U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

WASHINGTON

JHD:ANK
I-6

Letter
Circular
LC-614

RADIO TRANSMISSION AND THE IONOSPHERE

October 23, 1940

JHD:ANK
I-6

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
Washington

Letter Circular
LC-614
(Supersedes LC-575)

October 23, 1940

RADIO TRANSMISSION AND THE IONOSPHERE

Radio transmission over great distances is made possible by reflection of the radio waves from ionized (electrically conducting) layers in the ionosphere, the upper region of the earth's atmosphere. How far the radio waves go, and what frequencies may be used, are determined by the heights and the degree of ionization of the ionized layers, which are located between about 50 kilometers (30 miles) and 400 kilometers (250 miles) above the earth's surface. Because of variations in the ionized layers, the conditions of radio wave transmission vary with time of day, with season, and from year to year. For the efficient maintenance of radio services it is important to have a constant supply of information on these changes. To this end an ionosphere observing, reporting, and predicting service is provided by the National Bureau of Standards. It is analogous to the weather reporting service, though quite independent of it; the factors producing or affecting weather exist at much lower levels of the atmosphere than the ionosphere.

The results of the Bureau's work on the ionosphere and radio transmission are made available to the public by a Science Service Ursigram and radio broadcast each week, and regular publication each month and each quarter, as well as through special papers (see References at end hereof) published from time to time on particular phases of the subject. The weekly report gives ionosphere conditions at noon and midnight for each day of the week and also ionosphere disturbances etc. whenever they occur; from the ionosphere data may be calculated the limiting radio frequencies usable for any distance and time. The monthly publication, in Proceedings of the Institute of Radio Engineers (address: 330 W. 42nd St., New York, N.Y.), reports the radio and ionosphere conditions for the second month before, and a prediction of radio conditions for the month following, the month of publication. Details are described below, pages 7 and 9. In a quarterly publication in Terrestrial Magnetism and Atmospheric Electricity are given monthly average ionosphere conditions. In the radio amateur magazine QST each quarter are given predictions of distance ranges and skip distances in the amateur frequency bands.

(over)

Part of the subject matter of this Letter Circular is supplemented by another Letter Circular of the Bureau, "Distance ranges of radio waves."

THE IONOSPHERE

In the high atmosphere, above about 50 kilometers (30 miles), the air particles are separated so far that collisions between them are far less frequent than in the lower atmosphere, and when an air particle is ionized by ultraviolet radiation from the sun it remains ionized for a considerable time. Therefore at any given time a large proportion of the air particles are in an ionized condition. This does not occur much below about 50 kilometers (30 miles), because the ionizing radiations from the sun are largely absorbed in the higher regions of the atmosphere. Likewise there is not very great ionization density above about 400 kilometers (250 miles), because the air is so rare at such heights that there are not enough atoms to provide for great ionization density. The region in which the ionization is great enough to affect radio wave transmission, is thus between 50 and 400 kilometers (30 and 250 miles) above the earth's surface, and this region is called the ionosphere.

The ionization in the ionosphere is not uniformly distributed with altitude but is stratified, and there are certain definite layers in which the ionization density is such as to reflect radio waves. These layers do not remain always the same as to height and ionization density, but vary diurnally, seasonally, and otherwise. There may be several such layers at a given time. There are two principal ones, called the E and F layers. The E layer is at a height of 90 to 140 kilometers at different times, usually about 110 kilometers. The term F-layer is ordinarily reserved for the other layer as it exists at night; in the daytime during most of the year the F layer divides into two layers which are called the F_1 and F_2. The night F layer is at a height of about 180 to 400 kilometers; the F_1 layer exists in the daytime, at a height of about 140 to 250 kilometers; the F_2 layer exists in the daytime, at a height of about 250 to 350 or more kilometers in the summer and about 150 to 300 kilometers in the winter day. (The "virtual" heights, defined later, are somewhat greater than these values). A fourth layer, which is semi-permanent, is the D layer; it exists only in the daytime, and its height is of the order of 50 to 90 kilometers. Little has been done on the determination of the quantitative characteristics of the D layer, its effects being largely inferred rather than directly observed. Existing knowledge covers mainly the E, F, F_1, and F_2 layers.

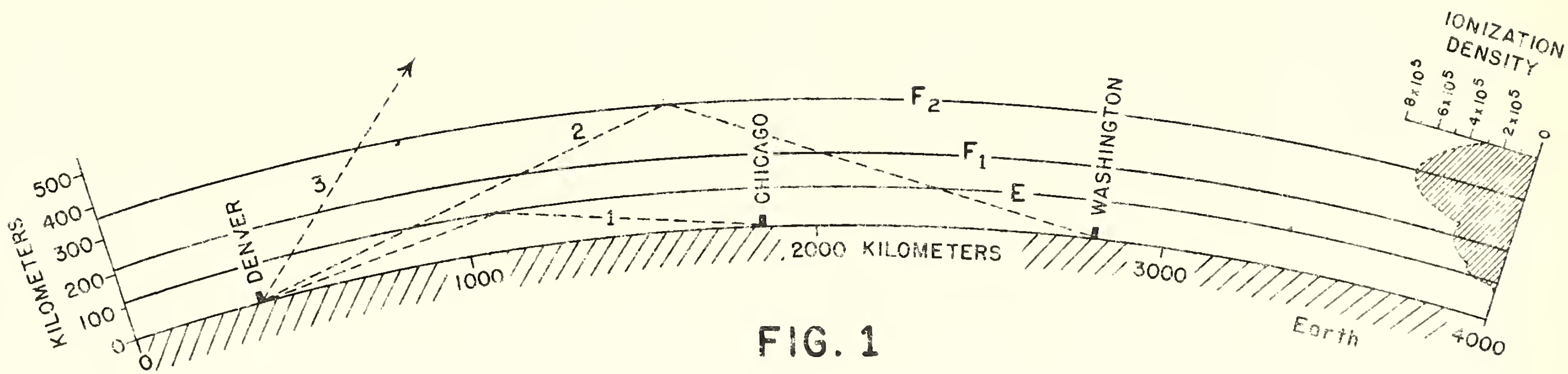

IONIZATION DENSITY
8x10⁵
6x10⁵
4x10⁵
2x10⁵
0
KILOMETERS
500
400
300
200
100
0
DENVER
CHICAGO
WASHINGTON
F2
F1
E
1
2
3
1000
2000 KILOMETERS
3000
4000
Earth

FIG. 1

The structure of the ionosphere may be visualized in an elementary way from Fig. 1, which is for a typical summer daytime condition, the E, F_1, and F_2 layers all being present. This diagram is drawn to scale, so the angles of reflection of radio waves from the layers may be estimated correctly. The three layers are shown as mere thin lines, for simplicity. The layers have in fact a certain thickness, and the density of ionization varies somewhat in this thickness. At the right of the diagram is a rough illustration of a possible distribution of ionization density with height.

Dotted lines 1 and 2 indicate two of many possible paths of radio waves from a transmitter to a receiver as transmitted by reflection from the ionosphere layers. This picture, simple as it is, does in fact represent the basic mechanism of radio wave transmission over long distances. When we consider the variations of ionization and height of the layers with time, and the effects of the ionization upon the received intensity and the limits of transmissible frequency at any particular time, the picture loses its simplicity. However, most of the phenomena of long-distance radio transmission are completely explainable in terms of the ionosphere.

Ionosphere Characteristics.- The principal ionosphere characteristics which control or determine long-distance radio transmission are the height and the ionization density of each of the ionosphere layers. Since each layer has a certain thickness it is necessary to define the sense in which the term, height, is used. When a ray or train of waves is reflected by a layer, it is slowed down as soon as it starts to penetrate into the layer. The process of reflection thus goes on from the place at which the waves enter the layer until they have been fully turned down and leave the layer. This is true whether the waves travel vertically or obliquely to the ionosphere. It is illustrated for the oblique case in Fig. 2. The waves follow a curved path in the layer until they emerge at a vertical angle equal to that at which they entered. The time of transmission along the actual path BCD in the ionized layer is, for the simple case, the same as would be required for transmission along the path BED if there were no ionized particles present. The height h from the ground to E, the intersection of the two projected straight parts of the path, is called the virtual height of the layer. This is an important quantity in all measurements and applications.

The virtual height of a layer is measured by transmitting a radio signal from A, and receiving at F both the signal transmitted along the ground and the echo, or signal reflected by the ionosphere, and measuring the difference in time of arrival of the two. Since the time differences are mere thousandths of a second, the signal is a very short pulse, in order that the ground-wave and reflection may be separated in an oscillograph.

The difference between the distance (AE + EF) and AF is found by multiplying the measured time difference by the velocity of light. From this and the known distance AF, the virtual height h is calculated. In practice, measuring equipment is calibrated directly in kilometers virtual height rather than time differences. It is usual to make AF zero, i.e., to transmit the signal vertically upward and receive it at the same place (and it is for this case that the term "virtual height" rigorously applies). The virtual height varies slightly with frequency of the radio waves used in the measurement.

The effectiveness of the ions in reflecting the waves back to earth depends on the number of ions present in a unit of volume, i.e., the ionization density. The higher the frequency, the greater is the density of ionization required to reflect the waves back to earth. It has been shown that, where the ions are electrons, the relation (for the ordinary wave, explained below) is $N = 0.0124 f^2$, where N is the number of electrons per cubic centimeter and f is the highest frequency, in kilocycles per second, at which waves sent vertically upward are reflected back to earth. Waves of all frequencies higher than this pass on through the ionized layer and are not reflected back to earth, while waves of all lower frequencies are reflected unless they are absorbed (see discussion of absorption below). This frequency is called the critical frequency, and measurement of it is, with the equation just given, a means of measuring the maximum ionization density in an ionized layer. (Waves of higher frequencies than the critical are sometimes reflected, by another mechanism - see discussion of "Sporadic E", below).

Measurements of critical frequency are usually made by means of vertical or nearly vertical transmission (i.e., with the transmitter and receiver not far apart). The process is to measure the virtual height, by the method described above, repeating the determination at successively increasing frequencies until the waves are no longer received back from the layer. The highest frequency at which waves sent vertically upward are received back from the layer is the critical frequency of that layer. Typical results of such measurements are illustrated in Figs. 3, 4, and 5, for different times of year, day and night. They show critical frequencies as sharp increases in virtual height.

For example, in Fig. 3, starting at a frequency below 2000 kc/s (2 Mc/s), the virtual height is found (in this example) to be about 110 kilometers, and remains at about this height until about 3.3 Mc/s. The critical frequency of the E layer at the time of this measurement is thus 3.3 Mc/s, i.e., this is the highest frequency at which vertically incident waves are reflected back to earth from this layer; all such waves of higher frequency penetrate through the E layer and go on up to a higher layer, the F_1.

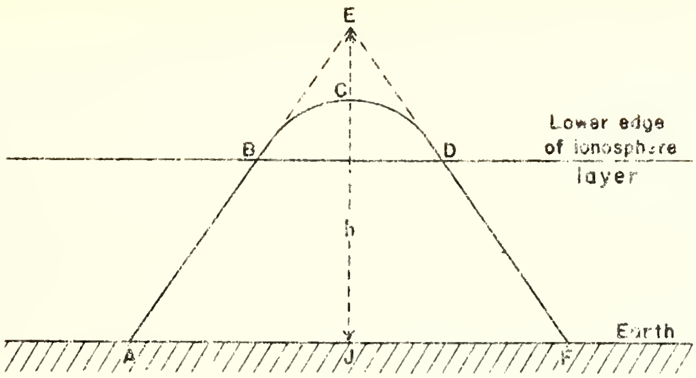


FIG. 2

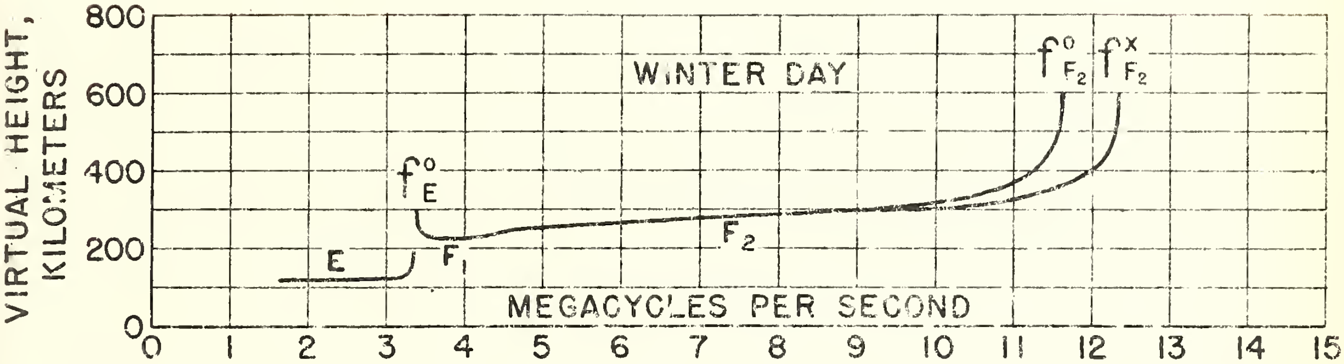


FIG. 3

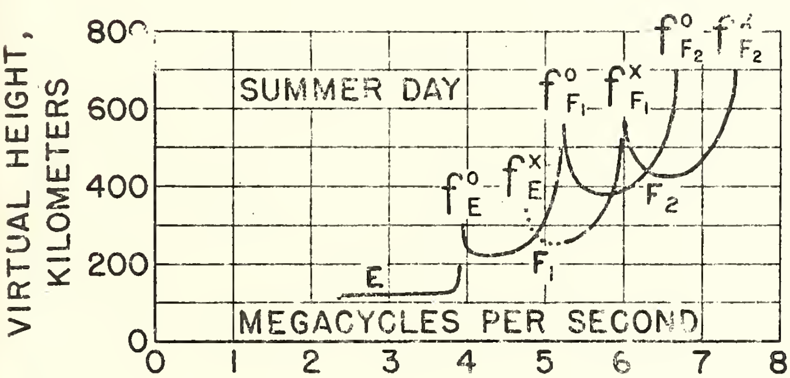


FIG. 4

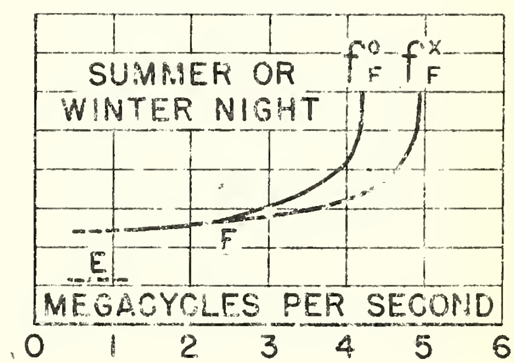


FIG. 5

At about 4.6 Mc/s the waves penetrate through the F_1 layer and go on up to the F_2 layer. The F_2 layer has a greater ionization density and so it reflects back waves of frequency greater than 4.6 Mc/s. It is not until frequencies greater than 11.6 Mc/s are used that the F_2 layer fails to reflect them, in the case illustrated.

Near the critical frequency the waves are excessively retarded in the ionized layer, which accounts for the rise of the curve at the critical frequency. At the right of the curve appear two critical frequencies for the F_2 layer. This is an indication of double refraction of the waves due to the earth's magnetic field, giving two components of different polarization. One is called the ordinary wave and the other the extraordinary wave. The symbols o and x, respectively, are used for these components. The critical frequency of a layer n is represented by the symbol f_n, and to such symbol the o or x is added as a superscript. Thus the critical frequencies of the F_2 layer for the ordinary and extraordinary waves are indicated by the respective symbols, $f^o_{F_2}$ and $f^x_{F_2}$. In the case of the E layer, the ordinary wave usually predominates and the extraordinary wave is so weak it does not affect radio reception. At Washington the critical frequency for the extraordinary wave is about 750 kc/s higher than for the ordinary wave for frequencies of 4000 kc/s or higher, The difference in frequency is proportional to the intensity of the earth's magnetic field at the place of reflection, and is therefore different at different places on the earth. In reporting results of measurements of critical frequency it is now customary to give the values for the ordinary wave; practice varied in the past.

Besides the virtual heights and critical frequencies, the absorption of the energy of radio waves by the ionosphere is an important factor in limiting radio transmission. This absorption exists because the ions set in motion by the radio waves collide with air molecules and dissipate as heat the energy they have taken from the radio waves. Consequently the energy thus absorbed from the radio waves is greater, the greater the distance of penetration of the waves into the ionized layer and the greater the density of ions and air molecules in the layer, i.e., the greater the number of collisions between ions and air molecules. Absorption is especially great in the daytime, and it occurs chiefly in the low ionosphere, in the D or E layers. It also occurs in the high ionosphere, near critical frequencies, The low-layer absorption is usually of greater significance in radio communication than the absorption near the critical frequencies. Much of the low-layer absorption disappears with the decrease of low-layer ionization at night. Higher frequencies are less affected by absorption than are lower frequencies, for waves passing through the same ionized layers.

Regular Variations of Ionosphere Characteristics.- There are three principal types of variation of critical frequencies which are fairly regular with time. These are diurnal variations, seasonal variations, and year-to-year variations with the sunspot cycle. See Fig. 6.

The diurnal and seasonal variations of the critical frequencies of the normal E layer are particularly regular. The critical frequencies vary with the altitude of the sun, being highest when the sun is most nearly overhead. Thus the diurnal maximum of the E critical frequency (f_E) is at local noon, and the seasonal maximum is at the summer solstice. At night this layer usually does not regularly reflect at vertical incidence waves of frequencies higher than about 1.0 Mc/s.

The diurnal and seasonal variations of the critical frequencies of the F_2 layer are quite different from those of the E layer. The winter F_2 critical frequencies exceed any regular critical frequency found during the summer. In the winter a broad diurnal maximum occurs in the daytime, centered around 1:00 P.M. local time. In the summer a broader diurnal maximum centers about sunset. During the night the winter critical frequencies are usually lower than the corresponding summer values. Thus, the highest F_2-layer critical frequencies occur during the winter day, and the lowest F-layer critical frequencies occur during the winter night; the summer day and night values are between.

The F_2 virtual heights are much lower during a winter day than during a summer day. The F virtual heights at night are about the same in winter as in summer.

The seasonal effects in the ionosphere synchronize with the sun's seasonal position, not lagging a month or two as do the seasons of weather. Winter conditions in the F_2 layer obtain during a period of several months from about the fall equinox to the spring equinox, and summer conditions for a period of several months from about May to August inclusive. On the summer side of the equinoxes, there is a transition period of about a month in which the change occurs between winter and summer conditions.

There are important changes in ionosphere characteristics in the 11-year sunspot cycle. See Fig. 6. From the sunspot minimum in 1933 to the sunspot maximum in 1937 the F- and F_2-layer critical frequencies doubled, for most hours of the day, and the E-layer critical frequencies became 1.25 times as great. A consequence is that the best radio frequencies for long-distance transmission were approximately twice as great in 1937 as in 1933, except for summer daytime, when they were about 1.5 times as great. In about 1944 they will return to minimum values.

The condition of the ionosphere varies somewhat with latitude. For all latitudes of continental United States the differences from the Washington values appear to be small, but the values in Alaska and in the Canal Zone are somewhat different. The values also vary with distance from the magnetic pole and auroral zone; thus, conditions are different in Canada than at the same latitude in Siberia, because the north magnetic axis pole is in northwestern Greenland.

The Bureau's monthly report on the ionosphere in the Proceedings of the Institute of Radio Engineers includes average data for the month on the virtual heights and critical frequencies of the ionosphere layers, data on their variations, and other data described below (p.9). The data are given graphically, showing values for all hours of the day and night. Examples of these monthly graphs are given in Fig. 6. These examples show summer and winter conditions at minimum and maximum phases of the sunspot cycle. The values shown for the minimum are those observed in 1933, which are expected to be approximately the same in about 1944.

The Science Service Ursigram each week gives the following data: midnight and noon ordinary-wave critical frequencies and minimum virtual heights of the regular layers for each day of the week ending the Tuesday preceding the issue of the Ursigram, ionosphere storms indicated by character figure, and sudden ionosphere disturbances for the same days. The critical frequencies can be translated into maximum usable frequencies by use of the ratios given in Table 1 below. These data and a schedule of the radio broadcasts are given in Science Service Research Aid Announcements, obtainable on request from Science Service, 2101 Constitution Avenue, Washington, D.C.

APPLICATIONS TO RADIO TRANSMISSION

From the vertical-incidence critical frequencies and virtual heights of the ionosphere layers, at any given time, it is possible to calculate the upper limit of radio frequency that can be transmitted over any distance, and, conversely, the minimum distance for any frequency. The calculated values of maximum usable frequency are found to agree with direct observation of radio transmission over such distances. The best frequencies to use are slightly below the maximum usable - see "Optimum Frequencies", below.

When radio waves are transmitted along the earth over any distance, they strike the ionosphere obliquely (Fig. 1). Such obliquely incident waves can be reflected back down with lower ionization densities than can vertically incident waves of the same frequency. It follows that the more obliquely the waves strike the layer, the higher is the upper limit of frequency of waves that can be reflected from a layer of given ionization density or critical frequency. In other words, the greater the transmission distance or the lower the layer, the higher the frequency which can be used. This upper limit of frequency, for transmission via an ionosphere layer, for a particular time and transmission distance, is called the maximum usable frequency. It may be calculated roughly, to a first approximation, by multiplying the critical frequency of the layer by the secant of the angle of incidence. Transmission at frequencies above the maximum usable frequencies of the regular layers may sometimes be observed. For a discussion of this see section "Effects of Ionosphere Irregularities" below.

The accurate calculation of maximum usable frequencies from vertical-incidence critical frequencies is complicated (see RP1013, 1096, 1100, 1167, and other papers given in References at end hereof). For convenience, typical values for the conversion are given in Table 1.

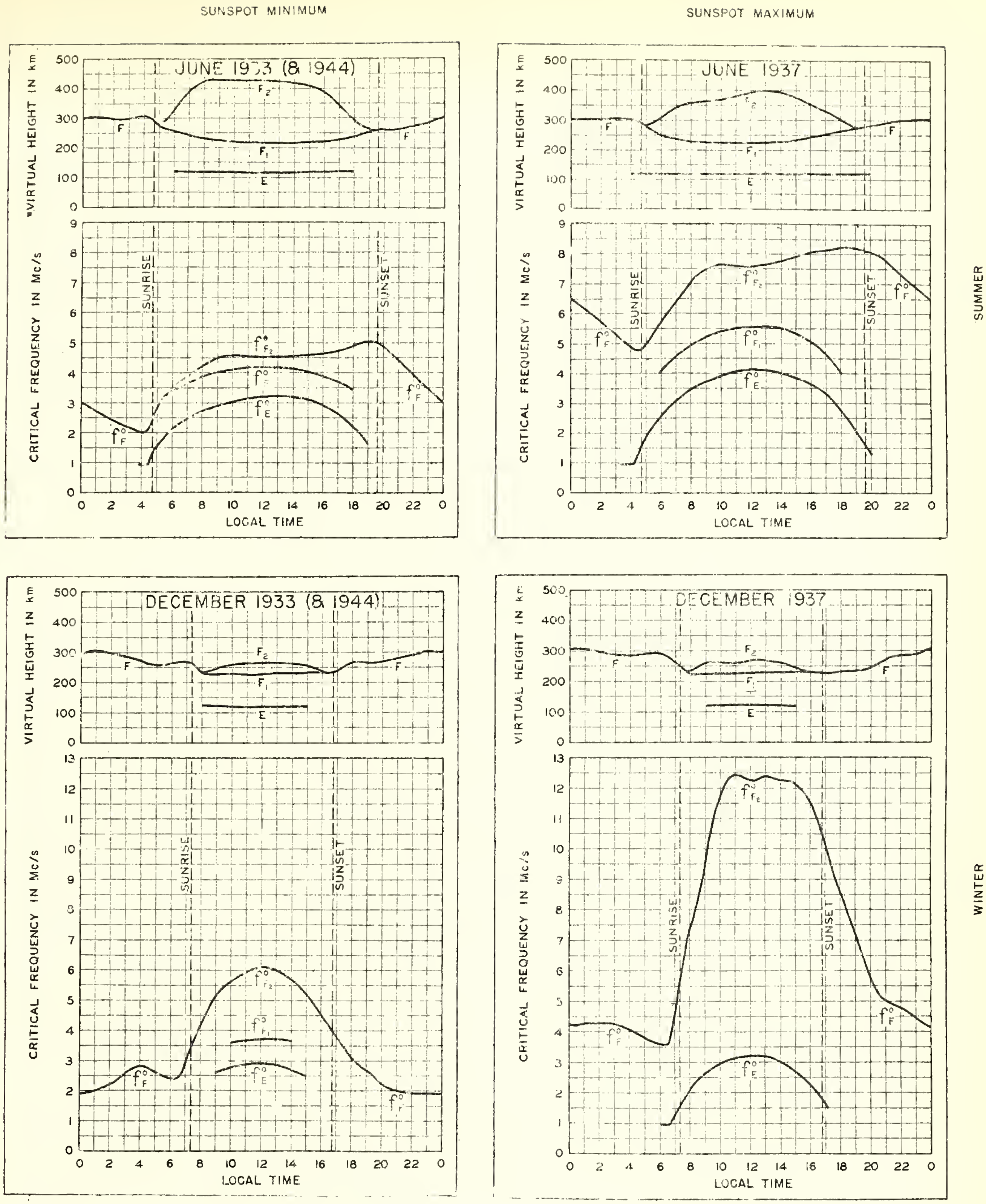
Table 1.

Typical Average Ratios of Maximum Usable Frequency to Critical Frequency (for One-Hop Transmission)

	Distance, km				
	500	1000	1500	2500	3500
Winter					
Midnight F	1.2	1.5	1.8	2.5	2.9
Noon F_2	1.2	1.6	2.1	2.9	3.4
Summer					
Midnight F	1.2	1.4	1.7	2.4	2.8
Noon F_2	1.2	1.5	1.8	2.5	2.9
Noon F_1	1.3	2.0	2.7	3.6	-
Noon E	2.0	3.4	4.4	-	-
Sporadic E*	2.5	4.2	5.1	-	-

*Sporadic E transmission has no critical frequency. The values given are ratios of maximum usable frequency to the approximate upper limit of frequency of the stronger sporadic-E reflections at vertical incidence.

To obtain the maximum usable frequency for transmission over a given distance by way of a given layer, multiply the critical frequency by the ratio given in the table. Where blanks appear in the table, and for distances over 3500 kilometers, the distance is too great for one-hop transmission, i.e., transmission over such distances requires multiple reflec-



SUNSPOT MINIMUM
SUNSPOT MAXIMUM
SUMMER
WINTER
JUNE 1933 (& 1944)
JUNE 1937
DECEMBER 1933 (& 1944)
DECEMBER 1937
VIRTUAL HEIGHT IN km
CRITICAL FREQUENCY IN Mc/s
LOCAL TIME
SUNRISE
SUNSET

FIG. 6

tion from the ionosphere with intervening reflection from the ground. Information is given below on such multihop transmission, for which calculations must be made separately for each hop.

The distance at which a given frequency is the maximum usable frequency is also the minimum distance over which that frequency is receivable by sky wave. This minimum distance for any frequency is called the skip distance; at any less distance it is impossible to receive on that or higher frequencies except for ground wave, or sporadic or scattered reflections - see below.

The Bureau's monthly reports include the maximum usable frequencies for various distances, in addition to the ionosphere data (critical frequencies and virtual heights). Examples of the data on maximum usable frequencies, as published each month in Proceedings of the Institute of Radio Engineers, are given in Fig. 7. Each point on the graphs gives not only the upper limit of frequency usable over the distance, but also conversely gives the skip distance, i.e., the lower limit of distance over which the frequency gives satisfactory sky-wave transmission.

Each graph in Fig. 7 shows, for each hour of the day and night, the average values for the month. The examples in Fig. 7 show summer and winter conditions at minimum and maximum phases of the sunspot cycle (i.e., for the same months and years as Fig.6).

For a given month, the shape of the graphs changes little from year to year, but the absolute values change materially. The general level of absolute values changes gradually, and it is therefore possible to predict specific values of maximum usable frequencies months in advance. This is regularly done by the National Bureau of Standards. In its published monthly report in Proc.I.R.E. the Bureau includes a predicted set of graphs of maximum usable frequencies for the month following the month in which the publication appears. These predictions are well verified by the measurements made subsequently.

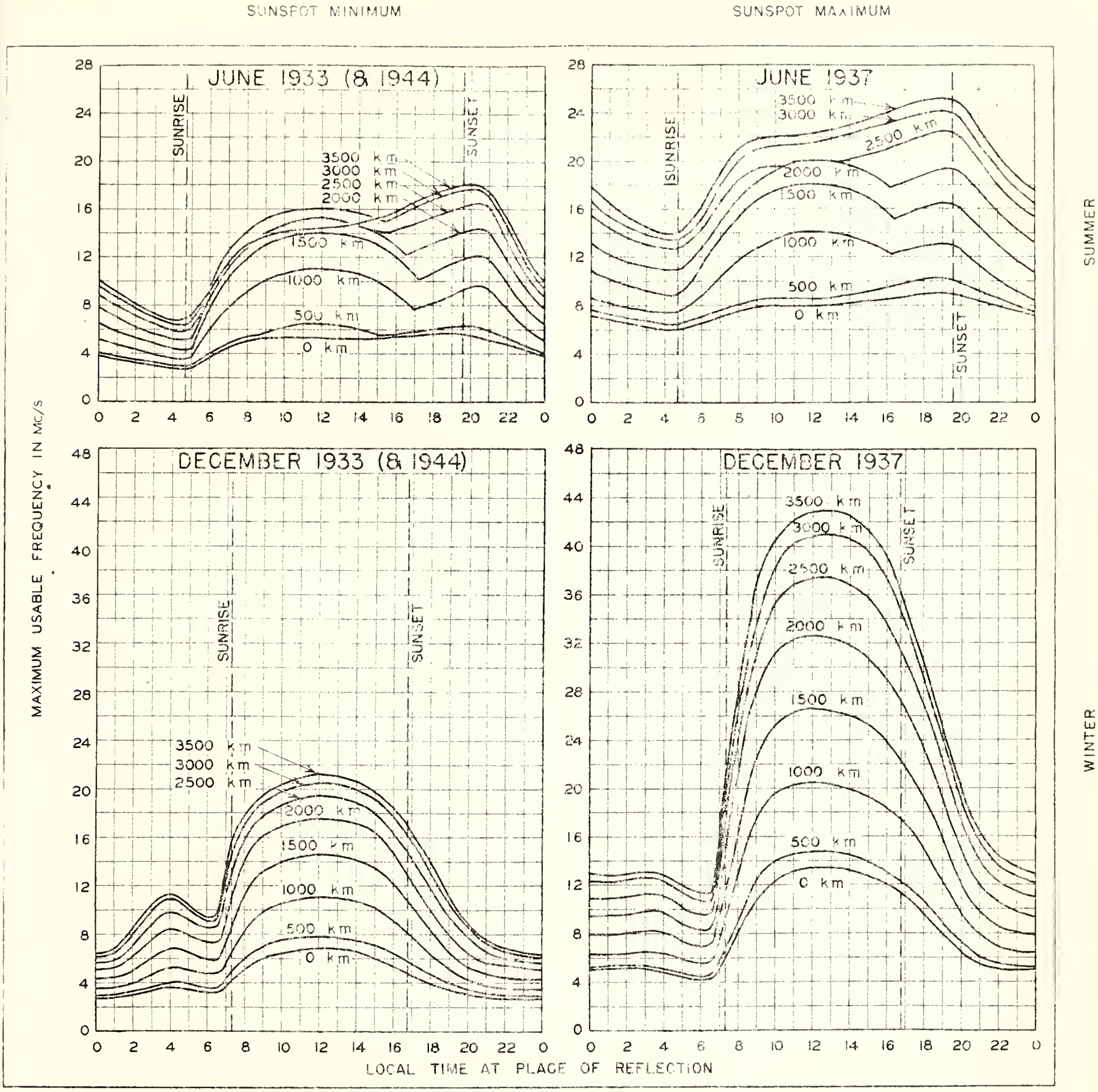
The highest regular maximum usable frequencies in north temperate latitudes occur during the winter day and the lowest during the winter night. The summer values for both night and day lie between these two extremes except as modified by sporadic-E reflections (see below).

Maximum Usable Frequencies over Long Paths.- Since the local time of day, and hence the ionosphere characteristics, may vary a large amount throughout a long transmission path, it is necessary to consider what part of the path determines the conditions of transmission. For single-hop transmission, i.e., for transmission by a single reflection from the ionosphere, it is the region half-way between the transmitter and receiver whose conditions determine the transmission, because it is there that the reflection from the ionosphere takes place. In the case of multi-hop transmission, i.e., when the radio waves are reflected from the ionosphere, then from the ground, then again from the ionosphere, etc., the determining conditions are in the middle of each hop.

The maximum possible distance of transmission by a single hop, i.e., reflection from any one ionosphere layer, is limited by the geometry of the earth's surface and the layer, and also by absorption or other limitation at the ground of those waves which are nearly tangential to the earth's surface. It is found in practice that the minimum angle with the ground of the radio waves transmitted or received (over land) averages about 3 1/2 degrees. From these considerations the geometry indicates that the maximum distance along the earth by a single hop is ordinarily about 3500 kilometers for the F_2 layer, and about 1700 kilometers for the E layer. Single-hop transmission may sometimes be possible at greater distances than these while at the same time multi-hop transmission over the same path may be more efficient.

The curves of maximum usable frequencies are drawn for single-hop transmission; they are nevertheless available also for solving problems of multi-hop transmission. Calculation of the maximum usable frequency for multi-hop transmission is necessarily somewhat complicated. In the first place, it is necessary to consider the time of day of the locality where each reflection from the ionosphere layer takes place. The maximum usable frequency is the lowest one of the several corresponding to the times of day at the localities where reflection takes place, i.e., at the mid-points of the successive hops. To a first approximation these several frequencies are obtained from the curve for that distance which is equal to the total transmission distance divided by the number of hops.

In determining the maximum usable frequencies for a given time and transmission path it is necessary to ascertain the number of hops and the mode of transmission to be expected over the path. Also the antenna design depends on the vertical angle of departure or arrival of waves. These angles depend on the lengths of the hops and the heights of the layers involved. For single-hop transmission these angles depend only on the height of the layer and the transmission distance. Table 2 gives approximately the heights in kilometers which may be used in estimating the number and lengths of the hops for frequencies at, 20% below, or 40% below, the maximum variable frequency (abbreviated muf). The height depends on the frequency; the closer this is to the maximum usable frequency the greater the virtual height.



SUNSPOT MINIMUM
SUNSPOT MAXIMUM
SUMMER
WINTER
JUNE 1933 (& 1944)
JUNE 1937
DECEMBER 1933 (& 1944)
DECEMBER 1937
SUNRISE
SUNSET
3500 km
3000 km
2500 km
2000 km
1500 km
1000 km
500 km
0 km
MAXIMUM USABLE FREQUENCY IN Mc/s
LOCAL TIME AT PLACE OF REFLECTION

FIG. 7

Table 2

Virtual heights to be used in estimating the number and length of hops for transmission via different layers.

Layer	Frequency		
	at muf	20% below muf	40% below muf
E	130 km	115 km	110 km
Night F	420 km	350 km	310 km
Summer day F_2	450 km	380 km	(via lower layer
Summer day F_1	220 km	200 km	(via E layer)
Winter day F_2	350 km	300 km	250 km

Because of the variation of ionosphere characteristics with longitude, different frequencies may be necessary for transmission in different directions from a given place. For example, around sunset in winter lower frequencies are used in transmitting eastward than in transmitting westward from the same location. This does not mean, however, that different frequencies would be necessary or desirable in opposite directions over the same path.

For very long paths in which widely different longitudes (i.e., times of day) are involved, it sometimes happens that the waves travel different parts of the way by different layers. To determine maximum usable frequencies for such cases, it is necessary to take account of the heights of the different layers to determine the lengths of the several hops, and also to employ a separate curve of maximum usable frequency for each layer.

The waves reaching a given point may be a combination of waves having traveled by different numbers of hops. To determine maximum usable frequencies it is necessary for each of these to take account of the time of day, and to consider which layer is effective, for the locality where each reflection from the ionosphere occurs.

Optimum Frequencies.- It is found that in general (especially in the daytime) the absorption is greater, i.e., received intensities are less, the lower the frequency below the maximum usable frequency. Thus much greater power is required to get satisfactory communication on frequencies very much below the maximum usable. On the other hand, it is necessary in practice to use a frequency somewhat below the values indicated in the curves of monthly average, because of the variability from day to day, which is generally within 15% of the monthly average.

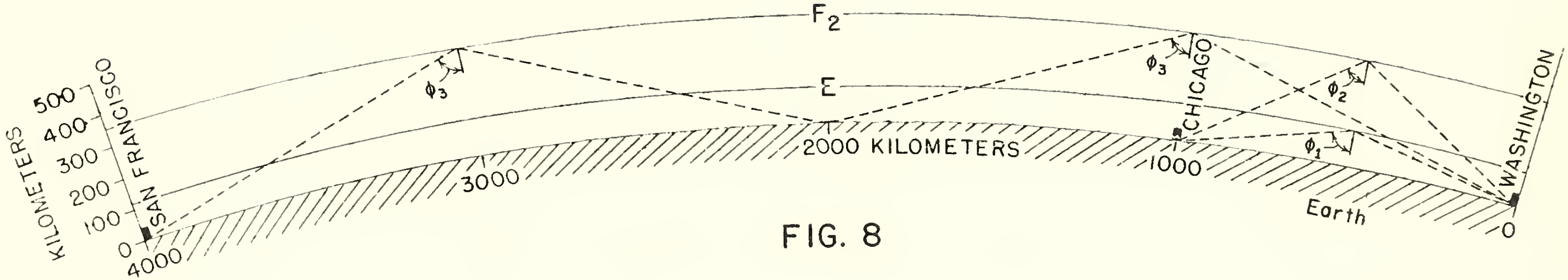
Fair efficiency of communication is usually provided in the daytime by frequencies down to about 50% of the maximum usable frequencies, and at night by frequencies down to somewhat less than 50% of the maximum usable frequencies. Definite limits cannot be set because there are large irregular variations of absorption with time. At frequencies near the maximum usable frequencies there is relatively little difference between night and day absorption. As the frequency is lowered, however, the daytime absorption increases relatively much more rapidly.

It is desirable, therefore, to use frequencies not much below the maximum usable. A satisfactory general rule is to use a frequency between 50% and 85% of the monthly average maximum usable frequency for the given distance and time. It is not ordinarily possible to keep changing frequency continuously, so some such range of choice is necessary. Below 50%, the received waves may be too weak for use, and above 85% communication will be impossible on some days because of skipping due to the variability from day to day.

Calculation of Working Frequencies.- The procedure in calculating frequencies to use over a given transmission distance for one-hop transmission is as follows. From the graph for the given distance, frequencies are selected for certain times of day as outlined just above. Each frequency may be used with reasonable satisfaction for a certain number of hours before it becomes desirable to shift to another. The times for such shifts of frequency are determined from the graph. To these times half the difference between the local times at the transmitter and receiver should be added if the transmission path lies to the west, and subtracted if the path lies to the east, of the place for which the calculations are being made. This is because reflection of the waves takes place halfway between the transmitter and the receiver. The resulting times for the shifts of frequency are in terms of time at the place for which the calculations are made.

For multi-hop transmission the same calculation should be made for each hop, and the results for the several hops combined according to the rule that the maximum usable frequency over the whole path is the least of the maximum usable frequencies over the several hops.

Consider the case of single-hop transmission between Washington, D.C., and Chicago, Ill., a distance of about 1000 kilometers (620 miles). Fig. 8 shows the path taken by the radio waves. The local time at Chicago is about 40 minutes earlier than at Washington. Therefore the local time at the reflection point (midpoint of the transmission path) is 20 minutes earlier than at Washington. From the graphs (Fig. 7) for 1000 km it may be seen that a possible set of transmission frequencies, between 50 and 85% of the maximum usable frequency, are those given in table 3.



KILOMETERS
500
400
300
200
100
0
4000
SAN FRANCISCO
3000
2000 KILOMETERS
1000
0
CHICAGO
WASHINGTON
F_2
E
ϕ_3
ϕ_3
ϕ_2
ϕ_1
Earth

FIG. 8

Table 3

Frequencies for Dependable Transmission over a Distance of 1000 Kilometers

Month and year	Frequency Mc/s	Local time at midpoint of path from	Local time at midpoint of path to	Eastern Standard Time from	Eastern Standard Time to	Layer
June 1933	3.0	2100	0700	2120	0720	one-hop F
	7.0	0700	2100	0720	2120	one-hop F_2 or one-hop E.
Dec. 1933	3.0	1830	0730	1850	0750	one-hop F
	5.0	0730	0930	0750	0950	one-hop F_2
	8.0	0930	1530	0950	1550	one-hop F_2
	5.0	1530	1830	1550	1850	one-hop F
June 1937	6.0	2100	0700	2120	0720	one-hop F
	10.0	0700	2100	0720	2120	one-hop F_2 or one-hop E
Dec. 1937	4.5	1900	0800	1920	0820	one-hop F
	10.0	0800	0930	0820	0950	one-hop F_2
	16.0	0930	1530	0950	1550	one-hop F_2
	10.0	1530	1900	1550	1920	one-hop F

Consider another case: transmission between Washington, D.C., and San Francisco, California, a distance of 4000 kilometers (2500 miles). Such transmission is not ordinarily possible by one hop. It is a case of two-hop or three-hop transmission. Table 4 gives data similar to table 3, calculated for this transmission path. At times (e.g., daytime in summer during the sunspot minimum), the maximum usable frequency over this path is determined by E-layer transmission. At other times it is determined by two-hop F- or F_2-layer transmission or by a combination of E- and F_2-layer transmission. In determining the frequencies of Table 4, calculations are made for each hop separately in terms of local time at the midpoint of the hop and these local times are reduced to Eastern Standard Time. The frequency given in the table for any particular Eastern Standard Time is the lowest of the frequencies selected for each of the hops at the given time. The underlining of certain times indicates which hop determines the maximum usable frequency for the entire path. For further information on the calculation of working frequencies, see RP1167, 5th last reference at end hereof.

Table 4

Frequencies for Dependable Transmission over a Distance of 4000 Kilometers.

Month and year	Freq., Mc/s	Local time at midpoint of path		EST for eastern hop		EST for western hop		EST for entire path		Layer
		from	to	from	to	from	to	from	to	
June 1933	4.5	2100	0700	2145	0745	2315	0915	2145	0915	two-hop F
	10.0	0700	2100	0745	2145	0915	2315	0915	2145	three-hop E or two-hop F_2
Dec. 1933	4.0	1900	0730	1945	0815	2115	0945	1945	0945	two-hop F
	7.0	0730	0930	0815	1015	0945	1145	0945	1145	two-hop F_2
	13.0	0930	1530	1015	1615	1145	1745	1145	1615	two-hop F_2
	7.0	1530	1900	1615	1945	1745	2115	1615	1945	two-hop F
June 1937	9.0	2100	0800	2145	0845	2315	1015	2145	1015	two-hop F
	15.0	0800	2100	0845	2145	1015	2315	1015	2145	two-hop F_2 or three-hop E
Dec. 1937	6.0	1900	0800	1945	0845	2115	1015	1945	1015	two-hop F
	13.0	0800	0930	0845	1015	1015	1145	1015	1145	two-hop F_2
	27.0	0930	1530	1015	1615	1145	1745	1145	1615	two-hop F_2
	13.0	1530	1900	1615	1945	1745	2115	1615	1945	two-hop F

The optimum frequencies were much higher in 1937, the time of sunspot maximum, than in 1933, the time of sunspot minimum. The next sunspot minimum will be about 1944, and it is likely that the optimum frequencies will decrease till then, reaching values somewhere near those of 1933.

Distance Range Graphs.- Average distance ranges for day, night, summer, and winter are given for the current year in the Bureau's Letter Circular, "Distance Ranges of Radio Waves". It is impossible to show in such simplified graphical form all the details and complexities involved in the calculation of working frequencies. Some of the complexities such as the calculations for long paths have been discussed above. Additional details such as hour-to-hour and month-to-month variations are given in the monthly and quarterly reports in Proceedings of the Institute of Radio Engineers and in QST respectively.

EFFECTS OF IONOSPHERE IRREGULARITIES

The primary effects of the ionosphere on radio wave propagation are those already described, which are due to the normal or regular characteristics of the ionosphere. The modes of variation of those characteristics have been shown to be of a regular and fairly predictable nature. There are some other ionosphere phenomena which are irregular in their times of occurrence, and make radio phenomena less predictable in detail. Five types of such phenomena have been identified: sporadic-E-layer reflections, scattered reflections, sudden ionosphere disturbances, prolonged periods of low-layer absorption, and ionosphere storms. While all five are irregular in time, the first two are primarily due to irregularities in space.

Detailed information on sudden ionosphere disturbances and ionosphere storms are included in the Bureau's weekly and monthly report on the ionosphere. The monthly report includes also information on sporadic E.

Sporadic E.- Strong reflections often occur from E-layer heights but at frequencies considerably in excess of the regular upper limit for the E layer. Thus in the example shown in Fig. 4 waves of frequencies up to about 12 Mc/s may sometimes be reflected, at vertical incidence, at E-layer heights, although this would not regularly occur for frequencies above 3.9 Mc/s as shown. Such reflections are called sporadic-E reflections and are probably produced by "partial reflection" at a sharp boundary of stratified ionization. This does not necessarily involve great ionization densities. Thus radio transmission may take place to points within the normal skip zone, by such sporadic reflections. The existence of these sporadic reflections necessitates a redefinition of the term "critical frequency", previously defined as the highest frequency at which waves sent vertically upward are received back from the layer. When sporadic E reflections occur they may often be received simultaneously with reflections from higher layers; thus, in the case referred to above, vertical-incidence reflections might be received at 7 Mc/s from both the E and the F_2 layers. The E-layer critical frequency, more precisely defined, is the value (3.9 Mc/s in the example shown in Fig. 4) at which the observed virtual height shows a sudden rise to large values as the frequency is increased. Except for the occasional occurrence of sporadic E reflections, all waves of higher frequency pass through the E layer and are not reflected by it.

Sporadic E leads to interesting results in long-distance radio transmission. As stated, it can produce transmission within the normal skip zone of the regular layers, and it accounts for long-distance transmission up to higher frequencies than by any other means. Strong vertical-incidence reflections by sporadic E sometimes occur at frequencies up to above 12 Mc/s. By reason of the large angles of incidence possible with the E layer, this makes occasional long-distance communication possible on frequencies as high as 60 Mc/s. Such communication is generally for only a short time and for restricted localities. Sporadic E is thus patchy or sporadic in both geographical distribution and time.

Sporadic E occurs most commonly in the summer, May to August, particularly in the forenoon and early evening but may occur at any time of day or night. It occurs occasionally at all seasons, particularly in the early evening. It occurs more at high latitudes than in equatorial regions.

Scattered Reflections.- An irregular type of reflection from the ionosphere occurs at all seasons and is prevalent both day and night. These reflections occur within the skip zone of the regular layers, or at frequencies higher than those well receivable from the regular layers. They are complex and jumpy thus causing signal distortion and flutter fading, and are almost useless for communication purposes. Except during ionosphere storms they are of low intensity. The scattered reflections are characterized by great virtual heights, usually from about 400 to 1500 kilometers. Their occurrence was for a time thought to indicate the existence of another layer above the F_2 layer which might be called the G layer. It is now however thought that they are of several types, and that some of them are due to complex reflections from small, ephemeral, scattered patches or "clouds" of ionization in or between the normal ionosphere layers.

Sudden Ionosphere Disturbances.- The most startling of all the irregularities of the ionosphere and of radio wave transmission is the sudden type of disturbance manifested by a radio fadeout. This phenomenon is the result of a burst of ionizing radiation from a bright chromospheric eruption on the sun, causing a sudden abnormal increase in the ionization in the D layer (below the E layer), frequently with resultant disturbances in terrestrial magnetism and earth currents as well as radio transmission. The radio effect is the sudden cessation of radio sky-wave transmission on frequencies usually above 1500 kc/s. It has occasionally been observed on somewhat lower frequencies. At the very low frequencies the effect of the sudden ionosphere disturbance is a strengthening of the sky wave.

The drop of the radio signals to zero usually occurs within a minute. The effects occur simultaneously throughout the hemisphere illuminated by the sun, and do not occur at night. The effects last from about ten minutes to an hour or more, the occurrences of greater intensity in general producing effects of longer duration. The effects are more intense, and last longer, the lower the frequency in the high-frequency range (i.e., from about 1500 kc/s up). It is consequently sometimes possible to continue communication during a radio fadeout by raising the working frequency.

The radio and magnetic effects are markedly different from other types of changes in these quantities. The effects are most intense in that region of the earth where the sun's radiation is perpendicular, i.e., greater at noon than at other times of day and greater in equatorial than in higher latitudes.

Taking due account of the variation of the effects with frequency and distance, varying effects in differing directions can be explained. Reception in the United States from stations in the southern hemisphere usually exhibits greater effects than reception from other directions (because of passing the equatorial regions). Similarly, when the disturbance occurs at a time when it is morning at the receiving point the effects are usually greater in reception from the east than from the west, and vice versa for the afternoon (because of passing the region where it is noon). A radio fadeout sometimes occurs when it is night at the receiving point, but only when the path of the waves is somewhere in daylight.

<u>Prolonged Periods of Low-Layer Absorption.</u>- This phenomenon is similar to the sudden ionosphere disturbance in its effects and characteristics except that its beginning as well as recovery is gradual and it has a longer time duration, commonly several hours. The intensity diminution is in general not as severe as in the more intense fadeouts, but sometimes the intensities fall to zero.

The low-layer absorption effect appears to be due to increased ionization in the D layer (below the E layer), exactly as for the sudden ionosphere disturbances. The increased ionization is caused by an abnormally great outpouring of ultraviolet light from the sun, but in this case it is not so sudden as in the eruptions which cause the sudden ionosphere disturbances. The variation of the effects with frequency, and other characteristics, are the same as for the sudden ionosphere disturbances.

Both phenomena occur at all seasons, but the prolonged periods of low-layer absorption have been found to occur irregularly in groups of several weeks duration at periods of high sunspot activity, the groups being separated by more or less quiet periods of several months. They frequently but not always occur during periods when sudden ionosphere disturbances are numerous.

<u>Ionosphere Storms.</u>- An ionosphere storm is a period of disturbance in the ionosphere in which there are great anomalies of critical frequencies, virtual heights, and absorption. High-frequency radio sky-wave transmission above about 1500 kc/s is of low intensity and subject to flutter fading caused by complex reflections from an unstable ionosphere. The flutter fading is especially marked at night and may then be present over high-

latitude paths for even minor storms. At frequencies below about 1500 kc/s the sky wave is considerably weakened at night. At the very low frequencies the daytime sky-wave increases in intensity while at broadcast frequencies it sometimes increases and sometimes decreases in intensity. The high-frequency effects usually last for one or two days while the low-frequency effects persist for several days or sometimes weeks. An ionosphere storm is usually accompanied by a magnetic storm (i.e., a period of unusual fluctuation of terrestrial magnetic intensity). During the first few hours of very severe ionosphere storms the ionosphere is turbulent, stratification is destroyed, and radio wave propagation erratic. During the later stages of very severe storms and during the whole of more moderate storms, the upper part of the ionosphere, principally the F_2 layer, is expanded and diffused. The critical frequencies are much lower than normal and the virtual heights much greater, and therefore the maximum usable frequencies are much lower than normal. It is often necessary to lower the working frequency in order to maintain communication during one of these storms. There is also increased absorption of radio waves during an ionosphere storm. Ionosphere storms are most severe in auroral latitudes and decrease in intensity as the equator is approached. Ionosphere storms occur approximately simultaneously over wide geographical areas. The condition of the ionosphere is much less uniform from point to point than on undisturbed days.

REFERENCES

A great literature is in existence on this subject. Herewith are a few selected references.

Ionosphere Characteristics

Note on a multifrequency automatic recorder of ionosphere heights. T. R. Gilliland. BS J. Research 11, 561 (1933); RP608.

Studies of the ionosphere and their application to radio transmission. S. S. Kirby, L. V. Berkner, and D. M. Stuart. BS J. Research 12, 15 (1934); RP632. Proc. I.R.E. 22, 481 (1934).

Multifrequency ionosphere recording and its significance. T. R. Gilliland. J. Research NBS 14, 283 (1935); RP769. Proc. I.R.E. 23, 1076 (1935). (f_E and f_{F_1} 0700 to 1700 EST, f_F 1900 to 0700 EST, May 1933 to April 1934; at Washington).

Diurnal and seasonal variations in the ionosphere during the years 1933 and 1934. J. P. Schafer and W. M. Goodall. Proc. I.R.E. 23, 670 (1935). (f_{F_2} at 0300, 1200 and 1800 EST, Dec. 1932 to April 1934; f_E and f_{F_1} at noon, March 1933 to April 1934 at Deal, N.J.).

Recent studies of the ionosphere. S. S. Kirby and E. B. Judson. J. Research NBS 14 (1935); RP780.

Some further measurements of upper atmospheric ionization. E. V. Appleton and R. Naismith. Proc. Roy. Soc. 150A, 685 (1935). (f_E, f_{F_1}, and f_{F_2} at noon and times when f_F rose through 3.0, 3.5, 4.0, and 4.5 Mc/s, Dec. 1933 to Nov. 1934; at London).

Measurements of the ionosphere. K. Maeda, M. Konomi, and Y. Isagawa. Report of Radio Research in Japan 5, No.3, p.151 (1935). (f_E for 1934 and 1935).

Characteristics of the upper region of the ionosphere. L. V. Berkner, H. W. Wells, and S. L. Seaton. Terr. Mag. 41, 173 (1936). (h_{F_2} and f_{F_2} 0600 to 1800 local time, Feb. 1935 to Jan. 1936, Watheroo, Australia; h_{F_2} and f_{F_2}, 0600 to 1800 local time, Jan. 1934 to Feb. 1935 and July 1935 to Dec. 1935, Huancayo, Peru).

Ionospheric and magnetic records in Japan. T. Minohara and Y. Ito. Report of Radio Research in Japan 6, No.2, p.L1 (1936). (f_{F_2} for 08 to 20 local time once a week for Oct. 1935 to April 1936).

Comparison of data on the ionosphere, sunspots, and terrestrial magnetism. E. B. Judson. J. Research NBS 17, 323 (1936); RP913. Proc.I.R.E. 25, 38 (1937). (Noon f_{F_2} and h_{F_2}, Sept. 1930 to Dec. 1935, at Washington, compared with sunspots at Zurich).

Averages of critical frequencies and virtual heights of the ionosphere observed by the National Bureau of Standards, Washington, D.C. T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer. Terr. Mag. 41, 379 (1936) and each subsequent issue. (Virtual heights and critical frequencies in tabular form, beginning with May, 1934).

Characteristics of the ionosphere and their application to radio frequmission. T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer. J. Research NBS 18, 645 (1937); RP1001. Proc.I.R.E. 25, 823 (1937). (Same data as in preceding paper but in graphical form).

Characteristics of the ionosphere at Washington, D.C., _____ T. R. Gilliland, S. S. Kirby, N. Smith. Jan. 1937 to date. Published each month in the Proceedings of the Institute of Radio Engineers, starting with the Sept. 1937 issue. (Virtual heights and critical frequencies in graphical form, beginning with January, 1937; data from May, 1934, through 1936 are in the two preceding

papers. Data on ionosphere storms, sudden ionosphere disturbances, and sporadic-E reflections; graphs of maximum usable frequencies; all for the second month before date of issue. Also, predictions of maximum usable frequencies for the month after issue).

Predictions of useful distances for amateur radio communication, ______. Published quarterly by National Bureau of Standards in QST, starting in 1940.

Annual variations in upper atmospheric ionization. K. Maeda, T. Tukada, and T. Kamoshida. Report of Radio Research in Japan 7, No.2, p.109 (1937). (f_F and f_{F_2} for 24 hours once a week for July 1936 to June 1937).

Results of radio echo observations for the years 1935 and 1936 at Tromso. L. Harang. Published by the Norske Institutt for Kosmisk Fysikk (1937). (f_E, f_{F_1}, and f_{F_2}, for 1000, 1200, and 1400 local time, April 1935 to Dec. 1936).

Non-seasonal change of F_2-region ion-density. L. V. Berkner and H. W. Wells. Terr. Mag. 43, 15 (1938). (Noon f_{F_2} at Watheroo compared with values obtained at Washington by National Bureau of Standards, Feb. 1935 to Dec. 1937).

Annual variation of the critical frequencies of the ionized layers at Tromso during 1937. L. Harang. Terr. Mag. 43, 41 (1938).

The ionosphere at Huancayo, Peru. H. W. Wells and H. E. Stanton. Terr. Mag. 43, 169 (1938) and each subsequent issue. (Virtual heights and critical frequencies in tabular and graphical form, beginning with November, 1937).

Ionospheric measurements at Central China College, Wuchang, China, Oct. 1937 to June 1938. P. L. Sung and C. T. Kwei. Terr. Mag. 43, 453 (1938). (Virtual heights and critical frequencies, for Oct. 1937 to June 1938 at 1300, and March and April 1938 at 2000 or 2100; 120° east meridian time).

Trends of characteristics of the ionosphere for half a sunspot cycle. N. Smith, T. R, Gilliland, and S. S. Kirby. J. Research NBS 21, 835 (1938); RP1159. (Summary of E, F, and F_2 critical frequencies from June 1933 to Sept. 1938, at Washington, compared with sunspot numbers).

The ionosphere at Watheroo, Western Australia. W. C. Parkinson and L. S. Prior. Terr. Mag. 44, 199 (1939) and each subsequent issue. (Virtual heights and critical frequencies in tabular and graphical form, beginning with May, 1938).

Critical ionospheric frequencies observed in Rome from Dec. 1938 to Sept. 1939. I. Ranzi. La Ricerca Scient., 10, 926 Oct. 1939.

Heights of reflection of radio waves (6 Mc/s, F_2 region) in Rome from Jan. to Sept. 1939. A. Bolle. La Ricerca Scient., 10, 930, Oct., 1939.

Applications to Radio Transmission

Extension of normal-incidence ionosphere measurements to oblique-incidence radio transmission. N. Smith. J. Research NBS 19, 89 (1937); RP1013. (Method of deriving maximum usable frequencies from vertical-incidence measurements).

Characteristics of the ionosphere at Washington, D.C. T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer. Published each month in Proc.I.R.E. . (Graphs of monthly average maximum usable frequencies for the second month before began in the December 1937 number; predictions for the month after issue began in the March 1939 number).

Sudden disturbances of the ionosphere. J. H. Dellinger. J. Research NBS 19, 111 (1937); RP1016. Proc.I.R.E. 25, 1253 (1937).

Maximum usable frequencies for radio sky-wave transmission 1933-1937. T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer. J. Research NBS 20, 627 (1938); RP1096. Proc.I.R.E. 26, 1347 (1938). (Graphs of maximum usable frequencies against distance for various times of day for winter, summer and equinoctial periods).

Application of vertical-incidence ionosphere measurements to oblique-incidence radio transmission. N. Smith. J. Research NBS 20, 683 (1938); RP1100. (Method of deriving maximum usable frequencies taking account of the curvature of the earth and the ionosphere layers).

The relation between ionospheric transmission phenomena at oblique incidence and those at vertical incidence. G. Millington. Proc. Phys. Soc. (London), 50, 801 (1938). (Method of deriving maximum usable frequencies taking account of the curvature of the ionosphere and the earth).

Trends of characteristics of the ionosphere for half a sunspot cycle. N. Smith, T. R. Gilliland, and S. S. Kirby. J. Research NBS 21, 835 (1938); RP1159. (Indicates diurnal seasonal and year-to-year variations of ionosphere characteristics at Washington).

Application of graphs of maximum usable frequency to communication problems. N. Smith, S. S. Kirby, and T. R. Gilliland. J. Research NBS 22, 81 (1939); RP1167.

The relation of radio sky-wave transmission to ionosphere measurements. N. Smith. Proc.I.R.E. 27, 332 (1939).

The estimation of wireless transmission data from ionospheric observations. F. W. G. White. New Zealand Jour. of Science and Tech. 21, 113 (1939).

The role of the ionosphere in radio wave propagation. J. H. Dellinger. AIEE Trans. 58, 803 (1939).

Analysis of the effect of scattering in radio transmission. T. L. Eckersley. J. Inst. E.E. (London) 86, 548 (June 1940).

o