SKY WAVE PROPAGATION AT MEDIUM AND HIGH FREQUENCIES

SPECTRUM CONSIDERATIONS

Medium frequencies and high frequencies are usually defined as the frequency bands from 300 kHz to 3000 kHz and from 3 MHz to 30 MHz, respectively. However, as far as ionospheric propagation is concerned, there are no sharp divisions. The medium-frequency band is dominated by the amplitude modulated (*AM*) broadcasting band between about 500 kHz and about 1700 kHz, which is designed primarily for ground-wave usage. On the other hand, high-frequency systems are designed for long-distance sky wave propagation and for some 50 years (from about 1925 to about 1975) provided the primary vehicle for global communications. High frequencies are still used extensively for communications because of the following advantages: (1) low cost of terminal equipment, (2) low power requirements, and (3) adequate bandwidths. By contrast, medium frequencies suffer heavy ionospheric absorption during daytime and, therefore, there is relatively little co-channel interference; whereas by night, when the absorption is small, interference between closely spaced channels is common. High-frequency sky waves suffer from several disadvantages brought about by (1) the temporal and geographical variability of the ionosphere, (2) the large number of possible propagation paths and the consequent time dispersion of the resulting signal, (3) large and rapid amplitude and phase fluctuations, (4) high interference because of spectrum congestion, and (5) frequency distortion of wideband signals. An important disadvantage is the occurrence of several types of ionospheric disruptions caused by solar disturbances. These disruptions can be hemispheric, such as those on the dayside caused by bursts of solar X rays (sudden ionospheric disturbances) or confined mostly to high latitudes (e.g., polar cap disturbances and ionospheric storms that originate in the auroral zones and spread to populated middle latitudes). Ionospheric storms are major concerns for high-frequency (*HF*) users. They occur mostly at high sunspot numbers when the higher critical frequencies help to mitigate their adverse effects (see ***Propagation of broadcast transmissions***).

In this article we shall discuss the following topics:

1. Basic physical properties of sky wave propagation (namely, refraction, reflection, penetration, and absorption)
2. relationships between vertical propagation and oblique propagation
3. ionospheric models
4. characteristics of medium frequencies
5. characteristics of high frequencies
6. prediction programs for ionospheric sky wave performance
7. real-time channel evaluation

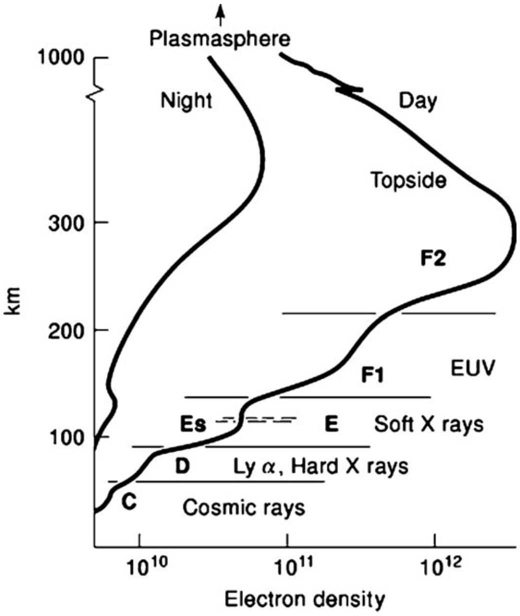

Figure 1. Ionospheric structure on a summer day and night in middle latitudes, and the main bands of solar and cosmic-ray ionizing radiations.

There is an extensive literature in the field of ionospheric radio propagation, and the interested reader is referred to books by Davies (1), Goodman (2), Hunsucker (3), and McNamara (4) and the bibliographies therein. Groundwaves are particularly important on medium frequencies (see ***Radiowave Propagation Concepts***).

PROPAGATION CHARACTERISTICS

The Ionosphere

Sky waves result from radio refraction and reflection from the ionosphere. The ionosphere is usually defined as that part of the upper atmosphere where sufficient ionization exists to affect the propagation of radio waves. The ionosphere lies between about 50 km and about 2000 km. The peak electron density usually occurs in the F region (above 140 km) (Fig. 1). The F region often contains two layers: the lower F1 layer and the upper F2 layer. Below the F region is the E region (90 km to 140 km), which contains the normal E layer and sporadic E. The D region (50 km to 90 km) contains the D layer and the C, or cosmic ray, layer. Above the F peak is the topside, and above about 2000 km is the protonosphere. The boundaries between these regions are not well defined. The alphabetic nomenclature was introduced by Appleton (see Ref. 1, Sec. 1.1), who used the letter E for electric and F for field. These letters left room for the discovery of other layers. Ionospheric electron densities vary by orders of magnitude depending on altitude, time of day, season, sunspot number, solar disturbances, and geographical location. It is this variability that renders sky waves so difficult to manage.

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Refraction, Reflection, and Penetration

In an ionized plasma, with electron density N el·m^{-2}, in the absence of collisions and an external magnetic field, the radio refractive index μ of a wave of frequency f Hz, is given by

$$\mu^2 = 1 - (f_N/f)^2 = 1 - 80.5N/f^2 \tag{1}$$

where f_N is the plasma frequency in Hz. Ionospheric electron densities are such that typical E layer and F layer plasma frequencies lie in the range from 0.5 MHz to 30 MHz. Thus, for medium and high frequencies, the refractive index of the ionosphere is less than unity and application of Snell's law shows that, on entry into the ionosphere, a wave is refracted away from the vertical. When the electron density is sufficient, the direction of propagation becomes horizontal and reflection occurs. The main sky wave propagation mechanisms are illustrated in Fig. 2: absorption, reflection, scatter, and penetration. When the maximum electron density is insufficient, the wave penetrates; this is essential for ground-to-satellite communication. Because ionospheric scatter propagation is considered elsewhere (see ***Meteor burst communication***), it will not be discussed in detail in this article.

Absorption

The neutral atmosphere affects the propagation of radio waves because of electron-neutral collisions that convert the ordered momentum of the wave into heat and electromagnetic noise. To a first approximation the loss L, in decibels per kilometer, is

$$L = 0.00117N\nu/\mu f^2 \tag{2}$$

where ν is the number of collisions made by one electron per second. From Eq. (2) we see that with $\mu \approx 1$, the nondeviative absorption is inversely proportional to the frequency squared so that, in general, signals are stronger on high frequencies than on medium frequencies. The product $N\nu$ maximizes in the D region. The loss L can be large where $\mu \approx 0$; this deviative absorption occurs near reflection, or where there is pronounced refraction of the wave.

Effects of the Earth's Magnetic Field

The earth's magnetic field affects sky waves by splitting the incident wave into ordinary and extraordinary waves that are oppositely polarized and by affecting the global structure of the ionosphere (see ***Electromagnetic Waves in the Ionosphere***). The ordinary (o) wave is polarized such that, with the thumb pointing in the direction of the earth's magnetic field, the electric field rotates in a left-handed sense whereas the extraordinary (x) wave rotates in a right-handed sense. For example, an incident, vertically polarized wave on exit from the ionosphere will be elliptically polarized, which depends on the relative amplitudes and polarizations of the emerging o and x waves. The relative amplitudes of the o and x waves are determined by the extent to which the incident power is divided between the two component waves and the relative absorptions of the two waves thereafter. The relative absorptions are

$$L(o,x) = A/(f \pm f_H)^2 \tag{3}$$

where the + sign refers to the ordinary wave and the − sign to the extraordinary wave, and A is essentially the same for both waves. The electron gyrofrequency f_H is the natural frequency of rotation of an electron (right-handed) about the magnetic field. In the ionosphere f_H varies from about 0.8 MHz at the magnetic equator to about 1.6 MHz near the magnetic poles. Current models of the geomagnetic field are available on the Internet (e.g., Ref. see 9). Equation (3) shows that the absorption of the ordinary wave is less than that of the extraordinary wave so that an antenna should be designed to excite as much of the ordinary wave as possible (see Ref. 1, Sec. 7.6).

The global effects of the geomagnetic field are 2-fold. Near the magnetic equator there is an F2-layer anomaly in which the peak electron densities maximize in the late afternoon at magnetic latitudes near ±15°. Magnetic latitude Φ is defined in terms of the dip angle I by which the earth's magnetic field dips below the horizontal.

$$\tan\Phi = 0.5 \tan I \tag{4}$$

Another way in which the earth's field affects the ionosphere is via the precipitation of magnetospheric charged particles into the polar caps and the auroral zones (65° to 70° magnetic latitude), where energy is deposited that produces ionospheric storms. In the auroral zones, D-region electron densities are enhanced producing auroral absorption. Energetic solar protons enter the atmosphere over the polar caps (latitudes >70°) and produce intense polar cap absorption (*PCA*) that can black out HF signals for several days.

VERTICAL AND OBLIQUE PROPAGATION

Equivalence of Vertical and Oblique Reflection

Equation (1) shows that, with a radio wave incident at an angle ϕ with the vertical on a plane ionosphere, reflection occurs when

$$f_N = f \cos\phi \tag{5}$$

With vertical propagation, $\phi = 0°$, so $f = f_N$ and, therefore, for a given maximum electron density (i.e., maximum f_N) a maximum, or critical, frequency is reflected. With oblique propagation, the maximum frequency depends jointly on the critical frequency and on the incident angle, which is determined by the ground range and the layer height. The subject of vertical-to-oblique conversion has been discussed extensively by numerous authors (e.g., Ref. 1, Chapter 6; Ref.2, Chapter 4; Ref. 4, Chapter 4). With a flat earth and flat ionosphere the relationship between a frequency f_o incident obliquely at an angle ϕ and a frequency f_v reflected vertically from the same true height is

$$f_o = f_v \sec\phi = f_v[1 + (D/2h')^2]^{1/2} \tag{6}$$

where D is the ground range and h' is the virtual height of reflection. The variation of virtual height with frequency is called an ionogram, and the relationship between sec ϕ

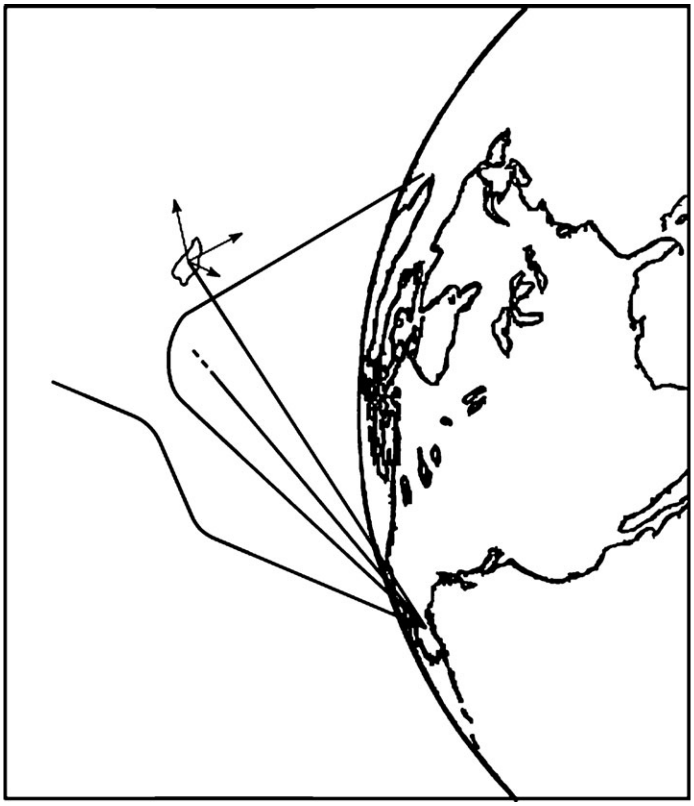


Figure 2. The four main mechanisms in MF and HF sky wave propagation: absorption, reflection, scatter, and penetration.

and h', when presented graphically, is called a transmission curve. The intersection of a transmission curve with the ionogram trace gives the virtual heights of reflection of the obliquely traveling signal. When the transmission curve is tangent to the ionogram, we have the maximum reflected frequency. On frequencies below the maximum frequency there are two intersections of the transmission curve and the ionogram trace (for a single layer) showing that, for a given ground range, there is a low-angle ray and a high-angle ray. Modifications to the plane ionosphere geometry are required for ground ranges over about 200 km and for the extraordinary ray that determines the maximum frequency, but the principles are essentially the same (the reader is referred to the aforementioned texts and references therein).

Parabolic Layer Theory

Transmission curves were used extensively for the determination of maximum usable frequencies (*MUF*) for a number of years (approximately 1940 to 1980). With the advent of inexpensive and fast computers an alternative method has come to the fore. Essentially, the method consists of using ionogram data to approximate the electron-density profile by an analytic function such as a parabola, or a quasi-parabola, and calculating the maximum frequency. A parabolic profile is defined by its critical frequency f_c, the semithickness y_m, and the height of the peak h_m. More complicated ionospheres can be approximated by two (or more) parabolas or by two parabolas joined by linear segments. The International Reference Ionosphere (5) also uses a segmented profile. The ground range in each segment is calculated analytically.

Ray Tracing

With realistic profiles obtained by ionogram inversion, which have horizontal and vertical structures and which cannot be represented by simple analytical formulas, there is recourse to ray tracing. This involves starting with a ray from a specified transmitting site and with specified angles of elevation and azimuth, and plotting the flow of energy step by step until it returns to earth or escapes into space. This is a complicated procedure and is feasible only with adequate computers. A comprehensive three-dimensional ray tracing program has been constructed by Jones and Stephenson (6) and is available on the Internet (7). In Fig. 3a we see what happens to the ray paths (on a given frequency) as the angle of elevation slowly increases. For low angles the ground range is long. As the elevation increases, the ground range decreases until the skip is reached, after which the range increases rapidly. Eventually penetration occurs. Figure 3b shows the equivalent triangular paths for different angles of elevation. The apexes of the equivalent triangles lie on a smooth curve, called a reflectrix, as shown in Fig. 3c. The ray with its apex at the “nose” of the reflectrix is the skip-ray and its frequency is the MUF. Rays reflected at lower virtual heights are low-angle rays, and rays reflected on the upper side of the reflectrix are high-angle rays. For a given reflectrix, the relationship between virtual height and angle of elevation (β) is given by Fig. 3d (8).

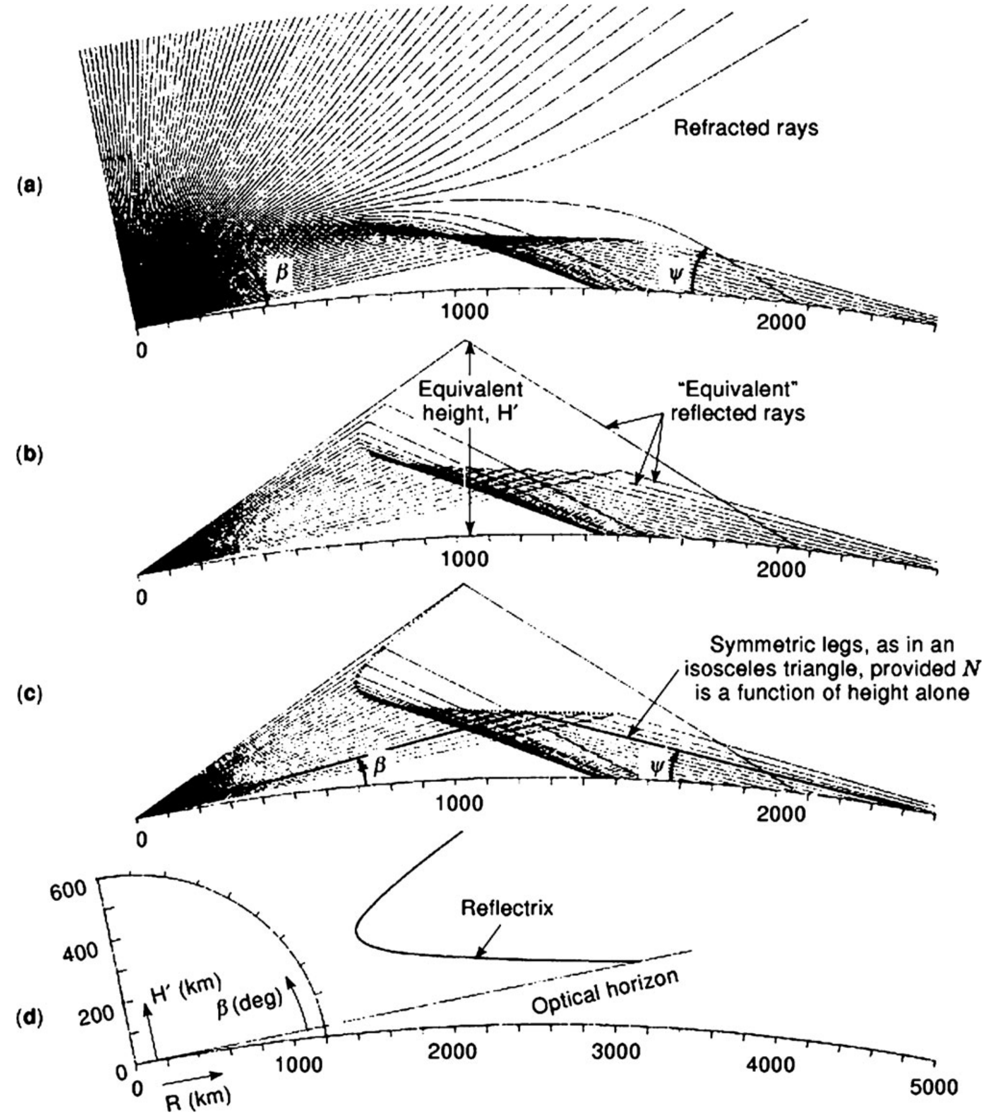


Figure 3. (a) Real rays in a concentric earth and Chapman ionosphere, $f = 8$ MHz, $f_c = 4$ MHz, $h_{\max} = 300$ km, semithickness = 200 km. (b) Equivalent or virtual paths reflected at the apexes of the fictitious triangular paths. (c) The reflectrix as the locus of the virtual reflection heights. (d) The reflectrix as a function of virtual height, range, and elevation angle. (Adapted from Croft (8) by permission of the American Geophysical Union.)

Maximum Frequencies

When the ground range, D, is plotted against the angle ϕ we find that, for $f > f_c$, there is a minimum range, D_s, called the skip distance, within which no power is received via the normal reflection process. However, signal power in the skip zone may result from ground waves, ground scatter, and scatter from ionospheric irregularities. At the edge of the skip zone the signal frequency corresponds to the maximum usable frequency for the skip distance, MUF(D_s). The MUF for a distance D is related to the critical frequency by

$$\mathbf{MUF}(D) = f_c M(D) \tag{7}$$

where $M(D)$ is called the MUF factor corresponding to the distance D. The M(3000)F2 is used extensively both as a reference and as a measure of the height of the F2 layer.

IONOSPHERIC MODELS

Ionospheric models are of two types: (1) empirical models based on data, and (2) physical models based on production, loss, and movement of plasma by winds and/or electric fields. For long-term skywave predictions it is customary to use monthly median models of the main ionospheric characteristics, such as critical frequencies ($f_oE_{\mathrm{h_mE}}$, $fE_{\mathrm{s_{hm}}}\mathrm{F2}$, f_oF1, f_oF2) and layer heights (h_mE, h_mF2) or equivalent M factors. The diurnal, seasonal, and sunspot number dependencies of the regular E and F1 layers are well behaved and are represented by analytical expressions (e.g. see Ref. 1, Chapter 5). However, the most important (F2) layer varies irregularly, and its characteristics are expressed in the form of numerical maps of median values. The day-to-day variability is expressed in terms of upper-decile and lowerdecile values. D-region absorption, while highly variable in space and time, is represented by an analytical expression (see Ref. 1, Eq. 12.12). Electron-density profiles can be represented numerically or, for ray tracing, more conveniently by integrable segments. Several such approximations are discussed in Davies (Ref. 1, Sec. 5.3.2, 5.3.4, and 5.3.5). Of particular interest is the International Reference Ionosphere (*IRI*) which produces electron-density profiles, ion– and electron–temperature profiles, layer heights, and so on and is available from World Data Centers on the Internet (7, 9). Some models, such as PRISM (10), can be updated using current ionospheric data, such as total electron contents (see Ref. 1, Chapter 8) and/or critical frequencies.

PROPAGATION ON MEDIUM FREQUENCIES

Importance of Medium Frequencies

The medium frequency (*MF*) band is dominated by the AM broadcast band ($\approx$ 500 kHz to 1700 kHz), which during daytime depends on groundwave propagation. This frequency band has a major economic, social, and political impact on everyday life and is intensively used. Knowledge of sky-wave properties in the MF band is restricted because of (1) the congested spectrum, (2) high ionospheric absorption, (3) the role of the earth's magnetic field, (4) difficulty in separating deviative ($\mu \approx 0$) from nondeviative ($\mu \approx 1$) effects, (5) effects of collisions, and (6) the medium not always slowly varying on the lower frequency end, so that ray theory may be inapplicable. For efficient use of the MF band it is essential for several users to operate on the same, or adjacent, channels with minimum interference. Thus determination of the signal strength in distant regions is important in channel sharing (11). Atmospheric radio noise on the MF band has been modeled by Herman and DeAngelis (12). It is difficult to collect sky wave data during the daytime because the signals are weak and/or over short distances the ground wave may mask the sky wave. For estimating sky wave field strengths, the Radio Communications Sector of the International Telecommunications Union (*ITU*) has recommended the Wang (11) method for North America and the CCIR (Consultative Committee on International Radio) (13) Recommendation 435-8 elsewhere. These two methods are in reasonable agreement throughout Europe.

Temporal Variations

Diurnal Variations. Because the MF band is dominated by the broadcast band, relatively little is known about the sky wave signal structure. Yet this band has the heaviest usage. During daylight high D-region absorption suppresses sky wave signals to an extent sufficient for interference-free broadcasting in most areas. However, in areas remote from an MF transmitter, weak sky waves may suffice to produce unwanted interference. Shortly after sunset, when the electron content of the D region essentially disappears, sky wave strengths increase and AM stations can be received at distances of several thousand kilometers. During daytime MF waves are reflected from the E layer, but during nighttime sky waves may be received from both E and F layers, especially on the upper end of the MF band.

Seasonal Variations. Measurements in Europe (see Ref. 14, Report 431-4) show equinoctial maxima of signal strength and minima in summer and winter, the summer minimum being the more pronounced. The overall seasonal variation may be as much as 15 dB at the lower end of the MF band, decreasing to about 3 dB at the upper end of the band. Over the western hemisphere there is little seasonal variation, and over the United States there is a slight minimum in summer. The sensitivity to length of day and to magnetic disturbance of broadcast signals received in Canada is illustrated in Fig. 4. This figure shows the frequency-integrated power in the AM broadcast band (550 kHz to 1600 kHz) received in Arviat, Northwest Territories during a six-month interval, September 1994 through April 1995. Local time is on the vertical axis, with local midnight (0600 UT) near midscale. The figure shows the normal diurnal pattern of MF sky wave reception in that signals are strong at night (middle of the figure) and weak during the day (top and bottom of the figure). The span of reception extends from near sunset ($\approx$ 00 UT) to near sunrise ($\approx$ 12 UT), corresponding to the seasonal variations of the terminator. The reception is longest near midwinter. In summer reception is short lived. There is an asymmetry between the dawn and dusk terminators: The dawn terminator produces a sharper transition between nighttime conditions and daytime conditions than is the case near dusk. This phenomenon results from the prompt production of the D layer at sunrise versus the relatively slow decay of the D layer after sunset.

The lower panel in Fig. 4 shows the daily magnetic index from September 1994 to April 1995 and illustrates the dependence on geomagnetic activity of the high-latitude reception of distant AM broadcast band transmissions. Several-day intervals with high magnetic disturbance correlate one-to-one with intervals when the integrated power in the AM broadcast band at night is nearly the same as it is during the day. The latter intervals appear as light vertical bands in the top panel of Fig. 4. On shorter time scales, prompt absorption of distant AM transmissions is a sensitive indicator of auroral disturbance (15). Another indication of the seasonal variation is the average daily number of hours of MF reception at Fairbanks, Alaska of signals from five stations in the United States and Canada: Hunsucker and DeLana (16) found these hours to be 13.3 h in winter and spring, 4.0 in summer, and 11.0 in autumn. Daytime field strengths, though weak, are higher in winter than in summer. The winter-to-summer ratio is typically 10 dB to 20 dB. For planning purposes "annual median" field strengths are used (Ref. 11, Sec.4.1). Measurements indicate that the annual median value at noon is some 42.5 dB lower than at 6 hours after sunset, which is the reference time used by Europeans.

Sunspot Dependence. In Europe Ebert (17) found that the 11-month smoothed midnight signal, $F(11)$, and the corresponding smoothed sunspot number, $R(11)$, are related by

$$F(11) \approx 60 - 0.02R(11)\,\mathrm{dB} \tag{8}$$

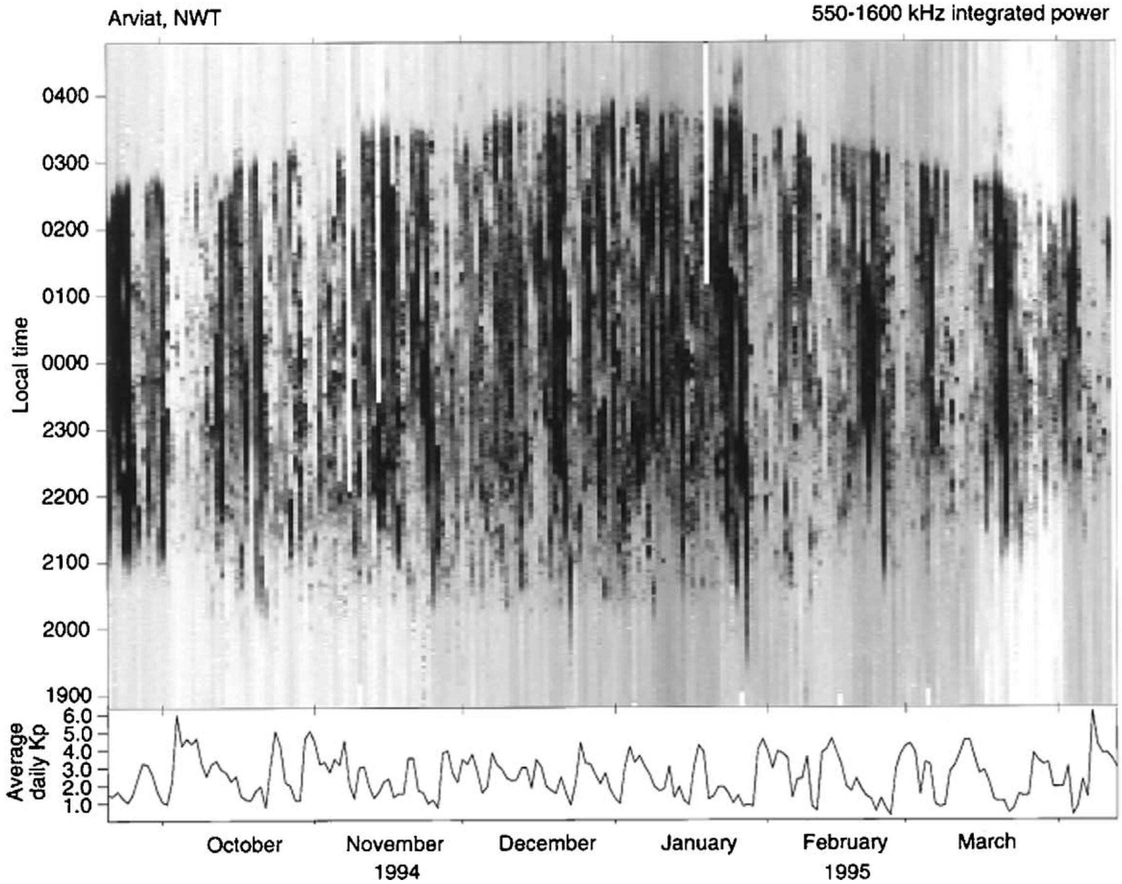


Figure 4. Integrated power in the frequency range 550 kHz to 1600 kHz received in Arviat, North West Territories, Canada from September 1994 through April 1995. Local meridian (270 °E) time is on the vertical axis. The reception is best near the winter solstice. (Courtesy of J. LaBelle.)

The sensitivity to sunspot number depends on the hour of observation. In Europe, the reference hour is normally 6 h after sunset, whereas in North America it is customary to use sunset + 2 h, at which the difference between field strengths at sunspot maximum and sunspot minimum during 1944 through 1947 was 14 dB compared with only 8 dB at sunset + 6 h.

Dependence on Wave Frequency

Some measurements indicate that the signal strength increases with wave frequency, whereas others suggest a decrease of signal strength with increase of frequency. Both these conclusions have some basis because, at night, an appreciable fraction of the ionospheric absorption may occur near the reflection level (i.e., deviative absorption, which may increase with increasing frequency; see (Ref. 1, Sec.11.5.3, which gives several formulas for the frequency dependence of MF field strengths). For many practical purposes it is sufficient to take the field strength on 1000 kHz as representative of the entire band.

Dependence on the Geomagnetic Field

The CCIR (13) basic loss factor is

$$K = 3.2 + 0.19 f^{0.4} \tan^2(\Phi + 3) \tag{9}$$

where the frequency, f, is in kHz and Φ is the magnetic latitude at the center of the path for $\Phi \leq 60^\circ$ and $\Phi = 60^\circ$ for magnetic latitudes greater than 60°. Thus reception is poor near the auroral zones. This is illustrated in Fig. 4, which shows gaps in the reception of signals on days with high magnetic indexes. This is the result of increased auroral absorption on the path due to increased D-region electron content and equatorial motion of the auroral zone. MF signals are sensitive to auroral absorption and above a certain threshold of disturbance are blacked out.

For east–west and west–east propagation in low magnetic latitudes (e.g., in Africa), polarization coupling loss is important. This arises because the electric field, from a vertical antenna, is perpendicular to the (horizontal) magnetic field and excites only an extraordinary wave, which suffers high D-region absorption [see Eq. (3), with $f \approx f_{\mathrm{H}}$].

Predicting Field Strengths

Methods for predicting MF sky wave field strengths are given in CCIR [see Ref. 13, pp. 311 to 390; PoKempner (18); and Davies (1), Sec. 11.7]. The CCIR method takes into account antenna gain, propagation loss, polarization coupling, and, where appropriate, sea gain.

Fading on MF

Nearly all sky waves fluctuate, or fade, with time as a result of interference between component echoes, absorption changes, polarization changes, and so on. To determine a station's sky wave service area and its interference potential, it is important to know the percentage of time that a given field strength is exceeded. For example, fields exceeded for 1% and 10% of the time are about 13 dB and 8 dB, respectively, higher than the median. In high geomagnetic latitudes, the corresponding differences are 15 dB and 10 dB (19).

PROPAGATION ON HIGH FREQUENCIES

The Available Spectrum

The HF sky wave spectrum is bounded on the upper end by the MUF, which is essentially determined by the maximum electron density in the reflecting layer, and on the lower end by the lowest usable frequency (*LUF*), which is determined by D-region absorption and/or by E-layer cutoff. Because of day-to-day fluctuations (≈15% about the monthly median) of the F2 critical frequencies, operation on the MUF would provide reception for 50% of the time at a particular hour. To ensure communications 90% of the time, it is customary to operate at, or below, the optimum working frequency (or *FOT* from the French initials), which is defined empirically as 0.85 of the monthly median MUF. Since the MUF can be defined in several ways, the CCIR (Ref. 14, Recommendation 373-5) has adopted the following: (1) Basic MUF is the highest frequency by which a radio wave can propagate between given terminals, on a specified occasion, by ionospheric refraction alone; and (2) operational MUF, or simply MUF, is the highest frequency that would permit acceptable operation of a radio service between given radio terminals at a given time under specified working conditions (such as antennas, transmitter power, class of emission, information rate, and required signal-to-noise ratio).

The operational MUF refers to propagation in the actual ionosphere and includes effects of scattering, partial reflection, and so on, whereas the basic MUF essentially depends only on ionospheric refraction. Hence, in general, the operational MUF is equal to or greater than the basic MUF.

Path Structure

The layered structure of the ionosphere can produce complicated oblique echoes. A composite echo may consist of the following: high- and low-angle rays from the *E* (including *E*s), F1, and F2 layers (See Characteristics of the Ionosphere for a discussion of ionospheric structure and variability); one-hop, two-hop, and so on echoes; and scatter from the ground and from ionospheric irregularities. Figure 5 shows a sample oblique ionogram taken, during magnetically quiet conditions, over a geographically east–west path. The traces are sharp and the maximum, or junction (*J*), frequency of the one-hop F_2 trace is well defined. The high-angle, or Pedersen, trace can be seen for the one-hop trace. Splitting of the high (H)-angle, two-hop trace into ordinary and extraordinary traces can be seen. The time spread sets a limit to the rate of transmission of information because overlapping echoes can result in errors. Roughly speaking, the maximum rate of transmission (in binary units per second) is equal to the reciprocal of the time spread, which is a function of signal frequency, path length, geographical location, season, sunspot number, and so on. Ionospheric structures, both vertical and horizontal, produce echoes with various angles of elevation and azimuth. The interested reader should consult Ref. 4, Chapters 12 through 15, for a detailed discussion of direction finding.

Fading on HF

When the ionosphere changes with time and/or space with moving terminal(s), the relative phases of the component echoes change and the resultant signal fluctuates or fades. Fading may result from interference between (1) echoes reflected from different parts of the ionosphere; (2) ordinary and extraordinary waves, called polarization fading; (3) reflection or penetration, called MUF fading or skip fading; (4) absorption fading; and (5) focusing. The fading rate depends largely on the type of fading and may range from 100/s (flutter fading) to once per day (MUF fading). The speed of interference fading is related to the width of the fading power spectrum. The autocorrelation falls to 0.37 after a time, *t*, called the fading time, given by

$$t = \lambda/4\pi v \tag{10}$$

where λ is the signal wavelength and v is a measure of the velocity of the reflecting sources.

For practical purposes, it is customary to make fading allowances to ensure that the field strength is exceeded a certain percentage (e.g., 90%) of the time. Circuit planning requires comparison of the strengths of the wanted signal relative to (1) natural and synthetic noise, and (2) cochannel and adjacent channel interference (called electromagnetic compatibility). Hence, in addition to monthly medians, fading allowances are necessary that depend on short-term (<1 h) and long-term (day-to-day), fading of the wanted signal and the background interference. Some proposed fading allowances are discussed in ITU (20), Recommendations 339 and 411.

In high magnetic latitudes, rapid ionospheric motions ($\approx 1\ \mathrm{km \cdot s^{-1}}$) result in Doppler frequency shifts and, hence, frequency spreading on great-circle paths of 0.1 Hz to 0.5 Hz. On nongreat-circle paths, spreading of 5 Hz to 10 Hz is typical. Some typical time-delay spreads are 100 ms to 200 ms. Sky wave fading models are available (e.g. see (21). Further, in high latitudes, vertical antennas (which generate vertical electric fields) are preferred to horizontal antennas because they excite ordinary waves, which suffer less absorption than extraordinary waves.

HF Propagation Programs

Because the ionosphere varies in space and time (local time, season, sunspot numbers, etc.) so does the usable frequency spectrum and, also, the characteristics of the received signals (e.g., signal strength, fading). Hence, knowledge of the variability of the ionosphere has been invaluable in the design and operation of point-to-point and

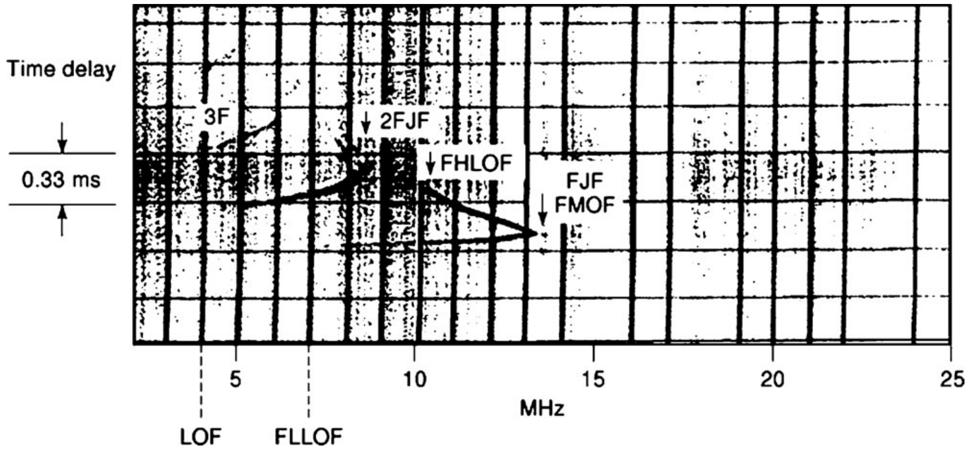


Figure 5. Oblique ionogram for the 2370 km, geographic approximately west–east path from Boulder, Colorado, to Sterling, Virginia, September 1, 1954, 2112 (90° West Meridian Time). Here the junction frequency (*FJF*) or basic MUF is the same as the maximum observed frequency (*FMOF*). *LOF* is the lowest observed frequency.

broadcasting HF systems. For continuous operation of a given point-to-point circuit a set of frequencies is required to avoid MUF failure (e.g., at night) and excessive ionospheric absorption by day. For long-term planning the f_0F2 is the most important single parameter in controlling the MUF, and it is highly variable. In spite of the increase in the number of solar disturbances, HF sky wave propagation is better near sunspot maximum than near sunspot minimum because of the broader available frequency band.

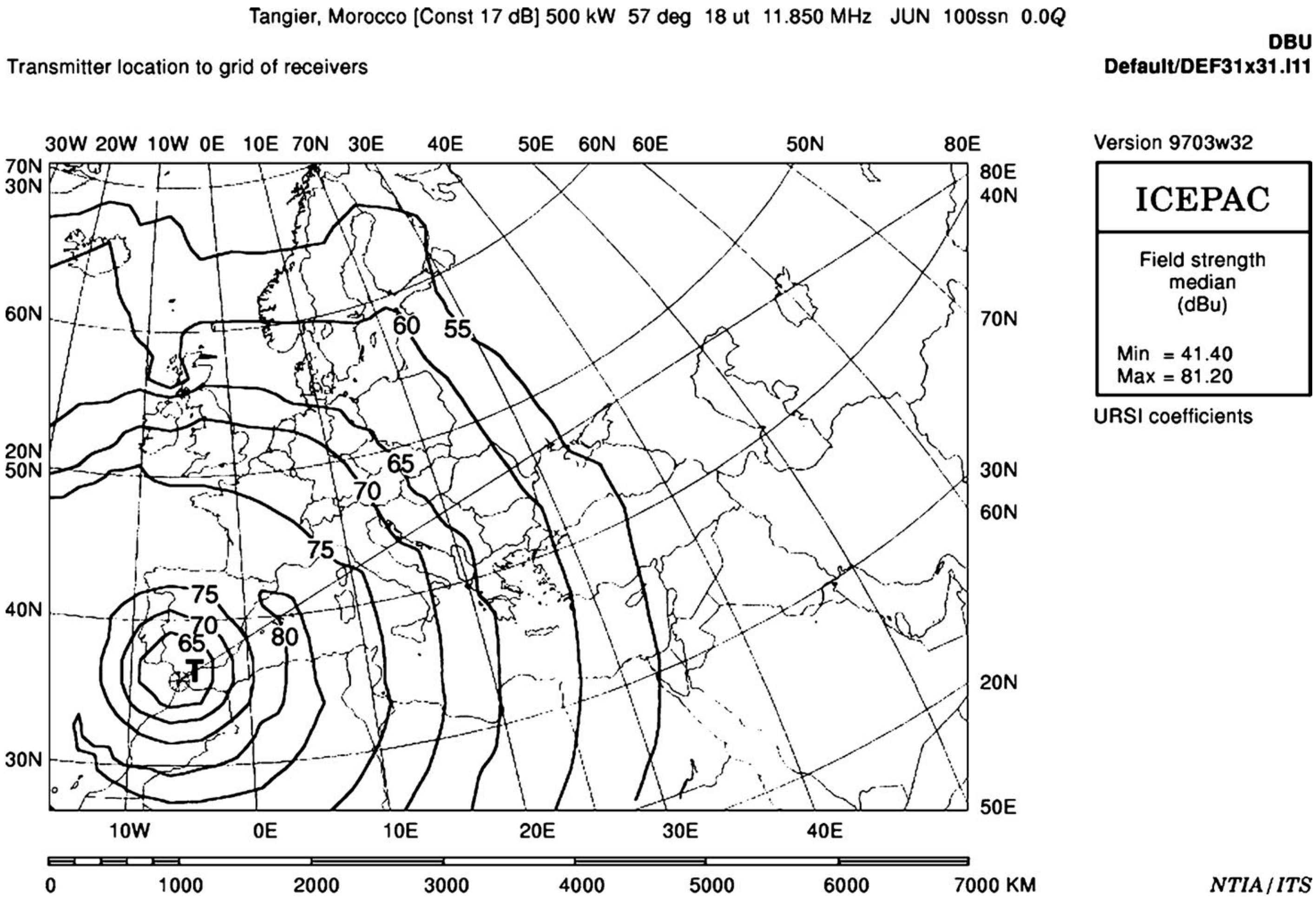
When the f_0F2 and the layer height [or M(3000)F2] are known, from vertical soundings, the basic MUF can be calculated by graphical methods or by parabolic theory. The behaviors of the E and F1 layers are regular and are expressed by analytic formulas (see Ref. 1, Sec. 5.2) and are such that the smaller F1 M factor essentially compensates for the higher f_0F1 so that the products, the MUFs, for both layers are nearly equal. During daytime the E layer is usually the controlling layer for distances up to about 2000 km and the F1 layer for distances between 2000 km and 3000 km. Over distances of 4000 km and longer, the F2 is normally the controlling layer. Single-hop propagation is limited to paths shorter than about 4000 km. Empirically, it has been found that as the distance increases beyond the “limit,” sky wave propagation is maintained by such mechanisms as ionospheric and ground scatter, high-angle rays that have longer one-hop limits, and ionospheric tilts that produce “super-modes” such as those that occur on transequatorial circuits. Propagation fails only when the ionosphere fails to support propagation at one of two “control points” on the great-circle path at 2000 km from each end (see Ref. 1, Sec. 12.2). The path MUF is the lower of the two MUFs for 4000 km with the ionospheric parameters at the control points. In the cases of the E, Es, and F1 layers for paths longer 2000 km, control points 1000 km from each end are used and the MUFs for a range of 2000 km are calculated (the lower of the two MUFs is taken as the circuit MUF). Global numerical maps of f_0F2 are available at reference high- and low-sunspot numbers (or equivalent indexes), and the values for other sunspot numbers are obtained by interpolation or extrapolation. There is a saturation of f_0F2 at sunspot numbers ≥ 150 so that for sunspot numbers greater than 150 the value is set at 150. The monthly median f_0F2 correlates better with the 12-month smoothed sunspot number than with the individual monthly number. For prediction purposes, the zero distance MUF ($= f_0\text{F2} + 0.5 f_H$) together with the MUF at a reference distance (e.g., 3000 km or 4000 km) and, for paths with other lengths, the MUFs are found by interpolation. The M(3000) is related to the virtual height, in km, by

$$M(30000) = (67.6542 - 0.014938h')/\sqrt{h'} \tag{11}$$

The optimum working frequency (FOT) is 0.85 (monthly median MUF) and it ensures sky wave propagation 90% of the days of the month at a particular hour (usually local or universal time). Operating on the monthly median MUF results in skywave reliability of 50%. The highest probable frequency, or *HPF*, is exceeded 10% of the time. The higher the signal frequency the greater is the signal strength, but this has to be balanced against the spectrum congestion caused by many operators using similar circuits. An advantage of using a frequency close to the MUF is that the time dispersion is a minimum.

In planning a circuit it is necessary to determine (1) the maximum MUF for the various layers and, hence, the FOT; (2) the radiation angle for the appropriate layer; (3) the power delivered to a receiver (using spatial spreading, ionospheric absorption, fading and polarization losses, antenna gains); and (4) the noise and interference (see ***Radio noise***; ***Radio system performance***).

Before about 1970, individual circuit evaluations were necessary using laborious methods, and graphical techniques were customary for the determination of skywave propagation parameters such as those discussed previously. Today these laborious methods are replaced by convenient user-friendly computer programs, many written for personal computers, that only require basic circuit information, such as time of day, month, sunspot number (or equivalent), and path terminals (or area coverage for broadcasting). The computer programs normally include numerical maps, or formulas, for calculating the necessary



ionospheric characteristics and noise and interference; the more comprehensive models include reference antennas for calculation of received signal-to-noise ratios. The sophistication of these PC programs ranges from basic frequency outputs to broad coverage. A list of some commercially available programs is given in Goodman (Ref. 2, Table 5.16; see also Ref. 22, Resolution ITU-R25). An example of a prediction program is the Ionospheric Communications Enhanced Profile Analysis and Circuit (*ICEPAC*), which includes, in addition to a global ionospheric model, models of the subauroral trough, auroral zones, and polar caps. This software is available (free) on the Internet (23). A sample output from ICEPAC is shown in Fig. 6, which includes contours of signal strength around a broadcasting transmitter that has an isotropic antenna.

Besides the basic sky wave characteristics, such as MUF, FOT, and LUF, the more comprehensive of these computer programs give signal-to-noise ratio for a given circuit performance (see ***Radio noise***) and the following characteristics that depend on the ionosphere (see Ref. 2, Sec. 5.11, and references therein). Mode availability, Q $(0 < Q < 1)$, is the fraction of time that a path is available (see Ref. 1, Sec. 12.6.2). To a first approximation the standard deviation of f_oF2 about the monthly average is about 15%. On the median MUF, $Q = 0.5$; on the FOT, $Q = 0.9$; and on the HPF, $Q = 0.1$.

Circuit reliability, ρ, $(0 < p < 1)$ is the fraction of days that successful communication may be expected at a given hour of a month on a specified operating frequency

$$\rho = QP \tag{12}$$

where P is the probability that the mean received signal-to-noise ratio exceeds a specified level. The reliability, ρ, depends on P increasing with increasing frequency, while Q decreases with increasing frequency.

Grade of service defines the quality of communication desired (for example, the percentage of error-free messages in teletype transmitted or the percentage of satisfied customers of a given service). Service probability is the fraction of time that a specified grade of service (e.g., signal to noise) or better is achieved.

Above-the-MUF loss, L_m, accounts for the fact that signals may be received on frequencies above the basic MUF (e.g., resulting from ionosphere scatter, E_s, etc.). The CCIR (14), Report 252-2, recommends

$$L_m = 130\{(f/\mathrm{MUF}) - 1\}^2 \tag{13}$$

To account for a wide variety of ionospheric effects, such as Es, spread F, off-great-circle propagation, focusing, day-to-day variability, and aurora, ITU (20) Report 252 contains information on additional system loss resulting from these extra effects.

Compatibility is defined as the percentage of time during which a specified criterion of service quality is achieved at a receiver in the presence of interference, relative to the value that would be obtained if only noise were present.

Digital System Considerations

Digital systems are particularly affected by ionospheric dispersion, which produces fading (e.g., by multipath, polarization, etc.). The performance of a digital system is characterized by its bit error rate, which is the probability that a transmitted binary digit is wrongly detected by the receiver. On HF, intervals with high error densities alternate with intervals of low error densities. Error bursts occur when the signal-to-noise ratio temporarily falls below a critical level (e.g., selective fading). Curves are available in the ITU (20) Report 197, that gives the duration and probability of fades as a function of the signal level for specific circuits. In the absence of fading the signal-to-noise ratio (*SNR*) is the controlling factor for digital transmission speed. The theoretical error-free channel capacity, *C*, is

$$C = B\log_2(1 + \mathrm{SNR})\,\mathrm{bits}\cdot\mathrm{s}^{-1} \tag{14}$$

where *B* is the channel bandwidth (Hz). Because of all the effects described above these ionospheric channels usually operate far below the theoretical capacity (Eq. 14).

Real-time Channel Evaluation

While the prediction systems discussed previously are valuable for circuit planning and frequency allocation, they have limited value for operational purposes, primarily because of the high hour-to-hour and day-to-day variability of the F2 layer. To meet operational requirements, several real-time circuit evaluation (*RTCE*) systems have been developed (see Ref. 14, Report 889-1). The first such system involved oblique-sweep-frequency sounding over the operational circuit and, from the oblique ionogram, selection of a suitable frequency with low time dispersion, adequate signal, and minimum noise and interference. The channel selection is normally limited by the channel allocation. A critical feature of this technique is the interval between soundings. When the interval is long, changing ionospheric conditions can catch the operator unaware. On the other hand, too frequent soundings generate excessive interference to other services. An alternative, and less bothersome, approach is channel sounding on the allocated channels only. This technique has the following advantages: simpler equipment, lower installation costs, and less interference. When the optimum channel is identified, a message is dispatched to the sender, who can commence transmission. This method assumes reciprocity (that is, the sender-to-receiver conditions are the same as the receiver-to-sender conditions). This is usually a good assumption. Adaptive systems are essential for RTCE in order to respond to rapidly changing sky wave conditions. An adaptive system needs (1) a fast frequency response, (2) antenna agility, and (3) the ability to adjust rates of information.

Use of RTCE allows adaptive frequency management by which usage of the HF spectrum can be maximized. Such an approach is preferable to increasing the transmitter power and/or transmitting simultaneously on all allocated frequencies, both of which may be self-defeating. The term *channel estimation* is used to describe the process of monitoring channel characteristics with the aim of describing the states of a set of channels. Real-time adaptive systems are of particular value when one of the terminals is mobile (e.g., ship, airplane, vehicle) and the other is fixed so that the fixed terminal can avail itself of high power and directive antennas. One advantage of RTCE over prediction is to maximize above-the-median MUF propagation, in which interference is usually lower than on the FOT.

COMMUNICATIONS DISRUPTIONS

As mentioned under Spectrum Considerations, medium frequencies and high frequencies can be adversely affected by solar events. Such solar events are particularly disruptive on high frequencies. The main solar phenomena that cause communication outages are as follows: x-ray bursts that result in sudden ionospheric disturbances SIDs, coronal (charged- particle) emissions that produce ionospheric storms, and energetic solar protons that cause polar cap absorptions (PCAs). While x-ray bursts last for a few minutes (less than 1 h), storms and PCAs can endure for several (3 or 4) days. To help minimize these communications outages, forecasting centers are operated in several countries around the world. These centers observe the sun's surface over a broad range of frequencies from x-rays through radio noise. The data are evaluated by skilled obsevers who assess the likelihood of a geo-effective result. The leading forecasting service is at the Space Weather Prediction Center (SWPC) of the National Oceanic and Atmospheric Administration (NOAA) located in Boulder, Colorado. The SWPC provides real-time monitoring and forecasting of solar and geophysical disturbances and it is the United States and world warning center for a number of disturbances that affect human affairs. The job of the SWPC is to provide timely warnings of the state of the earth's environment and alert users to prevailing conditions, this is called "situation awareness".

Among the numerous services, of importance to HF and MF communicators, porvided by SEC are:

A. Global maps of SID absorption
B. Maps of the geographical extent of PCAs
C. Maps of total energy deposition in the auroral zones
D. Forecasts of the state of the geomagnetic field and associated atmospheric disturbances
E. Educate users of systems affected by the environment.

Current Space-Weather conditions, including radio blackouts, can be obtained on the Internet (24).

CONCLUSIONS

The medium-frequency and high-frequency bands have great commercial, social, and scientific value and are used extensively for broadcasting and for point-to-point communications. The pronounced (orders of magnitude) variability of the ionosphere makes sky wave communications problematic, both as a means of communicating and as a source of interference. Using HF systems, frequency agility is essential for continuous operation and, therefore, a set of suitable assigned frequency channels. Even with such a frequency allocation, by the appropriate national authority, sky wave propagation is liable to disruption by several solar disturbances (see ***Propagation of broadcast transmissions***) and synthetic disturbances (e.g., nuclear explosions and ionospheric modification). For many purposes satellite communications, on gigaHertz frequencies, have replaced HF for global communications. However, sky waves will continue to be used well into the foreseeable future.

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