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Technical Note No. 82

Boulder Laboratories

A SURVEY OF SPREAD - F

BY

F.N. GLOVER

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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ERRATA SHEET

for

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November, 1960

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ABSTRACT

Examples of spread-F forms occurring at different latitudes are presented, illustrating the classification of spread into range type and frequency type. The occurrence patterns of spread-F at different latitudes are correlated with other geophysical phenomena. Magnetic latitude and time within the sunspot cycle appreciably affect the pattern of spread occurrence. Instrumental techniques and their advantages for spread studies are outlined. The principal theoretical explanations of spread-F are summarized. A single mechanism need not be postulated as responsible for all types of spread occurrence or at all latitudes.

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A STUDY OF SPREAD-F

by

F. N. Glover

1. INTRODUCTION

Spread-F, like sporadic E, is a familiar and sometimes frequent "abnormality" encountered in radio soundings of the ionosphere. It occurs at some time or other at every station although its form and frequency of occurrence differ widely. The existence of the phenomenon which is now commonly termed "spread-F" has been known for more than twenty years. Booker and Wells (1938) were the first to give a detailed account of the diffuse or spread appearance of the F-layer echo on many Huancayo ionograms.

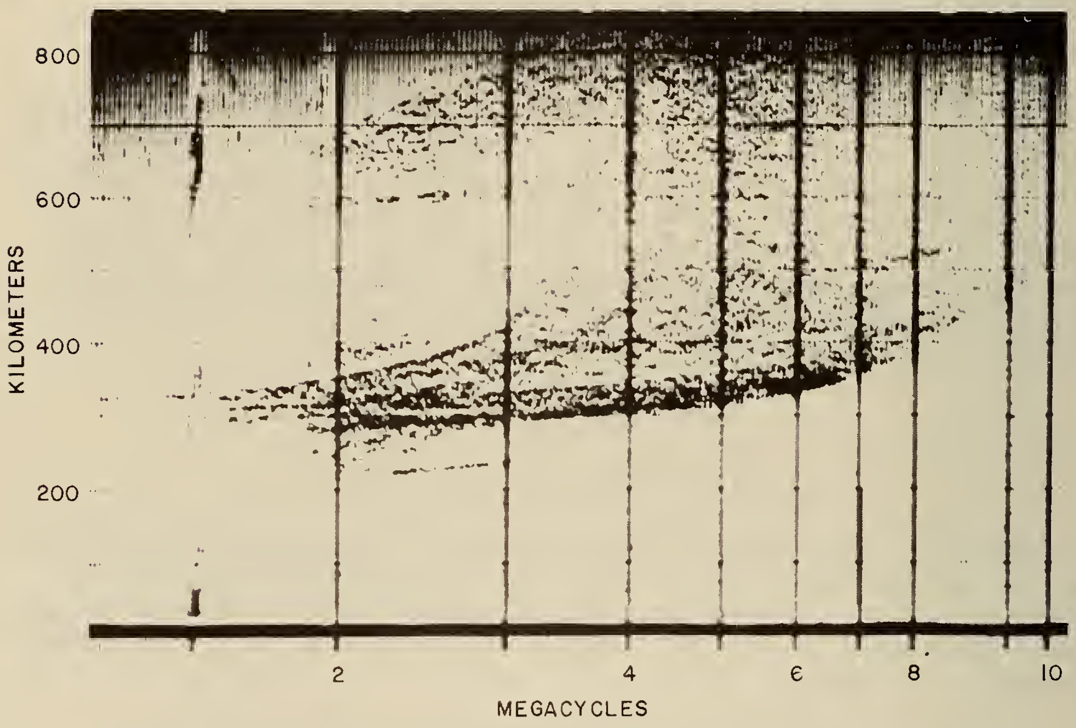
2. THE MORPHOLOGY OF SPREAD-F

2.1 Definition of Spread-F

Spread-F, also known as "spread echo", "scattering in the F region", "diffuse echo", etc., is usually described in terms of the appearance of the conventional virtual height versus frequency ionogram. The annals of the IGY (Wright, Knecht and Davies, 1957) define spread-F as follows:

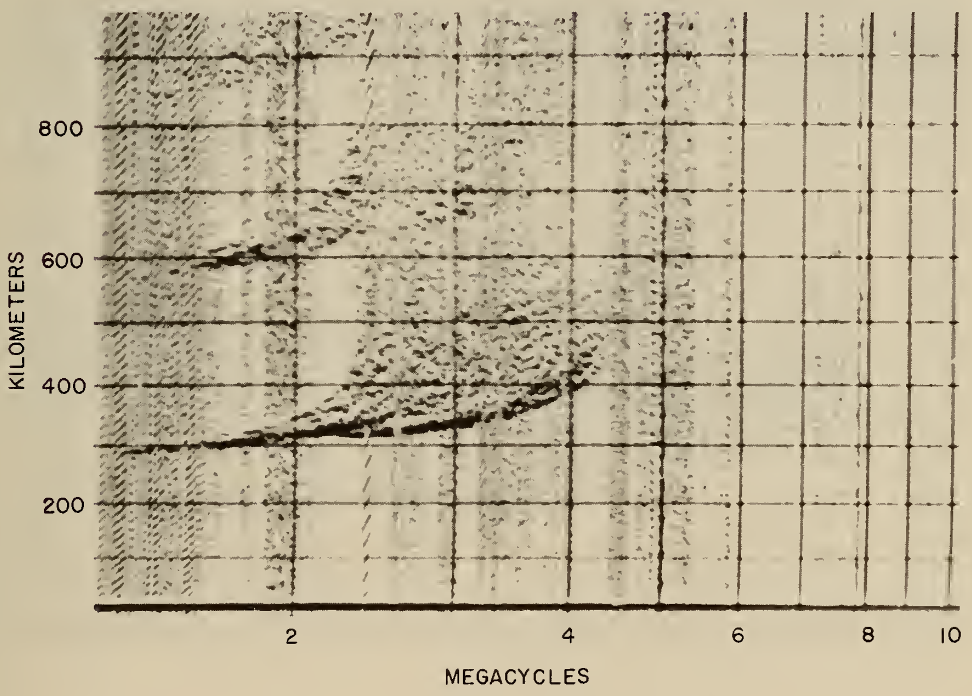
> "The term 'spread echo' is applied to the condition observed at middle and low latitudes, and quite often in polar regions, when the ionospheric echo becomes quite diffuse, loses its sharply defined structure, and extends to frequencies sometimes far above those indicative of the actual ion density of the layer. When it occurs in F region echoes, this condition is called spread-F. Although spread-F is the most frequent and most troublesome case, spread echo is occasionally observed from all layers."

It is to be noted that spread-F is here defined in terms of the appearance of an h'-f (virtual height versus probing frequency) ionogram, rather than in terms of some physical mechanism operative in



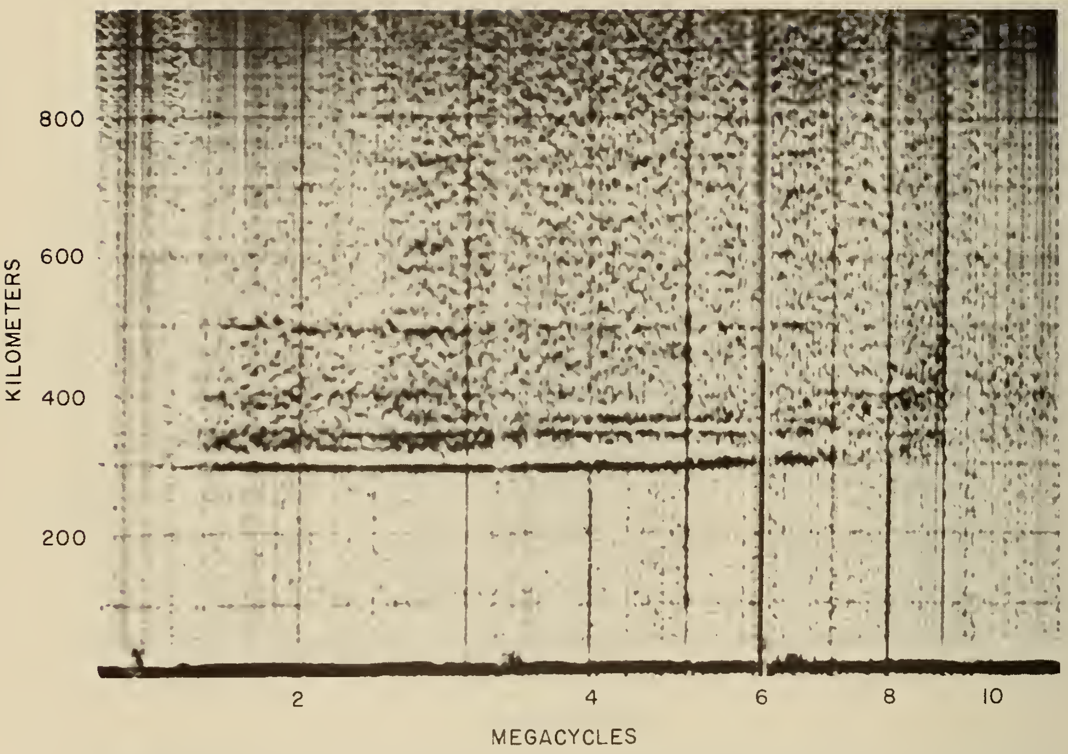
SPREAD-F AT HIGH LATITUDE. (THULE, GREENLAND, GEOMAGNETIC LATITUDE 88.1° N, DECEMBER 5, 1957, 5:01 AM) FREQUENCY TYPE SPREAD.

FIGURE 1



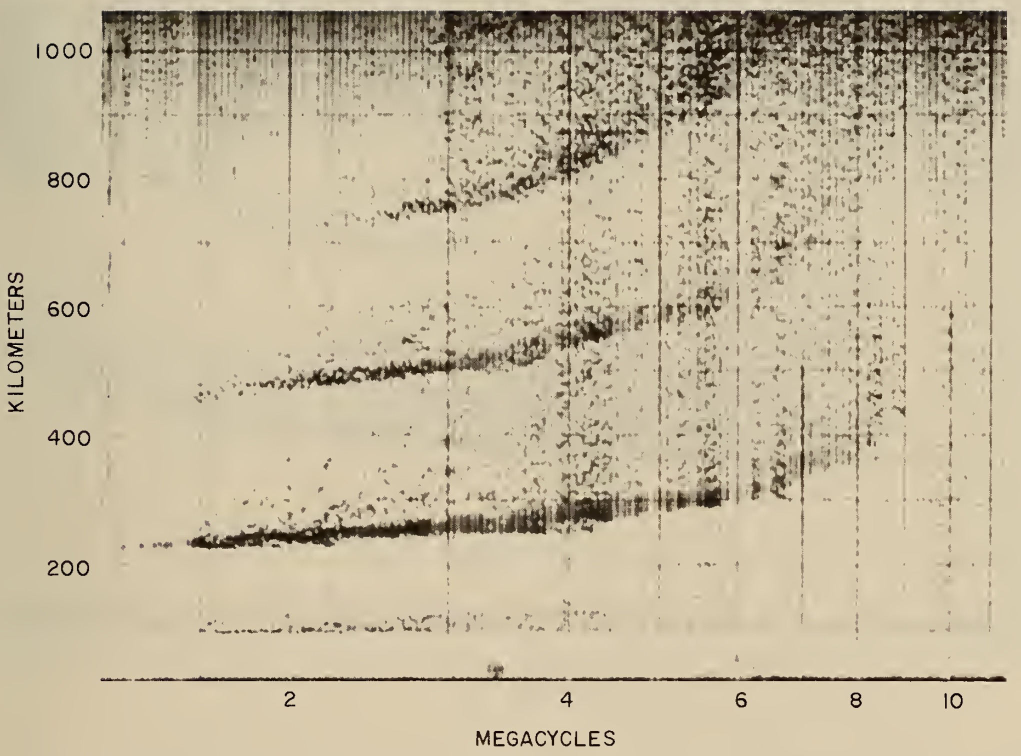
SPREAD-F AT MEDIUM LATITUDE. (FT. MONMOUTH, N.J., GEOMAGNETIC LATITUDE 51.7°N, DECEMBER 4, 1954, 2:54 AM) FREQUENCY TYPE SPREAD.

FIGURE 2



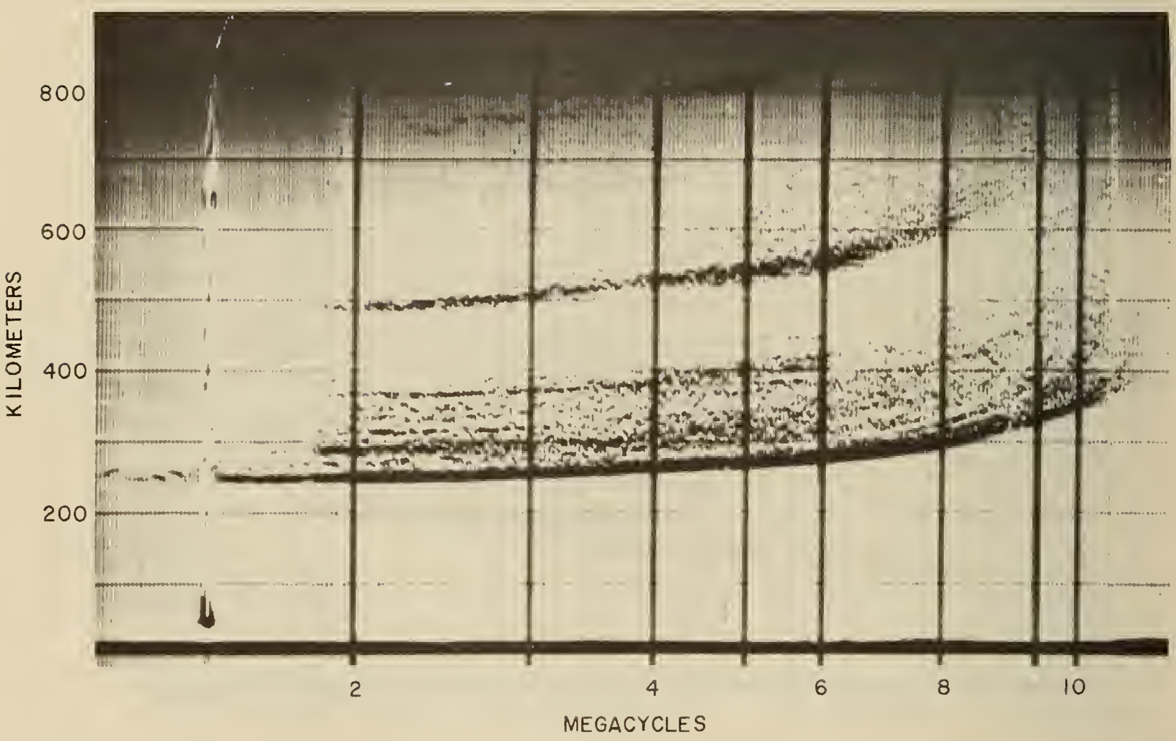
SPREAD-F AT LOW LATITUDE. (HUANCAYO, PERU, GEOMAGNETIC LATITUDE 0.6°S, SEPTEMBER 3, 1957, 11:00 PM) RANGE TYPE SPREAD.

FIGURE 3



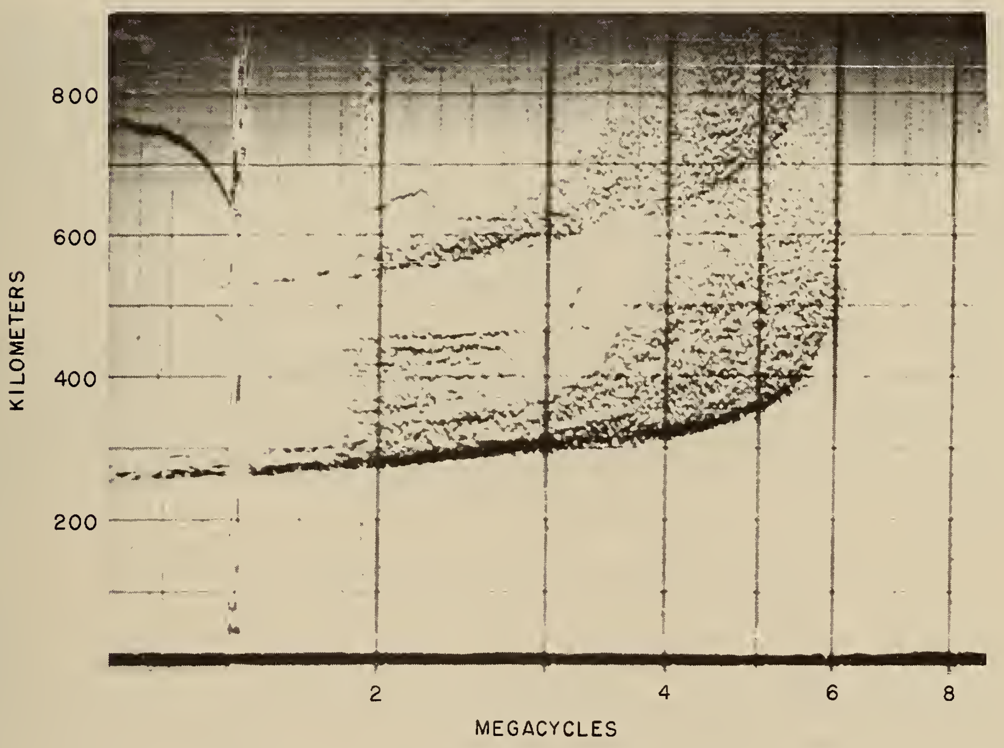
A LOW LATITUDE SPREAD-F IONOGRAM THE UPWARD SWEEPING TRACES SUGGEST HIGH LATITUDE SPREAD-F. (HUANCAYO, SEPTEMBER 27, 1957, 12:59AM)

FIGURE 4



A HIGH LATITUDE SPREAD-F IONOGRAM. THE FREQUENCY INDEPENDENCE OF THE SPREAD OFER A WIDE RANGE OF FREQUENCIES SUGGESTS LOW LATITUDE SPREAD-F. (THULE, DECEMBER 3, 1957, 9:30 AM)

FIGURE 5



IONOGRAM DISPLAYING RANGE TYPE SPREAD-F (SPREAD OF VALUES FOR VIRTUAL HEIGHT, OR SLANT RANGE, OF THE F LAYER), AND FREQUENCY TYPE SPREAD-F (SPREAD OF VALUES FOR THE PENETRATION FREQUENCY OF THE F LAYER). (THULE, DECEMBER 14, 1957, 2:45 AM)

FIGURE 6

the upper atmosphere. The possibility is at once apparent that two or more distinct and different mechanisms in the ionosphere might each be separately responsible for the same sort of diffuse trace on an ionogram. This possibility appears to be less remote if one recalls that almost any kind of diffuseness appearing on the F layer trace is termed spread-F.

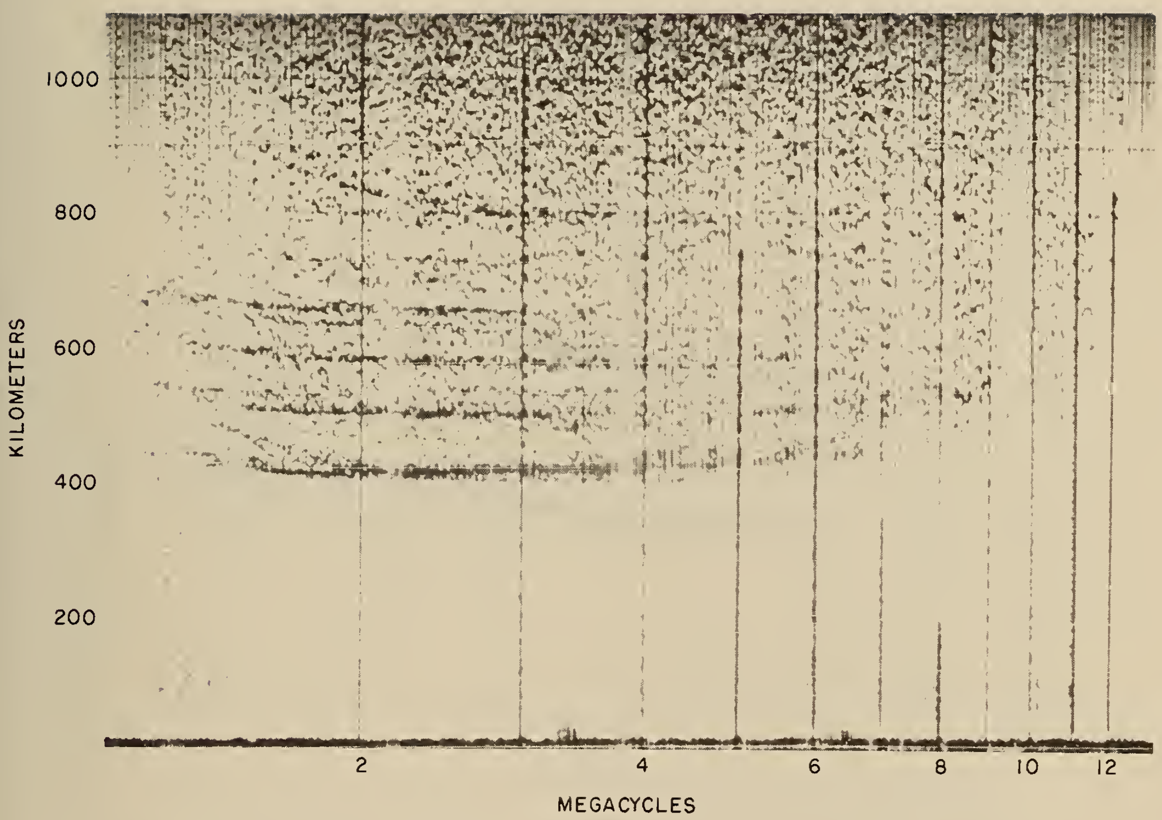
2.2 High, Medium and Low (Geomagnetic) Latitude Spread-F

The common division of ionograms showing diffuse F region echoes is that of high, medium, and low latitude spread-F (Wright and Knecht, 1957) according to the geomagnetic latitude of the station at which certain characteristic patterns usually occur. Figures 1, 2, and 3 present examples of spread conditions found at high, medium and low (geomagnetic) latitude stations. The traces of the high- and middle-latitude spread-F ionograms appear to sweep upward, presenting apparently a wide range of critical frequencies. In the low latitude spread-F ionogram, the spread condition appears to be independent of frequency over a wide range of frequencies.

Figure 4, however, presents a Huancayo ionogram with upward sweeping traces, resembling the ionogram of a high latitude station whereas Figure 5 presents a spread condition at Thule, Greenland, suggestive of a low latitude station. These examples indicate that the division into high, medium, and low latitude spread-F is not altogether satisfactory.

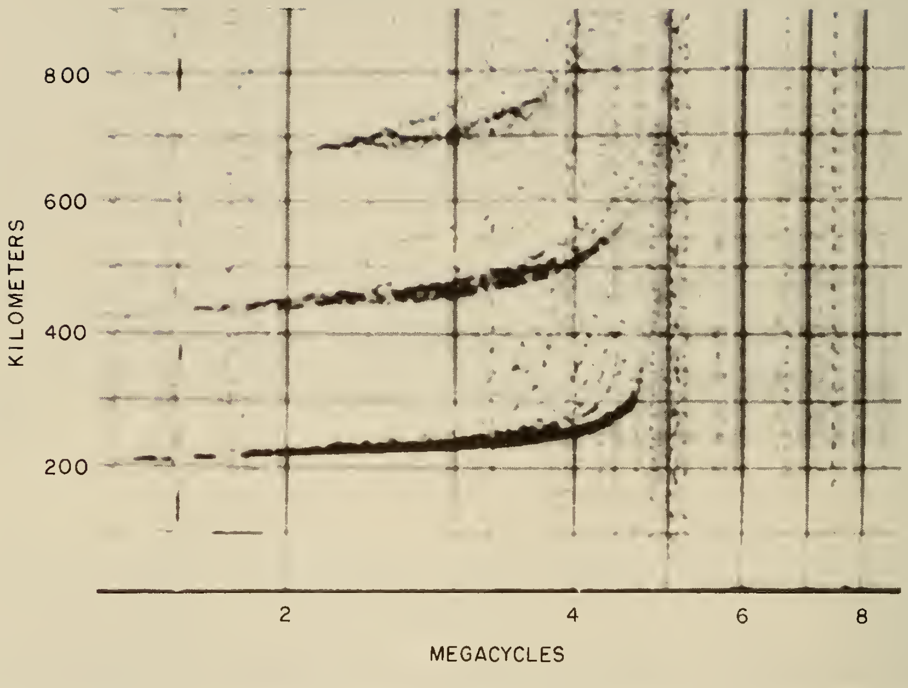
2.3 Range Type and Frequency Type Spread-F

McNicol, Webster and Bowman (1956) suggest an alternative division, that of "range type" and "frequency type" spread-F. If the diffuseness is pronounced along the section of the trace that sweeps upward, such that there is some ambiguity regarding the value of the penetration or critical frequency, the spread is to be termed "frequency type". The ionograms in Figures 1 and 2 are examples of frequency type spread-F. If, however, the spread is more or less independent of frequency over a wide range of frequencies, and the diffuseness is principally along the horizontal part of the trace, giving rise to ambiguity in virtual height, or more generally in virtual slant range, the spread effect is classed as "range type". Figures 3 and 5 are examples of range type spread-F. Some ionograms appear to exhibit both range type and frequency type spread-F, as is shown in Figure 6. Although not widely used in the past, this classification of range type and frequency type spread-F is to be preferred to that of low, medium and high latitude spread, since it is based on the appearance of the ionogram trace rather than on the geographic location of the ionosonde.



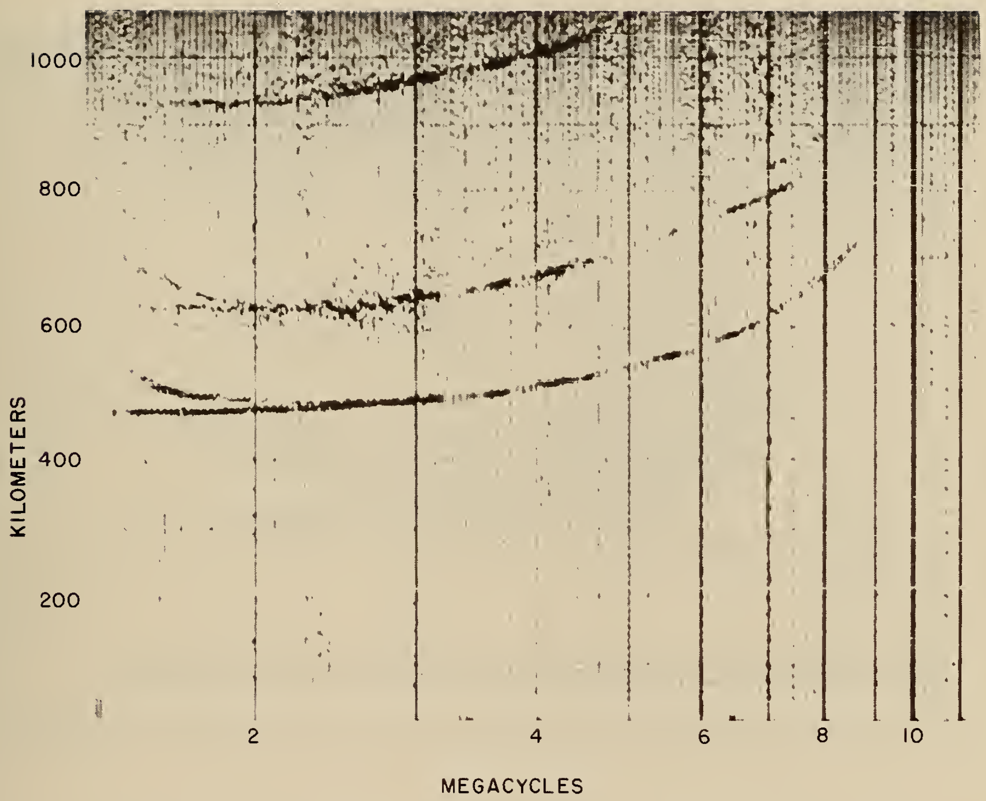
RANGE TYPE SPREAD-F SHOWING SATELITE TRACES. (HUANCAYO, SEPTEMBER 23, 1957, 4:43 AM)

FIGURE 7



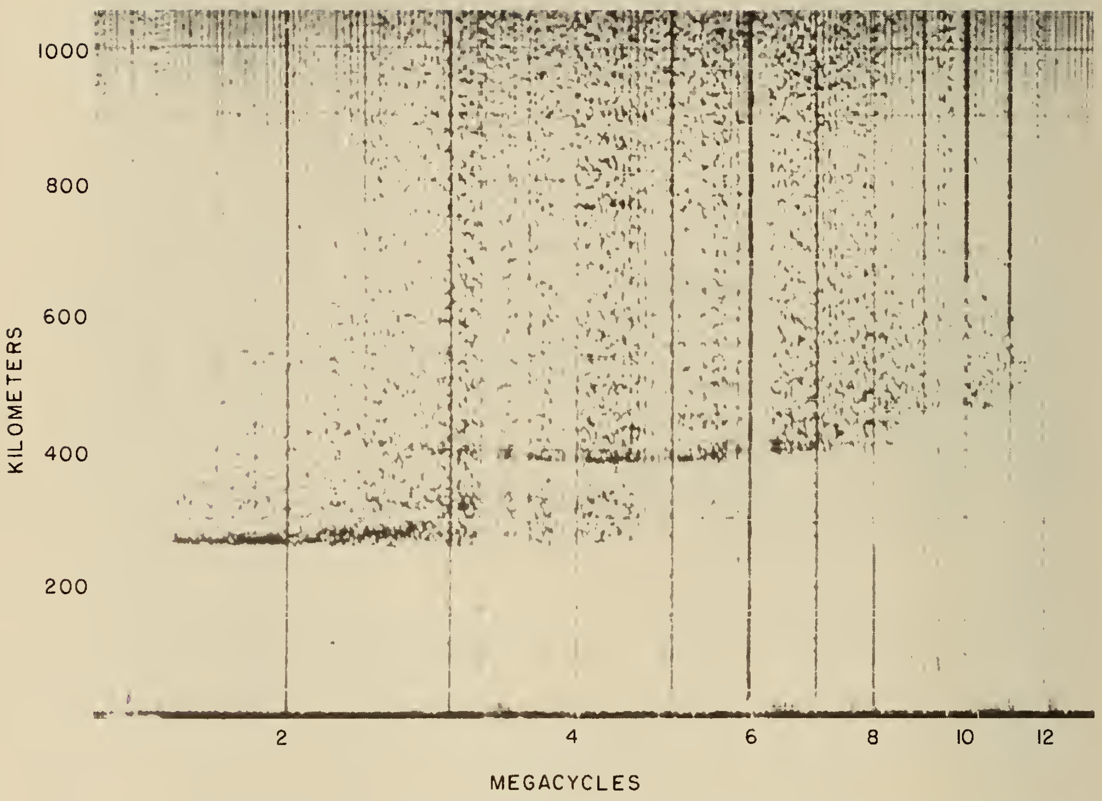
FREQUENCY TYPE SPREAD-F SHOWING SATELLITE TRACES. (WHITE SANDS, NEW MEXICO, DECEMBER 20, 1954, 2:30 AM)

FIGURE 8



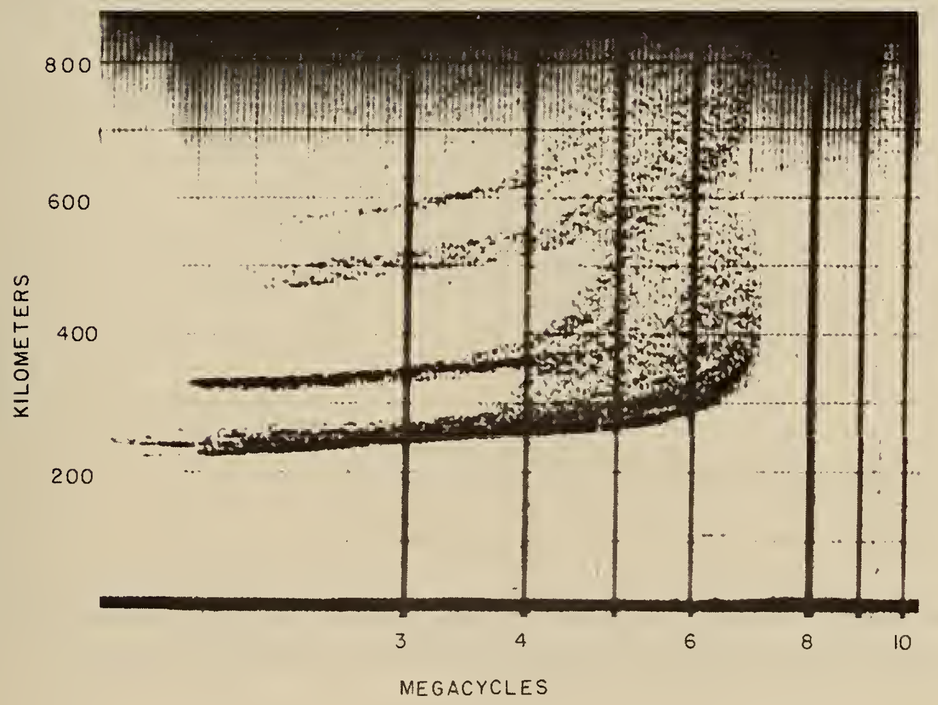
A DOUBLE TRACE FROM THE F REGION. WITHIN 45 MINUTES THIS CONDITION DEVELOPED INTO A FULL RANGE TYPE SPREAD-F CONDITION. (HUANCAYO, SEPTEMBER 25, 1957, 6:59 PM)

FIGURE 9



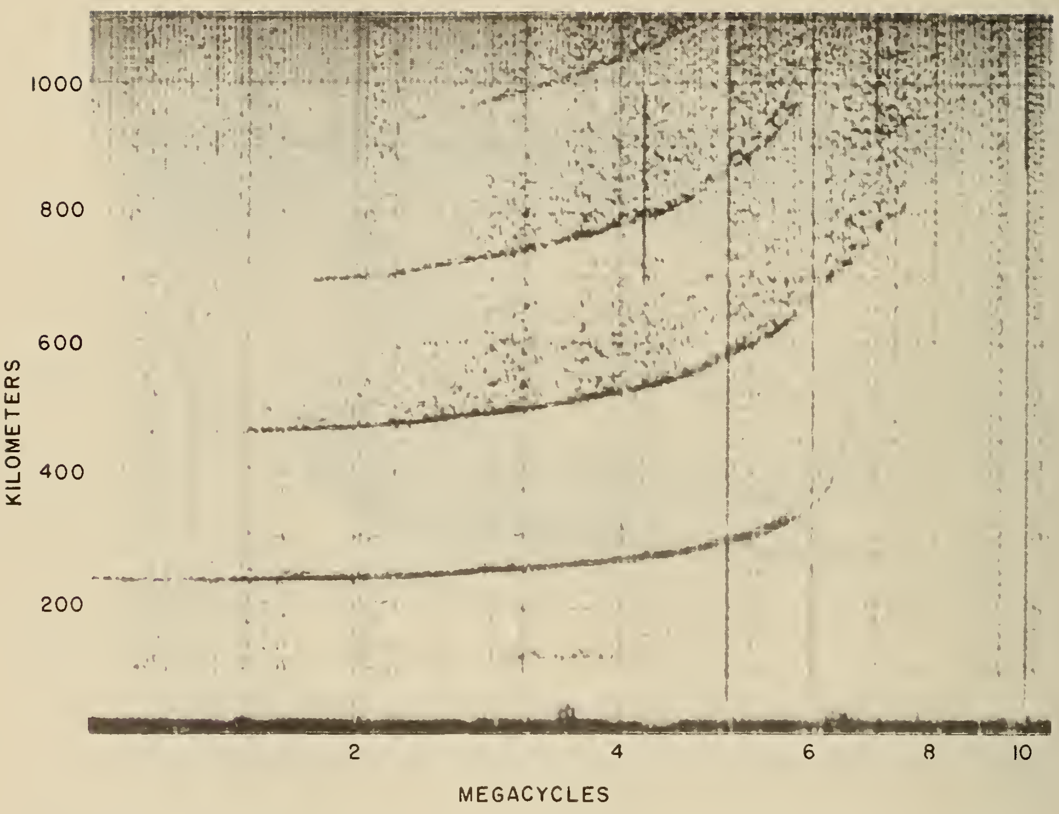
A DOUBLE RANGE TYPE SPREAD-F CONDITION. (HUANCAYO, SEPTEMBER 24, 1957, 9:58 PM)

FIGURE 10



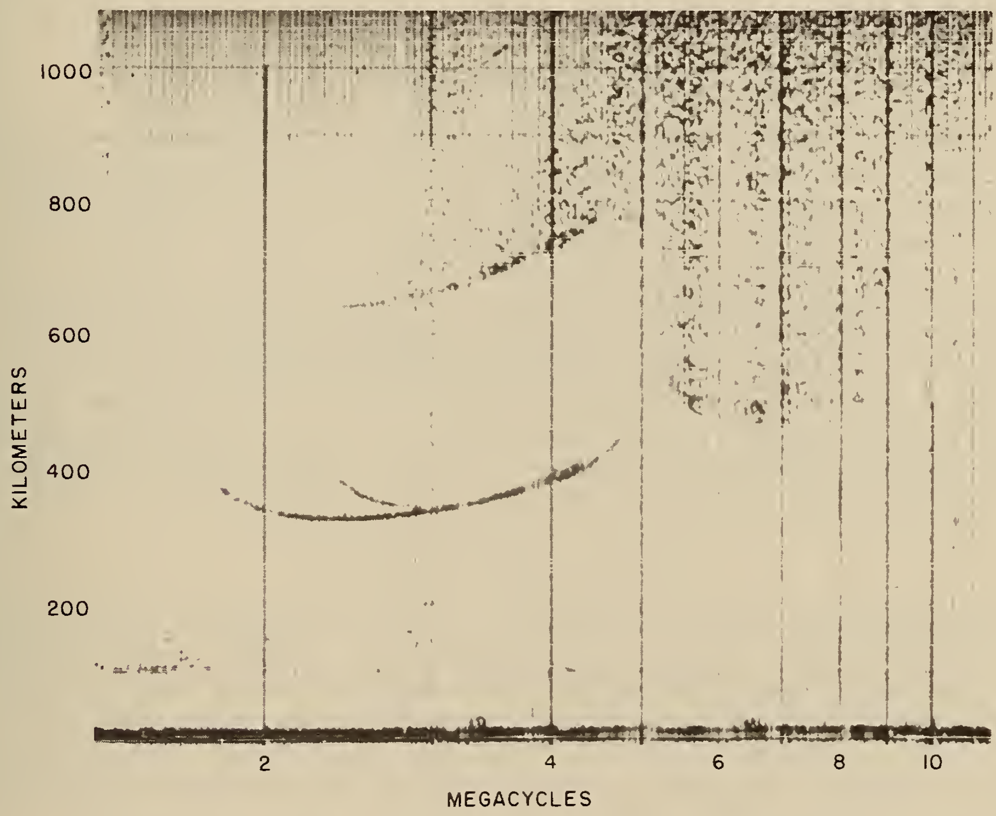
A DOUBLE FREQUENCY TYPE SPREAD-F CONDITION. (THULE, DECEMBER 10, 1957, 12:45 PM)

FIGURE 11



GROUND SCATTER, THOUGHT TO BE DUE TO BACK SCATTER FROM GROUND IRREGULARITIES VIA TWO OR MORE REFLECTIONS FROM A SMOOTH F LAYER. SPREAD ECHOES WERE ALSO PRESENT ON THE I F TRACE A FEW HOURS PREVIOUS. (HUANCAYO, SEPTEMBER 16, 1957, 3:45 AM)

FIGURE 12



SUNRISE EFFECT, FOLLOWING SEVERAL HOURS OF NIGHT TIME SPREAD-F. THE CONDITION ONE HOUR EARLIER IS SHOWN IN FIGURE 7. (HUANCAYO, SEPTEMBER 23, 1957, 5:49 AM)

FIGURE 13

2.4 Multiplets or Satellites

Many ionograms exhibiting spread conditions actually present a number of multiplet or satellite traces lying close to the main F region trace, and only imperfectly resolved from it. Figures 7 and 8 are examples of this multiplet structure in range type and frequency type spread-F. Webster (1958) has considered in some detail this multiplet structure of the F trace. Frequently a well developed spread condition is preceded by a number of weaker satellite traces adjacent to the main trace.

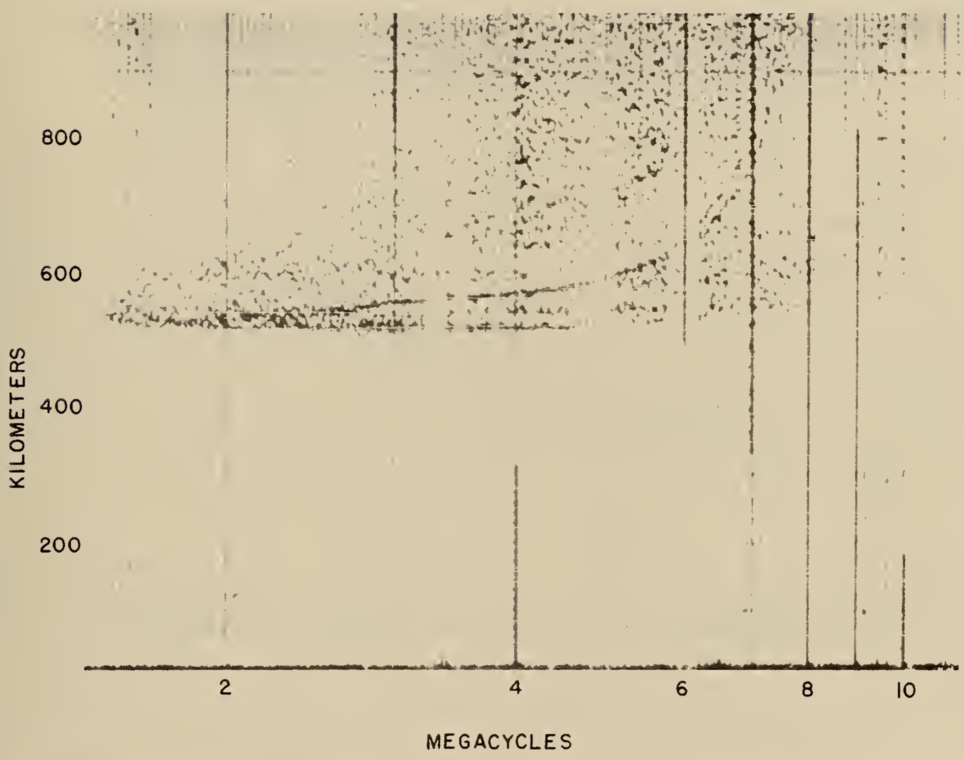
2.5 Double Traces

At times a spread condition is preceded by, or associated with, double traces from the F region. Figure 9 shows such a double trace, at a greater virtual height than the main F trace. The additional trace is too low to be two hop F, and since no E region trace is visible, a combination of E and F layer reflection is excluded. The condition in Figure 9 later developed into full range spread in less than forty-five minutes. It should be recalled that the "vertical incidence" ionosondes look not only toward the zenith, but also "see" somewhat obliquely. This oblique seeing, along with ionosphere variations in the horizontal plane, may, in part, be the explanation of the double traces in Figure 9. Figures 10 and 11 exhibit double traces for range type and frequency type spread-F conditions.

2.6 Special Spread-F Effects

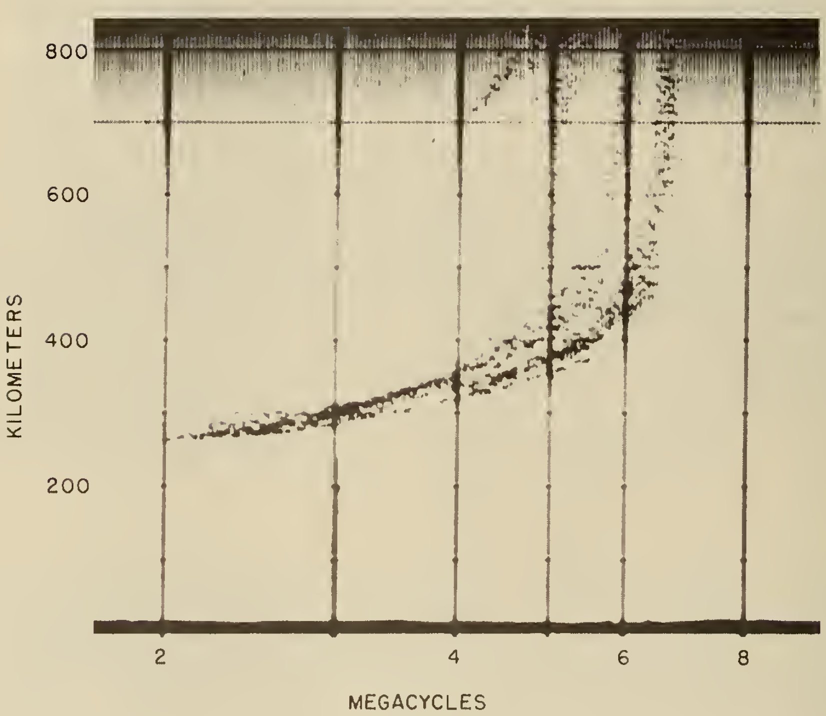
The Huancayo ionogram in Figure 12 shows no spread on the 1 F trace but pronounced spreading on higher order traces. Such a condition is termed ground scatter, and is thought to result from back scatter from ground irregularities via two or more reflections from the F layer. Dieminger (1951) reports that this ground scatter can always be observed at Lindau, provided sufficiently high transmitter power and receiver sensitivity are employed.

The ionogram in Figure 13 shows diffuseness on frequencies above the F layer critical and at virtual heights greater than those associated with the normal F layer. Such ionograms are not uncommon at Huancayo just at dawn following several hours of spread conditions. Booker and Wells (1938) suggest that this is due to a gradient in ionosphere conditions in the east-west direction just at sunrise. Looking west the ionosonde views the nighttime spread conditions, and looking east it views the fresh ionization formed by the rising sun. Figure 7 shows the condition of the ionosphere one hour prior to Figure 13.



RANGE TYPE SPREAD-F SUPERIMPOSED ON A WELL DEFINED F TRACE.
(HUANCAYO, SEPTEMBER 22, 1957, 8:59 PM)

FIGURE 14



A MILD FREQUENCY TYPE SPREAD-F CONDITION AT A HIGH LATITUDE STATION. (THULE, DECEMBER 5, 1957, 12:55 PM)

FIGURE 15

A range type spread-F condition with the ordinary and extraordinary trace showing through the spread is shown in Figure 14. It is possible that the ionosonde is looking in two different directions and sees two different sets of ionosphere conditions. At 1800 local time, some three hours prior to the ionogram shown in Figure 14, a ground scatter condition prevailed, similar to that in Figure 12. At 2000, some 200 km above the main trace there appeared a double trace (as in Figure 9) which rapidly descended and became diffuse. Subsequent to the ionogram in Figure 14 the range type spread condition continued to descend to about 325 km. By 2300 this spread developed into a clearly defined F trace, while the former F trace, at about 550 km dissolved into range type spread at this same virtual height.

2.7 Use of Hourly Tabulated Data

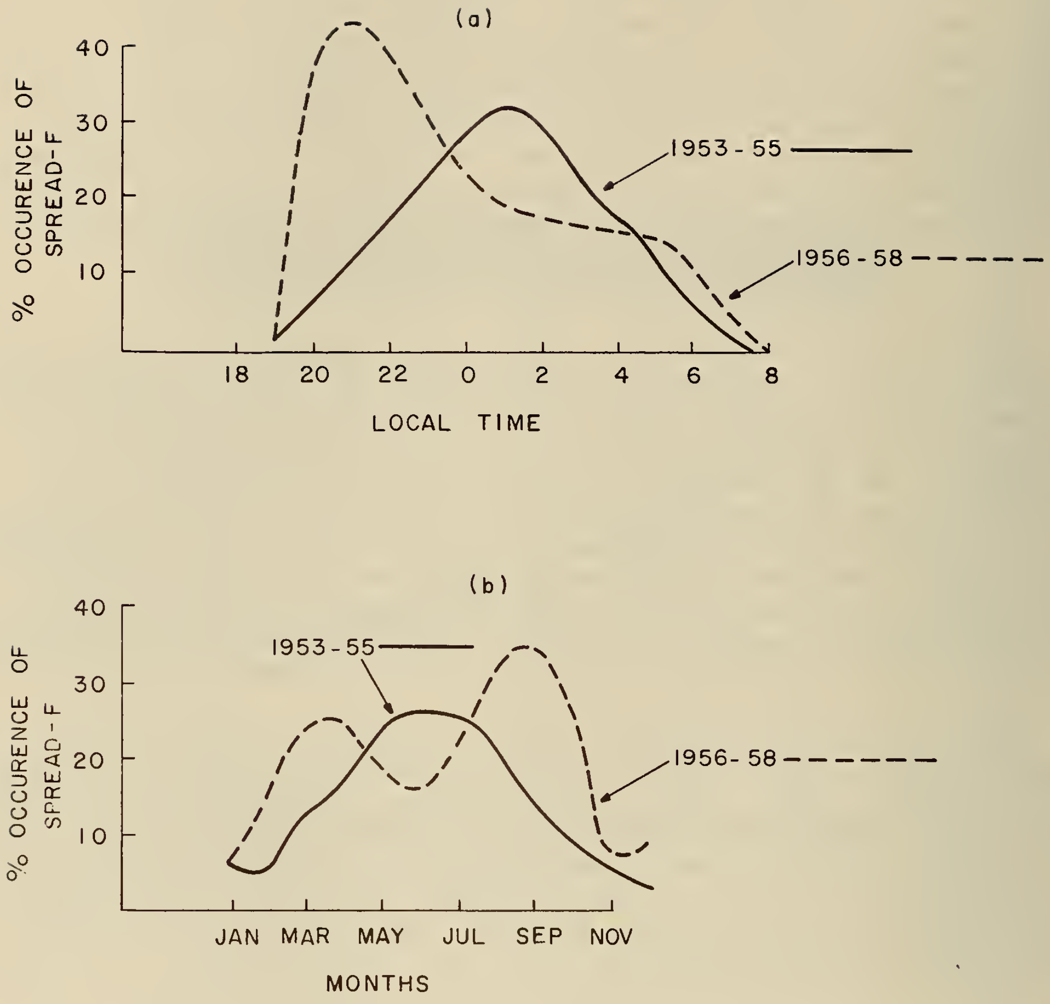
The presence of spread-F is immediately apparent on viewing the ionogram. However, most statistical studies of spread-F are based on the tabulated ionospheric hourly values rather than directly from the ionograms. The presence of spread-F can be known by the symbol F attached to, or in place of, the values for foF2, F2 M3000 or h'F. Spread-F on the ionogram is a necessary, but not sufficient, condition for the symbol F to appear in the tabulated hourly values. Singleton (1957) made a detailed comparison of ionograms with tabulated foF2 values over a nine month period. He found that over fifty percent of the occurrences of range type spread-F over Brisbane were not indicated by any qualifying symbol associated with the tabulated foF2 values.

The mild spread conditions shown in Figure 15, as well as the ground scatter shown in Figure 12 do not have any F qualifications in their tabulated values. The spread condition of Figure 13 is recorded only by UF (value uncertain due to spread condition) associated with the F2 M3000 value, and the spread condition of Figure 4 is recorded by the symbol F in place of the h'F value. In no one of these four cases is the occurrence of spread conditions indicated by the tabulated foF2 critical frequency values.

The f-plot is usually a more reliable indication of the presence of spread conditions than is the tabulated data. However, for the four ionograms in Figures 12 - 15, only the f-plot corresponding to the ionogram of Figure 13 gives an indication of the presence of spread-F.

2.8 Degree of Spread Condition

The degree of the spread condition may vary from a slight spread not obscuring the critical frequencies, as in Figure 15, to a heavy blanket of spread, as in Figures 3 and 7, which completely obliterates



PROBABILITY OF OCCURENCE OF SPREAD-F AT BAGUIO

(a) DIURNAL VARIATION

(b) ANNUAL VARIATION

FIGURE 16

TABLE 1

Various Methods Employed to Classify the
Degree of Spread-F Appearing on an Ionogram

Scale of Spread-F	Reference
0 to 3	Wright, Koster, and Skinner (1956) Briggs (1958)
0 to 4	Singleton (1957)
1 to 8	Meek and McKerrow (1951)
"faint", "moderate" and "strong"	Reber (1954 a)

TABLE 2

List of Studies Treating of Spread-F
at Particular Locations

Mag. Lat.	Location	Authors
74°N	Baker Lake	Meek, (1952)
74°N	Spitzbergen	Whatman, (1949)
57°N	Ottawa	Hartz, (1955)
54°N	Slough	Briggs, (1958 a, b); Dagg, (1957 c)
50°N	Washington	Reber, (1954 b)
25°N	Japan	Kasuya, Katano and Taguchi, (1955)
21°N	Hawaii	Reber, (1954 a)
14°N	Ahmedabad	Kotadia, (1959)
11°N	Ibadan	Lyon, Skinner and Wright, (1958)
1°S	Huancayo	Wells, (1954) Booker and Wells, (1938)
10°S	Singapore	Osborne, (1951)
36°S	Brisbane	McNicol, Webster and Bowman, (1956) McNicol and Webster, (1956) Singleton, (1957) Bowman, (1960)

the F region critical frequencies. A number of different systems have been employed to record the amount of spread appearing on the ionograms (see Table 1). Such methods are desirable for detailed studies of spread-F, particularly for those of a comparative nature. However, variations in equipment, antenna design, transmitter output and receiver gain, as well as the human factor in scaling records must all be given due consideration.

3. THE OCCURRENCE OF SPREAD-F

The diurnal and seasonal pattern of spread-F occurrence changes markedly with magnetic latitude and sunspot cycle. Shimazaki (1959) has made a comprehensive world-wide survey of the probability of spread-F occurrence for 1954 (year of sunspot minimum) and for the IGY (sunspot maximum). Reber (1956) made a briefer study on a world-wide basis. Table 2 lists a number of studies of spread-F at particular stations.

3.1 Diurnal Variations

Spread-F is generally a nighttime occurrence except at polar or near polar stations, where it occurs also during the day. Figure 16 (a), representing the diurnal variation of spread-F occurrence probability at Baguio (5°N geomagnetic) at times of sunspot minimum and sunspot maximum, illustrates the relation of the sunspot cycle to the diurnal pattern of spread-F occurrence. The Baguio data are roughly typical of other equatorial stations (see Shimazaki, 1959). In middle latitudes, there appears to be a consistent tendency for spread-F occurrence to peak somewhat in the post midnight hours.

3.2 Seasonal Variations

For stations near the geomagnetic equator the occurrence of spread-F is significantly greater during local summer than during local winter. Although the seasonal pattern may vary with the sunspot cycle, as indicated in Figure 16 (b) (see also Kotadia, 1959) generally the occurrence of spread-F in this equatorial region is greater in summer than in winter. For higher (north and south) magnetic latitudes just the opposite is usually observed, with spread-F more frequent in the winter than in summer. However, it has been observed (Reber, 1956; Shimazaki, 1959) that the region where spread-F occurs more frequently in summer than in winter also includes, besides the equatorial stations, a number of high northern latitude stations in the Pacific area, and a corresponding number of high southern latitude stations in South America. The dividing lines separating those high latitude stations where spread-F predominates in summer from those where it predominates in winter lie roughly along a great circle, defined as the "spread-F equator". The position of this spread-F equator varies with sunspot activity. The nearest approach of the spread-F equator to the magnetic equator occurs at sunspot minimum.

3.3 Solar Cycle Variation

The yearly average spread-F occurrence probability is dependent on geomagnetic latitude and on sunspot activity. At geomagnetic latitudes above 60° the occurrence probability of spread-F increases with sunspot number. At lower magnetic latitudes, the correlation between yearly average spread-F occurrence probability and sunspot activity is inverse (Shimazaki, 1959).

3.4 Correlation with Magnetic Activity

The correlation of spread-F with magnetic activity is dependent on latitude as well as sunspot cycle. Shimazaki (1959) found that the correlation between the occurrence probability of spread-F and magnetic activity is strongly negative for magnetic latitudes lower than 20°, shifting to strongly positive for latitudes between 20° and 60°, while at latitudes higher than 60° it again becomes negative.

In the equatorial regions (Wright, Koster and Skinner, 1956; Lyon, Skinner and Wright; 1958, 1959; Wright, 1959) spread-F during IGY was regularly present on magnetically quiet days, but markedly inhibited on magnetically disturbed days. For several African stations in the vicinity of or north of the magnetic equator during 1952-53, Wright and Skinner (1959) find an enhancement of spread-F on magnetically quiet days to be pronounced only during the summer solstice. From an analysis of spread-F data at Baguio from 1953 to 1958 Marasigan (1960) notes that magnetically disturbed days generally inhibit spread only during the years of high sunspot number.

For magnetic latitudes between 40° and 60° North a direct correlation of magnetic activity with the probability of spread-F occurrence increases with increase of latitude (Dagg, 1957 c; Hartz, 1955; Appleton, Naismith and Ingram, 1937). For magnetic latitudes over 60° the correlation again becomes negative. However, as Shimazaki (1959) points out, at such high latitudes, magnetic disturbances are usually associated with polar blackouts, which preclude the possibility of spread-F observations.

Additional studies over complete sunspot cycles and at various locations would be desirable. Cohen (1959) has suggested investigating some possible connection of spread-F at a given height above the magnetic equator with the magnetic activity at the base of the field line passing through this region.

3.5 Correlation with the Virtual Height of the F2 Region

There is a marked correlation between the virtual height of the F2 layer and spread-F occurrence (see, for example, Bowman, 1960). Spread usually occurs only when the virtual heights are relatively high for the station in question. Kasuya, Katano and Taguchi (1955) observed that in Japan the diurnal peaks of spread-F occurrence coincide with the times of virtual height maxima for the F2 layer. At Baguio the evening onset of spread-F is preceded by virtual heights of 400 km, higher on the average than at any other time. The disappearance of spread is frequently correlated with the decrease of virtual heights (Booker and Wells, 1938). Osborne (1952) at Singapore found a striking positive correlation between the mean monthly rate of increase of the virtual height of the F2 layer between 1800 and 1900, local time, and the occurrence of spread-F at 2000. He also found that the virtual height of the F2 layer attained its peak height at the moment of sunset at the 400 km level, and that the time of greatest rate of increase of virtual height is the period from terrestrial sunset till sunset at the 400 km level, some hour-and-a-half later.

3.6 Inverse Correlation with the Maximum Critical Frequency, foF2

There is a rather marked inverse correlation between the probability of occurrence of spread-F and the maximum critical frequency foF2. Kasuya, Katano and Taguchi (1955) correlated spread-F occurrence at four Japanese stations over a six-year period with the reciprocal of the monthly mean noon values of foF2. The correlation coefficient was + 0.82.

The evening onset of range type spread-F, characteristic of many equatorial stations, is normally preceded by a significant drop in the value of foF2 (Wells and Stanton, 1938, 1939). However, it is to be noted that there is a much sharper decrease in foF2 during the pre-dawn period at equatorial stations, and yet the probability of spread-F decreases toward sunrise. Brisbane (38°S geomagnetic) lies in a region where spread-F has a pre-dawn peak, but the diurnal variation of foF2 is not as great there as at equatorial stations. Singleton (1957) reports that significant pre-dawn frequency spread occurs at Brisbane only when the value of foF2 falls below 4 Mc.

3.7 Correlation with Radio Star Scintillations

Although the existence of spread-F has been known for over twenty years (Booker and Wells, 1938), it is only since its connection with the scintillation of radio stars was pointed out (Ryle and Hewish, 1950; Little and Maxwell, 1951) that significant attention has been given to spread-F.

Galactic radio noise was first identified by K.G. Jansky in 1932 (Haddock, 1958). Later work showed that this radiation comes from discrete sources (Bolton and Stanley, 1948) and that it exhibits irregular short period fluctuations (Hey, Parsons and Phillips, 1946). Such fluctuations of "radio stars" can be shown to be either fluctuations in the apparent position of the discrete source, "phase scintillations"; or fluctuations in the intensity of the received radiation, "amplitude scintillations" (Lawrence, 1958). Under highly disturbed conditions, the shift in apparent position of a radio star can be as great as one-half a degree (Hewish, 1952). The question arose early as to whether the fluctuations were due to actual intensity variations in the source itself, or were imposed on the signal by some property of the medium traversed by the signal. Little and Lovell (1950) showed that if the scintillations are observed by two receivers 100 meters apart, there is complete correlation of the scintillation patterns. Increasing the separation of the receivers decreases the correlation, which indicates that the cause of the fluctuations is not located in the source. In seeking a cause for these fluctuations in the ionosphere, it was found that a definite correlation can exist between the occurrence of spread-F and that of radio star scintillation (Ryle and Hewish, 1950; Little and Maxwell, 1951).

Whatever the mechanism responsible for the scintillation phenomena, it must be operative essentially along the line of sight from the observer to the source. When the radio star is near the horizon, the line of sight passes through the F region at a point many hundreds of kilometers away from the observer. Also, the spread echoes returning to a vertical incidence ionosonde need not always return from directly overhead (McNicol, Webster and Bowman, 1956). The difficulty in correlating accurately the occurrence of spread-F and scintillation is therefore apparent.

Little and Maxwell (1951) found that, for high angles of elevation, the occurrence of scintillations coincided with the observation of spread-F 75 percent of the time, even though the scintillation measurements were made at Jodrell Bank while the ionosonde was located at Slough, some 230 km to the south. For radio sources located close to the horizon, continual scintillations are observed. Similar results have been reported (Mills and Thomas, 1951). For low angles of arrival, however, of the order of 10° or less, Dueno (1955) at Ithaca, and Bolton, Slee, and Stanley (1953) in Australia found only a small correlation of scintillation with spread F, but a rather good correlation with sporadic E (see also Wild and Roberts, 1956).

The difference in results is probably closely connected with the angle of observation, which modifies the effective thickness of the disturbing region, and with the increased separation of the disturbing

TABLE 3

Experimental Procedures for
Obtaining Data on Spread-F

Method	Reference
h'-f ionogram	Conventional
A-scan	Conventional
h'-t	Conventional
h'-t, swept gain	McNicol, Webster and Bowman, (1956)
h'-t, swept frequency	Nakata, Kan and Uyeda, (1953 a)
f_c-t	Nakata, Kan and Uyeda, (1953 b)
Direction of Arrival	Thomas and McNicol, (1955) Miya, et al, (1957) Bibl, Harnishmacher and Rawer, (1955)
Phase Path	Findlay, (1951) Jones, (1953) Yuhara, Koseki and Aono, (1954) McNicol, Webster and Bowman, (1956)

region from the location of the observer (Little, Rayton and Roof, 1956).

The correlation of the occurrence of spread-F with the scintillation of radio stars has been useful, since a fair amount is known about the conditions of the ionosphere at the time of scintillations. The dimensions of the irregularities in ion-density in the F region thought to be responsible for scintillation are of the order of five km in width (Bolton, Slee, and Stanley, 1953), often quite elongated, with a tendency to lie in bands parallel to the magnetic field (Spencer, 1955). The irregularities have a horizontal drift motion in an approximately east-west direction, with a drift velocity reaching at times several hundred meters per second (Salzberg and Greenstone, 1951; Skinner, Hope and Wright, 1958).

3.8 Correlation with Scintillations of Radio Signals from Satellites

The character of radio signals received from artificial satellites provides information on the state of the ionosphere along the path of propagation. Parthasarathy, Balser and DeWitt (1959) detected irregularities in ionization in the auroral zone up to heights of 800-1000 km, by employing two spaced receivers. Yeh and Swenson (1959) suggest that the region producing scintillations on the satellite signals is between 200 and 300 km, and find a strong positive correlation between such scintillation and the occurrence of spread-F, see Table 3.

4. INSTRUMENTATION

Spread-F is usually defined with respect to the appearance of the trace on the conventional virtual height versus frequency ionogram (h'-f). In making detailed studies of the occurrence and nature of spread-F a number of other experimental techniques have been employed. Table 3 presents some of these.

4.1 A-scan

At times it is helpful to present an A-scan pattern of the returned echo at a fixed frequency, by displaying the intensity of the returned echo versus the delay time on the face of an oscilloscope tube. This procedure yields information on the relative intensity of the different portions of the spread echo, which may exhibit a multiplet structure. A-scan, used in conjunction with the conventional sweep-frequency ionosonde, can serve as a useful indicator for adjusting the receiver gain setting to minimize the effect of background noise.

4.2 Virtual Height Versus Time (h'-t) Records

The conventional h'-f ionograms are usually taken at fifteen-minute intervals. It is sometimes desirable to have a continuous record of the conditions of the ionosphere. However, successive h'-f sweeps can produce possible local interference, and also necessitate additional scaling time to obtain the data from the successive ionograms. For the purpose of spread-F studies it is frequently satisfactory to employ a single pulsed frequency rather than the swept frequency method. In this method of fixed frequency probing, the recording film is continually moved to produce a time base, while the returning echo intensity modulates the electron beam, which is deflected at right angles to the direction of film travel to indicate virtual height. The result is an h'-t plot. Such a procedure is useful in studying range type spread-F, since, over a wide range of frequencies, the degree of range-spread is independent of frequency.

4.3 Swept Gain h'-t Records

Since the extent of spread-F appearing on an ionogram is somewhat gain-sensitive, McNicol, Webster and Bowman (1956) included a swept gain technique in their h'-t records. They permitted the gain of the receiver to fall in steps of 2 db through a total of 80 db over a period of two minutes, after which the receiver is returned to maximum gain and the cycle repeated. They find that as the gain decreases, what at first appeared to be a diffuse spread resolved itself into a set of multiplets.

4.4 Swept Frequency h'-t Records

Depending on the fixed frequency selected, either the E, F_1 or F_2 regions may be studied. Usually blanketing by the lower layers prevents the viewing of several layers at the same time. Nakata, Kan and Uyeda (1953 a) combined a limited but rapid variation in the probing frequency together with the h'-t procedure. In one experiment the frequency was varied from 1.8 Mc to 3.5 Mc in ten seconds, while the film speed was only about 3.5 centimeters per hour. This rapid variation of frequency over a limited range, superimposed on the h'-t records, does not cause any appreciable blurring of the record. Good resolution is thus obtained, and the film shows layer thickness, spread echoes absorption, and the minimum height of each layer.

4.5 Critical Frequency versus Time (f_c-t) Records

Another variation by this group (Nakata, Kan and Uyeda, 1953 b) yields a continuous record of the maximum critical frequency. The method may be visualized by considering first the standard h'-f ionogram. Let the h' axis be collapsed. The film is then continuously moved at right angles to the horizontal or frequency axis, while the oscilloscope is z-modulated by the returning echo. The resulting pattern on the film is a plot versus time of the maximum frequency returned from the ionosphere. Frequency type spread-F will readily show up on such records.

4.6 Direction of Arrival

In any detailed study of spread echoes it is important to know the direction of arrival of the returning echo. The normal delta antenna system used on vertical incidence equipment has its maximum sensitivity in the direction of the zenith, but it still has appreciable gain in directions other than the vertical.

Thomas and McNicol (1955) employed two sets of parallel loop antennas separated by one-half wave length. Each of the two sets is mounted at right angles to the other set, one north-south, and the other east-west. An echo returning from directly overhead will arrive at all four loop antennas in phase. However, there will be a relative phase difference at the different loop antennas if the wave returns from any direction other than the zenith.

For the north-south pair of antennas, the phase difference ϕ of the echo pulses in the two antennas will be proportional to the angle the returning wave makes with the north. Thomas and McNicol show that the ratio of the absolute value of the difference of the signals in the two antennas to the absolute value of the sum of the two signals is proportional to ϕ and therefore proportional to the angle of arrival. In practice the sum and difference voltages are applied to the Y and X plates of an oscilloscope, and the slant of the resulting trace indicates the angle of arrival the returning echo makes with the north. A similar arrangement is also used for the east-west pair of antennas.

A more sophisticated version of the above has been developed by Miya, Sasaki, Ishikawa and Matsushita (1957). They use four vertical antennas instead of the loops, and insert a fifth vertical antenna in the center of the array to remove a 180° ambiguity in the direction of arrival of the returning echo.

A rather simple arrangement that can be used with the already established vertical incidence sounding equipment is described by Bibl, Harnischmacher, and Rawer (1955). This procedure consists in interchanging the antenna feeding arrangement for the rhombic antennas, so that the antenna will alternately have a null and a maximum in the zenith direction. With such an arrangement traces on the h'-f ionogram produced by echoes returning from directly overhead will have an interrupted appearance, while oblique echoes are more continuous. There is, however, no indication of azimuth on the ionogram.

4.7 Phase Path Measurements

The conventional vertical incidence pulse technique measures the time taken for the transmitted pulse to return to the receiver via a particular path from the reflecting region. The accuracy of this measurement will depend on the pulse width, receiver characteristics, focus of the oscilloscope, film grain-size, etc. Small height variations, of a kilometer or two, can be detected only with difficulty from successive h'-f ionograms. The "phase path" measurement, however, indicates any small variation in phase path in the medium through which the signal is passing.

Let the probing frequency of a fixed frequency h'-t vertical incidence sounder be f. A signal of frequency $(f - \epsilon)$ from a stable local oscillator is fed into the detector stage of the receiver along with the returning echo from the ionosphere. The injected signal has an angular dependence given by

$$\cos (ft - \epsilon t) ,$$

while the angular dependence of the returned echo signal is

$$\cos (ft - P/\lambda) ,$$

where P is the total phase path of the signal and λ is the wave length. Due to the non-linearity of the detection process in the receiver a difference frequency is generated, with an angular dependence given by

$$\cos (\epsilon t - P/\lambda) .$$

With suitable low pass filters, if there is no returned echo signal there will be no output signal from the receiver. When there is a returned signal, the receiver output can be approximated by a wave packet, where the number of cycles in the packet will depend on the value selected for ϵ, the original duration of the transmitted pulse, and the pulse deformation during the time of travel in the ionosphere. This means that the usual h'-t echo traces will then appear to be striated, and any change in the phase path length will cause the striations to be inclined with respect to the horizontal or time axis. The whole process is much like the counting of interference fringes in an interferometer, and each striation corresponds to a phase path difference of λ. However, it is to be recalled that λ is itself a function of the index of refraction and therefore will differ with changes of the ion density along the path of propagation. With this type of equipment small changes of phase path are readily detected.

4.8 Indirect Methods

Other observational methods have been employed in conjunction with studies of spread-F. These methods, while they do not measure spread-F directly, do study phenomena that appear to have an intimate connection with spread-F occurrence. Some of these are listed in Table 4.

5. POSSIBLE MECHANISMS RESPONSIBLE FOR SPREAD-F

It is generally felt that spread-F owes its origin to irregularities in the electron density of the ionosphere. In this connection two questions arise:

(1) What is the configuration of electron density which produces the observed spread-F patterns?

(2) How does such a configuration arise?

The patterns of spread-F occurrence suggest the possibility that the responsible mechanism may differ with season, location and spread-F type. The first question will be discussed in the present section, while the second question will be treated in the section following. Table 5 lists several proposed mechanisms thought to be responsible for the appearance of spread-F on certain ionograms.

5.1 Reflections from Horizontally Moving Fronts

A detailed study of range type spread-F has been carried on by a Brisbane group (McNicol and Webster, 1956; McNicol, Webster and Bowman, 1956). Evidence is presented to indicate that range multiplets have their origin in reflections from horizontally moving fronts in the F region, with dimensions of up to several hundred kilometers, and that range type spread-F is generally a series of closely spaced multiplets in the vicinity of the main F trace. Frequency type spread-F is not considered, as it is thought to have its origin in another mechanism.

McNicol and Webster (1956) fit their theory of range type spreading into the pattern of large scale ionospheric movements. They consider in some detail three types of irregularities, an inverted trough (Munro, 1953), a gap, and a step, and suggest that each satellite trace is a reflection of the incident pulse from such irregularities.

By the use of three pulse transmitters located at the corners of a right triangle of 95 km base and altitude, simultaneous measurements were made of slant virtual range, R', of the satellites of the main F

TABLE 4

Indirect Methods for Obtaining Data
Relative to Spread-F Occurrence

Method	Reference
Radar echoes	Peterson, Villard, Leadabrand and Gallagher, (1955)
Oblique incidence pulses	Bateman, Finney, Smith, Tveten and Watts, (1959)
Radio Star scintillations	Booker, (1958)
Horizontal drift motions	Briggs and Spencer, (1954)

TABLE 5

Some Proposed Mechanisms
Responsible for Spread-F

Mechanism	References
Reflection from horizontally moving ionospheric fronts	McNicol and Webster, (1956) Uyeda and Ogata, (1954)
Reflections from large irregularities in ionization	Singleton, (1957)
Reflection from horizontal stratification	Eckersley, (1953) Sung and Kwei, (1938)
Forward scatter plus reflection	Eckersley, (1937) Renau, (1959)
Backscatter	Booker and Wells, (1938)
Aspect sensitive backscatter	Renau, (1958) Bowles and Cohen, (1959)

trace. Taking the virtual height of the main F trace as h', the horizontal displacement, x, was deduced from the relation

$$x = (R'^2 - h'^2)^{\frac{1}{2}} \qquad (1)$$

for each of the three transmitters.

It was found that if three points, T_1, T_2 and T_3 are plotted to represent the geographical location of the transmitters, one can draw about these points circles of radius x_1, x_2 and x_3 respectively, corresponding to the echo measurements at a given time. There is rarely, if ever, a common intersection of these three circles, but it is usual for the three circles to have a common tangent. Continued observation showed the common tangent to move roughly parallel to itself, although at times this direction was somewhat changed. The azimuth of the returned echo corresponded roughly to a normal to this common tangent. Variations in the zenith angle, θ, of the returned echo conformed quite closely to the relation

$$R' = h' \sec \theta \, . \qquad (2)$$

The h'-f ionograms indicate that for range type spread-F the separation of the satellite traces from the main trace is independent of frequency over a wide range of frequencies. McNicol and Webster were able to obtain a good deal of data from h'-t measurements at a fixed frequency, sufficiently low to eliminate any effect of ordinary and extraordinary trace separation. Detailed studies of the results show the motions of these irregularities, indicating the time and distance of closest approach. The intensity of the satellite trace decreases with increasing slant range, obeying approximately a linear relationship of -0.4 db/km. The average length of these moving fronts in the F region was found to be of the order of 300 km, with a mean duration of from one to two hours. The speed generally varied from 150 to 350 km/hr, with the mean direction toward a little north of west.

The explanation of range multiplets as reflections from horizontally moving disturbances, as presented by McNicol and Webster (1956) is inviting. The authors restrict themselves to range spread alone. Their explanation fits most clearly the case of a single satellite trace, although the extension to a number of such satellites all closely spaced is immediate.

Using continuous observations of virtual height at a fixed frequency interval, Uyeda and Ogata (1954) obtained evidence of apparent ionospheric undulations moving with a horizontal speed of from 300 to 420 km/hr. The length of the undulations was about 300 km and the maximum depth appeared to be greater than 100 km. The corresponding virtual height versus frequency ionograms indicated a range multiplicity and at times a diffuse range type spread-F. There may, therefore, be some connection between spread F and systematic ionospheric drifts.

Horizontal drift motions of the ionosphere have been recognized for some time. Pawsey (1935) separated two receivers by 170 meters and noted that on occasion the recorded fading curves were displaced from each other by up to one second. This he interpreted to be the result of an ionospheric wind. Munro (1948), employing a more elaborate arrangement, utilized three transmitters placed at the corners of a right triangle with legs of 13 and 27 miles. He estimated winds with speeds of up to 100 m/sec. Mitra (1949), with a single pulse transmitter and three receivers spaced 100 and 200 meters apart at the corners of a right triangle, found the most frequent velocity to be about 50 m/sec. Much work has been done along these lines, both experimental and theoretical, and excellent summaries are given by Ratcliffe (1955) and by Briggs and Spencer (1954).

Tilts in the F layer were first noted by Ross and Bramley (1949) and subsequently Price (1953) reported large scale traveling disturbances, responsible for peaks and dips of F layer virtual height, and splitting of ordinary and extraordinary rays. Such disturbances are reported to have an average speed of about 100 - 200 m/sec, and the velocity of the disturbance to remain substantially constant over distances of up to several thousand kilometers.

In general these F region ripples drift in such a way that the east-west component of their motion is eastward by day and westward by night, with an appreciable increase of velocity in times of magnetic disturbance. The maximum vertical displacement of the ripple is of the order of 5 km. There are few points understood concerning these irregularities. It is not clear if the movement involves the neutral air as well as the ions, and electrons, and if there is any net transfer of ionization or merely a wave motion, as the name ripple seems to suggest. The origin of these large scale movements and their ultimate decay process is still undetermined.

5.2 Reflection from Large Irregularities in Ionization

Singleton (1957) suggested that frequency type spread-F is, due to reflections from irregularities in the F region large, compared to the wave length of the incident wave. Noting the correlation between spread-F occurrence and the scintillation of radio stars, he assumes that the same ionization irregularities are responsible for both effects.

A. Relative Ion Density of Irregularities Responsible for Radio Star Scintillations

The irregularities in the F region ionization thought to be responsible for the scintillations of radio stars are taken to be of the order of 5 km in diameter (Ryle and Hewish, 1950; Little, 1951; Booker, 1958). Little (1951) has shown what must be the difference in plasma frequency between the irregularity and the surrounding medium for scintillations to occur. The difference in phase path for a wave traveling through the irregularity or through the surrounding medium must amount to one-half wave length for destructive interference to occur. From the definition of the index of refraction, μ, the change in wave length, $\Delta\lambda$, of a wave of length λ due to a change $\Delta\mu$ of the refractive index of the medium is given by

$$\Delta\lambda = \frac{\lambda\,\Delta\mu}{\mu} . \qquad (3)$$

For an irregularity of diameter ℓ the total path difference required for scintillation is given by

$$(\ell/\lambda)\,\Delta\lambda = (\ell/\lambda)\left(\frac{\lambda\,\Delta\mu}{\mu}\right) \geqq \lambda/2 . \qquad (4)$$

Provided that the refractive index of an ionized medium does not depart appreciably from unity, it may be expressed as

$$\mu = \left\{1 - (f_p/f)^2\right\}^{\frac{1}{2}} = 1 - \frac{1}{2}\,(f_p/f)^2 + \ldots \qquad (5)$$

For scintillation observations, a plasma frequency, f_p, of 3 Mc and an observing frequency, f, of 50 Mc are not unreasonable, and justify dropping the additional expansion terms in (5). The difference in refractive index, $\Delta\mu$, between the background region and the irregularity of plasma frequency f_p', is

$$\Delta\mu = \frac{1}{2f^2}\,(f_p'^2 - f_p^2) . \qquad (6)$$

Using this value of $\Delta\mu$ in (4) we obtain the inequality

$$\frac{\ell}{fc}\left(f_p'^{2} - f_p^{2}\right) \geqq 1. \tag{7}$$

For an irregularity diameter of 5 km, the difference in plasma frequency between the irregularity and the background ionization necessary for scintillation may be as small as 0.5 Mc. This value is comparable to the extent of frequency type spread encountered on many ionograms.

B. Reflection and Interference

On the assumption that the irregularities which produce scintillation are identical with those responsible for spread-F, (5 km in extent, differing in plasma frequency from the background by about 0.5 Mc) wave from the ionosonde will be reflected since the dimensions are large compared to the incident wave length. However, interference will occur between the reflections from several irregularities and the background layer. Also, a spread of critical frequencies will be obtained.

The angular power spectrum for a wave reflected from a screen of irregularities has been given by Booker, Ratcliffe, and Shinn (1950) and also by Briggs and Phillips (1950). The reflected power falls off rapidly for directions at large angles to the normal to the reflecting screen. If the F region is to be considered as such a screen above a vertical incidence sounder, the irregularities directly overhead will reflect back maximum power (with a minimum delay time), while those at greater lateral distances will reflect back proportionately less power (and with a greater delay time). The reflected waves from each irregularity will interfere to produce marked fading.

Suppose an arbitrary minimum power, determined by the sensitivity of the receiving and recording equipment, is required of the wave returned from the individual irregularity in order that its contribution affect the ionogram. The ionosonde can then observe only those irregularities lying within a certain cone whose semi-angle is a function of the height of the irregularities and their mean dimensions. Singleton has shown that the number of irregularities, n, observable in a layer at a height, h, above an ionosonde using a probing frequency, f, is of the form

$$n \propto h^2/b^4f^2 , \tag{8}$$

where b is the average horizontal distance between the irregularity centers. Under conditions obtaining in the ionosphere, n can be great enough to account for the rapid fading of the returned spread echoes.

The degree of frequency spread in the penetration frequency is, in general, independent of any assumptions regarding the horizontal distribution pattern of the irregularities. Rather, it is a function of the extremes of ion density along the horizontal layer. According to (8), a small decrease in probing frequency below the maximum penetration frequency implies that effectively the ionosonde can view more irregularities, and these at slightly greater virtual ranges. This would result in a slight range broadening of the echo trace, and also fading due to interference of the echoes returning from the different irregularities. Further decrease in the probing frequency would heighten this effect. However, since the irregularities are thought to be embedded in the F region ionization, a decrease in the probing frequency means that irregularities embedded more deeply in the F region will not be observed. This effect will be the more pronounced the greater is the zenith angle of the irregularity.

An increase in receiver gain has the effect of increasing the semi-angle of the cone of admissible echoes. This should increase the density of the diffuse trace, and also the virtual range. In general this will not result in a spread of penetration frequencies, provided the variations in peak electron density are randomly spread throughout the horizontal layer.

C. Scintillation and Spread-F

Irregularity in ionization is a necessary and sufficient condition for radio star scintillation. However, according to Singleton's explanation it is not a sufficient condition for frequency type spread-F. If the irregularities exist above the F layer maximum ion density, scintillations will be observed, but not spread-F. Hewish (1952) has pointed out that fluctuations in the intensity of cosmic radio noise start in the evening, reach a maximum shortly after midnight, and decay slowly, lasting late into the following morning. Spread-F, however, appears to be predominately a nighttime phenomenon. The sharp cutoff of spread-F with local sunrise may be associated with the predawn drop in virtual height, so that irregularities are obscured by the F layer maximum beneath them (Booker and Wells, 1938). The world-wide summer increase in the virtual heights of the F region might be a factor expected to account for the seasonal variation of spread. In latitudes less than 20°, this seems to be the case. However, for latitudes greater than 20°, spread-F is more common in the winter than in the summer. At present insufficient knowledge is available concerning the heights of the irregularities responsible for scintillations to clarify these matters completely.

5.3 Reflection from Horizontal Stratifications

A. Simple Stratification

A much oversimplified explanation of range type spread-F would suggest that the region above the F layer maximum is stratified, which somehow accounts for satellite traces above the main trace of the ionogram. There are, however, indications that this explanation is not correct.

Irrespective of spread, the main trace frequently remains unchanged in appearance, suggestive of a well defined layer maximum of uniform consistency. For range type spread there is at times a single sharply defined critical frequency which indicates a definite uniformity in the structure of the layer. It is difficult to see how the probing wave could actually penetrate this F layer to get to the stratification above the F region maximum. Yet considerable penetration would at times be required to account for the observed intensity of the spread echo.

A second factor against the simple stratification hypothesis, at all but polar latitudes, is the angle of arrival of the returning echo. For satellites of large range separation, McNicol, Webster and Bowman (1956) have found that the returning signal arrives at a considerable angle with the vertical. In many instances, the virtual height of the main trace, h', of the satellite trace, R', and the zenith angle θ, of the returning satellite echo follow the simple relationship,

$$\cos \theta = h'/R' , \tag{9}$$

which is what would be expected if the satellite echoes are all reflected from the same height as the main trace.

B. Stratification in the Polar Regions

Eckersley (1953) points out that spread-F in the polar regions is frequently a daylight occurrence, and that spread echoes in these regions generally return from the zenith. When the effects of vertical radiation are neglected, solar radiation, on a simple Chapman theory (Chapman, 1931) will produce the usual well defined E and F layers. If charged particles from the sun approach the earth, their easiest path of approach will be in the polar regions, due to the action of the earth's magnetic field. If the ionizing effect of these incoming particles is to be included in a simple Chapman theory, Eckersley points out that the vertical diffusion term can no longer be neglected.

Eckersley believed that the vertical distribution of electron density, ρ (z), is governed by the equation

$$\frac{d\rho}{dt} = q - \alpha\rho^2 + D\frac{d^2\rho}{dz^2}, \qquad (10)$$

where q accounts for the ionizing effects of solar radiation and the incident particles, α is the recombination coefficient, and D is the diffusion coefficient, including the effects of the magnetic field. He solved this equation for the steady state ($d\rho/dt = 0$), and found that the admissible solutions for ρ (z) involved doubly periodic elliptic functions. Physically this means that while the solar radiation causes layers to be formed that are many wave lengths thick with respect to the probing frequency of the ionosonde, the incident particles cause the formation of very thin layers, only a few wave lengths thick, embedded in the background of the thick layers. Eckersley also showed mathematically that this type of layer structure would cause a single incident pulse to return a series of delayed echoes, sufficient to account for the spread effects on an ionogram. This theory applies only to polar spread, where the geomagnetic field is predominately vertical.

Additional angle of arrival studies and correlations with solar flares and radio noise outbursts should prove enlightening. It would seem that some seasonal variation of polar spread-F should be predictable on this theory due to the changing length of the polar day.

C. Multiple Reflection Between the F1 and F2 Layers

Sung and Kwei (1938) noted from a limited number of observations that a spread condition resulted after the coming together of the F1 and F2 layers in the evening. They suggested that the spread effect might result from multiple reflections between closely adjacent layers. Such an explanation, if correct, would account for only a very limited number of occurrences of spread-F.

5.4 Forward Scatter Plus Reflection

A. E Region Scatter with F Region Reflection

An early suggestion advanced by Eckersley (1937) attributed spread-F to scatter from moving irregularities in the E region followed by a regular reflection process in the F region (or alternatively, F reflection followed by E scatter). Evidence of this mode of propagation has been presented by Meek (1952) in observational data obtained at Baker Lake, Canada. He even noticed a brief return directly from the E region at the moment when the sporadic E cloud was computed to be directly overhead. Meek (1952) observed a difference in critical frequency between the main trace and the satellite traces, which is consonant with the different angle of arrival of the main trace, reflected vertically from the F layer, and the satellite, reflected obliquely via the E scatter.

In a great number of range spread instances, McNicol and Webster (1956) find no difference observable between the critical frequency of the main trace and of the satellite traces. There are many occasions when Es echoes occur with no spread-F, and vice versa. Also McNicol, Webster and Bowman (1956) present instances where the F + Es echo is either absent or quite weak, while the satellite traces are of high intensity.

However, from the observational data presented by Meek (1952) it is clear that the process suggested by Eckersley can actually be operative on certain occasions.

B. A Postulated Scattering Screen Below the F Region

A theory of spread-F involving an F layer reflection coupled with a scattering process below the F region has been considered by Renau (1959). A thin scattering screen, invisible on the ionograms, is postulated to exist above the E region. Propagation is considered to be that of forward scatter from this screen followed by F layer reflection. A parabolic F region of arbitrary semi-thickness and height is assumed, and a thin scattering screen is set beneath it at an arbitrary height above the flat earth. Delay time as a function of probing frequency is calculated for various sets of parameters. Depending on the position on the thin screen of the forward scatter, a family of admissible delay times are obtained, bounded by a suitable envelope. Comparison with ionograms shows that some cases of spread actually do admit of such an analysis. However, in general, the minimum delay times exceed those actually observed on the ionograms, even with all possible variations of the height of the thin scattering screen below, and even coinciding with, the F region maximum.

In a transequatorial transmission experiment Bowles and Cohen (1959) found that propagation via F scatter occurred only about 10 percent of the time along their 2580 km propagation path, and this during evening hours, generally before midnight. A sufficient and nearly necessary condition for the occurrence of such oblique F scatter was found to be the presence of range type spread-F on the vertical incidence Huancayo ionograms, located close to the midpoint of the transmission path. By variation of the ionosonde antenna pattern, and by oblique incidence pulse delay measurements, the height of the propagation medium sustaining this F scatter was established, in general, as the lowest height of the associated equatorial spread-F on the Huancayo ionograms. Such results are not compatible with the scatter plus reflection theory of Renau (1959).

5.5 Back Scatter

An early attempt to explain the spread echoes on the Huancayo records by back scatter is due to Booker and Wells (1938). They point out that, to a first approximation in Rayleigh scatter, the ratio of the intensity of the scattered radiation, i, to the incident radiation I, is given by

$$i/I \propto f^4 (\mu^2 - \mu_o^2)^2 , \qquad (11)$$

where f is the frequency of the radiation in question, and μ and μ_o are the refractive indices of the scattering medium and the surrounding medium respectively. However, for Rayleigh scatter it is necessary that the scatterer be small with respect to the incident wave length.

Equation (11) appears to indicate a definite frequency dependence for the scattered radiation, but the Huancayo ionograms do not bear this out. It should be recalled, however, that to a first approximation the index of refraction of the ionosphere may be expressed in terms of particle charge, mass and density as

$$\mu^2 = 1 - \frac{N}{(\pi m/e^2)\, f^2} , \qquad (12)$$

and therefore

$$\mu^2 - \mu_o^2 = \frac{(N_o - N)\, (e^2/\pi m)}{f^2} . \qquad (13)$$

Substituting (13) in (11) we find that the ratio of scattered to incident radiation is independent of frequency but depends on the relative difference of ion density in adjacent regions of the ionosphere:

$$i/I \propto (N - N_o)^2 \, (e^2/\pi m)^2 . \qquad (14)$$

This is valid as long as the wave length of the radiation is large compared to the dimensions of the scattering areas. On the Huancayo ionograms the spread becomes weaker toward the higher frequencies and generally disappears entirely at 11 or 12 Mc, corresponding to a wave length of about 25 meters. Therefore irregularities in ion density of some 25 meters in diameter are postulated to explain this spread phenomena.

These irregularities are thought to exist above the F layer maximum during the early evening. For probing frequencies below the penetration frequency of the F layer maximum, these irregularities are effectively out of sight, while for higher frequencies, the irregularities are too large, in comparison with the small wave length, to permit appreciable scattering. However, later in the evening, the F region maximum rises above the level of these irregularities and Rayleigh scatter can take place for frequencies below 12 Mc accounting for the spread echo occurring on the ionograms at that time. Wells (1954), however, questioned the importance of this masking effect in accounting for the diurnal characteristics of spread-F.

This theory was advanced before radio star scintillations were observed. Such scintillation effects seem to suggest irregularity sizes of the order of five kilometers. Bowles and Cohen (1959) suggest the scale size of the irregularities measured normal to the magnetic field lines can be as small as 10 meters.

5.6 Aspect Sensitive Back Scatter

Renau (1960) has suggested that the observed spread-F ionograms may be the outcome of aspect sensitive back scatter from columns of ionization aligned along the earth's magnetic field. In accord with the work of Chapman (1953) and Booker (1956 b) this back scatter is assumed to be most intense when the incident ray is perpendicular to the field aligned column of ionization.

For an ionosonde at the dip equator the geometry is quite simple and echoes would be returned only in a plane in the east-west direction. The varying delay times responsible for the spread effect would depend on the existence of such field-aligned irregularities and their height relative to the F layer maximum. At stations away from the dip equator a wider selection of admissible paths is possible. North of the dip equator, a ray returned from the magnetic north should have the minimum delay time, while one returned from the south should have a maximum, and all intermediate delay times should be possible for other azimuth values of the returning echo. Bowles and Cohen (1959) report that at Huancayo, polarization measurements indicate that range spread echoes arrive from the magnetic east-west direction.

The theory is attractive and a number of ionograms lend support although others do not conform to this analysis. At middle latitudes Peterson et al (1955) obtained aspect sensitive echoes over a frequency

TABLE 6

Factors Suggested as Being Responsible for Irregularities in Ionization

Factor	Reference
E region turbulence communicated to the F region	Dagg (1957 a, b)
Instability of drifting ionization configurations	Martyn (1959 a, b, c) Clemmow, Johnson and Weeks (1955)
Corpuscular matter of inter-stellar origin	Ryle and Hewish (1950)
Charged particles of solar origin	Shimazaki (1959)
Evaporation of terrestrial atmosphere	Ratcliffe (1956)

range of from 6 to 30 Mc, provided the line of sight of the transmitter intersected a magnetic field line at a height corresponding to that of the E or F layer maximum. Attempts were made to correlate the times of these echoes with the occurrence of spread-F, since the aspect sensitive echoes are essentially a nighttime phenomena. Detailed correlation, however, was lacking, due perhaps to the fact that the spread-F observations were made in the vicinity of the transmitter, while the slant range of the aspect sensitive echoes varied from 600 to 1700 km. {See also Nichols (1959)}.

6. Factors Responsible for Irregularities of Ionization

All the foregoing possible mechanisms for spread-F postulate some type of irregularities of ionization. Several suggested processes for the formation of suitable irregularities have been advanced (Dagg, 1957 a), and are listed in Table 6.

6.1 E Region Turbulence Communicated to the F Region

A. Turbulence below 120 km

Visual observations of meteor trails and noctilucent clouds (Millman, 1959) and radio echoes from meteor trails (Greenhow and Neufeld, 1959) suggest that turbulence is a common occurrence in the ionosphere at least up to 100 km. Golitsyn (1959) has shown that the influence of the earth's magnetic field has little influence in suppressing turbulent motions in the lower atmosphere, and Howells (1959) has pointed out that a combination of turbulence, diffusion, and a magnetic field cannot alone be expected to produce irregularities that are strongly elongated along the magnetic field, certainly not with dimensions much in excess of two to one. It is to be recalled that the ratio of neutral to charged particles is never less than 1000 to 1. On the experimental side, Nichols (1959) presents evidence based on radio observations of back scatter from ionospheric irregularities that there do exist at heights of from 80 to 300 km, small scale irregularities definitely elongated along the earth's magnetic field. There is general feeling (Booker, 1959) that turbulence does not exist in any marked degree above 120 km (See Maxwell, 1954).

B. Richardson's Criterion

In the upper regions of the earth's atmosphere there are drift motions (Ratcliffe, 1955; Briggs and Spencer, 1954). Their horizontal velocity, $\vec{u}$, varies with height and therefore laminar flow and shear can be envisioned, and under certain conditions laminar flow may develop into turbulence.

In turbulent motion a mass of fluid may be moved upward into a region of lower density. Work is required and therefore the displaced mass can be considered to have increased potential energy. Due to the velocity gradient with height, the fluid mass will be swept along in the higher region with increased velocity, and therefore its kinetic energy will also be changed. A dimensionless quantity, Richardson's number, R_i, is defined for a unit mass of displaced fluid as

$$R_i = \frac{\text{Change in Potential Energy}}{\text{Change in Kinetic Energy}} . \tag{15}$$

Thus for a large value of R_i, the potential energy change, and hence the work required for such a vertical displacement is many times greater than the increased kinetic energy resulting from such a displacement. This implies a high degree of stability and the suppression of turbulence. However for R_i appreciably less than unity, the kinetic energy increment arising from a vertical displacement is greater than the work required for the displacement and turbulence is possible and even fostered. Thus, Richardson's number is a criterion for turbulence. It may be expressed as

$$R_i = \frac{(g/T)\left(\frac{\partial T}{\partial z} + \Gamma\right)}{\left(\frac{\partial u}{\partial z}\right)^2} , \tag{16}$$

where T and g are the absolute temperature and the acceleration due to gravity; $\frac{\partial u}{\partial z}$ is the vertical velocity gradient, and Γ is the adiabatic lapse rate.

With sunset the upper atmosphere cools with a corresponding decrease in the temperature gradient, tending to make R_i smaller. Although, as Lowan (1955) has shown, during the first two-and-a-half hours after sunset the drop in temperature at 360 km is of the order of 400°K, yet at heights below 160 km the temperature has hardly changed during this same period. Moreover the adiabatic lapse rate, Γ, is generally several times larger than the temperature gradient term. Since the velocity gradient appears to the second power, this term has a greater effect on the value of R_i. Dagg (1957 b) finds R_i to be 700 at 90 km, and not much different at 135 km. Such a large value indicates that turbulence should be greatly inhibited at these heights, which is apparently not the case. This points up the approximate nature of Richardson's criterion as applied to the upper atmosphere, and of the present state of the question of turbulence in the ionosphere.

C. Magnetic Field Lines as Equipotentials

Dagg (1957-b) suggests that turbulence of ionization below 120 km sets up a varying electric field, superimposed on a mean electric field arising from the interaction of the tidal flow of ionization with the geomagnetic field (Baker, 1953; Baker and Martyn, 1952, 1953; Chapman and Bartels, 1940). Since the conductivity along the magnetic field lines is so much greater than that transverse to them, these magnetic field lines determine lines of equal electric potential. Thus the variations in the electric field in the E region are transmitted up along the magnetic field lines into the F region. In this region of enhanced ionization, irregularities in the ion and electron density result. It is not necessary to postulate a turbulent motion of the unionized atmosphere at F region heights, and indeed such turbulence of the neutral air is thought not to occur.

Such a propagation of the electric field from the dynamo region up into the F region via the so-called equipotentials is thought to be quite possible by Martyn (1959 a, b, c). Horizontal electric fields produced in the dynamo region, of the order of 1000 km in extent can readily be thought to produce an effect in the higher F region via the magnetic field lines. However, field variations a few kilometers in extent in the dynamo region could much less readily be propagated the requisite distance into the F region. Farley (1959) has considered this question and finds that such a process is theoretically possible, but it depends rather critically on limited conditions of source height, and to a lesser extent, on temperature and ionization profiles. Such small fields propagated into the F region can be shown to vary by one or two powers of ten for plausible diurnal variations of the ionosphere parameters. Such variations may be associated with the diurnal behavior of spread-F.

If the above explanation offered by Dagg is substantially correct, at least some effects of the turbulence in the dynamo region should be observed at the time of occurrence of spread-F. However, there is little or no consistent correlation between the occurrence of spread-F and sporadic E (Lawrence, 1958).

6.2 Instability of Drifting Ionization Configurations

It might be objected against Dagg that the perturbing fields communicated to the F region from below may not be sufficient to produce the irregularities thought to be responsible for spread-F. A theory advanced by Martyn (1959 a, b, c) explains how such small perturbations in the F region may become appreciably enhanced under certain circumstances.

Martyn considers that the F layer as a whole will drift vertically, under the action of large scale electric fields from below and interactions with the earth's magnetic field. He shows the perturbations in ionization on the undersurface of an upward drifting layer are inherently unstable, and will move, relative to the drifting medium, in such a way as to enhance their difference in ionization from the surrounding medium.

A. Development According to Martyn

Martyn considers the ionosphere as a thin ionized sheet. He notes that while currents can flow in the plane of the sheet, a current flow normal to the sheet will be inhibited due to the finite thickness of the ionized region. At the dip equator the magnetic field is running north-south in the plane of the ionized sheet. A horizontal east-west electric field would tend to set up vertical Hall currents. However, due to the finite thickness of the ionosphere, these vertical Hall currents will at length be inhibited by polarization effects at the upper and lower surfaces of the layer. At other regions away from the dip equator the situation is more involved. Here, there will be a magnetic component both in the layer and also normal to it. The resultant conductivities are a function of the magnetic dip angle and also of the heights, since the different conductivities have a different dependence on ν, the collisional frequency, which is itself a function of height (see Appendix A). Due to this polarization, Baker and Martyn (1953) show that in the F region the Hall conductivity is much less significant than the Pedersen conductivity and therefore may be neglected.

Let a cylinder of neutral ionization be embedded in a region of differing ion density, and be aligned with the geomagnetic field. Let the entire region be drifting vertically under the action of an electric field. If the surrounding medium were non-conductive, Chapman and Ferraro (1931) showed that the cylinder would be free to move at right angles to the magnetic field. Viewed from the outside the cylinder is electrically neutral. Inside, the walls of the cylinder become polarized in such a way that the effect of the magnetic field is neutralized within.

However when the surrounding medium has a non-zero conductivity some of the polarization will leak away, giving rise to a leakage current in the medium and also within the cylinder. Martyn assumes that this leakage current will be divergenceless. Physically this means that while there may be accretions or depletions of (neutral) ionization at the boundary of the cylinder, yet there will be no build up of un-neutralized positive or negative charge. The plausibility of such an assumption stems from the fact that the electrostatic forces opposing accumulations of free (un-neutralized) charge are much greater than the diffusion forces opposing concentrations of neutral ionization.

If the background medium of ionization density N has a vertical drift velocity V, then Martyn states that the cylinder of ionization density $N + \Delta N$ will move relative to the background medium with a velocity given by

$$- V \left(\frac{\epsilon}{2 + \epsilon} \right) , \tag{17}$$

where $\epsilon = \Delta N/N$. (see Appendix B).

Suppose the F region as a whole to be drifting upwards, and that somewhere on the underside of this region is a field aligned blob of ionization of differing density. If this blob is slightly denser than its surroundings, then $V > 0$ and $\epsilon > 0$ and therefore by (17) this blob will drift downwards with respect to the medium, into regions of still less dense ionization. Likewise an underdense blob ($\epsilon < 0$) would drift into regions of greater ionization. Conversely, should the layer as a whole be drifting downwards, such an overdense blob on the under-surface would move relatively upward into regions of comparable ion density, and become identical with its surroundings.

Martyn thus shows that spread-F should occur only if the F region is moving upwards, and should be inhibited if the F region is moving downwards. Also a steep ionization gradient on the underside of the F layer should enhance spread-F occurrence. The upper surface of the F layer is thought to have a gentle ionization gradient. For a descending F region, an overdense blob of ionization ($V < 0$, $\epsilon > 0$) above the F layer maximum would move into regions of still less electron density. Since this is on the upper surface, the effects should not be manifest as spread-F but possibly as radio star scintillations. However, this effect for a descending F region should be less pronounced since the top-side ionization gradient is more gradual than the underside.

B. Development According to Clemmow, Johnson and Weeks

An alternate approach to this same problem of instability has been taken by Clemmow, Johnson and Weeks (1955). They make no assumptions regarding the smallness of the Hall conductivity, but do assume that not only is the net ionization current divergenceless, but also that the positive ion current and negative ion current are each separately divergenceless. They seek a steady state solution in which the irregularity will retain its original shape over the given period of interest. They find such a solution possible provided that the cylinder has a velocity with respect to the surrounding medium. No steady state solution appears possible for a three dimensional irregularity due to the high conductivity along the magnetic field lines (Ratcliffe, 1959). While their conclusions differ from Martyn's in detail (especially that there is no build up of neutral ionization at the boundary of the cylinder), the general results of movement with respect to the surrounding medium remain the same. The occurrence of spread at times of increasing F layer virtual height appears to be in accord with this explanation.

6.3 Corpuscular Matter of Extraterrestrial Origin

The irregular ionization of the E region has been correlated with the incidence of meteors (Appleton and Naismith, 1947; Lovell, 1948). However, there appears to be no general relation between the occurrence of spread-F, and known meteor showers.

Interstellar corpuscular matter, other than meteors as a possible cause of scintillations and spread-F has been proposed by Ryle and Hewish (1950). Such matter would be attracted by the sun's gravitational field and would tend to impinge on the dark side of the earth. Due to the orbital velocity of the earth, this would occur from about 2000 to 0800 local time, with a maximum at 0200. The earth's magnetic field might possibly modify this diurnal distribution, and seasonal variations in spread-F occurrence could be accounted for by the general motions of the solar system with respect to this interstellar matter.

The shift in seasonal characteristics of spread-F occurrence with sunspot cycle (see Figure 16) is not accounted for by the above explanation. Such a process should be operative from night to night. Also it is not clear how such a mechanism would produce patch-like irregularities only a few kilometers or less in extent.

6.4 Charged Particles of Solar Origin

Charged particles approaching the earth find their easiest path of approach at high latitudes. Shimazaki (1959) suggests that such charged particles are the cause of spread-F at high latitudes. He notes for latitudes in excess of 40° the gradual increase of spread-F occurrence probability with latitude, and also the correlation, at higher latitudes of spread occurrence with geomagnetic disturbances, especially striking if the masking effects of "blackouts" are considered.

The suggestion is inviting, and a fuller explanation is desired, indicating in what way the incident particles produce the variations in electron density apparently required for spread-F.

6.5 Evaporation of Terrestrial Atmosphere

A different approach suggested in a symposium by Ryle has been reported by Ratcliffe (1956). Ryle discussed the work of a group in the USSR on the counterglow or "gegenschein". The tenuous outer regions of the earth's atmosphere are repelled by the radiation pressure of the sun much like the effect on a comet's tail. This process would occur on the dark side of the earth and, Ryle suggests, the streaming would tend to occur along the lines of magnetic force. Irregularities in the ionization of the upper regions of the atmosphere could be caused by such a streaming, or "evaporation" process.

This model does have the advantage of explaining nicely the field aligned orientation of these irregularities. However, it would seem also to require that spread-F and scintillation should occur every evening rather than randomly, as is actually observed. Daytime spread, an occasional occurrence, is difficult to explain. In the equatorial regions the magnetic field lines are almost parallel to the earth's surface, making the escape of charged particles a difficult process. Moreover the onset of spread-F and scintillations is frequently delayed until several hours after the F region has entered the earth's umbra, and it is hard to see how radiation pressure could have the desired effect in the F region at this time.

7. CONCLUDING REMARKS

(1) The division of spread-F into high-, middle-, and low-latitude type is not completely satisfactory. The designation of spread as range type and frequency type is desirable, although even this division is not necessarily comprehensive.

(2) Statistical studies of spread-F occurrence based solely on the qualifying symbols appearing with the tabulated data of foF2, F2 M3000 and h'F, leave something to be desired.

(3) The pattern of spread occurrence changes over the sunspot cycle. Care must be used in generalizing from records covering only a part of one cycle. Further studies at particular locations over a full sunspot cycle will be useful.

(4) More direction of arrival studies for spread echoes should prove significant in determining the extent of spread areas and something of the nature of the spread mechanism.

(5) A single mechanism need not be postulated to explain all types of spread occurrences. The same phenomena may be produced by significantly different mechanisms.

as

$$\vec{J} = \sigma_o \vec{E}_{11} + \sigma_1 \vec{E}_{\perp} + \sigma_2 \, (\vec{H} \times \vec{E}) \, H^{-1}. \tag{A3}$$

The current density may also be expressed in terms of the density of charge carriers, N, as follows

$$\vec{J} = N \, e \, \vec{v} \, . \tag{A4}$$

By combining (A4) with (A3) and using the solution of (A2) in terms of $\vec{v}$, the following values for the conductivities are obtained:

$$\sigma_o = \frac{Ne^2}{m} \cdot \frac{1}{\nu} \, , \quad \text{Longitudinal conductivity} \tag{A5-a}$$

$$\sigma_1 = \frac{Ne^2}{m} \; \frac{\nu}{\omega^2 + \nu^2} \, , \quad \text{Pedersen conductivity} \tag{A5-b}$$

$$\sigma_2 = \frac{Ne^2}{m} \; \frac{\omega}{\omega^2 + \nu^2} \, , \quad \text{Hall conductivity,} \tag{A5-c}$$

where $\omega = eH/m$. If more than one type of charge carrier is significant, additional terms involving the charge, mass, number density and collision frequency of each type are included. Note that the longitudinal conductivity is appreciably greater than the conductivity transverse to the magnetic field. This tends to make the magnetic field lines act as equipotentials.

9. APPENDIX B

Martyn's Theory of Vertical Drift Motions

The following is a simplification of the treatment presented by Martyn (1953) since the original paper is somewhat condensed.

Consider a cylinder of ionization density N + $\triangle$ N of radius r_o, aligned with a magnetic field $\vec{H}$ directed along the negative z-axis in a medium of ion-density N. Suppose a uniform, constant electric field, $\vec{E}$, is perpendicular to $\vec{H}$ (a z-component of the electric field is of no particular interest here as the resulting motion is well understood), and assume that in the surrounding region the Hall conductivity is effectively neutralized.

The external electric field may be expressed in polar coordinates as

$$E_r = E \cos \phi , \tag{B1-a}$$

$$E_\phi = -E \sin \phi . \tag{B1-b}$$

Since the medium is of non-zero conductivity a leakage current of ionization will develop which is assumed to be divergenceless. The ionization distribution gives rise to a polarization potential S, and a corresponding electric field, - grad S, which is imposed on the constant field given by (B1). The resultant current pattern, employing the Pedersen conductivity, is given by

$$J_r = \sigma \left(E \cos \phi - \frac{\partial S}{\partial r}\right) , \tag{B2-a}$$

$$J_\phi = \sigma \left(-E \sin \phi - \frac{1}{r} \frac{\partial S}{\partial \phi}\right) . \tag{B2-b}$$

The requirement that the ionization current be divergenceless leads to

$$\nabla \cdot \vec{J} = 0 = \frac{1}{r} \frac{\partial}{\partial r} (r J_r) + \frac{1}{r} \frac{\partial}{\partial \phi} (J_\phi) . \tag{B3}$$

By using the current distribution of (B2) in (B3) we find the restriction that must be placed on the polarization potential S:

$$\frac{\partial^2 S}{\partial r^2} + \frac{1}{r} \frac{\partial S}{\partial r} + \frac{1}{r^2} \frac{\partial^2 S}{\partial \phi^2} = 0 . \tag{B4}$$

To obtain the solution for (B4), assume that

$$S = R(r)\, \Phi(\phi) , \tag{B5}$$

which yields the pair of equations

$$\Phi''(\phi) = -\lambda^2 \Phi(\phi) , \qquad \text{(B6-a)}$$

$$r^2 R''(r) + rR'(r) - \lambda^2 R(r) = 0 , \qquad \text{(B6-b)}$$

where λ^2 is the separation constant. The solution of (B6-a) is of the form

$$\Phi = A' \cos(\phi + \eta) , \qquad \text{(B7)}$$

where A' and η are constants of integration (by symmetry considerations, $\lambda = 1$).

For the radial equation (B6-b) we require $R(o) = 0$ from symmetry, and also $\lim_{r \to \infty} R(r) = 0$. Since σ, the conductivity of the medium, is a function of ion-density, it will differ within and outside the cylinder and therefore two solutions will be sought, for $r < r_o$ and $r > r_o$. Clearly we expect continuity of the two solutions for $r = r_o$. The simplest solutions that will satisfy these requirements are

$$R(r) = A'' r \qquad \text{for} \qquad r \leq r_o , \qquad \text{(B8-a)}$$

$$R(r) = A'' r_o^2/r \qquad \text{for} \qquad r \geq r_o . \qquad \text{(B8-b)}$$

The full solution of (B4) is

$$S = Ar \cos(\phi + \eta) \qquad \text{for} \qquad r \leq r_o , \qquad \text{(B9-a)}$$

$$S' = A(r_o^2/r) \cos(\phi + \eta) \qquad \text{for} \qquad r \geq r_o , \qquad \text{(B9-b)}$$

where primed quantities refer to the region external to the cylinder.

Since the dimensions of S, the polarization potential, are (field strength) x (length), A may be expressed as QE, where Q is a dimensionless constant and E is the electric field strength of the uniform

(6) The explanations of McNicol and Webster (1956) for range type spread, and of Singleton (1957) for frequency type spread, seem to be valid for the observational data presented. However, it is quite possible that other mechanisms may be operative in other regions.

(7) The theoretical work of Dagg (1957) and of Martyn (1959) need not be contradictory, as both processes may be operative at the same time. Additional investigations on the occurrence of turbulence, and also on layer height changes with spread-F occurrences are desirable.

8. APPENDIX A

Ionospheric Conductivity

The conductivity, σ, of a unit volume of a substance may be expressed in terms of the applied electric field, $\vec{E}$, and the resultant current density, $\vec{J}$, as

$$\vec{J} = \sigma\vec{E} , \tag{A1}$$

where σ is in general a tensor and a function of the number of available charge carriers and their mobility. In the ionosphere, the more free electrons and ions present, the greater the conductivity. Even in the more highly ionized regions, however, the ratio of neutral to charged particles is hardly ever less than 1000 to 1, and therefore collisions of charged particles with neutral particles will significantly affect the conductivity.

Since the net force acting on a particle is equal to the rate of change of the particle's momentum, we obtain the equation of motion of a particle of charge e, and mass m in an electric and magnetic field, $\vec{E}$ and $\vec{H}$, as follows:

$$\vec{E} e + e \vec{v} \times \vec{H} = m \dot{\vec{v}} + \nu m \vec{v} , \tag{A2}$$

where ν is the collisional frequency with neutral particles and $\vec{v}$ is the particle velocity.

If E is resolved into two components, $\vec{E}_{11}$ and $\vec{E}_{\perp}$, parallel with and perpendicular to the magnetic field, equation (A1) may be expressed external field. By using (B9) in (B2-a) we obtain $J(r)$ and $J'(r)$, the radial current distribution inside and outside the cylinder. Since it has been assumed that no net un-neutralized charge accumulated at the boundaries of the cylinder, we require that for all values of ϕ,

$$J(r_o) = J'(r_o) . \tag{B10}$$

The condition (B10) determines Q and η as follows

$$Q = \left(\frac{\sigma - \sigma'}{\sigma + \sigma'} \right) ; \; \eta = 0 . \tag{B11}$$

The Pedersen conductivity is directly proportional to N, the ion density. To a first approximation we have

$$\frac{\sigma}{\sigma'} = \frac{N + \Delta N}{N} , \tag{B12}$$

and therefore

$$Q = \frac{\epsilon}{2 + \epsilon} , \quad \text{where } \epsilon = \frac{\Delta N}{N} , \tag{B13}$$

and the expressions for the components of the current become

$$J_r = \sigma E \left(1 - \frac{\epsilon}{2 + \epsilon} \right) \cos \phi , \tag{B14-a}$$

$$J'_r = \sigma' E \left[1 - \frac{\epsilon}{2 + \epsilon} \left(\frac{r_o^2}{r^2} \right) \right] \cos \phi , \tag{B14-b}$$

$$J_\phi = - \sigma E \left(1 - \frac{\epsilon}{2 + \epsilon} \right) \sin \phi , \tag{B14-c}$$

$$J'_\phi = - \sigma' E \left[1 - \frac{\epsilon}{2 + \epsilon} \left(\frac{r_o^2}{r^2} \right) \right] \sin \phi . \tag{B14-d}$$

Note that each first term on the right side of (B14) represents the current flow due to the static external electric field, while the second term represents the "leakage" current, due to the non-zero conductivity of the medium. Since these currents flow in a plane perpendicular to the magnetic field, a lateral drift motion is to be expected. Let the velocity of this lateral drift be expressed by $\vec{U}$ and the resultant current as $Ne\vec{U}$. Since the conductivity is σ, the electric field must be $Ne\vec{U}/\sigma$, and the lateral force on a single charge is $Ne^2\vec{U}/\sigma$. But such a lateral force, produced by a velocity perpendicular to the magnetic field, must be equal to $\vec{J} \times \vec{H}/N$ and therefore

$$\vec{U} = \vec{J} \times \vec{H} \frac{\sigma}{N^2 e^2} \tag{B15}$$

and

$$U_r = \frac{H\sigma}{N^2 e^2} J_\phi = \frac{H\sigma^2 E}{N^2 e^2} \left(1 - \frac{\epsilon}{\epsilon + 2}\right) \sin \phi , \tag{B16}$$

$$U_r' = \frac{H\sigma'}{N^2 e^2} J_\phi' = \frac{H\sigma'^2 E}{N^2 e^2} \left[1 - \frac{r_o^2}{r^2} \left(\frac{\epsilon}{\epsilon + 2} \right) \right] \sin \phi . \tag{B17}$$

The desired result is given by (B17). This motion is in the direction of $\phi = \pi/2$, at right angles to the external electric field. For $r \gg r_o$, (B17) represents the drift motion of the medium as a whole. For $r = r_o$ we have a picture of the absolute drift motion of the cylinder, which is somewhat different than that of the surrounding medium. If V is the velocity of the medium as a whole, and v the absolute velocity of the cylinder, then

$$v = V - \frac{\epsilon}{2 + \epsilon} V , \tag{B18}$$

while the drift velocity of the cylinder relative to the surrounding medium is given by

$$- V \left(\frac{\epsilon}{2 + \epsilon} \right) . \tag{17}$$

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11. REFERENCES

Appleton, E.V. and Naismith, R., The radio detection of meteor trails and allied phenomena, Proc. Phys. Soc. 59, 461 (1947).

Appleton, E.V., Naismith, R., and Ingram, L.J., British radio observations during the Second International Polar Year, 1932-1933, Phil. Trans. Roy. Soc. 236, 191 (1937).

Baker, W.G., Electric currents in the ionosphere, II. The atmospheric dynamo, Phil. Trans. Roy. Soc. A 246, 295 (1953).

Baker, W.G. and Martyn, D.F., Conductivity of the ionosphere, Nature 170, 1090 (1952).

Baker, W.G. and Martyn, D.F., Electric currents in the ionosphere, I. The conductivity, Phil. Trans. Roy. Soc. A 246, 281 (1953).

Bateman, R., Finney, J.W., Smith, E.K., Tveten, L.H., Watts, J.M., IGY observations of F-layer scatter in the Far East, J. Geophys. Research 64, 403 (1959).

Bibl, K., Harnishmacher, E., and Rawer, K., Some observations on ionospheric movements, Physics of the Ionosphere, Physical Soc. (1955).

Bolton, J.G., Slee, O.B. and Stanley, G.J., Galactic radiation at radio frequencies, VI. Low-altitude scintillations of the discrete sources, Australian J. Phys. 6, 434 (1953).

Bolton, J.G. and Stanley, G.J., Observations of the variable source of cosmic radio frequency radiation in the constellation Cygnus, Australian J. of Sci. Research 1, 58 (1948).

Booker, H.G., Turbulence in the ionosphere with applications to meteor trails, radio star scintillations, auroral radio echoes and other phenomena, J. Geophys. Research 61, 673 (1956 a).

Booker, H.G., A theory of scattering by non-isotropic irregularities with applications to radar reflections from the aurora, J. Atmospheric Terrestrial Physics 8, 204 (1956 b).

Booker, H.G., The use of radio stars to study irregular refraction of radio waves in the ionosphere, Proc. IRE 46, 298 (1958).

Booker, H.G., Transactions of the International Symposium on Fluid Mechanics in the Ionosphere, J. Geophys. Research 64, 2042 (1959).

Booker, H.G., Ratcliffe, J.A. and Shinn, D.H., Diffraction from an irregular screen with applications to ionospheric problems., Phil. Trans. Roy. Soc. 242, 579 (1950).

Booker, H.G. and Wells, H.W., Scattering of radio waves by the F region of the ionosphere, Terr. Mag. and Atmos. Elect. 43, 249 (1938).

Bowles, K.L. and Cohen, R., Studies of scattering phenomena in the equatorial ionosphere based on VHF transmissions across the magnetic equator, Paper presented at URSI - Brussels meeting, September, 1959.

Bowman, G.G., Further studies of "Spread-F" at Brisbane - I. Experimental, Planet, Space Sci. 2, 133 (1960).

Briggs, B.H., A study of ionospheric irregularities which cause spread-F echoes and scintillation of radio stars, J. Atmospheric Terrestrial Physics 12, 34 (1958).

Briggs, B.H., The diurnal and seasonal variations of spread-F ionospheric echoes and the scintillations of a radio star, J. Atmospheric Terrestrial Physics 12, 89 (1958).

Briggs, B.H. and Phillips, G.J., A study of the horizontal irregularities of the ionosphere, Proc. Phys. Soc. B 63, 907 (1950).

Chapman, S., The absorption and dissociative or ionizing effect of monocromatic radiation in an atmosphere on a rotating earth, Proc. Phy. Soc. 43, 26 (1931).

Chapman, S., The geometry of radio echoes from the aurora, J. Atmospheric Terrestrial Physics 3, 1 (1953).

Chapman, S. and Bartels, J., Geomagnetism, Oxford University Press, (1940).

Chapman, S. and Ferraro, V.C.A., A new theory of magnetic storms, Terr. Mag. Atmos. Elect. 36, 77, 171 (1931), 37, 147 (1932).

Clemmow, P.C., Johnson, M.A. and Weeks, K., A note on the motion of cylindrical irregularities in an ionized medium, Physics of the Ionosphere, Physical Soc. (1955).

Cohen, R.S. (Private Communication, 1959).

Dagg, M., The origin of the ionospheric irregularities responsible for radio star scintillations and spread-F, I. Review of existing theories, J. Atmospheric Terrestrial Physics 11, 133 (1957 a).

Dagg, M., The origin of the ionospheric irregularities responsible for radio star scintillations and spread-F, II. Turbulent motion in the dynamo region, J. Atmospheric Terrestrial Physics 11, 139 (1957 b).

Dagg, M., Diurnal variations of radio star scintillations, spread-F, and geomagnetic activity, J. Atmospheric Terrestrial Physics 10, 204 (1957 c).

Dieminger, W., The scattering of radio waves, Proc. Phys. Soc. B 64, 142 (1951).

Dueño, B., Study and interpretation of low angle fluctuations from the radio star Cassiopeia as observed at Ithaca, N.Y., School of Elec. Eng., Cornell University, Research Dept., E.E. 263, Ithaca, N.Y., 1955.

Eckersley, T.L., Irregular ionic clouds in the E layer of the ionosphere, Nature 140, 846 (1937).

Eckersley, T.L., Recombination and diffusion and spread echoes from the ionosphere, Proc. Phys. Soc. B 66, 1025 (1953).

Farley, Jr., D.T., A theory of electrostatic fields in a horizontally stratified ionosphere subject to a vertical magnetic field, J. Geophys. Research 64, 1225 (1959).

Findlay, J.W., The phase and group paths of radio waves returned from the E region of the ionosphere, J. Atmospheric Terrestrial Physics 1, 353 (1951).

Golitsyn, G.S., On the influence of the magnetic field on the character of turbulence in the ionosphere, J. Geophys. Research 64, 2212 (1959).

Greenhow, J.S. and Neufeld, E.L., Measurements of turbulence in the 80 to 100 km region from radio echo observations of meteors, J. Geophys. Research 64, 2129 (1959).

Haddock, F.T., Introduction to radio astronomy, Proc. IRE 46, 3 (1958).

Hartz, T.R., Radio star scintillations and the ionosphere, Canadian J. Phys. 33, 476 (1955).

Hewish, A., The diffraction of galactic radio waves as a method of investigating the irregular structure of the ionosphere, Proc. Roy. Soc. A 214, 494 (1952).

Hey, J.S., Parsons, S.J. and Phillips, J.W., Fluctuations in cosmic radiation at radio frequencies, Nature 158, 234 (1946).

Howells, I.D., On the spectrum of electron density produced by turbulence in the ionosphere in the presence of a magnetic field, J. Geophys. Research 64, 2198 (1959).

Jones, R.E., Instrumentation for measuring changes in phase of ionospheric echoes, Rev. Sci. Instruments 24, 433 (1953).

Kasuya, I., Katano, S. and Taguchi, S., On the occurrence of spread echoes in the F region over Japan, J. Radio Research Labs. (Tokyo) 2, 329 (1955).

Kotadia, K.M., Spread-F in the ionosphere over Ahmedabad during the years 1954-57, Proc. Ind. Acad. Sci. A, 50, 259 (1959).

Lawrence, R.S., An investigation of the perturbations imposed on radio waves penetrating the ionosphere, Proc. IRE 46, 314 (1958).

Little, C.G., A diffraction theory of the scintillation of stars on optical and radio wave-lengths, Mon. Not. Roy. Astron. Soc. 111, 289 (1951).

Little, C.G., and Lovell, A.C.B., Origin of the fluctuations in the intensity of radio waves from galactic sources, Nature 165, 423 (1950).

Little, C.G. and Maxwell, A., Fluctuations in the intensity of radio waves from galactic sources, Phil. Mag., ser. 7, 42, 267 (1951).

Little, C.G., Rayton, W.M. and Roof, R.B., Review of ionospheric effects at VHF and UHF, Proc. IRE 44, 992 (1956).

Lovell, A.C.B., Meteoric ionization and ionospheric abnormalities, Report Prog. Phys. 11, 415 (1948).

Lowan, A.N., The cooling of the upper atmosphere after sunset, J. Geophys. Research 60, 421 (1955).

Lyon, A.J., Skinner, N.J. and Wright, R.W., Equatorial spread-F and magnetic activity, Nature 181, 1724 (1958).

Lyon, A.J., Skinner, N.J. and Wright, R.W., The geomorphology of equatorial spread-F, Paper presented at Brussels URSI meeting, September, 1959.

Marasigan, V., Geomagnetic and sunspot influences on spread-F in Baguio, (in press, 1960).

Martyn, D.F., Electric currents in the ionosphere, III. Ionization drift due to winds and electric field, Phil. Trans. Roy. Soc. A 246, 306 (1953).

Martyn, D.F., The normal F region of the ionosphere, Proc. IRE 47, 147 (1959 a).

Martyn, D.F., Sporadic-E region ionization, 'spread-F' and the twinkling of radio stars, Nature 183, 1382 (1959 b).

Martyn, D.F., Large-scale movements of ionization in the ionosphere, J. Geophys. Research 64, 2178 (1959 c).

Maxwell, A., Turbulence in the upper atmosphere, Phil. Mag. 45, 1247 (1954).

McNicol, R.W.E., and Webster, H.C., A study of 'spread-F' ionospheric echoes at night at Brisbane, II., Australian J. of Phys. 9, 272 (1956).

McNicol, R.W.E., Webster, H.C. and Bowman, C.G., A study of 'spread-F' ionospheric echoes at night at Brisbane, I., Australian J. of Phys. 9, 247 (1956).

Meek, J.H., Oblique reflexions of radio waves by way of a triangular path, Nature 169, 327 (1952).

Meek, J.H. and McKerrow, C.A., Ionospheric Observer's Instruction Manual, Ottawa, Defence Research Telecommunications Establishment, (1951).

Millman, P.M., Visual and photographic observations of meteors and notilucent clouds, J. Geophys. Research 64, 2122 (1959).

Mills, B.Y., Observations of the source of radio frequency radiation in the constellation of Cygnus, Australian J. Sci. Res. A 4, 158 (1951).

Mitra, S.N., A radio method of measuring winds in the ionosphere, Proc. IEE 96, III., 441 (1949).

Miya, K., Sasaki, T., Ishikawa, M. and Matsushita, S., Direct vision type direction finder for high frequency, Rep. Ionospheric Res. Japan 11, 1 (1957).

Munro, G.H., Short period changes in the F region of the ionosphere, Nature 162, 886 (1948).

Munro, G.H., Reflexions from irregularities in the ionosphere, Proc. Roy. Soc. A 219, 447 (1953).

Nakata, Y., Kan, M. and Uyeda, H., Sweep-frequency h't measurement of the ionosphere, Rep. Ionospheric Res. Japan 7, 1 (1953).

Nakata, Y., Kan, M. and Uyeda, H., Simultaneous measurements of sweep frequency h't and $f_c t$ of the ionosphere, Rep. Ionospheric Res. Japan 7, 129 (1953).

Nichols, B., Evidence of elongated irregularities in the ionosphere, J. Geophys. Research 64, 2200 (1959).

Osborne, B.W., Ionospheric behavior of the F2 region at Singapore, J. Atmospheric Terrestrial Physics 2, 66 (1952).

Parthasarathy, R., Basler, R.P. and DeWitt, R.N., A new method of studying the auroral ionosphere using earth satellites, Proc. IRE 47, 1660 (1959).

Pawsey, J.L., Further investigations of the amplitude variations of downcoming wireless waves, Proc. Cambridge Phil. Soc. 31, 125 (1935).

Peterson, A.M., Villard, O.G., Leadabrand, R.L., and Gallagher, P.B., Regularly-observable aspect-sensitive radio reflections from ionization aligned with the earth's magnetic field and located within the ionosphere layers at middle latitudes, J. Geophys. Research 60, 497 (1955).

Price, R.E., Traveling disturbances in the ionosphere, Nature 172, 115 (1953).

Ratcliffe, J.A., A survey of existing knowledge of irregularities and horizontal movements in the ionosphere, Physics of the Ionosphere, Physical Soc. (1955).

Ratcliffe, J.A., Movements in the ionosphere, Nature 177, 307 (1956).

Ratcliffe, J.A., Ionization and drifts in the ionosphere, J. Geophys. Research 64, 2102 (1959).

Reber, G., Spread-F over Hawaii, J. Geophys. Research 59, 257 (1954).

Reber, G., Spread-F over Washington, J. Geophys. Research 59, 445 (1954).

Reber, G., Worldwide spread-F, J. Geophys. Research 61, 157 (1956).

Renau, J., A theory of spread-F based on a scattering screen, J. Geophys. Research 64, 971 (1959).

Renau, J., Theory of spread-F based on aspect sensitive backscattered echoes, J. Geophys. Res. 65, 2269 (1960).

Ross, W. and Bramley, E.N., Tilts in the ionosphere, Nature 164, 355 (1949).

Ryle, M. and Hewish, A., The effects of the terrestrial ionosphere on radio waves from discrete sources in the galaxy, Mon. Not. Roy. Astron. Soc. 110, 381 (1950).

Salzberg, D.C. and Greenstone, R., Systematic ionospheric winds, J. Geophys. Research 56, 521 (1951).

Shimazaki, T., A statistical study of world-wide occurrence probability of spread-F, J. Radio Research Labs. (Tokyo) 6, 669 (1959).

Singleton, D.G., A study of "spread-F" ionospheric echoes at night at Brisbane, III. Frequency spreading, Australian J. of Phys. 10, 60 (1957).

Skinner, N.J., Hope, J. and Wright, R.W., Horizontal drift measurements in the ionosphere near the equator, Nature 182, 1363 (1958).

Spencer, M., The shape of irregularities in the upper ionosphere, Proc. Phys. Soc. B 68, 493 (1955).

Sung, P.L. and Kwei, C.T., Ionospheric measurements at Central China College, Wuchang, China, October, 1937 to June 1938, Terr. Mag. Atmos. Elect. 43, 453 (1938).

Thomas, J.A. and McNicol, R.W.E., Automatic recording of the direction of arrival of radio waves reflected from the ionosphere, Proc. IEE 102, B, 793 (1955).

Uyeda, H., and Ogata, Y., An example of the records of a traveling F2 layer in the nighttime, Rep. Ionospheric Res., Japan, 8, 103 (1954).

Webster, H.C., A study of 'spread-F' ionospheric echoes at night at Brisbane IV. Range spread, Australian J. of Phys. 11, 322 (1958).

Wells, H.W., F scatter at Huancayo, Peru, and its relation to radio star scintillations, J. Geophys. Research 59, 273 (1954).

Wells, H.W. and Stanton, H.E., The ionosphere at Huancayo, Peru November-December, 1937, Terr. Mag. Atmos. Elect. 43, 169 (1938).

Wells, H.W. and Stanton, H.E., Ionospheric characteristics at Huancayo, Peru, December, 1937 through December, 1938, Terr. Mag. Atmos. Elect. 44, 326 (1939).

Whatman, A.B., Observations made on the ionosphere during operations in Spitzbergen in 1942-43, Proc. Phys. Soc. 62 B, 307 (1949).

Wild, J.P. and Roberts, J.A., Regions of the ionosphere responsible for radio star scintillations, Nature 178, 377 (1956).

Wright, J.W. and Knecht, R.W., Atlas of Ionograms, National Bureau of Standards, Boulder, Colorado, 1957.

Wright, J.W., Knecht, R.W. and Davies, K., Ann. IGY III, Pt. I (1957).

Wright, R.W., The geomorphology of spread-F and characteristics of equatorial spread-F, J. Geophys. Research 64, 2203 (1959).

Wright, R.W., Koster, J.R. and Skinner, N.J., Spread-F layer echoes and radio star scintillations, J. Atmospheric Terrestrial Physics 8, 240 (1956).

Wright, R.W. and Skinner, N.J., Equatorial spread-F, J. Atmospheric Terrestrial Physics 15, 121 (1959).

Yeh, K.C. and Swenson Jr., G.W., The scintillation of radio signals from satellites, J. Geophys. Research 64, 2281 (1959).

Yuhara, H., Koseki, T. and Aono, Y., Equipment for the measurement of changes of the phase path of ionospheric echoes, J. Radio Research Labs. (Tokyo) 1, 11 (1954).

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THE NATIONAL BUREAU OF STANDARDS

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WASHINGTON, D.C.

ELECTRICITY. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics.

METROLOGY. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.

HEAT. Temperature Physics. Heat Measurements. Cryogenic Physics. Rheology. Molecular Kinetics. Free Radicals Research. Equation of State. Statistical Physics. Molecular Spectroscopy.

RADIATION PHYSICS. X-Ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

CHEMISTRY. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

MECHANICS. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Combustion Controls.

ORGANIC AND FIBROUS MATERIALS. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

METALLURGY. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

MINERAL PRODUCTS. Engineering Ceramics. Glass. Refractories. Enameled Metals. Constitution and Microstructure.

BUILDING RESEARCH. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials.

APPLIED MATHEMATICS. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

DATA PROCESSING SYSTEMS. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Applications Engineering.

ATOMIC PHYSICS. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics.

INSTRUMENTATION. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Office of Weights and Measures.

BOULDER, COLO.

CRYOGENIC ENGINEERING. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

IONOSPHERE RESEARCH AND PROPAGATION. Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services.

RADIO PROPAGATION ENGINEERING. Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.

RADIO STANDARDS. High frequency Electrical Standards. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time Standards. Electronic Calibration Center. Millimeter-Wave Research. Microwave Circuit Standards.

RADIO SYSTEMS. High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Space Telecommunications.

UPPER ATMOSPHERE AND SPACE PHYSICS. Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.

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