AIRCRAFT
COMMUNICATIONS AND NAVIGATION SYSTEMS

MIKE TOOLEY AND
DAVID WYATT

SECOND EDITION

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Aircraft Communications and Navigation Systems

Second edition

Introducing the principles of communications and navigation systems, this book is written for anyone pursuing a career in aircraft maintenance engineering or a related aerospace engineering discipline, and in particular will be suitable for those studying for licensed aircraft maintenance engineer status. It systematically addresses the relevant sections (Air Transport Association of America chapters 23/34) of Modules 11 and 13 of Part-66 of the European Aviation Safety Agency (EASA) syllabus and is ideal for anyone studying as part of an EASA and FAR-147-approved course in aerospace engineering.

- Delivers the essential principles and knowledge base required by Airframe and Propulsion (A&P) Mechanics for Modules 11 and 13 of the EASA Part-66 syllabus and BTEC National awards in aerospace engineering
- Supports mechanics, technicians and engineers studying for a Part-66 qualification
- Comprehensive and accessible, with self-test questions, exercises and multiple choice questions to enhance learning for both independent and tutor-assisted study
- Additional resources and interactive materials are available at the book's companion website at www.66web.co.uk

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Second edition

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Contents

Preface

Aircraft Communications and Navigation Systems, first edition, was published in 2007, as part of a series designed for both independent and tutor-assisted studies. This second edition has been updated with reference to the latest version of EASA's Part 66 syllabus as well as technology updates and requests from readers/reviewers. This book forms part of a series of titles:

- *Aircraft Engineering Principles* (AEP)
- *Aircraft Communications and Navigation Systems* (ACNS)
- *Aircraft Flight Instruments and Guidance Systems* (AFIGS)
- *Aircraft Electrical and Electronic Systems* (AEES)

ACNS is designed to cover the essential knowledge base required by certifying mechanics, technicians and engineers engaged in engineering maintenance activities on commercial aircraft. In addition, this book should appeal to members of the armed forces and others attending training and educational establishments engaged in aircraft maintenance and related aeronautical engineering programmes (including BTEC National and Higher National units as well as City and Guilds and NVQ courses).

The book provides an introduction to the principles, operation and maintenance of aircraft communications and navigation systems. The aim has been to make the subject material accessible and presented in a form that can be readily assimilated. The book provides syllabus coverage of the communications and navigation section of Module 13 (ATA 23/34). The book assumes a basic understanding of aircraft flight controls as well as an appreciation of electricity and electronics (broadly equivalent to Modules 3 and 4 of the EASA Part-66 syllabus).

It is important to be aware that this book is not designed to replace aircraft maintenance manuals. Nor does it attempt to provide the level of detail required by those engaged in the maintenance of specific aircraft types. Any maintenance statements made in this book are for training/educational purposes only. Always refer to the approved aircraft data and applicable safety instructions.

Chapter 1 sets the scene by providing an explanation of electromagnetic wave propagation and the radio frequency spectrum. The chapter also describes the various mechanisms by which radio waves propagate together with a detailed description of the behaviour of the ionosphere and its effect on radio signals.

Antennas are introduced in Chapter 2. This chapter explains the principles of isotropic and directional radiating elements and introduces a number of important concepts including radiation resistance, antenna impedance, radiated power, gain and efficiency. Several practical forms of antenna are described including dipoles, Yagi beam antennas, quarter wave (Marconi) antennas, corner reflectors, horn and parabolic dish radiators. Chapter 2 also provides an introduction to feeders (including coaxial cable and open-wire types), connectors and standing wave ratio (SWR). The chapter concludes with a brief introduction to waveguide systems.

Radio transmitters and receivers are the subject of Chapter 3. This chapter provides readers with an introduction to the operating principles of AM and FM transmitters as well as tuned radio frequency (TRF) and supersonic-heterodyne (superhet) receivers. Selectivity, image channel rejection and automatic gain control (AGC) are important requirements of a modern radio receiver, and these topics are introduced before moving on to describe more complex receiving equipment. Modern aircraft radio equipment is increasingly based on the use of digital frequency synthesis, and the basic principles of phase-locked loops and digital synthesisers are described and explained.

Very high frequency (VHF) radio has long been the primary means of communication between aircraft and the ground. Chapter 4 describes the principles of VHF communications (both voice and data). The chapter also provides an introduction to the Aircraft Communications Addressing and Reporting System (ACARS).

High frequency (HF) radio provides aircraft with an effective means of communicating over long distance oceanic and trans-polar routes. In addition, global data communication has recently been made possible using strategically located HF datalink (HFDL) ground stations. Chapter 5 describes the principles of HF radio communication as well as the equipment and technology used.

As well as communication with ground stations, modern passenger aircraft require facilities for local communication within the aircraft. Chapter 6 describes flight-deck audio systems including the interphone system and all-important cockpit voice recorder (CVR) which captures audio signals so that they can be later analysed in the event of a serious malfunction of the aircraft or of any of its systems.

The detection and location of the site of an air crash is vitally important to the search and rescue (SAR) teams and also to potential survivors. Chapter 7 describes the construction and operation of emergency locator transmitters (ELT) fitted to modern passenger aircraft. The chapter also provides a brief introduction to satellite-based location techniques.

Chapter 8 introduces the subject of aircraft navigation; this sets the scene for the remaining chapters of the book. Navigation is the science of conducting journeys over land and/or sea. This chapter reviews some basic features of the earth's geometry as it relates to navigation, and introduces some basic aircraft navigation terminology, e.g. latitude, longitude, dead reckoning, etc. The chapter concludes by reviewing a range of navigation systems used on modern transport and military aircraft. Many aircraft navigation systems utilise radio frequency methods to determine a position fix; this links very well into the previous chapters of the book describing fundamental principles of radio transmitters, receivers and antennas.

Radio waves have directional characteristics as described in the early chapters of the book. This is the basis of the automatic direction finder (ADF), one of earliest forms of radio navigation that is still in use today. ADF is a short/medium-range (200 nm) navigation system providing directional information. Chapter 9 looks at the historical background to radio navigation, reviews some typical ADF hardware that is fitted to modern commercial transport aircraft, and concludes with some practical aspects associated with the operational use of ADF.

During the late 1940s, it was evident to the aviation world that an accurate and reliable short-range navigation system was needed. Since radio communication systems based on VHF were being successfully deployed, a decision was made to develop a radio navigation system based on VHF. This system became the VHF omni range (VOR) system and is described in Chapter 10. This system is in widespread use throughout the world today. VOR is the basis of the current network of 'airways' that are used in navigation charts.

Chapter 11 develops this theme with a system for measuring distance to a navigation aid. The advent of radar in the 1940s led to the development of a number of navigation aids including distance measuring equipment (DME). This is a short/medium-range navigation system, often used in conjunction with the VOR system to provide accurate navigation fixes. The system is based on secondary radar principles.

ADF, VOR and DME navigation aids are installed at airfields to assist with approaches to those airfields. These navigation aids cannot however be used for precision approaches and landings. The standard approach and landing system installed at airfields around the world is the instrument landing system (ILS). Chapter 12 describes how the ILS can be used for approach through to autoland. The ILS uses a combination of VHF and UHF radio waves and has been in operation since 1946.

Chapter 13 continues with the theme of guided approaches to an airfield. There are a number of shortcomings with ILS; in 1978 the microwave landing system (MLS) was adopted as the long-term replacement. The system is based on the principle of time-referenced scanning beams and provides precision navigation guidance for approach and landing. MLS provides three-dimensional approach guidance, i.e. azimuth, elevation and range. The system provides multiple approach angles for both azimuth and elevation guidance. Despite the advantages of MLS, it has not yet been introduced on a worldwide basis for commercial aircraft. Military operators of MLS often use mobile equipment that can be deployed within hours.

Long-range radio navigation systems are described in Chapter 14. These systems are based on hyperbolic navigation; they were introduced in the 1940s to provide en route operations over oceans and unpopulated areas. Several hyperbolic systems have been developed since, including Decca, Omega and Loran. The operational use of Omega and Decca navigation systems ceased in 1997 and 2000 respectively. Loran systems are still available for use today as stand-alone systems; they are also being proposed as a complementary navigation aid for global navigation satellite systems.

Chapter 15 looks at a unique form of dead reckoning navigation system based on radar and a scientific principle called Doppler shift. This system requires no external inputs or references from ground stations. Doppler navigation systems were developed in the mid-1940s and introduced in the mid-1950s as a primary navigation system. Being self-contained, the system can be used for long distance navigation and by helicopters during hover manoeuvres.

The advent of computers, in particular the increasing capabilities of integrated circuits using digital techniques, has led to a number of advances in aircraft navigation. One example of this is the area navigation system (RNAV); this is described in Chapter 16. Area navigation is a means of combining, or filtering, inputs from one or more navigation sensors and defining positions that are not necessarily co-located with ground-based navigation aids.

A major advance in aircraft navigation came with the introduction of the inertial navigation system (INS); this is the subject of Chapter 17. The inertial navigation system is an autonomous dead reckoning system, i.e. it requires no external inputs or references from ground stations. The system was developed in the 1950s for use by the US military and subsequently the space programmes. Inertial navigation systems (INS) were introduced into commercial aircraft service during the early 1970s. The system is able to compute navigation data such as present position, distance to waypoint, heading, ground speed, wind speed, wind direction, etc. The system does not need radio navigation inputs, and it does not transmit radio frequencies. Being self-contained, the system can be used for long distance navigation over oceans and undeveloped areas of the globe.

Navigation by reference to the stars and planets has been employed since ancient times; aircraft navigators have utilised periscopes to take celestial fixes for long distance navigation. An artificial constellation of navigation aids was initiated in 1973 and referred to as Navstar (navigation system with timing and ranging). This global positioning system (GPS) was developed for use by the US military; it is now widely available for use in many applications including aircraft navigation. Chapter 18 looks at GPS and other global navigation satellite systems that are in use, or planned for future deployment.

The term ‘navigation’ can be applied in both the lateral and vertical senses for aircraft applications. Vertical navigation is concerned with optimising the performance of the aircraft to reduce operating costs; this is the subject of Chapter 19. During the 1980s, lateral navigation and performance management functions were combined into a single system known as the flight management system (FMS). Various tasks previously routinely performed by the crew can now be automated with the intention of reducing crew workload.

Chapter 20 reviews how the planned journey from A to B could be affected by adverse weather conditions. Radar was introduced onto passenger aircraft during the 1950s to allow pilots to identify weather conditions and subsequently re-route around these conditions for the safety and comfort of passengers. A secondary use of weather radar is the terrain-mapping mode that allows the pilot to identify features of the ground, e.g. rivers, coastlines and mountains.

Increasing traffic density, in particular around airports, means that we need a method of air traffic control (ATC) to manage the flow of traffic and maintain safe separation of aircraft. The ATC system is based on secondary surveillance radar (SSR). Ground controllers use the system to address individual aircraft. An emerging ATC technology is ADS-B; this is also covered in Chapter 21.

With ever-increasing air traffic congestion, and the subsequent demands on ATC resources, the risk of a mid-air collision increases. The need for improved traffic flow led to the introduction of the traffic alert and collision avoidance system (TCAS); this is the subject of Chapter 22. TCAS is an automatic surveillance system that helps aircrews and ATC to maintain safe separation of aircraft. TCAS is an airborne system based on secondary radar that interrogates and replies directly with aircraft via a high-integrity datalink. The system is functionally independent of ground stations and alerts the crew if another aircraft comes within a predetermined time to a potential collision.

The book concludes with four useful appendices, including a comprehensive list of abbreviations and acronyms used with aircraft communications and navigation systems.

The review questions at the end of each chapter are typical of these used in CAA and other examinations. Further examination practice can be gained from the four revision papers given in Appendix 2. Other features that will be particularly useful if you are an independent learner are the 'key points' and 'test your understanding' questions interspersed throughout the text.

Preface to the second edition

When producing the second edition of the book the authors took into account advances in technology as well as suggestions and feedback from readers (students and lecturers) and a review by the National Aerospace Library (NAL), one of the most prestigious aerospace and aeronautical library collections in the world.

New content developed specifically for this edition includes:

- **Satellite communications (SATCOM)**. SATCOM is becoming increasingly important in its ability to facilitate global communication between aircraft and the ground for both crew and passenger use. Chapter 1 has been updated accordingly.
- **Space weather**. The subject of space weather was not included in the first edition but has been given some attention in recent EASA and CAA publications. The UK CAA (CAP 1428) recommends the aviation industry should "initiate educational programmes that provide staff with a greater understanding of the impact of severe space weather events on their operations and to ensure that the risk of extreme space weather is captured in their Safety Management System (SMS)". Conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere can influence the performance and reliability of aircraft avionic systems. Space weather can impact on several of the systems included in this book, e.g. HF communications, GNSS and satellite communications. Introductory notes havetherefore been included in Chapter 1.
- **GPS**. Although GPS operates in the same was as it always has, there are more aircraft flying now using GPS for approaches and landings. Chapter 18 has been updated accordingly.
- **Electronic instruments/displays and Integrated systems**. (e.g. GA combined nav/com/GPS). Chapter 19 has been updated to reflect these changes.
- **Weather radar**. Chapter 20 has been updated to incorporate additional technologies used on General Aviation (GA) aircraft: lightning detection, and satellite datalink weather services.
- **Air traffic control (ATC)**. ADS-B is currently being introduced in Europe, North America and other areas worldwide. Chapter 21 has therefore been expanded to include Single European Sky and Future Navigation Systems (FANS).
- **Traffic alert and collision avoidance systems**. The low-cost FLARM® traffic awareness system for GA is becoming increasingly popular. Chapter 22 now includes a new section on FLARM.

In addition to this important new material the authors have attempted to respond to requests and suggestions from readers. For example, a review via the National Aerospace Library noted that the low range radio altimeter (LRRA) was "buried" within Chapter 12 (Instrument landing systems). It was not the intention of the authors to diminish the purpose or value of an LRRA. Although the LRRA is an integral part of ILS/autoland, the authors acknowledge that radio altimeters are often used as stand-alone systems, e.g. on rotorcraft for low-level operations. Accordingly, the section describing LRRA has been relocated to Chapter 8.

MLS, Doppler and hyperbolic navigation systems, although not currently in widespread use for aviation, continue to feature in the EASA Part -66 syllabus and so remain in order to satisfy the need for full coverage of this important syllabus.

New EASA rules for aircraft maintenance for GA have been introduced via EASA 208598 leaflet 03; Flying in the EU'. This leaflet describes simpler Part-66 licences for GA aircraft mechanics (B2L and L licences). It also describes CS-STAN; this has been introduced for standard changes and standard repairs. These can be incorporated on the aircraft by a mechanic immediately, i.e. there is no need to have it approved by the EASA or by a design organisation. Examples include installation of VHF voice communication systems and FLARM equipment (as mentioned earlier, the latter has been added as a new section in Chapter 22.)

A new section has been added into Chapter 8 for minimum navigation performance specifications (MNPS) required for remote areas, e.g. in the North Atlantic. This new section also references reduced vertical separation minimums (RVSM); this allows aircraft to fly with a vertical separation of 1000 feet between FL290 and FL410 inclusive. Further information on RVSM is given in another title in this book series, AFIGS. Chapter 8 also includes a new section on electronic flight bags (EFB); these are replacing traditional paper-based documents, e.g. navigation charts.

Several high-profile accidents have occurred since the first edition was published, in particular flight AF447 (June 2009) and flight MH370 (March 2014). These accidents have highlighted shortcomings in the way that flights are currently tracked. The subsequent investigations into these two accidents is beyond the scope of this book, and indeed the book series; however, the subjects covered by the book series are very topical in the context of the accident investigations:

- Air Traffic Control (Chapter 21)
- Emergency Locator Transmitters (Chapter 7)
- Flight Data Recorders (covered in AEES)
- Satellite Communications (Chapter 1)
- Satellite Navigation (Chapter 18).

Aeroplanes flying over land with a high density of population are permanently tracked by air traffic control (ATC) systems, as described in Chapter 21. Aeroplanes flying over remote regions, e.g. oceans, polar routes, etc., will have limited, if any, ATC surveillance. The frequency of position reports by pilots or aircraft to ATC in remote and oceanic airspace is not systematic. Instead, it varies at certain intervals, depending on the density of the airspace and the procedures in place. In order to improve the positioning of aeroplanes in remote areas, the International Civil Aviation Organization (ICAO) has adopted international standards for the:

- location of aircraft and recorders using underwater beacons
- tracking of aircraft
- location system for aircraft in distress
- fast recovery of data from flight recorders.

These standards are expected to be introduced between 2018 and 2021. The reader is encouraged to follow developments, mandates and rule making via the industry media.

One technology that has become both an opportunity and a threat is that of remotely piloted aircraft systems (RPAS), unmanned aerial vehicles (UAV), or 'drones'. A recent EASA report, 'Drone Collision' Task Force Final Report (04/10/16), illustrates the increasing number of RPAS occurrences per year between 2010 (virtually zero) and 2015 (circa 500). The report discusses airborne conflict (defined as a potential collision between a drone and an aircraft in the air) being the most common type of occurrence. There are increasing commercial and military requirements for using RPAS in controlled airspace. This subject is not specifically addressed in this new edition. However, some of the technology described in this book could be adapted in the future to account for RPAS. The reader is encouraged to follow industry media on this subject, e.g. mandates and rule making.

A recent article published by the RAeS (Aerospace, November 2016) discusses the subject of "remote control tower" technology, i.e. enabling air traffic controllers to manage flights from remote airports without the need for a manned control tower. The authors believe that this will not affect the on-board systems, e.g. VHF communications, transponders, etc., and so the technology is not described in any detail in this second edition. At the time of publishing this second edition, trials are still being conducted; the reader is encouraged to monitor developments via the industry press, e.g. mandates and rule making.

Unscheduled maintenance for any aircraft system is more expensive than scheduled maintenance. Furthermore, an avionic unit that is removed, but subsequently tested and found to be serviceable is deemed No Fault Found. The cost of NFFs, i.e. cost of time to remove, logistics costs for returning it to a repair shop, costly test equipment, higher inventories etc. can all be reduced when the maintenance technician has a thorough understanding of systems and equipment. NFFs may also cause expensive flight delays or cancellations. Although NFFs are common with avionic equipment, it is in everyone's interest to minimise occurrences.

Importantly, this second edition introduces "Key Maintenance Points" covering very basic system testing to give additional understanding of systems. Troubleshooting starts (where possible) with a debriefing from the pilots and asking the right questions. The latter can be greatly enhanced by having a thorough understanding of how the system works, theory of operation, etc.

Finally, please note that, in order to be consistent with the EASA definitions, this book adopts the following terminology:

- 'Aeroplane' means an engine-driven, fixed -wing aircraft heavier than air that is supported in flight by the dynamic reaction of the air against its wings.
- 'Rotorcraft' means a heavier-than-air aircraft that depends principally for its support in flight on the lift generated by one or more rotors.
- 'Helicopter' means a rotorcraft that, for its horizontal motion, depends principally on its engine-driven rotors.
- 'Aircraft' means a machine that can derive support in the atmosphere from the reactions of the air other than the reactions of the air against the earth's surface. In this book, 'aircraft' applies to both aeroplanes and rotorcraft.

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Online resources

Additional resources and interactive materials are available at the book's companion website at **www.66web.co.uk**.

Chapter 1 Introduction

Maxwell first suggested the existence of electromagnetic waves in 1864. Later, Heinrich Rudolf Hertz used an arrangement of rudimentary resonators to demonstrate the existence of electromagnetic waves. Hertz's apparatus was extremely simple and comprised two resonant loops, one for transmitting and the other for receiving. Each loop acted both as a tuned circuit and as a resonant antenna (or 'aerial').

Hertz's transmitting loop was excited by means of an induction coil and battery. Some of the energy radiated by the transmitting loop was intercepted by the receiving loop, and the received energy was conveyed to a spark gap where it could be released as an arc. The energy radiated by the transmitting loop was in the form of an **electromagnetic wave**—a wave that has both electric and magnetic field components and travels at the speed of light.

In 1894, Marconi demonstrated the commercial potential of the phenomenon that Maxwell predicted and Hertz actually used in his apparatus. It was also Marconi that made radio a reality by pioneering the development of telegraphy without wires (i.e. 'wireless'). Marconi was able to demonstrate very effectively that information could be exchanged between distant locations without the need for a 'land-line'.

Marconi's system of **wireless telegraphy** proved to be invaluable for maritime communications (ship to ship and ship to shore) and was to be instrumental in saving many lives. The military applications of radio were first exploited during the First World War (1914 to 1918) and, during that period, radio was first used in aircraft.

This first chapter has been designed to set the scene and to provide you with an introduction to the principles of radio communication systems. The various topics are developed more fully in the later chapters, but the information provided here is designed to provide you with a starting point for the theory that follows.

1.1 The radio frequency spectrum

Radio frequency signals are generally understood to occupy a frequency range that extends from a few tens of kilohertz (kHz) to several hundred gigahertz (GHz). The lowest part of the radio frequency range that is of practical use (below 30 kHz) is only suitable for narrow-band communication. At this frequency, signals propagate as ground waves (following the curvature of the earth) over very long distances. At the other extreme, the highest frequency range that is of practical importance extends above 30 GHz. At these microwave frequencies, considerable bandwidths are available (sufficient to transmit many television channels using point-to-point links or to permit very high definition radar systems), and signals tend to propagate strictly along line-of-sight paths.

At other frequencies signals may propagate by various means including reflection from ionised layers in the ionosphere. At frequencies between 3 MHz and 30 MHz ionospheric propagation regularly permits intercontinental broadcasting and communications.

For convenience, the radio frequency spectrum is divided into a number of bands (see Table 1.1), each spanning a decade of frequency. The use to which each frequency range is put depends upon a number of factors, paramount among which is the propagation characteristics within the band concerned. In addition, various bands are set aside for radar use, and these are designated by letters (see Table 1.2). The use to which each band is put depends largely on how radio waves propagate within the band in question and also on the working range and target resolution that can be achieved.

Other factors that need to be taken into account include the efficiency of practical aerial systems in the range concerned and the bandwidth available. It is also worth noting that, although it may appear from Figure 1.1 that a great deal of the radio frequency spectrum is not used, it should be stressed that competition for frequency space is fierce and there is, in fact, little vacant

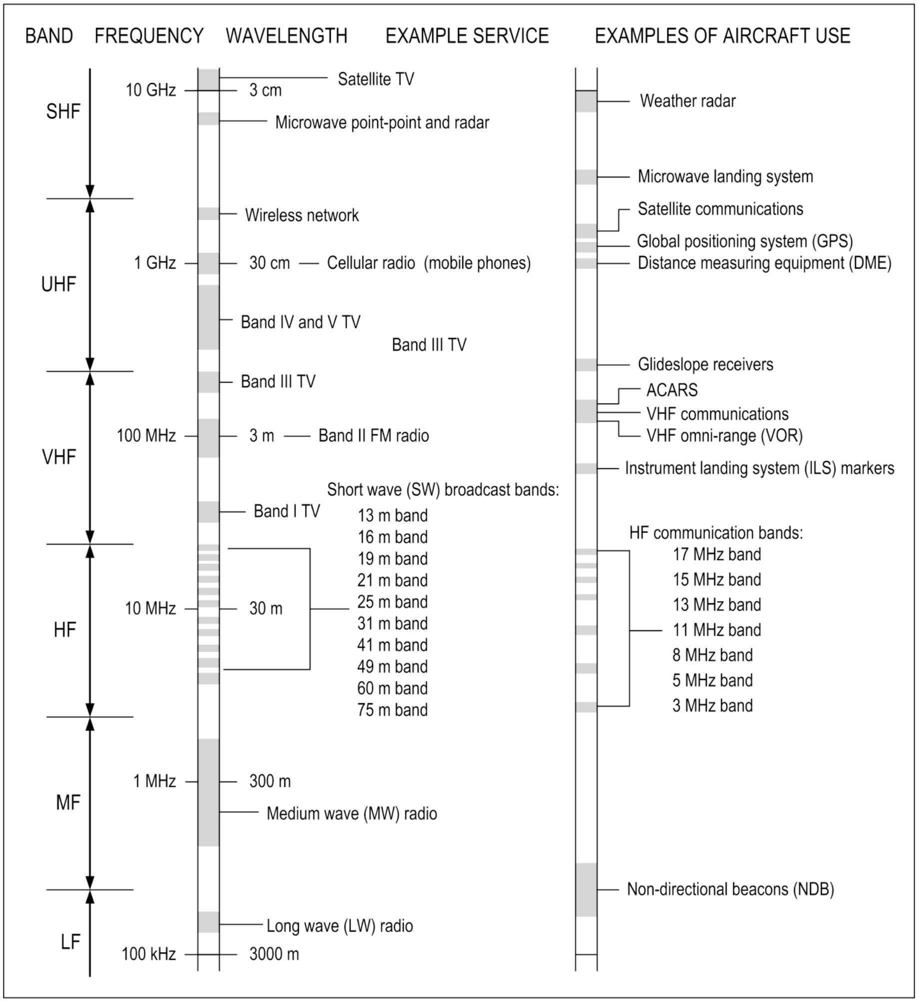

Figure 1.1 Some examples of frequency allocations within the radio frequency spectrum

Table 1.1 Frequency bands

Frequency range	*Wavelength*	*Designation*
300 Hz to 3 kHz	1000 km to 100 km	Extremely low frequency (ELF)
3 kHz to 30 kHz	100 km to 10 km	Very low frequency (VLF)
30 kHz to 300 kHz	10 km to 1 km	Low frequency (LF)
300 kHz to 3 MHz	1 km to 100 m	Medium frequency (MF)
3 MHz to 30 MHz	100 m to 10 m	High frequency (HF)
30 MHz to 300 MHz	10 m to 1 m	Very high frequency (VHF)
300 MHz to 3 GHz	1 m to 10 cm	Ultra high frequency (UHF)
3 GHz to 30 GHz	10 cm to 1 cm	Super high frequency (SHF)

Table 1.2 Radar bands

Band designation	*Frequency*	*Wavelength*	*Typical aircraft radar application*
L	1 GHz to 2 GHz	30 cm to 15 cm	Distance measuring equipment (DME)
S	2 GHz to 4 GHz	15 cm to 7.5 cm	Airport surveillance radar (ASR)
C	4 GHz to 8 GHz	7.5 cm to 3.75 cm	Microwave landing systems (MLS)
X	8 GHz to 12 GHz	3.75 cm to 2.5 cm	Weather radar (WXR)
K_u	12 GHz to 18 GHz	2.5 cm to 1.67 cm	
K	18 GHz to 26 GHz	1.67 cm to 1.11 cm	
K_a	26 GHz to 40 GHz	1.11 cm to 7.5 mm	Military combat aircraft

space! Frequency allocations are, therefore, ratified by international agreement and the various user services carefully safeguard their own areas of the spectrum.

1.2 Electromagnetic waves

As with light, radio waves propagate outwards from a source of energy (transmitter) and comprise electric (E) and magnetic (H) fields at right angles to one another. These two components, the **E-field** and the **H-field**, are inseparable. The resulting wave travels away from the source with the E and H lines mutually at right angles to the direction of **propagation**, as shown in Figure 1.2.

Radio waves are said to be **polarised** in the plane of the electric (E) field. Thus, if the E-field is vertical, the signal is said to be vertically polarised, whereas, if the E-field is horizontal, the signal is said to be horizontally polarised.

Figure 1.3 shows the electric E-field lines in the space between a transmitter and a receiver. The transmitter aerial (a simple dipole, see page 26) is supplied with a high frequency alternating current. This gives rise to an alternating electric field between the ends of the aerial and an alternating magnetic field around (and at right angles to) it.

The direction of the E-field lines is reversed on each cycle of the signal as the **wavefront** moves outwards from the source. The receiving aerial intercepts the moving field and voltage and current is induced in it as a consequence. This voltage and current is similar (but of smaller amplitude) to that produced by the transmitter.

Note that in Figure 1.3 (where the transmitter and receiver are close together) the field is shown spreading out in a spherical pattern (this is known more correctly as the **near field**). In practice there will be some considerable distance between the transmitter and the receiver, and so the wave that

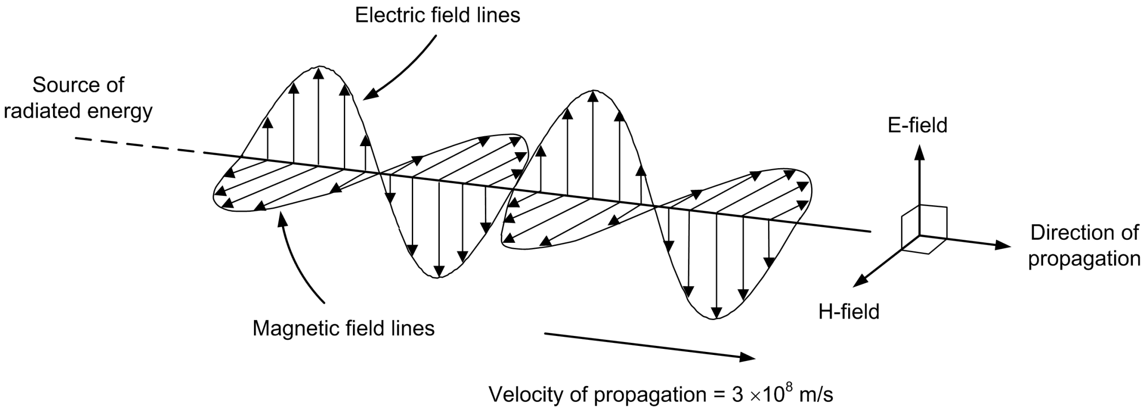

Figure 1.2 An electromagnetic wave

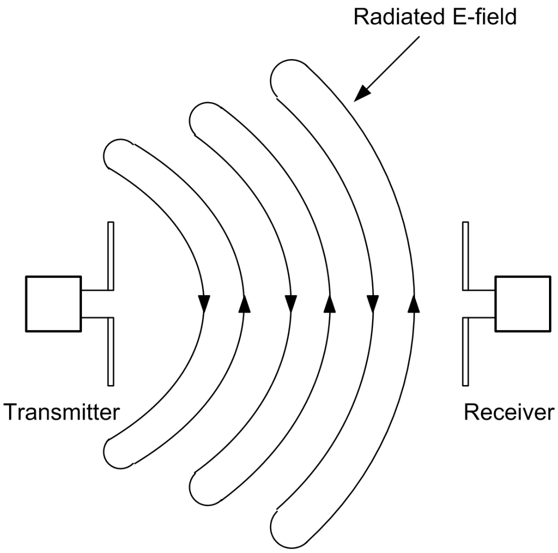

Figure 1.3 Electric field pattern in the near field region between a transmitter and a receiver (the magnetic field has not been shown but is perpendicular to the electric field)

reaches the receiving antenna will have a plane wavefront. In this far field region the angular field distribution is essentially independent of the distance from the transmitting antenna.

1.3 Frequency and wavelength

Radio waves propagate in air (or space) at the **speed of light** (300 million meters per second). The velocity of propagation, *v*, wavelength, *λ*, and frequency, *f*, of a radio wave are related by the equation:

$$v = f\lambda = 3 \times 10^8 \text{ m/s}$$

This equation can be arranged to make *f* or *λ* the subject, as follows:

$$f = \frac{3 \times 10^8}{\lambda} \text{ Hz} \quad \text{and} \quad \lambda = \frac{3 \times 10^8}{f} \text{ m}$$

As an example, a signal at a frequency of 1 MHz will have a wavelength of 300 m, whereas a signal at a frequency of 10 MHz will have a wavelength of 30 m.

When a radio wave travels in a cable (rather than in air or 'free space') it usually travels at a speed that is between 60% and 80% of that of the speed of light.

Example 1.1

Determine the frequency of a radio signal that has a wavelength of 15 m.

Here we will use the formula $f = \frac{3 \times 10^8}{\lambda}$ Hz

Putting $\lambda = 15$ m gives:

$$f = \frac{3 \times 10^8}{15} = \frac{300 \times 10^6}{15} = 20 \times 10^6 \text{ Hz or } 20 \text{ MHz}$$

Example 1.2

Determine the wavelength of a radio signal that has a frequency of 150 MHz.

In this case we will use $\lambda = \frac{3 \times 10^8}{f}$ m

Putting $f = 150$ MHz gives:

$$\lambda = \frac{3 \times 10^8}{f} = \frac{3 \times 10^8}{150 \times 10^6} = \frac{300 \times 10^6}{150 \times 10^6} = 2 \text{ m}$$

Example 1.3

If the wavelength of a 30 MHz signal in a cable is 8 m, determine the velocity of propagation of the wave in the cable.

Using the formula where *v* is the velocity of propagation in the cable, $v = f\lambda$, gives:

$$v = f\lambda = 30 \times 10^6 \times 8 \text{ m} = 240 \times 10^6 = 2.4 \times 10^8 \text{ m/s}$$

Test your understanding 1.1

An HF communications signal has a frequency of 25.674 MHz. Determine the wavelength of the signal.

Test your understanding 1.2

A VHF communications link operates at a wavelength of 1.2 m. Determine the frequency at which the link operates.

1.4 The atmosphere

The earth's atmosphere (see Figure 1.4) can be divided into five concentric regions having boundaries that are not clearly defined. These layers, starting with the layer nearest the earth's surface, are known as the troposphere, stratosphere, mesosphere, thermosphere and exosphere.

The boundary between the troposphere and the stratosphere is known as the **tropopause** and this region varies in height above the earth's surface from about 7.5 km at the poles to 18 km at the equator. An average value for the height of the tropopause is around 11 km or 36,000 feet (about the same as the cruising height for most international passenger aircraft).

The thermosphere and the upper parts of the mesosphere are often referred to as the **ionosphere** and it is this region that has a major role to play in the long distance propagation of radio waves, as we shall see later.

The lowest part of the earth's atmosphere is called the **troposphere** and it extends from the surface up to about 10 km (6 miles). The atmosphere above 10 km is called the stratosphere, followed by the mesosphere. It is in the stratosphere that incoming solar radiation creates the ozone layer.

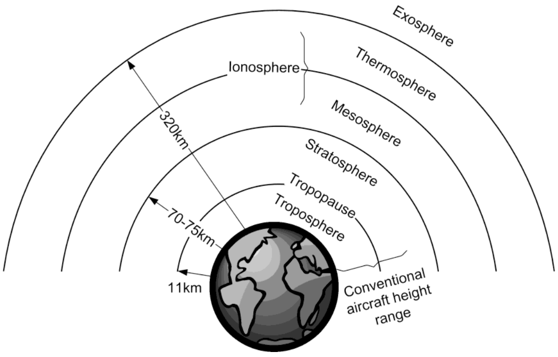

Figure 1.4 Zones of the atmosphere

1.5 Radio wave propagation

Depending on a number of complex factors, radio waves can propagate through the atmosphere in various ways, as shown in Figure 1.5. These include:

- ground waves
- ionospheric waves
- space waves
- tropospheric waves.

As their name suggests, **ground waves** (or **surface waves**) travel close to the surface of the earth and propagate for relatively short distances at HF and VHF but for much greater distances at MF and LF. For example, at 100 kHz the range of a ground wave might be in excess of 500 km whilst at 1 MHz (using the same radiated power) the range might be no more than 150 km and at 10 MHz no more than about 15 km. Ground waves have two basic components; a **direct wave** and a **ground reflected wave** (as shown in Figure 1.6). The **direct path** is that which exists on a line-of-sight (**LOS**) basis between the transmitter and receiver. An example of the use of a direct path is that which is used by terrestrial microwave repeater stations which are typically spaced 20 to 30 km apart on a LOS basis. Another example of the direct path is that used for satellite TV reception. In order to receive signals from the satellite the receiving antenna must be able to 'see' the satellite. In this case, and since the wave travels largely undeviated through the atmosphere, the direct wave is often referred to as a **space wave**. Such waves travel over LOS paths at VHF, UHF and beyond.

As shown in Figure 1.6, signals can arrive at a receiving antenna by both the direct path and by means of reflection from the ground. **Ground reflection** depends very much on the quality of the ground, with sandy soils being a poor reflector of radio signals and flat marshy ground being an excellent reflecting surface. Note that a proportion of the incident radio signal is absorbed into the ground and not all of it is usefully reflected. An example of the use of a mixture of direct path and ground (or building) reflected radio signals is the reception of FM broadcast signals in a car. It is also worth mentioning that, in many cases, the reflected signals can be

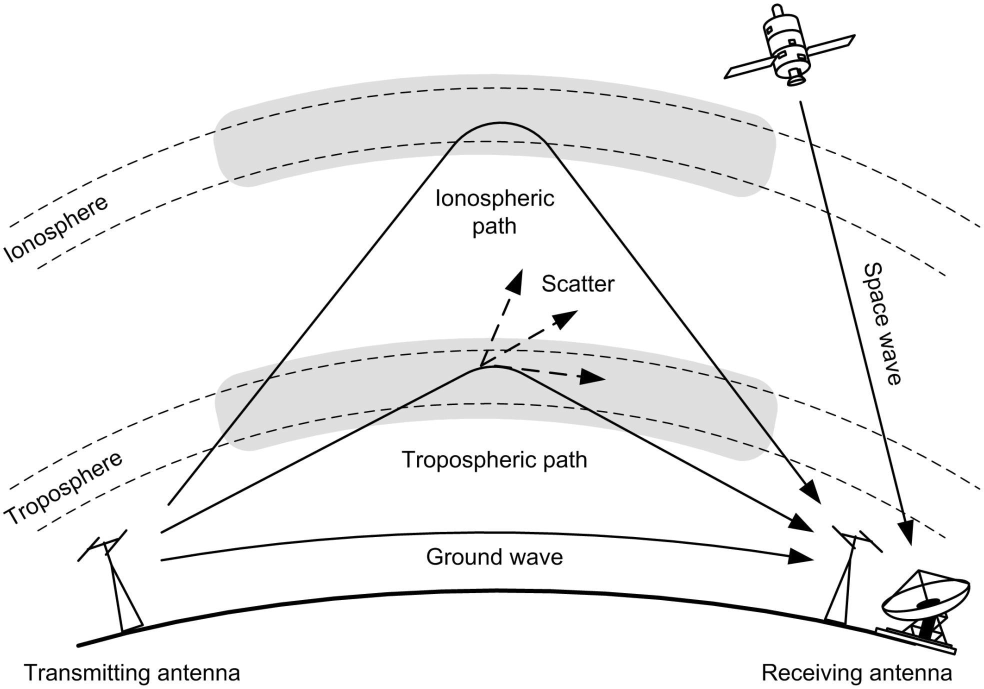

Figure 1.5 Radio wave propagation through the atmosphere

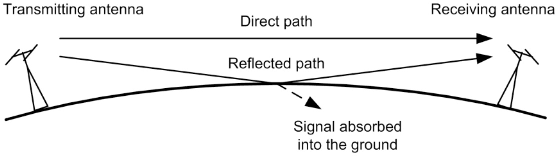

Figure 1.6 Constituents of a ground wave

stronger than the direct path (or the direct path may not exist at all if the car happens to be in a heavily built-up area).

Ionospheric waves (or **sky waves**) can travel for long distances at MF, HF and exceptionally also at VHF under certain conditions. Such waves are predominant at frequencies below VHF, and we shall examine this phenomenon in greater detail a little later, but before we do it is worth describing what can happen when waves meet certain types of discontinuity in the atmosphere or when they encounter a physical obstruction. In both cases, the direction of travel can be significantly affected according to the nature and size of the obstruction or discontinuity. Four different effects can occur (see Figure 1.7) and they are known as:

- reflection
- refraction
- diffraction
- scattering.

Reflection occurs when a plane wave meets a plane object that is large relative to the wavelength of the signal. In such cases the wave is reflected back with minimal distortion and without any change in velocity. The effect is similar to the reflection of a beam of light when it arrives at a mirrored surface.

Refraction occurs when a wave moves from one medium into another in which it travels at a different speed. For example, when moving from a more dense to a less dense medium the wave is bent away from the normal (i.e. an imaginary line constructed at right angles to the boundary). Conversely, when moving from a less dense to a more dense medium, a wave will bend towards the normal. The effect is similar to that

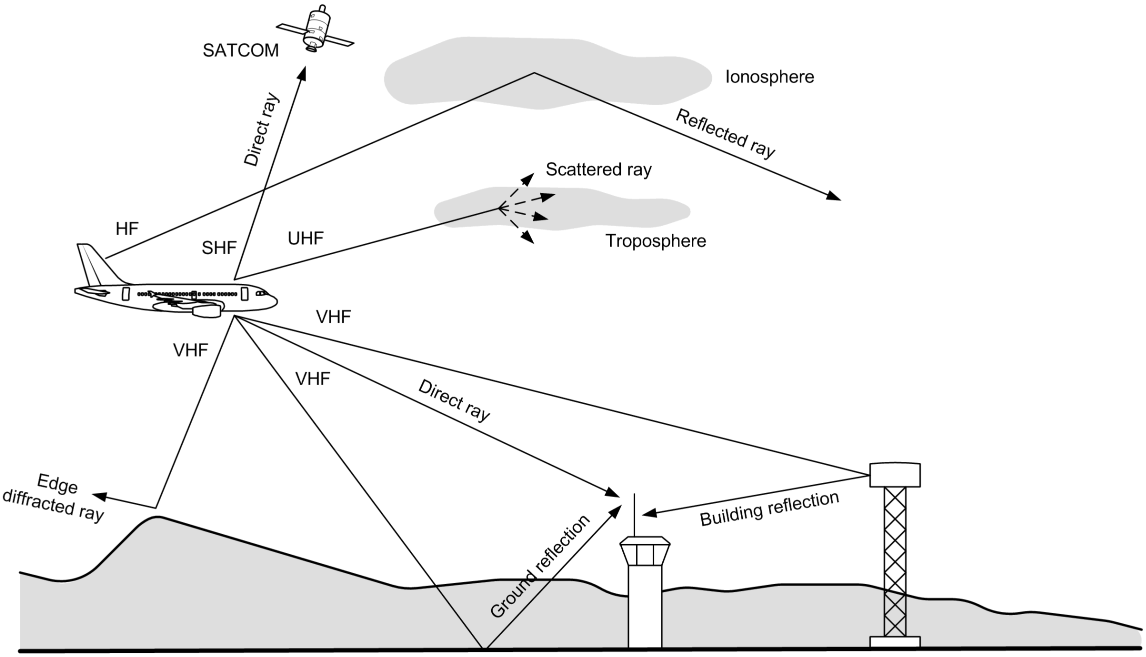

Figure 1.7 Various propagation effects

experienced by a beam of light when it encounters a glass prism.

Diffraction occurs when a wave meets an edge (i.e. a sudden impenetrable surface discontinuity) which has dimensions that are large relative to the wavelength of the signal. In such cases the wave is bent so that it follows the profile of the discontinuity. Diffraction occurs more readily at lower frequencies (typically VHF and below). An example of diffraction is the bending experienced by VHF broadcast signals when they encounter a sharply defined mountain ridge. Such signals can be received at some distance beyond the 'knife edge' even though they are well beyond the normal LOS range.

Scattering occurs when a wave encounters one or more objects in its path having a size that is a fraction of the wavelength of the signal. When a wave encounters an obstruction of this type it will become fragmented and re-radiated over a wide angle. Scattering occurs more readily at higher frequencies (typically VHF and above) and regularly occurs in the troposphere at UHF and EHF.

Radio signals can also be directed upwards (by suitable choice of antenna) so that signals enter the troposphere or ionosphere. In the former case, signals can be become scattered (i.e. partially dispersed) in the troposphere so that a small proportion arrives back at the ground. **Tropospheric scatter** requires high-power transmitting equipment and high-gain antennas but is regularly used for transmission beyond the horizon particularly where conditions in the troposphere (i.e. rapid changes of temperature and humidity with height) can support this mode of communication. Tropospheric scatter of radio waves is analogous to the scattering of a light beam (e.g. a torch or car headlights) when shone into a heavy fog or mist.

In addition to tropospheric scatter there is also **tropospheric ducting** (not shown in Figure 1.7) in which radio signals can become trapped as a result of the change of refractive index at a boundary between air masses having different temperature and humidity. Ducting usually occurs when a large mass of cold air is overrun by warm air (this is referred to as a temperature inversion). Although this condition may occur frequently in certain parts of the world, this mode of propagation is not very predictable and is therefore not used for any practical applications.

1.6 The ionosphere

In 1924, Sir Edward Appleton was one of the first to demonstrate the existence of a reflecting layer at a height of about 100 km (now called the E-layer). This was soon followed by the discovery of another layer at around 250 km (now called the F-layer). This was achieved by broadcasting a continuous signal from one site and receiving the signal at a second site several miles away. By measuring the time difference between the signal received along the ground and the signal reflected from the atmosphere (and knowing the velocity at which the radio wave propagates) it was possible to calculate the height of the atmospheric reflecting layer. Today, the standard technique for detecting the presence of ionised layers (and determining their height above the surface of the earth) is to transmit a very short pulse directed upwards into space and accurately measure the amplitude and time delay before the arrival back on earth of the reflected pulses. This **ionospheric sounding** is carried out over a range of frequencies.

The ionosphere provides us with a reasonably predictable means of communicating over long distances using HF radio signals. Much of the short and long distance communications below 30 MHz depend on the bending or refraction of the transmitted wave in the earth's ionosphere which are regions of ionisation caused by the sun's ultraviolet radiation and lying about 60 to 200 miles above the earth's surface.

The useful regions of ionisation are the E-layer (at about 70 miles in height for maximum ionisation) and the F-layer (lying at about 175 miles in height at night). During the daylight hours, the F-layer splits into two distinguishable parts: F_1 (lying at a height of about 140 miles) and F_2 (lying at a height of about 200 miles). After sunset the F_1 and F_2 layers recombine into a single F-layer (see Figures 1.8 and 1.10). During daylight, a lower layer of ionisation known as the D-layer exists in proportion to the sun's height, peaking at local noon and largely dissipating after sunset. This lower layer primarily acts to absorb energy in the low end of the high frequency (HF) band. The F-layer ionisation regions are primarily responsible for long distance communication using **sky waves** at distances of up to several thousand km (greatly in excess of those distances that can be achieved using VHF **direct wave** communication, see Figure 1.9). The characteristics of the ionised layers are summarised in Table 1.2 together with their effect on radio waves.

1.7 MUF and LUF

The **maximum usable frequency** (**MUF**) is the highest frequency that will allow communication over a given path at a particular time and on a particular date. MUF varies considerably with the amount of solar activity and is basically a function of the height and intensity of the F-layer. During a period of intense solar activity the MUF can exceed 30 MHz during daylight hours but is often around 16 to 20 MHz by day and around 8 to 10 MHz by night.

The variation of MUF over a 24-hour period for the London to New York path is shown in Figure 1.11. A similar plot for the summer months would be flatter with a more gradual increase in MUF at dawn and a more gradual decline at dusk.

The reason for the significant variation of MUF over any 24-hour period is that the intensity of ionisation in the upper atmosphere is significantly reduced at night and, as a consequence, lower frequencies have to be used to produce the same amount of refractive bending and also to give the same critical angle and skip distance as by day. Fortunately, the attenuation experienced by lower frequencies travelling in the ionosphere is much reduced at night and this makes it possible to use the lower frequencies required for effective communication. The important fact to remember from this is simply that, for a given path, the frequency used at night is about half that used for daytime communication.

The **lowest usable frequency** (**LUF**) is the lowest frequency that will support communication over a given path at a particular time and on a particular date. LUF is dependent on the amount of absorption experienced by a radio wave. This absorption is worse when the D-layer is most intense (i.e. during daylight). Hence, as with MUF, the LUF rises during the day and falls during the night. A typical value of LUF is 4 to 6 MHz during the day, falling rapidly at sunset to 2 MHz.

Table 1.2 Ionospheric layers

Layer	*Height (km)*	*Characteristics*	*Effect on radio waves*
D	50 to 95 km	Develops shortly after sunrise and disappears shortly after sunset. Reaches maximum ionisation when the sun is at its highest point in the sky	Responsible for the absorption of radio waves at lower frequencies (e.g. below 4 MHz) during daylight hours
E	95 to 150 km	Develops shortly after sunrise and disappears a few hours after sunset. The maximum ionisation of this layer occurs at around midday	Reflects waves having frequencies less than 5 MHz but tends to absorb radio signals above this frequency
E_S	80 to 120 km	An intense region of ionisation that sometimes appears in the summer months (peaking in June and July). Usually lasts for only a few hours (often in the late morning and recurring in the early evening of the same day)	Highly reflective at frequencies above 30 MHz and up to 300 MHz on some occasions. Of no practical use other than as a means of long-distance VHF communication for radio amateurs
F	250 to 450 km	Appears a few hours after sunset, when the F_1- and F_2-layers (see below) merge to form a single layer	Reflects radio waves up to 20 MHz and occasionally up to 25 MHz
F_1	150 to 200 km	Occurs during daylight hours with maximum ionisation reached at around midday. The F_1 -layer merges with the F_2-layer shortly after sunset	Reflects radio waves in the low HF spectrum up to about 10 MHz
F_2	250 to 450 km	Develops just before sunrise as the F-layer begins to divide. Maximum ionisation of the F_2-layer is usually reached one hour after sunrise and it typically remains at this level until shortly after sunset. The intensity of ionisation varies greatly according to the time of day and season and is also greatly affected by solar activity	Capable of reflecting radio waves in the upper HF spectrum with frequencies of up to 30 MHz and beyond during periods of intense solar activity (i.e. at the peak of each 11-year sunspot cycle)

The frequency chosen for HF communication must therefore be somewhere above the LUF and below the MUF for a given path, day and time. A typical example might be a working frequency of 5 MHz at a time when the MUF is 10 MHz and the LUF is 2 MHz.

Figure 1.12 shows the typical MUF for various angles of attack together with the corresponding working ranges. This diagram assumes a **critical frequency** of 5 MHz. This is the lowest frequency that would be returned from the ionosphere using a path of vertical incidence (see ionospheric sounding on page 8).

The relationship between the critical frequency, $f_{\text{crit.}}$, and electron density, N, is given by:

$$f_{\text{crit.}} = 9 \times 10^{-3} \times \sqrt{N}$$

where N is the electron density expressed in cm^3.

The angle of attack, α, is the angle of the transmitted wave relative to the horizon.

The relationship between the MUF, $f_{\text{m.u.f.}}$, the critical frequency, $f_{\text{crit.}}$, and the angle of attack, α, is given by:

$$f_{\text{m.u.f.}} = \frac{f_{\text{crit.}}}{\sin \alpha}$$

Example 1.4

Given that the electron density in the ionosphere is 5×10^5 electrons per cm^3, determine the critical frequency and the MUF for an angle of attack of 15°.

Now using the relationship $f_{\text{crit.}} = 9 \times 10^{-3} \times \sqrt{N}$ gives:

$$f_{\text{crit.}} = 9 \times 10^{-3} \times \sqrt{5 \times 10^5} = 6.364 \text{ MHz}$$

The MUF can now be calculated using:

$$f_{\text{m.u.f.}} = \frac{f_{\text{crit.}}}{\sin \alpha} = \frac{6.364}{\sin 15°} = \frac{6.364}{0.259} = 24.57 \text{ MHz}$$