船舶电子导航

(Marine Electronic Navigation)

内 部 使 用

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Preface

This book has been written for all who have a professional involvement with marine electronic navigation systems, with the hope that it will provide a deeper insight into each of the systems described. Each of the navigation aids can be considered from three viewpoints: equipment use, basic theory, and system deficiencies. Within this book the first is considered to be the least important since most equipment user manuals will describe operational aspects in adequate detail and should always be carefully studied before attempting to use unfamiliar equipment. However, following instructions in a step by step manner will never lead to the optimum benefit being gained from any navigation system. So no excuse is given for including basic theory which, in some cases, will require a little effort in digesting. But the benefits gained by not using equipment as a black-box but with a real understanding, should make the effort worthwhile. Finally, it is most important to be aware of the deficiencies of a system, since the consequences of believing any system to be perfect can cause at the very least a loss of confidence, when it is found through practical experience that this is a mistaken belief.

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1 Radiation and propagation

An understanding of the behaviour of radio waves during propagation from their source to point of reception is fundamental to an understanding of all radio navigation systems. It is particularly relevant to an appreciation of their limitations, since propagational effects are invariably the major source of error.

1.1 Electromagnetic waves

Radio waves form a specific part of the total spectrum of electromagnetic radiation of which light is also a part. An electromagnetic wave can be considered as an oscillating electric force travelling through space, and inseparably accompanied by an oscillating magnetic force in a plane at right angles to it (Figure 1.1). The plane of the electric field in space provides the basis of defining the wave's polarization. A wave with a vertical electric field is said to be vertically polarized.

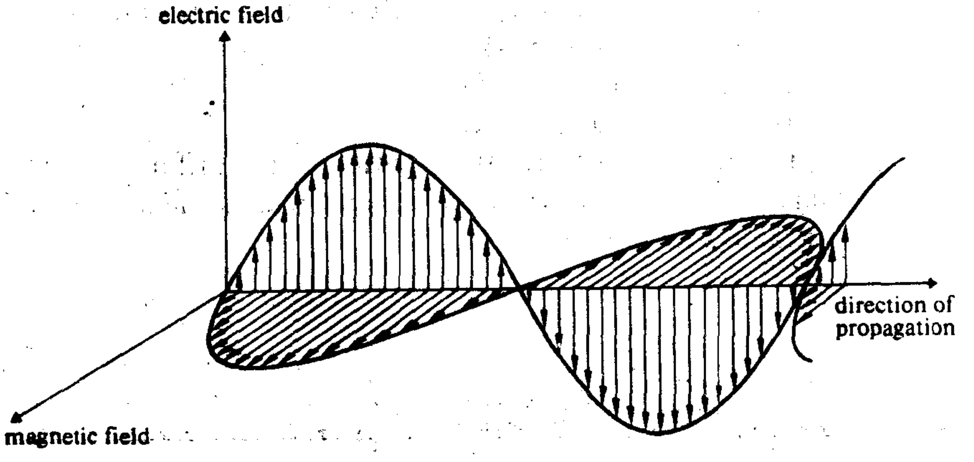

Figure 1.1 The electromagnetic wave, illustrating the relationship between electric and magnetic fields, and direction of propagation.

The relationship of radio waves with the rest of the spectrum of electromagnetic radiation is illustrated in Figure 1.2. Radio waves are usually specified in terms of their frequency (f), which is related to wavelength (λ) by the expression:

$$f = \frac{c}{\lambda} \qquad \textbf{[1.1]}$$

where c is the velocity of electromagnetic radiation in a vacuum (free space) and has been determined as being 299, 792 km/s, although the approximation of 3×10^5 km/s is often used in equation **[1.1]**.

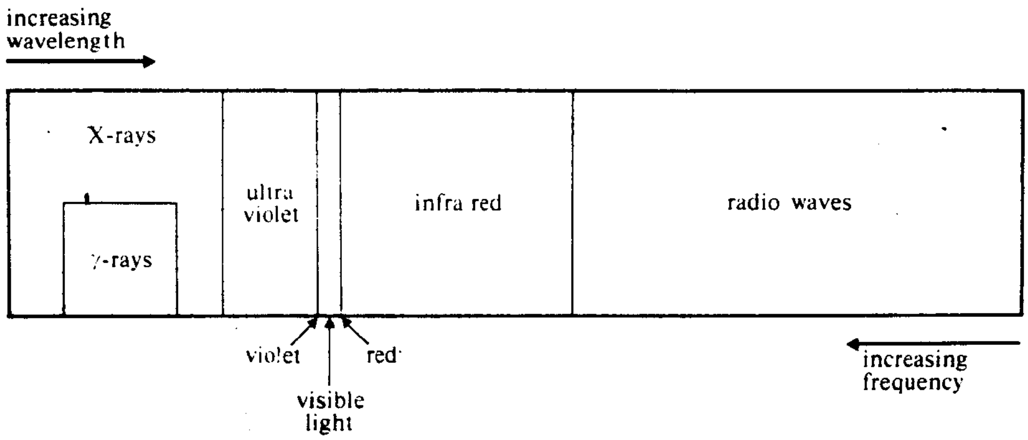

Figure 1.2 The spectrum of electromagnetic radiation.

The unit of frequency is the Hertz (Hz), and the radio wave part of the electromagnetic spectrum extends from 3×10^3 Hz to 30×10^9 Hz, although these are not rigidly defined limits. Since very large numbers are involved the following prefixes are assigned:

10^3 Hz = 1 kilohertz (kHz)
10^6 Hz = 1 Megahertz (MHz)
10^9 Hz = 1 Gigahertz (GHz)

Figure 1.3 illustrates the position of the different radio navigation aids in the radio wave spectrum and relates them with other sources of radio waves.

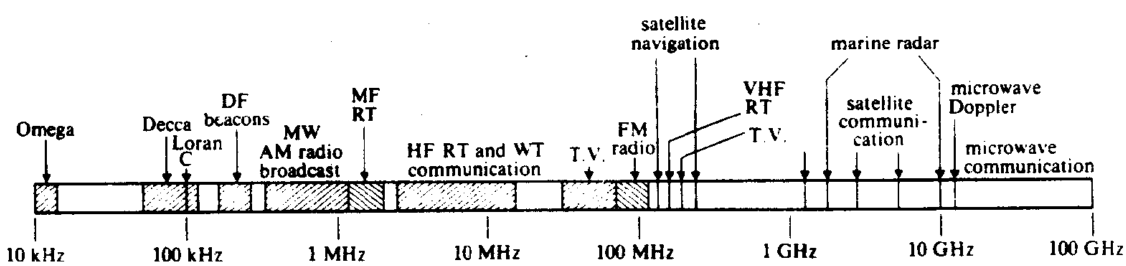

Figure 1.3 The radio wave spectrum.

1.2 Propagation

The behaviour of radio waves and the influences which affect them during their passage from transmitter to receiver are dependent upon the frequency of the wave. All radio waves within a given frequency band will have the same propagational characteristics irrespective of their use, and so the following descriptions of propagation apply equally to other radio signals on the same or adjacent frequencies.

When energy is radiated from an omnidirectional transmitting antenna some energy will travel away from the earth, and some will travel away from the antenna remaining (initially) parallel with the ground. In explaining the mechanisms of propagation these two directions are considered separately, and are termed 'skywave' and 'groundwave' respectively. The relative importance of the skywaves and groundwaves depends upon many factors, which include the frequency of the transmission, the time of day, and the distance between transmitter and receiver.

1.2.1 Groundwaves

The groundwave can be subdivided into two components, the 'space wave' and the 'surface wave'. The space wave can be further divided into the 'direct wave' and the 'ground reflected wave'. These latter two waves illustrated by Figure 1.4 are of little significance in the various radio navigation systems described in this book, since their range is short and in many cases the two waves cancel at the receiver.

Of more significance is the surface wave, since in this case the earth's surface and the lower atmosphere influence the wave in such a way as to cause it to follow the curvature of the earth. Since energy is transferred from this wave to the ground, the distance over which the wave can propagate depends upon the frequency of the transmission, and the properties of the ground over which the wave passes.

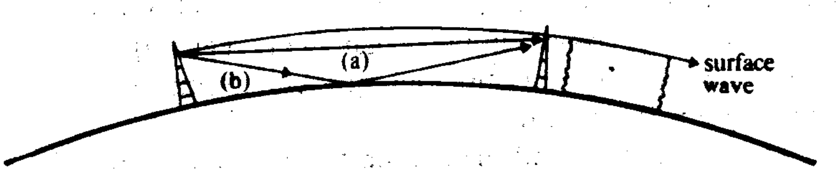

Figure 1.4 ***The two components of groundwave propagation, space wave and surface wave. Space wave has two components,*** **(a)** ***direct wave, and*** **(b)** ***ground reflected wave.***

The distance over which a surface wave can travel before suffering unacceptable attenuation varies from only hundreds of feet to many thousands of miles.

At low and medium frequencies, horizontally polarized surface waves suffer much greater attenuation than vertically polarized surface waves. In this frequency range therefore, antennas are designed to transmit and receive vertically polarized waves.

Since the space wave does not play any significant part at the frequencies of the radio navigation aids described in this book, the general expression groundwave is used throughout to mean surface wave.

1.2.2 Skywaves

It may be thought that waves travelling away from the surface of the earth would be lost into space and thus play no further part. This is by no means always the case since around the earth is the ionosphere, a belt of ionized gases which extends from approximately thirty miles to several hundreds of miles from the earth's surface. The effect of the ionosphere is to cause waves of certain frequencies to refract, and ultimately reflect back to the surface.

1.3 The ionosphere

During day-time the densest region of ionization exists between altitudes from sixty to six hundred miles. Throughout this region there are several layers in which the ionization density is at a maximum, known as the D-, E- and F-layers, (Figure 1.5a). During the day, the F-layer splits into two layers and these are designated F1 and F2. The density of ionization of these layers depends upon many factors including time of day, season, latitude, and the phase of the eleven-year sunspot cycle. During night-time, all layers of the ionosphere slowly de-ionize. In particular the D-region quickly disappears in the absence of the sun and quickly ionizes shortly after the following sunrise (Figure 1.5b).

During both day- and night-time the ionosphere has the effect of refracting the radio waves which pass through it. The amount by which the waves are refracted is dependent upon the density of the ionization of each of the layers, and on the frequency of the radio

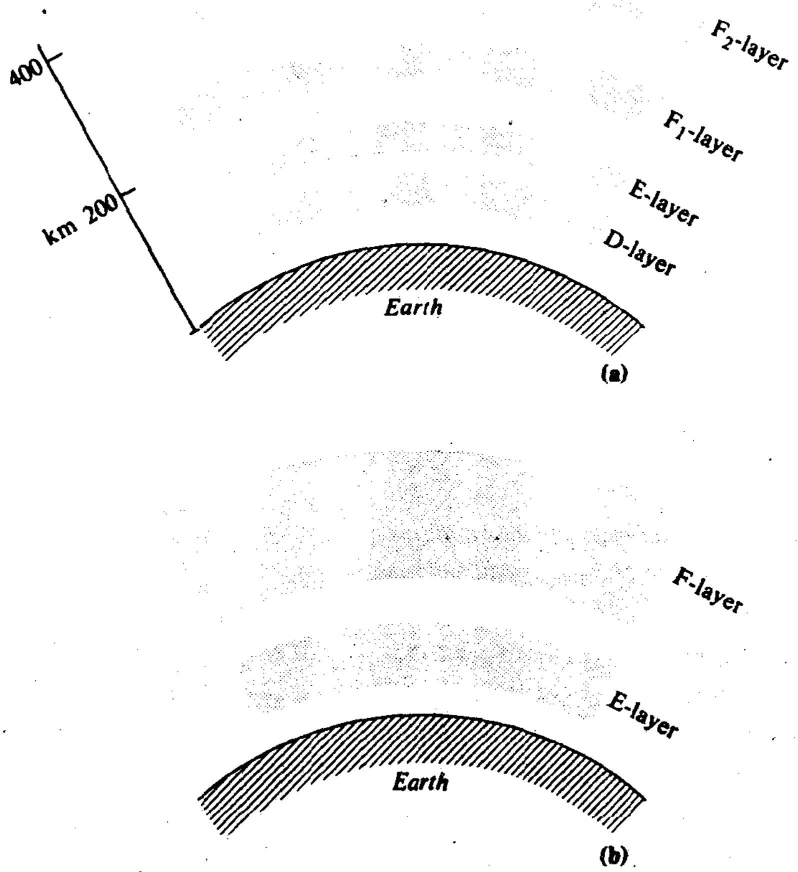

Figure 1.5 *The ionosphere:* (a) *day-time;* (b) *night-time.*

waves. In general, as the frequency decreases the amount of refraction increases, until the point is reached where the wave is actually reflected back from the ionosphere (Figure 1.6). Since the density of the ionosphere varies daily and seasonally, a radio wave of a given frequency may be reflected at some times and not at others.

The skywave returning to earth provides signal reception at a distant point from the transmitter, termed the skip distance (Figure 1.6). Skywaves can undergo two or more reflections. When radio signals are used for communication, the presence of the reflected skywave is of great value since it makes communication over many thousands of miles possible, far beyond the range of the groundwave signal. Communication frequencies are therefore often chosen to make optimum use of skywave signals.

The opposite to this is generally the case for radio navigation systems, since these rely upon a precise knowledge of the propagation

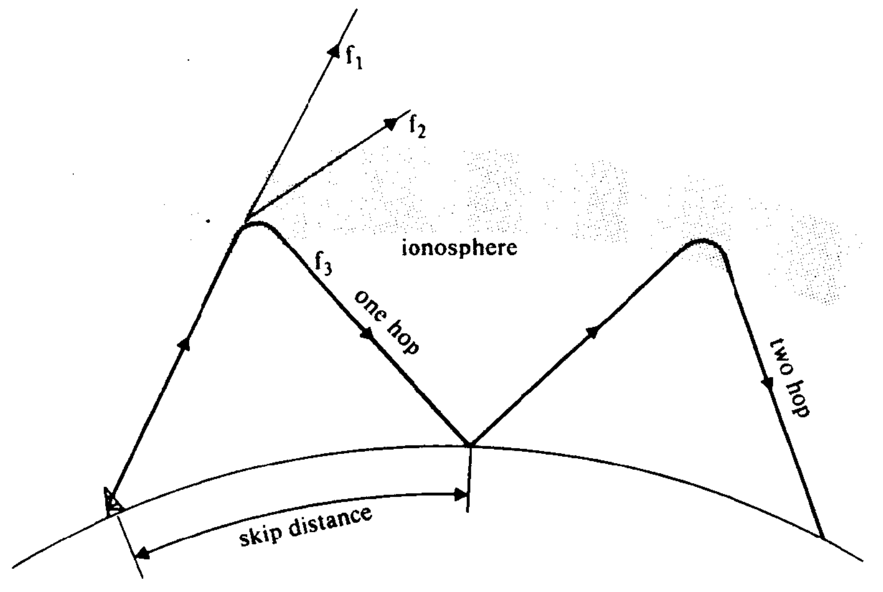

Figure 1.6 *Ionospheric refraction and reflection of radio waves, frequency* $f_1 > f_2$ *and* $f_2 > f_3$.

times of the signal from transmitter to receiver. For communication purposes accurate ionospheric predictions can be made relating to the presence of skywave reflections for given frequencies, but it is the precise time delays caused by the ionosphere which are difficult to predict with precision. In certain cases skywaves are used to give extended operation, Loran C being one example, but the positional accuracies are considerably reduced from those normally achieved with groundwaves. Usually the presence of a skywave is a matter of nuisance,and in extreme cases the skywave interferes with the groundwave to cause a system to become unusable.

Transmissions from Loran C (100 kHz), Decca (70–130 kHz) and direction-finding (DF) beacons (up to 350 kHz) behave in a similar manner. During day-time the ionized D-region attenuates the sky-wave both before and after it is reflected by the E-region. The skip distance falls within the groundwave, but the skywave has been attenuated sufficiently to prevent serious interference with the groundwave.

At night the D-region de-ionizes and the attenuation of the sky-wave is now less. Reflections occur from both the E- and F-layers, with some signals returning within the groundwave and some beyond. The precise effect of these skywaves on the performance of each of the radio navigation skywaves is discussed under the heading of the particular system.

1.4 Very low frequency (VLF) propagation

The ray method of describing and analysing skywave propagation becomes cumbersome at very low frequencies (<30 kHz), since for distances beyond about 1000 kilometres from the transmitter the signal has suffered many successive ionospheric reflections. A more convenient method of describing VLF propagation is to use waveguide theory, one wall of the waveguide being the surface of the earth and the opposite wall being the lower region of the ionosphere. The effective height of the waveguide varies daily (and seasonally), between approximately seventy kilometres by day and ninety kilometres by night. At the frequencies of the Omega VLF navigation system (10.2–13.6 kHz), this represents some two to four wavelengths.

The normal waveguide theory of two component waves travelling obliquely to the walls of the guide, fully applies in the case of the earth-ionosphere waveguide. A wave which makes the double passage across the guide and back, and undergoes reflections at two walls must be self consistent. This is only possible for certain discrete directions of the wave normals, and so leads to a series of discrete modes. In a loss-free system there is no change of amplitude on reflection, and so the condition for self consistency is that the total change of phase in the double passage across the guide and back (with two reflections) is an integral multiple of 2π radians.

In a conventional waveguide the walls are clearly defined, reflecting waves incident upon their surface. Waves can also be reflected from a wall whose boundary is not clearly defined, but with a refractive index which varies continuously across the boundary. Such is the case with the ionosphere, although at Omega frequencies the wave has totally reflected within the D-layer. The layer can be considered as having a discrete boundary at a specific reflecting height, and with an equivalent reflection coefficient.

When the earth ionosphere waveguide is excited by a radiating antenna, many modes exist within the first 500 kilometres from the antenna, consequently within this distance the mode theory becomes cumbersome. Fortunately the high-order modes are attenuated more than the low-order and so beyond 500 kilometres it is necessary only to consider the first- and second-order modes.

Omega transmissions are launched from vertically polarized antennas which create transverse-magnetic propagation modes within the waveguide (Figure 1.7). At a distance of 1000 kilometres from

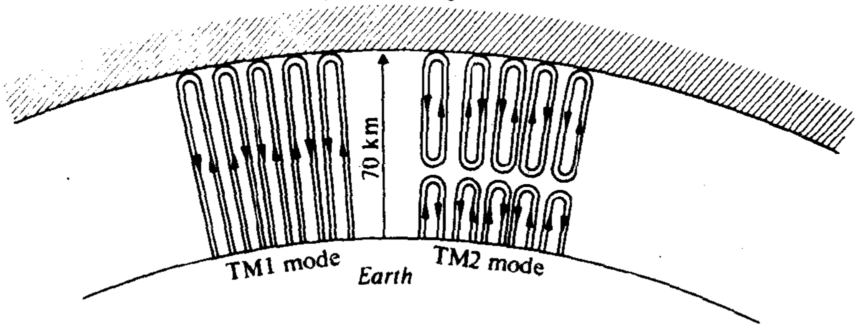

Figure 1.7 ***VLF propagation within the earth-ionosphere waveguide, illustrating the two primary modes TM1 and TM2.***

the antenna only the TM1 and TM2 modes are large enough to be of interest, beyond this the amplitude of the TM2 mode falls below that of the TM1, and then only this latter mode remains significant.

1.4.1 *Phase and group velocity*

Figure 1.8 is a plot of the transverse field along the longitudinal axis of a waveguide. The diagram is drawn for one instant of time and for a guide transmitting an unmodulated sinusoidal wave. If Figure 1.8 is redrawn for several successive instants of time, a changing field pattern is obtained and the wave appears to move along the X-axis with a velocity V_p called the 'phase velocity'.

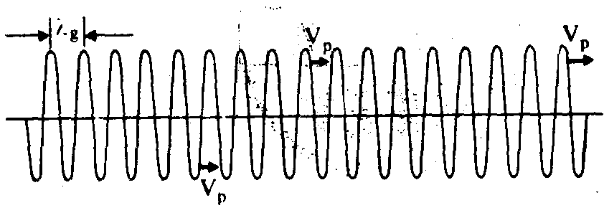

Figure 1.8 ***Unmodulated sinusoidal wave in a waveguide.***

The value of V_p may be found from the fact that the wave in Figure 1.8 moves forward a distance equal to λ_g in one cycle. Thus, in one unit of time the wave moves forward f cycles, or a distance $f.\lambda_g$, where f is the frequency of the wave. That is:

$$V_p = f.\lambda_g.$$

In a similar way, the velocity of any electromagnetic wave in free space is:

$$c = f.\lambda_a.$$