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DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

Letter
Circular
LC499.

May 15, 1937.

THE WEEKLY RADIO BROADCASTS OF THE NATIONAL BUREAU OF STANDARDS ON THE IONOSPHERE AND RADIO TRANSMISSION CONDITIONS.

Every Wednesday the National Bureau of Standards broadcasts information on high-frequency radio transmission conditions, based on its continuous measurements of the ionosphere at Washington, D.C. The broadcasts are by radio telephony from the Bureau's station, WWV, at Beltsville, Md., near Washington, D.C. They are given each Wednesday at 1:30 P.M. (EST) on a frequency of 10 000 kc/s, at 1:40 P.M. on 5 000 kc/s, and at 1:50 P.M. on 20 000 kc/s. These broadcasts are made with a radiated power of approximately 20 kilowatts with 30% modulation.

The object of these broadcasts is to make current ionosphere information available to interested parties on the day of observation. This information should aid communication services in choosing optimum frequencies for long-distance communication, and in interpreting results. It supplements published information giving long-time trends and averages.

The broadcasts include statements of critical frequencies for normal incidence and virtual heights of the layers of the ionosphere, followed by estimated skip distances for a number of frequencies, all based on observations made at Washington on the day of the broadcast. The data are given for noon and midnight, and estimated variations from these values for other hours are also given. Any unusual conditions during the preceding week, such as those accompanying magnetic storms, are described briefly. A sample broadcast is attached as Appendix A.

This service may be extended later, if the demand warrants, to a more frequent dissemination of ionosphere data and the inclusion of data from other parts of the world.

DESCRIPTION OF THE IONOSPHERE

The term "ionosphere" is the name for the upper part of the earth's atmosphere where there are strata ionized sufficiently to reflect or refract radio waves back to the earth's surface. High-frequency radio communication over all but very short distances (a few kilometers) takes place by means of these reflected or sky waves. Skip distance and fading, as well as the received intensity and maximum distance range, are all dependent directly upon the state of the ionosphere.

There are two principal layers in the ionosphere - the E and the F layers. During the summer day the F layer is separated into two regions, the lower called the F_1 and the upper the F_2 layer. When the F layer is not clearly split, as at night and during the winter day, no distinction is made in the nomenclature between F and F_2. Typical virtual heights are shown in figures 1 to 5, attached. The symbols h_E, h_{F_2}, etc., represent the virtual heights of the E, F_2, etc. layers respectively.

If we plot virtual height against frequency of the waves for a series of observations made as rapidly as possible, we obtain what is called a critical frequency sweep. The critical frequency is indicated by a sharp increase in the virtual height of a given layer, followed by a cessation of reflections from this layer, due to penetration of the layer as the frequency is increased. Typical sweeps are plotted in Figures 1, 2 and 3 for a winter day, a summer day and a summer or winter night, respectively.

As a result of the presence of the earth's magnetic field the F_1 and F_2 layers each have two critical frequencies. At Washington these differ by about 800 kc/s. The difference in frequency is proportional to the intensity of the earth's magnetic field, and therefore varies over the surface of the earth. The ray corresponding to the lower critical frequency is called the ordinary ray and that corresponding to the upper critical frequency the extraordinary ray. The extraordinary ray for the E layer is so highly absorbed that it usually is not observed in the daytime. The critical frequency for the ordinary ray in a given layer is a measure of the maximum ionization density of that layer. The symbols f^o_E, $f^o_{F_1}$, $f^x_{F_1}$, represent the critical frequencies of the E layer (ordinary ray), the F_1 layer (ordinary ray), the F_1 layer (extraordinary ray) etc., respectively.

The diurnal and seasonal variations of the critical frequencies of the normal E layer are 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 in midsummer. At night this layer usually does not reflect waves of frequencies higher than the broadcast band.

Another kind of E reflection is often found at frequencies considerably in excess of the maximum daytime f_E. Reflections of this kind are especially prevalent during the summer, both day and night. They are called sporadic E reflections and are frequently very intense. They are somewhat erratic, however, and their occurrence cannot be predicted as well as can the behavior of the normal E and F layers. During the summer these sporadic E reflections frequently control high-frequency transmission.

The diurnal and seasonal variations of the critical frequencies of the F_2 layer at Washington are quite different from those of the E layer. The winter daytime F_2 critical frequencies exceed any values found during the summer. In the winter a broad diurnal maximum occurs in the daytime centered at about 1:00 P.M. local time. In the summer a broad diurnal maximum centers about sunset. The night minima are roughly the same in summer as in winter and occur about one hour before sunrise. During most of the night, however, the winter critical frequencies are lower than the corresponding summer values.

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.

Winter conditions in the F_2 layer obtain during a period of several months centered on December, and summer conditions for a period of several months centered on June or July. During the spring and fall, and especially around April and September, there is a transition period of one or two months, in which the change occurs between winter and summer conditions. The transition periods are marked by erratic behavior of the F_2-region, a period of typical winter days being interspersed with typical summer days.

The F_1 layer is unimportant for transmission over long distances and is usually found only on a summer day.

The evidence indicates that for the same local time and the same latitude, average ionosphere conditions at different stations are the same. On individual undisturbed days any differences which do exist are believed to be small, except for sporadic E. The evidence indicates that the sporadic E is spotted both in time and geographical distribution.

The condition of the ionosphere varies with latitude. For latitudes approximately those of the United States the differences from the Washington values appear to be small. Results considerably different from the Washington observations, however, have been reported from the southern hemisphere. This subject has not yet been fully investigated.

Besides the virtual heights and critical frequencies, absorption in the ionosphere is an important factor limiting transmission. Absorption is especially great in the daytime and occurs chiefly in the lower ionosphere below or in the E layer. Most of the absorption disappears at night. The higher frequencies are less affected by absorption than are the lower frequencies.

A knowledge of the more or less regular diurnal and seasonal variations of the ionosphere will aid greatly in interpreting the data broadcast. Data for the year May 1933 to April 1934 have been published in graphical form[1] by the National Bureau of Standards. More complete data for the period May 1934 to December 1936 have also been published but in tabular form.[2] Additional data will be published regularly, several times per year. These data are all taken near Washington, D.C. Some data for stations in the southern hemisphere have been published in tabular form by the Carnegie Institution of Washington.[3]

APPLICATION TO RADIO TRANSMISSION

Radio waves incident obliquely upon the layers of the ionosphere are more easily reflected than those incident normally, that is, they can be reflected from regions of smaller ionization density. In general, the larger the angle of incidence, the less the ionization density required for reflection. Thus if a given layer will reflect rays up to a certain frequency at normal incidence, the same layer will reflect the oblique rays up to very much higher frequencies.

The angle of incidence (angles i_1, i_2, etc., figures 4 and 5) of a radio wave upon the layer depends on (1) the distance of transmission for one hop, and (2) the virtual height of the layer. Given these two quantities, therefore, the angle of incidence i may be calculated, and the maximum frequency f which can be used may be calculated approximately from the normal-incidence critical frequency f_c by the relation known as the "secant law":-

$$f = f_c \sec i = \frac{f_c}{\cos i}$$

The given distance will be within the "skip zone" for all frequencies higher than this. (In appendix B, attached, is given a chart for calculating the factor sec i).

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[1] Multifrequency ionosphere recording and its significance. T. R. Gilliland. J. Research NBS 14, 283 (1935). Proc.I.R.E. 23, 1076 (1935).

[2] Averages of critical frequencies and virtual heights of the ionosphere, observed by the National Bureau of Standards, Washington, D.C., 1934-1936. T. R. Gilliland, S. S. Kirby, N. Smith, and S. E. Reymer. Terr. Mag. 41, 379 (1936).

[3] Characteristics of the upper region of the ionosphere. L. V. Berkner, H. W. Wells, and S. L. Seaton. Terr. Mag. 41, 173, 1936.

The secant law is subject to a correction because of the presence of the earth's magnetic field. It is sufficiently accurate without modification, for the ordinary ray, provided that not too much of the wave path parallels the direction of the earth's magnetic field. For high frequencies the critical frequency for the extraordinary ray is always higher than for the ordinary ray, the skip distance is thus smaller, and the maximum usable frequency higher for the extraordinary component. Except for short distances, the difference is not great, and becomes smaller the greater the distance of transmission. The percentage difference is smaller, the higher the frequency, so that for practical communication problems the critical frequency for the ordinary ray may be used and the secant law applied, at least at considerable distances.

Figures 4 and 5 are simplified diagrams indicating the manner in which radio waves are propagated by the ionosphere. Rays at different angles with the earth are shown emanating from the transmitting station at T. These rays are all emitted simultaneously.

In Figure 4 conditions are shown for a typical winter day condition in the latitude of Washington. The transmitting frequency is supposed to be high enough to penetrate the E layer at any possible angle of incidence, but low enough to be reflected by the F_2 layer at angles of incidence equal to or greater than i_2. Lower frequencies would be reflected from the E layer over long distances. E-layer transmission for distances of a few hundred kilometers, however, could occur only if the transmitting frequency were considerably decreased, say to less than half the values reflected by the E layer over long distances.

Figure 5 is a diagram for summer-day conditions. The F_2-layer critical frequency is much lower and the virtual height much greater than during the winter day. At the same time the E-layer critical frequency is higher than during the winter day. Because the virtual height of the E layer is much less than that of the F_2 layer, the angle of incidence at the E layer for a given distance is greater than the angle of incidence at the F_2 layer. Therefore, although the F_2-layer critical frequency is still considerably higher than the E-layer critical frequency, it is usually not enough higher to control summer daytime transmission over long distances, and the E layer then controls transmission.

In Figure 5 the ray r_1 is projected at such an angle that if it were reflected by the F_2 layer it would be returned to earth at the same point as would the ray r_3 reflected from the E layer. It may be seen from figure 5 that the angle of incidence i_3 is considerably greater than i_1. Therefore the ray r_3 would be reflected by a layer of much lower ionization density than would the ray r_1. The ray r_1 is shown penetrating through both the E and F_2 layers because the ionization densities are assumed to be insufficient to reflect it. The dashed line shows the path the ray would take if reflected from the F_2 layer.

Usually in the latitude of the United States and Europe higher frequencies may be transmitted by way of the ionosphere during a winter day than during a summer day. At night the reverse is more likely to be true.

The geographical part of the ionosphere which controls long-distance high-frequency propagation is that part at which the wave in the useful direction strikes the reflecting layer. This point on the transmission path may be as much as 1000 to 2000 kilometers from the transmitter and also from the receiver. Consequently, depending on the time of day different frequencies might be necessary for transmission in different directions. For example, around sunset in winter, lower frequencies would have to be used in transmitting eastward than might be used 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.

Because of large differences in local time and latitude encountered in long transmission paths, involving more than one reflection, widely different conditions sometimes prevail over different parts of these paths. In such cases the transmission frequency will have to be lowered to satisfy conditions in the part of the path in which the critical frequency is lowest. Under such conditions absorption is likely to occur in the part of the path with the high critical frequencies.

For frequencies near the critical frequency the virtual height is considerably greater than the minimum values given. This increased virtual height results in a maximum useful frequency lower than would be expected from a consideration of the virtual heights given, since at the maximum useful frequency reflection takes place at a height corresponding to a point well up on the bend of the critical frequency curve. Consideration of the virtual height-frequency curves gives the following approximate values for the factor by which the normal-incidence critical frequency must be multiplied to give the maximum useful frequency for great distances.

Sporadic E layer -	5.0
Normal E layer -	4.5
F_2 layer (winter day and summer sunset)- - - - - -	2.5 to 3.0
F layer (summer and winter night)- - - - - - - - - -	2.2 to 2.7
F_2 layer (summer day)- - - - - - - - - - - - - - - - -	2.0 to 2.5

The maximum possible distance for one-hop transmission, corresponding to zero angle of elevation of the ray above the horizon, is about 2400 kilometers for the E layer and about 3500 to 4400 kilometers for F_2 layer, depending on the virtual height of the layer. Practically, it is usually impossible to accomplish high-frequency transmission at this zero angle because of absorption at the earth's surface. If a practical limit of 3 1/2 degrees is assumed for the angle of elevation, the maximum distance for one hop is about 1700 kilometers for the E layer and 2800 to 3600 kilometers for the F_2 layer. Single-hop transmission may often be possible at these or greater distances, while at the same time multi-hop transmission over the same path may be more efficient.

APPENDIX A. SAMPLE BROADCAST

This is station WWV of the National Bureau of Standards. We have just completed a standard-frequency emission on________ kilocycles, which will be repeated on__________and___________ kilocycles. We now give a summary of radio transmission conditions.

Based on observations at noon today, March 3, 1937, the normal-incidence critical frequencies and virtual heights of the ionosphere layers at Washington, D.C., latitude 39° North, were as follows: For the E-layer, critical frequency 3940 kilocycles, height 120 kilometers. For the F_2-layer, critical frequency 13,700 kilocycles, height 240 kilometers.

The frequencies corresponding to several skip distances are approximately as follows:

300	kilometers	for	a	frequency	of	14 400	kilocycles.
800	"	"	"	"	"	18 000	"
1500	"	"	"	"	"	25 800	"
2500	"	"	"	"	"	33 900	"

The frequencies corresponding to the skip distances lie approximately between the values given and 10 percent less, from about 10 A.M. to 6 P.M., local time.

At midnight last night the normal-incidence critical frequency of the F layer was 7600 kilocycles and the minimum virtual height 270 kilometers. The night skip distances for several frequencies are approximately as follows:

300	kilometers	for	a	frequency	of	7800	kilocycles
800	"	"	"	"	"	9500	"
1500	"	"	"	"	"	13 600	"
2500	"	"	"	"	"	17 900	"

The frequencies corresponding to these skip distances hold from about 9 P.M. to 7 A.M. within about plus 15% and minus 25%.

During recent weeks the day-to-day variations of ionosphere conditions have been small except during occasional magnetically disturbed days. No sudden ionosphere disturbances were observed during the past week.

This announcement will be given again at________P.M. Eastern Standard Time, on_________kilocycles.

APPENDIX B. DETERMINATION OF RATIO OF MAXIMUM USABLE FREQUENCY TO NORMAL-INCIDENCE CRITICAL FREQUENCY.

The chart shown in Fig. 6 provides a simple means of determining the secant of the angle of incidence for any distance up to 5000 km and any height of layer up to 500 km. To use the chart, place a straight-edge so that it passes through the desired virtual height and the desired distance laid off on the distance scale at the lower left-hand edge of the chart (increasing distances lie to the left). The ordinate of the intersection of the straight-edge with the vertical line corresponding to the same desired distance on the main distance scale (increasing distances to the right) will give the value of the secant of the angle of incidence. If they do not intersect within the limits of the chart, this indicates an impossible case, where the ray would have to "take off" below the horizon.

For example, a distance of 2400 km and a virtual height of 300 km will correspond to a secant of 3.07. A wave of 4900 kc/s incident normally upon the layer will behave in many respects approximately like a wave of frequency 3.07 times 4900 kc/s or about 15 000 kc/s over the path. In other words, the absorption and depth of penetration measured at normal incidence for 4900 kc/s are approximately the same as would be observed for 15 000 kc/s over the 2400-km path.

Department of Commerce,
Washington, D.C.

FIG. 1

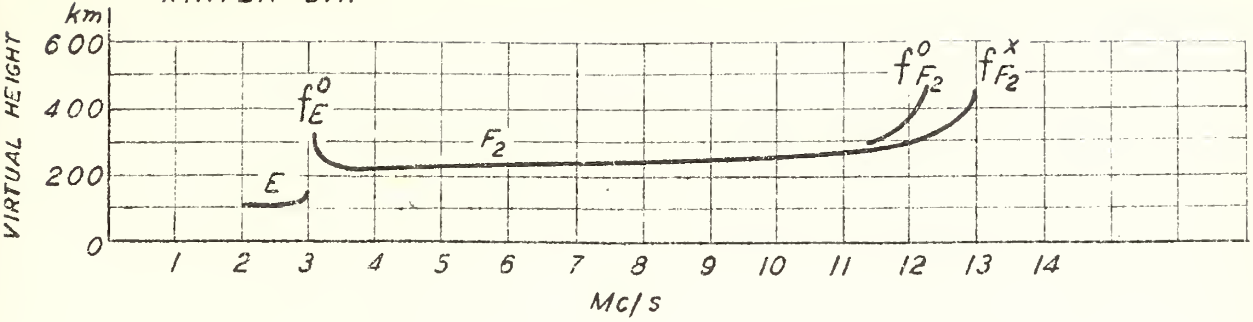

WINTER DAY

FIG. 2

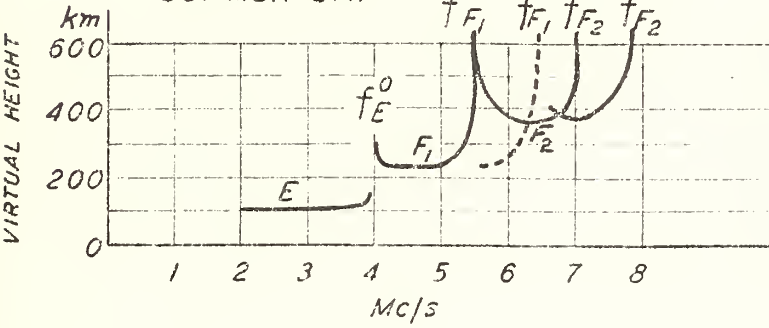

SUMMER DAY

FIG. 3

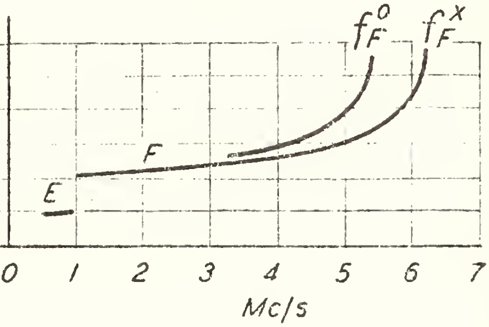

SUMMER OR WINTER NIGHT

FIG. 4

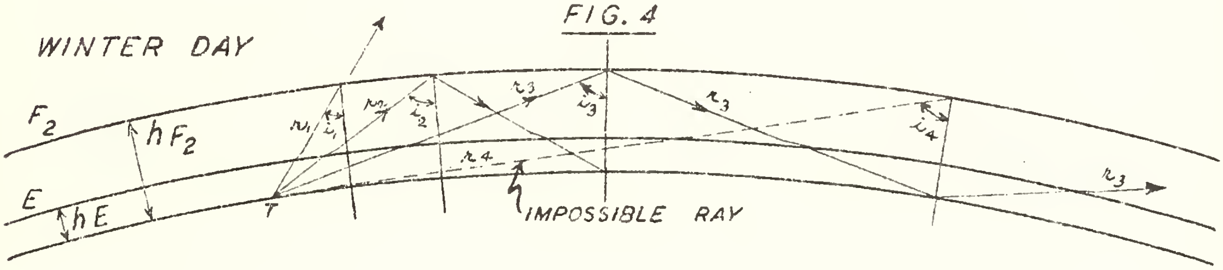
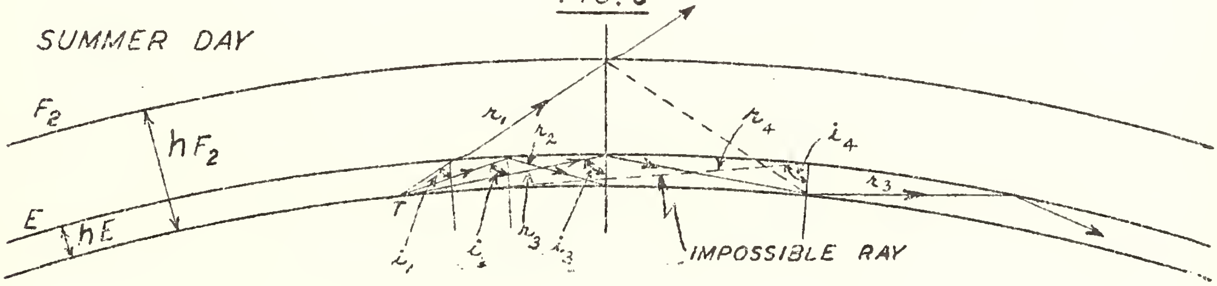
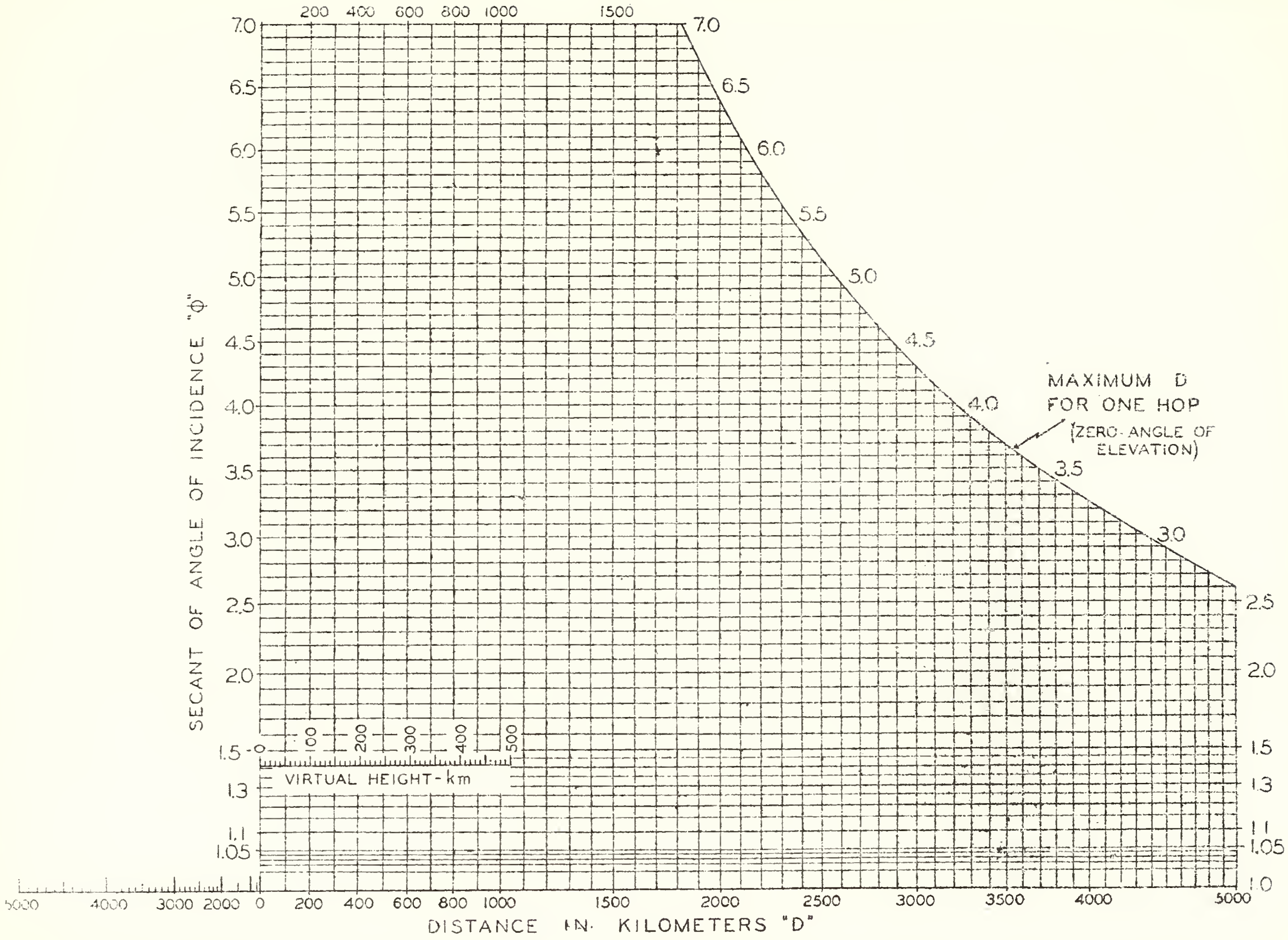

WINTER DAY

FIG. 5


SUMMER DAY


SECANT OF ANGLE OF INCIDENCE "φ"
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.3
1.1
1.05
1.0
200 400 600 800 1000 1500
MAXIMUM D FOR ONE HOP
(ZERO ANGLE OF ELEVATION)
VIRTUAL HEIGHT - km
0 100 200 300 400 500
5000 4000 3000 2000 0 200 400 600 800 1000 1500 2000 2500 3000 3500 4000 5000
DISTANCE IN KILOMETERS "D"