PROPAGATION OF BROADCAST TRANSMISSIONS

RADIOWAVE PROPAGATION

Radio waves may be propagated from a transmitting site to a receiving site by a number of different mechanisms. At broadcast frequencies, the most practical and important ones are ground wave, sky wave, and space (or tropospheric) wave.

The ground wave, as the name implies, exists when the transmitting and receiving antennas are on or near the surface of the Earth. Thus, it is also called the *surface wave*. Ground waves exist at all times. Broadcast signals at low and medium frequencies received in daytime are all ground waves.

The sky wave represents energy that travels from the transmitting antenna to the receiving antenna as a result of a "bending" by the Earth's upper atmosphere called the ionosphere. The ionosphere, which consists of several different layers, begins about 50 kilometers above the Earth's surface. Short-wave signals and nighttime medium-wave signals are examples of sky waves. Under certain conditions, the ground-wave and sky-wave components from the same source may be comparable in amplitude but arrive at slightly different times, resulting in interference. This is particularly important for broadcasting systems using digital modulation techniques.

The space wave represents energy that travels from the transmitting to the receiving antenna in the Earth's troposphere. Hence, it may also be called *tropospheric* wave. The troposphere is the lower part of the Earth's atmosphere extending upwards from the Earth's surface, in which temperature decreases with height. This part of the atmosphere extends to an altitude of about 9 km at the Earth's poles and 17 km at the equator. Television (at both very high and ultrahigh frequencies) and frequency-modulation (*FM*) radio signals are examples of space waves.

In the subsequent sections these different modes of propagation will be discussed in more detail. Factors affecting different modes of propagation will be investigated. Methods of predicting field strengths and interference levels at different frequencies will also be presented and analyzed.

Definitions of the most important terms relating to propagation are given in the Glossary.

GROUND-WAVE PROPAGATION

Early Theoretical Work

At frequencies between about 10 kHz and 30 MHz, ground-wave propagation is possible because the surface of the Earth is a conductor, although not a perfect one. The ground wave is vertically polarized. Any horizontal component of an electrical field on the surface of the Earth is short-circuited by the Earth. The earliest work on ground-wave propagation was carried out by Summerfield (1). His flat Earth theory states that ground-wave field strength, E_g, can be expressed in the form:

$$\mathbf{E_g = A(E_0/d)} \tag{1}$$

where

E_o field strength of wave at the surface of the Earth at a unit distance from the transmitting antenna, neglecting Earth's losses
d distance to transmitting antenna
A factor taking into account the ground losses

The field strength E_o at unit distance in Eq. (1) depends upon the power radiated by the transmitting antenna and the directivity of the antenna in the vertical and horizontal planes. If the radiated power is 1 kw and the short vertical antenna is omni-directional in the horizontal plane, then, E_o = 300 mV/m when the distance is 1 km. The reduction factor A, which takes into account the effect of ground loss, is a complicated function of electrical constants of the Earth, frequency, and the distance to the transmitters in wavelengths. The reduction is highly frequency dependent; it increases with increasing frequency. Thus, at LF (Band 5, 30 kHz to 300 kHz) and MF (Band 6, 300 kHz to 3000 kHz) ground-wave signals can be sufficiently strong for broadcasting service. On the other hand, at HF (Band 7, 3 MHz to 30 MHz), ground-wave signals are usually very weak, not suitable for broadcasting purposes. The Summerfield flat-earth approach, the subsequent Watson transformation (2), and the Bremmer residue series (3) were the important milestones and theoretical advances upon which the modern ground wave theory is still based.

The Development of Ground-Wave Curves

Intensive efforts to convert the theoretical advances to simple and practical field-strength curves took place between 1930 and 1940. Extensive measurement programs were conducted by many organizations including the Federal Radio Commission, the predecessor of the Federal Communications Commission (FCC). A variety of empirical formulas were developed and tested while exact solutions were being sought to the fundamental mathematical equations. In 1936, Kenneth Norton, a young engineer working for the FCC, constructed a universal curve for predicting ground-wave field strength at short distances. Later that year, he extended his universal curve for greater distances to include the *diffraction zone* (4). In 1939 the FCC released a complete set of ground-wave curves as an appendix to the Standards for Good Engineering Practice Concerning Standard Broadcast Stations (5). This set of curves, which covers the frequency range between 540 kHz and 1600 kHz, became effective on January 1, 1940. These curves, together with a comprehensive discussion, were included in a paper by Norton (6).

Similar but not identical ground-wave curves can also be found in ITU-R Recommendation P.368.8 (7). The most recent FCC curves cover the frequency range of 535 kHz to 1705 kHz. The ITU curves cover a much wider range of frequencies, from 10 kHz to 30 MHz. Note: ITU-R, which appears frequently in this paper, is the abbreviated name of the Radiocommunication Study Groups of the International Telecommunication Union, formerly known as the

International Radio Consultative Committee, CCIR P denotes propagation. Numeral 8 after dash means it is the 8th revised edition. Figure 1 illustrates FCC ground-wave curves.

Computer Programs

Currently, there are three computer programs available for calculating ground-wave field strengths. The first program, called ITSGW, was developed by Berry (8, 9). The second program, the program that has been used to generate curves in Recommendation P.368-8, was developed by Rotheram (10) and is called GRWAVE. This program takes into account the effect of refraction in an exponential atmosphere. This program is available from ITU Sales Service, Place des Nations, 1211 Geneva 20, Switzerland; http://www.itu.ch. The third program is called FCCGW, developed by Eckert (11). FCCGW has been used to generate the metric version of the FCC curves. The FCC program takes into account the effect of refraction by using an effective radius that is 4/3 times the actual radius of the earth. Refraction is insignificant at distances less than about 100 km. At greater distances, it becomes progressively more significant. Eckert has also carried out an extensive comparative study and has determined that the three methods give ground-wave field strength predictions sufficiently close in value that they could be considered identical for frequency management purposes.

Ground-Wave Propagation over Mixed Paths

For the prediction of ground-wave field strengths over paths composed of successive sections of terrain (including over-water sections) of different conductivities, there are two basic methods available. These are the equivalent-distance or Kirke method (12) and the equivalent field or Millington method (13). The Kirke method has the advantage of simplicity but in cases where the successive sections show considerable differences in conductivities it can lead to large errors. On the other hand, the Millington method does not suffer from this problem. Furthermore, the Millington method is now no longer as difficult to apply as before, because a simplified graphical approximation has been developed by Stokke (14). The Millington method and the Stokke approximation are presented in Recommendation P.368-8 as Annex I and Annex II, respectively.

Ground Conductivity Information

Ground-wave propagation can be considered a reasonably well understood topic. In one area, however, more work is needed. Ground conductivity is a very important factor in calculating ground-wave field strengths. Accurately measured data should always be used. Although several maps are available, they present estimates and are not very accurate. A map showing the estimated ground conductivities of the continental United States has been published by the FCC (15). An atlas of ground conductivities in different parts of the world can be found in ITU-R Recommendation P.832-2 (16). Furthermore, recognizing the need for more accurate ground conductivity data, the ITU-R has issued an opinion (Opinion 91) urging administrations to carry out such important measurements.

Conductivities are usually expressed in siemens per meter (S/m) or millisiemens per meter (mS/m). Conductivity of sea water is typically 5 S/m while that of fresh water is about 10 mS/m. Conductivities of rocky land, hills, and mountains vary between 1 mS/m and 2 mS/m. Conductivity of rich agricultural land is typically 10 mS/m. Cities and residential areas have a conductivity of about 2 mS/m. In industrial areas it is even less.

THE SKY-WAVE PROPAGATION ENVIRONMENT

The Solar-Terrestrial System

In 1901, Guglielmo Marconi (1874–1937), a young Italian engineer, succeeded in sending a Morse code message from Cornwall, England across the Atlantic Ocean to Newfoundland. It is generally believed that the frequency Marconi used was about 1.6 MHz, in the MF band. This history-making wireless experiment not only brought him a Nobel prize later in 1909 but also created a new frontier in the scientific world and generated a tremendous amount of research work that is still going strong today. Perhaps the earliest satisfactory explanation of his experiment was given by Oliver Heaviside, an English physicist. He theorized that in the Earth's upper atmosphere, there is a "sufficiently conducting layer" (17). This conducting layer (actually, layers) is now known as the ionosphere, so called because it consists of heavily ionized molecules. To understand sky-wave propagation, it is essential to study the entire solar-terrestrial system, not just the ionosphere alone. The literature on this subject is very rich; see for example, books by Davies (18) and by Goodman (19). Due to the limited amount of space available, in this paper we shall only discuss this subject briefly. It should be mentioned that materials presented in this section can be applied to LF, MF, as well as HF. HF sky-wave propagation, however, is more complicated and additional features will be presented later in this article. The ionized region in the Earth's atmosphere extending from about 50 kilometers to about 600 kilometers above the surface is called the ionosphere. Above that it is called the magnetosphere.

The Ionosphere

The ionosphere is divided into three regions (or layers): the D, E, and F regions, respectively, in increasing order of altitude. Figure 2 shows the regions of the ionosphere.

The D Region. The D region spans the approximate altitude range of 50 to 90 km; it exists only at daytime and disappears shortly after sunset. For virtually all applications in this article, the D region can be considered as an absorber, causing significant signal attenuation. The absorption is frequency dependent, it decreases with increasing frequency. At extremely low frequencies (*ELF*) and very low frequencies (*VLF*), however, waves are reflected by the D region. The absorption is also influenced by the Earth's magnetic field, tending to be high at frequencies near the gyro frequency.

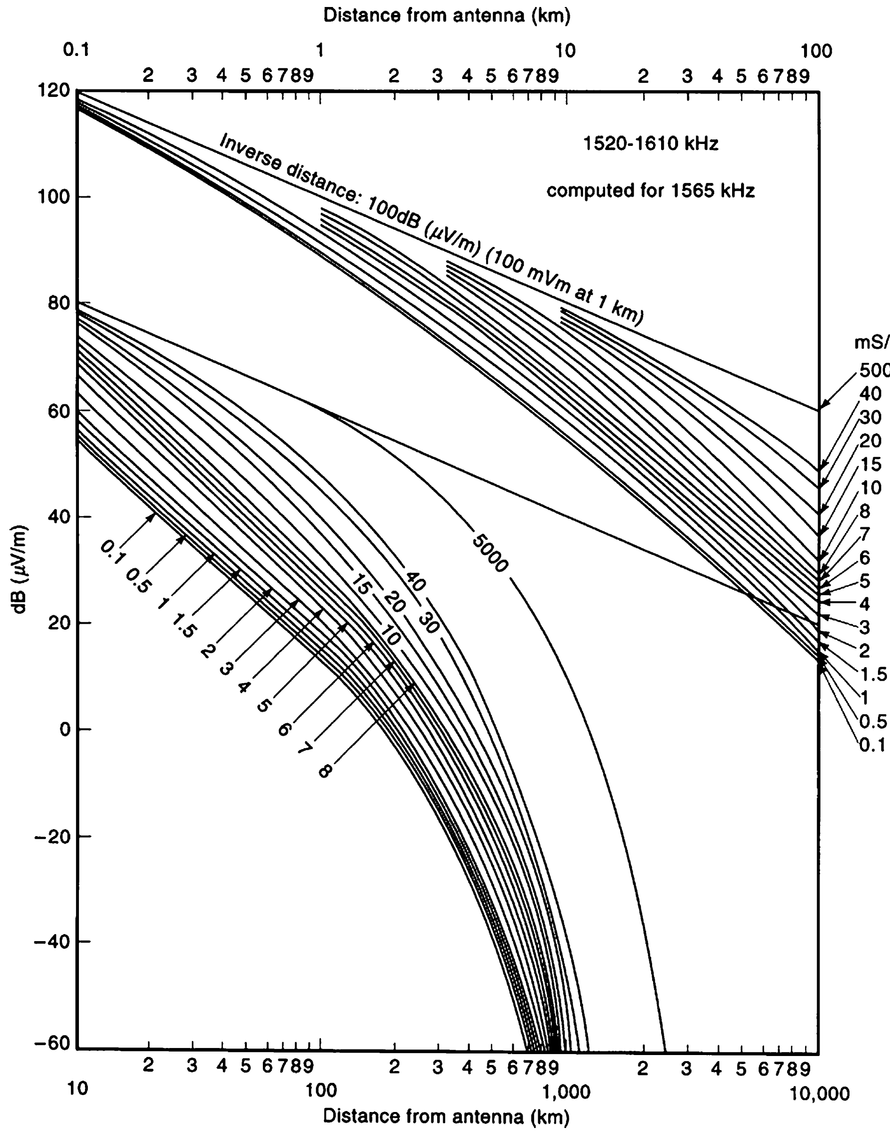

Figure 1. Sample FCC ground-wave curves.

The E Region. The altitude range from about 90 to 130 km constitutes the E region. This region is important for night-time low- and medium-frequency propagation at distances greater than about 200 km. The E region exhibits a solar cycle dependence with maximum electron density occurring at solar maximum.

Sporadic E. Embedded within the E region is an anomalous form of ionization called Sporadic E (Es). It has very little relationship with solar radiation. It assumes various different forms, sometimes irregular and patchy, sometimes smooth. It can have significant effects on propagation at high frequencies (HF) and very high frequencies (VHF).

F Region. The F region extends upward from about 130 km to about 600 km.The lower and upper portions of the F region display different behaviors at daytime, resulting in a further subdivision into F1 and F2 layers. The F1 layer is the region between 130 and 200 km above the surface of the Earth. The F2 layer is the highest and the most prominent ionospheric layer. It generally displays the greatest electron densities and is the only layer which persists during the night. The F2 layer is the principle reflecting region for long-distance high-frequency communication. At night, the F1 layer merges with the F2 layer and the average height of the combined layer (still called the F2 layer) is about 350 km.

Solar Activity

The ionosphere owes its existence to the Sun; or more precisely, to the radiation, both electromagnetic and corpuscular, from the Sun. The electromagnetic radiation, which includes ultraviolet and X-rays, travels toward the Earth at the speed of light, and the journey takes about 8.3 minutes. The ionization process is linked with the intensity of solar radiation which in turn varies with factors such as time of day, latitude, season, and solar activity. Solar activity changes drastically from time to time. Sunspot number is a reasonably good index of the state of solar activity although several other indices are also available. Sunspots are dark areas on the surface of the Sun and were first no-

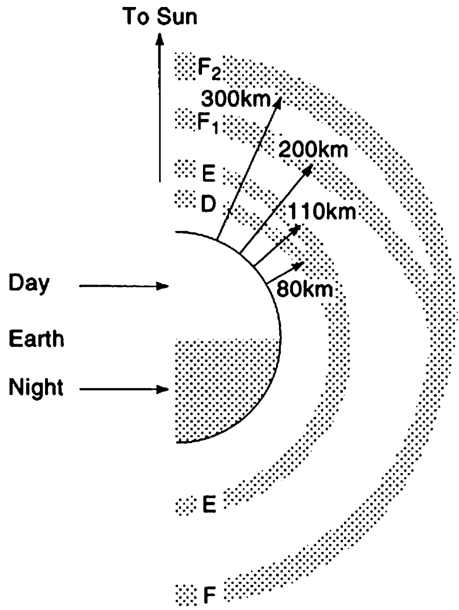

Figure 2. The ionosphere.

ticed and documented by the Chinese on March 17, 20 AD (20) during Han Dynasty (206 BC–220 AD). Sunspots appear dark because the temperature is low, only abut 3000 degrees Kelvin while the average temperature of the surface of the Sun is about 6000 degrees Kelvin. Sunspots tend to group together and display an 11-year cyclic nature. The astronomical records of the Jin Dynasty (265–418 AD) of China (21) indicate that for quite a while in the fourth century, sunspots were observed every 11 years (e.g.; 359, 370, 381, and 393 AD). Sunspot numbers varies from day to day and year to year. Routine observations have been made since 1749. The cycle beginning in 1755, a year of minimum sunspot number, is considered Cycle 1. Currently, we are at the second (descending) half of Cycle 23. The ascending portion of a cycle (on the average, 4.5 years) is usually much shorter than the descending one (6.5 years). The Zurich (or Wolf) sunspot number R is given by

$$R = k(10g + s) \tag{2}$$

where g is the number of sunspot groups; s is the number of observed individual spots and k is a correction factor, approximately unity, used to equalize the results from different observations and equipments. The sunspot number is subject to wide variations from month to month and is of little usefulness. Furthermore, it is known that the characteristics of the ionosphere do not follow the short-term variations. In order to achieve a better correlation, some kind of "smoothing" technique is desirable. Consequently, the 12-month smoothed sunspot number (R_{12}) has been adopted and is the most widely used index in ionospheric work today.

$$R_{12} = (1/12)\left[(0.5)(R_{n+6} + R_{n-6}) + \sum_{n-5}^{n+5}(R_n)\right] \tag{3}$$

Thus, the value of R_{12} is, by definition, only known 7 months after the recorded observation. R_{12} varies from a minimum of about 10 to a maximum generally of 100 to 150, although in December 1957 it reached a record high of 239.4. Note that the ionospheric effects tend to saturate for R_{12} greater than about 150.

Atmospheric Radio Noise

For the estimation of the performance to be expected in an HF system, it is insufficient to consider signal level alone. Equally important are the characteristics of radio noise in the bandwidth of the receiving equipment. That is, signal-to-noise ratio (S/N) at the receiving site must also be considered. There are many different noise sources: the atmosphere, the receiving system, human activity, the Sun, and galaxies. In this article, emphasis has been placed on atmospheric noise, the most important one as far as broadcasting service is concerned. An excellent discussion on other types of noises can be found in ITU-R Recommendation P. 372-8 (22).

Atmospheric noise is produced mainly by lighting discharges in thunderstorms. There are about 50,000 thunderstorms worldwide per annum, yielding about 100 lightning flashes per second. Each lighting flash includes two discharges. The discharge current varies between 10 and 100 kiloamperes (kA). Discharges take place between two and four kilometers above ground. The power released is very great, typically greater than 10 gigawatts (GW) (23). Atmospheric radio noise obey the same propagation laws as sky-wave signals. Thus, it travels to distances several thousands of kilometers away from the source via sky wave. The noise level, thus, depends on time of day, season of the year, weather, geographical location, and frequency. Multiple paths with various reflections and scattering are very common, resulting in continuous noise. In general, atmospheric noise level is the highest: (1) when the receiver is located near a thunderstorm center; (2) during local summer; (3) during the night; or, (4) when the frequency is low. There are three major thunderstorm (hence, noise) centers in the world: the Caribbean, equatorial Africa, and Southeast Asia. Stations serving the high noise areas need higher power to produce strong enough signals to ovecome high noise levels. Maps showing the atmospheric noise levels for different parts of the world corresponding to different seasons of the year and different hours of the day have been developed by the CCIR since 1964. The most recent maps, which are based on work by Spaulding and Washburn (24), can also be found in ITU-R Recommendation P. 372.8 (22).

Magnetic Coordinates

There are several definitions of latitude connected with the geomagnetic field. The *centered dipole* latitude, or simply the *dipole* latitude, is an approximation and has been used for ionospheric work for decades. It is adequate for applications where high degree of accuracy is not required. *Corrected* geomagnetic latitude more accurately represents the real geomagnetic field and should be used when accuracy is desired. Conversion tables from geographical coordinates to the corrected latitudes are readily available (25).

SKY-WAVE PROPAGATION AT LF AND MF

In the next few sections, a brief historical background leading to the development of currently used field strength prediction methods will be given. The purpose is twofold: to document some valuable historical facts, and more importantly, to help the users to select the right propagation models for their particular applications. Variations of field strengths will also be discussed in some detail.

The Early CCIR Studies

The earliest world-wide concerted efforts to study LF/MF sky-wave propagation began in 1932. At its meeting held in Madrid, the International Radio Consultative Committee (CCIR, now known as ITU-R) established a committee (Balthasar van der Pol, Holland, Chairman) to study propagation at frequencies between 150 and 2000 kHz. With support from the International Broadcasting Union (UIR), three measurement campaigns were carried out between 1934 and 1937. Measurements were made on 23 propagation paths between North America and Europe, between North America and South America, and between Europe and South America. At that time, it was generally believed that sky-wave field strength was a simple function of distance and results of measurements would enable the van der Pol Committee in *curve-fitting*. Consequently, two sky-wave propagation curves were drawn. One of the curves is for paths far away from the Earth's magnetic poles; this is better known as the North-South curve, because it was derived from measurements made on north-south transequatorial paths. The other curve is for paths which approach the Earth's magnetic poles and is better known as the East-West curve because it was derived from measurements made across the North Atlantic. The two curves were formally adopted by the CCIR at the 1938 International Radio Conference, Cairo. Therefore, these curves are known as the Cairo curves.

The Early American Activities

Recognizing the needs for a set of sound engineering standards, the Federal Communications Commission (FCC) of the USA, under the leadership of the late Ken Norton, carried out a sky-wave field strength measurement program in the spring of 1935. At that time there were eight clear-channel stations. Nighttime signals of these stations were monitored at eleven receiving sites located in different parts of the United States. From these measurements, the FCC clear-channel sky-wave curve was derived. For many years this method was included in the FCC Rules. The 1950 North American Regional Broadcasting Agreement (NARBA) adopted this method for official use in North America. Furthermore, the 1980 Regional Administrative Broadcasting Conference for Region 2 (the Americas) adopted this method (with minor modifications) for applications in the entire ITU Region 2. Hence, this method will be called the Region 2 method in this article. A newer and more accurate method has been developed by the staff of the FCC and is part of the current FCC Rules for domestic applications. See also the section titled Predicting LF/MF Sky-wave Field Strengths.

Knowing the clear-channel curve has some limitations (e.g., it does not take into consideration the effect of the latitude) and the need for more sky-wave field strength data, the FCC, initiated a long-term large scale measurement program in 1939. Measurements from more than 40 propagation paths were collected. The measurement lasted for about one sunspot cycle; in four cases it lasted for two cycles and ended in 1958. Frequencies of these paths range from 540 to 1530 kHz. Path lengths range from 165 to 4176 km. Midpoint geomagnetic latitudes of the majority of the paths range from 45 to 56 degrees north, a narrow range of 11 degrees, although some paths from lower latitudes were later added. The Canadian Department of Transport also took some measurements in 1947, a year of maximum sunspot number and minimum field strengths. It is to be noted that in the study of sky-wave propagation, latitude means the geomagnetic latitude of the midpoint of a path under study.

Activities Prior to the 1974–1975 Low Frequency/Medium Frequency Conference

Recognizing the need for a simple field strength prediction method for worldwide applications, the CCIR at its Xth Plenary Assembly (Geneva, 1963) established International Working Party (IWP) 6/4 to undertake such a task (the word international was later replaced with interim). This IWP was first chaired by J. Dixon (Australia), succeeded by G. Millington, P. Knight (UK), and J. Wang (USA). In the late 1960s and early 1970s a number of administrations and scientific organizations made valuable contributions. For example, the European Broadcasting Union (EBU), which started its sky-wave studies soon after World War II, reactivated its efforts and collected data from more than 30 propagation paths. Its counterpart in Eastern Europe, the International Organization of Radio and Television (OIRT) was also active. OIRT contributed data from 12 short intra-European paths between 600 and 1400 km at frequencies between 164 and 1554 kHz. Their efforts were supplemented by measurements made by different administrations. The administration of the former USSR also collected a significant amount of measurements. Summary of their results was published in 1972 (26), but to-date, data have not been made available to the public. Most of the European measurements were taken before the 1974–75 LF/MF Regional Conference. The Finnish receiving site, however, is still very active. Altogether, data from more than 70 paths are documented by IWP 6/4.

Three international organizations jointly planned and carried out a very extensive measurement campaign in Africa between 1963 and 1964. They are the EBU, the OIRT, and the Union of National Radio and Television Organizations (URTNA). Later, the British Broadcasting Corporation (BBC) set up seven receiving stations in Africa and signals from two transmitters on the British Ascension Islands were monitored. The British project was intended to study polarization coupling loss and sea gain. The Max Planck Institute of Germany also conducted measurements at Tsumeb, South-West Africa. Altogether, the African measurement campaign involved 15 receiving sites and data from 33 paths were documented by CCIR IWP 6/4.

Frequencies range from 164 kHz to 1484 kHz. Distances range from 550 km to 7540 km. Of these 33 paths, three are from Europe to Africa.

Administrations in ITU Region 3 (parts of Asia, Australia and New Zealand), in cooperation with the Asian-Pacific Broadcasting Union (ABU), were equally active and productive. In the northern part of this Region, data from 84 paths have been documented and used in this study (27, 28). In the southern part of Region 3, Australia and New Zealand collectively collected data from 85 paths in the "Down Under" areas. Furthermore, the Japanese administration carried out a number of mobile experiments in the low-latitude areas of the Pacific (29).

While the ITU and administrations in the eastern hemisphere were busy preparing for the 1974–1975 Regional LF/MF Conference for ITU Regions 1 and 3, IWP 6/4 was actively developing a propagation model to be used as part of the technical bases for such a conference. After extensive studies and lengthy deliberations, the IWP was able to agree on the following: the method proposed by the former USSR based on a paper by Udaltsov and Shlyuger (26) was recommended together with the Knight sea gain formula (30) and the Phillips and Knight polarization coupling loss term (31).

Recent Activities in the Americas

Recognizing the need for additional data, particularly data from the low- and the high-latitude areas, the FCC initiated two separate projects in the early 1980s. In 1980, the FCC and the Institute for Telecommunication Sciences of the Department of Commerce jointly began to collect low-latitude sky-wave data at two receiving sites: Kingsville, Texas and Cabo Rojo, Puerto Rico. The FCC-ITS efforts in the low-latitude areas were supplemented by Mexico and Brazil; both administrations also collected a significant amount of low-latitude data. In 1981, the FCC awarded a contract to the Geophysical Institute, University of Alaska. This project called for the acquisition and the analysis of sky-wave data from the high-latitude areas. The Alaskan project lasted for about seven years; data representing different levels of solar activity have been successfully collected.

To date, measurements from more than 400 propagation paths are well documented and statistically processed and studied. Based on the most recent and enlarged data bank, a new field strength prediction method has been developed (32) and has been adopted by the FCC for applications in the United States. All of the four major methods mentioned in this section will be discussed qualitatively and compared quantitatively in this paper.

Variations of Field Strengths

Amplitude Distribution. Unlike ground-wave field strengths which change very little from day to day, nighttime sky-wave field strengths vary greatly from minute to minute and night to night. The within-the-hour shortterm variation usually takes the form of Rayleigh distribution. Night-to-night median values of field strengths for a given reference hour are log-normally distributed. Nighttime yearly median value of field strength at six hours after sunset is usually used to determine sky-wave (or secondary) service area of a station while the yearly upper-decile value is used to determine interference level. The difference between the annual upper-decile and median values varies with latitudes, from 6 dB in the tropical areas to 12 dB or more at high latitudes. See also the section titled Upper Decile Field Strength.

Diurnal Variation. At LF, the transition from daytime to nighttime condition in winter is very gradual and field strength does not reach its maximum value until about two hours before sunrise. The change at sunrise is more rapid. In summer, field strength increases much more rapidly at sunset.

At MF, field strength changes very rapidly at sunset as well as sunrise. Field strength reaches its maximum value shortly after midnight, or about six hours after sunset. For this reason, six hours after sunset is used as the reference hour for frequency management purposes. Based on US data, field strength is highly frequency-dependent during transition hours. For example, the signal of a 1530 kHz station is about 15 dB stronger than that of a 700 kHz station at sunset or sunrise. Field strength at six hours after sunset is still frequency dependent, the difference being only about 3 dB in favor of the higher frequencies (33).

Seasonal Variation. At low latitudes (e.g., Mexico), both day-to-day and seasonal variations are not very pronounced. A slight minimum can be expected in summer months.

As latitude increases, so do night-to-night and seasonal variations. No fixed pattern, however, can be concluded from available data collected at temperate latitudes (69). However, it seems safe to say that in winter months field strengths are usually near or greater than the annual median values. In summer months, field strengths are usually weaker than the annual median value.

Data collected at high latitudes show a more consistent pattern. Field strengths are usually strong in spring and fall. Date collected in Alaska, for example, show that the maximum field strength, which is typically 10 to 15 dB stronger than the annual median value, usually occurs in April (34). A pronounced minimum can be expected in summer months.

Daytime sky-wave field stengths display a consistent seasonal variation pattern. Maximum field strengths usually occur in winter months while minimum values in summer months. The maximum-to-minimum ratio is typically 10 to 20 dB.

Effect of Solar Activity. At LF, the effect of solar activity is negligible. At MF, it is an entirely different story. It is well known that MF sky-wave field strength levels are reduced during periods of high solar activity. This effect is more pronounced in some parts of the world (e.g., the United States and Canada) than in other parts. The reduction of field strength due to solar activity (or Lr in the subsequent equations) is a function of sunspot number, latitude, distance, and frequency (35).

The effect of solar activity is clearly latitude dependent (36). In low-latitude areas, annual median values of field strengths vary slightly within a sunspot cycle. For example, on a path from Havana, Cuba to Kingsville, Texas (640 kHz, 1626 km, 36 degrees N) measured field strength levels fluctuate within a range of 3 dB, without any detectable pattern, during sunspot cycle 18. Data collected at comparable latitudes in Mexico display a similar variation. A pattern of correlation begins to surface at higher latitudes. For example, measured field strengths from a path in the southern parts of the United States (San Antonio, Texas to Grand Island, Nebraska; 1200 kHz, 1279 km, 45.1 degrees N) decreased by about 3 dB when sunspot number increased from minimum to maximum in cycle 18. The correlation becomes more pronounced at still higher latitudes. For example, measured field strengths of a path in the northern United States (Chicago, Illinois to Portland Oregon, 890 kHz, 2821 km, 54 degrees N) decreased by 15 dB in the same cycle. In Alaska, in a year of maximum solar activity, there are virtually no sky waves from northern-tier US stations although signals can be very strong in a year of low or moderate solar activity (34).

The effect of solar activity is also frequency dependent, within the MF band, in early evening hours (e.g., 2 hours after sunset). When other factors are nearly the same, the signal of a lower-frequency (e.g., 700 kHz) station varies more widely than that of a higher-frequency station (e.g., 1530 kHz). The difference is typically 5 to 6 dB (36). At six hours after sunset, this phenomenon is virtually diminished.

The effect of solar activity has a diurnal variation of its own. In other words, Lr is different at different hours of the night. Lr at six hours after sunset is considerably smaller than that at two hours after sunset. For example, consider a long path from Cincinnati, Ohio to Portland, Oregon (700 kHz, 3192 km, 53.2 degrees N). From 1944 (a year of minimum sunspot) to 1947 (a year of maximum sunspot number), field strength for the sixth hour after sunset decreased by 7.3 dB; that for the fourth hour decreased by 13.3 dB; and that for the second hour decreased by 16.9 dB. For a more detailed discussion on the effects of solar activity, see a paper by Wang (36).

Polarization Coupling Loss. Polarization coupling loss, Lp, occurs when waves enter the ionosphere, because some of the incident power passes into the extraordinary wave, which is then absorbed. Further loss occurs when the wave leaves the ionosphere, because it is elliptically polarized and only its vertical component normally couples with the receiving antenna. At LF, polarization coupling loss is negligible. At MF, polarization coupling loss is negligible in temperate and high latitudes. In tropical latitudes, however, it can be very large and depends on the direction of propagation relative to that of the Earth's magnetic field. In some extreme cases (e.g., east-west paths in the near equatorial areas of Africa), polarization coupling losses of more than 20 dB have been observed. This phenomenon is not yet fully understood, and more data are needed. An interim formula, however, has been developed by Phillips and Knight based on the African data mentioned previously (31).

Influence of Sea Water. When one or both terminals is situated near the sea and a significant portion of the path is over sea water, the received signal is significantly stronger than otherwise. This is commonly called *sea gain, Gs.* The word "gain" here is a rather unfortunate selection. It is not exactly a gain. It is actually a reduced *ground loss.* Sea gain is a complicated function of several factors, including path length (i.e., elevation angle), distance from antenna to the sea, frequency, and so on. Under ideal conditions (elevation angle = 0, antenna is on the coast), sea gain is about 4 dB at LF and about 10 dB at MF. If a path is over fresh water (e.g., river, lake, bay), sea gain does not apply. For a more detailed discussion on sea gain, see a paper by Knight (30).

Propagation at Daytime. Interference from the daytime sky-wave signal of one station to the ground-wave signal of a co-channel station located several hundred kilometers away has been observed in certain parts of the world. Therefore, daytime propagation is a very important topic. It is extremely difficult to collect sky-wave data during the day. First of all, signals are very weak. Secondly, ground-wave signals, under certain conditions, may be strong enough to mask sky-wave reception. Furthermore, co-channel interference from stations near the monitoring site may also be a problem. Nevertheless, daytime measurements from more than 30 propagation paths are believed to be sky waves and have been studied by Wang (37). While more measurements and work are needed, some trends have been observed and are briefly stated as follows:

LF Cases. Midday sky-wave field strengths at LF can be surprisingly strong, particularly in winter months. Daytime annual median field strength is typically 20 dB lower than its counterpart at night. Daytime upper-decile value is about 13 dB stronger than the median value.

MF Cases. Midday sky-wave field strengths at MF display a consistent seasonal variation pattern with maximum occurring in winter months. The average winter-month field strength is about 10 dB stronger than the annual median value and the winter-to-summer ratio can exceed 30 dB. The annual median value of midday field strength is about 43 dB lower than its counterpart at six hours after sunset. Field strength exceeded for 10% of the days of the year is about 13 dB stronger than the median value.

Discussions on Field Strength Prediction Methods

Today, there are four major LF/MF sky-wave field strength prediction methods that are being used in different parts of the world. They are (in chronological order): the Region 2 method (i.e., the old FCC clear-channel curve), the Cairo curves, the Udaltsov-Shlyuger method, and the Wang method. A qualitative discussion is given below. This is followed by a brief quantitative comparison of calculated field strengths by using these methods with measured data. This section will enable users to select the right method for their particular application.

The Region 2 Method (or the FCC Clear Channel Curve). This method presents field strength as a function of great-circle distance for a characteristic field strength at unit distance. It does not take into account effects of other factors such as latitude, frequency, sunspot number, and so on. The detailed calculation procedures can be found in Ref. .38 It has been reported (32, 39) that this method offers reasonable accuracy when applied to temperate latitudes. When applied to low-latitude areas (e.g., Puerto Rico) it displays a tendency to underestimate. On the other hand, when applied to high-latitude areas (e.g., northern United States, Canada), it displays a strong tendency to overestimate. Clearly, this results from the fact that this method lacks a treatment of the effect of latitude. The Region 2 method has served its purpose well and cannot handle the present day's heavy demands for frequencies. It is definitely not a candidate for worldwide applications.

The Cairo Curves. As mentioned in the section titled The Early CCIR Studies, at its 1938 meeting in Cairo the CCIR adopted two curves from the van der Pol working group, one for propagation paths "distant from the Earth's magnetic poles" (the North-North curve) and one for propagation paths "near the Earth's magnetic poles" (the east-west curve). Similar to the FCC clear-channel curve, the Cairo curves present field strength as a function of distance only. When converted to the same conditions, the two Cairo curves and the FCC clear-channel curve are similar for distances up to about 1400 km. At 3000 km, the north-south curve is about 8 dB greater than the east-west curve; at 5000 km, the difference is about 18 dB. The FCC clear-channel curve falls between the two Cairo curves. The Cairo curves did not gain much recognition (in part, due to World War II) until 1974 when the LF/MF Conference adopted the Cairo north-south curve for use in the Asian part of Region 3. The Cairo east-west curve, because it often underestimates field strength levels, has virtually been disregarded. Therefore, hereafter in this article, the north-south curve will be called the Cairo curve for simplicity. Like the Region 2 method, the Cairo curve cannot be considered as a candidate for worldwide applications either.

The Udaltsov-Shlyuger Method. Derived from measurements collected in the former USSR, this method was also called the USSR method. At its XIIIth Plenary Assembly (1974, Geneva), the former CCIR adopted this method, with modifications, as Recommendation 435, for provisional use worldwide. The 1974 LF/MF Conference also adopted this method for use in Region 1 and the southern part of Region 3 (40). This method, which includes a sound treatment of the effects of latitudes, appeared to be very promising at that time. When applied to one-hop intra-European paths, reasonably accurate results were obtained (41). After years of extensive testing against measured data from other parts of the world, however, some major limitations have surfaced. For example, when applied to paths longer than, say, 4000 km, the method has a strong tendency to underestimate field strength levels, in some cases by more than 20 dB (41). Furthermore, Region 2 (the America) data do not seem to corroborate the frequency term of this method (39). Although this method is a great step forward from the two previous methods, it is something short of a true worldwide method.

The Wang Method. Like the Udaltsov-Shlyuger method, the Wang method also contains a similar latitude term. This method has essentially linked the Cairo and the FCC clear-channel curves together mathematically. The special case corresponding to a geomagnetic latitude of 35 degrees in the Wang method is extremely close to the Cairo curve. The special case corresponding to 45 degrees is very similar to the FCC curve. More importantly, it works well for long paths and short paths alike. This method became part of the Rules and Regulations of the FCC in 1990, replacing the old clear-channel curve. This method has recently been adopted by the ITU-R as Recommendation P. 1147-3 for worldwide applications (42).

Quantitative Comparisons. Calculated field strengths by using the previously mentioned methods have been compared with measured data from different parts of the world (39,41,43). It should be mentioned that the Phillips-Knight formula for polarization coupling loss and the Knight formula for sea gain have been included in all methods wherever applicable. For reader's convenience, measured data are grouped together according to ITU Regions. Long intercontinental paths are discussed separately although some overlapping may exist. Long-term measurements from more than 400 propagation paths have been used. The following is a brief summary.

Region 1. When compared with measured field strength values from some 50 intra-European one-hop paths, excellent and similar results have been obtained by using either the Udaltsov-Shlyuger or the Wang method. In an overwhelming number of cases, the errors are less than 5 dB. In Africa, prediction is complicated by the fact that magnetic dip angles are usually low, resulting in pronounced polarization coupling loss with east-west paths. Furthermore, in many cases, measurements are short term in nature (e.g., 30 days) and do not necessarily reflect the true propagation conditions. When compared with measured field strengths from 35 intra-African and 6 Europe-to-Africa paths, the rms error of the Udaltsov-Shlyuger method is 9.3 dB and that of the Wang method is 7.8 dB. This suggests that more data from this part of the world are urgently needed to better understand polarization coupling loss.

Region 2. Sky-wave propagation in North America is a very complicated matter. This is primarily due to its proximity to the Earth's magnetic north pole. The impact of solar activity is, therefore, the most profound. For frequency management purposes, often the worst-case field strength (i.e., maximum field strength which usually occurs in a year of minimum solar activity) is used. When compared with measured field strength values from 87 paths in Region 2, taken in a year of minimum sunspot number, the rms errors of the Region 2, the Udaltsov-Shlyuger and the Wang methods, are 8.9 dB, 5.8 dB and 4.9 dB, respectively.

Region 3 North. From LF/MF propagation point of view, this is the "luckiest" area of the world. First, geomagnetic latitudes are low (e.g., Singapore, 10 degrees South; Tokyo, 26 degrees North). Therefore, solar disturbances have very little influence. On the other hand, magnetic dip angles of this part of the world are sufficiently high (>45 degrees) such that polarization coupling loss is negligible. When compared with measured field strength values from 84 paths, the rms errors of the Cairo curve, the Udaltsov-Shlyuger and the Wang methods, are 4.6 dB, 4.9 dB and 3.5 dB, respectively.

Region 3 South. The administrations of Australia and New Zealand carried out extensive sky-wave measurement projects independently. Altogether, field strengths from 85 paths have been documented. It should be mentioned that of these 85 paths, 11 are long trans-equatorial paths with transmitters located in different parts of Asia and a receiving site at Darwin, Australia. Transmitters and receiving sites of the other 74 paths are all located in the down-under areas. When compared with these measurements, the rms errors of the Udaltsov-Shlyuger and the Wang methods are both about 7 dB. In an overwhelming number of cases, the errors are negative, i.e., predicted values are lower than measured values. Similar observations have been previously reported by Dixon (44). Measured field strengths of the 11 Asia-to-Australia paths, which follow the Wang method much closer than the Udaltsov-Shlyuger method, do not show this trend. The 1974/1975 LF/MF Conference adopted the Udaltsov-Shlyuger method for applications in this area but some modifications were made. One of the modifications was that a correction factor of 3 dB was added. This is one way to improve the accuracy. A seemingly better approach is to use corrected geomagnetic latitude. This is left for future work.

Long Paths. If we arbitrarily define a long path as one whose length is greater than 4000 km, then there are 66 paths which belong in this category. This figure includes part of the Japanese mobile experiments near Antarctica (29). Frequencies of these paths range from 164 kHz to 1602 kHz while path lengths range from 4163 km to 11,890 km. Most of these 66 paths are intercontintental in nature and cover every continent and every ocean of this world. When compared with these measurements, the rms errors of the Cairo curve, the Udaltsov-Shlyuger and the Wang methods, are 10.98 dB, 13.31 dB and 5.76 dB, respectively. Clearly, this convincingly demonstrates that the Wang method has a superior treatment of path length.

For additional comments on analyses of these field strength prediction methods see Refs. 45–47.

Predicting Low Frequency/Middle Frequency Sky-Wave Field Strengths

Due to limited space available, this section is not meant to be self-contained. In fact, only one method will be presented. In this section, we recommend and present the Wang method for predicting sky-wave field strengths, the method developed from the most recent and largest data bank. Most important equations are given in this section. Equations for associated terms, if readily available from other sources (e.g., polarization coupling loss, sea gain), are not repeated here. Symbols and abbreviations used in the ITU-R texts are maintained to the fullest extent possible.

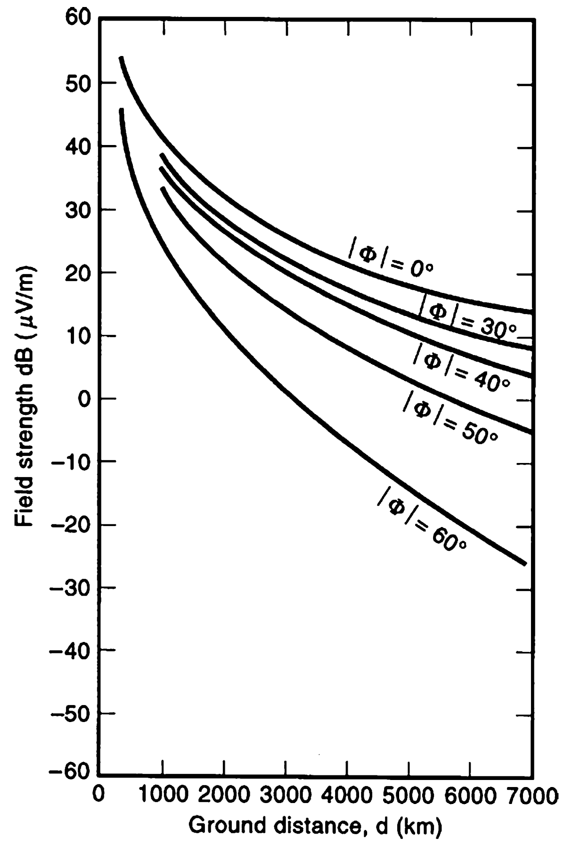

Figure 3. Calculated LF/MF sky-wave field strengths according to Eq. (3) for P = 0 dB (kW) and G = 0 dB.

Annual Median Field Strength. According to the Wang method, the annual median sky-wave field strength at six hours after sunset, E (in dB above 1 μV/m), is given by:

$$E = P + G + (107 - 20\log p) - k(p/1000)^{0.5} - Lp + Gs - Lr \tag{4}$$

Figure 3 shows LF/MF sky-wave field strengths as calculated in Eq. (4).

$$k = 2\pi + 4.95\tan^2(\Phi) \tag{5}$$

where

P = radiated power in dB above 1 kW,
G = transmitting antenna gain in dB,
p = actual slant distance of the path under study, in km, assuming the average height of the E layer is 100 km,
Φ = geomagnetic latitude of the mid-point of the path in degrees,
Lp = polarization coupling loss in dB (42),
Gs = sea gain in dB (42),
Lr = loss of field strength due to solar activity in dB (36).

Figure 4 shows absorption coefficient k.

Upper Decile Field Strength. Field Strength Exceeded for 10% of the time, E(10), is greater than the annual median

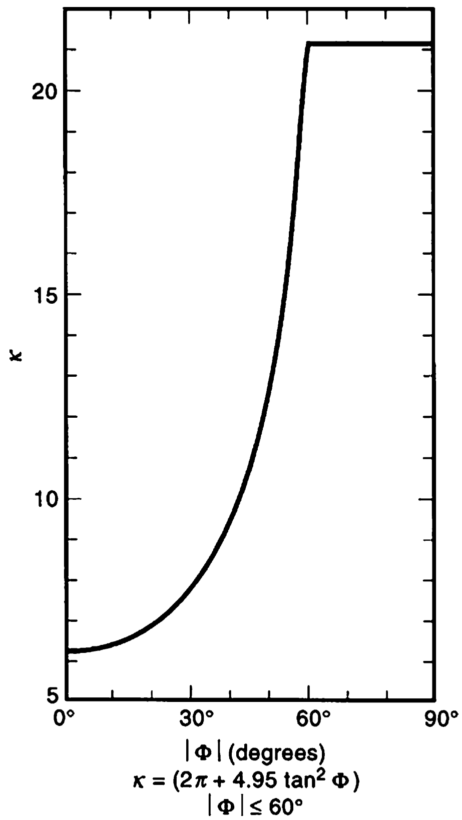

Figure 4. Graphical presentation of absorption coefficient k.

value by Δ dB. Then:

$$\Delta = 0.2|\Phi| - 2 \quad (6)$$

where Δ is limited between 6.0 and 10 dB.

Accuracy of Method. This method has been verified for frequencies between 150 and 1630 kHz and can be used confidently for the entire standard broadcasting band of 150 kHz to 1700 kHz. Although this method has been verified for geomagnetic latitudes up to 65 degrees north, caution should be exercised for latitudes greater than 60 degrees. If the absolute value of the latitude is greater than 60 degrees, Eq. (4) is evaluated for $\Phi = 60$ degrees. The most accurate dipole latitude is adequate in most cases. For the most accurate results, however, corrected latitude (25) should be used. It is to be noted that a hand-held calculator is sufficient to carry out all necessary calculations.

SKY-WAVE PROPAGATION AT HIGH FREQUENCY

High Frequency Propagation Characteristics

Materials presented in the Sky-Wave Propagation Environment section, also apply to HF propagation. In this section, some additional materials relevant to HF propagation will be presented.

HF sky-wave propagation may be represented by rays between ground and ionosphere. In the ionosphere, the radio waves experience dispersion and changes in polarization. The propagation is affected by, among other factors, the ionospheric ionization, operating frequency, ground conductivity and elevation angle. HF waves in the ionosphere undergo continuous refraction (i.e., bending of the ray path). At any given point, refraction is less at lower electron densities, for higher frequencies, and for higher elevation angle. For a given elevation angle, there exists a certain frequency below which the rays will be reflected back to Earth. At a higher frequency, the refraction is too low for the rays to be returned to Earth. Waves launched vertically may be reflected, if their frequency is below the *critical frequency* (see Glossary).

The apparent height of reflection varies between about 100 km and 350 km. Radio waves that are launched more obliquely travel to greater range. The maximum range attained after one hop arises for rays launched at grazing incidence. For typical E, F1, and F2 layers, it is about 2000, 3400, and 4000 km, respectively. In HF communication, several propagation paths are often possible between a given transmitter and a given receiver, e.g., a single reflection from the E region (1E mode), a single reflection from the F region (1F mode), and double reflection from the F region (2F mode). Mode 2F is said to have higher *order* than mode 1F in propagation terms. This feature is known as multipath.

At frequencies above the critical frequency, there is an area surrounding the transmitter defined by *skip distance* in which sky wave cannot be received because the elevation angle is too high. The maximum usable frequency (MUF), a very important concept in HF propagation, may be defined as the frequency that makes the distance from the transmitter to a given reception point equal to the skip distance. See also the Glossary. The MUF increases with path length and decreases with the height of the ionospheric layer. The MUF also undergoes diurnal, seasonal, solar cycle, and geographical variations. The MUF tends to be high during the day and low during the night. Also, the MUF is higher in summer than in winter during the night. Furthermore, the MUF tends to increase with increasing sunspot number. The F2-layer MUF may increase as much as 100 percent from sunspot minimum and sunspot maximum. The MUF has a very complex geographical variation. The most authoritative presentation of MUF is undoubtedly the CCIR Report 340, Atlas of ionospheric characteristics (48), which presents world maps of MUF for the F2-layer corresponding to different month of the year, solar activity levels, and distance ranges.

Fading

Fading may be caused by several different effects. The most common types of fading are:

Interference Fading. Interference fading results from interference between two or more waves which travel by different paths to arrive at the receiving point. This type may be caused by interference between: multiple reflected sky waves, sky wave and ground wave. This type of fading may last for a period of a fraction of a second to a few seconds, during which the resultant field intensity may vary over wide limits.

Polarization Fading. Polarization fading occurs as a result of changes in the direction of polarization of the downcoming wave, relative to the orientation of the receiving antenna, due to random fluctuations in the electron density along the path of propagation. This type of fading also lasts for a fraction of a second to a few seconds.

Absorption Fading. Absorption fading is caused by variation in the absorption due to changes in the densities of ionization and it may sometimes last longer than one hour.

Skip Fading. Skip fading may be observed at receiving locations near the skip distance at about sunrise and sunset, when the basic MUF for the path may oscillate around the operating frequency. The signal may decrease abruptly when the skip distance increases past the receiving point (or increase with a decrease in the skip distance).

Regional Anomalies

Tropical Anomalies. In the tropical zone, sky-wave propagation is characterized by the presence of equatorial sporadic E and the spread F. Equatorial sporadic E (*Es-q*), which appears regularly during daytime in a narrow zone near the magnetic equator, is the principal cause for fading at daytime. In the equatorial zone after local sunset, some irregularities develop in the F-region ionization and is called spread F. Under these conditions, the F-region increases markedly in height and seems to break up into patchy irregular regions. As a result, a peculiar type of rapid fading, called flutter fading, usually occurs after sunset. Flutter fading is one of the most important factors in the degradation of HF broadcast service in tropical areas. Flutter fading is most pronounced following the equinoxes. Flutter fading correlates negatively with magnetic activity. On magnetically quiet days, it is usually evident; whereas on magnetically disturbed days, it is absent. The fading rate is proportional to the wave frequency and may range between 10 per minute and 300 per minute (19).

High Latitude Anomalies. As mentioned in the D region section, the D region can be considered as an absorber. At high latitudes, the ionosphere is exposed to the influence of disturbances in interplanetary space and in the magnetosphere, since the magnetic field lines extend far from the Earth. Electrically charged particles can move easily along the field lines and perturb the high-latitude ionosphere. Absorption is inversely proportional to frequency squared. Absorption may be preceded by a sudden ionospheric disturbance (SID) on the sunlit side of the Earth, at all latitudes, caused by X-rays from solar flares. At HF, absorption can be greater than 100 dB (49). The magnetic storm related absorption in the sunlit part of the polar cap is much stronger than in the dark side. The average duration of the event is about two days, but may be as long as four days. It may spread to lower latitudes too. See a paper by Hunsucker (50) for a discussion of high-latitude anomalies.

Predicting High Frequency Sky-Wave Field Strength

The calculation of HF field strengths is a very complicated and tedious process. It requires a computer. In the succeeding section, a survey of existing programs will be presented. In this section, only a brief outline of the calculation procedure is given. The purpose is to illustrate the general procedures and terms involved. No attempt is made to make this article a self-contained one. For a more detailed presentation, see, for example, ITU-R Recommendation P. 533-8 (51).

The median value of sky-wave field strength for a given mode of propagation, in dB (μV/m), is given by:

$$E_{ts} = 136.6 + P_t + G_t + 20\log f - L_{bf} - L_i - L_m - L_g - L_h - 12.2 \quad (7)$$

where

$$\begin{aligned} P_t &= \text{transmitter power in dB relative to 1 kW,} \\ G_t &= \text{transmitting antenna gain, dB,} \\ f &= \text{transmitting frequency in MHz} \\ L_{bf} &= \text{basic free space transmission loss} \\ &= 32.45 + 20\log f + 20\log p \\ p &= \text{slant distance in km} \\ L_i &= \text{absorption loss in dB,} \\ L_m &= \text{above MUF loss in dB,} \\ L_g &= \text{ground reflection loss in dB,} \\ L_h &= \text{auroral and other signal losses.} \end{aligned} \quad (8)$$

Performance Prediction Software

A large number of computer programs have been developed for predicting HF circuit performance. Many of them are for point-to-point military applications. For broadcasting purposes, the following is a brief list of the programs that are widely used today. For an excellent discussion on this topic, see a paper by Rush (52) and the book by Goodman (19).

Ionospheric Communications Analysis and Prediction Program. Ionospheric Communications Analysis and Prediction Program (IONCAP), which was developed by staff of the Institute for Telecommunication Sciences (ITS) of the National Telecommunications and Information Administration (NTIA), Department of Commerce (53), is one of the most popular programs available today. This program consists of a set of subroutines for the prediction of HF sky-wave system performance. The propagation features include refraction bending, scattering on frequencies above the MUF, and sporadic-E propagation. The predicted field strength and noise levels can help the designer to determine, among other things, optimum frequencies, correct antennas, and required transmitter powers. The original program was intended for use with mainframe computers. The latest version, however, can be used with personal computers. IONCAP is available from NTIA/ITS, Department of Commerce, Boulder, Colordo USA 80303.

Voice of America Coverage Analysis Program. At the request of the Voice of America, the previously mentioned IONCAP has been modified by staff of the ITS and Naval Research Laboratory. In order to avoid confusion, the resultant program is called VOACAP (54). VOACAP is available from US Information Agency, Voice of America, 330 Independence Ave., NW, Washington, D.C. USA 20547.

ITU-R Recommendation 533-4 (REC533). In preparation for the 1984 HF World Administration Radio Conference (*WARC* HFBC-84), the CCIR established Interim Working Party 6/12 (D. L. Lucas, USA, Chairman). More than twenty propagation models were evaluated. After extensive deliberations, it adopted a method which is a combination of two different methods. For paths shorter than 7000 km, IWP 6/12 adopted a simplified version of the method described in CCIR Report 252-2, similar to IONCAP. For paths longer than 9000 km, the FTZ method (55) was adopted. For in-between paths, a linear interpolation scheme is used. The FTZ method, developed from a very large database with the majority of the paths terminating in Germany, has been known for its simplicity and accuracy when applied to very long paths. Results of the work of IWP 6/12 were first documented in CCIR Report 894. As a result, in some references this method and corresponding computer program have been called CCIR894. It should be mentioned that Report 894 has become part of Recommendation P. 533-8 (51). This software is now formally known as REC533, available from the ITU Sales Service, Place des Nations, CH 1211 Geneva 20, Switzerland (http://www.itu.ch).

Input Data and Results of Calculations. In order to use any of the previously mentioned programs, the following required input information is usually needed for each given circuit: (1) time of day, month, year; (2) expected sunspot number; (3) antenna type; (4) geographical locations of the transmitter and receiver; (5) man-made noise level; (6) required reliability; (7) required signal-to-noise ratio, etc. The results of calculations usually include the following: (1) great-circle and slant distances; (2) angles of departure and arrival; (3) number of hops; (4) time delay of the most reliable propagation mode; (5) the virtual height; (6) MUF and the probability that the frequency exceeds the predicted MUF: (7) median system loss in dB; (8) median field strength in dB above 1 μV/m; (9) median signal power in dBW; (10) median noise power in dBW; (11) median signal/noise ratio in dB and (12) LUF, the lowest useable frequency.

SPACE-WAVE PROPAGATION AT VHF AND UHF

At frequencies greater than about 30 MHz, the ionosphere is not able to reflect energy back to Earth while the ground wave attenuates to neglible amplitude in just a few hundred meters. Radio waves at these frequencies can, however, travel from elevated transmitting antennas to elevated receiving antennas by means of the space wave.

General Considerations in Space-Wave Propagation

Free Space Attenuation. As free space propagation is often used as a reference, it is appropriate to start this section with the derivation of some basic relevant formulas.

From basic geometry, it follows that the power flux density at a given receiving point d meters away from the source (transmitter) can be expressed by:

$$\text{p.f.d} = p/4\pi d^2 \tag{9}$$

where p is the equivalent isotropically radiated power (e.i.r.p.) of the transmitter in watts. In the engineering of broadcasting service, it is convenient to express the intensity of radiation in terms of the strength of the electric field rather than in terms of power flux density. Equation (9) can be rearranged by noting that power flux density is equal to the square of field strength divided by impedance of the medium. For free space propagation where the impedance is 120π, the following equation is developed for the r.m.s. field strength:

$$e = (30p)^{0.5}/d \tag{10}$$

where e is field strength in volts per meter. It usually is more convenient to express power in kilowatts and distance in kilometers. Furthermore, it is a common practice to express field strength in dB above 1 microvolt per meter. Consequently, Eq. (10) becomes:

$$E = 104.77 + P - 20\log\ d \tag{11}$$

where

E = field strength in dB relative to 1 μV/m
P = power in dB relative to 1 kW, and
d = distance in km.

Basic Free Space Transmission Loss (in dB) Is Given by:.

$$L_{bf} = 20\log[(4\pi d)/\lambda] \tag{12}$$

where λ is the wavelength. Alternatively, if frequency is used instead of wavelength, Eq. (12) becomes:

$$L_{bf} = 32.4 + 20\log f + 20\log d \tag{13}$$

where f is frequency in MHz and d the distance in km.

Influence of the Atmosphere. In a vacuum, electromagnetic waves propagate along straight lines with velocity c (velocity of light in a vacuum). The electromagnetic properties of the air, which are slightly different from those of a vacuum, are characterized by the refractive index n = c/v where v is the local electromagnetic propagation velocity. The refractive index depends on the composition of the atmosphere which varies with both position (altitude above Earth's surface and geographic location) and with time. The refractive index is larger than unity, since the waves propagate at a speed less than c. Moreover, the propagation is greatly affected by spatial variations of the index. Refractivity N is given by $N = (n - 1)10^6$. N at an altitude h kilometers above ground is given by (56):

$$N = (n-1)10^6 = 289e^{-0.136h} \tag{14}$$

A vertical variation of n (dn/dh) of −40N/km is considered a standard refractivity gradient which corresponds approximately to the median value of the gradient in the first kilometer of altitude in temperate regions. Standard atmosphere may be defined as a horizontally homogeneous atmosphere in which the refractive index varies with altitude according to Eq. (14). Propagation in such a medium is called standard propagation. Propagation associated with abnormal vertical distribution of the refractive index is known as nonstandard propagation.

Effective Radius of the Earth. The concept of the effective radius of the Earth is a very important one in space-wave propagation. Since the refractive index decreases with increasing altitude, it follows that the speed of the wave is lower near the ground than at higher altitudes. This variation in speed in height results in *bending* of the radiowaves. Uniform bending may be represented by straight line propagation, but with the Earth's radius modified so that the relative curvature between the radiowave and the Earth remains unchanged. This modified radius of the Earth is commonly known as the effective radius. The ITU-R defines the effective radius of the Earth as "the radius of a hypothetical spherical Earth, without atmosphere, for which propagation paths are along straight lines, the heights and ground distances being the same as for actual Earth in an atmosphere with a constant vertical gradient of refractivity" (57). The ratio of the effective radius to the actual radius of the Earth is commonly called "effective Earth radius factor," or k. For an atmosphere having a standard refractivity gradient, k is about 1.33, yielding an effective radius of approximately 8500 km. The factor k is related to the vertical gradient dn/dh of the refractive index n and to the actual radius a by the following equation:

$$k = 1/(1 + a(dn/dh)) \tag{15}$$

Tropospheric Ducting. When the vertical gradient of the refractive index in a layer of the atmosphere is sufficiently large, a tropospheric duct can be formed. There is a concentration of energy in the duct and hence low attenuation, so that propagation to very great distances, distances well beyond the horizon, may be possible. Tropospheric ducts occur most commonly over water. In fact, it is believed that such ducts are nearly always present over an ocean, particularly in the trade-wind belt. Ducts can also occur over land, but this happens less frequently. When it does happen, it is always a temporary rather than a continuing condition. Duct propagation is also called superrefraction.

Tropospheric Scattering. Even in the absence of ducts, extended range tropospheric propagation is still possible. There appear to be several contributing factors to this result. First of all, inhomogeneities and discontinuities in the refractive index of the atmosphere cause *tropospheric scattering,* sending energy to areas beyond the horizon. Furthermore, the waves may diffract around the curved surface of the Earth in the same way that sound waves bend around the corner.

Factors Affecting Space-Wave Propagation

Atmospheric Absorption. Oxygen and water vapor may absorb energy from a radiowave by virtue of the permanent magnetic and electric dipole moments of the oxygen and water molecules, respectively. Attenuation due to rain increases with frequency. ITYU-R Recommendation PN.836 (58) presents surface water vapor density of different parts of the world.

Effects of Buildings. Buildings have very little effects on propagation at LF and MF, because the size of any obstruction is usually small compared with the wavelength. At HF, they begin to have a mild impact. At VHF and UHF, the loss can no longer be neglected. The attenuation through a brick wall, for example, may vary from 2 to 5 dB at 30 MHz and from 10 to 40 dB at 3 GHz. The median field strength at random locations in downtown New York is about 25 dB lower than the corresponding plane-earth value (59).

Effects of Trees and Other Vegetation. Trees and other forms of vegetation contain water and, therefore, affect space-wave propagation. When an antenna is surrounded by moderately thick trees and below tree level, the average loss resulting from the trees at 30 MHz is usually 2 to 3 dB for vertical polarization and near zero for horizontal polarization. At 100 MHz, the average loss may be 5 to 10 dB, and 2 to 3 dB respectively. As expected, there is a seasonal variation, with less absorption in winter month when trees are bare (60).

Effects of the Ionosphere. The reception of VHF television signals from a station located several hundred or several thousand kilometers away from the receiving site has been documented in several cases. For example, a signal from a VHF station in Arabia was received in India (distance is about 2700 km). This observation has been reported and analyzed by Saksena (61). Similar observations at frequencies up to about 144 MHz have been documented in Europe and the Americas. VHF propagation by way of regular E-layer is highly unlikely at any time. It is more likely that these occurrences were made possible by Sporadic E- or F-layer. Near the peak of the solar cycle, long-distance transmission via the F2-layer in temperate latitudes can occur for a significant fraction of the time, at frequencies up to 50 MHz or more. In low latitudes regular transmission will occur around 30 to 40 MHz, and such transmission can occur at 60 MHz and above. Anomalous ionization usually occurs during the hours between 2000 and 0100, local time. The occurrence decreases with increasing frequency. This was the main reason that the FCC moved the FM broadcasting service from 44–50 MHz to 88–108 MHz in 1946. For a more detailed discussion on this topic, see for example, a paper by Smith and Davis (62) or ITU-R Recommendation P.844-1 (63).

Effects of Antenna Height. Antenna height plays a very important role in VHF and UHF space-wave propagation. A higher transmitting antenna not only increases the line-of-sight distance and coverage area but also improves the quality of the received signal. This is why there usually is a concentration of FM and TV antennas on top of very tall buildings such as the Empire State Building in New York City. An illustrative example is in order. Consider a typical FM station operating with an equivalent radiated power of 100 kW and a receiving site 50 km away. If the transmitter's antenna height above average terrain (*HAAT*) is 100 meters, then the received median field strength, according to section 73.333 of the FCC Rules and Regulations (64), is about 60 dB above 1 microvolt per meter (dB(μV/m)). If the HAAT is increased to 200 meters, the received median field strength is about 66 dB (μV/m). If the HAAT is 1000 meters, the received median field strength is about 82 dB (μV/m).

Predicting VHF and UHF Space-Wave Field Strengths

In the FCC Rules and Regulations (64), different space-wave propagation curves are presented for different broadcasting services (i.e., FM, low-VHF TV, high-VHF TV, UHF TV). In each case, field strength versus distance curves are given for different transmitting antenna heights. Both median- and upper-decile values of field strengths are given. These curves are used by the FCC for applications within the USA. These curves, which were developed from extensive measurements carried out by the FCC (65), are considered to be very accurate. Similar propagation curves developed from different data banks can also be found in ITU-R Recommendation P.1546-2 (66). When applied to paths over land, these two sets of curves can be considered almost identical. Both sets of curves include a correction factor for terrain roughness. The ITU-R curves include a sound treatment of sea water. The FCC curves, on the other hand, lack such a treatment. For further discussions on this topic, see references (60,67,68).

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GLOSSARY

Broadcasting service A radiocommunication service in which the transmissions are intended for direct reception by the general public.

CCIR French initials for International Radio Consultative Committee, now called ITU-R.

Critical frequency (fo) The highest frequencies at which a radio wave is reflected by a layer of the ionosphere at vertical incidence. There is usually one such frequency for each ionospheric component—e.g., foE, foF2. The critical frequency is determined by the maximum electron density in that layer. Waves with their frequency below fo will be reflected. As the frequency is increased beyond this, the ray will penetrate the layer.

Fading The temporary and significant decrease of the magnitude of the electromagnetic field or of the power of the signal due to time variation or the propagation conditions.

FCC Federal Communications Commission.

Free space propagation Propagation of an electromagnetic wave in a homogeneous ideal dielectric medium which may be considered of infinite extent in all directions, see also section on space-wave propagation.

Frequency band Continuous set of frequencies in the frequency spectrum lying between two specific limiting frequencies; generally includes many channels.

Low-frequency (LF) band The part of the spectrum between 30 and 300 kHz. This band is also known as Band 5 because the center frequency is 1×10^5 hertz. The corresponding waves are sometimes called the kilometric or long waves.

Medium-frequency (MF) band The part of the spectrum between 300 and 3000 kHz. This band is also known as Band 6. The corresponding waves are sometimes called the hectometric or medium waves.

High-frequency (HF) band The part of the spectrum between 3 and 30 MHz. This band is also known as Band 7. The corresponding waves are sometimes called decametric or short waves.

Very-high frequency (VHF) band The part of the spectrum between 30 and 300 MHz. This band is also known as Band 8. The corresponding waves are sometimes called metric waves.

Ultra-high frequency (UHF) band The part of the spectrum between 300 and 3000 MHz. This band is also called band 9. The corresponding waves are sometimes called decimetric waves.

ITU International Telecommunication Union.

ITU-R Radiocommunication Study Groups of the ITU (formerly, CCIR).

ITU Region 1 Africa, Europe, the entire territory of the former USSR, Outer Mongolia, and Turkey.

ITU Region 2 The Americas and Greenland.

ITU Region 3 Australia, New Zealand, and all other Asian countries.

Ionosphere The ionized region of the Earth's upper atmosphere.

Lowest useable frequency (LUF) The lowest frequency that would permit acceptable performance of a radio circuit by signal propagation via the ionosphere between given terminals at a given time under specific working conditions.

MUF Maximum useable frequency.

Basic MUF The highest frequency by which a radio wave can propagate between given terminals, on a specific occasion, by ionospheric refraction alone. Note: Where the basic MUF is restricted to a particular propagation mode, the values may be quoted together with an indication of that mode (e.g., 2F2 MUF, 1E MUF). Furthermore, it is sometimes useful to quote the ground range for which the basic MUF applies. This is indicated in kilometers following the indication of the mode type (e.g., 1F2(4000) MUF).

Operational MUF (or simply MUF) The highest frequency that would permit acceptable performance of a radio circuit by signal propagation via the ionosphere between giving terminals at a given time under specific working conditions.

Median Values of Field Strengths

Monthly median The median of daily values for the month, usually for a given reference hour.

Yearly median The median of daily values for the year, usually for a given reference hour.

Multipath propagation Propagation of the same radio signal between a transmission point and a reception point over a number of separate propagation paths.

Noise

Atmospheric noise Radio noise produced by natural electric discharges below the ionosphere and reaching the receiving point along the normal propagation paths between the Earth and the lower limit of the ionosphere. See also section on Atmospheric Radio Noise.

Man-made noise Radio noise having its source in manmade devices.

Galactic noise Radio noise arising from natural phenomena outside the Earth's atmosphere.

Propagation Energy transfer between two points without displacement of matter.

Reference hour in LF/MF broadcasting Six hours after sunset at the midpoint of a path under study is considered as the reference hour. This is necessary because sky-wave field strength is usually the greatest at that time.

Refractive index The ratio of the speed of radio waves in vacuo to the speed in the medium under consideration.

Reliability Probability that a specific performance is achieved.

Basic reliability The reliability of communications in the presence of background noise alone.

Overall reliability The reliability of communications in the presence of background noise and of known interference.

Service area Area associated with a transmitting station for a given radiocommunication service, within which reception is protected against interference in accordance with international agreements.

Skip distance The minimum distance from the transmitter at which a sky wave of a given frequency will be returned to Earth by the ionosphere.

Solar activity The emission of electromagnetic radiation and particles from the Sun, including slow-varying components and transient components caused by phenomena such as solar flares.

Sudden Ionospheric Disturbance (SID) A sudden marked increase in electron density of the lower ionosphere during the daylight hours. This is caused by X-ray emission from the Sun.

Transmission loss The ratio, usually expressed in decibels, for a radio link between the power radiated by the transmitting antenna and the power that would be available at the receiving antenna output.

Basic free-space transmission loss (L_{bf}) The transmission loss that would occur if the antennas were replaced by isotropic antennas located in a perfectly dielectric, homogeneous, isotropic, and unlimited environment. See also Eq. (8).

Troposphere The lower part of the Earth's atmosphere extending upwards from the Earth's surface, in which the temperature decreases with height except in local layers of temperature inversion. This part of the atmosphere extends to an altitude of about 9 km at the Earth's poles and 17 km at the equator.

Virtual height The height of the ionosphere at which a signal would be reflected if it always travelled at the speed of light.

Zenith angle The angle between the Sun and the zenith (i.e., directly overhead) at a given geographical location.

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