

HF Communication During Ionospheric Storms

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A hypothetical communication network is set up to study systematically the problem of HF communications during disturbed ionospheric conditions. Vertical incidence radio data is used as the basis for determining the condition of the ionosphere. Frequencies and links available have been computed for a period of severe ionospheric disturbance. Important spatial and temporal variations are clearly evident by this analysis. A comparison of the results with recorded WWV reception indicates that ionospheric vertical incidence data can be used to determine propagation conditions during disturbed periods.

1. Introduction

At present, HF radio communication between middle and high latitude transmitting and receiving stations is rendered ineffective during ionospheric storms. In most instances there is little or no attempt to avoid absorbing regions or to utilize anomalous reflecting regions in any systematic or knowledgeable way. It is tacitly assumed that all communication links are simultaneously affected in a more or less like manner. However, analysis of ionospheric data for several storms has shown that the spatial locations of the absorbing and reflecting layers vary in a coherent but complex pattern throughout the lifetime of a storm.

The problem, then, is to determine practical ways by which the communication difficulties associated with ionospheric storms can be overcome, or in other words, to determine what is the optimum way in which the disturbed ionosphere should be used for a given system of transmitters and receivers. Also, it may be necessary to make alterations of an existing system so that the optimum operating procedure will lead to the reliability desired. That is, for example, the optimum operating procedure of a network of four stations is likely to give a significantly higher overall reliability than there would be with only three stations. Thus, the problem should be studied in such a way that improvements to a given system may be found.

To study this problem systematically, an idealized network of transmitters and receivers is introduced. It will be possible to find, or approximate, the optimum operating procedure for an ideal network. Then, when the optimum operating procedure is found for an existing system, its "effectiveness" in terms of the ideal system will be known. Recommendations for modification will be greatly facilitated by this method of study.

2. Computations

Before proceeding to an example, it will be helpful to show how the available frequencies and links are

established. First, consider four points along a line separated by 1200 km. A transmitter operates at one end and there are receivers at each of the remaining positions. At the receiver nearest to the transmitter we consider the arrival of a one-hop E or E_s signal, at the next, a one-hop F_1 or F_2 signal, and at the farthest, an M-hop signal. Multiple hops or combinations of different modes will be considered later.

In figure 1 the E , F , and M modes are shown along with the required ionospheric parameters. In the case of an E hop to be received at the first receiver, measurements of both the E or E_s critical frequency and absorption, using f_{min} , are taken midway between the transmitter and receiver, i.e., midway between two neighboring points in the ideal network. In the case of an F -layer hop, the f_0F_2 is measured at the middle point where reflection occurs, and absorption is measured midway between the transmitter and the middle point for the upgoing wave and midway between the middle point and the receiver for the downcoming wave.

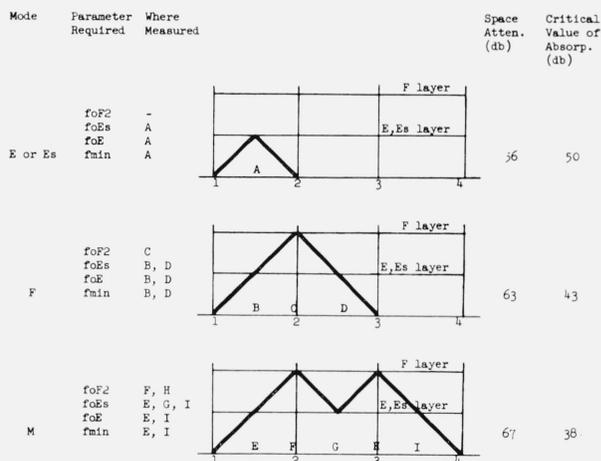


FIGURE 1. Schematic diagrams of modes and ionospheric parameters required to determine the frequency range applicable. The space attenuation and critical values of absorption refer to an example given in the text.

To determine what reception is available, we will assume the signals are being transmitted at a power of 10 kw. This corresponds to about 115 db above $1\mu\text{v/m}$ at 1 km from the transmitter, [Rawer, 1956]. If man-made noise is neglected and atmospheric noise is assumed to be at a level of 0 db, then 115 db are available for the various losses encountered between the transmitter and receiver. However, the signal-to-noise ratio at the receiver must be above a certain value for adequate reception. It is assumed that this ratio is 10, so instead of 115 db, the available amount is reduced to 105 db. About 60 db will be lost in space attenuation. The exact amount will, of course, depend upon the particular mode. In determining whether or not the remaining 45 db is lost, the most important factor is absorption.¹ For purposes of this study it is supposed that if absorption of a signal remains less than a critical value of around 45 db it will be detectable at the receiver. The actual critical values of absorption and amount of space attenuation for each mode are shown in figure 1.

To understand how absorption is calculated by the use of f_{min} , we first consider the expression for nondeviative absorption. The signal loss, expressed in decibels, is given by

$$L = 8.7p \sec \phi \int k ds \quad (1)$$

where p =number of penetrations through the D region and $\sec \phi$ =incidence angle of radio wave to ionosphere with

$$k = \frac{2\pi e^2}{mc\mu} \left(\frac{N\nu}{\nu^2 + 4\pi^2(f \pm f_L \cos \theta)^2} \right) \quad (2)$$

where

- e =charge of an electron,
- N =electron-number density,
- ν =electron-collision frequency,
- m =mass of an electron,
- c =velocity of light,
- μ =refractive index,
- f_L =gyrofrequency,
- θ =angle between direction of propagation and magnetic field, and
- f =wave frequency.²

For vertical incidence soundings, $p=2$, $\sec \phi=1$, and f is set equal to f_{min} . L at this frequency is found from the fact that at f_{min} the received signal strength is just sufficient for detection by an

¹ Losses are assumed not to take place during ionospheric reflection except in the case when sporadic E is involved. Ground losses only occur when multiple hops or combinations are considered. Focusing and defocusing resulting from irregularities or waves in the ionosphere have been neglected.

² The positive and negative signs in the denominator of (2) correspond to the ordinary and extraordinary waves, respectively. The electron collision frequency in the lower D region (from 60 to 70 km) is of the same order of magnitude as $2\pi f$ if $f \leq 5$ Mc/s, so that ν^2 in the denominator of (2) must not be neglected in determining the integral of $k ds$. For nondeviative absorption, the refractive index, μ , is approximately equal to unity. For the computations, the value of $f_L \cos \theta = 0.3$ Mc/s was used.

ionosonde, or, in other words, the absorption is at the critical value for the ionosonde. For a C-4 this value (L) is about 50 db.

So eq (1) becomes

$$50 = 0.92 \int \frac{N\nu}{\nu^2 + 4\pi^2(f_{\text{min}} + 0.3 \times 10^6)^2} ds \quad (3)$$

where

$$\begin{aligned} f_L \cos \theta &= 1.5 \text{ Mc/s,} \\ f &= f_{\text{min}}, \\ L &= 50 \text{ db.} \\ p &= 2, \\ \mu &= 1, \\ \sec \phi &= 1, \\ 2\pi e^2/mc &= 5.3 \times 10^{-2} \text{ (cgs).} \end{aligned}$$

In this equation the electron-density, N , is still unspecified even though f_{min} is specified and the electron-collision frequency, ν , is approximately a fixed function of height. Of course, N must be such that eq (3) is satisfied. This may be accomplished for each value of f_{min} by a whole family of electron-density height distributions. However, particular electron-density height distributions, listed in table 1, have been given by several workers for various ionospheric conditions [Bailey, 1959; Nicolet and Aikin, 1960; and Kane, 1960]. Although there are many other distributions leading to the same f_{min} , the set used here is considered to be representative of real conditions.

Returning to eq (1), the amount of absorption as a function of frequency is computed for each of these electron-density distributions, and from eq (3) the corresponding value of f_{min} is found. The results are shown in figure 2. Similar curves have been derived for a signal passing through the D region obliquely and only once, i.e., $p=1$ and $\sec \theta=5$. By interpolation of these curves the amount of absorption as a function of frequency for values of f_{min} in steps of one Mc/s has been found. These results are shown in figure 3.

TABLE 1. Particular electron-density height distributions for various ionospheric conditions

Height	Distribution (el/cm ³)				
	A	B	C	D	E
km					
90	1.5×10^3	1.5×10^3	1.5×10^4	1.5×10^4	7×10^4
80	10^3	2×10^3	5×10^3	2×10^4	6×10^4
70	2×10^2	1×10^3	6×10^2	6×10^3	1.5×10^4
60	0	20	3×10^2	1×10^3	2×10^3

Source: A and C, Nicolet and Aikin; B, D, and E, Bailey.

With the aid of figure 3 it is possible to determine the amount of absorption at any frequency by simply finding the value of f_{min} at the places of signal passage through the D region. For example, consider a 10 Mc/s signal propagated by the F mode with $\sec \phi=5$ at the D region penetration points, B and D , as shown in figure 1. If f_{min} is 1.5 Mc/s at B and 3.0 Mc/s at D , then from figure 3 it is seen that the

3. Network and Application

The idealized network used in this study is formed by an array of equilateral triangles with a transmitter and a receiver located at the vertices. At an interior point of the network there are six directions from which signals may arrive or depart. Each point is a distance of 1200 km from the neighboring ones, so that a one-hop signal covers 1200 km via an *E* mode, 2400 km via an *F* mode, and 3600 km via an *M* mode.

To determine the frequency range and modes available over the network, values of ionospheric parameters are taken from the appropriate points as indicated in figure 1. Then, at a given frequency, the modes possible are found from the critical frequency of the various layers and the signal's angle of incidence. Whether the resulting modes can actually be realized depends upon whether absorption is below the critical value.³

Sample tests have been made for the period of September 11-15, 1957, during which time a severe ionospheric storm took place. First, maps of the ionospheric parameters at intervals of three hours were drawn. Then, with the aid of these, communication maps were prepared for transmission frequencies of 5, 10, 15, 20, and 25 Mc/s. For purposes of illustration only, selected communication charts are shown. These are for 10 and 20 Mc/s. With these charts it is still possible to show the main effects of the ionospheric disturbance on communication. The various modes or lack of modes are indicated on these charts according to the diagram in figure 4.

In figure 5 the communication and ionospheric charts for 1200 UT September 12 are shown. At this time the sun is illuminating the portion of the ionosphere east of the curve (on the communication charts) running through North America. Elsewhere the ionosphere is in darkness. In general, conditions in the ionosphere at this time are about normal except for polar cap absorption. The ionospheric charts are shown so that the reader may visualize the condition of the ionosphere. The curves on these charts connect points of equal f_oE_s values in units of Mc/s. Notice that on the f_oE_s charts there are

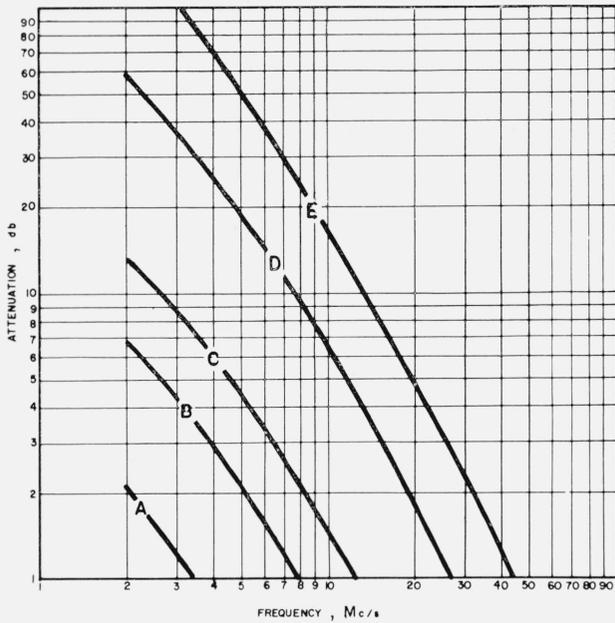


FIGURE 2. Amount of absorption as a function of frequency for vertical incidence using particular electron density distributions. (See table 1.) Each distribution has a corresponding value of f_{min} : A, <1.0; B, 1.0; C, 1.6; D, 4.0; and E, 7.6.

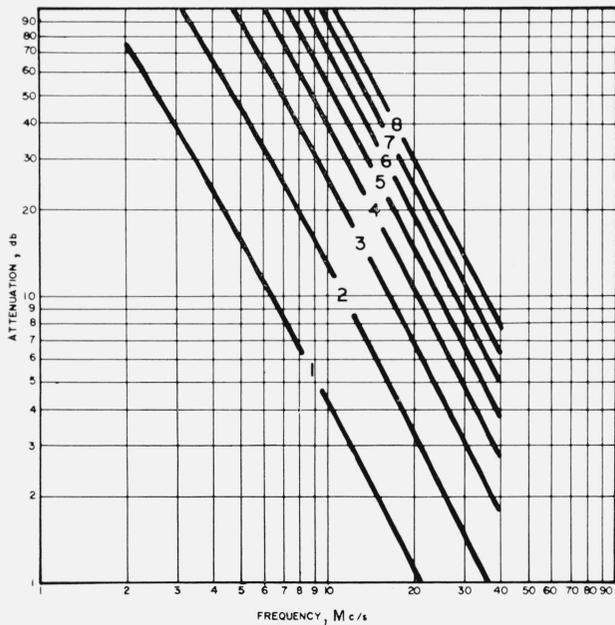


FIGURE 3. Amount of absorption as a function of frequency for oblique incidence (see $\phi=5$) using the particular electron density distributions shown in figure 2.

From the values of f_{min} associated with the electron density distributions, A through E, new curves of absorption versus frequency for oblique incidence are found for values of f_{min} in steps of one Mc/s by interpolation.

absorption is 7 and 24 db, respectively, making a total of 31 db. This value is well below the critical value of 43 db from figure 1 for reception of a 10 kw signal. In fact, a 1 kw signal would also be of sufficient strength for reception.

³ For simplification it is assumed that the transmitter power, receiver gain, the minimum detectable signal-to-noise ratio, and radio noise are all constant in time, location, and frequency.

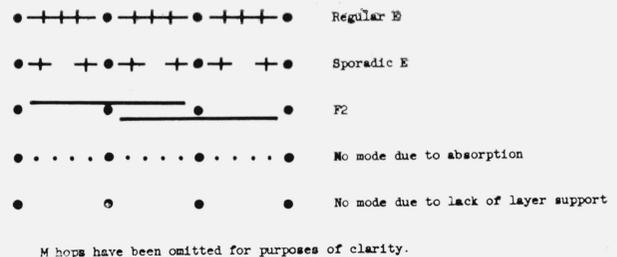


FIGURE 4. Representation of communication conditions at a fixed frequency.

number of curves parallel to the sunrise-sunset line shown on the communication charts. These represent the regular E -layer critical frequency.

In accordance with the condition of the ionosphere, communication is about normal. On 10 Mc/s E modes prevail in the east, and F and E_s modes in the west.⁴ In the far north absorption is sufficient to cause outage on several links. South of Alaska there is another small region in which there is outage. This is not due to absorption, but to lack of F layer support.

On 20 Mc/s F modes prevail in the east. In the west there are no available modes due to a lack of layer support. There are a few links where sporadic- E support is available both in the sunlit and darkened portion of the network, but mostly in northern latitudes. No outage due to absorption is found on the 20 Mc/s chart.

To summarize, communication in the sunlit portion of the network is accomplished by E -layer support on 10 Mc/s and F layer support on 20 Mc/s. In the darkened portion communication is supported by the F and E_s layers on 10 Mc/s, but is not supported by any layer on 20 Mc/s. Some absorption on 10 Mc/s is found in polar regions. Finally, it should be mentioned that if the two charts are considered together, there are no points which are inaccessible to any other point. This condition is to be expected because the ionosphere is only slightly disturbed at this time.

⁴ The presence of both F and E_s modes indicates that M modes are also present, although they are not indicated on the charts.

In figure 6 the charts for 0000 UT September 13 are shown. While the F layer is found to be about normal, polar cap absorption is widespread and intense at this time. The communication condition is different from the previous one in two important ways. First, the illuminated portion of the network is in the west rather than the east. So, on 10 Mc/s E modes are found in the west and F and E_s modes in the east. On 20 Mc/s F modes are found in the west. However, F modes are also found in the east because the F_2 -layer critical frequency is still high just after sunset. The second difference is that absorption in polar regions is more widespread and more intense than before. So on 10 Mc/s the region of outage due to absorption covers the whole polar cap. On 20 Mc/s only the northernmost links are out.

In figure 7 the charts for 1200 UT September 13 are shown. At this time the ionosphere is strongly disturbed; f_0F_2 is well below normal over a wide region, a large area of sporadic E is found over Canada, and there is enhanced absorption in the east. However, the large region of polar cap absorption is no longer found. On the 10 Mc/s chart, the available modes show several differences from 24 hours before. First, in the west there are many links on which F -layer support is no longer available. Secondly, there is in the west an extensive region where E_s modes are available. Fortunately this E_s support comes when the F_2 -layer support is weakened. Thirdly, on several links in the east there is outage due to absorption. This occurs at relatively low

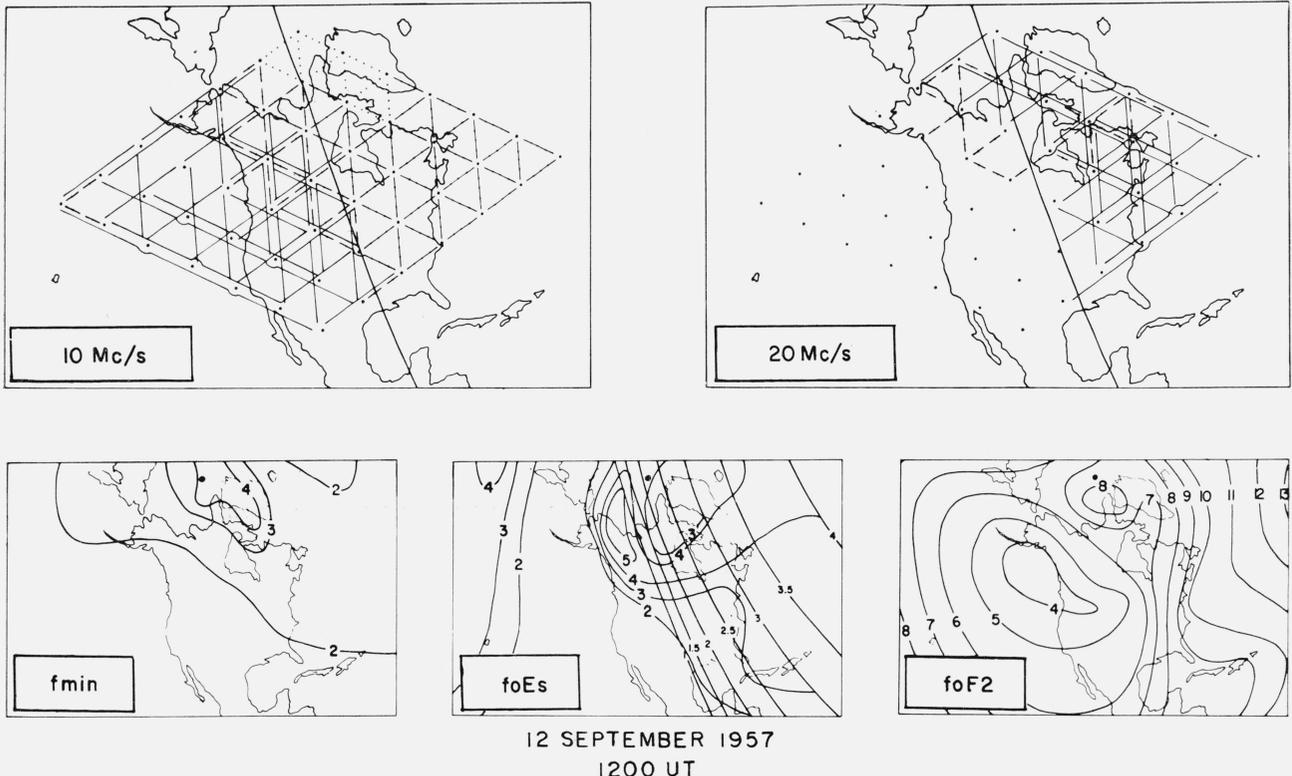
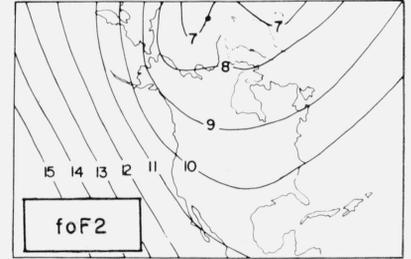
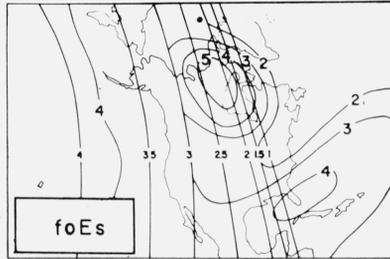
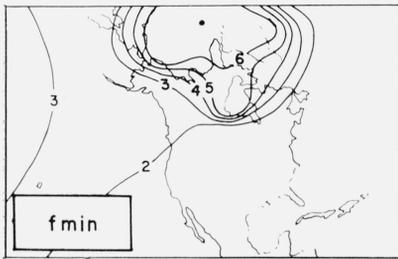
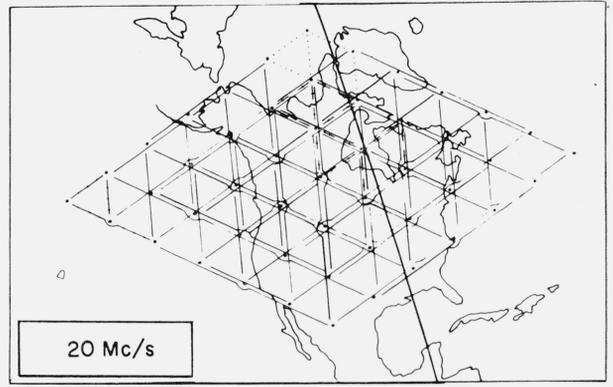
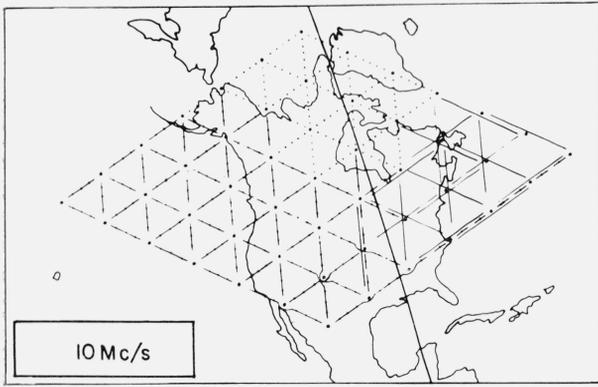
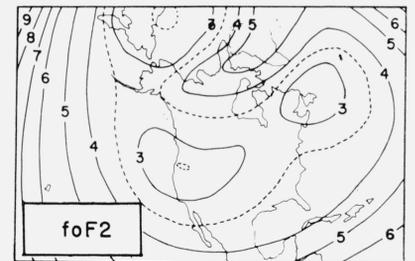
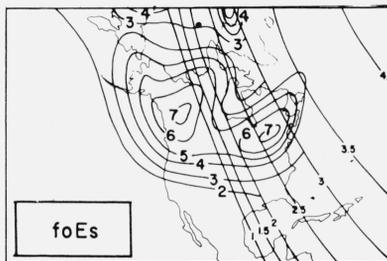
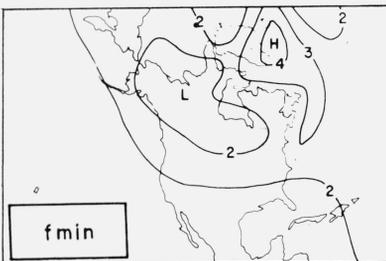
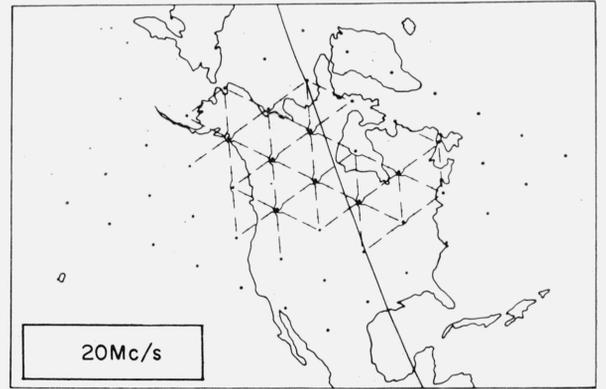
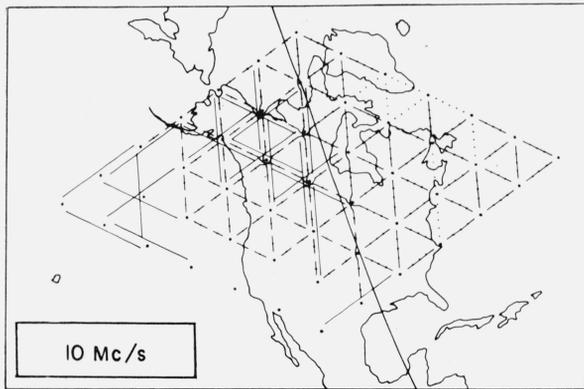


FIGURE 5. Communication and ionospheric charts for 1200 UT September 12, 1957.



13 SEPTEMBER 1957
0000 UT

FIGURE 6. *Communication and ionospheric charts for 0000 UT September 13, 1957.*



13 SEPTEMBER 1957
1200 UT

FIGURE 7. *Communication and ionospheric charts for 1200 UT September 13, 1957.*

latitudes compared to outages due to polar cap absorption. Elsewhere in the east regular E -layer support is available as usual.

On the 20 Mc/s chart, communication is quite different than on the day before. The normal F -layer modes in the illuminated portion of the network are absent. However, over most of Canada the E_s mode is available. Absorption at 20 Mc/s is not intense enough at this time to cause any additional outage.

To aid the understanding of what is found on the communication charts, a summary of the available modes is given in table 2 according to the state of the ionosphere. Only the modes, or lack of modes, which are characteristic of the particular ionospheric state under consideration are given. These characteristic communication conditions are broken down into parts according to the frequency and whether the network is illuminated or not.

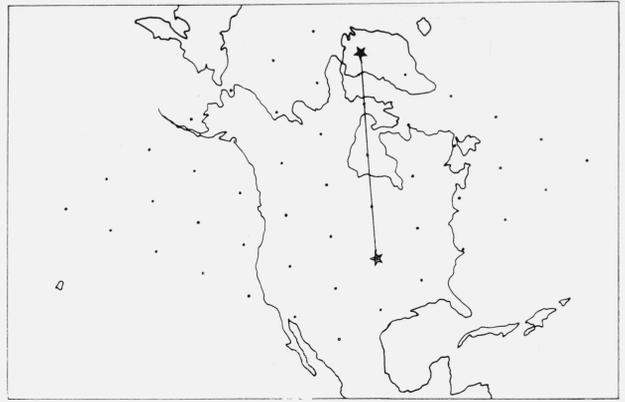


FIGURE 8. Map of network and hypothetical link.

TABLE 2. Main effects of the ionospheric disturbance on communication conditions over the network taken from figures 5, 6, and 7, 12/1200 UT, 13/0000 UT, and 13/12000 UT

State of ionosphere	Frequency	Illuminated portion of network	Darkened portion of network
1. Undisturbed ionosphere-----	10 Mc/s	12/1200—Regular E modes except in far north.	12/1200— F modes and scattered E_s .
	20 Mc/s	13/1200—Regular E modes except in polar cap.	13/0000— F modes except in polar cap.
2. Development of polar cap absorption.	10 Mc/s	12/1200— F modes and scattered E_s in Canada.	12/1200—Scattered E_s in north.
	20 Mc/s	13/1200—Absorption outage in polar cap.	13/1200— F modes.
3. Dissipation of polar cap absorption.	10 Mc/s	13/0000—Absorption outage throughout polar cap.	13/0000—Absorption outage throughout polar cap.
	20 Mc/s	13/0000—Absorption outage in far north.	
4. Sporadic- E cloud-----	10 Mc/s	13/1200—Lack of widespread absorption in polar cap.	13/1200— E_s modes throughout Canada and northern U.S.
	20 Mc/s	13/1200—No additional effect due to presence E_s of regular E -layer.	13/1200— E_s modes throughout Canada and northern U.S.
5. Auroral zone absorption-----	10 Mc/s	13/1200— E_s modes in Canada-----	
6. F_2 layer disturbance-----	10 Mc/s	13/1200—Scattered absorption outage in auroral zone latitudes.	
	20 Mc/s	13/1200—Complete loss of F_2 modes (compare with 12/1200).	13/1200—Nearly complete loss of F_2 modes (compare with 12/1200).

4. Analysis of Sample Link

To show what improvements can be achieved by the use of such communication charts as described here, analysis of a particular link will be carried out. This link is a hypothetical one which has one terminal in northern Greenland and the other in central United States. These terminals have been indicated on figure 8 by a star. From the complete series of charts the frequencies available over this link have been found and are shown in figure 9. In this figure the areas covered by heavy shading show the frequency range available for *direct* communication between the two terminals and the areas covered by light shading apply to *indirect* communication. Indirect communication may be accomplished by successive relays directly between the terminals or by relays using links away from a direct path.

On the 11th, the frequency range available is about what would be expected for a quiet day. This range has been indicated by dashed curves for all five days so that communication on every day may be easily compared. After 1200 UT on the 12th, normal direct communication is disrupted. The outage starts at the lower frequencies and proceeds to higher ones. Thus, the available frequencies for direct communication are reduced to a narrow band and are finally cut off altogether when the f_0F_2 decreases sufficiently, i.e., 2300 UT. However, indirect communication is still available. In fact, indirect communication is available throughout the whole period of the storm. On the 13th there are occasions due to the presence of sporadic E , when direct communication is possible, but only over a narrow bandwidth. On the 14th, there is some recovery toward normal conditions and on the 15th there is further recovery. It should be noted that

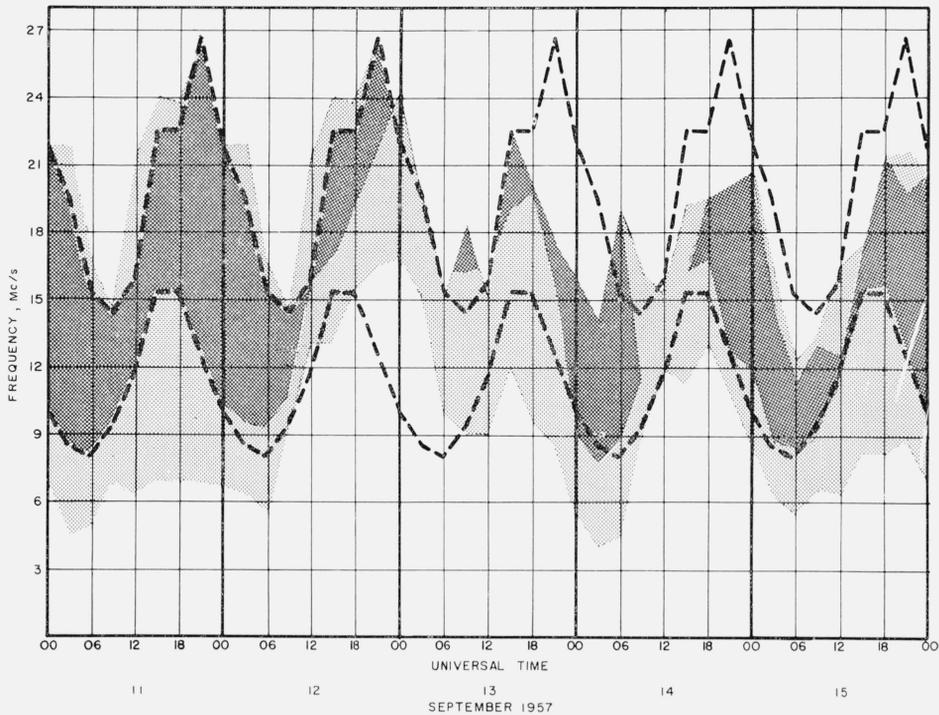


FIGURE 9. Frequency range available on hypothetical link.

although indirect communication is possible at all times during the five-day period on this link, it does not necessarily mean that communication on other links in the network can be maintained during the storm. However, the degree of improvement with relaying and alternate routing is considerable. It should also be noted that frequency switching at relay points has not been included in the example shown in figure 9. In practice it is expected that one frequency may be used for initial transmission and another frequency for relay from an intermediate station. Such frequency switching will increase the range available and will add to the overall flexibility of network operations.

TABLE 3.—Hours available per day on indirect (i) and direct (d) links using communicating frequencies 3 Mc/s apart.

Day	Number of frequencies—at least:						
	1i	2i	3i	1d	1d+1i	1d+2i	2d
11	24	24	23	24	24	23	21
12	24	23	20	21	20	19	10
13	24	23	11	6	6	6	1
14	24	24	16	16	16	12	12
15	24	24	20	20	22	18	13

To show the improvement in communication if intermediate contacts are made, a simple numerical index is used. The index is based on the number of hours per day that communication is possible on a specific number of frequencies at 3 Mc/s intervals as shown in figure 9. In table 3 the number of hours found from figure 9 is shown by day according to the number of available frequencies. For example, at 1800 UT on the 14th, 18 Mc/s is available for direct

communication and 15 Mc/s is available for indirect communication. So this hour would count as being available under column 1d+1i. Also, this hour is available under columns 1i, 2i, and 1d.

If only one frequency on an indirect path is required (column 1i), communication is available 24 hr on all five days. However, if at least one frequency on a direct path is required (column 1d), communication is reduced on the 13th, for example, to only 6 hr. It is noted that normal operations are represented by the column 1d. That is, communication is maintained on at least one frequency selected from several spaced 3 Mc/s apart. While the number of hours available drops to six on the 13th, using normal operations, there is no outage on any day using relays and link switching.

5. Concurrent WWV Reception

As a check on the validity of the results shown on the communication charts, the reception quality of WWV transmitted from Washington, D.C., is analyzed. WWV data of several Canadian stations are recorded hourly on the basis of a quality index, which consists of whole numbers 0-9, representing no reception to excellent reception [Canadian Defense Research Board, 1957]. This quality index is dependent upon signal strength, noise level, amount of fading, and personal bias. In spite of the number of factors affecting the index, it provides a means to analyze quantitatively the reception of WWV during changing ionospheric conditions. The reception quality of WWV for 10 and 20 Mc/s at four Canadian stations is shown in figure 10.

The darkened portions of the figure represent nighttime hours at the longitude of the stations. The remaining portions represent daytime hours. The three heavy vertical lines indicate the times applicable to figures 5, 6, and 7.

As stated before, communication on the 11th is representative of quiet ionospheric conditions. At this time, WWV reception on 20 Mc/s is low at night and high in the day, and on 10 Mc/s reception is high at night and somewhere between low and high in the day. On the 12th, this pattern holds throughout the day on 20 Mc/s, but only until about 1200 UT on 10 Mc/s due to the presence of polar cap absorption.

On the 13th, the pattern of reception bears little resemblance to the normal one. Reception on 20 Mc/s is enhanced intermittently during the night hours by sporadic *E*, and reduced during the daylight hours by the reduction of f_0F_2 . On 10 Mc/s, reception is somewhat reduced by the presence of auroral zone absorption. In addition, reception on 10 Mc/s fluctuates strongly. This is due to both sporadic *E* and to the narrowness of the band of auroral zone absorption.

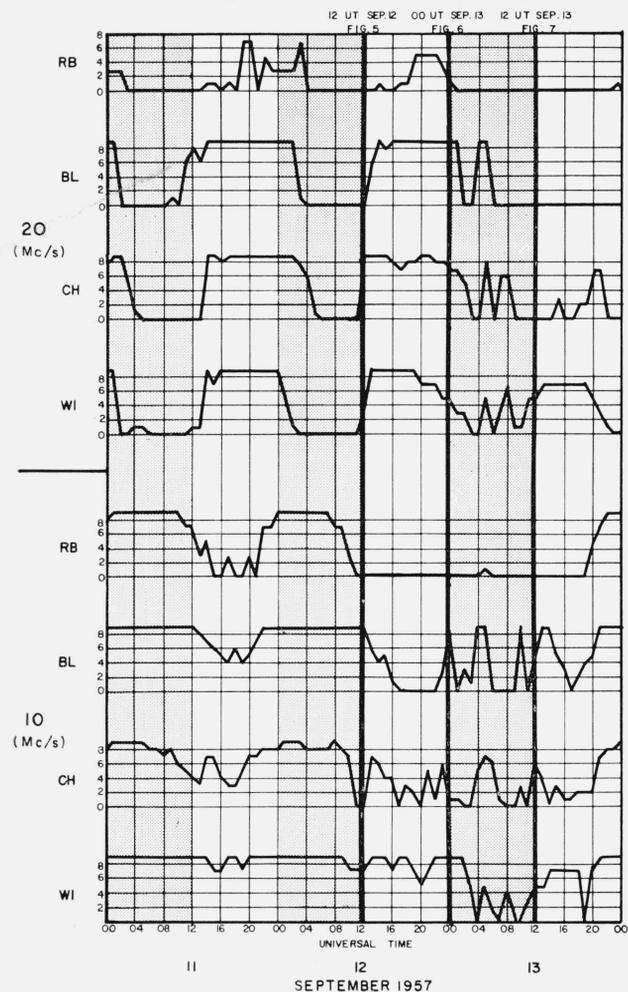


FIGURE 10. Reception quality index (0-9) of WWV for 10 and 20 Mc/s at four Canadian stations.

A comparison of the experimental data shown on figure 10 with the communication charts or with the data for the sample link shows that the results of the hypothetical network are not very different from real conditions. It should be noted that WWV reception before and after the times indicated by the heavy lines on figure 10 can be compared in a general way with propagation conditions in portions of the network other than what is found between Washington and the four receiving stations. Remembering that 15 degrees of longitude is equivalent to 1 hr, it can be seen that conditions in the western portion of the network are equivalent to what is found up to about 4 hr before the chart time (on fig. 10) and in the eastern portion, up to about 3 hr after the chart time. One additional point is that at these chart times the twilight zone lies just over the four receiving stations, so daytime and nighttime conditions are separated on the charts by the longitude of the stations.

6. Conclusions

According to the preceding results, HF signals can be continuously propagated in polar regions even during a period of severe ionospheric storminess. By a systematic analysis of ionospheric data it is possible to find the available frequencies and routes. It was found that communication between polar stations and mid-latitude stations should have been possible most of the time with frequency and link switching. It was also found that the results of the network analysis were supported by recordings of WWV transmissions. It is suggestive, at least, that the communications concept discussed here may well set the stage for establishment of a reliable global-polar communication system.

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