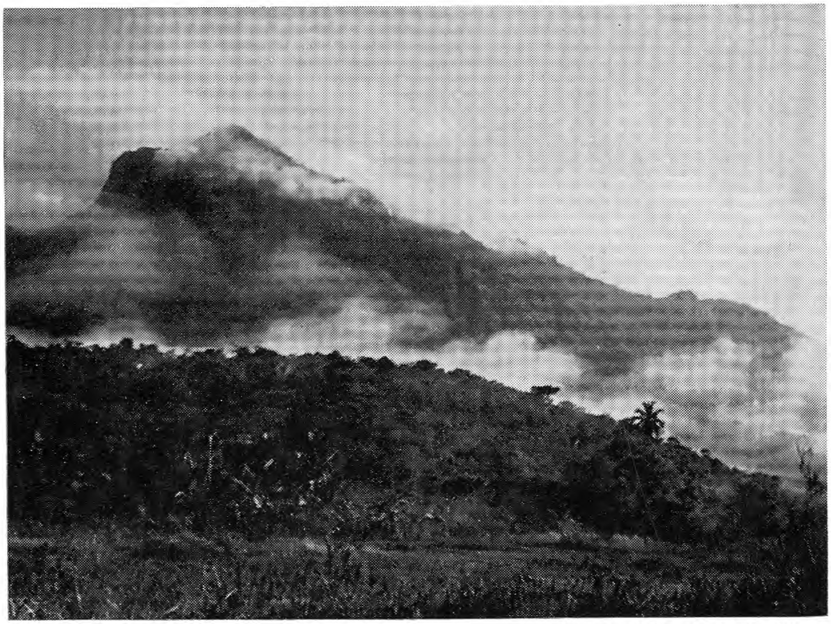

Photo by the late Mr. M. C. Gillman

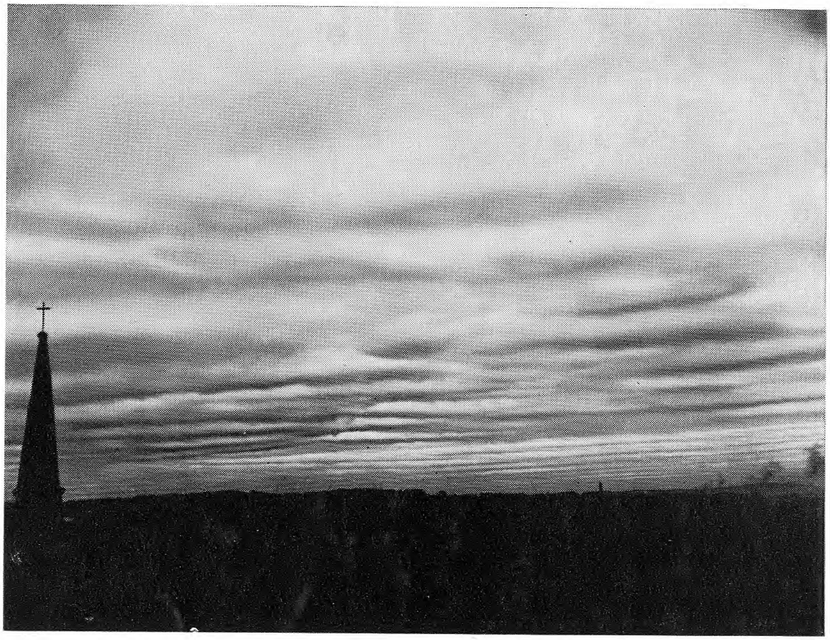

Photo by: Mr. G. A. Clarke

Fig 30–15 Stratocumulus

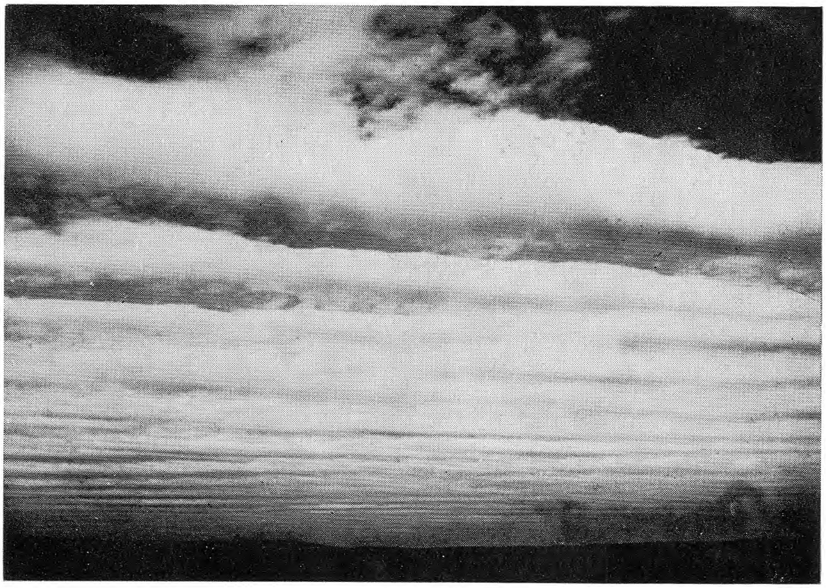

Photo by: Mr. G. A. Clarke

Fig 30-

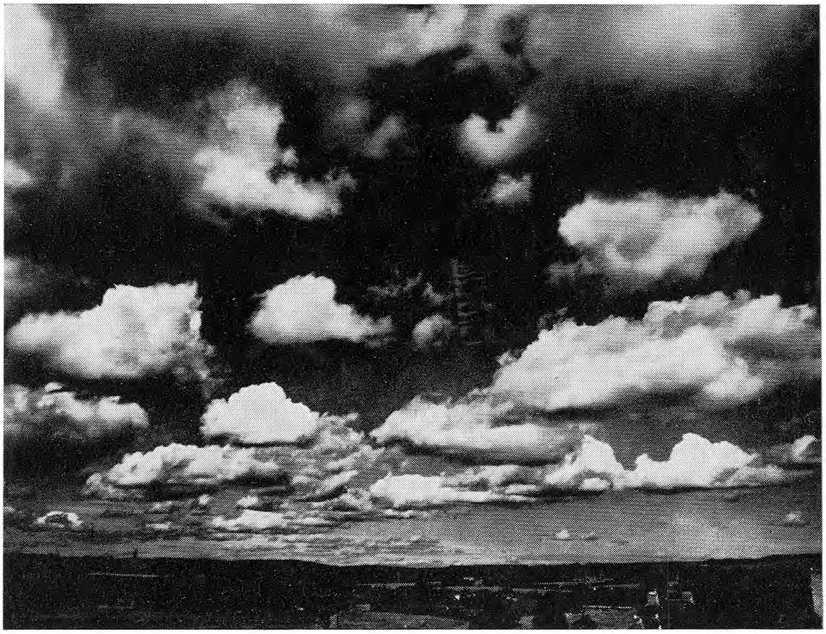

Photo by: Mr. G. A. Clarke

Fig 30–17 Fair Weather Cumulus

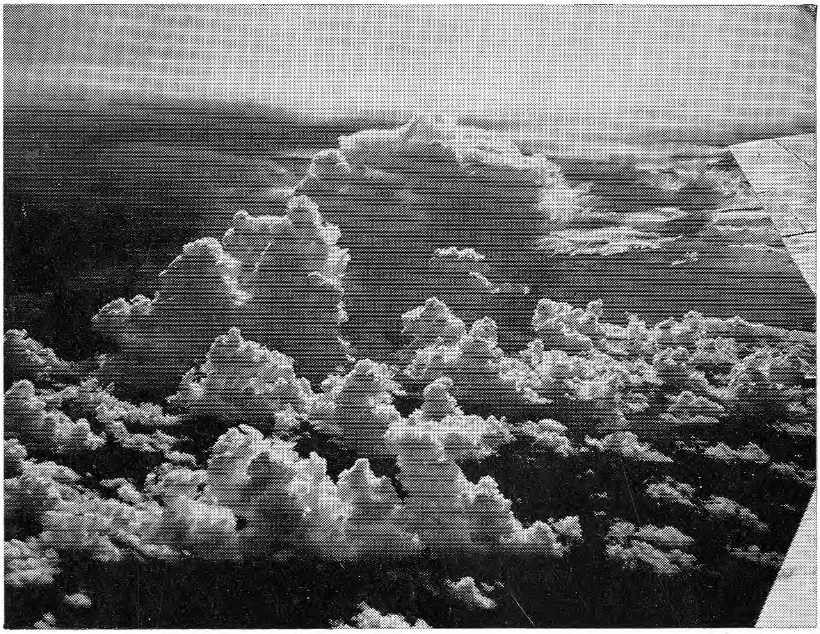

Photo by: The Times

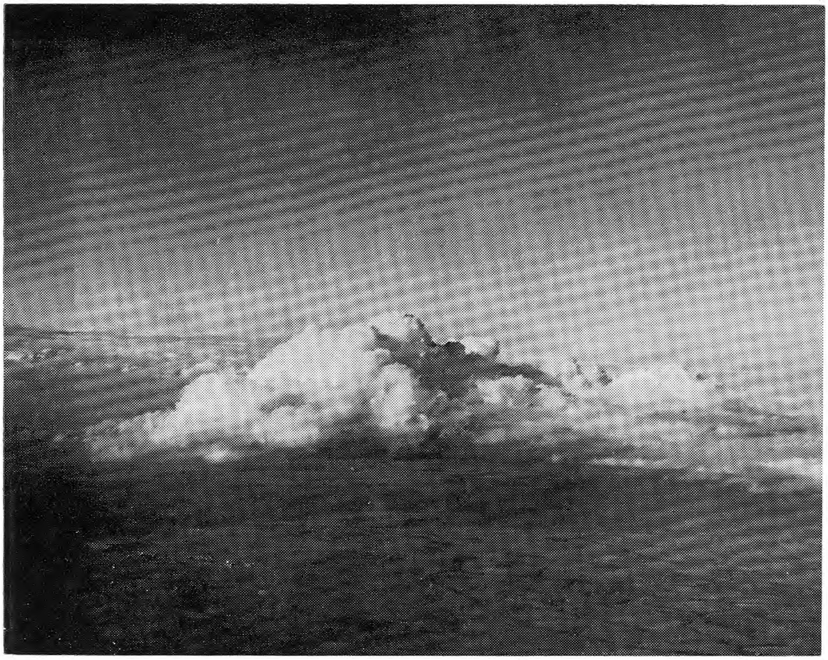

Fig 30–19 Large Towering Cumulus

Photo: by: Mr. G. A. Clarke

Fig 30–21 Cumulonimbus with Particularly Well-Defined Anvil

3051. **Types of Cloud and their Significance to Controllers.**

a. *Cirrus* (*Ci*). Cirrus clouds are detached clouds of delicate appearance, without shading, generally white in colour and often of silky appearance (*see* Fig 30–9).

b. *Cirrostratus* (*Cs*). Cirrostratus cloud appears as a thin whitish veil which does not blur the outline of the sun or moon, but gives rise to halos (*see* Fig 30–10).

c. *Cirrocumulus* (*Cc*). Cirrocumulus is a uniform layer or patch composed of small white flakes, or very small globular masses without shadows and arranged in groups or lines, but more often in ripples like those sometimes seen in sand on the seashore (*see* Fig 30–11).

d. *Significance of Cirriform Cloud to Controllers.* Cirriform clouds consist of ice crystals, and are so tenuous that pilots may not realize that they are flying in cloud. However the presence of cirrus type clouds often indicates that conditions are favourable for the formation of contrails (*see* paras 3077–3081). Vertical visibility is only slightly affected.

e. *Altocumulus* (*Ac*). Altocumulus appears as a layer, or patches composed of laminar or rather flattened globula elements of the regularly arranged layer being fairly small and thin, with or without shading. The elements may be arranged in groups, lines, or waves, following one or two directions. The cloud often resembles cirrocumulus but on a larger scale. (*See* Fig 30–12.)

f. *Altostratus* (*As*). Altostratus appears as a striated or fibrous veil, more or less grey or bluish in colour. The sun or moon shines through the cloud vaguely, as through ground glass, and may eventually be completely obscured by the cloud. Altostratus is like thick cirrostratus but does not produce a halo. (*See* Fig 30–13.)
Visibility is often as much as 200 yds in thin altostratus, but may decrease to less than 100 yds as the cloud thickens.

g. *Nimbostratus* (*Ns*). Nimbostratus is a low, amorphous, rainy layer, dark grey in colour and nearly uniform in appearance. Nimbostratus usually gives rain, sleet, or snow, but the precipitation need not necessarily reach the ground. Nimbostratus is usually associated with a frontal system, and may be considered as a medium or low cloud according to the height of the cloud base. The cloud may be 10,000 to 15,000 ft deep, and its base often covers low hills at the passage of a front or Moderate turbulence, perhaps severe at times, may be encountered, icing may occur on aircraft and visibility in the cloud is very poor.

h. *Stratus* (*St*). Stratus is a uniform but usually shallow layer of cloud resembling fog but with its base above the general ground level (*see* Fig 30–14).

It is often less than 1,000 ft thick, and it may develop suddenly and almost simultaneously over wide areas, particularly inland at night.

j. *Stratocumulus* (*Sc*). Stratocumulus cloud forms a layer or patches, composed of globular masses or rolls. The smallest of the regularly arranged element are fairly large; they are soft and grey with darker parts. The cloudlets are often arranged in groups, lines, or waves, and are aligned in one or two directions. The rolls may be so close that their edges join. This cloud often occurs in Britain, and in association with winter high pressure systems it may persist for several days. Flight in and below stratocumulus is often rather bumpy, but smoother conditions may sometimes be found above the layer. (*See* Figs 30–15 and 30–16.)

k. *Cumulus* (*Cu*). Cumulus appears as thick white clouds with vertical development; the upper surface is dome-shaped while the base is horizontal. In Britain the base is usually between 1,000 and 5,000 ft, while tops are variable but may exceed 15,000 ft. The clouds are usually isolated and often occur near coastlines or hills. Sometimes they occur in lines, forming cloud lanes. At a cold front or occlusion, cumulus clouds may be almost continuous along a narrow belt, of the order of 10 to 50 miles wide. (*See* Figs 30–17, 30–18 and 30–19.)

In large cumulus clouds flying conditions are often bumpy.

l. *Cumulonimbus* (*Cb*). Cumulonimbus cloud is characterized by heavy masses of cloud with great vertical development. The summits rise in the form of mountains or towers, while the upper parts have a fibrous texture and often spread out in the shape of an anvil. (*See* Figs 30–20 and 30–21.) Cumulonimbus clouds usually produce heavy showers, sometimes accompanied by thunder. Severe turbulence, hail, lightning and aircraft icing may also occur. The tops of cumulonimbus clouds are generally about 25,000 ft in polar regions, but increase to about 55,000 ft in tropical regions. The height of the base is usually from 2,000 to 5,000 ft in Britain. Vertical currents of more than 1,000 ft per minute may be experienced.

3052. **Constitution of Clouds.** Clouds consist of water droplets or ice crystals, or a mixture of both. At levels where the temperature is above 0°C clouds consist almost entirely of water droplets, whereas at the comparatively low temperatures prevailing at cirrus levels clouds consisting of ice crystals predominate. However water droplets do not necessarily freeze immediately the air temperature falls below 0°C. Even down to −10°C clouds frequently consist of water droplets, and *small* droplets can persist at temperatures as low as at least −40°C. Such droplets are said to be supercooled and are the commonest cause of airframe icing on aircraft.

3053. **Formation of Clouds.** Clouds are formed owing to moist air being cooled below its dew point. The cloud droplets or ice crystals which thus form are supported by rising air currents. If the water droplets or ice crystals grow so large that upward currents can no longer support them, they fall as precipitation.

3054. **Clouds at High Altitude.** The temperature in the stratosphere is so low that, even if the air were saturated, the total water content would be very small. Usually the air in the stratosphere is quite dry; consequently only rarely can cloud be present. Therefore, the highest level at which cloud can occur is normally determined by the height of the tropopause. This means that, in temperate latitudes, cloud tops are normally limited to about 30,000 to 35,000 ft, though exceptionally they do extend up to 40,000 to 45,000 ft. In tropical and sub-tropical regions there is no reason why cloud should not be found up to 55,000 ft or even higher.

Precipitation

3055. **Types of Precipitation.**

a. *Drizzle.* Drizzle consists of water droplets so small that their individual impact on a water surface is imperceptible. It is often associated with mist or fog, and usually falls from thin layer clouds.

b. *Rain.* Rain consists of water drops of appreciable size, up to about $\frac{1}{4}$ in in diameter. In temperate latitudes rain usually originates in cloud as aggregates of ice crystals, which melt on falling below the freezing level and turn into raindrops. Hence it is quite usual for aircraft to encounter snow when flying in temperate regions at an altitude where the temperature is near or below 0°C, although the precipitation reaching the ground may be in the form of rain.

c. *Snow*. The ice crystals in cloud above the freezing level may grow and interlock until they become too large to be supported by updrafts in the cloud; they then fall as snowflakes, and these reach the ground without melting if the air temperature below the cloud is sufficiently low.

d. *Sleet*. In Britain sleet is defined as rain and snow falling together, or snow melting as it falls.

e. *Hail*. Hail consists of small lumps of ice. Hailstones bigger than golf balls have fallen in Britain on rare occasions.

3056. **Continuity of Precipitation.** The distinction between showers, and intermittent or continuous precipitation are important, for the causes are not the same and the accompanying flying conditions differ. Showers always fall from heap-type clouds such as cumulonimbus, which may cover the sky temporarily but soon break to show patches of blue sky. Both intermittent and continuous precipitation however, normally fall from a layer cloud which covers the whole sky.

3057. **Lifting Processes Causing Clouds and Precipitation.** There are four basic causes of the upward motion of air which results in cloud or precipitation. These are:

a. Turbulence.

b. Convection.

c. Rising ground, hills or mountains (orographical).

d. Ascent over a wide area (air mass movement).

The clouds and precipitation associated with each of these factors is briefly discussed in paras 3058 to 3061.

3058. **Turbulence Clouds and Precipitation.** Turbulence caused by friction between moving air and the irregular surface of the earth may produce a layer of stratus or stratocumulus cloud, provided that the lifted surface air reaches a height at which it becomes saturated. Turbulence cloud is rarely more than two or three thousand feet thick, but sometimes occurs

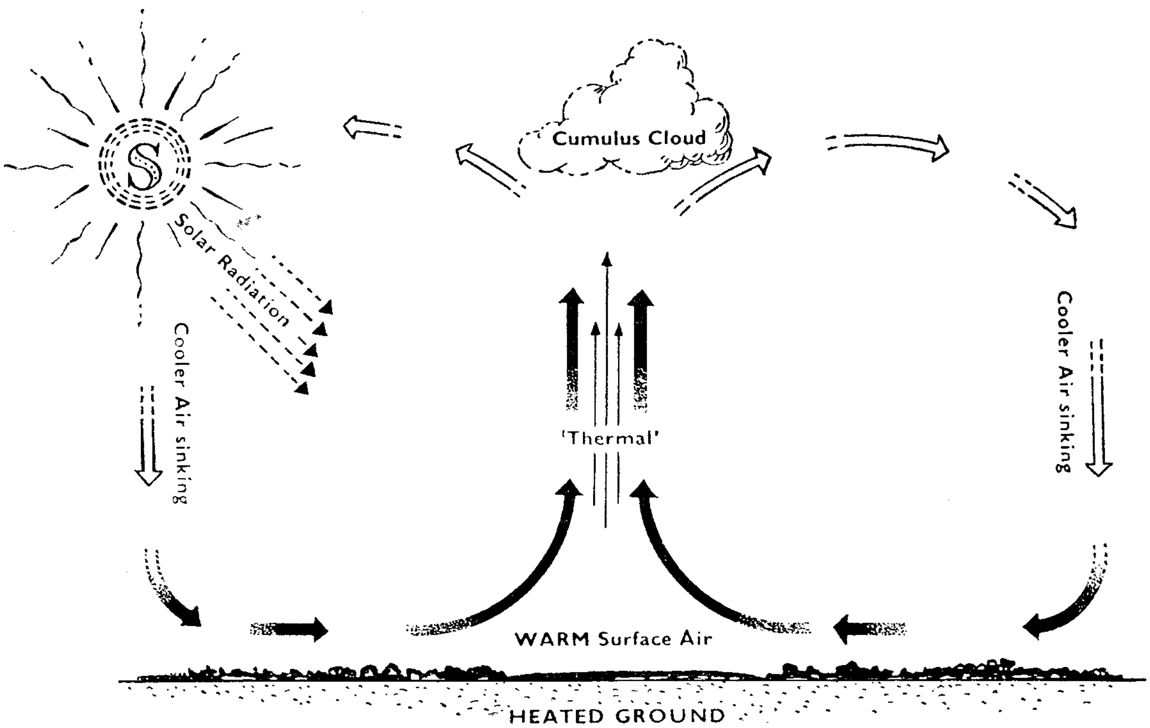

Fig 30–22 Convection

together with towering cumulus or cumulonimbus. Turbulence clouds rarely give precipitation unless they are quite thick, in which case local drizzle or perhaps slight rain, sleet, or snow, may result.

3059. **Convection Clouds and Precipitation.** Ground warmed by absorbed solar radiation transfers some of its heat to the layer of air in contact with it by the process of conduction. In consequence this warmed layer of surface air expands, becomes less dense, and so rises, carrying its heat energy with it, and is replaced by cooler air from above: this process of heat transfer by physical movement is known as convection. The rising convection currents are known to glider pilots as "thermals": they are often topped by a formation of cumulus clouds, and account for the bumpiness usually experienced on low-level flights on a sunny day (*see* Fig 30–22). Convection clouds may be formed not only as a result of direct solar heating of the ground, but by various processes causing air to become unstable. For example, the steep temperature lapse rate necessary for instability may result from over-running cold air at high levels, or the warming of air at low levels as it moves over a warmer surface. Heap-type clouds are therefore commonly observed in a polar air stream over warmer land or sea. Isolated convection clouds are rarely more than 10 miles across, and frequently much less. Their vertical thickness varies from a few thousand feet for small cumulus clouds to 30,000 ft and more for large cumulonimbus clouds. The height attained by the cloud tops depends on the stability of the air. In extremely unstable conditions tops of cumulonimbus clouds can extend to the tropopause, or about 55,000 ft in equatorial regions and 25,000 ft in polar regions. Convection tends to reach maximum intensity during the afternoon. Consequently if small cumulus clouds appear over land in the morning, they normally grow to maximum size about mid-afternoon and become large cumulus or cumulonimbus clouds. At night inland, convection dies down as the ground cools, so that cumuliform clouds generally flatten out and disperse. When cumulus clouds appear over land earlier than usual on a summer morning, thunderstorms frequently develop in the afternoon; whereas if cumuliform clouds do not form until midday the development of thunderstorms due to convection alone is unlikely. Shallow convection clouds do not give precipitation; hence their name "fair weather cumulus". However, if their vertical thickness exceeds about 10,000 ft and their tops reach the freezing level, cumulus clouds often develop into cumulonimbus giving heavy thundery showers. Upward air currents in large convection clouds may exceed the rate of fall of many of the raindrops, so the latter may be carried upwards and grow larger. These raindrops are eventually precipitated when the upcurrents become less intense or the drops become too big to be supported, but the precipitation although often heavy rarely lasts longer than an hour or so in any locality.

3060. **Orographic Clouds and Precipitation.** Typical orographic clouds such as those shown in Fig 30–23 form when sufficiently moist air is forced to rise over a barrier of mountains or hills. The growth of orographic clouds depends on the relative humidity of the air and its temperature lapse rate. Sometimes the air near the surface may be too dry to form orographic clouds, but moister air at a higher level may be forced to ascend and thus form cloud at a level well above the high ground. This cloud often appears stationary, as new cloud is formed by rising currents while cloud dissolves in the downcurrent to leeward. Normally a layer-type cloud is produced, but sometimes when the air is unstable a heap cloud may form (*see* Fig 30–23).

3061. **Clouds and Precipitation Due to Ascent of Air over a Large Area.** One of the most common causes of cloud is the ascent of air within a low pressure area, and this is responsible for the well-known association between low barometric pressure and bad weather. The ascent of air in depressions is usually concentrated near certain zones known as "fronts". Fronts are boundaries between extensive air masses at different temperatures. The boundaries are inclined plane surfaces extending from the ground to a level at which it is impossible to distinguish one air mass from the other. The frontal surface is not vertical, but forms an inclined plane so that cold air forms a wedge under the warm air. When warmer air is overtaking cold air the front is known as a *warm* front, and when cold air is overtaking warm air the front is a *cold* front (*see* Fig 30–24).

The normal sequence experienced during the passage of a depression is a warm front followed by a cold front. A typical frontal depression is shown in vertical section in Fig 30–25. The cold front however, moves faster than the warm and eventually overtakes it to form an *occlusion* (*see* Fig 30–26).

a. *Warm Front Cloud and Precipitation.* The warm front is forced up along the frontal

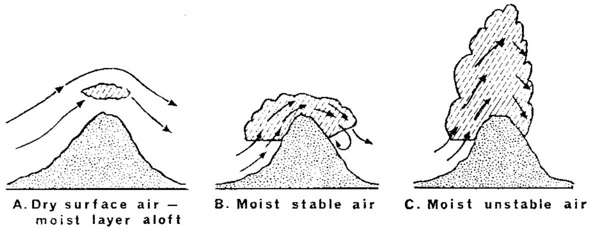

Fig 30–23 Various Types of Orographic Clouds

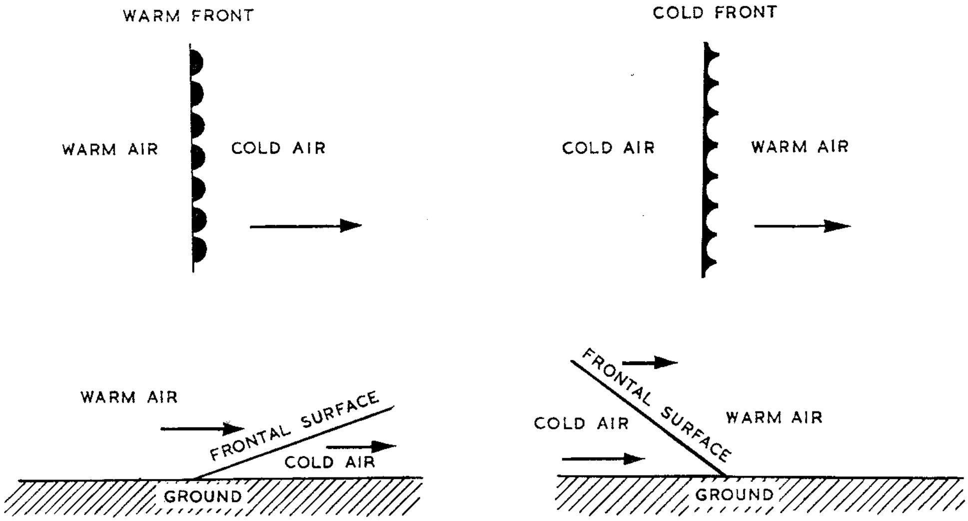

Fig 30–24 Warm and Cold Fronts

surface, which is an inclined plane with an average slope of between 1 in 100 and 1 in 150. Ascent to higher levels where the pressure is lower produces cooling, and clouds form above the frontal surface. The highest clouds yielded are cirrus: these are at a height of perhaps 30,000 ft and about 600 miles in advance of the front. As the surface front is approached the cloud-base becomes lower and the cloud thicker, changing progressively from cirrostratus to altostratus, and finally to nimbostratus whose base may fall almost to the ground near the front. Rain or snow falls from the higher altostratus, perhaps from 20,000 ft, but is slight at the forward edge and evaporates before reaching the ground; as the clouds lower and thicken, the precipitation gets heavier, and ultimately reaches the ground as much as 200 miles in advance of the surface front. From then onwards, rain (or snow, *etc*) is usually continuous till the surface front arrives, after which the rain clouds quickly clear. Apart from the true frontal clouds, there is generally a lot of low fractostratus and fractonimbus (called scud) within the cold air below the altostratus and nimbostratus; this is produced by turbulence, and by the moistening of the cold air by the evaporation of falling rain.

b. *Warm Sector Cloud and Precipitation.* The relatively warm air between the warm and cold fronts is termed the warm sector. Weather in the warm sector depends on locality and time of year, and on the previous history of the warm air, *ie* whether it has come from maritime or continental regions, and from high or low latitudes. There may, on occasions, be a clear sky, but more usually there is low turbulence cloud, or perhaps fog or drizzle.

c. *Cold Front Cloud and Precipitation.* It might well be expected that a cold front would present the same phenomena as the warm

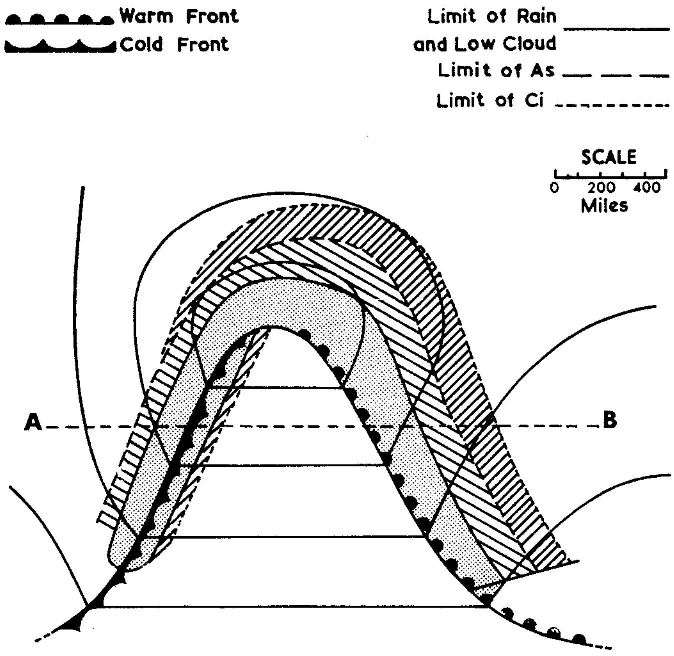

Fig 30–25a Distribution of Cloud Around a Warm Sector

Fig 30–25b Cross-Section of Cloud Structure on line AB in Fig 30–25a

front, with a reversal of order. As the cold air undercuts the warm air the ascent of the latter might be expected to produce layer clouds above the frontal surface, with rain beginning after the passage of the front and extending in a wide belt behind. On some occasions cold fronts do behave in this way; but they are not typical. The simple upsliding movement is usually complicated by an outbreak of vertical instability, yielding the normal phenomena of unstable conditions, *ie* large towering cumulus or cumulonimbus, and heavy rain of short duration, perhaps with hail or thunder. In these circumstances there may be violent disturbances, and the cold front may arrive as a line squall. The rain often begins well ahead of the surface front and may be preceded by cirrus or altostratus. The weather experienced near a cold front cannot be explained simply in terms of a front dividing warm air from cold; it is complicated by the instability that results, perhaps, from a gradual transition from warm to cold air in the upper atmosphere in advance of the frontal surface. The rain area may extend on both sides of the front, and the prefrontal high clouds may be regarded as an anvil projected from the cumulonimbus clouds and carried forward by the stronger winds aloft. The main frontal surface, behind the surface front, is usually marked by clouds of the altostratus or altocumulus type, but these often break quickly. The phenomena of the cold front vary widely, depending on the degree of instability: the line squall characteristics are not always produced, and some cold fronts pass over with little disturbance in the weather.

d. *Cloud and Precipitation at an Occlusion.* It is difficult to pick out any features that may be described as characteristic of an occlusion, the bare information that an occlusion lies in

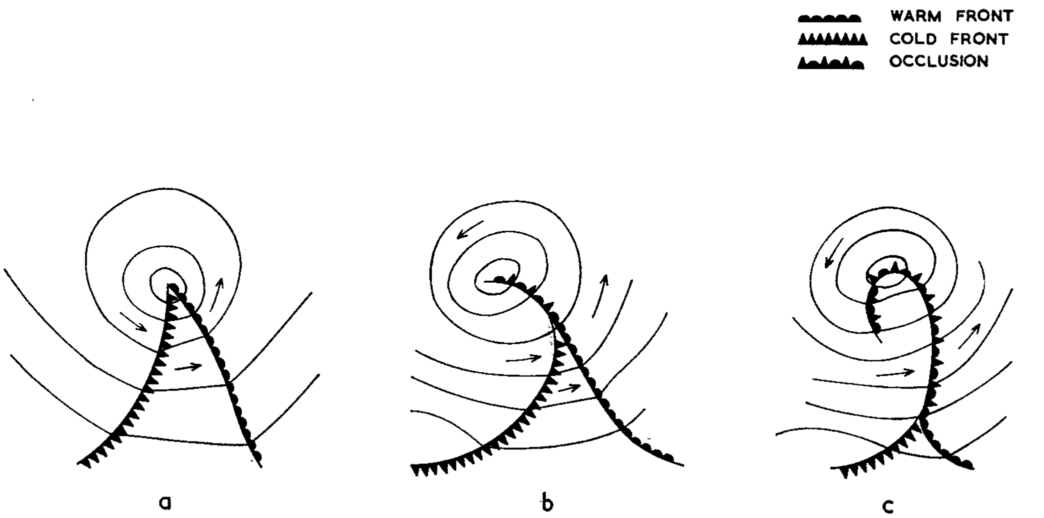

Fig 30–26 Occluding of a Depression

the path of an aircraft gives little indication of the weather it will encounter. Occlusions are always degenerating, and eventually disappear. In the early stages of an occlusion, low cloud and rain are common; but old occlusions may present no noticeable features other than perhaps a little cloud or, not unusually, fog if the winds are light, for the air is usually moist.

3062–3064. (*Not allotted*).

VISIBILITY AND FOG

Visibility

3065. **Definitions.** Visibility is defined as the greatest horizontal distance at which objects can be seen and recognized by an observer with normal sight under the prevailing conditions of daylight atmospheric obscurity. At night the equivalent daylight visibility is reported: that is, the visibility that would be reported if it were daylight and the same conditions of obscuration existed. However aircrew at night are often concerned with the distance at which they can see lights; this is not generally equal to the reported visibility as the following table shows:

3066. **Terminology.** Certain terms concerning visibility are used loosely in everyday speech which have precise meanings in meteorological terminology, and these are shown in the following table:

Visibility	Description
Less than 44 yds	Dense fog
44–220 yds	Thick fog
220–440 yds	Fog
440–1,100 yds	Moderate fog
1,100–2,200 yds	Mist or Haze
1·0–2·0 nm	Poor visibility
2·0–5 nm	Moderate visibility
5–11 nm	Good visibility
11–22 nm	Very good visibility
Over 22 nm	Excellent visibility

Generally an actual distance is quoted as the visibility in reports and forecasts, but the terms in the table above are also often used.

Visibility in Cloud and Precipitation

3067. **In Cloud.** There is an extremely wide range of visibility within cloud, but, except in certain abnormally diffuse forms, the visibility generally is that of thick fog, *ie* less than 220

Reported Visibility and Visibility of Lights at Night

Visibility	100 yds	1,000 yds	4,000 yds	5 miles	10 miles	50 miles
Maximum distance at which a 100-cp lamp can be seen	250 yds	1,600 yds	4,000 yds	4 miles	5 miles	11 miles

yards. Low rain-bearing clouds are the densest, with visibility down to a few yards.

3068. **In Precipitation.** Though the amount of moisture present in the atmosphere in the form of raindrops may be as much as, or more than, that in the form of cloud, the number of particles in a given volume is smaller. For this reason moderate rain does not reduce visibility below 2½ miles and heavy rain rarely below 1,100 yards. Very bad visibility may be associated with rain, but only when cloud or mist is also present. Snow, however, is a most effective agent in reducing visibility, and quite a light fall will give fog visibility (less than 1,100 yards). In heavy snow the visibility may be only a few feet.

Visibility at High Altitudes

3069. Although the horizontal visibility is frequently good at high altitudes, aircrew may often find it difficult to detect other high-altitude aircraft visually, except at fairly close range. The distance at which one aircraft can be distinguished from another depends greatly on the position of the sun in relation to both aircraft. Reflections of the sun from a highly polished aircraft may be detected at considerable distances.

3070. The size and attitude of an aircraft with respect to the observer are also important when the maximum visual range at which an aircraft can be detected is being considered. Obviously a large bomber aircraft is likely to be visible at a greater distance than a small fighter aircraft. An aircraft viewed from the side, and thus showing a large area of fuselage, is also likely to be detected at a greater distance than when viewed from the head-on position in similar conditions.

3071. **Windscreen Obscuration.** The visibility ranges that have been mentioned as typical of cloud or precipitation are true only if the observer's vision is not otherwise obstructed. The visibility enjoyed by the pilot in flight may be very much less, because of moisture or ice on his windscreen: the degree of obscuration varies with different types of aircraft, but even in rain it can be so complete as to render the pilot's vision virtually nil. Various devices are used to prevent windscreen obscuration.

Effect of Smoke

3072. Much of the bad visibility experienced in industrial and in highly populated areas is not truly a weather phenomenon at all, but is caused simply by smoke from industrial and domestic fires. The larger particles that constitute the smoke quickly settle under gravity and so do not drift far; much of the pollution, however, is in the form of very fine particles, comparable in size to the water droplets in a cloud, and may remain suspended in the air for a long time. Probably most of it reaches the ground only when it is washed out of the air by falling rain or snow.

3073. The thickness of smoke haze depends largely on the rate at which the smoke particles are dispersed through the air. Dispersion may take place in two ways:

a. Horizontally, by particles being carried in the wind, *ie* by advection.

b. Vertically, by particles rising on upward currents of air, *ie* by convection.

3074. Advection merely extends the trouble from one locality to another; though the concentration is reduced if the wind is strong and the smoke is therefore less noticeable. The smoke trail from London can often be traced to the South Coast and across the English Channel. Smoke is not noticeable however, at medium or high altitudes.

3075. Convection currents disperse smoke more effectively as they lift it to higher levels, where it is usually carried away in the stronger winds aloft; in any case, the smoke is prevented from accumulating near the surface.

Fog

3076. Fog (with the exception of smoke fog) is caused by the cooling of moist air below its dew point. The names given to different types of fog relate to the way the cooling is brought about. The types of fog and their characteristics are summarized in Annex B to this Chapter.

CONTRAILS

3077. **Formation.** Occasionally an aircraft flying in clear air produces a trail behind it. This trail is known as a condensation trail or a "contrail" because it results from the condensation of water vapour, produced by the combustion of fuel. A typical contrail is illustrated at Fig 30–27. The exhaust gases from an aircraft alter the relative humidity of the air in two opposite ways. They contain a high proportion of water, and this tends to raise the relative

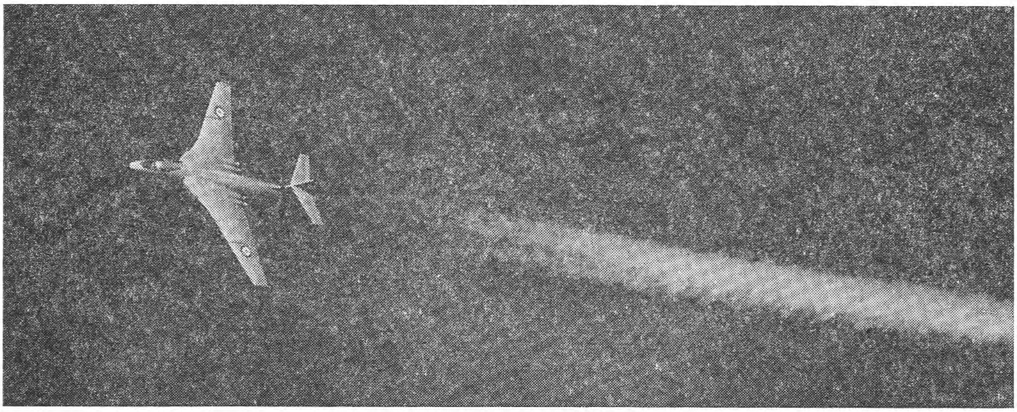

Fig 30–27 Aircraft Leaving Contrails

humidity, but on the other hand they heat the air, and this tends to lower the relative humidity. Which effect is the more important depends mainly on the temperature of the air through which the aircraft is flying. The amount of water needed to saturate warm air is very much greater than in the case of cold air; for example, saturated air at 60°F contains about 120 times as much water as at −40°F. Evidently, therefore, the small amount of water ejected by the aircraft engine is much more likely to produce saturation in cold air than in warm. Any additional water ejected, beyond what is needed to saturate the air, will be condensed and will appear as a trail of cloud behind the aircraft.

3078. The net effect of the increases in temperature and water vapour content can be calculated, and it can be shown that for a given altitude there is a definite critical temperature, known as the mintra temperature, above which exhaust contrails are unlikely. The altitude at which the air temperature falls to the mintra temperature is known as the mintra level.

3079. The turbulence due to the passage of the aircraft causes the condensation trail to mix fairly rapidly with the surrounding air. If the surrounding air is very dry it will soon absorb the condensed water in the trail, which will therefore disappear quickly. Air in the stratosphere is frequently very dry, and for this reason condensation trials are often short in the stratosphere. In nearly saturated air, on the other hand (*eg* at or near the level of cirrus clouds) trails are likely to be persistent.

Contrail Heights

3080. Over Western Europe dense trails seldom form below 25,000 ft in summer or 18,000 ft in winter, although in very cold conditions they may form appreciably lower. In tropical and sub-tropical regions the minimum contrail height is unlikely to be below 33,000 ft.

Avoidance of Contrails

3081. Dense and persistent contrails provide an enemy with an easy method of detecting aircraft, so it is useful to know that contrails can be avoided by:

a. Flying at a level where the air temperature is above the critical mintra temperature.

b. Avoiding levels where cirriform clouds are present.

c. Seeking a dryer layer of atmosphere. This may often be found by ascent into the stratosphere, but sometimes a relatively dry layer may be found just above a cloud layer or temperature inversion.

SUMMARY OF CLOUD CHARACTERISTICS

Serial No	Name of Cloud	Usual Abbrevia-tion	Continuity	Usual Range of Height of Cloud Base above Ground in UK (Ft)	Vertical Thickness of Cloud	Visibility in Cloud	Bumpiness	Other Significant Features
1	Cirrus	Ci	Poor	20,000–40,000	Perhaps a few thousand feet thick	Moderate to good	Usually nil but perhaps moderate to heavy near jet streams	This could often indicate the proximity of a frontal system.
2	Cirrostratus	Cs	Often good	20,000–40,000	Perhaps a few thousand feet thick	Moderate to good	Usually nil but perhaps moderate to heavy near jet streams	As above, and often produces halos.
3	Cirrocumulus	Cc	Poor to moderate	20,000–40,000	Fairly thin	Moderate to good	Usually nil but perhaps moderate to heavy near jet streams	No special significance.
4	Altocumulus	Ac	Variable, occasionally moderate to good	8,000–20,000	A few thousand feet thick	Usually less than 200 yds	Moderate at times especially in castellatus	Banded types often associated with fronts, and castellated types with unstable thundery conditions.
5	Altostratus	As	Good	8,000–20,000 but base often merges into nimbostratus	Thick, perhaps up to about 15,000 ft thick	Variable, but may be less than 200 yds	Slight	Usually indicates close proximity of precipitation area or front. Good for cloud flying.
6	Nimbostratus	Ns	Good	Often 300 ft up to 2,000 ft or more	Thick, perhaps up to about 15,000 ft thick	Usually less than 100 yds	Moderate but may be severe some-times at lower levels	Usually associated with precipitation. Tops may merge with altostratus.
7	Stratus	St	Often good but sometimes patchy	500–2,000	Thin, about 100–1,000 ft in thickness	Variable, but probably less than 200 yds	Slight	Usually covers high ground.
8	Stratocumulus	Sc	Variable, often moderate to good	1,000–4,500	Thin, about 500–3,000 ft in thickness	Usually less than 200 yds	Moderate unless penetrated by heap cloud	Smoother flying conditions often found above cloud layer, particularly in clouds having very flat tops.
9	Cumulus	Cu	Poor; clouds are usually isolated	1,000–5,000	Often thick; perhaps about 5,000–15,000 ft or more in thickness	Less than 100 yds	Moderate to severe	May give some indication of atmospheric stability. Inexperienced pilots should avoid larger clouds as strong vertical currents and turbulence may be encountered.
10	Cumulonimbus	Cb	Poor; clouds are usually isolated	2,000–5,000	Thick clouds, usually about 10,000–30,000 ft thick	Less than 100 yds	Often severe	Inexperienced pilots should avoid these clouds. Heavy showers, hail, lightning, icing and severe turbulence may be encountered in cumulonimbus clouds.

SUMMARY OF FOG CHARACTERISTICS

Serial No	Type of Fog	Season	Areas Most Affected	Fog Formations	How Dispersed	Best Diversion Areas
1	Radiation	October to March	Inland areas, chiefly low lying wet ground	Cooling due to radiation from ground on clear nights with winds less than about 10 knots, chiefly in anticyclonic weather	Dispersed by solar radiation or increased turbulence associated with freshening winds, or by the influx of drier air	High level or coastal airfields or regions with stronger winds or previously existing cloud.
2	Advection a. Over land	Winter and Spring	Often widespread inland	Cooling of warm air by movement over cold ground when warm air arrives after a cold spell	Lifted to low stratus by increasing winds, or dispersed by change to drier air mass, or by gradual warming of ground	Better conditions may sometimes be found well inland in the lee of high ground, or occasionally on windward coasts when there is no fog over the sea (sea warmer than land).
	b. Over sea and adjacent coasts	Spring and early Summer	Sea and adjacent coasts; often penetrating a short distance inland where coast is flat, particularly at night	Cooling of warmer air by movement over colder sea	Over sea usually dispersed by change of air mass. Over land near coasts usually dispersed or lifted by solar heating	When airfields on coast are affected by sea fog drifting inland better conditions will be found farther inland, particularly in the lee of high ground.
3	Frontal	All seasons	High ground	Near fronts due to the usual lowering of cloud base in rain	Movement of front and change to drier air mass	Low-level airfields and areas well removed from the front. (Frontal fog seldom lasts more than an hour or two.)
4	Hill	All seasons	High ground	By adiabatic cooling: sometimes associated with other types of fog	Movement of cloud or lifting of base due to solar heating	Low-level airfields in the lee of high ground.
5	Smoke	Winter	Near industrial areas and large towns	Near industrial areas and large towns in conditions similar to those for radiation fog, especially in stable air	By convection and increasing turbulence, or increasing wind speed	Better visibility is usually to be found upwind of sources of smoke pollution, or at coastal airfields where there is a sea breeze blowing.

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CHAPTER 31

FIGHTER OPERATIONS

CONTENTS

DEPLOYMENT OF FIGHTER FORCES

3101. Generally it is desirable to have fighters deployed on the most likely line of enemy approach to the defended area and as far forward as possible, though this disposition may well have to be modified by geographical and early-warning considerations. This will tend to create zones where fighters are concentrated. An attempt to afford equal protection to all threatened points simultaneously will usually result in attenuated defences which are likely to prove ineffective at the main point of an attack.

Governing Factors

3102. The aim of a fighter force is to destroy the enemy aircraft before the point of weapon release, and its ability to do so is governed by the following factors:

a. The performance of the enemy aircraft.

b. The performance of the defensive fighters.

c. The range, accuracy, and discrimination of the control and reporting system.

d. The distance the enemy has to penetrate before reaching his objective.

e. The siting of the fighter bases.

f. The length of time between initial detection of an approaching raid and the defensive fighters becoming airborne.

g. The time taken to destroy the enemy after contact has been gained.

h. The siting of SAM defences.

Defensive Tactics

3103. Defensive tactics will largely depend upon the method adopted by the attacking force. Whether the enemy attempts to overwhelm the defences by concentrating in time and space, or whether he attempts to disperse them by attacking at several points on a broad front simultaneously, the aim of the defence must be to intercept and destroy enemy aircraft as far from their objectives as possible. The enemy will make every effort to confuse and deceive the defences and skilled judgement will be necessary to interpret the air situation and to dispatch defensive fighters at the correct moment.

Role of the Fighter Force

3104. In addition to the foregoing factors which generally dictate the deployment of a fighter force, the roles which the fighter force has to fulfil will also govern its deployment. For example, in the United Kingdom the roles of the fighter force are as follows:

a. *Anti-Intruder Role.* Fighter aircraft, in peacetime, are used to preserve the integrity of the United Kindgom air space and its approaches.

b. *Overseas Reinforcement Role.* Defensive fighter aircraft, based in the United Kingdom, provide a mobile strategic reserve which can be used to prevent, or if it occurs, prosecute a limited war overseas.

c. *Air Defence of Great Britain Role.* Should a general war occur, the defensive fighter aircraft based in the United Kingdom would defend the main deterrent bases as effectively as their numbers and facilities would allow.

FEATURES OF A FIGHTER AIRFIELD

Permanent Fighter Airfields

3105. Permanent fighter airfields usually have a single runway 7,500 ft long by 150 ft wide with operational readiness platforms (ORPs) at each end. The runway is fitted with high intensity elevated edge lighting, and a centre-line and cross-bar approach lighting system is installed at each end. Permanent fighter airfields in the United Kingdom are all fitted with automatic direction finding and GCA equipments. A typical airfield layout of a fighter airfield is shown at Fig 31–1.

Master Airfields

3106. A number of master airfields are established in the United Kingdom, suitably spaced out across the country. These airfields, in addition to their normal service functions, act as diversion airfields and as links in the Emergency Organization. They are well equipped with radar and radio approach aids and are available for use at all times.

Number of Squadrons at an Airfield

3107. The number of squadrons at an airfield varies, but it is limited by the time taken to scramble the fighters from an airfield and the rate at which they can be recovered safely in poor weather conditions.

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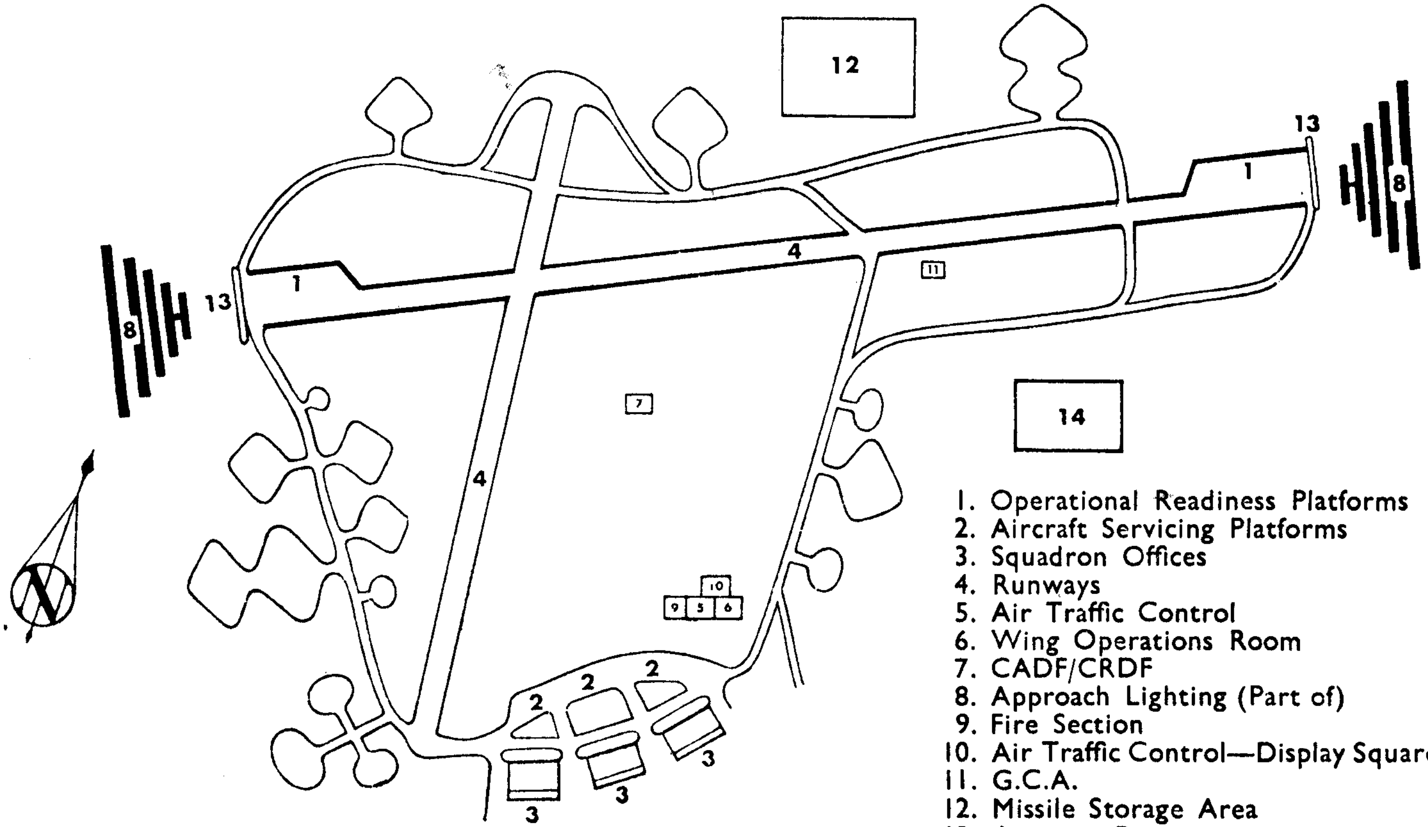


1. Operational Readiness Platforms
2. Aircraft Servicing Platforms
3. Squadron Offices
4. Runways
5. Air Traffic Control
6. Wing Operations Room
7. CADF/CRDF
8. Approach Lighting (Part of)
9. Fire Section
10. Air Traffic Control—Display Squares
11. G.C.A.
12. Missile Storage Area
13. Arrester Barriers
14. Fuel Storage

Fig 31–1 Layout of a Typical Fighter Airfield

Number of Fighters in a Squadron

3108. The number of fighters per squadron is between 10 and 20. All-weather fighters would normally operate singly, either by day or night; should the enemy fighter opposition be likely to be encountered however, they would operate either in pairs or as a section of four for mutual protection. It must be stressed that the likelihood of encountering enemy fighters over the United Kingdom is extremely remote, but when considering overseas theatres of operation it is still a valid possibility.

3109. In the United Kingdom, aircraft normally operate from either the Aircraft Servicing Platform (ASP) adjacent to permanent hangars on a centralized site, or from the Operational Readiness Platform (ORP). Alternatively, fighters may well be dispersed around the airfield to decrease vulnerability, but such dispersion is costly in material (*eg*. transport) and labour.

Operational Readiness Platforms

3110. Operational Readiness Platforms are areas of concrete, immediately adjacent to each end of the main runway on which approximately 10 or 12 aircraft can be parked in line; the aircraft have only to move forward a few yards to reach take-off position, ORPs being intended for use by fighter aircraft at the highest state of preparedness. An objection to the use of ORPs, especially overseas, is that the fighters gathered together are vulnerable and could present an easy target; however, the reduced vulnerability offered by dispersal must be weighed against the ability of the fighters to scramble more quickly from an ORP.

Runway Numbering

3111. Runways are always numbered in accordance with the magnetic heading of the approach to the nearest 10° (to resolve the ambiguity should a runway approach heading end in 5° the runway figure becomes the nearest one above). Each runway has two numbers corresponding to the two directions in which it can be used. Two-figure numbers are used, representing headings in tens of degrees; thus, a runway whose heading is 082° (M) is numbered "08", one whose heading is 217° (M) is numbered "22", and one whose heading is 355° (M) is numbered "36". The existence of these three runways implies the existence of three others ("26", "04", and "18" respectively) corresponding to reversed directions of approach.

3112. Conventional fighters need long runways for take-off and landing, and cost prohibits more than one main runway per airfield. This main runway is equipped with approach lighting, runway lighting, an approach aid (ILS, GCA or both), and will normally have ORPs and aircraft arrester barriers at each end. An airfield may have a subsidiary runway at an angle to the main one, but this runway is normally too short to be of any use except in an emergency, and it has none of the landing aids listed above.

Telebriefing

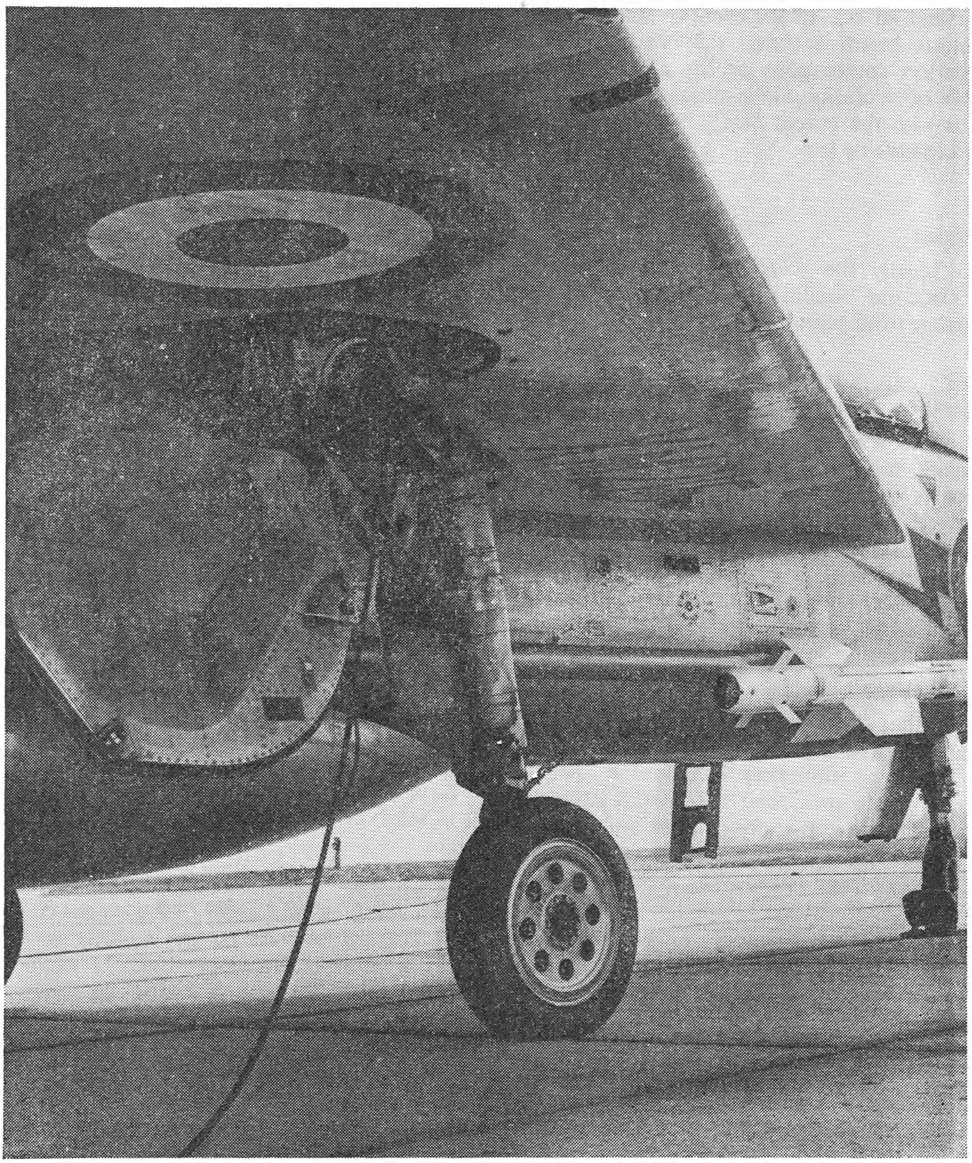
3113. Telebriefing is a landline communication system whereby a SOC/CRC/ACC is linked to an airfield and to the aircraft on the ORP, so that as they await the order to take-off, the executives at the SOC/CRC/ACC can speak direct to the pilots in their cockpits, briefing them about the current air situation and giving them scramble orders when the time comes. The landline spurs, plugged into the fighters, are designed to drop free from the aircraft as soon as they start to taxi forward. A link from the telebriefing line goes to the airfield's wing operations room, and often to air traffic control and the squadron operations room; it is possible to speak to pilots connected to the telebriefing circuit from either wing operations or air traffic control. Plug-in points for the telebriefing circuit are provided on both ORP and ASP. A mobile telebriefing installation, providing the same service, has been developed for use at forward airfields in tactical theatres overseas.

Fuel Supplies

3114. A jet fighter may use up to about 22,000 lb of fuel in one sortie, so that if each aircraft of two squadrons (one 16 Phantoms, and the other 12 Lightnings Mk 6) flew three sorties in a 24-hour period, the base would need about 180,000 gallons of fuel a day. Bulk fuel stores or pipeline supplies direct to the airfield are therefore a very important feature of a fighter airfield. There is also a problem in refuelling fighters quickly from the airfield stores which may be solved in various ways, *eg* mobile pressure refuellers and underground static tanks near aircraft parking areas.

Re-arming of Fighters

3115. The re-arming of fighters after air combat presents problems similar to those of refuelling. If arrangements are not carefully organized, the aircraft will remain out of action on the ground for long periods between sorties. Specially designed trolleys are used to transport gun packs, rocket batteries and air-to-air missiles, from the missile storage centre or armoury to the aircraft. The weapons have to be winched up into position on the fighter, or in some cases, the guns reloaded by hand. Speed with safety is the all important factor, and to this end a number of "turn-round" teams are formed on each squadron. Each team is self-contained and can replenish the fuel, oxygen, oil, starter system and re-arm the aircraft ready for take-off. With practice it is possible to achieve turn-round times of 8–12 minutes.



THE WING OPERATIONS ROOM

3116. The wing operations room is the fighter airfield operations centre of the control organization, and in peacetime is virtually a relay station between the SOC/CRC and aircraft on alert states. During normal day-to-day operations in peacetime it maintains a state board showing all aircraft airborne from the station, what they are doing, how long they will be airborne and so on. In the event of war, the wing operations room becomes the headquarters of the station commander or his deputy, and is capable of operating alone should all communications with the parent SOC/CRC or ACC and other airfields be lost.

Protection

3117. Ideally the wing operations should be in a concrete building to afford a degree of protection from blast damage and/or fall-out.

Composition

3118. The wing operations room staff varies according to the situation, but the standard nucleus is always a room manned by one or two wing operations officers, and airmen or airwomen assistants who maintain the display boards and the wing operations log books. In peace or war, direct internal communications are necessary between the wing operations officers and:

a. *Air Traffic Control.* This is necessary to ensure that aircraft scrambling, or returning to base for refuelling and re-arming should not be hindered; diversion information can be quickly exchanged, and the SOC/CRC/ACC supplied with up-to-the-minute information on the airfield state (for example, whether a crash has blocked the runway, or blast damage would prevent aircraft taking off or landing).

b. *Airfield Meteorological Office.* Weather is an important factor in the recovery of aircraft although take-off is usually possible in any conditions other than very dense fog. The rate at which aircraft can be landed will depend upon the limitations of the approach aid equipment (*eg* GCA or ILS) and the weather pertaining at the time in terms of low cloud and/or poor visibility.

3119. Since, in the United Kingdom, the wing operations room would become the centre from which the station commander could be called upon, should all other communications be lost, to direct the conduct of the air battle for his station, certain other sections would become an integral part of the wing operations room to assist him in this task; these sections are:

a. The Radiological Monitoring Unit.

b. Logistics.

c. Wing Intelligence Officer.

3120. **Displays.** The main display in front of the wing operations officer is the aircraft state board. This shows the current state of preparedness of each aircraft which is serviceable for operations and, if the aircraft is on alert, what the crew has been pre-briefed to do. In addition, either in the wing operations room or in ATC an airfield state board is maintained showing the weather conditions and serviceability of possible diversion airfields. The airfield state is indicated by either coloured lights or discs and certain visibility and cloud base minima are used to establish a colour state as follows:

a. *Blue or White.* Airfield fully operational with no adverse weather conditions.

b. *Green, Yellow or Amber.* Airfield fully operational but cloud and/or visibility necessitates the use of an airfield or runway approach aid. (Amber indicates worse weather than Green.)

c. *Red.* Low cloud and/or poor visibility prevent aircraft from landing. Although an airfield is red, it will still normally be possible to take off in any conditions other than dense fog.

d. *Black.* Airfield unserviceable through strong crosswinds, snow or ice on the runway, or crashed aircraft on the runway or other major damage. The word "Black" if applicable will precede the actual colour code.

Fig 31–3 shows the current UK minima. One of the routine tasks of the wing operations room is to notify the SOC/CRC/ACC and any other airfield, for which it is acting as a diversion, of any change in state of its own airfield.

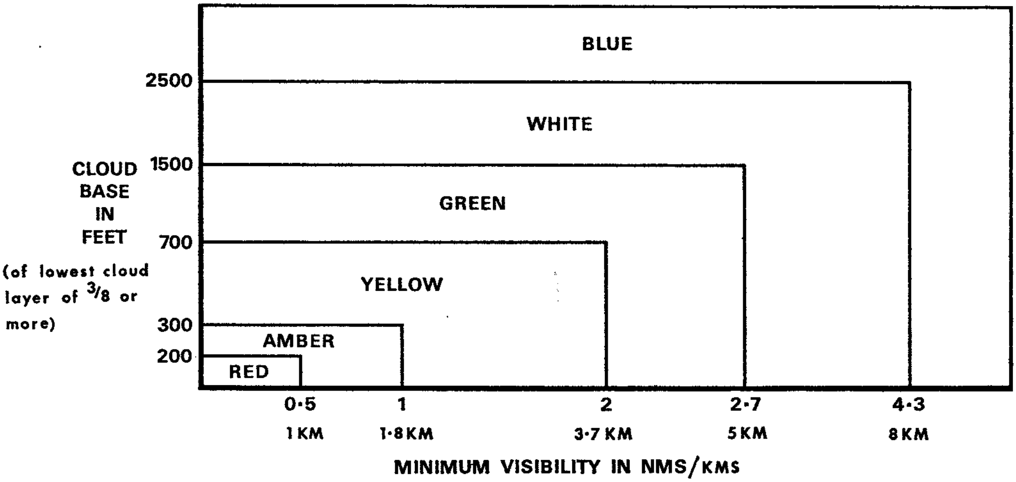


Fig 31–3 Airfield Colour State Visibility and Cloud Base Minimas

3121. **Communications.** The wing operations room has its own telephone keyboard with direct communications to the SOC/CRC/ACC each squadron on the airfield, ORP points, PBX, ATC, Meteorological Section, *etc.* This keyboard is often backed up with two-way intercommunication or tele-talk. There is also often a telebriefing monitor set which is used to monitor SOC/CRC/ACC to aircraft conversation and if necessary talk to either party.

Limited Role

3122. The wing operations room is essentially a control centre and has no administrative role; the latter is the concern of station or flying wing headquarters.

SQUADRON ACCOMMODATION

Facilities

3123. Each squadron needs suitable buildings at its site on the airfield to house air and ground crews on duty, and to store their equipment. As the modern fighter becomes more complex, so the ground equipment needed for servicing increases and this alone poses a storage or housing problem. The flying clothing of the aircrew needs special storage arrangements and checking and servicing facilities; on many airfields large annexes to hangars have been built solely to resolve this problem. Squadrons normally have their own operations room with direct communication to wing operations and also to their own ground personnel, so that immediately an aircraft becomes serviceable and ready for operations, wing operations (and the SOC/CRC) can be informed without delay.

Aircraft Standings

3124. Dispersal schemes are usually designed to allow aircraft to be parked in clutches for greater ease of operational and administrative control. The distance over which aircraft are dispersed varies with the land available and the threat of enemy air attack. Aircraft would normally operate either from the ASP or the ORP, but may also be dispersed on individual pans around the airfield, each pan possibly having blast walls to afford a degree of protection against air attack using conventional weapons.

3125. **Consequences of Wide Dispersal.** Where aircraft are parked on individual dispersal pans there are operational and administrative penalties that should be borne in mind, these are:

a. Should aircraft be scrambled from the dispersal pans, there will be a time penalty which is dependent upon the distance the aircraft has to taxi.

b. Unless individual dispersal points are equipped with underground storage tanks and refuelling facilities, extra time is needed for the high pressure refuelling bowsers to move from pan to pan.

c. Re-arming presents the same problem as refuelling. Once again, more time is needed to move from pan to pan with re-arming equipment and missiles, *etc*.

d. Refuelling and re-arming times are dependent upon the number of ground crew available.

e. More transport is needed to convey men and materials to and from the dispersals.

f. For efficient operation, communications are needed between dispersal pans and the squadron.

States of Preparedness

3126. Fighter aircraft are held at various states of preparedness to take-off; for example, the following states may be used:

a. Alert 2.

b. Alert 5.

c. Alert 10.

d. Alert 30.

e. Alert 60.

f. Turnround.

g. Released.

These states prescribe maximum times within which aircraft must be airborne once the order to scramble is given. To be Alert 2 means being able to become airborne within 2 minutes of the order to take-off, this requires the aircraft to be on the ORP with the crew strapped in the cockpit.

3127. The most relaxed state during wartime is "Released" until a specified time. At that specified time, the crew(s) would report to the squadron, find out which higher state they were required to meet and be briefed on the weather and general situation. When brought to Alert 60 (able to be airborne within 60 minutes from the order to take-off) they would probably change into their flying clothing and check their helmets, oxygen masks and RT on the rig provided. When detailed to a particular aircraft they would go out to it, and as far as possible at that stage, prepare it for take-off, returning to the crew room afterwards. As they were brought to progressively higher states of preparedness, so they would be given a more detailed briefing on their particular task.

3128. **Avoidance of Long Periods at High Alert States.** The highest states of preparedness require the crews to be strapped in the cockpit. Under the strain of nervous tension, and the possible discomfort of hot sunshine, it can become extremely exhausting to be at these high states for a long time. Quite apart from any consideration of the crew's welfare, it is clearly in the interests of the defence system that air crews enter combat as fresh as possible and are kept at high states of preparedness for no longer than is absolutely necessary.

Take-Off and Climb

3129. **Warming-Up of AI.** Most AI equipment takes from three to five minutes to warm up after it is switched on, and until then, it can give no information. To reduce this warm-up period, the Lightning uses an external power supply prior to take-off, and the Phantom has safety circuits which can be overridden for fast warm-up.

3130. **Night Familiarization.** It takes several minutes at night for a pilot's night vision to become fully adapted to the dark. In the immediate post take-off period the crew is busy settling down to instrument flight, setting-up radar and so on. During this early period of the flight it is therefore particularly important that the controller should give his directions clearly and calmly.

3131. **Unserviceability of AI.** Sometimes the AI operator can see that his AI is unserviceable before he ever attempts to acquire a target. With no video on the AI scopes at all, the usefulness of the aircraft is reduced, but it is still possible by accurate close controlling to position the fighter behind a target and within missile firing range. Under these conditions it is easier to see the target if it is contrailing, as these trails often show up well at night at high altitude.

Turnaround

3132. It will normally take longer at night to make a fighter aircraft ready for a further sortie after landing than it does in the daytime, purely because all the refuelling, re-arming and checking of the aircraft needs to be done in conditions of restricted lighting.

FIGHTER (GROUND ATTACK) (F(GA)) AND FIGHTER RECONNAISSANCE (FR) AIRCRAFT USED IN THE DAY FIGHTER ROLE

Before Take-Off and States of Preparedness

3133. States of preparedness for the Fighter (Ground Attack) and Fighter Reconnaissance aircraft when used in the Day Fighter role are usually the same as for all-weather fighter aircraft, *see* paras 3126 and 3127.

Take-Off and Climb

3134. When used in the air defence role, F(GA) and FR aircraft operate either singly or in pairs. As a pair they take-off and climb in formation: close formation is used in cloud, and open formation for better mutual protection and visual search when out of cloud.

Approach and Combat

3135. Ideally, these fighters should be close-controlled because their means of accurate navigation are limited, and they have to rely on visual sighting of the target. Visual sighting range at high altitude, discounting the assistance given by a target making contrails, is very variable, and whilst an average of about four miles might be expected, it could never be guaranteed. One of the main causes of range limitation is that, having to devote some of their attention to cockpit instruments, pilots tend to look for other aircraft without consciously re-focusing their eyes for distant vision. Other factors which affect sighting range are size, colour and aspect of the target, its position relative to the pilot and its position relative to the sun.

3136. **Use of Condensation Trails.** If the target aircraft is producing a persistent contrail, it enables the fighter to sight it a long way off. However, controllers should note that a pilot is apt to derive a vague or wrong impression of the heading of an aircraft from a distant view of its contrail, and the interception needs to be directed just as carefully after the trail has been sighted.

3137. **Height Differential** The armament of the F(GA) and FR aircraft in the air defence role is the 30-mm Aden gun, and to be effective this needs to be fired from relatively close range; in any case not farther away than 800 yards. To enable the fighter to close quickly with the target it is normally preferable for the fighter to have a height advantage which can either be used for manoeuvre or converted into speed, but one important factor that must be considered is the possibility of trim changes due to near-sonic speed making accurate firing of the guns difficult.

3138. **Target Wake.** With the requirement of close-range engagement for the effective use of the armament, the fighter attack may terminate in the stern cone of the target. Here the air is disturbed by jet wash and wing tip vortices of the target and the pilot may have considerable difficulty in aiming the fighter's guns accurately.

After Combat

3139. **Join-Up of Returning Fighters.** Even though fighters may have scrambled singly, when returning to base it is advantageous to join up with another fighter that is also returning. In this way, not only will aircraft afford each other a measure of mutual protection against possible attack, but the recovery problem will be eased by the two aircraft flying in formation becoming one speech unit.

3140. **Procedures and Restrictions.** In good or bad weather conditions there will probably be special procedures or control restrictions to be observed on the return to base, in order to avoid being attacked by other elements of their own air defence system (*eg* SAM); controllers guiding fighters home must therefore be aware of any such restrictions in force.

CHAPTER 32

INTERCEPTION TECHNIQUES

CONTENTS

BASIC INTERCEPTION TECHNIQUES

The Elements of Interception

3201. The main task of a fighter control organization is to intercept and recognize unidentified aircraft and to destroy hostile aircraft approaching the defended area with the fighters at its disposal. Such interceptions should possess the following elements:

a. Quickness.

b. Surprise.

c. Early sighting of the target.

d. Flexibility.

3202. **Quickness.** A fighter should approach its target by the most direct path consistent with the other interception elements to minimize the depth to which the target penetrates the defended area before interception.

3203. **Surprise.** The line of approach to a target which a fighter follows should give it the advantage of surprise and enable it to complete its attack successfully at the first attempt. The approach should allow the fighter to remain outside the cover of the target's interception warning radar for as long as posssible, and also take into consideration any tactical advantage to be gained from the position of the sun or moon. Further, if a fighter can avoid making contrails, a visual sighting by the target's aircrew will be delayed.

3204. **Early Sighting.** The approach path of a fighter is normally designed to give the earliest possible AI radar or visual sighting of the target, commensurate with surprise.

3205. **Flexibility.** The approach path of a fighter to its target should be planned so that the fighter can intercept its target in spite of any change of course which the target may make in the general direction of the defended area once the interception has started.

Basic Principles

3206. There is only one point at which a fighter can intercept a target for any given velocities. Referring to Fig 32–1 in which F and T are respectively the positions of a fighter and its target, X is the only point at which the fighter and target can intercept if the target follows the track TT and both aircraft maintain constant speeds and headings. X is known as the "collision point". FX is known as the "collision heading" and FXT as the "collision angle"; this should not be confused with the "angle-off" which is XFT.
Further:

$$\frac{FX}{TX} = \frac{\text{Fighter Groundspeed}}{\text{Target Groundspeed}}$$

If the velocities of both target and fighter remain constant, the angle-off XFT remains constant as they approach the collision point X and the line FT is known as the *line of constant bearing.* (*See* Fig 32–2). If however the fighter is not heading towards the collision point, the angle-off will increase (fighter going ahead of collision point) or decrease (fighter going behind collision point) and FT is not a line of constant bearing. Frequent measurement of the angle-off provides the most important indication of the progress of an interception.

The Phases of an Interception

3207. For both manual and computer assisted interception control purposes each interception is broken down into certain phases (illustrated in Fig 32–3) as defined in the following paragraphs.

3208. **Scramble Phase.** The scramble phase is the period from the initial allocation of the interceptor to a target until it is airborne and has completed its initial turn onto the outbound heading. This scramble phase does not apply to fighters already airborne or on CAP.

3209. **Climb Phase.** The climb phase starts after the scramble phase and consists of a climb on the outbound heading to the required cruise altitude. For aircraft on CAP or already airborne this phase may be either a climb or a descent.

3210. **Mid-Course Phase.** The mid-course phase consists of the outbound cruise to the target. Command instructions involving changes in heading, cruise altitude and cruise speeds may be given in this phase.

3211. **Transition Phase.** The transition phase covers the period from the end of the outbound cruise to the time when a position is reached in space, defined in three dimensions relative to the target, from which the combat phase can

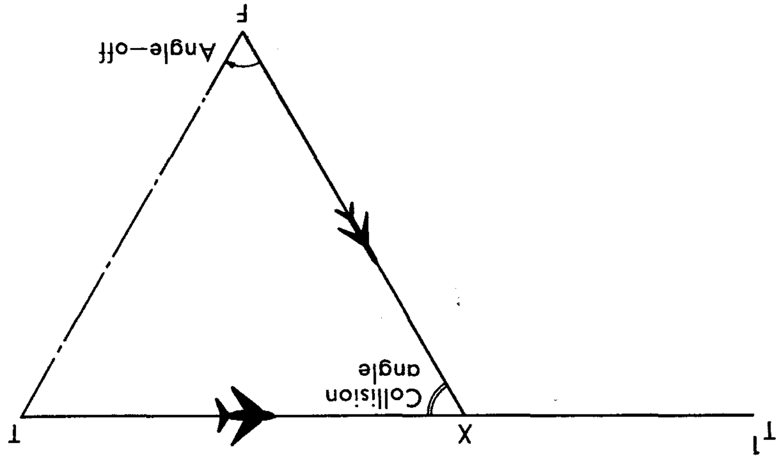


Fig 32–1 The Basic Interception Problem

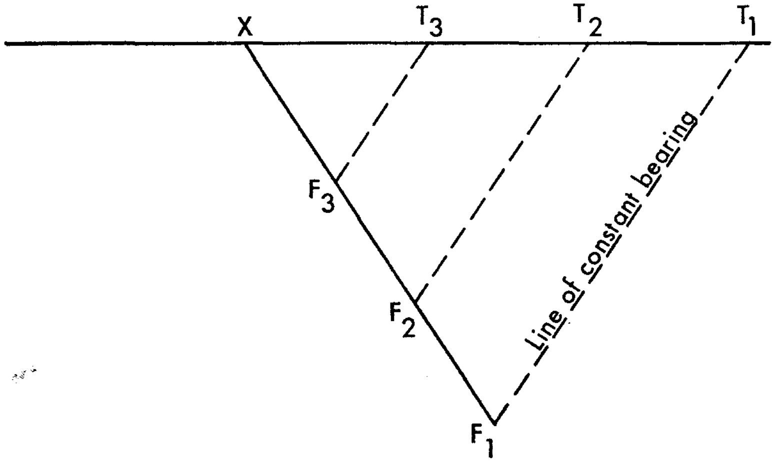


Fig 32–2 Lines of Constant Bearing

begin. This position is called the "offset point". In the transition phase the speed, altitude, and heading of the interceptor are adjusted so that the required values are reached at the offset point ready for the start of the combat phase.

3212. **Combat Phase.** The combat phase commences at the offset point and terminates at "breakaway" after completion of the attack. During this phase the fighter will be controlled entirely by the pilot obeying AI steering demands or by making a manual attack, either visually or by AI scope interpretation. The pilot may, however, take control of the interception at a point prior to the offset in certain interceptions.

3213. **Re-Attack Phase.** If the interceptor fails to complete the initial attack the ground control system may pass command instructions to place the fighter into a new position from which a re-attack may be made. The period between breakaway after the initial attack

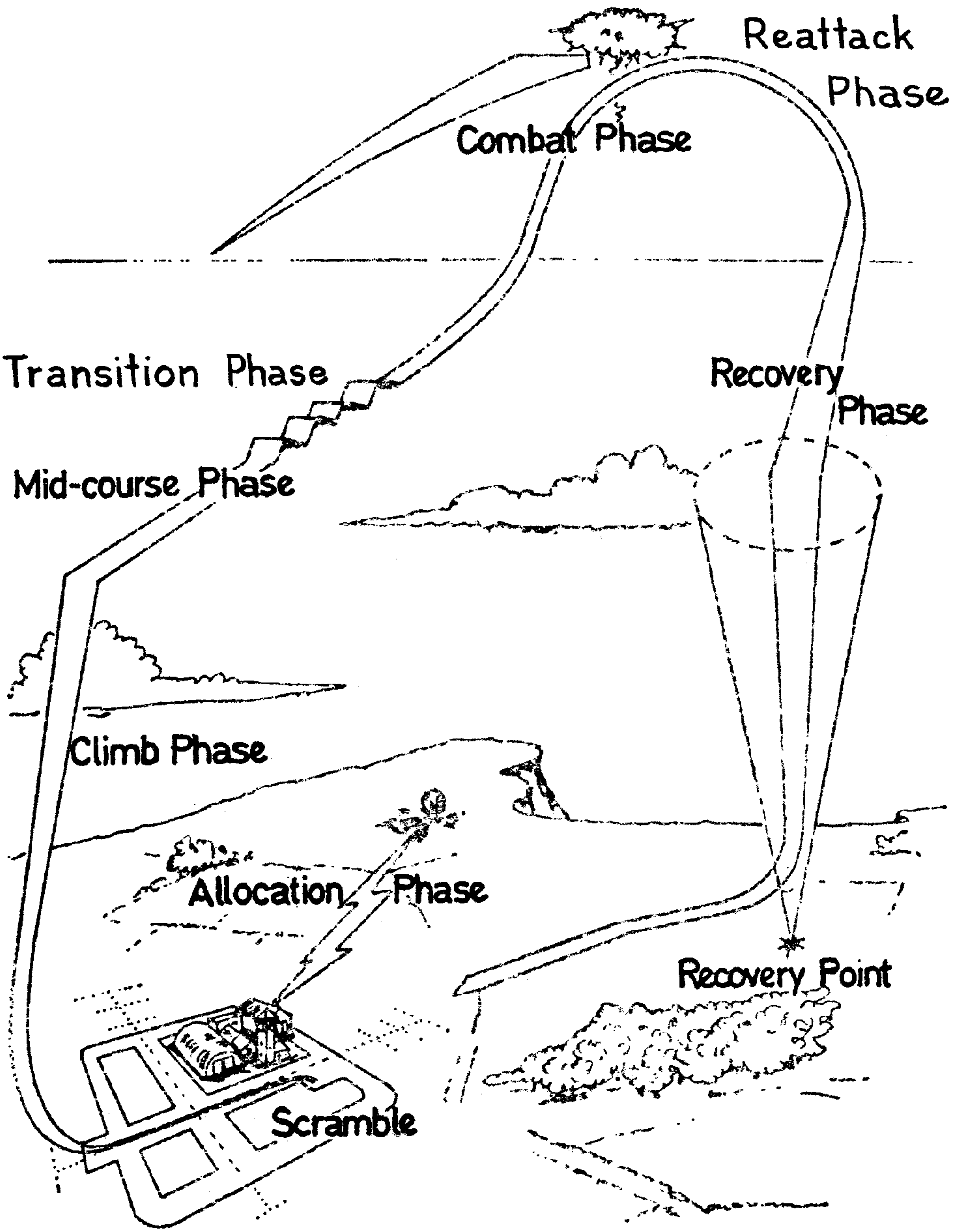


Fig 32–3 Interception Phases

and breakaway on the second attack is the re-attack phase.

3214. **Recovery Phase.** At the end of the combat phase (or re-attack phase if used) the pilot breaks away to recover at the optimum height and speed for range. The ground control system gives command instructions to bring the interceptor to a specified recovery point on a prescribed heading.

3215. As the scramble, climb, and mid-course phases lead in to the required form of transition phase, and the transition phase needed is in turn determined by the attack option available in the combat phase, it is convenient to discuss the phases in reverse sequence.

3216. **The Combat Phase.** The combat phase consists of the final tracking of the target by the fighter, the manoeuvring of the fighter into its weapon release position, and the breakaway after weapon launch. The form that the combat phase takes is largely determined by the type of weapons which the fighter is using, and will fall into one of the following four basic attack options:

a. *Rear Hemisphere.* In a rear hemisphere attack the fighter's weapons are launched from within the rear hemisphere of the target, generally within a cone of about 30° semi-angle from the target's tail. This form of attack is normally used with machine-guns and types of air-to-air missiles which have no forward hemisphere attack capability, and for visual identification (visident) interrogatory interceptions. Automatic machine-gun fire is generally used between 200 and 800 yards from the target, but missiles may be launched in a wide range bracket depending on the weapon in use and the launch conditions.

b. *Front Hemisphere.* Front hemisphere attacks are generally made while the fighter is flying on a reciprocal heading to the target with little or no lateral separation. This form of attack allows the minimum target penetration penalty, but can only be used with certain weapons systems which have an effective forward hemisphere capability. The high closing speeds inherent in this type of attack severely limit the time available for sighting and tracking the target and adjusting the fighter's heading. The fighter must break away from the target at a distance ahead of the target which increases proportionately with the fighter/target closing speed.

c. *Beam.* In a beam attack the fighter's weapons are launched or fired from the beam of the target, and at the time of release are generally aimed ahead so that the weapons are on a collision course with the target after release. This type of attack requires the launch conditions to be very accurately calculated but the use of computers and missiles with an all-round capability now make the beam attack a practical possibility. This form of attack permits slightly greater target penetration than a front hemisphere attack, has the advantage of being suitable for use against target flying at any speed, and of offering pilots a better chance to correct approach errors. It is also preferable to a stern attack because it reduces target penetration and, by avoiding the target's tail warning radar (if fitted) increases the probability of surprising the target.

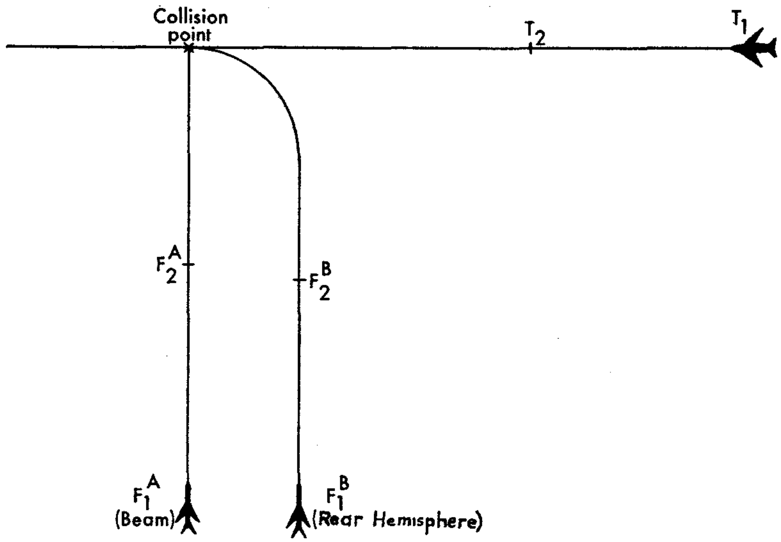
d. *Cut-off.* In a cut-off attack the fighter is kept on a collision course with the target until a suitable position is reached for releasing the fighter's weapon or, in the ultimate case, collision is achieved.

The armament of current fighters and the type of combat phase which their weapons systems require are discussed in Chap 26, and SD 727 Chap 10.

3217. **The Transition Phase.**

a. *Transition Phase Leading to a Rear Hemisphere Attack.* The transition phase leading to a rear hemisphere attack is not generally made from the astern position of the target because fighters normally intercept targets approaching the defended area by the most direct path, which is usually from ahead of the target. Moreover if the fighter's speed advantage is small it will take a long time for the fighter to come within weapon release range and surprise is likely to be lost. A 90° final approach to a rear hemisphere attack is therefore used whenever possible because:

(1) The turn in to the attack does not demand such critically fine judgement as is needed for the successful transition to the combat phase from approaches using a collision angle of more than 90°.



32–4 Transition Phases leading to Beam and Rear Hemisphere Attacks

(2) The interception is completed more quickly than by an approach from astern.

(3) The approach is more likely to achieve surprise.

(4) The target remains on approximately the same bearing relative to the fighter; the bearing only changes appreciably during the last few miles of the approach.

(5) The fighter is in level steady flight until the final turn with the target converging at a readily assessable rate which facilitates the sighting or detection of the target on the fighter's AI.

(6) Errors in the fighter's path of approach are easily corrected to ensure that the best position is reached from which to enter the combat phase.

b. *Transition Phase Leading to a Beam or Cut-Off Attack.* The transition phase leading to a beam or cut-off attack is similar to that leading to a rear hemisphere attack, except that the fighter is aligned to fly towards, or slightly ahead of, the collision point rather than behind it, as in the rear hemisphere case (*see* Fig 32–4). This type of transition phase requires greater accuracy and has less flexibility than that for the transition phase leading to a rear hemisphere attack.

c. *Transition Phase Leading to a Front Hemisphere Attack.* The combined closing speed of fighter and target during a head-on attack is so high that the fighter must be correctly aligned on a suitable heading for the target during the transition phase. Failure to attack successfully may place the fighter in a position from which he may be unable to recover and launch a second attack before the target has reached its weapon release point. Another disadvantage of this type of attack is that the fighter is unlikely to be able to confirm the identity of the target before weapon launch.

3218. **Duration of the Transition Phase.** The duration of the transition phase should be as brief as possible to reduce target penetration of the defended area, and should therefore be just long enough to:

a. Allow the fighter to reach the correct speed and height, and be on the correct heading, for the start of the combat phase.

b. Allow the fighter to sight and assess the target visually or on AI radar.

c. Allow the controller to correct any positioning error which may have been caused by:

(1) Misjudgements in planning or execution of the earlier phases of the interception.

(2) Unpredictable variations in the fighter's rate of turn or its pilot's speed of reaction to control instructions.

(3) Inaccuracies of radar data or inaccurate interception computer programming.

3219. **The Climb and Mid-Course Phases.** The climb phase starts after the fighter has completed its turn onto the outbound heading. The climb may be carried out by the fighter in several different ways according to the requirements imposed by the geometry of the interception. The most common types of climb are a maximum cold power climb, or a maximum re-heat power climb. The midcourse phase is a cruise outbound from the end of the climb phase until the start of the transition phase, and may consist of an acceleration or deceleration at the top of the climb, a cruise at a specified speed, and adjustments to the fighter's heading as required. The cruise speed and height are selected to provide the tactics required *eg* shortest time to interception (or least target penetration) would require highest cruise speed and height; least expenditure of fighter fuel would require the most economical cruise height and speed.

3220. **The Scramble Phase.** The scramble phase is the period between the allocation of the fighter (which may be on the ground or on combat air patrol (CAP)) to a target until the completion of the local air traffic control procedures after the fighter is airborne.

Interception Categories

3221. The phases of an interception which are of prime concern to an interception controller are the mid-course and transition phases. If these two phases alone are considered, and viewed in the horizontal plane only, the geometry of the interception can be categorized according to the angle between the headings of the fighter and target (*see* Fig 32-5).

3222. **Category A Interception.** Category A interceptions are those where the initial angle between heading of the fighter and target is between 120° and 180°. This type of interception is the one most likely to be encountered in air defence operations and has the advantages of minimum target penetration and minimum time to interception. However, if the interception is to terminate in a rear hemishpere or beam attack final turns must be judged accurately, and it is therefore a difficult intercept to control manually. Category A interceptions include both direct head-on intercepts and displaced parallel head-on (DPHO) intercepts. The DPHO approach can allow a crossing leg prior to the combat phase to overcome any errors, but his crossing leg should be of the minimum duration necessary or greater target penetration will result. Therefore a 180°

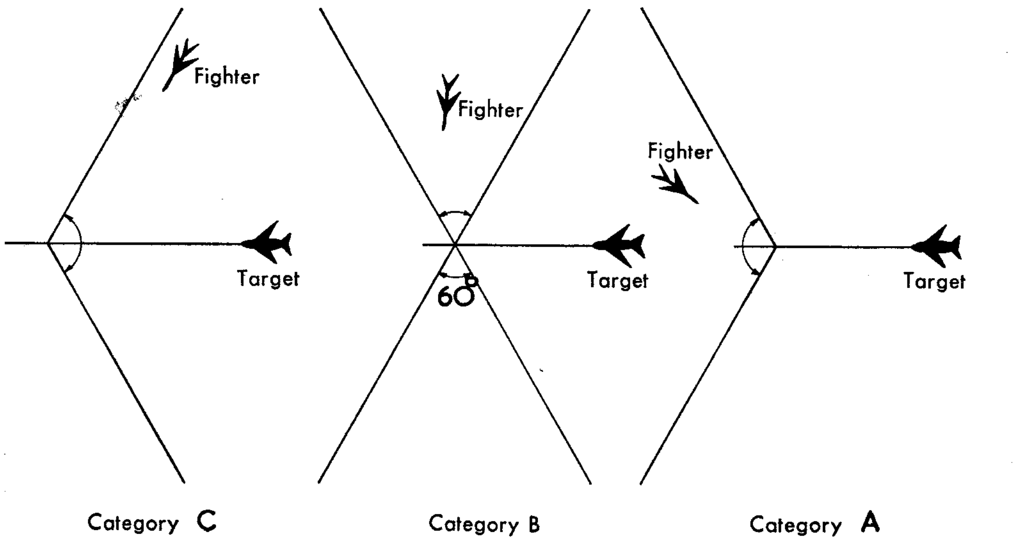


Fig 32–5 Interception Categories

displaced 8 nms to 10 nms is suitable for subsonic intercepts whilst a 180° displaced 10 nms to 14 nms is preferable for supersonic intercepts.

3223. **Category B Interception.** A category B interception is made when the angle between the headings of the fighter and target is between 60° and 120°. Category B interceptions have the following advantages:

a. The intercept is completed quickly.

b. The target bearing changes at a steady and predictable rate.

c. The AI presentation is easily interpreted and the target track can be quickly assessed by the fighter pilot.

d. The target should be detected at maximum AI range.

e. The controller can assess the progress of the intercept easily and can correct errors by small changes in fighter heading.

3224. **Category C Interception.** A category C interception occurs when the angle between fighter and target headings is between 0° and 60° at the start of the mid course phase. This type of intercept is used only when imposed on the controller by a late scramble of the fighter, target evasion, fighter positioning error, or late allocation. In these circumstances the fighter is presented with a chase from the start of the intercept and the following disadvantages result:

a. More fuel is used by the fighter, particularly if the fighters speed advantage is low and leads to a prolonged tail chase.

b. Target penetration is deeper.

c. There is no element of surprise.

d. The fighter is in the cone of fire of the target radar laid weapons (if fitted) for a considerable period of time.

INTERCEPTION PROFILES

The Head-on Approach (Category A)

3225. The most efficient method of intercepting an enemy aircraft which approaches a defended area is by using a head-on interception profile with no lateral displacement. Ideally the combat phase should be concluded from a dead ahead position with the launch of a missile having a front hemisphere capability. This type of attack is termed a lead collision attack.

3226. However it is frequently necessary to use beam (final turn lead collision) or rear hemisphere (final turn lead pursuit) attack options. Use of a rear hemisphere attack option with no lateral displacement requires a roll out behind the target aircraft, and ending a head-on approach by this form of attack concedes a target penetration. The extent of this penetration is equal to the distance the target has travelled in the time taken by the fighter to turn through 220° onto a converging heading; to close the lateral displacement, and finally to turn through 40° on to the target heading. The assessment of the fighter turn position is critical in this type of interception and may need to be judged by the controller between sweeps of the timebase on the plan position indicator (PPI). This type of interception has the following disadvantages and is seldom used operationally from choice, and is therefore not programmed for use in automatic data processing control systems:

a. The turning point for the fighter is critical.

b. There is no chance of correcting errors.

c. Day fighter pilots are presented with a head-on aspect of the target and poor sighting ranges are likely to result.

d. The fighter pilot will lose the target (visually or on AI) while turning away from the target.

e. The fighter is placed at a great disadvantage if the target evades while the fighter is turning.

f. There is very little time available to the fighter pilot/navigator for assessment of the AI presentation.

g. The range at which the turn needs to be initiated is likely to be greater than a day fighter pilot's visual capability and the controller must therefore generally instruct the pilot when to turn. The same considerations apply to an all-weather fighter with limited AI capability.

3227. The fighter must complete a turn of about 220° in order to arrive on a converging heading of 40° from the target's track. For a large proportion of this turn both day and all-weather fighters would be unable to "see" the target. Assuming a target speed of 0·85M, and a fighter speed of 0·95M, it will take the fighter about 1 min 50 sec (*ie* about 2½ times the period taken for the fighter to turn through 90° at 45° angle of bank). In this time the target will have travelled about 13·5 nm. At the completion of the fighter turn the target will be at about 45° off to the right and about 6 nm on the fighter's beam. The fighter must then close the lateral displacement prior to another 40° turn in behind the target at about 2 nm astern. The interception may be simply calculated as follows:

Time taken by the fighter:

2 × 90° turns	1 min 30 sec
Additional 40° turn ...	20 sec
Convergence	1 min
Turn through 40° to in behind position	20 sec
Total ...	3 min 10 sec

In 3 min 10 sec the target will have travelled about 26 nm. If the target is now back-tracked the fighter-to-target range at the start of the fighter turn equals 11 nm. It should be noted that these figures are approximate and apply to a 0·95M fighter and a 0·85M target only; similar calcuations for other parameters can be made in the same way.

The Parallel Displaced Head-On Approach (Category A)

3228. The parallel displaced head-on interception is also termed a final turn lead pursuit (FTLP) attack, and has two forms; the single turn to offset, and the double turn to offset. In the single turn to offset attack the turn through 180° onto the target's heading is accomplished in a single turn; in the double turn to offset attack the turn is split into two 90° turns separated by a crossing leg at 90° to the target's heading of (usually) 30 seconds duration.

3229. **Final Turn Lead Pursuit (FTLP) Single Turn to Offset.** In the FTLP single turn to offset attack the fighter is laterally displaced from the target's track by a distance equal to twice the radius of turn of the fighter (*see* Fig 32–6). It allows the fighter pilot or navigator to get an AI contact before the turn is started, and the day fighter pilot the chance of a sighting on the turn. This type of interception concedes little target penetration as the fighter is displaced only by sufficient distance to turn through 180° to a position in behind the target at weapon firing or launch range. In Fig 32–6 the fighter is on a heading parallel and reciprocal to that of the target but displaced laterally by 8 nm. The 180° turn onto the target's heading is started at a longitudinal range of 11 nm and a direct range of 13 nm, when the target will be at about 40° to the fighter's heading. The longitudinal distance is calculated as the distance travelled to turn through two 90° turns, *ie* 1 min 30 sec—12·75 nm. But the fighter is required to complete the turn two miles behind the target, so the longitudinal distance = 12·75 − 2 = 10·75 or say 11 nm. Similar calculations can easily be made for other target and fighter speeds.

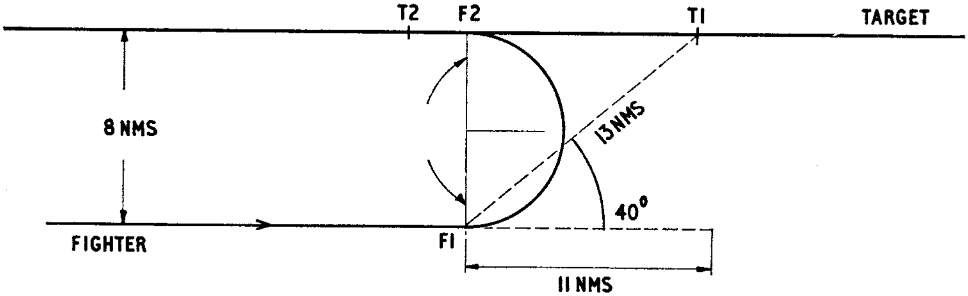


Fig 32–6 FTLP Interception With Single Turn to Offset

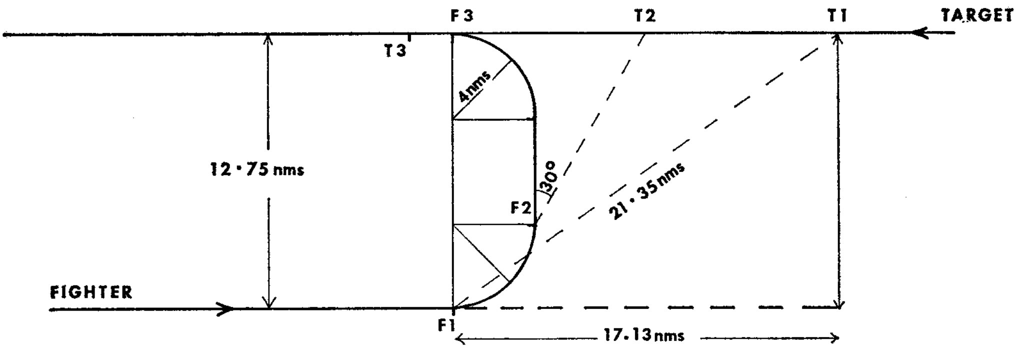


Fig 32–7 Parallel Displaced Head-on (FTLP) Interception With Double Turn to Offset

Final Turn Lead Pursuit (FTLP) Double Turn to Offset

3230. In the FTLP double turn to offset the fighter is laterally displaced from the target's track by a distance equal to twice the radius of turn of the fighter, plus the distance covered by the fighter on the crossing leg, which is normally of 30 seconds duration. The crossing leg at 90° to the target's track allows the pilot/navigator to assess the target and make any adjustments necessary. The method of correction for subsonic targets would be to turn 30° in the direction of the error, and for supersonic to turn twice the error in the direction of the error. In supersonic interceptions it may not allow the fighter time to resume the 90° crossing leg heading after adjustments have been made to ensure correct positioning. Fig 32–6 shows a 30 second displaced interception and the longitudinal fighter/target distance at start of the first 90° turn is calculated as follows:

Time for fighter to turn through 90° × 2	=	1 min 45 sec
30 second crossing leg	=	30 sec
Total	=	2 min 15 sec
2 minutes 15 seconds at target speed (0·85M)	=	19·13 nms
Less roll out distance	=	2 nms
Longitudinal range at start of first 90° turn	=	17·13 nms

Whilst the crossing leg can be used to correct errors, the time available is so short that such corrections must be made immediately the need is noticed, so that the action can be taken before the final 90° turn in behind the target.

The 150° and 120° Approaches (Category A)

3231. The interceptions described in paras 3228 to 3230 are operationally the optimum type of rear hemisphere attacks and are therefore programmed for use in automatic data handling control systems. However, an approach to the initial turning point on a reciprocal heading to that of the target may not always be possible. The controller is likely to be presented with a target at comparatively short range at an arbitrary attack angle dictated by the proximity of the target. This type of interception is likely to impose an initial attack angle between headings in the region of 150° or possibly 120°.

3232. **The 120° Approach** (*see* Fig 32–8). The 120° interception enables an all-weather fighter to detect a target at long range with the AI radar searching in an arc of less than 30° in the horizontal plane. The fighter is directed at a collision angle of 120° to a position from which it starts a final 120° turn onto the target's heading, and during the turn the target should remain almost in the dead ahead position. The angle-off should not exceed 30° in at 120° interception. Errors in the interception can be corrected by adjusting the final 120° turn without losing too many advantages. If the fighter is running ahead of the target, the final turn is delayed and the fighter turns through more than 120°, finally closing with the target from the other side (*see* Fig 32–9). Alternatively, if the fighter is running late, the interception may be converted into a 90° approach by turning the fighter at the appropriate moment onto a 90° collision course (*see* Fig 32–10).

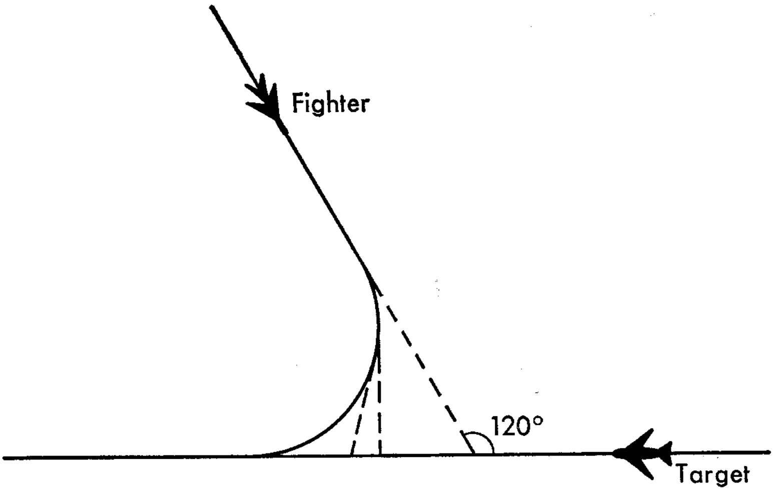


Fig 32–8 The 120° Approach

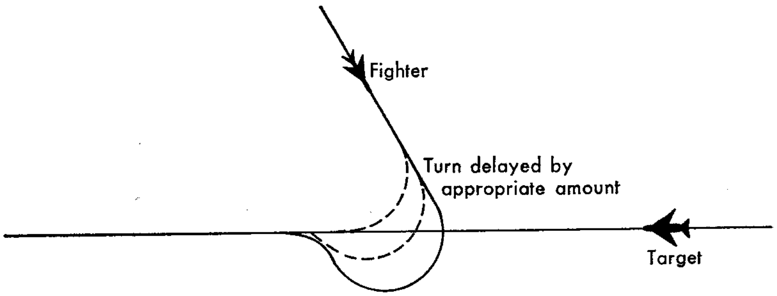


Fig 32–9 120° Approach Adjustment—Fighter Running Ahead of the Target

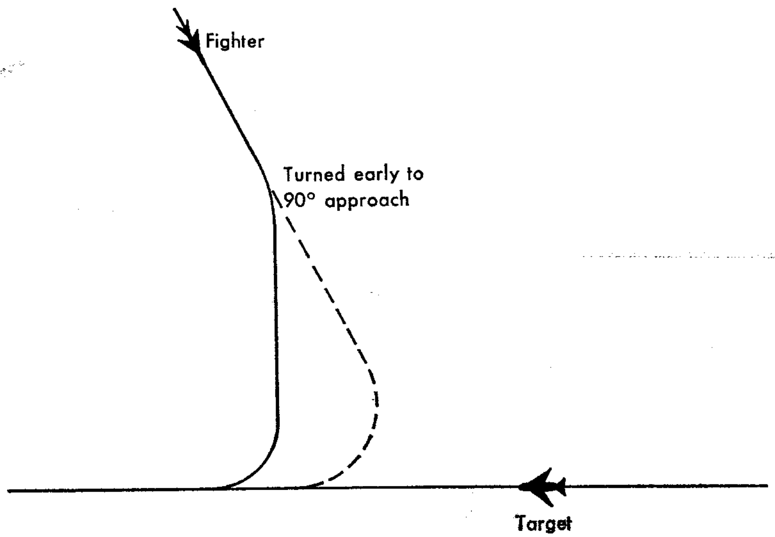


Fig 32–10 120° Approach Adjustment—Fighter Running Behind the Target

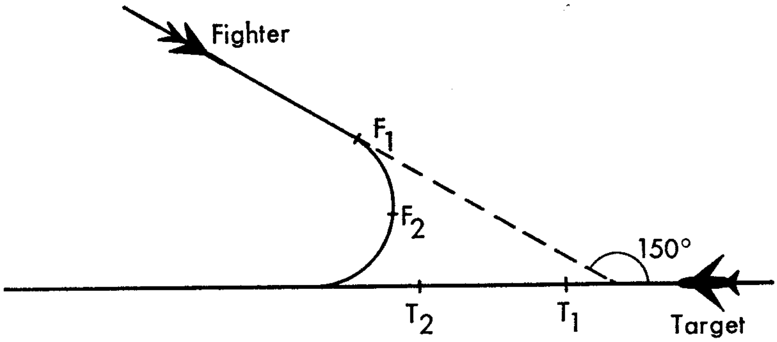


Fig 32–11 The 150° Approach

3233. **The 150° Approach.** The 150° interception is similar to the 120° approach described in para 3232 and uses the more obtuse angle of 150° to confine the target to an even smaller arc of angle-off from the fighter (*see* Fig 32–11). Because of the more obtuse angle, the start of the final turn is delayed until after the target has crossed ahead of the fighter.

The 90° (Beam) Approach

3234. The basic approach for a Category B interception is with an angle between headings of 90°. The fighter is directed on a collision course of 90° towards the collision point for a beam attack option, or astern of the collision point for a rear hemisphere attack option.

3235. **90° Approach to a Beam Attack Option.** If the fighter is being correctly directed for a beam attack option the target should remain at a constant bearing relative to the fighter until the attack point is reached. A high degree of accuracy is required if this approach is to culminate in a successful beam attack. If the fighter is not correctly aimed at the collision point, the angle-off of the target relative to the fighter will:

a. Decrease at a gradually increasing rate if the fighter is aimed astern of the collision point.

b. Increase at a gradually increasing rate if the fighter is aimed ahead of the collision point.

When the angle-off is seen to be changing the

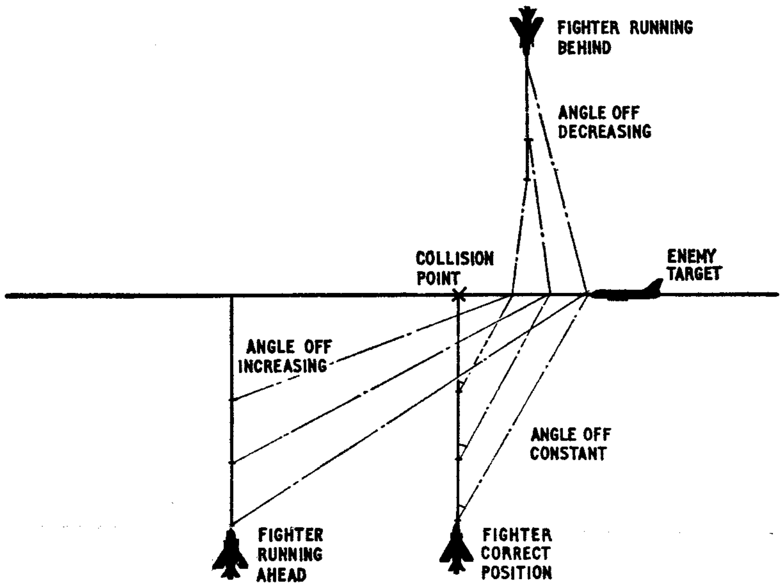


Fig 32–12 Significance of Angles Off on the 90° Approach to a Collision Point

fighter should be directed onto the correct line of approach to the collision point (*see* Fig 32–12) and the profile adjusted accordingly.

3236. **90° Approach to a Rear Hemisphere Attack Option.** When a fighter makes a rear hemisphere attack from a 90° approach, it should be directed to a point astern of the collision point to allow for its final turn in behind the target. The target should therefore cross ahead of the fighter if the fighter were to remain on the course at 90° to the target's. The distance at which the target would cross ahead of the fighter is used as a reference in describing interceptions, rather than using the distance behind the collision points along the target's track. The crossing ahead range of a target for a particular interception depends on:

a. The relative speeds of fighter and target.

b. The distance behind the target from which the fighter requires to launch or fire the weapons carried.

c. The fighter's radius of turn.

When the fighter is correctly aligned, the angle-off of the target should steadily reduce. If the target remains at a constant bearing to the fighter, or if the angle-off increases, the fighter will be running ahead of the target and should be manoeuvred to a new line of approach in a similar manner to that for the 90° approach to a beam attack option. The cross ahead range and the turning point will now require to be recalculated. If, however, there is not enough time to complete this manoeuvre, the fighter's final turn should be delayed until the target is immediately ahead of the fighter, when the fighter should be turned through about 120° in the direction of the target's heading, and the final approach made from the other side (*see* Fig 32–13). If the target appears to be passing too far ahead of the fighter and there is insufficient time to manoeuvre the fighter onto the correct approach path, the interception should be completed by using a Category C collision angle (*ie* less than 60°) or alternatively the fighter directed to make an extended final turn on to the target's heading (*see* Fig 32–14).

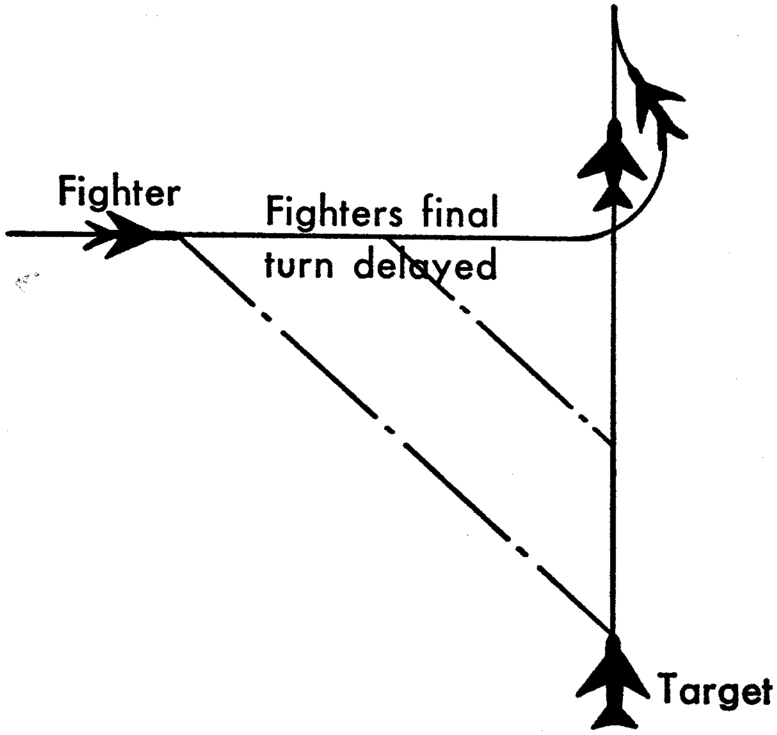


Fig 32–13 Adjustment to a 90° Approach to a Rear Hemisphere Attack Option

(AL 8, Jan 76)

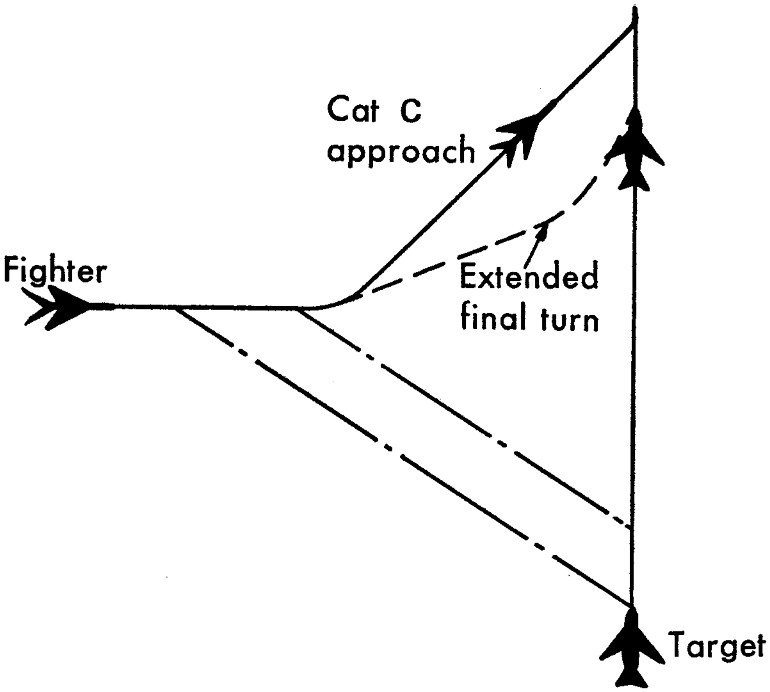


Fig 32–14 Fighter Running Late on a 90° Approach to a Rear Hemisphere Attack Option

Supersonic Interceptions

3237. Modern potential enemy aircraft are capable of carrying out at least part of their attack profile at supersonic speed. In order to intercept such targets it is necessary to ensure that the fighters available, and their weapons, are used to optimum effect. The most effective use of the fighter and its weapons depends, except in the combat phase, on ground control, and it is therefore important for controllers to understand the factors which particularly affect supersonic interceptions. These factors are:

a. The high fuel consumption of fighters at supersonic speeds.

b. The need to allow time for the fighter to accelerate to supersonic speed.

c. The effect of altitude on range and endurance.

d. The limitations on attack options imposed by the type of weapons system carried by the fighter.

3238. The many variables involved in calculating the optimum interception profile for a specific supersonic interception mission make computer control essential. However manual control of supersonic interceptions is likely to be required for some years, and even after the introduction of automatic systems it is still desirable that a controller should fully understand the problems involved.

3239. **Fuel Consumption.** The extra power normally required for a fighter to fly at supersonic speed is obtained by using an engine reheat system. Reheat is used to augment engine thrust by injecting fuel into the jet pipe and burning the fuel in the unconsumed portion of the air passed through the engine. Combustion of the injected fuel raises the temperature and efflux velocity of the exhaust gas and therefore increases the thrust. Fuel consumption with reheat in operation is extremely high, especially at medium and low altitudes. It can be seen that as much as five times the amount of fuel is required to sustain flight at 1·6M than at 0·9M (*see* Fig. 32–15). As supersonic flight results in such high fuel consumption a fighter normally cruises at high subsonic speed at its most economical altitude (normally near the tropopause) and acceleration to supersonic speed is delayed until the last moment which is tactically acceptable.

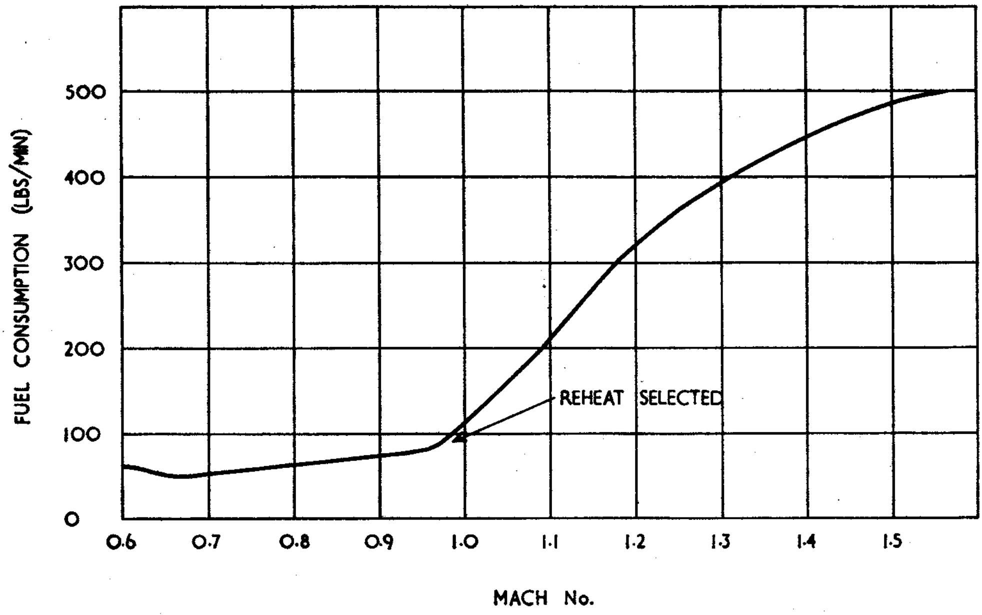


Fig 32–15 Typical Fuel Consumption at Increasing Mach Numbers

3240. **Time and Distance to Accelerate to Supersonic Speed.** It takes a fighter a certain time to accelerate from cruising speed to supersonic speed, and as the total time involved in the whole interception is small, the acceleration time is very significant. During the time taken for acceleration the fighter covers a considerable distance which is also significant in planning supersonic interceptions. Typical acceleration times and distances are shown in the following table:

Serial No	Final Speed from 0·83M (M)	Time Taken (sec)	Distance (nm)
(a)	(b)	(c)	(d)
1	1·0	24	4
2	1·2	84	14
3	1·4	150	27
4	1·6	195	39
5	1·8	250	52

3241. **The Effect of Altitude on Range and Endurance.** For each fighter there is an optimum altitude for range and endurance. Because fuel consumption is so high in supersonic interceptions it is important that the cruise phase of the interception is carried out at the optimum fuel consumption altitude, which is generally in the region of the tropopause. However, it may be advantageous to cruise at a slightly lower height than the optimum in order to achieve tactical surprise by avoiding contrail heights. A climb or descent to attack altitude is therefore normally required in the transition phase of the interception.

3242. **Limitations on Attack Options.** Many modern fighters can be armed with a variety of air-to-air weapons systems. Those currently in use are described briefly in Chap 26 and SD 727 Chap 10. Each weapon system has different characteristics which permit the fighter to attack a target from certain positions only, or from certain optimum positions from whence the kill probability of the system is highest. The weapons systems therefore dictate the attack options available to the fighter, and thus the parameters of the offset point and hence the transition phase parameters. In manually controlled supersonic interceptions it is therefore important for the controller to have a good understanding of the attack option required by the fighter's weapon system against the particular target to be intercepted.

3243. **Typical Supersonic Interception Profile.** Supersonic interceptions may be carried out using any of the mid-course and transition phases described. However, the approach most commonly used for manually controlled supersonic interceptions is the final turn lead pursuit (FTLP) double turn to offset, with a crossing leg of 30 seconds. Normally the aim is for the fighter to arrive at the attack point with an overtake speed over the target of 0·2M. The fighter is directed to accelerate early enough for it to achieve the attack speed before the final turn onto the target's heading. The timing of the fighter's final climb from the cruise altitude to attack height is left to the pilot. The fighters engine performance is normally at the optimum in the region of the tropopause. However, because this is often the contrail level accelerations are normally carried out well below the tropopause. Energy is gained during the acceleration and can be exchanged for height by a "zoom climb". The zoom climb does not rely on aerodynamic lift from the wings (which may be negligible) but follows the pattern of a car accelerating on a level road and using the kinetic energy gained to climb a hill. A typical supersonic interception profile is illustrated in Fig 32–16. It should be noted that by reducing the length of the fighter's supersonic flight to a minimum increases the target penetration. If target penetration of of paramount importance, a supersonic cruise phase should be employed and the resultant profile is termed a dash profile.

The Calculation of Interception Profiles

3244. It is useful for controllers to be aware of the elementary calculations involved in determining the turning points required for the most common approaches used in manually controlled interceptions. The following examples illustrate the method of calculation:

a. *Example* 1. The problem is to calculate the relative position of a target to a fighter when the fighter starts its turn onto the 90° crossing leg of a displaced parallel head-on

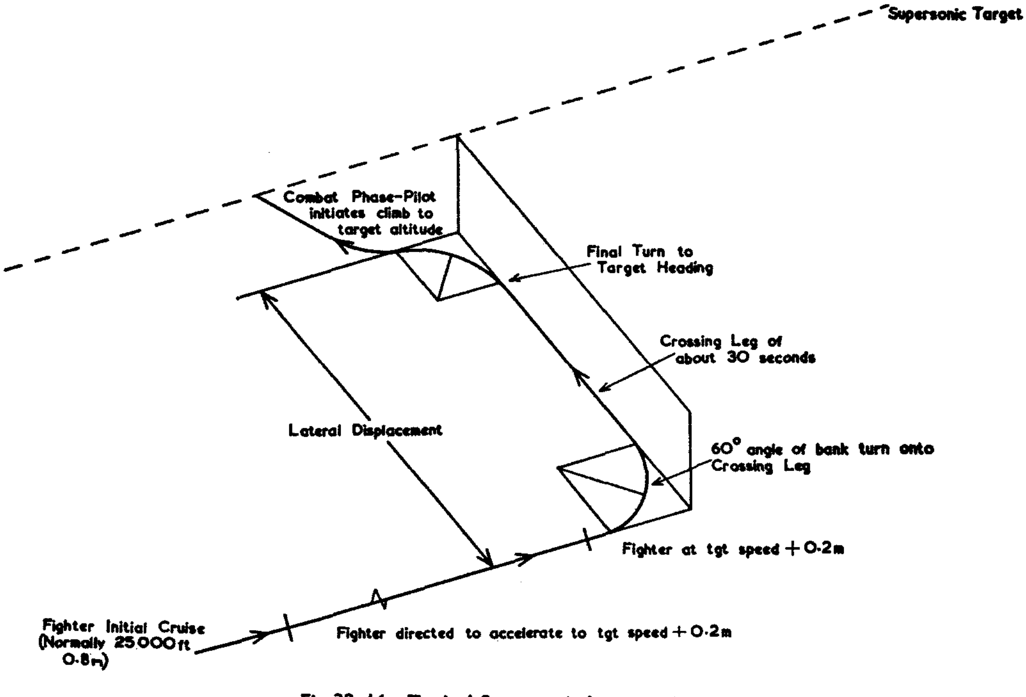


Fig 32–16 Typical Supersonic Interception

approach in which the fighter flies a steady 90° crossing leg to the target for 30 seconds. The following data is necessary before the problem can be solved:

(1) The fighter's roll out distance behind the target (assumed to be 2 nm).

(2) The fighter and target speeds (assumed to be 0·95M and 0·85M respectively) at the tropopause (where the speed of sound is assumed to be 570 kts).

(3) The fighter's turning radius at the altitude and speed given (assumed to be 4 nm).

The calculation is as follows (referring to Fig 32–17).

The fighter is at X when the target is at Y

$\therefore$ XY = 2 nm

The fighter is required to fly at 90° to the target's heading for 30 seconds (ST). Distance in nm = Speed in knots × Time in hrs. Fighter's speed = 570 × 0·95 knots.

$$\therefore ST = (570 \times 0{\cdot}95) \times \frac{1}{120} \text{ nm}$$

$$= 4{\cdot}5 \text{ nm}$$

The fighter's radius of turn = 4 nm

$\therefore$ RS and TU are both 4 nm long.

$$RU \text{ (the displacement)} = RS + ST + TU \text{ nm} = 4 + 4{\cdot}5 + 4 \text{ nm} = 12{\cdot}5 \text{ nm}$$

The curves QS and TX are each $\frac{2\pi R}{4}$ nm in length, where R = 4

$$\therefore QS = \frac{2\pi \times 4}{4.} = 2\pi \text{nm}$$

The distance the fighter travels between Q and X

$$= QS + ST + TX = 2\pi + 4{\cdot}5 + 2\pi = 4\pi + 4{\cdot}5 = 12{\cdot}6 + 4{\cdot}5 = 17{\cdot}1 \text{ nm}$$

While the fighter flies from Q to X the target flies from A to Y

$$\therefore AY = 17{\cdot}1 = \frac{85}{95} = 15{\cdot}3 \text{ nm}$$

$$\therefore AX = 15{\cdot}3 - 2 \text{ nm} = 13{\cdot}3 \text{ nm}$$

Considering the triangle XQA:

XQ = 12·5 nm
AX = 13·3 nm

$$\therefore \text{Tan } XAQ = \frac{12{\cdot}5}{13{\cdot}3} = {\cdot}94$$

$\therefore$ XAQ = 43°

But XAQ = AQR, because QR is parallel to XA and AQR is the angle off of the target

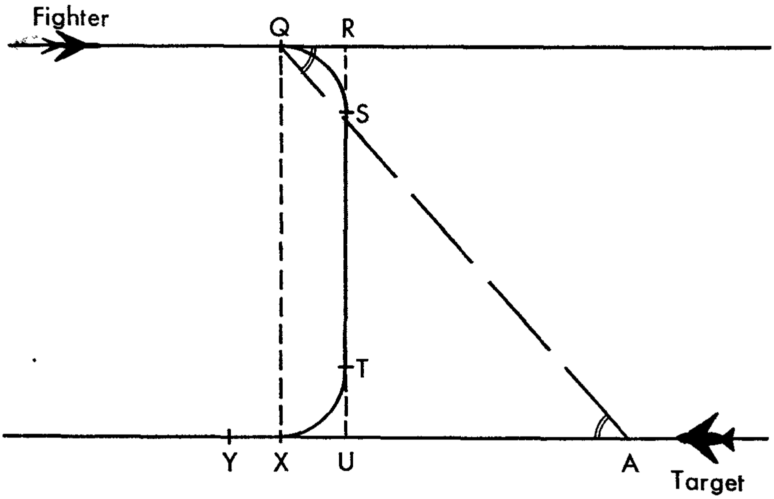


Fig 32–17 Example 1

relative to the fighter,

$\therefore$ Angle off (AQR) = 43°

$$\text{Further, } QA = \frac{XQ}{\text{Sin } XAQ}$$

$$= \frac{12 \cdot 5}{0 \cdot 686} = 18 \cdot 2 \text{ nm}$$

(the slant range)

The solution is therefore that the fighter should start its turn onto the crossing leg when the target is bearing 43° range 18 nm, the required target displacement being 12·5 nm. A controller should therefore direct the fighter to turn onto its 90° crossing leg as the target's angle off reaches 40° and the slant range is 19 nm, to achieve the desired final approach.

b. *Example 2.* The problem is to calculate when a fighter should start its final 90° turn in behind a target during a 90° approach. The fighter is assumed to be required to roll out 2 nm astern of the target for weapon release, and the relative speed and performance details are assumed to be the same as in Example 1.

The calculation is as follows (refer to Fig 32–18).

The fighter is at Z when the target is at W

$\therefore$ WZ = 2 nm

The fighter starts its final turn at X, when the target is at V. The length of the curve XZ is $\frac{2\pi R}{4}$, where R is the radius of turn (4 nm). But $\frac{2\pi R}{4} = 2\pi$

Because the target/fighter speed ratio is 85:95, the distance which the target will travel while the fighter travels along the curve XY is:

$$2\pi \times \frac{85}{95}$$

$$= \frac{6 \cdot 28 \times 85}{95}$$

$$= 5 \cdot 62 \text{ nm} = VW$$

$$\begin{aligned}
\text{Since } ZY &= 4 \text{ nm (radius of turn)} \\
WZ &= 2 \text{ nm} \\
VY &= ZY + WZ - WV \\
&= 6 - 5 \cdot 62 \\
&= 0 \cdot 38 \text{ nm} \\
XY &= 4 \text{ nm (radius of turn)}
\end{aligned}$$

$$\text{Tan } YXV = \frac{VY}{XY} = \frac{0 \cdot 38}{4}$$

$$= 5° = \text{Angle off.}$$

$$\text{But Cos } YXV = \frac{XY}{XV}$$

$$\therefore \quad XV = \frac{XY}{\text{Cos } YXV} = \frac{4}{\cdot 998}$$

$$= \text{Approximately 4 nm}$$

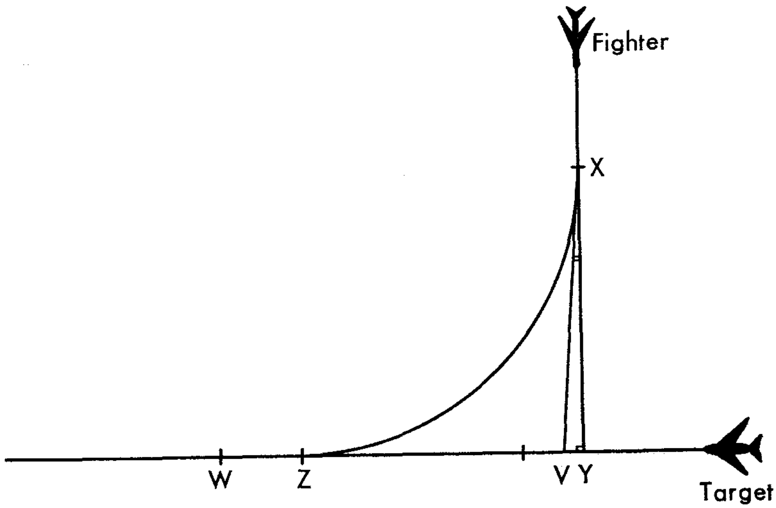


Fig 32–18 Example 2

The solution is therefore that the fighter should start its final 90° turn onto the target's heading after the target has crossed ahead and reached an angle off of 5° at range 4 nm. This means that an interception controller should plan for the target to cross slightly more than 4 nm ahead of the fighter, and direct the fighter pilot to turn in behind the target as the target reaches the dead ahead position.

PRACTICE INTERCEPTIONS

Introduction

3245. Practice interceptions (PIs) are designed to exercise both aircrew and interception controllers in their operational tasks. However fighter flying is extremely expensive and it is therefore essential to use the flight time available to give optimum training value, which is seldom gained by practising an operational interception in its entirety. PI training therefore tends to concentrate on the transition and combat phases of an interception, which give greatest benefit to aircrew and controllers.

3246. The techniques used for controlling practice interceptions are somewhat different from those used for controlling operational interceptions or practising a complete interception profile. The techniques for practice interceptions are described in this section.

Setting up Practice Interceptions

3247. **90° Split Method.** In Fig 32–19 a method is shown of setting up a 90° collision interception. But this pattern will only be of use if the fighter and target are flying at equal speeds and a collision interception is required. The basic pattern can, however, easily be adapted to provide both 90° collision interceptions, or final turn lead pursuit interceptions, with fighter/target speed ratio of 0·95/0·85—the ratio frequently used for subsonic practice interceptions. The method is shown in Fig 32–20. The fighter's arrival at the offset point has been delayed by the larger initial turn angle of 110°/120° for the fighter's new heading, which requires the fighter to fly a greater distance to the interception point. The fighter has therefore lost time in both having to turn through greater angles, and also by having to cover a greater distance compared with the target. This allows for the fighter's speed advantage and also for the target crossing-ahead distance for a final turn lead pursuit attack in the combat phase.

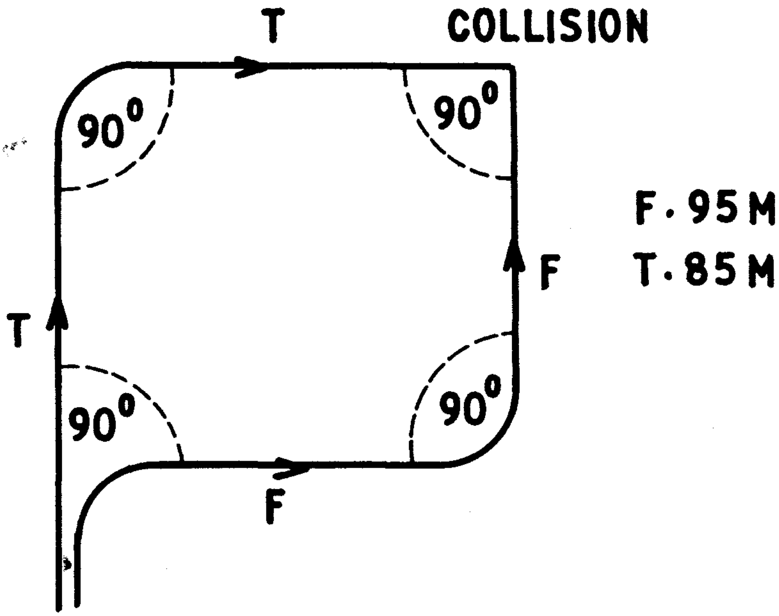


Fig 32–19 Basic 90° Split Method

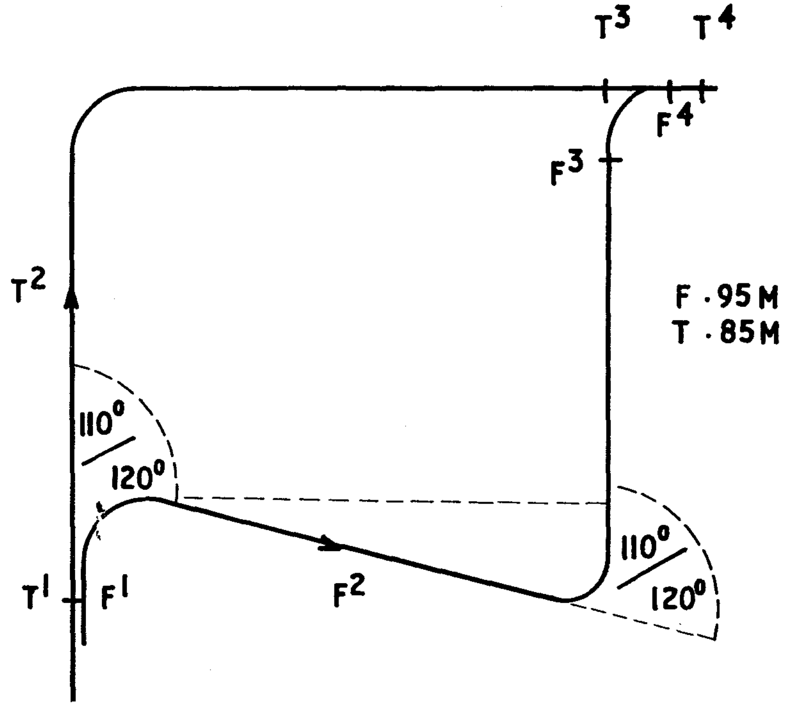


Fig 32–20 Adapted 90° Split Method

3248. **Alternative Split for a 90° Approach.** A 90° approach can also be set up from a 180° split as shown in Fig 32–21. The fighter is turned through the greater angle, and the fighter's speed advantage and larger turning angle 140° will displace the apex of the triangle to a position which will allow for the target crossing ahead distance.

3249. **Split for a Head-On or Displaced Parallel Head-On Approach.** The basic split can also be used for a head-on or parallel head-on approach as shown in Fig 32–22. The fighter and target are each turned away through 90°. When separated by a suitable distance each is turned through 180° towards each other. When a displaced parallel head-on interception is required the aircraft are turned through 190° and 170° respectively as also shown in Fig 32–22.

3250. **Split for a 120° or 150°.** The 120° or 150° approach may be set up using the split shown in Figs 32–23 and 32–24 which are self explanatory. The fighter is always turned through a greater angle after the split.

3251. **Split for a Random Contact Approach.** Pilots sometimes wish to practice the combat phase of an interception where no help is given in the transition phase by ground control. A suitable split for this type of practice is shown in Fig 32–25. The target should be turned "inbound" and directed to "stop turning" when the heading to achieve a suitable interception has been reached in the turn.

TYPES OF INTERCEPTION CONTROL

Introduction

3252. There are basically two different types of interception control:

a. Close control.

b. Broadcast control.

These basic forms of interception control and techniques which are refinements of the basic forms, are described in the following paragraphs.

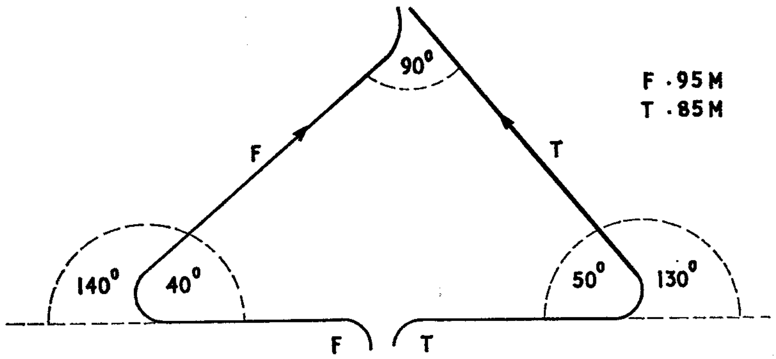


Fig 32–21 Alternative Split for a 90° Approach

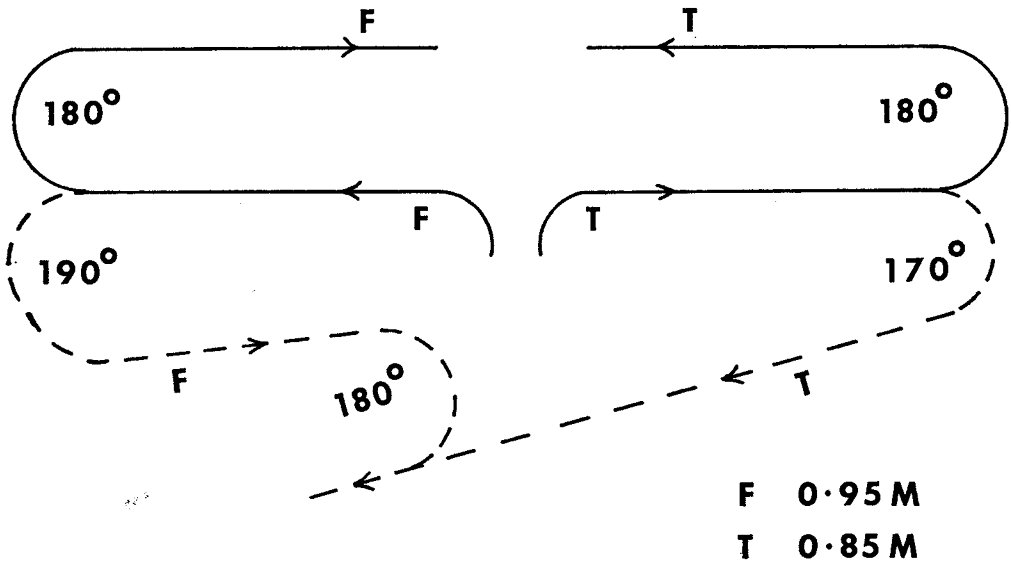


Fig 32–22 Split for a Head-on Approach

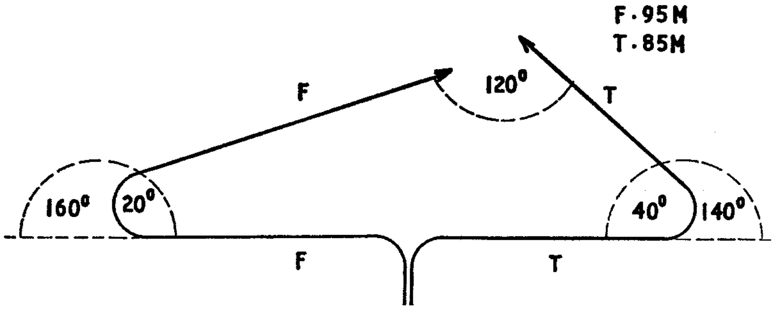


Fig 32–23 Split for a 120° Approach

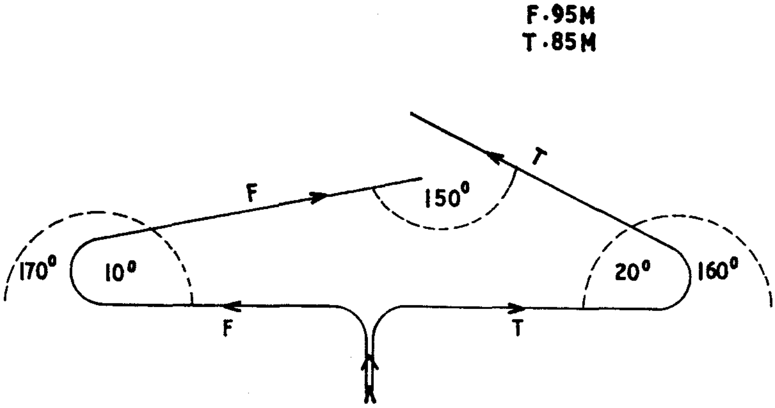


Fig 32–24 Split for a 150° Approach

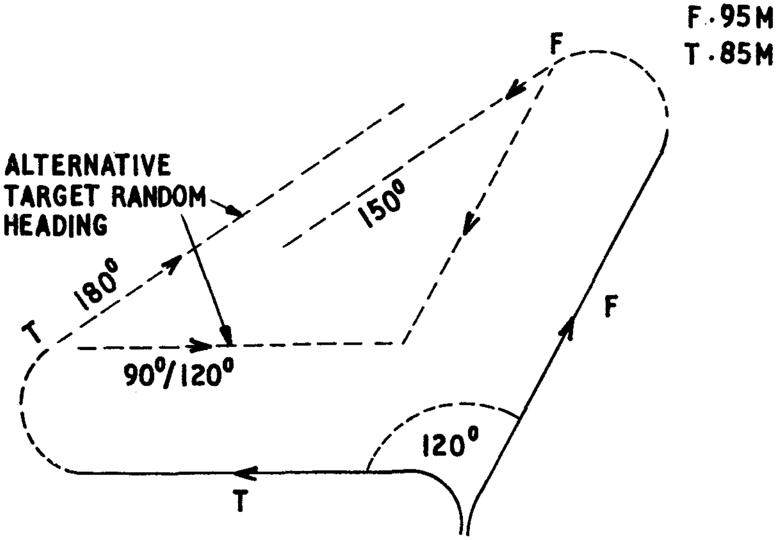


Fig 32–25 Split for a Random Contact Approach

Close Control

3253. Close control is a precision control technique in which an interception controller assumes complete responsibility for directing a fighter aircraft to a position from which the enemy aircraft can be successfully engaged. Of the many methods of fighter control, it is the most accurate and efficient form of direction and is normally used for interception purposes whenever circumstances allow. In automatic data processing control systems close control is used exclusively. The variations in close control techniques in manual air defence systems are many, depending on the type of fighter aircraft under control, the armament of the fighter, weather conditions, type of target aircraft and the height and speed of the target aircraft.

3254. **Cover point Control.** Cover point control is an extension of close control technique used in manual systems whereby two interception controllers use the same PPI tube and the same communications channel and work side by side, normally controlling up to three units of fighters at any one time. One controller marshals the fighters into a good tactical position before handing them over successively to the other controller for final directions to complete their engagements.

3255. **Combat Air Patrol (CAP) Control.** CAPs are used to eliminate the scramble and climb phases from an interception profile, and are frequently employed when early warning is limited. Fighters on CAP are close controlled, but remain within 20 nm of the CAP station until directed by the interception controller to intercept a target. The interception controller may intercept targets under his own initiative, but must inform his chief controller immediately of the action he is taking. CAPs are normally flown at altitudes clear of contrails.

Broadcast Control

3256. Broadcast control is the method of fighter control used to control an unlimited number of fighter aircraft in manual systems and is generally used when control capacity is limited, under conditions of target saturation, or in a degraded radar situation, when close control can no longer be employed. This form of control is based on the broadcast of target information in a voice commentary by the interception controller and the independent self-navigation and interception of the target by the fighter. The form which the broadcast or commentary takes is described in the various control and reporting procedure instructions and in ADOPS. In the event of complete communications failure the whole plan can be put into operation with fighter aircraft navigating and intercepting independently with the preplanned mounting of CAPS. Geometrically the CAPS are centred within the defended area with CAP orientation in the direction of the expected threat, spaced to allow for maximum effective visual and AI searching. Fighter CAP stations would be positioned to provide comprehensive autonomous AI search cover within the sector. Tanker aircraft will man towlines and refuel fighters as required. AEW aircraft will assume prebriefed barriers providing raid reports and maintaining a target broadcast.

MANUAL CONTROL AIDS

Introduction

3257. When controlling interceptions in a manual environment frequent use is made of interception overlays which assist a controller in providing the following data in an easily interpreted form.

a. The angle-off and range of the target relative to the fighter.

b. The required fighter path for interception.

c. The ground speed and track of the target.

d. The point at which a fighter intercepting a supersonic target should accelerate.

Overlays

3258. An interception overlay is a flexible transparent plastic sheet on which the required indications are drawn. It is placed over a PPI radar display and aligned with the fighter and target responses. Many overlays are drawn to suit a particular scale of PPI, but those based purely on angles may be used with PPIs set to any scale. There are two basic types of overlay:

a. Fighter overlay—drawn relative to the fighter.

b. Target overlay—drawn relative to the target.

Overlays are devised mathematically to suit specific interception profiles, and a wide variety are therefore in everyday use. In the following paragraphs however, one of the most common RAF overlays has been selected as it provides a typical example of a fighter overlay.

3259. **The Standard Lightning Overlay.** The standard Lightning overlay (illustrated in Fig 32–26 is a fighter overlay designed to aid the control of Lightnings flying standard practice interception profiles. The overlay is scaled to match the 160 nm diameter scale on a standard console but it can be used to assess angles-off on any scale. The overlay is based on fighter and target speeds of 0·95M and 0·85M respetively, but it is suitable for any speeds in similar ratio. The line of relative motion of the target for a particular interception profile is drawn in chinagraph on the overlay, the position of the line being determined by:

a. The collision angle.

b. The distance the target should pass ahead of the fighter, if the collision course were maintained.

Scales for collision angles of 90°, 120° and 150° are drawn on the outer rim of the overlay and each of the scales is marked with target crossing ahead distances ("c" indicating a simple collision or 0 nm). The line of relative motion (XY on Fig 32–26) is drawn for the required crossing ahead distance, from the appropriate collision angle scale, to an equivalent distance on the line FA. The overlay is placed on the PPI mask with the fighter response in the position F and turned until the target response is on the line of relative motion, drawn for the desired profile. The small arrow below F indicates the track which the fighter should fly. The overlay may be used for head-on interceptions by simply aligning the target on FA, which is the line of relative motion for this profile. To use the overlay for a parallel head-on interception profile a line parallel to FB is drawn at a lateral distance equivalent to the displacement required (line WZ in Fig 32–27). A further line XY is drawn to suit the appropriate final 90° crossing leg. The target is aligned on the line WZ and the fighter's course is, in this case, indicated by the line FB (*ie* at 90° to the arrow). The target's course is the reciprocal of the fighter's course. The fighter is turned through 90° in time to be at position F when the target reaches the intersection of the lines WZ and XY; the fighter would therefore have to start turning approximately 7 nm before the intersection using the figures quoted and a 40° angle of bank turn at 35,000 feet in ICAN conditions. The overlay is then used as for a 90° interception—the target following the line relative motion XY.

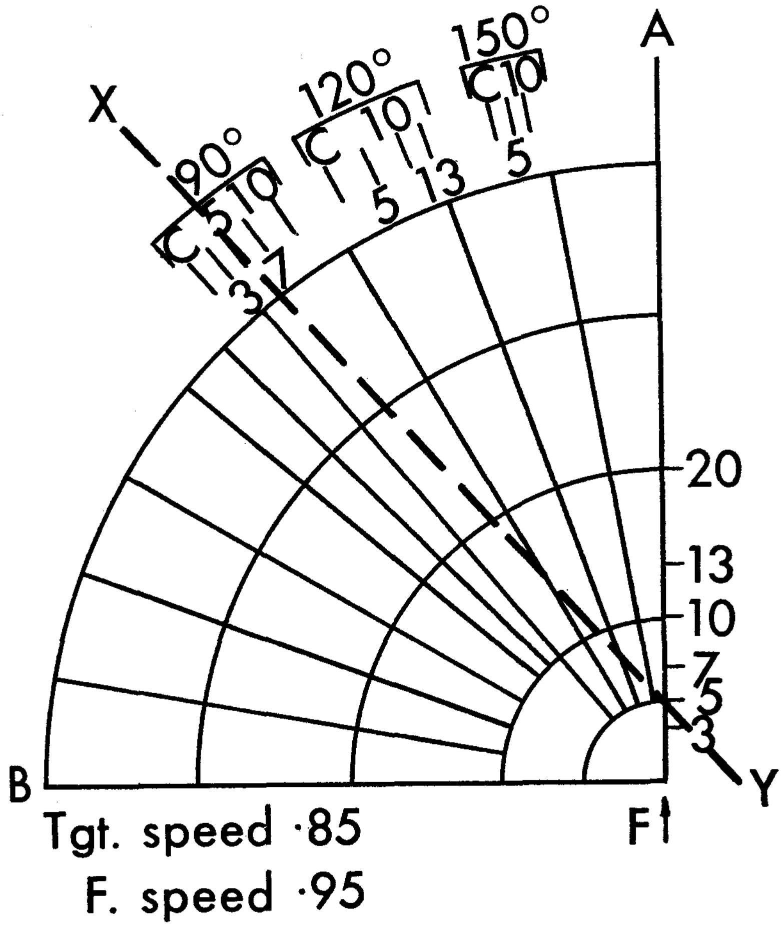


Fig 32–26 Standard Lightning Overlay

(AL 8, Jan 76)

ADP INTERCEPTION TECHNIQUES

Introduction

3260. Air Defence systems using automatic data processing (ADP) are in widespread use by the Royal Air Force and computer assistance for interceptions is available to controllers.

Displays

3261. Computer derived information is displayed to the controller on a Labelled Radar Display (LRD) and includes track data in terms of heading and speed for each track as sequenced. Interceptors, on being sequenced, display a command heading, to the nearest 5°, and the magnetic bearing and range of the associated target. This facility does not affect the track data display and an intercepted track will continue to show its own track data while the interceptors information is given and will only be removed by sequencing to a further track. This display of interceptor information can be positioned anywhere on the LRD whilst other track data is displayed 10 nm beyond the track to which it relates. If there is only one target/interceptor pair on the console, related data will be displayed continuously.

3262. **Types of Tracks.** Up to 8 tracks may be displayed on any one console and they may be any combination of the following:

a. *Normally Initiated Tracks.* Updating is based on previous track history. A normally initiated track may become an intercepted track or an interceptor.

b. *Intercepted Track.* Updating is carried out as for normally initiated tracks and each intercepted track has any number of associated interceptors up to a maximum of 7, each being sequenced in turn.

c. *CAP Fighter.* A CAP fighter has no allocated target and is updated from radar positional information and injected data. A CAP fighter may become an interceptor or target.

d. *Interceptor.* Updating is provided by the interceptor parameters demanded by the interception profile in use.

Interception Profiles

3263. **Basic Profile Geometry.** The initial calculation of a heading to intercept is based upon an isosceles triangle which assumes the co-speed case, *see* Fig 32–27. The attack speed is calculated as target speed plus ·2M and the length of the fighters intercept leg is adjusted to give a cruise at ·9M and an acceleration to reach attack speed at a collision point 5,000 feet below the target. The intercept heading is recalculated using this new distance and the turn from the fighter's original heading to the intercept heading is incorporated. Triangulation is carried out once more using the fighters calculated position at the end of the turn, and the targets compiled position at that time. The final interception heading, acceleration point and collision point is then calculated.

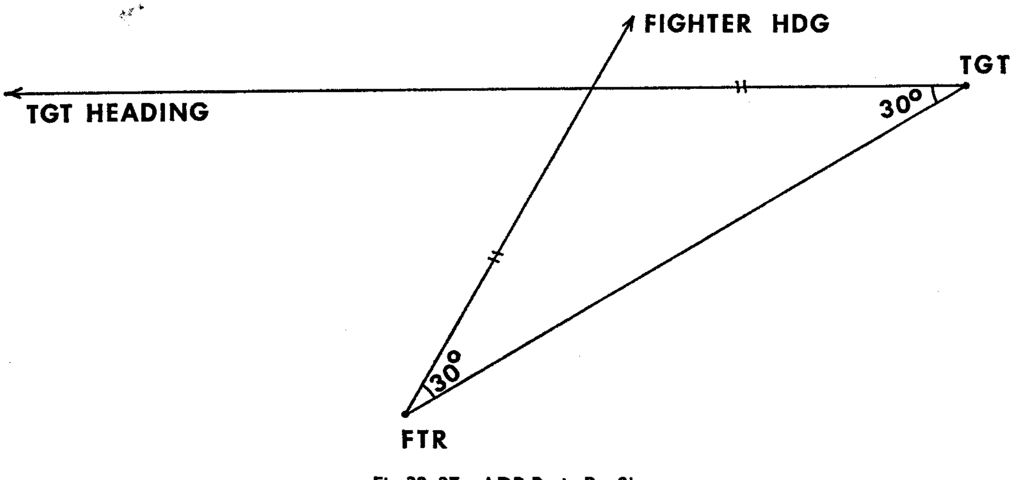


Fig 32–27 ADP Basic Profile

3264. **Interception Initiation.** An interception is called down by key sequence. No previous rolling ball movement is required, the positions of both tracks being updated at the precise moment of the key sequence. Acceleration is normally calculated for the Lightning but by further key sequence may be amended for the Phantom.

3265. The turn from the present fighter heading to the intercept heading is calculated and updated based on the interceptors present speed at a rate of 3° a second. An acceleration or decceleration point is displayed along the interceptor's predicted track and it will fade automatically as the interceptor's predicted position reaches that point.

3266. If no pre-interception parameters have been keyed, the profile will be based upon a ·9M cruise speed and an attack speed of target speed plus ·2M achieved at a collision point 5,000 ft below the target. However, any of the following parameters may be selected for each interception before or during the actual interception:

a. Cruise speed.

b. Attack speed.

c. Target cross ahead distance.

3267. The interception can be terminated without cancelling the interceptor involved. The interceptor reverts to a CAP fighter continuing on the last command heading until redirected.

3268. **Stern and Close Range.** When the convergence between interceptor and target is less than 90°, or the plan separation distance is less than 20 nm a modified pursuit heading is calculated. The lead angle varies with the convergence being a maximum of 30° when the convergence is 90° reducing proportionately. No allowance is made for turns and any cross ahead factor is ignored.

Summary

3269. Computer assistance can be of great value to interception controllers but should always be used in conjunction with a thorough knowledge of interception geometry and manual control techniques. A computer used alone to solve the interception problem does not have the flexibility that is found in the manual controller.

RADIOTELEPHONE SPEECH

Introduction

3270. A fighter controller usually passes instructions and information to a fighter pilot by radiotelephone (RT). Such messages need to be readily understood in spite of any jamming or interference on the RT channel. Standardized phrases are therefore used and a procedure peculiar to fighter control has been developed. The instructions in ACP 125 "Communication Instructions Radiotelephone Procedure" and the words in ACP 165 "Operational Brevity Codes" are however, followed and this chapter simply outlines the particular procedures used for interception controlling.

Technique

3271. **Voice Production.** RT speakers must observe the five principles of voice production if they are to be intelligible. The principles which follow, may easily be remembered by the mnemonic DRIPS:

a. *Diction.* Consonants should be clearly enunciated and vowels given their proper value. Words should not be run together.

b. *Rhythm.* The natural rhythm of ordinary conversation should be retained. A tendency to articulate messages word by word rather than to say them as a series of phrases must be avoided, as must natural speech faults such as "er" and "um".

c. *Intensity.* A normal conversational level should be maintained. Shouting causes distortion and reduces intelligibility.

d. *Pitch.* The higher voice frequencies are carried better than the low. Male speakers should therefore pitch up their voices.

e. *Speed.* Speech should be slightly slower than in normal conversation, but not laboured.

3272. **Manner.** The manner in which a controller speaks is most important. His voice should inspire confidence, reassuring the pilot that he has complete command of the situation. While he should never give the impression of being harassed or confused, neither should he sound detached or uninterested; the urgency of the occasion should enter into and animate the form of his speech. The pilot is reassured if he feels that the controller is devoting his entire attention to the task in hand; and the fact that the controller is physically remote ought not to obtrude on the pilot's consciousness; the controller should talk as it were, over the pilot's shoulder. Messages should be succinct.

3273. **Transmitter Keying.** Since hesitation gives a strong impression of uncertainty over the RT, a controller should always be sure of what he is going to say before depressing the TR transmit key. He should avoid holding down the transmitter key while deliberating since it is better to switch off and to start again.

Procedures

3274. **Callsigns.** RT callsigns are allocated to ground control stations within a fighter control organization. Fighters however, use mission number callsigns which are normally allotted as described in paras 3285 to 3288.

3275. **Vocabulary.** The vocabulary used for fighter control is largely taken from the brevity code words listed in Part I of ACP 165. These codewords were devised to aid brevity and clarity but they are not secret. Long phrases have been condensed into one or two easily pronounced words to provide a vocabulary common to all allied air forces.

3276. **Phonetics.** However clearly enunciated a message may be, it is always possible for the person receiving it to confuse certain letters or numerals (*eg* B and P, or M and N). To avoid this, the standard phonetics listed in Annex A to this chapter have been devised by the International Civil Aviation Organization (ICAO) and adopted by the RAF. They are always used when words are spelt out or numerals are passed over the RT.

3277. **The Components of a Message.** An RT message has three components:

a. The call.

b. The text.

c. The ending.

When a series of RT messages is passed in quick succession between two points, *eg* during an interception control commentary, the call and the ending may be abbreviated or omitted if there is no risk of confusion.

3278. **The Call.** The complete call consists of:

a. The callsign of the station called.

b. "THIS IS".

c. The callsign of the station calling.

eg "FOXTROT HOTEL JULIET FIVE SEVEN THIS IS BOULMER".

3279. **The Text.** The text is as short as possible, consistent with clarity.

3280. **The Ending.** There are two different ways of ending an RT message, each giving a clear indication of what the caller expects to happen next:

a. "OVER"—indicates that a reply or acknowledgement is required.

b. "OUT"—indicates that no reply is required.

3281. **General Rules of Procedure.** The following are useful general rules of procedure:

a. Care should be taken not to confuse the pilot by giving too many instructions, or too much information in any one message. A message should not consist of more than two instructions or sets of information or, alternatively, one set of each item.

b. When both an instruction and information are given, the instruction always precedes the information. This rule is observed even if both elements are included in a single message.

c. Acknowledgement of an instruction should always be obtained. When communication is more or less continuous however, as in the final stages of an interception, a fighter pilot is not expected to acknowledge receipt of information.

d. Long periods of silence should not be allowed to occur, otherwise an RT failure or an accident to a fighter could go unnoticed. Under close control, no period of silence should last more than a minute.

e. When a formation is being controlled, a controller should anticipate the formation leader's need to use the RT to brief and direct his pilots and thus avoid interfering with the leader's transmissions.

f. Units of measurement, *eg* degrees, feet, miles, *etc* are omitted from the text of a message.

g. Courses, mach numbers and numerical callsigns are passed as separate integers, *eg* 240° as "TWO FOUR ZERO", 0·85M as "EIGHT FIVE", mission 23 as "TWO THREE". Other quantities such as speeds in knots and altitudes are passed as whole numbers, *eg* 240 knots as "TWO FORTY", 42,000 feet as "FORTY TWO THOUSAND". This is an important distinction which reduces confusion when RT reception is poor.

h. Superfluous or courtesy words such as "please", "thank-you", "okay" and "on to" are avoided.

j. A change of course is always passed as "PORT" or "STARBOARD" when the previous course is known, whereas the angle-off of a target relevant to a fighter is always as "LEFT" or "RIGHT".

Quality of Reception

3282. A station is assumed to have good reception unless it notifies to the contrary, in accordance with ACP 125. However, when a formation of fighters comes under the control of a fighter controller, each fighter in the formation checks-in on the RT; once contact has been established with each member of the formation, only the formation leader speaks to the controller while they continue to operate as a single formation.

3283. If a station wishes to inform another of its signal strength and readability, it does so by means of a short and concise report of actual reception, *eg* "Weak, but readable", "Strong, but distorted", "Loud and clear", *etc.*

Disclosure of Information

3284. Since monitoring radio transmissions is one of the main methods used by countries to gather intelligence about a potential enemy's armed forces, it is of the utmost importance that fighter controllers do not disclose useful information when communicating by RT. They should particularly guard against:

a. Revealing the maximum performance of the aircraft they control.

b. Unnecessarily divulging the capabilities of radar equipment.

c. Mentioning the names, or locations of fighter bases during active operations.

d. Disclosing the significance of callsigns.

e. Referring to squadron numbers or aircraft types.

f. Relating RT frequencies to fighter studs.

FIGHTER MISSION NUMBER CALLSIGNS

3285. Mission number callsigns are used by all fighters flying within Strike Command and generally by fighters in overseas commands flying within their own theatre. Normal RAFJET callsigns are used for transit flights between commands overseas.

3286. A mission number callsign consists of a three letter mission root, known as a "trigraph", plus a two figure number. The trigraph is allocated to airfields by the appropriate command headquarters and changed twice monthly at irregular intervals. The two figure numbers are allocated at random daily by the Wing Operations at the fighter airfields. Individual mission numbers are allocated to specific aircraft formations before a sortie commences. Each aircraft within a formation is given a suffix letter, *eg* A, B, C, *etc*, to use should the formation split.

3287. The callsign may for convenience be shortened by local procedure to the first letter of the trigraph followed by the mission number.

3288. If a fighter formation lands away at another airfield, but intends returning to its parent airfield after turnaround, it will retain its original mission number. This number must not be re-issued to another formation until after the original fighter formation has landed back at its parent airfield. If a formation is deployed to another airfield, however, it will be allocated a new callsign for its next sortie by that airfield.

STANDARD PHONETICS

A	... ALFA	N	... NOVEMBER
B	... BRAVO	O	... OSCAR
C	... CHARLIE	P	... PAPA
D	... DELTA	Q	... QUEBEC
E	... ECHO	R	... ROMEO
F	... FOXTROT	S	... SIERRA
G	... GOLF	T	... TANGO
H	... HOTEL	U	... UNIFORM
I	... INDIA	V	... VICTOR
J	... JULIET	W	... WHISKEY
K	... KILO	X	... X-RAY
L	... LIMA	Y	... YANKEE
M	... MIKE	Z	... ZULU

0	... ZERO	5	... FIFE
1	... WON	6	... SIX
2	... TOO	7	... SE-VEN
3	... THREE	8	... EIGHT
4	... FO-WER	9	... NINER