The phase velocity ratio of mode 1 in the daytime is greater than 1 for frequencies less than about 13 kilohertz and less than 1 for higher frequencies. At night the crossover frequency is about 9 kilohertz.

In daylight the attenuation of mode 1 is always less than that of mode 2. At night the attenuation for the two modes may be of the same order.

LOW AND MEDIUM FREQUENCIES—30 TO 3000 KILOHERTZ*

For low and medium frequencies of approximately 30 to 3000 kilohertz with a short vertical antenna over perfectly reflecting ground

$E = 186.4(P_r)^{1/2}$ millivolts rms/meter at 1 mile
$E = 300(P_r)^{1/2}$ millivolts rms/meter at 1 kilometer

where P_r = radiated power in kilowatts.

Actual inverse-distance fields at 1 kilometer for a given transmitter output power depend on the height and power radiation efficiency of the antenna and associated circuit losses.

Typical values found in practice for well-designed stations are:

Small L or T antennas as on ships:

$40(P_t)^{1/2}$ millivolts/meter at 1 kilometer

Vertical radiators 0.15 to 0.25λ high:

$290(P_t)^{1/2}$ millivolts/meter at 1 kilometer

Vertical radiators 0.25 to 0.40λ high:

$322(P_t)^{1/2}$ millivolts/meter at 1 kilometer

Vertical radiators 0.40 to 0.60λ high or top-loaded vertical radiators:

$386(P_t)^{1/2}$ millivolts/meter at 1 kilometer

where P_t = transmitter output power in kilowatts. These values can be increased by directive antenna systems.

It has been found that the concept of basic transmission loss, also called path loss, is convenient for the analysis of radio communication systems. Basic transmission loss is the dimensionless ratio P_R/P_A, where P_R is the power radiated from a lossless, isotropic transmitting antenna and P_A is the power available from a lossless, isotropic receiving antenna in a matched load. The isotropic antennas are at the same physical locations and operate in the same band of frequencies as the actual antennas.

Surface-wave (commonly called ground-wave) basic transmission loss is plotted in Fig. 3 for vertically polarized propagation over land having a representative conductivity and dielectric constant and in Fig. 4 for vertically polarized propagation over sea water. Both antennas are 30 feet above the surface in both figures.

In the low-frequency and medium-frequency ranges, propagation losses for horizontally polarized transmission between antennas on the surface of the earth are impractically high. Ground constants typical of various terrain types are listed in Table 1.

Under the conditions used in Figs. 3 and 4, the earth's surface behaves like a nearly perfect reflector for the isotropic antennas that are only a small fraction of a wavelength from it and that are used to calculate the basic transmission loss. As a result, each isotropic antenna together with the surface of the earth has a gain of nearly 3.01 dB in the general direction of the horizon. By contrast, a lossless quarter-wave monopole erected over a good ground screen would have a gain of 5.16 dB, and a

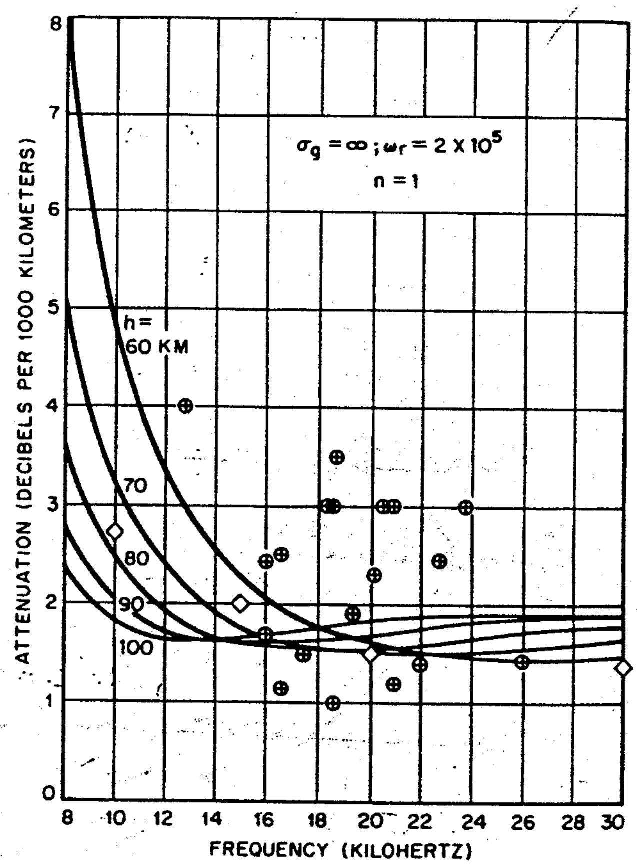

Fig. 1—Relation between attenuation, frequency, and height of the ionosphere. The diamonds represent some experimental observations by Taylor on the average daytime attenuation for west-to-east propagation over sea water. Attenuation rate in the opposite direction is greater by about 1 decibel per 1000 kilometers. *From "Radio Spectrum Utilization," Joint Technical Advisory Committee (IEEE and EIA), IEEE, New York; 1964: page 104.*

* "Radio Spectrum Utilization," Joint Technical Advisory Committee (IEEE and EIA), New York; 1964. CCIR XIth Plenary Assembly, Oslo; 1966: Vol. II, Propagation.

short lossless monopole would have a gain of 4.77 dB. It follows that the transmission loss between quarter-wave monopoles on the surface of the earth is very nearly 2×(5.16−3.01)=4.30 dB less than the basic transmission loss given in Figs. 3 and 4, and the transmission loss between short monopoles is 2×(4.77−3.01)=3.52 dB less.

Figures 3 and 4 do not include the effect of sky waves reflected from the ionosphere. Sky waves cause fading at medium distances and produce higher field strengths than the surface wave at longer distances, particularly at night. Sky-wave field strength is subject to diurnal, seasonal, and irregular variations due to changing properties of the ionosphere.

Figure 5 shows a family of propagation curves for F_0 computed from

$$F_0 = 80.2 - 10 \log D - 0.00176 f^{0.26} D$$

where D=distance in kilometers, f=frequency in kilohertz, and F_0 is the annual median received field strength in decibels above 1 microvolt per meter that would be produced by a short, vertical transmitting dipole at or near the earth's surface and *radiating* 1 kilowatt. The empirical equation is based on measured data. Figure 5 therefore includes the effects of both sky-wave and surface-wave propagation.

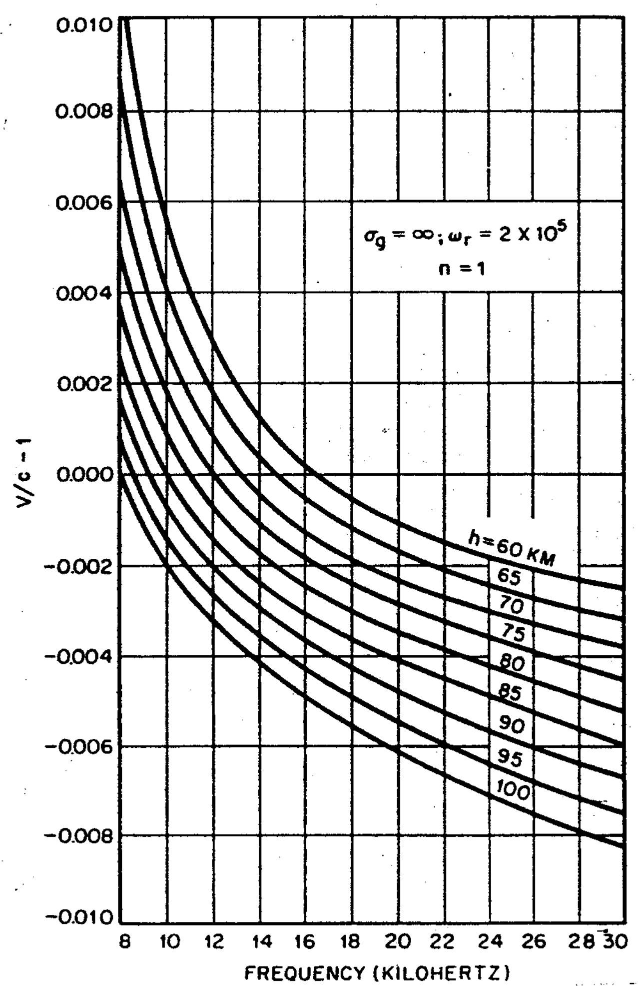

Fig. 2—Phase velocity V as a function of ionospheric height h and frequency, relative to the velocity in free space c. *From "Radio Spectrum Utilization," Joint Technical Advisory Committee (IEEE and EIA), IEEE, New York; 1964: page 105.*

TABLE 1—GROUND CONDUCTIVITY AND DIELECTRIC CONSTANT FOR MEDIUM- AND LONG-WAVE PROPAGATION TO BE USED WITH NORTON, BURROWS, BREMMER, OR OTHER DEVELOPMENTS OF SOMMERFELD PROPAGATION EQUATIONS.

Terrain	Conductivity σ (mhos/meter)	Dielectric Constant ϵ (esu)
Sea water	5	80
Fresh water	8×10^{-3}	80
Dry, sandy, flat coastal land	2×10^{-3}	10
Marshy, forested flat land	8×10^{-3}	12
Rich agricultural land, low hills	1×10^{-2}	15
Pastoral land, medium hills and forestation	5×10^{-3}	13
Rocky land, steep hills	2×10^{-3}	10
Mountainous (hills up to 3000 feet)	1×10^{-3}	5
Cities, residential areas	2×10^{-3}	5
Cities, industrial areas	1×10^{-4}	3

Penetration of Waves

The extent to which the lower strata influence the effective ground constants depends on the depth of penetration of the radio energy. This in turn depends on the value of the constants and the frequency. If the depth of penetration is defined as that depth in which the wave has been attenuated to $1/e$ (37%) of its value at the surface, then over the frequency range from 10 kHz to 10 MHz, δ has the values shown in Table 2. It will be seen that, at frequencies of 10 MHz and above, only the surface of the ground need be considered, but at lower frequencies, strata down to a depth of 100 meters or more must be taken into account. It is particularly important to take account of the lower strata when the upper strata are of lower conductivity, since more energy penetrates to the lower levels than happens with an upper layer of higher conductivity.

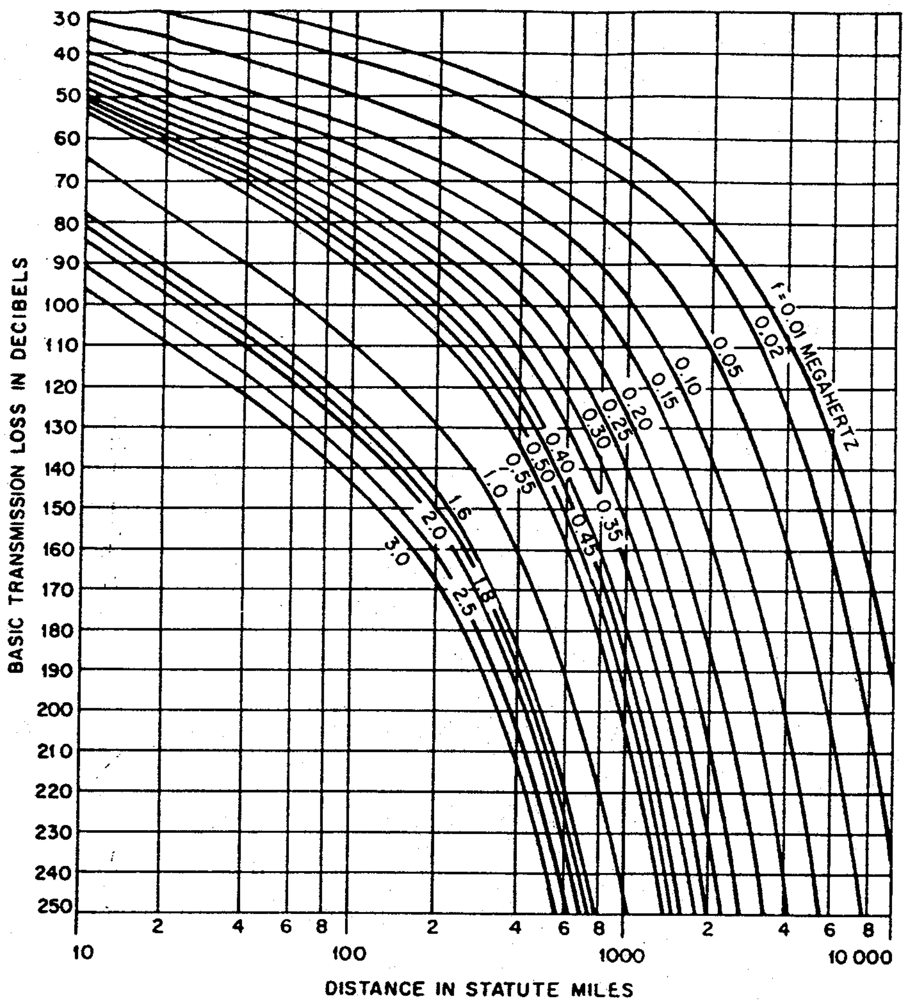

Fig. 3—Basic transmission loss expected for surface waves propagated over a smooth spherical earth. Over land: $\sigma = 0.005$ mho/meter, $\epsilon = 15$. Lossless isotropic antennas 30 feet above the surface. Vertical polarization. Adapted from *K. A. Norton, "Transmission Loss in Radio Propagation: II," National Bureau of Standards Technical Note 12, Fig. 7; June 1959.*

HIGH FREQUENCIES—3 TO 30 MEGAHERTZ*

At frequencies between about 3 and 25 megahertz and distances greater than about 100 miles, transmission depends chiefly on sky waves reflected from the ionosphere. This is a region high above the earth's surface where the rarefied air is sufficiently ionized (primarily by ultraviolet sunlight) to reflect or absorb radio waves, such effects being controlled almost exclusively by the free-electron density. The ionosphere is usually considered as consisting of the following layers.

D Layer: At heights from about 50 to 90 kilometers, it exists only during daylight hours, and ionization density corresponds with the elevation of the sun.

This layer reflects very-low- and low-frequency waves, absorbs medium-frequency waves, and weakens high-frequency waves through partial absorption.

* K. Davies, "Ionospheric Radio Propagation," Monograph 80, National Bureau of Standards, Washington, D.C.; 7 April 1965. CCIR XIth Plenary Assembly, Oslo; 1966: Vol. II, Propagation.

E Layer: At a height of about 110 kilometers, this layer is important for high-frequency daytime propagation at distances less than 1000 miles, and for medium-frequency nighttime propagation at distances in excess of about 100 miles. Ionization density corresponds closely with the elevation of the sun. Irregular cloud-like areas of unusually high ionization, called sporadic *E*, may occur up to more than 50 percent of the time on certain days or nights. Sporadic *E* occasionally prevents frequencies that normally penetrate the *E* layer from reaching higher layers and also causes occasional long-distance transmission at very-high frequencies. Some portion (perhaps the major part) of the sporadic-*E* ionization is ascribable to visible- and subvisible-wavelength bombardment of the atmosphere.

F_1 Layer: At heights of about 175 to 250 kilometers, it exists only during daylight. This layer occasionally is the reflecting region for high-frequency transmission, but usually oblique-incidence waves that penetrate the *E* layer also penetrate the F_1 layer and are reflected by the F_2 layer. The F_1 layer introduces additional absorption of such waves.

F_2 Layer: At heights of about 250 to 400 kilo-

TABLE 2—DEPTH OF PENETRATION OF WAVES INTO THE GROUND.

Frequency	Depth δ (m) $\sigma=4$ mho/m $\epsilon=80$	$\sigma=10^{-2}$ mho/m $\epsilon=10$	$\sigma=10^{-3}$ mho/m $\epsilon=5$
10 kHz	2.5	50	150
100 kHz	0.80	15	50
3 MHz	0.14	5	17
10 MHz	0.08	2	9

meters, F_2 is the principal reflecting region for long-distance high-frequency communication. Height and ionization density vary diurnally, seasonally, and over the sunspot cycle. Ionization does not follow the elevation of the sun in any fashion, since (at such extremely low air densities and molecular-collision rates) the medium can store received solar energy for many hours, and, by energy transformation, can even detach electrons during the night. At night, the F_1 layer merges with the F_2 layer at a height of about 300 kilometers. The absence of the F_1 layer, and reduction in absorption of the E layer, causes nighttime field intensities and noise to be generally higher than during daylight.

As indicated to the right on Fig. 6, these layers are contained in a thick region throughout which ionization generally increases with height. The layers are said to exist where the ionization gradient is capable of refracting waves back to earth. Obliquely incident waves follow a curved path through the ionosphere due to gradual refraction or bending of the wave front. When attention need be given only to the end result, the process can be assimilated to a reflection.

Depending on the ionization density at each layer, there is a critical or highest frequency f_c at which the layer reflects a vertically incident wave. Frequencies higher than f_c pass through the layer at vertical incidence. At oblique incidence, and distances such that the curvature of the earth and ionosphere can be neglected, the maximum usable frequency is given by

$$\mathrm{MUF}=f_c \sec \phi$$

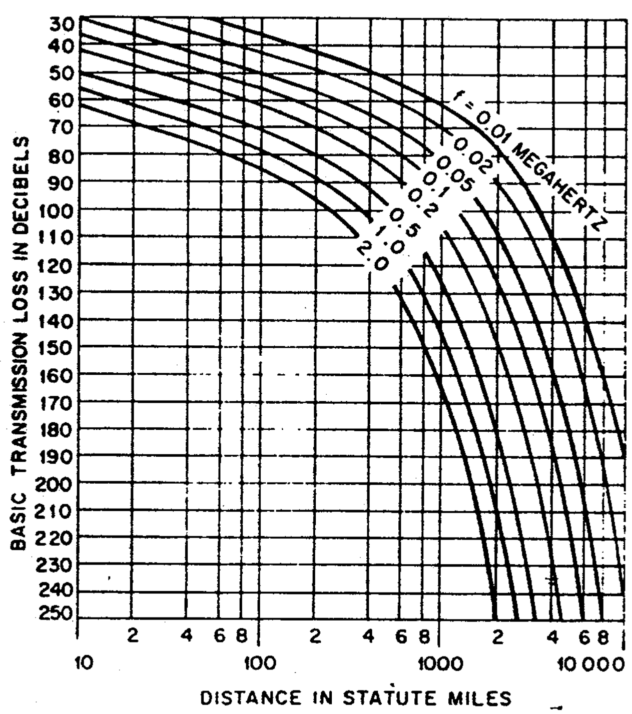

Fig. 4—Basic transmission loss expected for surface waves propagated over a smooth spherical earth. Over sea water: $\sigma=5$ mhos/meter, $\epsilon=80$. Lossless isotropic antenna 30 feet above the surface. Vertical polarization. Adapted from *K. A. Norton, "Transmission Loss in Radio Propagation: II," National Bureau of Standards Technical Note 12, Fig. 8; June 1959.*

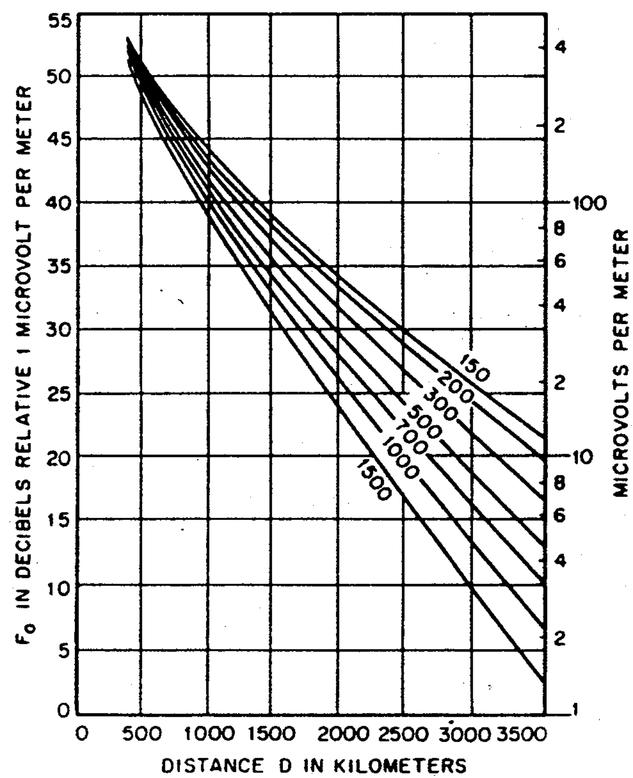

Fig. 5—Family of basic curves of F_0 to be used to determine the annual median value of the field strength for the frequencies (in kilohertz) indicated on the curves. *CCIR Tenth Plenary Assembly, vol. II, Report 264, p. 321, Geneva; 1963.*

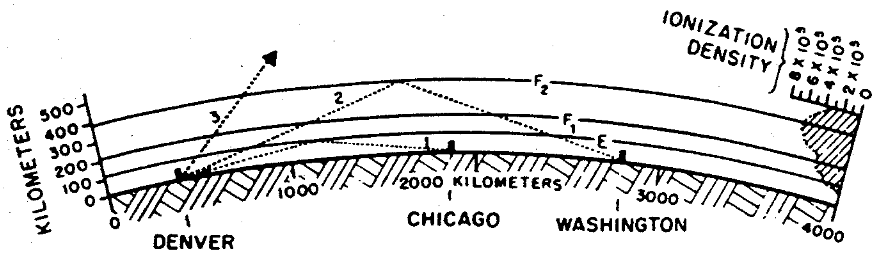

Fig. 6—Schematic explanation of skip-signal zones.

where MUF = maximum usable frequency for the particular layer and distance, and ϕ = angle of incidence at reflecting layer.

At greater distances, curvature is taken into account by the modification

$$\text{MUF} = kf_c \sec \phi$$

where k is a correction factor that is a function of distance and vertical distribution of ionization.

f_c and height, and hence ϕ for a given distance, vary for each layer with local time of day, season, latitude, and throughout the 11-year sunspot cycle. The various layers change in different ways with these parameters. In addition, ionization is subject to frequent abnormal variations.

Ionospheric losses are a minimum near the maximum usable frequency and increase rapidly for lower frequencies during daylight.

High frequencies travel from the transmitter to the receiver by reflection from the ionosphere and earth in one or more hops as indicated in Figs. 6 and 7. Additional reflections may occur along the path between the bottom edge of a higher layer and the top edge of a lower layer, the wave finally returning to earth near the receiver.

Figure 6 indicates transmission on a common frequency, (1) single-hop via E layer, Denver to Chicago, and (2) single-hop via F_2, Denver to Washington, with (3) the wave failing to reflect at higher angles, thus producing a skip region of no signal between Denver and Chicago. Figure 7 illustrates single-hop transmission, Washington to Chicago, via the E layer (ϕ_1). At higher frequencies over the same distance, single-hop transmission would be obtained via the F_2 layer (ϕ_2). Figure 7 also shows two-hop transmission, Washington to San Francisco, via the F_2 layer (ϕ_3).

Actual transmission over long distances is more complex than indicated by Figs. 6 and 7, because the layer heights and critical frequencies differ with time (and hence longitude) and with latitude. Further, scattered reflections occur at the various surfaces.

Typical values of critical frequency for Washington, D.C., are shown in Fig. 8.

Preferably, operating frequencies should be selected from a specific frequency band that is bounded above and below by limits that are systematically determinable for the transmission path under consideration. The recommended upper limit is called the *optimum working frequency* (FOT) and is selected below the MUF to provide some margin for ionospheric irregularities and turbulence, as well as for the statistical deviation of day-to-day ionospheric characteristics from the predicted monthly median value. So far as may be consistent with available frequency assignments, operation in reasonable proximity to the upper frequency limit is preferable, in order to reduce absorption loss.

The lower limit of the normally available band of frequencies is called the *lowest useful high frequency* (LUF). Below this limit ionospheric absorption and radio noise levels are likely to be such that radiated-power requirements become uneconomical. For a given path, season, and time, the LUF may be predicted by a systematic graphic procedure. Unlike the MUF, the predicted LUF must be corrected by a series of factors dependent on radiated power, directivity of transmitting and receiving antennas in azimuth and elevation, class of service, and presence of local noise sources. Available data include atmospheric-noise maps, transmission-loss charts, antenna diagrams, and nomograms facilitating the computation. The procedure is formidable but worthwhile.

The upper and lower frequency limits change continuously throughout the day, whereas it is ordinarily impracticable to change operating frequencies correspondingly. Each operating fre-

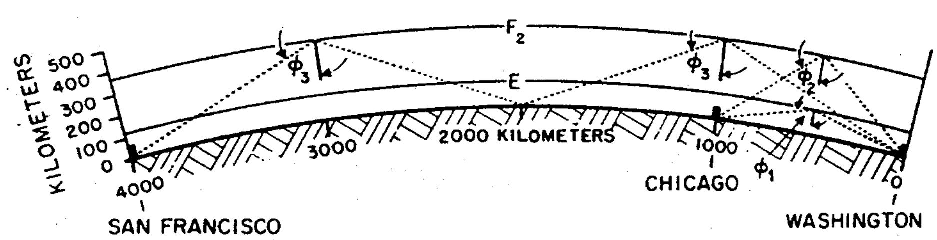

Fig. 7—Single-hop and two-hop transmission paths due to E and F_2 layers.

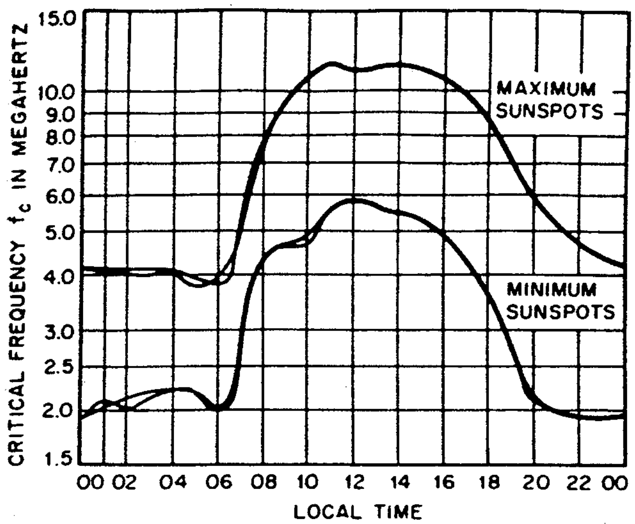

Fig. 8—Critical frequency for Washington, D.C. *National Bureau of Standards Circular 462.*

quency, therefore, should be selected to fall within the above limits for a substantial portion of the daily operating period.

Angles of Departure and Arrival

Angles of departure and arrival are of importance in the design of high-frequency antenna systems. These angles, for single-hop transmission, are obtained from the geometry of a triangular path over a curved earth with the apex of the triangle placed at the virtual height assumed for the altitude of the reflection. Figure 9 is a family of curves showing radiation angle for different distances.

D= great-circle distance in statute miles
H= virtual height of ionosphere layer in kilometers
Δ= radiation angle in degrees
ϕ= semiangle of reflection at ionosphere.

Forecasts of High-Frequency Propagation

In addition to forecasts for ionospheric disturbances, the Institute of Telecommunication Sciences of the Environmental Sciences Services Administration (ESSA) issues monthly predictions 3 months in advance, used to determine the optimum working frequencies for high-frequency communication.

In designing a high-frequency communication circuit, it is necessary to determine the optimum traffic frequencies, system loss, signal-to-noise ratio, angle of arrival, and circuit reliability. Manual methods for calculating the values of these factors are described,* as is the use of electronic computers for predicting the performance of high-frequency sky-wave communication circuits.†

Table 3 is a typical performance prediction prepared by computer. A general description of the circuit parameters used in the calculations is shown in the heading of the computer printout. Starting at the top of the page and reading from left to right, the heading may be described as follows.

The first line contains the month, the solar activity level in 12-month moving average Zurich sunspot number, and a circuit identification number. The second and third lines contain the transmitter and receiver locations, the bearings, and the distance. The fourth and fifth lines contain the antenna system for each terminal and their orientation relative to the great-circle path. The minimum angle indicates the lowest vertical angle considered in the mode selection.

The sixth line is the power delivered to the

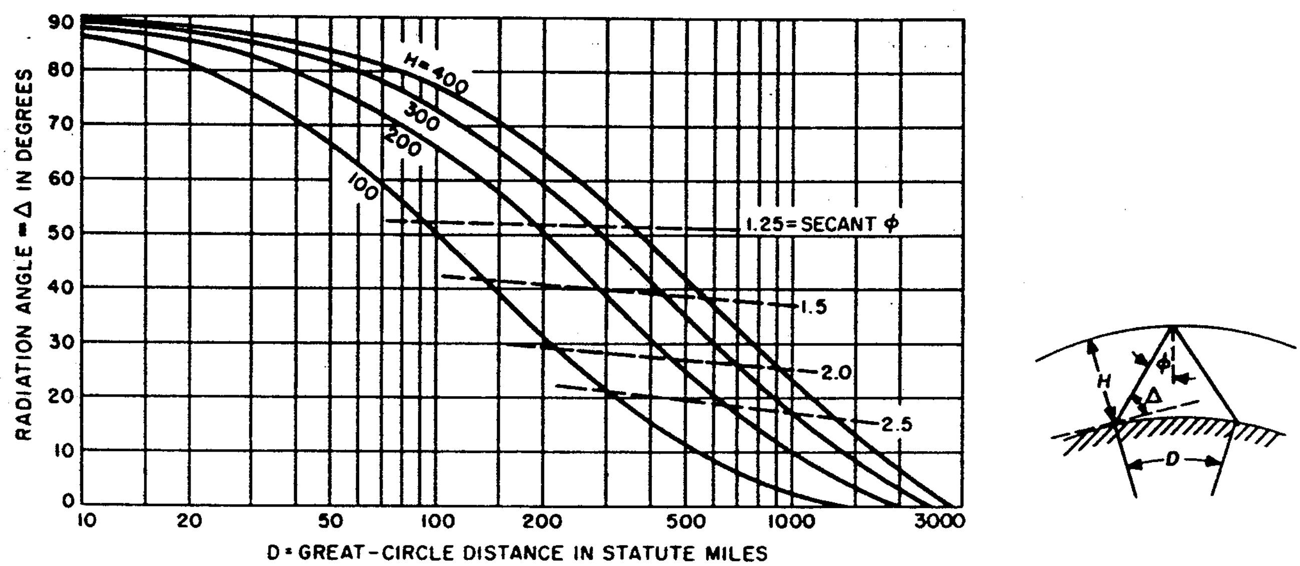

Fig. 9—Single-reflection radiation angle and great-circle distance.

* K. Davies, "Ionospheric Radio Propagation," National Bureau of Standards Monograph 80; 1 April 1965.

† D. L. Lucas and G. W. Haydon, "Predicting Statistical Performance Indexes for High-Frequency Ionospheric Telecommunication Systems," ESSA Technical Report IER1-ITSA; 1 August 1966.

WEATHER - RELATED INTERFERENCE

Many people are familiar with the interference to TV and FM Radio reception that can occur during abnormal weather conditions. Doesn't it always seem to happen in the middle of Wimbledon Tennis fortnight?

In fact, the weather conditions that can cause such events do occur most commonly in the summer months so the above can often be true. It is not possible to exclude completely interference due to the weather, but the broadcasters do their planning on the basis that service areas should be clear for at least 95% of the time. There is not much that viewers and listeners can do little about this interference when it occurs. However provided they live within the service area of their transmitter and are using as good directional aerials, the problem should be kept to 5% or less most of the time.

This factsheet explains what causes this interference and what the broadcaster can do to minimise its effects. The factors which occasionally enable a distant transmitter to blot out local reception are complex, depending very much on complicated atmospheric conditions over the British Isles.

The Atmosphere

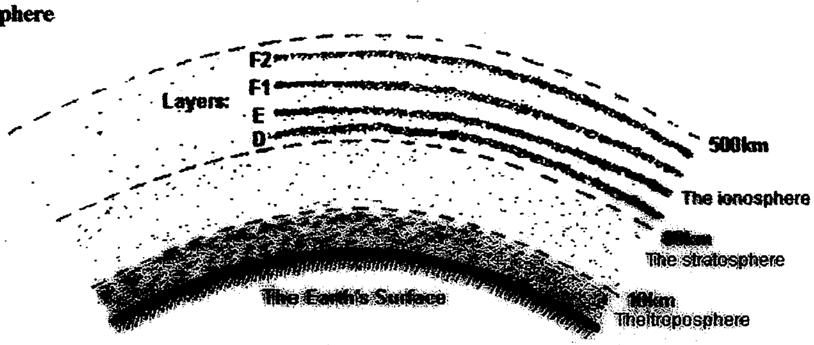

fig 1: the earth's atmosphere showing the troposphere, the stratosphere and the D, E, F1 and F2 layers of the ionosphere

The atmosphere surrounding the earth comprises a lower layer called the troposphere, which extends to a height of about 10 km above sea level; a middle layer called the stratosphere which extends to around 80 km high and an upper layer called the ionosphere which stretches about 500 km or more into space (see Fig 1). The ionosphere is usually sub - divided into layers D, E, F1 and F2. Although the ionosphere has an occasional effect on FM radio, as discussed later, the troposphere is the most important layer as far as VHF and UHF signals are concerned.

The Troposphere

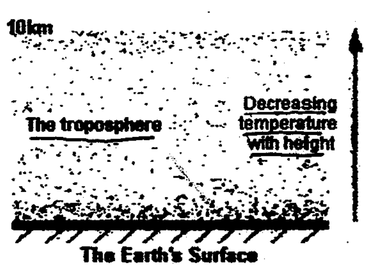

fig 2: in a normal troposphere the surface temperate decreases gradually with height

All our weather occurs in the troposphere and, during normal conditions, its temperature decreases with height as shown in Fig 2. During low pressure (cyclonic) weather, the air mass is rising gently and as it climbs, it cools and any moisture in it condenses to form clouds.

Under these conditions, the troposphere is generally well "stirred up" and unsettled. During high pressure (anticyclonic) weather, the air mass is sinking slowly and as it falls, its temperature increases to produce a warmer and drier atmosphere, very often without clouds. Under these conditions, the troposphere is generally very still and settled. Although temperature normally decreases with height, certain weather conditions can result in a layer of air being formed whose temperature remains constant or even increases with height.

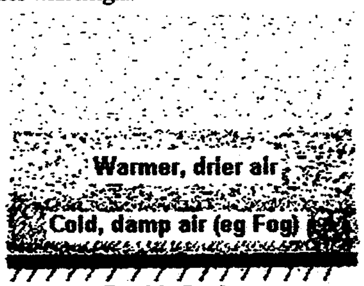

fig 3a: a temperature inversion at ground level

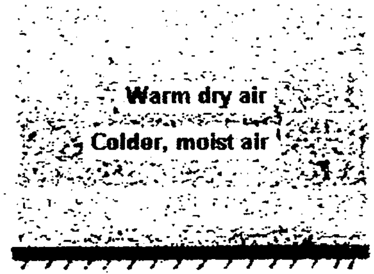

fig 3b: an elevated temperature inversion

In the United Kingdom, such a layer can occur anywhere from immediately above the earth's surface up to a height of around 3km. (see Figs 3a and 3b). This condition is known as a temperature inversion. Temperature inversions mostly occur during high pressure periods as the still air allows stratification of the atmosphere to take place. They have a pronounced effect on VHF radio and UHF television signals, particularly if there are corresponding changes in the humidity.

VHF/UHF Propagation

VHF and UHF signals normally propagate (ie travel) through the troposphere in a slightly curved path as shown in Fig 4. As a result of this bending, they are able to travel further than the geometrical horizon to a point known as the radio horizon. Beyond here, the signals attenuate rapidly and good reception is not generally possible.

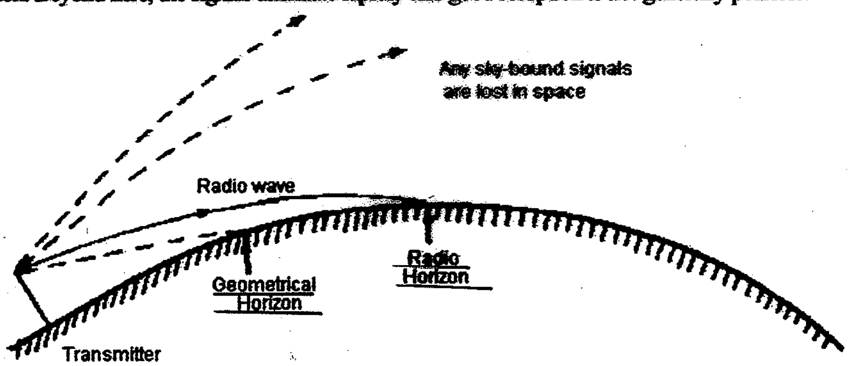

fig 4: normal propagation of a VHF or UHF signal in the troposphere

The bending of these waves is caused by refraction and the extent to which they curve depends on the refractive index of the troposphere. This in turn depends on the temperature and humidity of the air. In a normal atmosphere, the temperature (and humidity) generally decrease with height and this produces a steady fall in the refractive index with height. Under these stable conditions, the radio horizon can readily be calculated.