# Chapter 1

# Radio wave propagation and the frequency spectrum

## 1.1 Introduction

This chapter outlines the basic principles of signal propagation and the radio frequency spectrum used by the navigation systems likely to be encountered on board merchant ships. The use of radio waves for terrestrial global communications and navigation causes major problems, particularly in the areas of frequency allocation and interference. Consequently, for safe and efficient working practices to be maintained on the restricted radio frequency spectrum, it is essential that this limited resource is carefully policed.

Radio waves cannot and do not respect international boundaries and, consequently, disputes arise between nations over the use of radio frequencies. The international governing body for radio communications services is the International Telecommunications Union (ITU) which, quite rightly, strictly regulates the allocation and use of frequencies. Any dispute that arises is settled by the ITU through various committees and affiliated organizations. All users of radiocommunications systems must be aware that they are licensed to use only specific frequencies and systems in order to achieve information transfer. It would be chaos if this were not so. Essential services, aeronautical, maritime or land based, would not be able to operate otherwise and lives could well be put at risk.

## 1.2 Maritime navigation systems and their frequencies

Maritime radio navigation requirements have always posed unique problems for the shipboard operator. A ship at sea presents many difficulties to the radio communications design engineer. The ship is constructed of steel which, when floating in salt water, becomes a very effective electromagnetic screen capable of rejecting or reflecting radio waves. In addition, modern ocean-going vessels are streamlined, spelling an end to those sturdy structures, i.e. smoke stacks and masts, that traditionally were used for holding antenna systems. Consequently, shipboard antenna systems tend to be less efficient than was once the case, giving rise to difficulties in both transmission and reception.

Maritime radio navigation and communication systems operate in a number of frequency bands. Listed below is a brief summary.

- Loran-C on the medium frequency 100 kHz.
- Navtex data on 518 kHz.
- Voice, radiotelex and digital selective calling in medium frequency band 1.6–3.4 MHz.
- Voice, radiotelex and DSC in high frequency bands between 3 and 30 MHz
- Voice and DSC in the very high frequency band 30–300 MHz.

- RADAR and SART on the frequency of 9 GHz.
- GPS satellite signals on L-band frequencies.
- INMARSAT communications signals on L-band frequencies.

In each case, the carrier frequency used has been chosen to satisfy two main criteria, those of geographical range and the ability to carry the relevant information. The geographical range of a radio wave is affected by many parameters, but in the context of this book, range may basically be related to the choice of frequency band, which in turn determines the method of radio wave propagation.

## 1.3 Radio wave radiation

The propagation of radio waves is a highly complex natural phenomenon. It is simplified in the following pages to provide an understanding of the subject with a level of knowledge necessary to comprehend modern navigation systems.

Energy is contained in a transmitted radio wave in two forms, electrostatic energy and electromagnetic energy. The radiation of energy from a simple antenna may be described by considering a centre-fed dipole antenna, which is shown electrically in Figure 1.1.

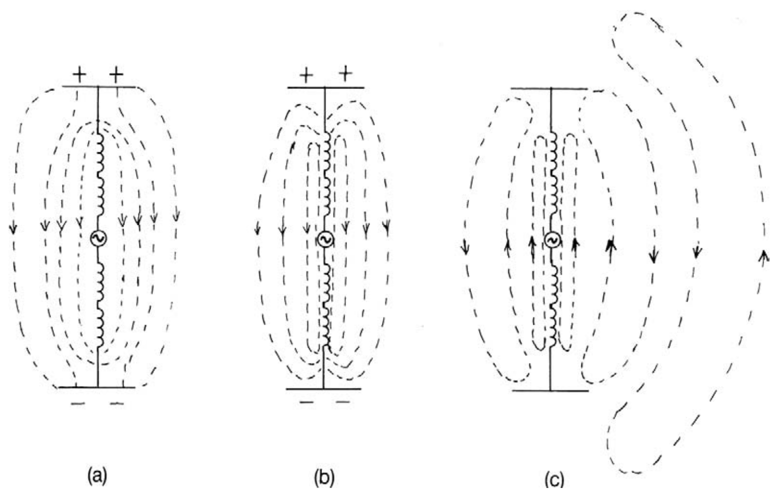


**Figure 1.1** Radio wave radiation from a centre-fed dipole antenna.

The antenna shown is formed of two coils, each end of which is at the opposite potential to the other with reference to the centre point. As a complete unit, the antenna forms a tuned circuit that is critically resonant at the carrier frequency to be radiated. The two plates, one at each end of the coil assembly, form a capacitor. Radio frequency current, from the output stage of a suitable transmitter, shown here as a generator, is applied at the centre of the two coils. One of the basic electrical laws of physics states that whenever an electron has its velocity altered by an accelerating force there will be a detachment of energy. In the case of an antenna system this detachment is the energy that is lost from the transmitter and radiated as electrical energy into the atmosphere.

The diagrams clearly show the distribution of the electric field produced around an antenna when an oscillatory radio frequency is applied to it. In Figure 1.1(a) the top plate of the antenna is instantaneously driven positive with respect to the base plate and the current flow in the wire is zero. At this instant the field produced is entirely electric and the electrostatic lines of force are as shown in the diagram.

After the peak of the signal has passed, electrons will begin to flow upwards to produce a current flow in the wire. The electric field will now start to collapse (Figure 1.1(b)) and the ends of the lines of force come together to form loops of electrostatic energy. After the potential difference (positive top plate to negative base plate) across the two plates of the effective capacitor has fallen to zero, current continues to flow and, in so doing, starts to charge the effective capacitor plates in the opposite direction. This charge forms new lines of force in the reverse direction to the previous field, negative to the top plate and positive at its base. The collapse of the initial electrostatic field lags the change in potential that caused it to occur and, consequently, the new electric field starts to expand before the old field has completely disappeared. The electric fields thus created (Figure 1.1(c)) will be caused to form loops of energy, with each new loop forcing the previous loop outwards, away from the antenna. Thus, radio frequency energy is radiated as closed loops of electrostatic energy.

Because a minute current is flowing around each complete loop of energy, a magnetic field will be created around the loop at 90° to it. Thus, the magnetic lines of force produced around the vertical electric field created by a vertical antenna, will be horizontal. Two fields of energy, in space quadrature, have thus been created and will continue in their relative planes as the radio wave moves away from the transmitting antenna.

The electric and magnetic inductive fields are in both time and space quadrature and are 90°out of phase with each other in time, and at right angles to each other in space. The electric field is of greatest importance to the understanding of radio wave propagation, the magnetic field only being present when current flows around the loop as the electric field changes.

Figure 1.2 shows the relative directions of the electric field ($E$), the magnetic field ($H$) and the direction of propagation. The oscillating electric field is represented by the vertical vector OE, the magnetic field by OH, and the direction of propagation by OD. Another electrical law of physics, Fleming's right-hand rule, normally applied to the theory of electrical machines, applies equally to the direction of propagation of the radio wave.

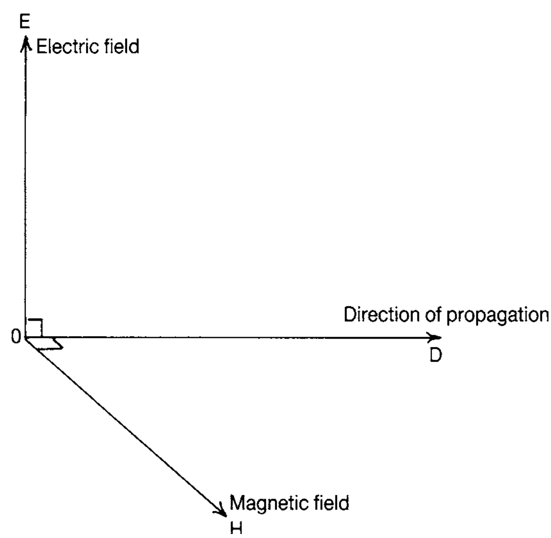


**Figure 1.2** The angular relationship of the E and H fields.

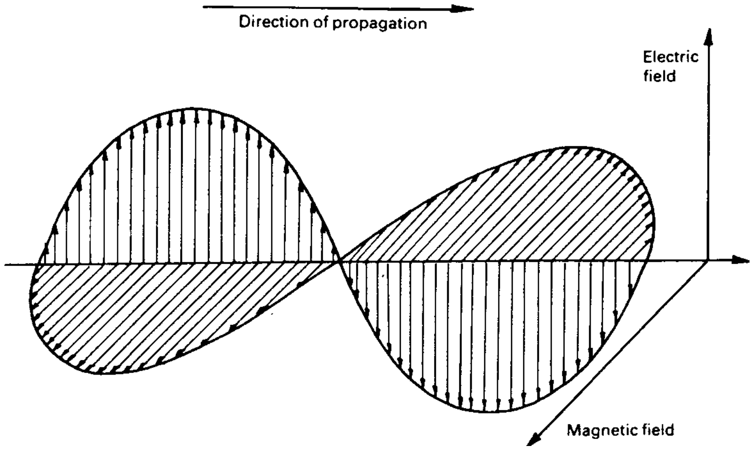


**Figure 1.3** Amplitude variations of the E and H fields.

At any instantaneous point along the sinusoidal wave of the electric field it is possible to measure a minute current flow in the loop of energy. The current will be increasing and decreasing as it follows the rate of change of amplitude of the sinusoidal frequency (carrier wave) of the radio wave (see Figure 1.3). It is this instantaneous change of current which, when in contact with a receiving antenna, causes a current to flow at the receiver input and a minute signal voltage, called an electromotive force (e.m.f.), to appear across the antenna input.

The transmitted signal may now be considered to be a succession of concentric loops of ever-increasing radius, each one a wavelength ahead of the next. Radio waves thus produced will be similar in appearance to the waves caused on the surface of a pond when a rock is tossed into it. Similarly, the radio waves radiate outwards from the source and diminish in amplitude with distance travelled from the transmitter. Each loop moves away from the transmitting antenna at the speed of light in free space, usually approximated to be $300 \times 10^6\,\mathrm{ms}^{-1}$, and it is common practice to call the leading edge of each loop a wavefront. The distance between each wavefront depends upon the frequency being radiated and is called the wavelength, λ (lambda).

## 1.4 Frequency, wavelength and velocity

Although a variable, the velocity of electromagnetic radio waves propagated in the troposphere, close to the earth's surface, is accepted to be $300 \times 10^6\,\mathrm{ms}^{-1}$. This figure is important because it enables the wavelength of a transmitted frequency to be calculated and from that a number of other essential parameters can be determined.

$$\text{Wavelength } \lambda = \frac{300 \times 10^6}{\text{Frequency}} \text{ (in metres)}$$

The actual length of one radio wave during one alternating cycle is a measure of the distance travelled, and the number of alternating cycles per second is a measure of the frequency.

## 1.5 Radio frequency spectrum

Table 1.1 indicates how the available frequency spectrum has been divided into usable bands. By referring to this table it is possible to gain some initial idea of the approximate range over which radio waves may be received. For instance, if all other parameters remain constant, the anticipated radio range of signals propagated on the VHF band, or those higher, is effectively that of 'line-of-sight'. Consequently, ship-to-ship communications between a life-raft and a surface vessel could expect to have a range of 2–7 nautical miles depending upon the system installation and the relative heights of the antennae. Because of its line-of-sight nature, VHF radio ranges beyond the horizon can only be achieved by using repeater stations or satellites. Maritime mobile satellite systems use much higher frequencies in what is termed the L band and the C band, each providing a line-of-sight link.

**Table 1.1** The frequency spectrum

| *Abbreviation* | *Band* | *Frequency range* | *Wavelength* |
|---|---|---|---|
| AF | Audio | 0 Hz–20 kHz | ∞ to 15 km |
| RF | Radio | 10 kHz–300 GHz | 30 km to 0.1 cm |
| VLF | Very low | 10–30 kHz | 30 km to 10 km |
| LF | Low | 30–300 kHz | 10 km to 1 km |
| MF | Medium | 300–3000 kHz | 1 km to 100 m |
| HF | High | 3–30 MHz | 100 m to 10 m |
| VHF | Very high | 30–300 MHz | 10 m to 1 m |
| UHF | Ultra high | 300–3000 MHz | 1 m to 10 cm |
| SHF | Super high | 3–30 GHz | 10 cm to 1 cm |
| EHF | Extreme high | 30–300 GHz | 1 cm to 0.1 cm |

### 1.5.1 Spectrum management

Radio waves do not respect international boundaries and an international framework has been established in order to control the use of frequencies, the standards of manufacture and the operation of radio equipment in order to limit the likelihood of interference. The forum for reaching international agreements on the use of the radio frequency spectrum is the International Telecommunications Union (ITU). Membership of the ITU is dependent upon acceptance of the strict convention which exists to uphold the regulations laid down by the various conferences and meetings of the ITU.

The radio spectrum management policies agreed among the signatories of the convention are published by the ITU as international radio regulations. One of these is the international Table of Frequency Allocations, which provides the framework for, and the constraints on, national frequency use and planning. The Table of Frequency Allocations and the radio regulations documents are revised at the World Administrative Radio Conferences (WARC) held at periods of 5–10 years.

The administrative structure established by the ITU convention comprises a Secretariat headed by the Secretary General, an Administrative Council, a registration board for radio frequencies, and the consultative committees for radio and telecommunications.

The International Radio Consultative Committee (CCIR) forms study groups to consider and report on the operational and technical issues relating to the use of radio communications. The International Telecommunications Consultative Committee (CCIT) offers the same service for telecommunications. The study groups produce recommendations on all aspects of radio communications. These recommendations are considered by the Plenary Assembly of the CCIR and, if accepted, are incorporated into the radio regulations. Another subgroup of the ITU, the International Frequency Registration Board (IFRB) considers operating frequencies, transmitter sites, and the location of satellites in orbit. Within Europe, a further body, the Conference of European Telecommunications Administrations (CEPT) assists with the implementation of the ITU radio regulations on a national level. Every country appoints an agency to enact the radio regulations thus laid down. In the United Kingdom for instance it is the Radiocommunications Agency and in the USA, civil use of the radio frequency spectrum is controlled by the Federal Communications Commission.

## 1.6 Radio frequency bands

Radio wave propagation characteristics (see Table 1.2) are dependent upon the frequency used.

**Table 1.2** Radio frequency band characteristics

| *Designation & Frequency* | *Propagation Mode* | *Characteristics* |
|---|---|---|
| Very low frequency 3–30 kHz | Large surface wave | Very high power transmitters and large antennae needed |
| Low frequency 30–300 kHz | Surface wave and some sky wave returns | High power transmitters; limited number of channels; subject to fading |
| Medium frequency 0.3–3 MHz | Surface wave during day. Some sky wave returns at night | Long range at night; subject to fading |
| High frequency 3–30 MHz | Sky waves returned over long distances | Global ranges using ionospheric returns |
| Very high frequency 30–300 MHz | Mainly space wave. Line of site | Range depends upon antenna height |
| Ultra high frequency 0.3–3 GHz | Space wave only | Line of sight; satellite and fixed link |
| Super high frequency 3–30 GHz | Space wave only | Line of sight; radar and satellite |
| Extreme high frequency 30–300 GHz | Space wave only | Not used for mobile communications |

### 1.6.1 VLF (very low frequency) band

VLF radio signals propagate using a combination of both ground and space waves. They require vast amounts of power at the transmitter to overcome earth surface attenuation and can be guided over great distances between the lower edge of the ionosphere and the ground. Because VLF possesses a very long wavelength, huge antenna systems are required. As an example, at 10 kHz the wavelength is 30 km. An efficient antenna, often quoted as ‘a half-wavelength antenna’, needs to be 15 km long and it is only possible to construct one on land, usually slung between mountain peaks.

### 1.6.2 LF (low frequency) band

Communication is mainly by a ground wave, which suffers increasing attenuation as the frequency increases. Range therefore depends upon the amplitude of the transmitted power and the efficiency of the antenna system. Expected range for a given low frequency and transmitter power is between 1500 and 2000 km. At LF the wavelength is reduced to a point where small-size antennae are practicable. Although the sky wave component of LF propagation is small it can be troublesome at night when it is returned from the ionosphere.

### 1.6.3 MF (medium frequency) band

Ground wave attenuation rapidly increases with frequency to the point where, at the higher end of the band, its effect becomes insignificant. For a given transmitter power, therefore, ground wave range is inversely proportional to frequency. Range is typically 1500 km to under 50 km for a transmitted signal, with a peak output power of 1 kW correctly matched to an efficient antenna.

In the band below 1500 kHz, sky waves are returned from the ionosphere both during the day and night, although communication using these waves can be unreliable. Above 1500 kHz the returned sky wave has greater reliability but is affected by changes in the ionosphere due to diurnal changes, seasonal changes, and the sun-spot cycle. From experience and by using published propagation figures it is possible for reliable communications to be achieved up to a range of 2000 km.

### 1.6.4 HF (high frequency) band

This frequency band is widely used for terrestrial global communications. Ground waves continue to be further attenuated as the frequency is increased. At the low end of the band, ground wave ranges of a few hundred kilometres are possible but the predominant mode of propagation is the sky wave.

Because ionization of the upper atmosphere is dependent upon the sun's radiation, the return of sky waves from the ionosphere will be sporadic, although predictable. At the lower end of the band, during the hours of daylight, sky waves are absorbed and do not return to earth. Communication is primarily by ground wave. At night, however, lower frequency band sky waves are returned and communication can be established but generally with some fading. Higher frequency band sky waves pass through the ionized layers and are lost. During the day the opposite occurs. Low frequency band skywaves are absorbed and those at the higher end are returned to earth. For reliable communications to be established using the ionized layers, the choice of frequency is usually a compromise. Many operators ignore the higher and lower band frequencies and use the mid-range for communications.

### 1.6.5 VHF (very high frequency) band

Both ground waves and sky waves are virtually non-existent and can be ignored. Communication is via the space wave which may be ground reflected. Space waves effectively provide line-of-site communications and consequently the height of both transmitting and receiving antennas becomes important. A VHF antenna may also be directional. Large objects in the path of a space wave create blind spots in which reception is extremely difficult or impossible.

### 1.6.6 UHF (ultra high frequency) band

Space waves and ground reflected waves are used with highly directional efficient antenna systems. Signal fading is minimal, although wave polarization may be affected when the wave is ground reflected resulting in a loss of signal strength. Blind spots are a major problem.

### 1.6.7 SHF (super high frequency) band

Frequencies in this band possess very short wavelengths and are known as microwaves. Communication is by space wave only. Because of the minute wavelength, compact and highly directional antennas can be designed. This band is used for maritime radar and satellite communications.

### 1.6.8 EHF (extreme high frequency) band

Communications is by space wave only. Highly directional antennas are used. Scattering and signal loss is a major problem. The band is not currently used for maritime communications.

## 1.7 Radio wave propagation

Whilst all transmitting antenna systems produce one or more of the three main modes of propagation (see Figure 1.4), one of the modes will predominate. If all other parameters remain constant, the predominant mode of propagation may be equated to the frequency used. For the purpose of this explanation it is assumed that the mode of propagation is dependent upon frequency because that is the only parameter that may be changed by an operator. The three modes of propagation are:

- surface wave propagation
- space wave propagation
- sky wave propagation.

### 1.7.1 Surface wave propagation

The surface wave is a radio wave that is modified by the nature of the terrain over which it travels. This can occasionally lead to difficulty in maritime navigation systems where the wave travels from

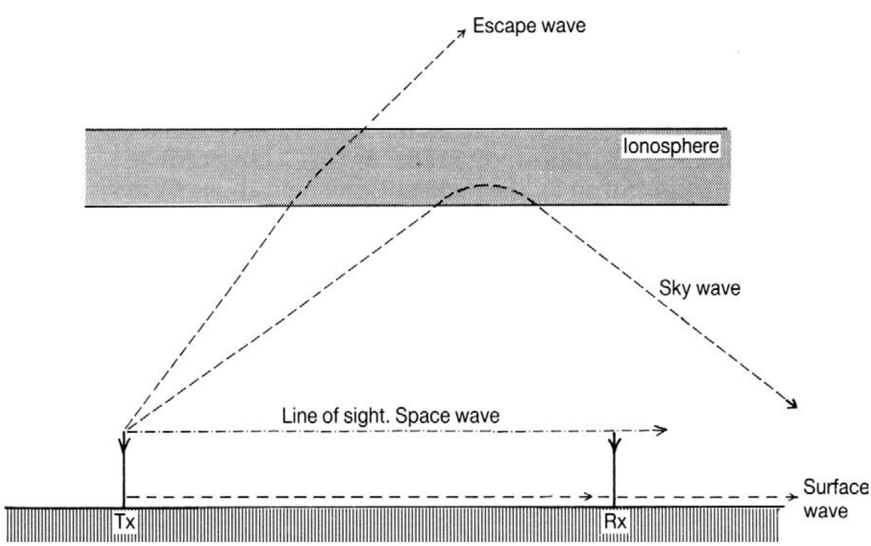


**Figure 1.4** Radio wave modes of propagation.

one medium to another, over a coastline for instance. The refraction caused in such cases is likely to induce errors into navigation systems.

A surface wave will predominate at all radio frequencies up to approximately 3 MHz. There is no clear cut-off point and hence there will be a large transition region between approximately 2 and 3 MHz, where the sky wave slowly begins to have influence.

The surface wave is therefore the predominant propagation mode in the frequency bands VLF, LF and MF. As the term suggests, surface waves travel along the surface of the earth and, as such, propagate within the earth's troposphere, the band of atmosphere which extends upwards from the surface of the earth to approximately 10 km.

### *Diffraction and the surface wave*

An important phenomenon affecting the surface wave is known as diffraction. This term is used to describe a change of direction of the surface wave, due to its velocity, when meeting an obstacle. In fact, the earth's sphere is considered to be a large obstacle to surface waves, and consequently the wave follows the curvature of the earth (Figure 1.5).

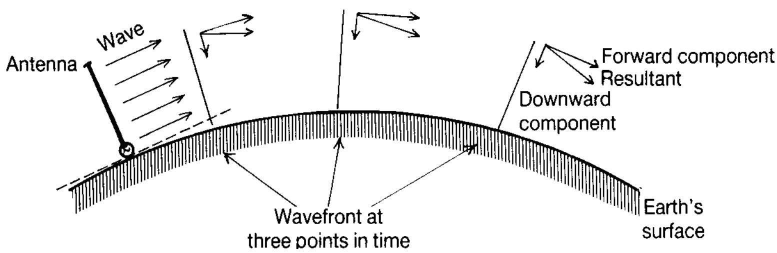


**Figure 1.5** Tilting of the surface wavefront caused by diffraction.

The propagated wavefront effectively sits on the earth's surface or partly underground and, as a result, energy is induced into the ground. This has two primary effects on the wave. First, a tilting of the wavefront occurs, and second, energy is lost from the wave. The extent of the diffraction is dependent upon the ratio of the wavelength to the radius of the earth. Diffraction is greatest when the wavelength is long (the lower frequency bands) and signal attenuation increases with frequency. This means that surface waves predominate at the lower end of the frequency spectrum and, for a given transmitter power, decrease in range as frequency increases.

The amount of diffraction and attenuation also depends upon the electrical characteristics of the surface over which the wave travels. A major factor that affects the electrical characteristics of the earth's surface is the amount of water that it holds, which in turn affects the conductivity of the ground. In practice, seawater provides the greatest attenuation of energy and desert conditions the least attenuation.

The propagation range of a surface wave for a given frequency may be increased if the power at the transmitter is increased and all other natural phenomena remain constant. In practice, however, transmitter power is strictly controlled and figures quoting the radio range are often wild approximations. For instance, NAVTEX data is transmitted on 518 kHz from a transmitter designed to produce an effective power output of 1 kW. This gives a usable surface wave range of 400 miles. But, under certain conditions, NAVTEX signals may be received over distances approaching 1000 miles.

Another phenomenon caused by radio-wave diffraction is the ability of a ground-propagated wave to bend around large objects in its path. This effect enables communications to be established when a receiving station is situated on the effective blind side of an island or large building. The effect is greatest at long wavelengths. In practice, the longer the wavelength of the signal in relation to the physical size of the obstruction, the greater will be the diffraction.

### 1.7.2 Sky wave propagation

Sky waves are severely influenced by the action of free electrons, called ions, in the upper atmosphere and are caused to be attenuated and refracted, possibly being returned to earth.

The prime method of radio wave propagation in the HF band between 3 and 30 MHz is by sky wave. Because under certain conditions, sky waves are refracted from the ionosphere, this band is used extensively for terrestrially-based global communications. Once again, however, there is no clear dividing line between surface and sky waves. In the frequency range between 2 and 3 MHz, surface waves diminish and sky waves begin to predominate.

Sky waves are propagated upwards into the air where they meet ionized bands of atmosphere ranging from approximately 70 to 700 km above the earth's surface. These ionized bands, or layers, have a profound influence on a sky wave and may cause it to return to earth, often over a great distance.

#### *The ionosphere*

A number of layers of ionized energy exist above the earth's surface. For the purpose of explaining the effects that the layers have on electromagnetic radiation it is only necessary to consider four of the layers. These are designated, with respect to the earth's surface, by letters of the alphabet; D, E, $F_1$ and $F_2$, respectively (Figure 1.6). They exist in the ionosphere, that part of the atmosphere extending from approximately 60 km above the earth's surface to 800 km.

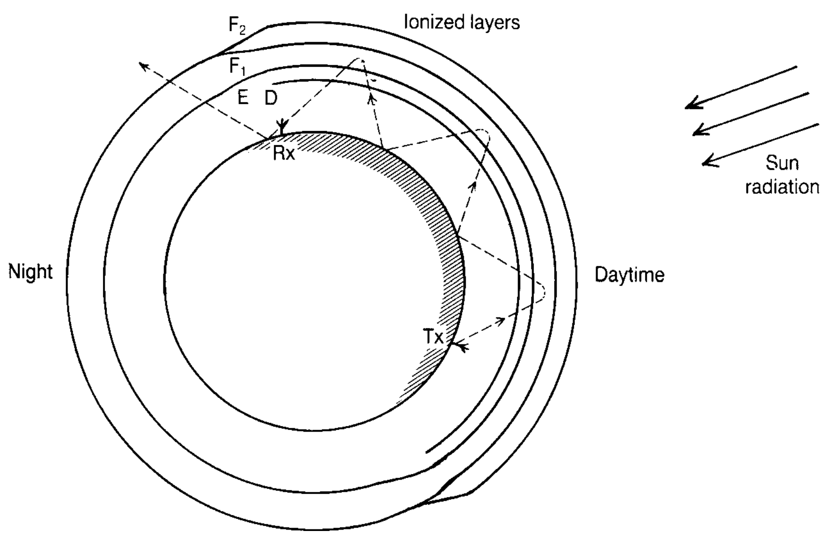


**Figure 1.6** Ionized layers and their effect on long-range communications.

Natural ultraviolet radiation from the sun striking the outer edge of the earth's atmosphere produces an endothermic reaction, which in turn, causes an ionization of atmospheric molecules. A physical change occurs producing positive ions and a large number of free electrons. The layers closer to the earth will be less affected than those at the outer edges of the atmosphere and, consequently, the D layer is less ionized than the $F_2$ layer. Also, the amount of ultraviolet radiation will never be constant. It will vary drastically between night and day, when the layers are in the earth's shadow or in full sunlight. In addition, ultraviolet radiation from the sun is notoriously variable, particularly during solar events and the 11-year sun-spot cycle. During these events, the ionized layers will be turbulent and sky waves are seriously affected.

Whilst it may appear that radio communication via these layers is unreliable it should be remembered that most of the environmental parameters affecting the intensity of an individual layer are predictable. The external natural parameters that affect a layer, and thus the communication range, are:

- the global diurnal cycle
- the seasonal cycle
- the 11-year sun-spot cycle.

### *Radio wave ionospheric refraction*

An electromagnetic radio wave possesses a wavelength, the velocity of which is affected when it passes from one medium to another of a different refractive index, causing a change of direction to occur. This change of direction is called refraction.

As previously stated, the atmosphere is ionized by the sun's radiation. It is convenient to view the ionized region produced by this action as ionized layers. The outermost layer, closest to the sun's radiation, will be intensely ionized, whereas the layer closest to the earth's surface is less ionized (Figure 1.7). Due to the collision of free electrons, an electromagnetic radio wave entering a layer will have its velocity changed causing the upper end of the wavefront to speed up. If, before the wave reaches the outer edge of an ionized layer, the angle of incidence has reached the point where the wavefront is at right angles to the earth's surface, the radio wave will be returned to earth where it will strike the ground and be reflected back into the ionosphere.

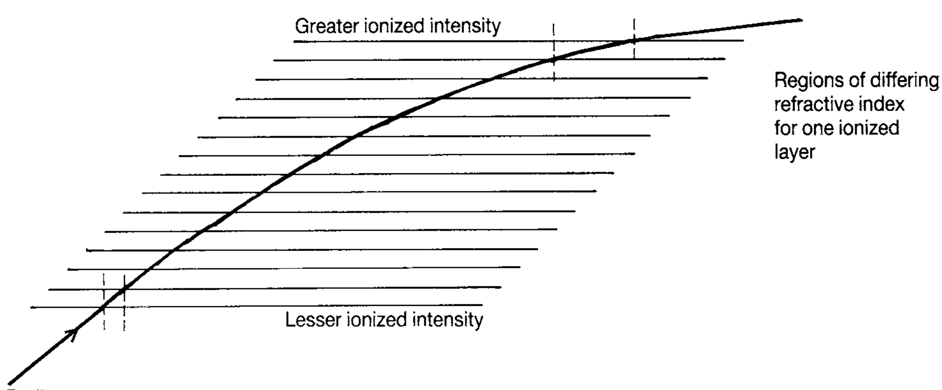


**Figure 1.7** Radio wave refraction due to progressively higher ionization intensity.

The extent of refraction, and thus whether a radio wave is returned to earth, can be controlled and is dependent upon three main parameters:

- the density of the ionosphere
- the frequency of propagation
- the angle of incidence of the radio wave with a layer.

Obviously it is not possible to control the density of the ionosphere, but other parameters may be changed by a shore-based radio station which has control over antenna systems. For a maritime mobile system, however, it is only the frequency that can be changed.

Despite its complexity, it is the phenomenon of refraction that enables terrestrial global communications to be achieved. Radio waves make several excursions between being refracted by the ionosphere and reflected from the earth's surface, with each journey being known as one hop.

### 1.7.3 Space wave propagation

The space wave, when propagated into the troposphere by an earth surface station, is subject to deflection by variations in the refractive index structure of the air through which it passes. This causes the radio wave to follow the earth's curvature for a short distance beyond the horizon making the radio horizon somewhat longer than the visible horizon. Ship's navigators will know the effect whereby the surface radar range extends slightly beyond the horizon. Space waves propagated upwards away from the troposphere may be termed free space waves and are primarily used for satellite communications.

Space waves are rarely returned from the ionosphere because the wavelength of the carrier frequency is reduced to the point where refraction becomes insignificant. Such a wave, when propagated upwards, passes through the ionized layers and is lost unless it is returned by an artificial or natural earth satellite.

If a space wave is propagated along the surface of the earth or at a short height above it, the wave will move in a straight line from transmitting antenna to receiving antenna and is often called a line-of-sight wave. In practice, however, a slight bending does occur making the radio horizon somewhat longer than the visual horizon.

The troposphere extends upwards from the earth's surface to a height of about 10 km where it meets the stratosphere. At the boundary between the two there is a region called the tropopause which possesses a different refractive index to each neighbouring layer. The effect exhibited by the tropopause on a radio space wave is to produce a downward bending action, causing it to follow the earth's curvature. The bending radius of the radio wave is not as severe as the curvature of the earth, but nevertheless the space wave will propagate beyond the visual horizon. In practice, the radio horizon exceeds the visual horizon by approximately 15%.

The actual range for communications in the VHF band and above is dependent upon the height of both the transmitting and receiving antennae. The formula below gives the radio range for VHF communications in nautical miles:

$$R = 2.5\sqrt{h_T + h_R}$$

where $h_T$ and $h_R$ are in metres.

Given a ship's antenna height of 4 m and a coastal radio station antenna height of 50 m the expected radio range is approximately 23 nmiles. This rises to 100 nmiles for antenna heights of 4 m and 100 m, respectively. Ship-to-ship communications with each ship having a 4-m high antenna gives a range of

10 nmiles. Search and rescue (SAR) communications between a life-raft and another surface vessel may have a range of only 4 nmiles.

It should be noted that VHF space waves cannot pass through, or be diffracted around, large objects, such as buildings or islands, in their path. This gives rise to extensive radio shadow areas behind large structures.

## 1.8 Signal fading

One of the major difficulties encountered when radio waves are propagated via the earth's atmosphere is that of signal fading. Fading is a continual variation of signal amplitude experienced at the antenna input to a receiving system. In practice, fading may be random or periodic but in each case the result will be the same. If the signal input to a receiver falls below the quoted sensitivity figure there may be no output from the demodulator and hence the communications link is broken. If the signal amplitude at the antenna doubles, a large increase in audible output will be produced either causing possible overloading of an automatic system or discomfort for an operator. Steps are taken at the receiver to overcome the problem of signal fading, which may be classified as one of three main types:

- general signal fading
- selective fading
- frequency selective fading.

### 1.8.1 General signal fading

In a global system, fading may occur because of the continually changing attenuation factor of an ionospheric layer. Ultraviolet radiation from the sun is never constant, and consequently, the intensity of the ionization of a layer will continually change. The signal attenuation of a specific layer may cause complete signal fade-out as the intensity of the sun's radiation changes. With the exception of this extreme case, the use of automatic gain control (AGC) circuits in a receiver effectively combats this phenomenon.

### 1.8.2 Selective fading

Selective fading occurs for a number of reasons. Radio waves arriving at an antenna may have travelled over two or more different paths between transmitter and receiver. Each path-length is different and the signals arriving at the receiving antenna produce a combined signal amplitude, which is the phasor sum of the two. The two signals, of the same frequency and the same origin, will be out of time-phase with each other and will therefore produce a resultant signal that is either larger or smaller in amplitude than the original. In most cases the signal path-lengths are unpredictable and often variable, leading again to the need for a good quality AGC circuit in the receiver. This effect can occur, as shown in Figure 1.8, when two sky waves are refracted from the ionosphere over different path-lengths, when a sky wave and a ground wave are received together, or when two ground waves are received over different paths.

### 1.8.3 Frequency selective fading

This occurs where one component of a transmitted radio wave is attenuated to a greater extent than other components. In any wideband communications link a large number of frequencies are contained

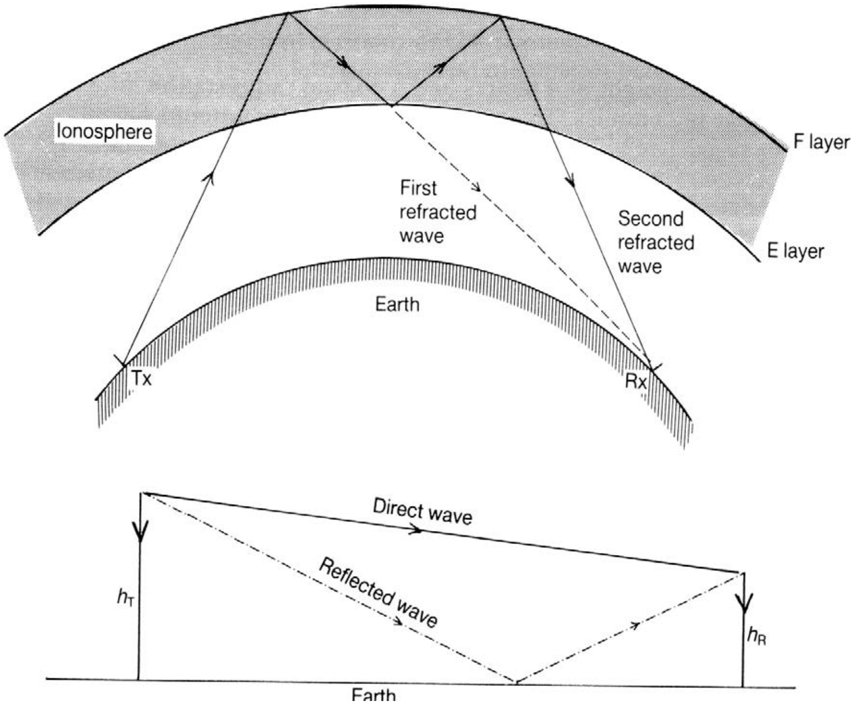


**Figure 1.8** Signal fading caused by multipath propagation.

within the bandwidth of the transmitted signal. The individual frequencies contained in the transmission are those of the fundamental carrier frequency plus the RF frequencies generated by the method of modulation employed. To produce an error-free or distortion-free communications link, all modulation baseband frequencies at the transmitter must be faithfully reproduced at the receiver output. If any of the modulated frequencies are lost in the transmission medium, which may happen when frequency selective fading is present, they cannot be reproduced by the receiver.

More importantly, however, if the carrier frequency is lost in the transmission medium it will be impossible to demodulate the audio intelligence at the receiver, unless specific circuitry is available and the carrier loss is predictable.

Frequency selective fading cannot be cured by the use of AGC circuits in a receiver. Its effects can, however, be limited by using:

- a transmission which radiates one mode only – a carrier frequency or narrow band signal
- single sideband (SSB J3E) fully suppressed carrier transmission telephony
- frequency modulation.

## 1.9 Basic antenna theory

An antenna is arguably the single most critical part of any radio communications system and those used by radio navigation systems are no exception. Unfortunately, however, it is often the part of a radio installation that is less than efficient, not because of deficiencies in antenna design but because of the major problems of antenna siting and installation. As ships become more streamlined, the available antenna space reduces, often to the point where multiple antenna systems simply cannot be fitted.

Radio navigation systems use a variety of antennae, each one designed with individual characteristics to suit operational needs, but whatever the construction, they all operate on similar principles.

Antenna design and construction is a complex area of radio communications theory and the following description is limited to that needed to understand radio navigation systems. Whilst some basic antenna theory is considered, it should be noted that it is only necessary for the reader to understand antennae from an operational and maintenance viewpoint.

An antenna is essentially a piece of wire that may or may not be open at one end. The shortest length of wire that will resonate at a single frequency is one that is critically long enough to permit an electric charge to travel along its length and return in the period of one cycle of the applied radio frequency. This period of one cycle is called the wavelength. The velocity of a propagated RF is that of light waves, i.e. 299 793 077 $ms^{-1}$, which is usually approximated to $300 \times 10^6\, ms^{-1}$ for convenience. The wavelength in metres of any RF wave is therefore:

$$\lambda = \frac{300 \times 10^6}{f}$$

Because the RF charge will travel the length of the wire and return, it follows that the shortest resonant wire is one half of a wavelength long. In fact many antenna systems are called half-wave or $\lambda/2$. If, as an analogy, the resonant length is assumed to be a trough with obstructions at each end and a ball is pushed from one end, it will strike the far end and return, having lost energy. If, at the instant the ball hits the near end obstruction, more energy is given to the ball it will continue on its way indefinitely. However, it is critically important that the new energy is applied to the ball at just the right time in order to maintain the action. In practice, if the timing is in error the length of the resonant trough may be changed to produce the optimum transfer of energy along the wire. Antennae, therefore, must be constructed to be a critical length to satisfy the frequency of the applied RF energy.

Antennae, exhibit the 'reciprocity principle', which means that they are equally as efficient when working as a transmitting antenna or as a receiving antenna. The main difference is that a transmitting antenna needs to handle high power and is usually more substantially built and better insulated than a corresponding receiving antenna. For efficient radio communications, both the transmitting and receiving antennae should possess the same angle of polarization with respect to the earth. Polarization refers to the angle of the transmitted electric field ($E$) and, consequently, if the $E$-field is vertical, both transmitting and receiving antennae must be vertical. The efficiency of the system will reduce progressively as the error angle between transmitting and receiving antennae increases up to a maximum error of 90°.

### 1.9.1 Half-wavelength antenna

An antenna operating at precisely half a wavelength is traditionally called a Hertz antenna. Many antennae do not operate at $\lambda/2$ because they would be excessively long. A $\lambda/2$ antenna is effectively a $\lambda/4$ transmission line with a signal generator, the transmitter, at one end and an open circuit at the other, as shown in Figure 1.9.

Ohm's Law states that when an open circuit exists the current will be zero and the potential difference (p.d.) across the open circuit will be maximum. Figure 1.10 shows voltage ($E$) and current ($I$) standing waves which indicate this fact.

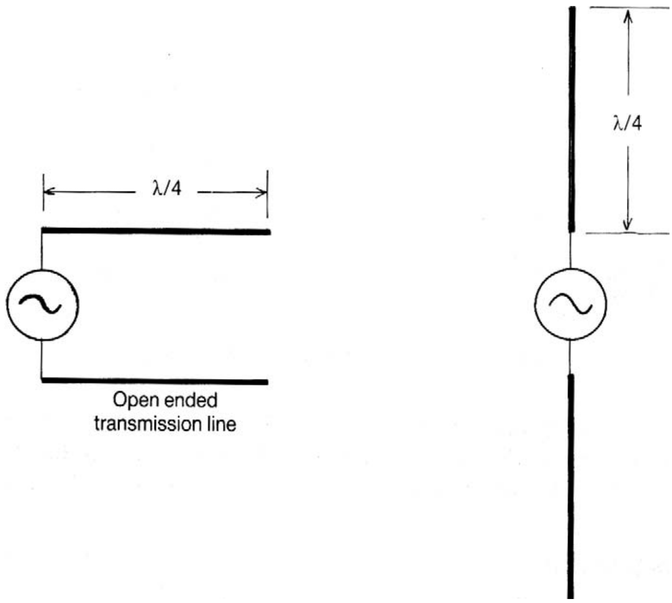


**Figure 1.9** Half-wavelength antenna derived from a quarter-wavelength transmission line.

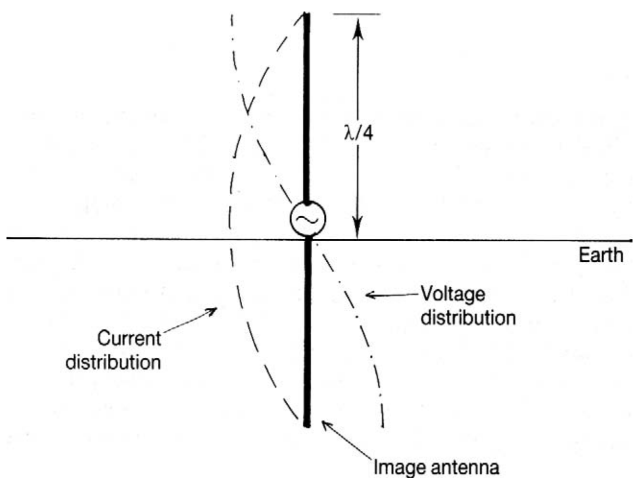


**Figure 1.10** A grounded quarter-wavelength antenna showing the voltage and current distribution curves.

*E* and *I* distribution curves are standard features of antenna diagrams. If the generator (signal source) is λ/4 back from the open circuit, the *E* and *I* curves show minimum voltage and maximum current at the antenna feed point. In most cases this is the desirable *E* and *I* condition for feeding an antenna. If the two arms of the transmission line are now bent through 90°, a λ/2 efficient antenna has been produced.

Ohm's Law also states that the resistance of a circuit is related to the voltage and the current. In this case the impedance of the antenna will be maximum at the ends and minimum at the centre feed point.

Again this is desirable because the centre impedance is approximately 73 Ω, which ideally matches the 75 Ω (or in some cases 50 Ω) impedance coaxial cable used to carry the output of the transmitter or the input to a receiver.

### 1.9.2 Physical and electrical antenna lengths

Ideally, an antenna isolated in free space would follow the rules previously quoted, whereby the actual and electrical lengths were the same. Both are calculated to be $\lambda/2$ of the transmission frequency. However, because the velocity of the radio wave along the wire antenna is affected by the antenna supporting system and is slightly less than that in free space, it is normal to reduce the physical length of the antenna by approximately 5%. In practice, the corrected physical length of an antenna is therefore 95% of the electrical length.

Antennae and feeders are effectively ‘matched transmission lines’, which, when a radio frequency is applied, exhibit standing waves, the length of which are determined by a number of factors outside the scope of this book. However, the waves are basically produced by a combination of forward and reflected power in the system. A measurement of the ratio between forward and reflected power, called the standing wave ratio (SWR), provides a good indication of the quality of the feeder and the antenna. Measurement of the SWR is made using voltage and becomes voltage standing wave ratio (VSWR).

### 1.9.3 Antenna radiation patterns

A graph showing the actual intensity of a propagated radio wave at a fixed distance, as a function of the transmitting antenna system, is called a radiation pattern or ‘polar diagram’. Most antenna radiation patterns are compared with that of a theoretical reference antenna called an isotropic radiator. Radiation patterns may be shown as the *H*-plane or the *E*-plane of transmission or reception. Figure 1.11 shows the *E*-plane radiation patterns of an isotropic radiator and a $\lambda/2$ dipole antenna.

It should be noted that this is a two-dimensional diagram whereas the actual radiation pattern is three-dimensional. The maximum field strength for the $\lambda/2$ dipole occurs at right angles to the antenna and there is very little radiation at its ends. In the horizontal plane, therefore, this type of antenna is directional, whereas an isotropic radiator is omnidirectional. However, a $\lambda/2$ antenna can be made omnidirectional when it is vertically polarized.

A second important principle of an antenna is its beamwidth. The radiation pattern is able to illustrate the antenna beamwidth. It is calculated at the ‘half-power points’ or –3 dB down from the

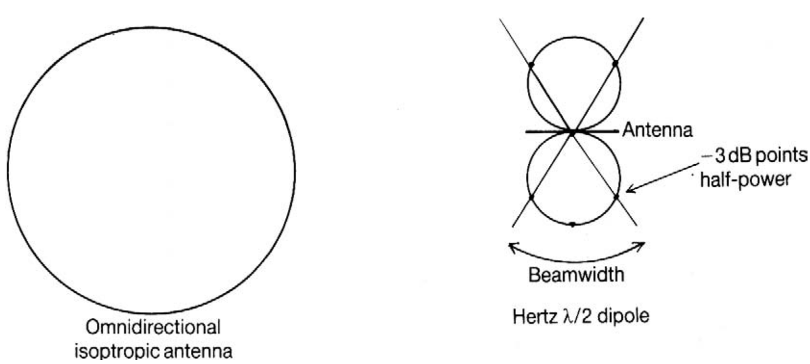


**Figure 1.11** Two-dimensional radiation patterns for an omnidirectional antenna and a $\lambda/2$ antenna.

peak point. If the receiving antenna is located within the beamwidth of the transmitting antenna good communications will be made.

Antenna gain patterns for receiving antennas are again called polar diagrams or azimuth gain plots (AGP).

### 1.9.4 Antenna gain and directivity

Antenna gain and directivity are very closely linked. The greater the directivity an antenna exhibits, the greater it will appear to increase the transmitted signal in a specific direction. The $\lambda/2$ dipole, for instance, possesses a gain of typically 2.2 dB, on those planes at right angles to the antenna, when compared with an isotropic radiator. As a consequence, zero signals will be propagated along the other two planes in line with the dipole.

Both properties of gain and directivity are reciprocal and apply equally to both transmitting and receiving antennae. In practice it is important to consider the effect of both the transmitter and receiver antenna gains in a complete radio communications system. The formula below provides a simple method of calculating the signal strength at a receiver input.

$$P_r = \frac{P_t G_t G_r \lambda/2}{16\pi^2 d^2}$$

where $P_r$ = power received in watts, $P_t$ = power output of transmitter in watts, $G_t$ = the ratio gain of the transmitting antenna, $G_r$ = the ratio gain of the receiving antenna, $\lambda$ = wavelength of the signal in metres, and $d$ = the distance between antennae in metres.

### 1.9.5 Ground effects

The overall performance of an antenna system is extensively changed by the presence of the earth beneath it. The earth acts as a reflector and, as with light waves, the reflected radio wave leaves the earth at the same angle with which it struck the surface. Figure 1.12 shows the direct and reflected radio waves at a receiving antenna.

Because the surface of the earth is rarely flat and featureless, there will be some directions in which the two waves are in phase, and thus are additive, and some where the two are out of phase, and thus subtractive.

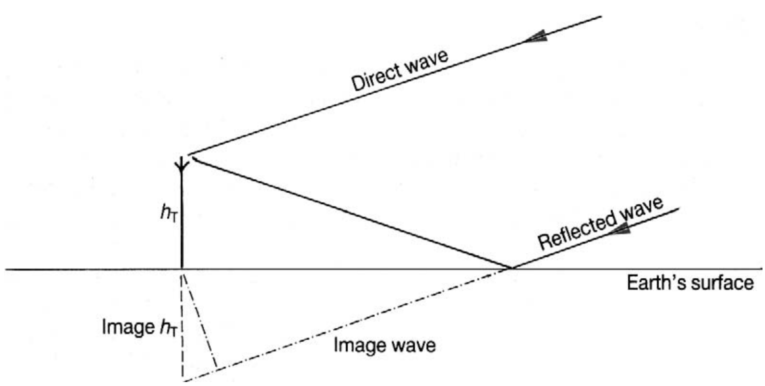


**Figure 1.12** Direct and earth reflected radio waves received by an antenna.

Because the effects of ground wave reflected waves are unpredictable, some antenna arrays are constructed with a ground plane. Reflections from the ground plane are, to some extent, predictable and may be compensated for in the receiving system. Satellite navigation antennas and VHF RDF fixed antennae often use a ground plane to improve sensitivity and limit signal reflections.

### 1.9.6 Antenna efficiency

Antenna efficiency is of particular importance in all communications systems. If the efficiency of an antenna drops to 50%, the maximum radiated signal also drops resulting in a consequent loss of range. It would be rare indeed to find any system that is 100% efficient and antennae are no exception. However, antenna losses are well documented and, consequently, the effective isotropic radiated power (EIRP) figure for a system is usually calculated with reference to known efficiency figures.

The losses leading to inefficiency in an antenna system may generally be classed as dielectric losses affecting the transmission properties of the antenna. Such losses in a transmitting antenna may be produced by arcing effects and corona discharge, and in a receiving antenna they may be produced by bad connections or damaged wiring. Most of these losses can be controlled by careful installation, good positioning of the antenna, and diligent maintenance.

### 1.9.7. Antenna feed lines

Whilst the connection between the transmitter output and the antenna input appears to be made by a simple wire it is, in fact, made by a balanced transmission line that possesses impedance. Usually, the feed line is a correctly terminated coaxial cable specifically designed for the purpose. For most transmitting and receiving antenna systems the feed line possesses an impedance of 50 or 75 Ω. Because of its need to handle more power, a transmitter coaxial cable will be physically larger than a corresponding receiver coaxial line, unless of course both use the same line. The inner copper conductor forms the live feed wire with the screen sheath providing the ground line. The outer sheath should be bonded to ground to prevent inductive pick-up in the centre conductor wire, which would generate interference in the communications link.

Coaxial cables used in a marine environment are double sheathed and occasionally armour plated. They are fully waterproofed and should remain so throughout their life. Moisture ingress into the cable insulation material will cause considerable losses as energy is absorbed and not radiated.

## 1.10 Glossary

The following lists abbreviations, acronyms and definitions of specific terms used in this chapter.

**Antenna** A carefully constructed device for the reception or transmission of radio energy into the air.

**Antenna gain pattern (AGP)** Occasionally also referred to as polar diagrams. These are a graphical representation of the transmitting or receiving properties of an antenna.

**CEPT** Conference of European Telecommunications Administrations. A group that assists with the implementation of ITU radio regulations on a national level.

**CCIR** International Radio Consultative Committee. The body that considers and reports on issues affecting the use of radio communications.

**CCIT** International Telecommunications Consultative Committee.

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|---|---|
| **Diffraction** | The term describing the 'bending' of a surface radio wave ground large obstacles in its path. |
| **E field** | Radio wave electrostatic energy field. |
| **EHF** | Extreme high frequency, the 30–300 GHz band. Still experimental. |
| **Fading** | The loss of power in a radio wave caused by environmental effects. |
| **FCC** | Federal Communications Commission. The body which polices the civilian use of radio communications in the USA. |
| **Feed line** | The wire connecting an antenna to the communications system. |
| **H field** | Radio wave electromagnetic energy field. |
| **HF** | High frequency, the 3–30 MHz band. Traditionally provides terrestrial global communications using medium power and acceptable antenna lengths. |
| **ITU** | International Telecommunications Union, the radio frequency watchdog. |
| **LF** | Low frequency, the 30–300 kHz band. Requires long antenna and large power input to be useful. Generally ground wave mode only. |
| **MF** | Medium frequency, the 300 kHz to 3 MHz band. Traditionally provides short-range communications using medium power and acceptable antenna lengths. |
| **Refraction** | The 'bending' of a sky wave by the effect of the ionosphere causing it to return to earth. |
| **RF spectrum** | The usable section of the extensive natural frequency spectrum. |
| **SHF** | Super high frequency, the 3–30 GHz band; microwaves. Line of sight communications. Generally used for satellite communications and RADAR. |
| **Sky wave** | A propagated radio wave that travels to the ionosphere from where it may or may not be returned to earth. |
| **Space wave** | A propagated radio wave that travels in a straight line. Used for point-to-point communications |
| **Surface wave** | A propagated radio wave that predominantly travels along the surface of the earth. |
| **UHF** | Ultra high frequency, the 300 MHz to 3 GHz band; microwaves. Line-of-sight transmission. Generally used for satellite communications. |
| **VHF** | Very high frequency. The 30–300 MHz band. Line-of-sight transmission from short antenna using low power. Maritime short-range communications band. |
| **VLF** | Very low frequency, the 10–30 kHz band. Requires huge antenna and great power for long-range communication. |
| **WARC** | World Administrative Radio Conference. The body that produces radio regulations and a Table of Frequency Allocations. |
| **Wavelength** | The physical length in metres between one cycle of the transmitted frequency. A parameter used in the calculation of antenna lengths. |

## 1.11 Summary

- Radio waves travel through free space at approximately $300 \times 10^6\,\mathrm{ms}^{-1}$.
- The frequency, wavelength and velocity of the radiowave are interrelated.
- The radio frequency spectrum is regulated by the International Telecommunications Union (ITU).
- The Table of Frequency Allocations and radio regulatory documents are revised at the World Administrative Conference (WARC).

- The radio frequency spectrum is divided into several bands: they are VLF, LF, MF, HF, VHF, UHF, SHF and EHF.
- A propagated radio wave contains both electromagnetic and electrostatic energy called the magnetic field and the electric field.
- A radio wave propagates from an antenna in one or more of three modes; surface wave, sky wave and space wave.
- Surface waves travel along the ground and consequently the transmitted power is attenuated, thus limiting communication range.
- Sky waves travel to the ionosphere from where they may or may not be returned to the earth. Sky waves provide terrestrial global communications.
- Space waves offer line-of-sight communications. Range is limited by the curvature of the earth, and large objects in the path of the wave will block the signal creating shadow areas.
- Amplitude and/or frequency fading of the signal are a major problem in communication systems.
- Antennae are critically constructed to satisfy frequency, power and environmental requirements.
- Transmitting antenna need to handle large power outputs and are more robust than receiving antenna, although a single antenna may be employed for both purposes.
- Antennas may be directional or not depending upon requirements.
- Antenna feed lines are often called coaxial cables and consist of an inner (signal) wire surrounded by a mesh of copper called the earth (ground) connection.

## 1.12 Revision questions

1. Why does it appear that the radiocommunications range on MF/HF is greater at night than during the day at your location?
2. How is it possible to receive LF radio waves in regions that are radio-shadow areas to VHF radio waves?
3. Unwanted sky wave reception gives rise to errors in some navigation systems, typically Loran-C. Why is the effect more prevalent at night?
4. How may frequency selective fading be minimized in a receiver system?
5. How are the receptive properties and an antenna's physical length related?
6. What is an antenna azimuth gain plot?
7. If a VHF antenna is remounted higher on the mast of a vessel, radio communications range is increased. Why is this?
8. If a vertical antenna is remounted horizontally at the same height above sea level, radio communications range is severely reduced. Why is this?
9. How are an antenna's directivity and gain related?
10. By carefully locating some antennas, problems of signal fading, and in the case of GPS, errors in the range calculation can be reduced. Why is this?