Vol. 6 No. 28 *Journal of the Radio Research Laboratories* *October 1959*

UDC 551.510.535

A STATISTICAL STUDY OF WORLD-WIDE OCCURRENCE PROBABILITY OF SPREAD-*F*

Part I. Average State

By

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(Received Aug. 10, 1959)

ABSTRACT

A statistical study of the occurrence probability of spread-*F* is made by the use of the IGY data for the whole world. The daily, latitudinal and seasonal variations of the probability are clarified. The comparison with the sunspot minimum year (1954) is also made. The statistical analyses are made for all sorts of days, including magnetically quiet or disturbed days. The result shows that all of the statistical properties much differs at higher and lower latitudes. This may suggest that the origin of spread-*F* essentially differs at these two latitudes. The entry of charged particles into the upper atmosphere certainly causes the spread-*F* at higher latitudes, while at lower latitudes the origin must be sought in the terrestrial atmosphere.

1. Introduction

Spread-*F* presents some useful information on turbulent motions in the upper atmosphere. There is no doubt that the upper atmosphere is more or less in a turbulent state. Irregularities of electron density that developed in ionospheric regions have made it possible to measure their drift velocities, and in particular, the scatter propagation due to *E*-region irregularities has already been put in practical use. But it is not seldom that a turbulent motion occurs in higher regions too, which may be learnt from the occurence of spread-*F* or radio star scintillations.

Theoretical study of turbulent motions in magnetohydrodynamics is certainly very difficult, and its experimental approach on the ground is restricted to some special cases. In these circumstances, particular value must be given to the study of occurrence probability of spread-*F* for the whole world, because it may give some knowledge of occurrence and development of turbulent motions in a rare ionized gas (ionosphere) under the influence of external (earth's) magnetic fields. In addition, for the practical use, the study of spread-*F* occurrence probability may afford some materials available for discussions on the possibility of the *F*-region scatter propagations.

The study of spread-*F* has been made by various workers. Booker and Wells (1938) and Welles (1954) studied the spread-*F* over Huancayo and found that the spread-*F* appears more clearly when the height of the *F*2 layer rises and the maximum electron density decreases at night. They interpreted the origin of spread-*F* as Rayleigh scattering due to spacial irregularities of electronic clouds in the *F* region. The similar result was also reported at Singapore by Osborne (1951). A statistical study of occurrence probability of spread-*F* was made by Kasuya, Katano, and Taguchi (1955) by making use of the observational data at four stations in Japan. Reber (1954 and 1956) also made a statistical study of spread-*F* occurrence probability by the use of widely distributed stations in the world. Workers in Australia published a series of bulky study of spread-*F* at Brisbane (McNicol, Webster & Bowman, 1956; McNicol & Webster, 1956; Singleton, 1957; and Webster, 1958). They developed some useful technique of observations by the fixed frequency equipment such as of virtual range measurement of fixed- and swept- gains, of phase-path measurement, and of measurement of the direction-of-arrival of waves, and could observe various ionospheric echoes, which were studied experimentally and theoretically in full detail in relation to the spread-*F* phenomenon.

In the present paper, the author intends to study the occurrence probability of spread-*F* for the whole world by the use of the observational data during the IGY (corresponding to the sunspot maximum) and in 1954 (the sunspot minimum year), in order to clarify its daily variations at various seasons and latitudes and also the dependency of the average probability upon the latitude, season, and solar activity. In part I (the present paper), the author will discuss the average state, including magnetically quiet or disturbed days. The relationship between the occurrence of spread-*F* and the geomagnetic activity will be discussed in the accompanying paper (part II).

2. Materials and Method

When scattered or spread echoes appear on the *h′–f* records, the symbol *F* may be written on the corresponding time of monthly tabulation sheets. From this symbolization we can not learn what kind and magnitude of spread-*F* occurred in reality, but it may be sufficient for the first stage of investigation to make clear the time and the place in which the spread echoes can be produced more frequently. So count was first taken of the number of *F*'s appearing on the sheets at each local hour of a day throughout the months. Then, dividing this by the number of all times of observations in each case, we can get the average probability of occurrence of spread-*F* at the local hour. After applying these calculations to various hours, we can get the average daily variation of occurrence probability at each station in the world.

The analysis was made of each season separately. For this purpose, the author classified all data from July, 1957, to June, 1958, into four groups according to the seasons, i. e. August, September, and October for autumn in the Northern hemisphere (or spring in the Southern hemisphere), November, December, and January for winter (or summer), February, March, and April for spring (or autumn), and May, June, and July for summer (or winter). The calculation was made of all stations whose data were available at Tokyo (C–2 Center) in Japan until April, 1959. From some stations the data are coming too late to make a full analysis throughout the year. Thus, it is very regrettable that, because of the delay of arrival of data and the partial distribution of existing observatories, there is a lack of very desirable data for some particular regions of the world. It may be safely said, however, that the world's morphology in general of the occurrence probability of spread-F may be satisfactorily obtained even from the present work.

In order to facilitate comparison between the sunspot maximum and minimum, similar analysis was also made of 1954 (January-December). The locations and abbreviations of the observatories used in the present study are tabulated in Table 1.

Table 1. Locations and abbreviations of ionospheric observatories available for the present paper (parts I and II)

	Station	abbreviation	Geomagnetic Lat.	Geomagnetic Long.	Geographic Lat.	Geographic Long.
1	Thule, Greenland	THU	87.0°	355.0°	76.6°	291.3°
2	Fletchers Ice, Canada	FLE	83.6°	222.0°	82.0°	258.0°
3	Resolute Bay, Canada	RES	83.0°	289.4°	74.7°	265.1°
4	Godhavn, Greenland	GOD	79.8°	32.7°	69.2°	306.5°
5	Svalbard, Norway	SVA	74.4°	133.5°	78.2°	15.5°
6	Baker Lake, Canada	BAK	73.7°	315.5°	64.3°	264.0°
7	Narsarssuak, Greenland	NAR	71.2°	36.9°	61.2°	314.6°
8	Reykjavik, Iceland	REY	70.1°	71.1°	64.1°	338.3°
9	Churchill, Canada	CHC	68.7°	322.8°	58.8°	265.8°
10	Point Barrow, Alaska	POB	68.5°	241.2°	71.3°	203.2°
11	Tromso, Norway	TRS	66.9°	116.2°	69.4°	19.0°
12	Kiruna, Sweden	KIR	65.2°	115.7°	67.8°	20.5°
13	Fairbanks, Alaska	FAI	64.6°	256.6°	64.9°	212.2°
14	Sodankyla, Finland	SOD	63.9°	114.6°	67.4°	26.6°
15	Lulea, Sweden	LUL	62.9°	114.7°	65.6°	22.1°
16	Lycksele, Sweden	LYC	62.5°	110.8°	64.6°	18.8°
17	Meanook, Canada	MEA	61.8°	300.7°	54.6°	246.7°
18	Anchorage, Alaska	ANC	60.9°	258.2°	61.2°	210.1°
19	Inverness, Scotland	INV	60.7°	83.4°	57.5°	355.7°
20	Victoria Beach, Canada	VIC	60.6°	323.7°	50.8°	263.5°

Station	abbreviation	Geomagnetic		Geographic	
		Lat.	Long.	Lat.	Long.
21 Kjeller, Norway	KJE	60.1°	103.0°	60.0°	11.1°
22 Oslo, Norway	OSL	59.5°	100.0°	59.6°	11.1°
23 Winnipeg, Canada	WIN	58.8°	322.9°	49.9°	262.6°
24 Upsala, Sweden	UPS	58.5°	106.0°	59.8°	17.6°
25 Saint Johns, USA	SAT	58.4°	21.4°	47.6°	307,3°
26 Nurmijarvi, Finland	NUR	57.8°	112.6°	60.5°	24.6°
27 Ottawa, Canada	OTT	56.9°	351.5°	45.4°	284.3°
28 Juliusruh/Rugen, Germany	JUL	54.5°	98.4°	54.6°	13.4°
29 Slough, England	SLO	54.3°	83.3°	51.5°	359.4°
30 De Bilt, Netherlands	DeB	53.7°	89.5°	52.1°	5.2°
31 Lindau, Germany	LIN	52.1°	93.9°	51.4°	10.1°
32 Doubres, Belgium	DOU	51.9°	87.6°	50.1°	4.6°
33 Fort Monmouth, USA	FOM	51.0°	354.0°	40.3°	285.9°
34 Moscow, USSR	MOS	50.8°	120.6°	55.5°	37.3°
35 Washington, USA	WAS	50.0°	350.3°	38.7°	282.9°
36 Schwarzenburg, Germany	SCH	48.0°	88.7°	46.5°	7.2°
37 Adak, Alaska	ADA	47.2°	240.1°	51.9°	183.4°
38 Graz, Austria	GRA	46.9°	97.0°	47.1°	15.5°
39 Monte Capellino, Italy	MON	45.8°	90.0°	44.6°	9.0°
40 San Francisco, USA	SAF	43.6°	298.6°	37,4°	237.8°
41 White Sands, USA	WHI	41.2°	317.0°	32.3°	253.5°
42 Grand Bahama, USA	GRB	37.8°	351.6°	26.7°	281.6°
43 Wakkanai, Japan	WAK	35.2°	206.1°	45.4°	141.7°
44 San Juan, Puerto Rico	SAN	29.9°	2.1°	18.5°	292.8°
45 Akita, Japan	AKI	29.4°	205.5°	39.7°	140.1°
46 Tokyo, Japan	TOK	25.4°	205.5°	35.7°	139.5°
47 Maui, Hawaii	MAU	20.8°	268.2°	20.8°	203.5°
48 Panama Canal Zone	PAN	20.6°	348.6°	9.4°	280.1°
49 Yamagawa, Japan	YAM	20.3°	197.9°	31.2°	130.6°

Station		abbreviation	Geomagnetic		Geographic	
			Lat.	Long.	Lat.	Long.
50	Delhi, India	DEL	18.8°	149.0°	28.6°	77.2°
51	Paramaribo, Surinam	PAR	17.0°	14.8°	5.8°	304.8°
52	Bogota, Columbia	BOC	16.0°	355.8°	4.5°	285.8°
53	Okinawa, Japan	OKI	15.2°	195.7°	26.3°	127.8°
54	Taipei, Formosa	TAI	14.0°	189.0°	25.0°	121.5°
55	Ibadan, Nigeria	IBA	10.6°	74.8°	7.4°	3.9°
56	Bombay, India	BOM	9.8°	143.9°	19.0°	73.0°
57	Talara, Peru	TAL	6.6°	350.0°	− 4.6°	278.7°
58	Baguio, Phil. Is.	BAG	5.0°	189.3°	16.4°	120.6°
59	Chiclayo, Peru	CHL	4.4°	350.2°	− 6.8°	280.2°
60	Madras, India	MAD	3.0°	150.1°	13.0°	80.2°
61	Chimboto, Peru	CHM	2.2°	350.4°	− 9.1°	281.4°
62	Tiruchirapall, India	TIR	1.0°	148.5°	10.8°	78.8°
63	Huancayo, Peru	HUA	− 0.5°	354.0°	−12.0°	284.8°
64	Trivandrum, India	TRV	− 1.2°	147.0°	8.4°	77.0°
65	Singapore, Malaya	SIG	−10.0°	172.7°	1.4°	103.7°
66	Sao Paulo, Brazil	SAO	−12.8°	22.5°	−23.4°	314.9°
67	Tucuman, Argentina	TUC	−15.5°	4.6°	−26.9°	294.6°
68	Rarotonga, Pacific	RAR	−20.9°	273.8°	−21.3°	200.2°
69	Johannesburg, S. Africa	JOH	−26.9°	91.4°	−26.1°	28.0°
70	Buenos Aires, Argentina	BUE	−23.1°	9.5°	−34.5°	301.5°
71	Townsville, Australia	TOW	−28.4°	219.0°	−19.3°	146.8°
72	Capetown, S. Africa	CAP	−32.7°	79.7°	−34.1°	18.2°
73	Brisbane, Australia	BRI	−35.7°	227.1°	−27.5°	153.0°
74	Falkland, S. America	FAL	−40.4°	12.0°	−51.7°	302.3°
75	Watheroo, Australia	WAT	−41.7°	185.8°	−30.3°	115.9°
76	Canberra, Australia	CAN	−43.9°	224.4°	−35.3°	149.0°
77	Christchurch, N. Z.	CHR	−48.0°	252.8°	−43.6°	172.7°

Station	abbreviation	Geomagnetic		Geographic	
		Lat.	Long.	Lat.	Long.
78 Deception, Antarctica	DEC	−51.5°	6.1°	−63.0°	299.3°
79 Hobart, Australia	HOB	−51.6°	224.5°	−42.9°	147.3°
80 Campbell Is., N. Z.	CAM	−57.2°	253.3°	−52.5°	169.2°
81 Macquarie Is., Pacific	MAC	−61.0°	243.3°	−54.5°	159.0°
82 Ellsworth, Antarctica	ELL	−66.9°	15.0°	−77.7°	318.9°
83 Cape Hallett, Antarctica	CAH	−74.9°	271.1°	−72.3°	170.3°
84 Pole Station, Antarctica	POE	−78.6°	0	−90.0°	0
85 Scott Base, Antarctica	SCT	−79.2°	293.8°	−77.8°	166.8°

3. Results and Discussion

3.1. Daily Variation

The average daily variations of the occurrence probability of spread-*F* at various stations are illustrated in Fig. 1, in which the result is arranged by seasons according to the geomagnetic latitude of each station. It can be seen in Fig. 1 that except at very high latitudes (polar cap region), the spread-*F* usually occurs only at night. Also, it can clearly be seen that at stations of latitude higher than 40 degrees in geomagnetic latitude the peak of the probability occurs slightly after midnight or even at hours just before sunrise, particularly in summer. On the contrary, at latitudes lower than 20 degrees, the time of the peak appreciably shifts to hours before midnight. Between 20 and 40 degrees the spread-*F* is a very rare event, although the similarity to higher latitudes as to the appearance of the peak between midnight and sunrise can partly be observed.

The shape of daily variation quite differs between the summer and winter. In summer, the spread-*F* occurs at rather short intervals at night concentrating at the hour of peak, which therefore makes a curve of daily variation having a single clear projection. On the contrary, in winter, the high probability extends over many hours. Therefore, the shape of daily variations gives a rather flat curve having several peaks. This seasonal difference in the shape of daily variations is certainly due to the difference in the length of night between the two seasons.

3.2. Latitudinal Variation

As is easily seen from Fig. 1, the average occurrence probability of spread-*F* depends largely upon the latitude. This can be seen more clearly in Fig. 2, which illustrates the variation of average occurrence probability with the geomagnetic latitude, the average being taken over 16–07 hours at night at each station. Fig. 2 shows four cases: the former two (a) and (b) are for the

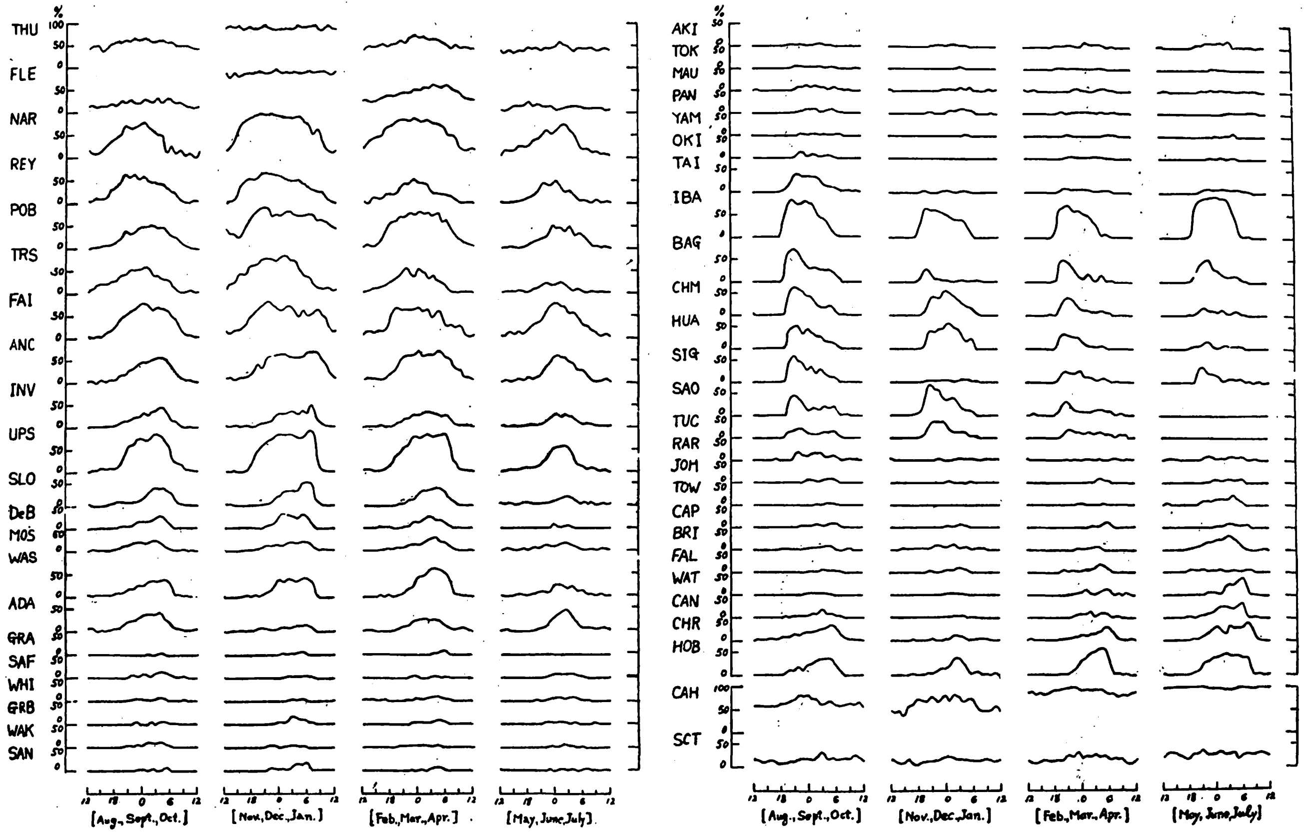
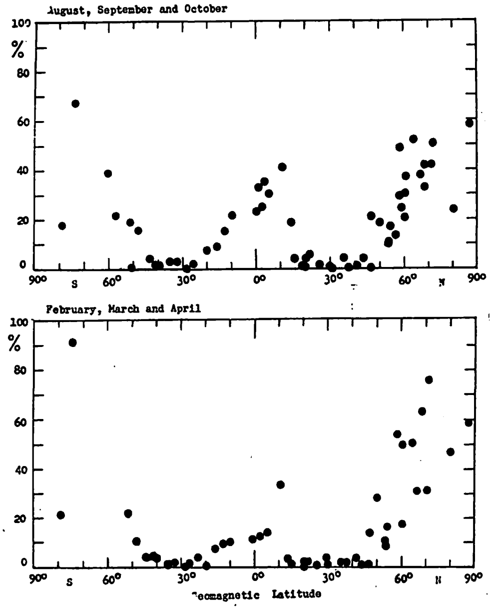
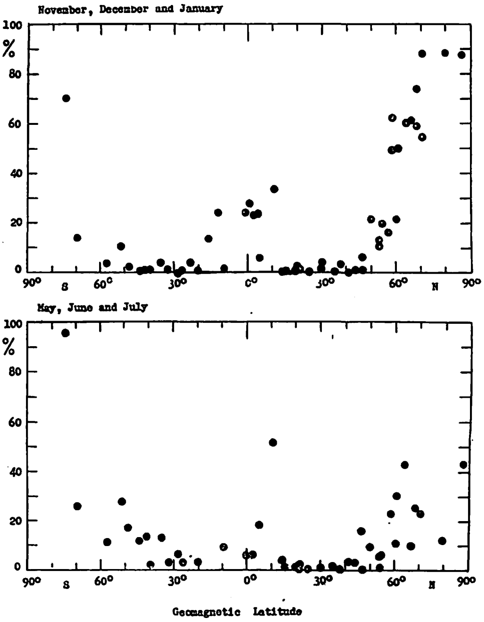


Fig. 1. Average daily variation of occurrence probability of spread-*F* at each station every season during the IGY (July, 1957 to June. 1958)



Figs. 2 (a) and (b) Latitudinal distribution of the average occurrence probability of spread-F at 16 to 07 hrs. in the equinoctial seasons.



Figs. 2 (c) and (d) Latitudinal distribution of the average occurrence probability of spread-F at 16 to 07 hrs. in the non-equinoctial seasons.

equinoctial seasons and the latter two (c) and (d) for the non-equinoctial seasons. Somewhat unsymmetrical distribution may be seen particularly at lower latitudes even in the equinoxes, but this is probably due to the longitudinal effect or to the unsuitable distribution of observatories in the world. As a general tendency, however, the distribution in Figs. 2 (a) and (b) show rather symmetrical variation in the Northern and Southern hemispheres, while Figs. 2 (c) and (d) illustrate rather unsymmetrical distribution, which may tell us the existence of appreciable seasonal variations.

It can remarkably be seen in Fig. 2 that the occurrence of spread-F is very rare at middle latitudes, while large occurrence probability appears at both higher and lower latitudes, i. e. at latitudes higher than 40°, we can see a gradual increase in occurrence probability with the latitude, although it seems rather to decrease at extremely high latitudes (polar cap region), whereas at latitudes lower than 20° we can see another increase with a maximum near the equator. Thus, it seems evident that there are two different origins of sread-F at higher and lower latitudes.

3.3. Seasonal Variation

It can be seen in Figs. 2 (c) and (d) that the occurrence probability is larger in winter than in summer. This is particularly true at higher latitudes, but it seems not certain at lower latitudes. In order to investigate this point more precisely, the author calculated the difference between the average occurrence probability in November, December and January and that in May, June and July at each station. The result is illustrated in Fig. 3, from which we can see that the occurrence probability is always higher in winter than in summer at higher latitudes, while at most stations at lower latitudes it is larger in summer than in winter. This is very interesting and will give further support to the consideration that the origin of spread-F differs at higher and lower latitudes.

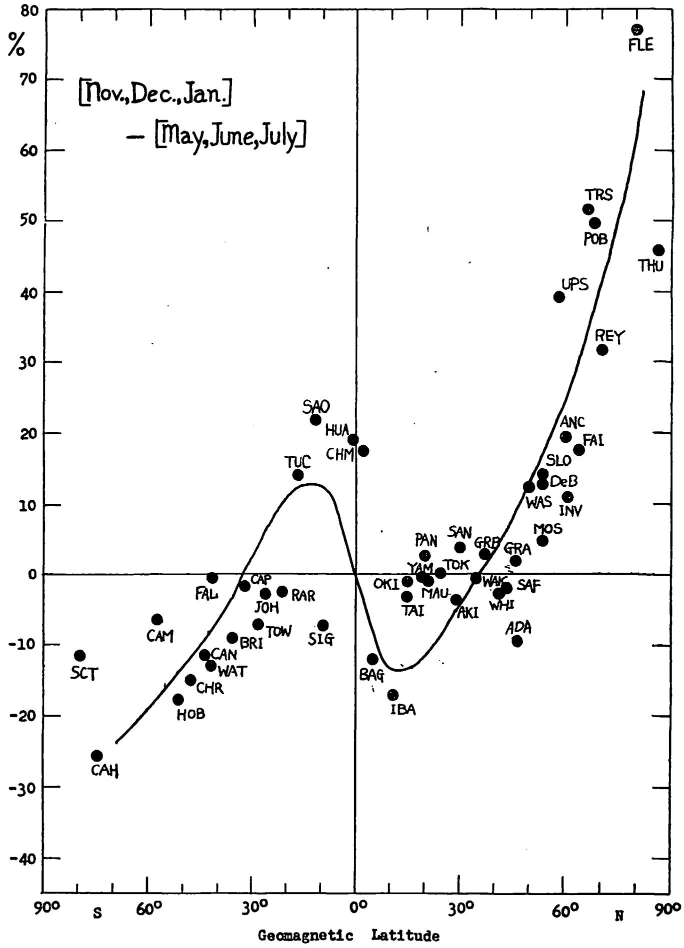


Fig. 3. Illustrating the seasonal difference of the average occurrence probability at various latitudes. At higher latitudes the spread-F occurs more frequently in winter than in summer in both hemispheres, while the reverse can be see at lower latitudes.

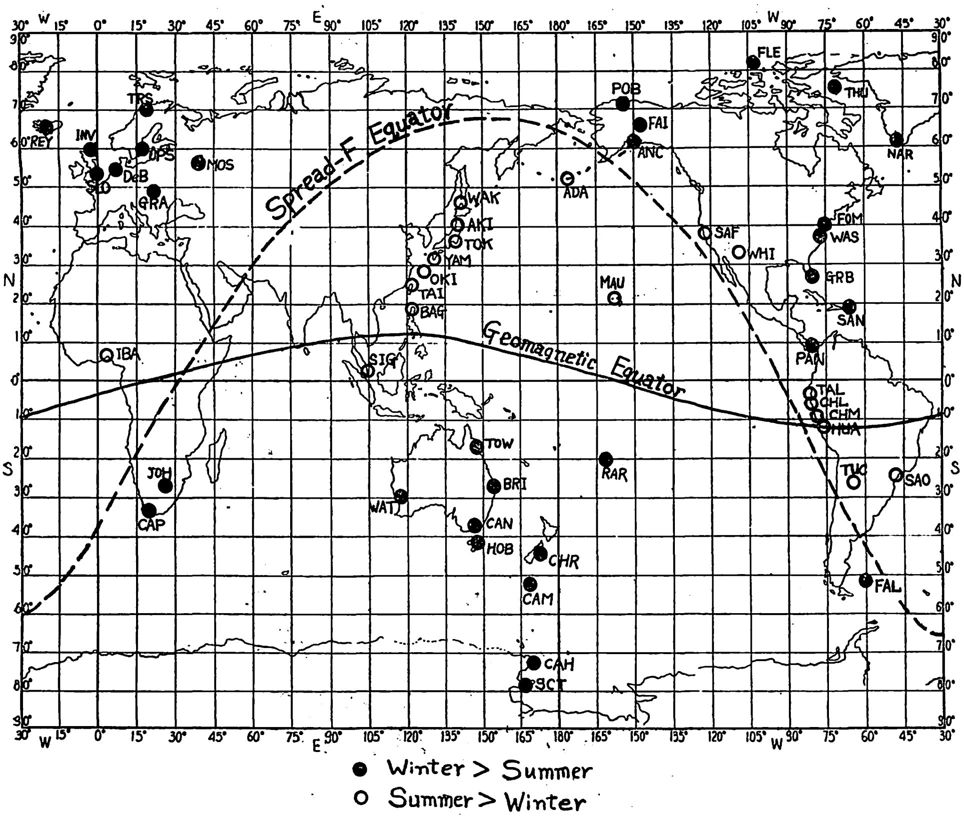


Fig. 4. Illustrating the seasonal difference of the average occurrence probability at various stations in the world.

The comparison between summer and winter is also illustrated in Fig. 4, in which a black circle indicates that the occurrence probability is larger in winter than in summer at the station, while a white circle indicates that it is larger in summer than in winter. From this figure it can be seen that all points at higher latitudes are black, while at lower latitudes they are white. At middle latitudes, there are two regions: one is the region of black circles in Northeastern America and Australia or South Africa, and the other is the region of white circles in the Far East and South America. In the former regions, the spread-*F* occurs more frequently in winter than in summer, having just the same characteristics as at higher latitudes, while in the latter regions it occurs more frequently in summer than in winter with just the same characteristics as at lower latitudes. It is very interesting to see that these two regions are composed of two antipolar regions in each case.

If we define the spread-*F* equator as the transition line between the two kinds of black and white points in each hemisphere, it differs quite largely from either geographic or geomagnetic equator, as is readily seen in Fig. 4.

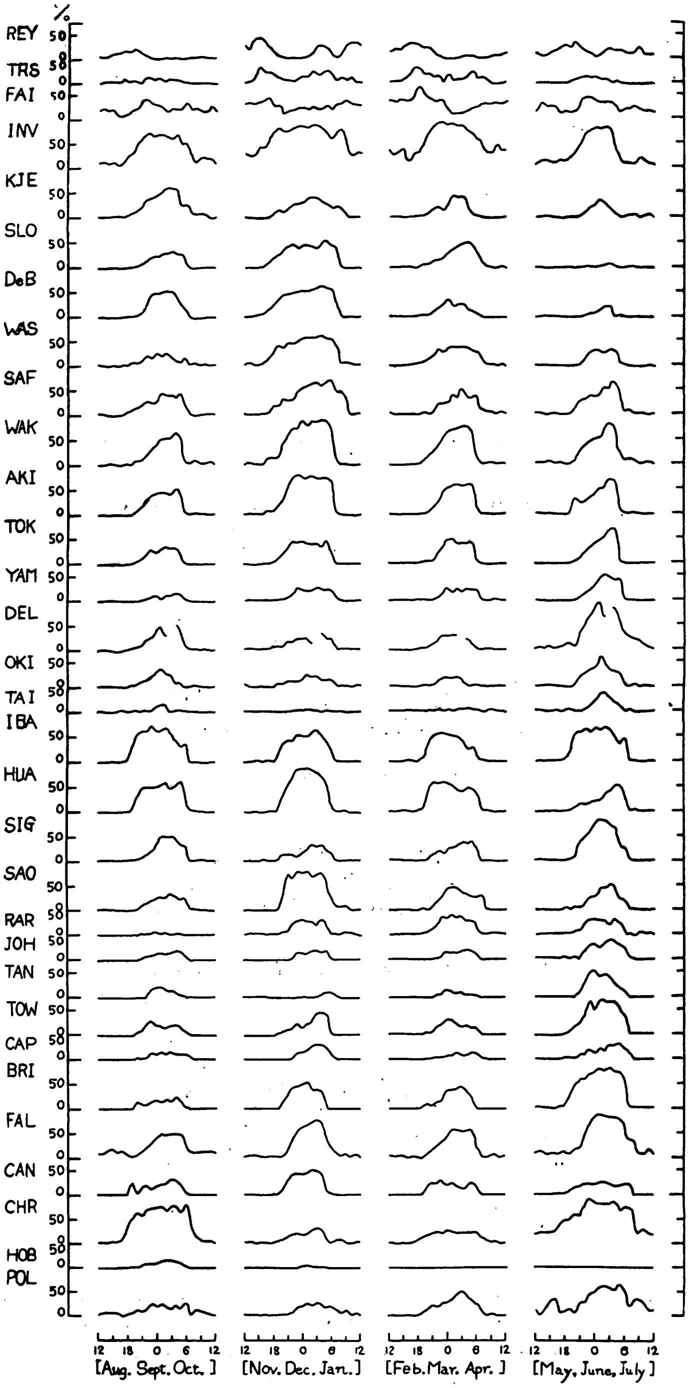


Fig. 5. Average daily variation of occurrence probability of spread-*F* at each station every season in 1954 (sunspot minimum year).

The result is the same as that obtained by Reber (1956), and it is easily supposed that the position of this spread-*F* equator may differ from year to year. This point will be discussed again in the following paragraph.

3.4. Solar Cycle Variations

In the foregoing paragraphs the author showed the result during the IGY. In order to compare the result with that at the sunspot minimum, the author presents here the result of similar analysis of the observational data for 1954. In Fig. 5, the daily variations at all available stations are illustrated in every season. It can clearly be seen in Fig. 5 that at latitudes higher than 20° the time of the maximum occurrence probability exists after midnight, while the tendency of its shifts to hours before midnight can be slightly observed at lower latitudes, although it is not so clear as at the sunspot maximum (compare with Fig. 1).

The latitudinal distribution of the average occurrence probability throughout

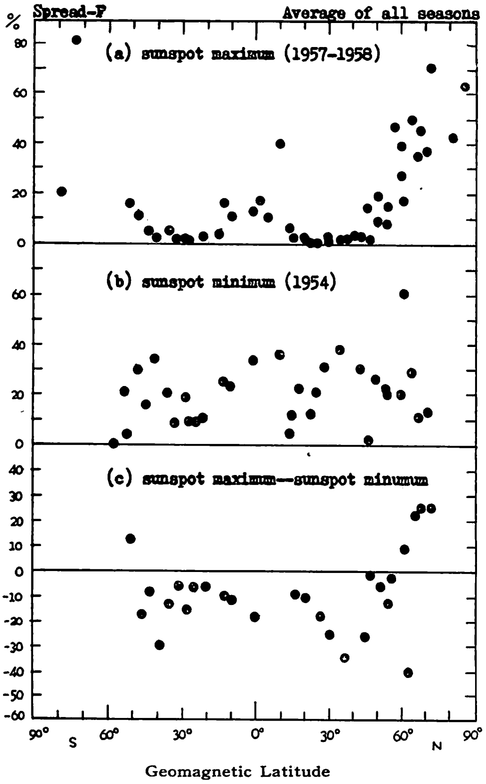


Fig. 6. Comparison between the latitudinal distributions of the average occurrence probability at 16 to 07 hrs. in the sunspot maximum and minimum years. (a) is the average throughout the sunspot maximum year (July, 1957 to June, 1958) (b) the average throughout the sunspot minimum year (1954) and (c) the difference between the two years.

the year is illustrated in Fig. 6, in which the distribution at the sunspot maximum (IGY) is also illustrated for comparison. It is very remarkable that at the sunspot minimum a considerable amount of spread-*F* occurs at middle latitudes, which is quite contrary to the result at the sunspot maximum (IGY), as is readily seen from the comparison of Figs. 6 (a) and (b). The difference between these two years of sunspot maximum and minimum is shown in Fig. 6 (c), in which we can see a remarkable fact that the spread-*F* occurs more frequently in the sunspot minimum year than in the maximum year except at stations at very high latitudes. The latitude at which these two opposite characteristics exchange is situated at about 60° in geomagnetic latitude.

We have already seen in § 3.3 that the spread-*F* equator passed the north of Wakkanai in 1957 to 58. But the relative magnitude of spread-*F* occurrence probability in summer and winter certainly differs with the sunspot activity at each station. For instance, we can see in Fig. 7 that the spread-*F* occurred more frequently in winter that in summer at Wakkanai, Akita, and Tokyo in 1954, while the reverse was the case at these three observatories in 1957 to 58. It may further be supposed from Fig. 7 that the spread-*F* equator passed between Tokyo (25.4° in geomagnetic latitude) and Yamagawa (20.3°) in 1954, between Wakkanai (35.2°) and Akita (29.4°) in 1955 and 1956, and the north of Wakkanai in 1957 to 58. Thus, it may be concluded that the position of the spread-*F* equator approaches gradually the geographic (or geomagnetic) equator as the sunspot activity decreases, although these two equators differ appreciably even in the sunspot minimum year.

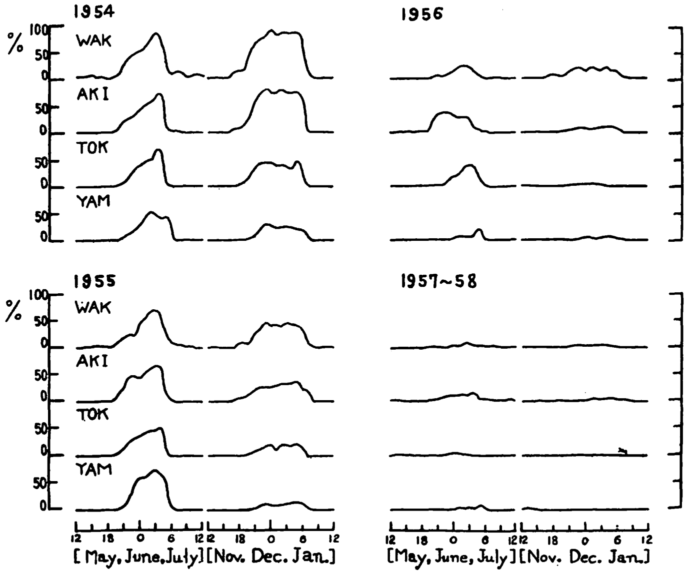


Fig. 7. Illustrating the average daily variation of occurrence probability at four stations in Japan. The comparison is made between summer and winter in each year of 1954 to 1958.

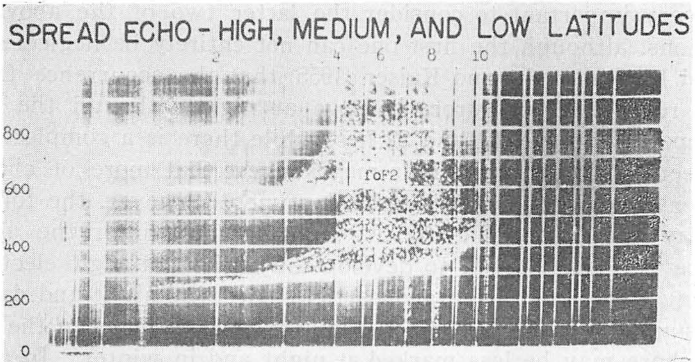
3.5. Some Considerations of the Origin of the Spread-*F*

It is generally known that there are two types of appearance of the spread-*F*: one appears as various traces on the *h'-f* records, all of which broaden considerably with scattered echoes at frequencies well below the critical frequency, and the other consists of widely scattered echoes over all frequencies. The former is usually observed at higher latitudes, while the latter at lower latitudes. The typical examples of these two types of spread-*F* are illustrated in Fig. 8. On the other hand, the present study shows that the statistical aspect of the occurrence probability is quite different at higher and lower latitudes. Thus, it seems quite evident that the spread-*F* has different origins at higher and lower latitudes.

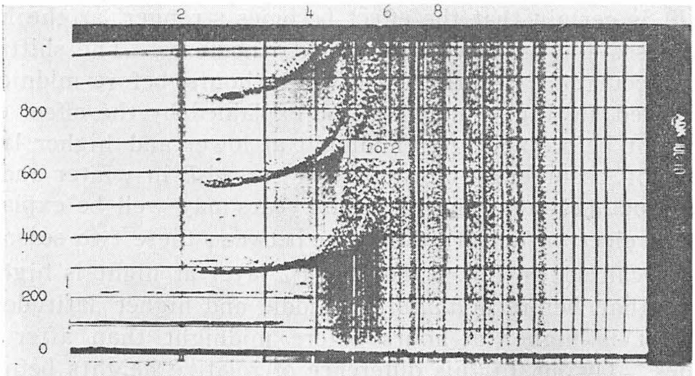
In general, the following three conditions must be satisfied in order to make possible observation of the spread-*F* on the *h'-f* records: the first is that (a) there is a certain origin of the excess-ionization or disturbances (or turbulences) in the upper atmosphere; the second is that (b) the abnormal state can develop strongly producing some irregularities of electron density, which are extensive and intense enough for the reflection or scattering of waves; and the third is that (c) these reflected or scattered echoes can be observed on the ground by overcoming the absorption of the waves in the lower ionosphere.

It is evident that the appearance of two types of the spread-*F* and the statistical aspects of their occurrence probability in each case must be explained on the basis of the above-mentioned three points. At first, it may safely be considered that the spread-*F* at higher latitudes has its origin in the charged particles entering the earth's upper atmosphere. The gradual increase of the occurrence probability at latitudes higher than 40° will easily be understood by this consideration. The charged particles impinging upon the upper atmosphere will produce some blobs or patches of excess-ionization, and the regions of these higher electron density may become the origin of various *h'-f* traces different from the normal one. If this consideration of the effect of charged particles is correct, it is naturally be expected that the effect can be observed most predominantly at the time of severe geomagnetic storms. This can practically be seen in the accompanying paper (part II). In addition, we can see in Fig. 1 in part II that the correlation coefficient between the occurrence probability of spread-*F* and the geomagnetic activity is generally positive at middle and higher latitudes except at very high latitudes, where it becomes negative apparently because of the occurrence of "black-out". It seems evident that this positive correlation indicates that the spread-*F* at higher latitudes has its origin in the charged particles entering the upper atmosphere, because it is easily supposed that the entry of charged particles has a close relation to the geomagnetic activity.

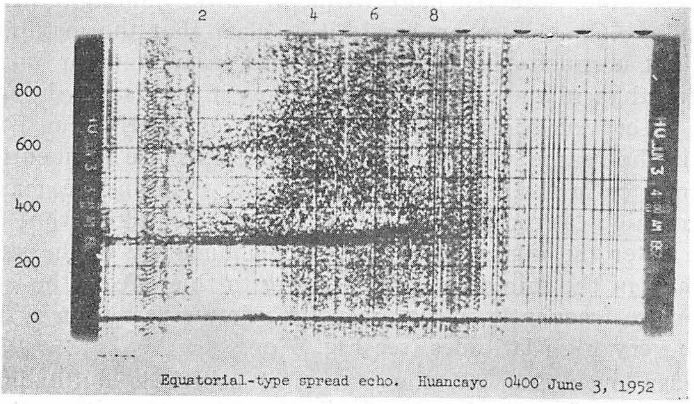
It is very clear that the spread-*F* can be observed mainly at night. And this may be explained by the accretion theory, which states that the interstellar matters attracted toward the sun attack the dark side of the earth, thus producing extra-ionization only at night. This can, however, not explain the seasonal difference of the occurrence probability of the spread-*F*. In explaining the fact that the spread-*F* occurs mainly at night and more frequently in winter



Spread echoe of the type commonly observed at high latitudes.
Godhavn 1640 Dec. 22, 1951



Middle latitude spread echo. Adak 2015 July 10, 1955



Equatorial-type spread echo. Huancayo 0400 June 3, 1952

Fig. 8. Typical examples of spread-*F* appearing at higher, middle, and lower latitudes. (Photographs are quoted from "Atlas of ionograms" produced at CRPL, National Bureau of Standards, Boulder, Cororado, USA, June, 1957).

than in summer except at lower latitudes and in some regions at middle latitudes, it is very important to consider the latter two of the above-mentioned three conditions, although the first one can not entirely be neglected. In fact, it is reported by Bullought and Kaiser (1955) that the occurrence frequency of radio echoes reflected from aurora is large at night although the well-defined minimum appears between 21 and 22 hrs, while there is a complete absence of echoes between 06 and 13 hrs. This may suggest that more of charged particles can enter at night than during the daytime. However, the following consideration may also be possible: (i) At night and in winter the upper atmosphere may be in a state easier to develop the regions of high electron density even if an equal amount of charged particles enters at night and daytime or in winter and summer, or (ii) the effect of absorption of waves in the lower parts of the ionosphere may be less marked at night and in winter. In practice, the effect of absorption will make it impossible to observe the spread-*F* even if there are some irregularities responsible for the spread-*F* in the upper *F*2 regions, and it is certain that the effect becomes stronger, as the height of the *F*2 layer decreases and/or the electron density increases. The shift of the time of maximum occurrence probability towards hours before midnight at lower latitudes observed in Fig. 1 may well be explained by the effect of difference of relative height before and after midnight at lower and higher latitudes, and the difference of occurrence probability of spread-*F* in winter and in summer or in the sunspot maximum and minimum years may well be explained mainly by the effect of electron density difference between these two seasons or years.

In fact, we can see in Fig. 9 that the *F*2 layer at night is higher at hours after midnight than before midnight at middle and higher latitudes, while, on the contrary, it is higher at hours before midnight than after midnight at lower latitudes. Owing to this difference of relative heights before and after midnight, the spread-*F* will be observed more frequently before midnight at lower latitudes, while observed more frequently after midnight at middle and higher latitudes. On the other hand, it is clear that the maximum electron density at night is much smaller in winter than in summer or in the sunspot minimum year than in the maximum year, thus it may safely be supposed that the effect of absorption becomes weak in winter or in the sunspot minimum year. This is the reason why the spread-*F* appears more frequently in winter than in summer or in the sunspot minimum year than in the maximum year except at very high latitudes, where it is naturally expected that the charged particles can enter the upper atmospher more abundantly in the sunspot maximum year than in the minimum year. Owing to this effect, the spread-*F* can be observed more frequently in the sunspot maximum year than in the minimum year at these very high latitudes (see Fig. 6(c)).

At latitudes lower than 20°, the statistical aspect is quite different from that at higher latitudes. And it is certain that the charged particles can not enter these lower latitudes. The appearance of spread echoes over wide frequencies may suggest that the origin of spread echoes extends over wide regions both vertically and horizontally and does not concentrate in some particular regions as at higher latitudes. The occurrence of turbulent motions

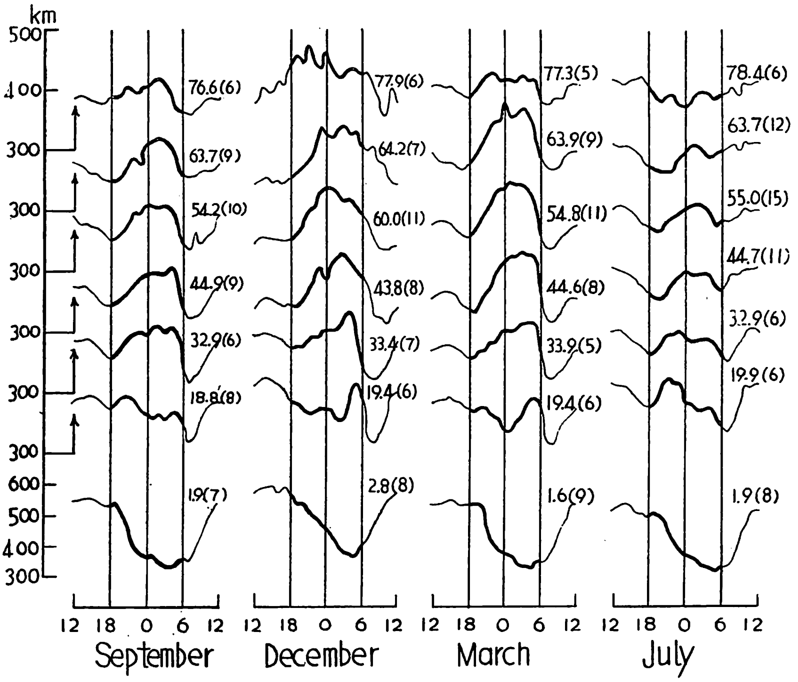


Fig. 9. Illustrating the change in height of the $F2$ layer at various latitudes every season during the IGY. The figures on each curve indicate the mean geomagnetic latitude of observatories to obtain the curve, and the parenthesized figure is the number of observatories involved in each case.

may be responsible for the spread-F echoes, although the mechanism of their occurrence has not yet been clarified. However, if these turbulent motions occur over wide regions by some mechanisms, many irregular surfaces of reflection or origins of scattering will also be produced over wide regions, thus the reflection or scattering of waves may be possible at various heights and frequencies on the h'-f records. It is very interesting to see in Fig. 1 in part II that the correlation coefficient between the occurrence probability of spread-F and the geomagnetic activity has high negative values at latitudes lower than 20°. This may tell us the fact that turbulent motions of ionized gases have a tendency to diminish at such lower latitudes on geomagnetically active days.

Fig. 4 shows that the phase of spread-F equator is almost the same as that of geomagnetic equator, although these two equators pass quite different points. In other words, it can be said that at middle latitudes the spread-F occurrence probability is larger in summer than in winter at stations of largest difference between geographic and geomagnetic latitudes (geomag.<geograph.) such as in the Far East or in South America, while it is larger in winter than in summer at stations of largest difference (geomag.>geograph.) such as in Northeastern America or in Australia. These facts enable us to consider that the earth's magnetic field must play an important part in the occurrence of spread-F at lower latitudes.

The existing theories of the origin of ionospheric irregularties responsible for radio star scintillations and spread-*F* were critically reviewed by Dagg (1957, a), whose conclusion is that any ionizing agent from outside of the earth's atmosphere is unlikely to be responsible for the ionospheric irregularities, and that the mechanism for their production must be sought in the terrestrial atmosphere. This conclusion may be correct for the spread-*F* at lower latitudes but is certainly incorrect at least at higher latitudes and probably in some regions at middle latitudes. Dagg (1957, b) also studied the turbulence in the dynamo region and considered that the turbulence in the *F* region may be produced by the electromagnetic effect due to component of turbulent electric fields communicated from the dynamo to higher regions. But it seems very hard to explain the occurrence of spread-*F* by this mechanism, because components of turbulent electric fields transmitted from lower dynamo region are too small to produce large scale irregularties responsible for the spread-*F* in the *F* region (Martyn, 1959).

It is certain that the development of turbulent motions in ionized gas will strongly be inhibited by the effect of magnetic fields, but it must also be taken into account that the component of turbulent velocities parrallel to the magnetic fields will not be affected by the magnetic fields (Dungey, 1958). There are also some experimental evidences indicating that the magnetic field has an agency destabilizing the laminar flow of a layer of mercury under a certain condition of experiments (Lehnert, 1955). Thus, it seems not always impossible to consider that the turbulence can be produced in the *F* region, although the problem of development of turbulent motions of ionized gas in the magnetic field is certainly very difficult to solve strictly.

Martyn (1959) proposed a new theory of the spread-*F*, in which he considered that the ionization on the undersurface of the *F* region is essentially unstable if it is moving upwards under the influence of electromagnetic drift, and pointed out that when the cylinder of reduced electron density moves upwards through the region moving into regions of greater *N*, the difference of electron density from the surroundings is much enhanced. Although the theory is very interesting and instructive, it may be safely considered that the spread-*F* does not always occur in regions lower than the level of maximum electron density, as is seen, for example, in Fig. 8.

Dagg (1957, b) considered Reynolds' and Richardson's numbers as conventional criteria for turbulent flow, and reached the conclusion that the decrease in temperature gradient is the main cause for the occurrence of spread-*F* at night and in winter. This seems correct qualitatively at least, but not quantitatively, because in the expression of Richardson number

$$R_i=\frac{g\left(\Gamma+\frac{d\overline{T}}{dz}\right)}{T\left(\frac{d\overline{u}}{dz}\right)^2}$$

the term of adiabatic lapse rate Γ is much larger (at least several times larger) in magnitude than the term of temperature gradient. Thus, the decrease in temperature gradient at night and in winter can not change so largely the magnitude of Richardson number, unless we assume unreasonably a large difference between day and night or summer and winter. Thus, it seems that the difference of temperature gradient does not explain completely the difference of spread-F occurrence probability between day and night or summer and winter, and some other factors controling the occurrence of spread-F must be sought. It this connection, it may be suggested that the velocity gradient may be the chief cause of the development of turbulent motions in the upper atmosphere, because it is involved in the above expression of R_i as the square of $d\bar{u}/dz$, so that a slight change in $d\bar{u}/dz$ affects more seriously than $d\bar{T}/dz$. In practice, it is shown by Booker (1957) that the velocity gradient in the dynamo region observed by rocket experiments reaches a high value, which lessens the value of R_i to develop turbulent motions, although the observation by meteor trail methods does not show such a large velocity gradient.

4. Concluding Remarks

The results obtained in the present statistical study may be summarized in the following conclusions:

(1) Spread-F appears mainly at night and most frequently between midnight and sunrise at middle and higher latitudes, while it does before midnight at lower latitudes.

(2) Spread-F occurs very frequently at higher (>40°) and lower latitudes (<20°), while it is very rare to occur between these two latitudes in the sunspot maximum.

(3) Spread-F occurs in winter more frequently than in summer at all stations at higher latitudes, while it occurs more frequently in summer than in winter at lower latitudes. In middle latitudes, the spread-F occurs in summer more frequently than in winter at stations in the Far East and South America, while the reverse is the case at stations in Australia or South Africa and North-eastern America.

(4) Spread-F occurs in the sunspot minimum year more frequently than in the sunspot maximum year except at very high latitudes (>60°).

(5) Spread-F occurs more frequently on geomagnetically active days at middle and higher latitudes, while, on the contrary, it does on quiet days at lower latitudes.

The above results enable us to consider that the origin of spread-F differs at higher and lower latitudes. At higher latitudes, the entry of charged particles into the earth's upper atmosphere may bring about the spread-F, while at lower latitudes the origin must be sought in the terrestrial atmosphere.

A STATISTICAL STUDY OF WORLD-WIDE OCCURRENCE PROBABILITY OF SPREAD-*F*

Part II. Abnormal State in Severe Magnetic Storms

ABSTRACT

An investigation is made into the correlation between the occurrence probability of spread-*F* and the geomagnetic activity. The result shows that the correlation is strongly negative at lower latitudes (<20°), while it is strongly positive at latitudes between 20° and 60°. At higher latitudes (>60°), the correlation becomes negative again, but it is shown that the result is much influenced by the occurrence of "black-out".

The abnormal state of the world's occurrence probability in some severe magnetic storms is studied in full detail. The result can be well explained by the consideration that the critical level of the charged particles penetrating into the upper atmosphere rises gradually with the decrease of latitude. At latitudes lower than a certain critical latitude, the effect of magnetic storms is not so appreciable.

1. Introduction

It is certain that the origin of the spread-*F* differs at higher and lower latitudes, and that at higher latitudes it can be attributed to the entry of charged particles into the earth's upper atmosphere, as was shown in part I dealing with the average state, including magnetic quiet and disturbed days. If this consideration is correct, it is naturally expected that the spread-*F* at higher latitudes appears most frequently at the time of severe magnetic storms. The purpose of the present paper is to detect these evidences and to investigate more generally the relationship between the occurrence probability of spread-*F* and the geomagnetic activity.

2. Correlation between the Occurrence Probability of Spread-*F* and the Geomagnetic Activity

2.1. General Consideration

It is well known that the geomagnetic activity has two peaks at the equinoxes of the year. On the other hand, any general tendency of large occurrence probability of spread-*F* at the equinoxes can not be seen (see, for example, Fig. 1 in part I). This is probably due to the fact that seasonal difference of spread-*F* occurrence probability is enough large to make invisible its variation with the geomagnetic activity. Thus, it seems clear that there is no correlation between the occurrence probability of spread-*F* and the geomagnetic activity, if we compare the season-to-season variations. However, if we compare the day-to-day variations, there can be seen a definite relation between both, although the characteristics differ clearly with latitudes. As

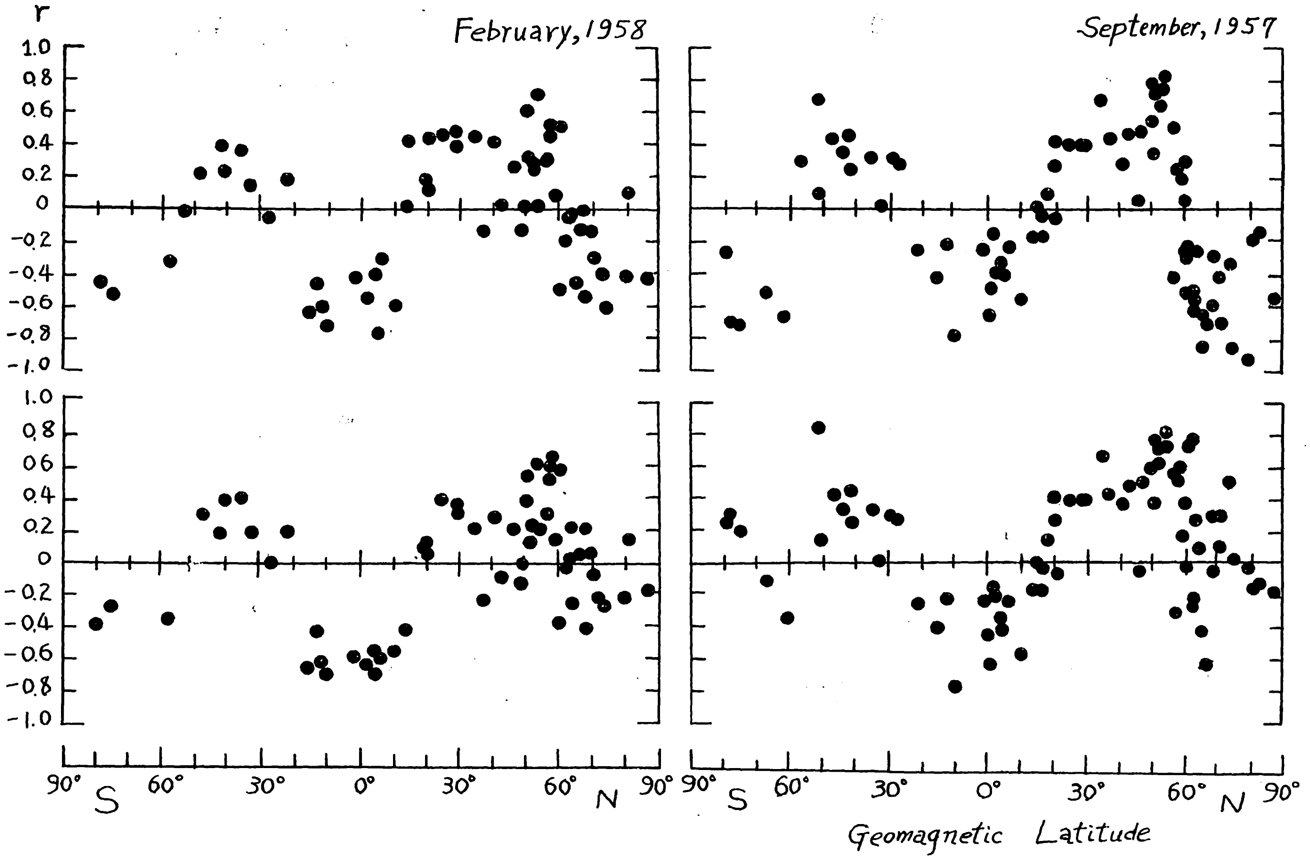


Fig. 1. Correlation coefficient between the occurrence probability of spread-F and the geomagntic activity (international character figure). The left is for February, 1958, and the right for September, 1957. The upper in each case is for all days in each month, while the lower in the left omits the day of a severe magnetic storm on the 11th, and the lower in the right omits the days involving the hours of "black-out" more than 3 hrs a day.

examples of this relationship, the author will show in Fig. 1 the correlation coefficients at various stations. The left illustrates the case of February in 1958, and the right the case of September in 1957. The upper illustration in each case is for all days in each corresponding month, while the lower one in the left omits the particular day of a large magnetic storm on the 11th in February and the lower one in the right omits the days involving the hours of "black-out" more than 3 hrs a day. The meaning of these omissions will become clear in the following paragraphs. In any way, we can see in Fig. 1 that the correlation is strongly negative at latitudes lower than 20°, while it is strongly positive at higher latitudes, although it becomes negative again at very high latitudes (>60°). The tendency of negative correlation at very high latitudes is much reduced when the days involving many hours of "black-out" are omitted for calculations, although the tendency can not be completely removed. On the other hand, the large nagative correlation at lower latitudes (<20°) and the large positive correlation at latitudes between 20° and 60° are not affected so seriously by this omission. Thus, it is very evident that the negative correlation at very high latitudes is only apparent, certainly on account of the occurrence of "black-out" which will absorb waves at any frequencies so that any reflected or scattered echoes can not be observed on the ground. This will be discussed in detail in the following paragraphs again.

The large negative correlation at Ibadan (10.6° in geomagnetic latitude) was found by Lyon, Skinner, and Wright (1958), which gives a powerful support to the result of the present investigation.

2.2. Abnormal State in Severe Magnetic Storms

If the spread-F at higher latitudes is due to the entry of charged particles into the earth's atmosphere, the effect must be observed most predominantly at the time of severe magnetic storms, because it is certain that charged particles can enter the upper atmosphere most abundantly and also can enter the lowest level and latitude at the time of such magnetic storms. With the purpose of indicating these evidences, the author examined particularly the cases of severe magnetic storms that occurred on the 11th of February, 1958, and during September, 1957. The former had a particularly large magnetic storm (the range of ΔH reached 617 γ at Kakioka) that occurred without accompanying any remarkable storms before and after that day during February, so that it is expected that the effect can be seen most clearly. On the contrary, in the latter (September, 1957) there occurred several magnetic storms succesively. Therefore, the after-effect of each storm may somewhat disturb the effect of the next storm and it may rather be difficult to see the effect very clearly. In these circumstances, the author will discuss in full detail the case of magnetic storm on the 11th of February, 1958, in the following, and the result in September, 1957, will be shown only for the sake of comparison and for the justification of the result of the discussion.

2.2.1. Case of Magnetic Storm on February 11, 1958

The average occurrence probability of spread-F was calculated on each universal day in February, 1958, and the result is illustrated in Fig. 2, which

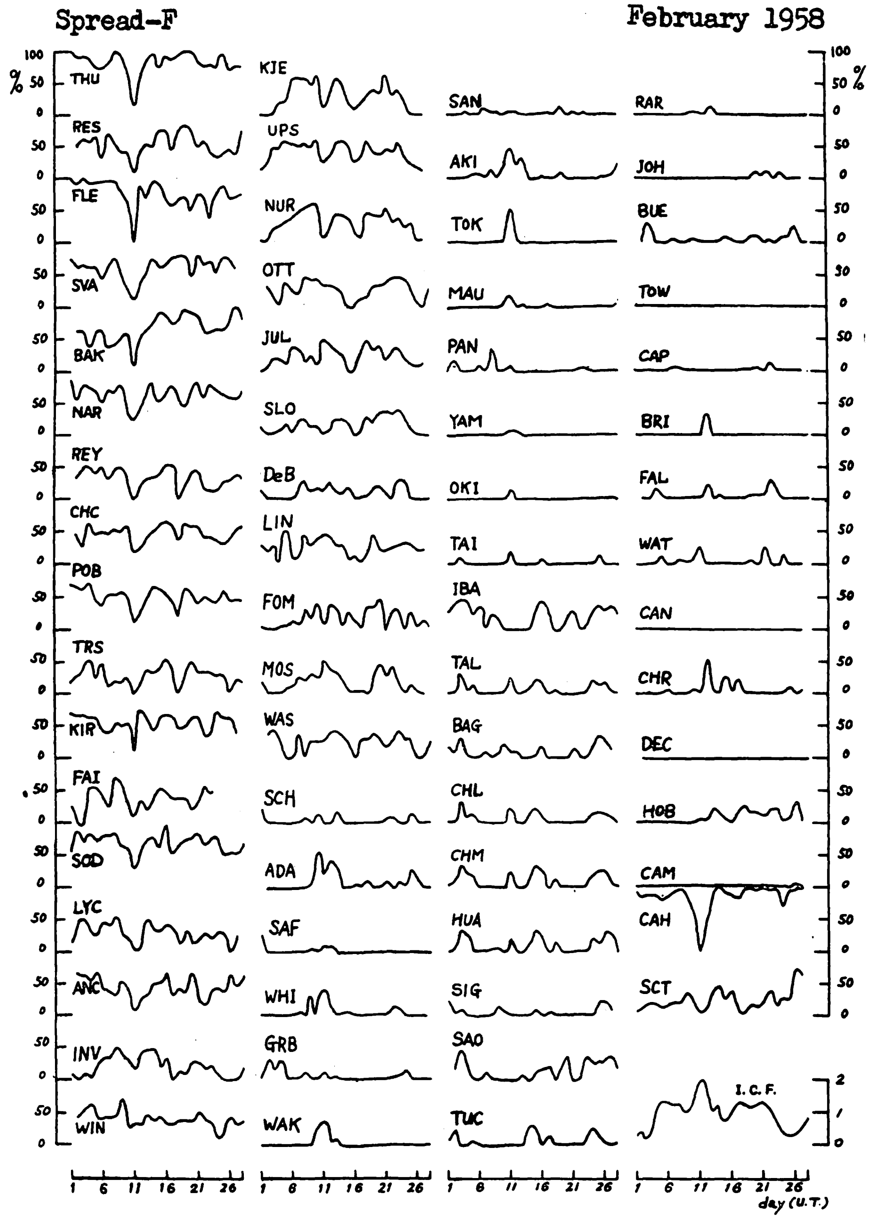


Fig. 2. Day-to-day variations in the occurrence probability of spread-*F* in February, 1958.

shows the day-to-day variations at each station. It can be seen in Fig. 2 that the probability was much reduced on the particular day of the 11th at higher latitudes, while on the contrary, it was much enhanced at middle latitudes. On the other hand, there can be seen any peculiar change to that day at lower latitudes. It must further be noted that at some stations at middle latitudes in the Southern hemisphere the enhancement of the probability could be seen on the 12th rather than on the 11th.

At first sight, it is very strange that the occurrence probability of spread-*F* is much reduced at higher latitudes on the day of a severe magnetic storm, but further examination shows that on such days the state of "black-out" occurs widely at high latitudes. Thus, the reduction of occurrence probability of spread-*F* at higher latitudes must be apparent, because in the "black-out" all waves reflected from, or scattered in, the ionospher will completely be absorbed and can not reach the ground. As the result of this absorption, the spread-*F* will disappear apparently at very high latitudes.

The author illustrates in Fig. 3 the latitudinal distribution of occurrence probability in February, 1958. Fig. 3 (a) shows the average state of the month, and Figs. 3 (b) and 3 (c) show the state on particular days of the 11th and the 12th, respectively. It can be seen in Fig. 3 (a) that the spread-*F* occurs very frequently at higher latitudes and rather frequently at lower latitudes, while it occurs very rarely at middle latitudes (compare with Fig. 2 in Part I), and that the "black-out" occurs only in auroral regions as the average state of the month. On the other hand, it can be seen in Fig. 3 (b) that the occurrence of spread-*F* at middle latitudes is very remarkable on the day of a severe geomagnetic storm (on the 11th), while at higher latitudes its occurrence probability is much reduced. And it can remarkably be seen in Fig. 3 (b) (lower) that the occurrence of "black-out" becomes very frequent at higher latitudes corresponding to those at which much reduction is made of the occurrence probability of spread-*F*. And these abnormal states could be seen more clearly in the Northern hemisphere than in the Southern hemisphere on the 11th. On the contrary, on the 12th the effect of a magnetic storm such as observed in the Northern hemisphere on the 11th could be appreciably seen at some stations in the Southern hemisphere, while the distribution in the Northern hemisphere approached the average state on the 12th.

The abnormal state on the 11th can be seen more clearly in Fig. 4 illustrating the difference between the occurrence probability of spread-*F* on the 11th and its monthly mean at each station. It must particularly be noted in Fig. 4 that at latitudes higher than 30° the points are distributed almost linearly; the large negative value at very high latitudes tends to zero linearly as the latitude descends, reaching zero at 50° to 60° and then increasing linearly to large positive values, reaching a maximum at about 30°. At latitudes lower than that of this maximum the departure on the 11th from the monthly mean is comparatively small, and its latitudinal distribution is not so regular as at higher latitudes. This linear distribution of points at higher latitudes is certainly due to the effect of the charged particles. The reason for the negative value at very high latitudes (>60°) in Fig. 4 is certainly that the impinging of

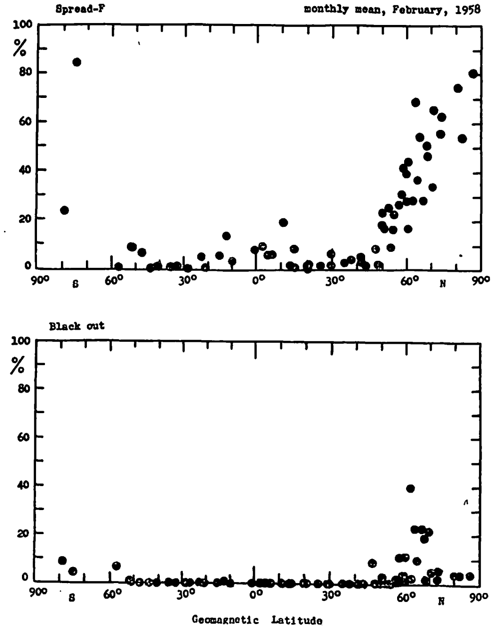


Fig. 3. (a) Latitudinal distribution of the occurrence probability of spread-*F* and "black-out". The average state in February, 1958.

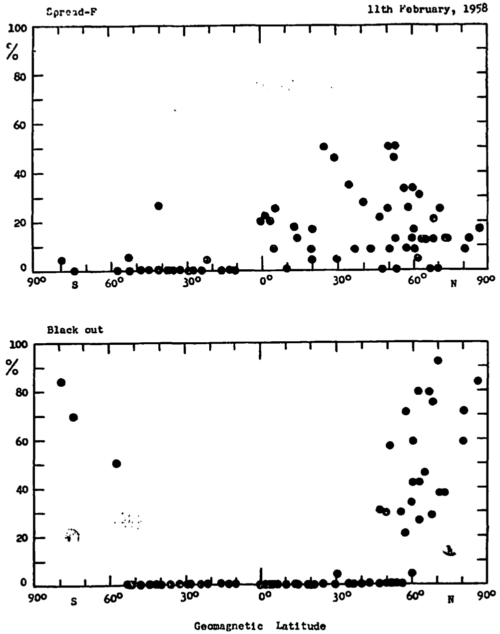


Fig. 3. (b) The state on the 11th of February, 1958.

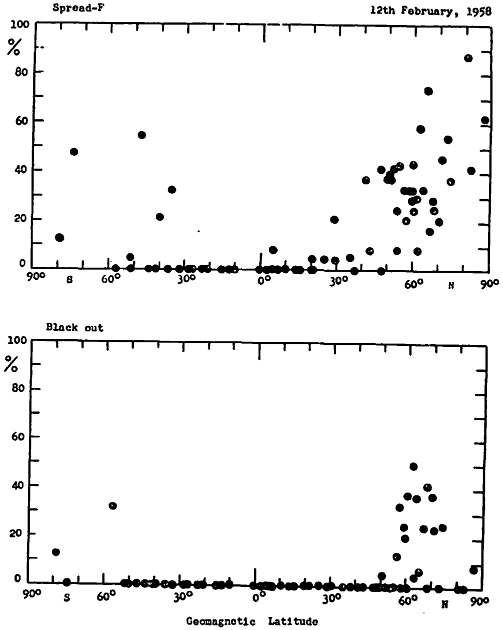


Fig. 3. (c) The state on the 12th of February, 1958.

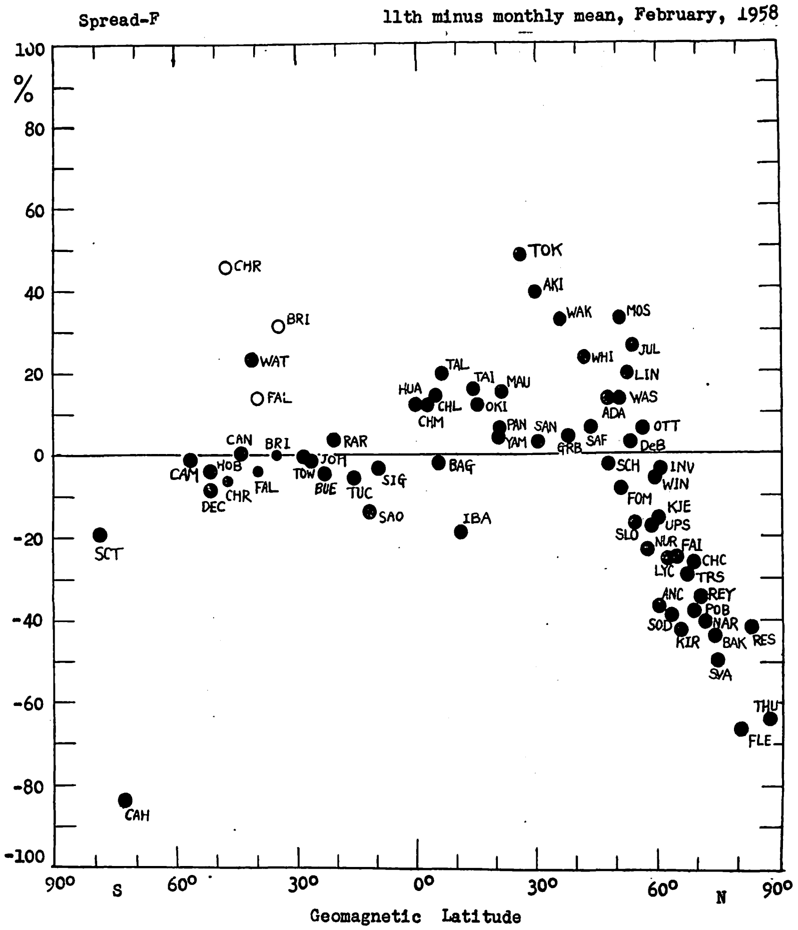


Fig. 4. Latitudinal distribution of the difference between the occurrence probability of spread-F on the 11th of February, 1958, and its monthly mean. The white circles indicate the difference between that on the 12th and the monthly mean.

charged particles can reach the lower levels (D or E regions), so that it produces the "black-out" which may absorb all energies of waves reflected from, and scattered in, the upper ionosphere. As a result, the remarkable reduction of the occurrence probability of spread-F may be made at these higher latitudes. On the other hand, as the latitude descends, the critical level into which charged particles can penetrate rises gradually, and at middle latitudes the charged particles can not reach the D or E regions, but only the F region. Thus, the "black-out" does not occur at these stations at middle latitudes, while the excess-ionization can be produced in the F region. As a result, the remarkable enhancement of the spread-F occurrence probability may be observed at the stations at middle latitudes such as at Tokyo and Akita in Japan. As the latitude descends further, charged particles can not reach even the *F* region, and any spread-*F* may not be produced in the *F* region by this mechanism. These are reasons why the gradual decrease of points with increasing latitudes in Fig. 4 is observed only at middle and higher latitudes, having a clear cut-off at a certain middle latitude. This tendency can be seen more clearly in the Northern hemisphere, but only slightly in the Southern hemisphere. It must be noted, however, that if we plot the points on the 12th instead of the 11th, as illustrated with white circles in Fig. 4, the tendency similar to that in the Northern hemisphere may also appear quite appreciably in the Southern hemisphere.

2.2.2. Case of Magnetic Storms in September 1957

The average occurrence probability of spread-*F* and of "black-out" on each universal day was calculated for September in 1957, and the results are illustrated in Figs. 5 and 6, respectively. As will be seen by the curves of day-to-day variations of international character figure on the lowest right side in Fig. 5, there were four large magnetic storms in September, 1957. Thus, because of the after-effect of the preceding storm, the effect of magnetic storms is not so clear as in February (compare with Fig. 2). In Fig. 6 it can remarkably be seen that the "black-out" occurred at higher latitudes always corresponding to the occurrence of magnetic storms.

The latitudinal distribution of the occurrence probability of spread-*F* and of "black-out" is illustrated in Fig. 7. Fig. 7 (a) shows the average state of the month, while Figs. 7 (b) to (g) the state on particular days of the 4th, 5th, 13th, 14th, 22nd, and 23rd of September, respectively. Three large magnetic storms occurred at 13 h 00 m on the 4th in universal time, at 00 h 45 m on the 13th, and at 13 h 44 m on the 22nd, and the range of ΔH reached 289 γ, 486 γ, and 240 γ, respectively, at Kakioka. The case of the magnetic storm that occurred on the 29th is not shown in the present illustration.

In general, effects very similar to those observed in Fig. 3 can be seen in Fig. 7. And the effects can be seen more clearly in Fig. 8 illustrating the difference between the occurrence probability of spread-*F* on each day of the 4th, 13th and 22nd of September and its monthly mean. In these figures, we can see the distribution very similar to that in Fig. 4, although the linear change at higher latitudes is somewhat ill-defined. The tendency that the enhancement of the occurrence probability at middle latitudes occurs somewhat late in the Southern hemisphere will also be slightly observed in the storms in September. Thus, it may safely be asserted that the result obtained in the storm on the 11th of February, 1958, is further confirmed by the result of analysis in the case of the storms in September. And the discussion on the result in the preceding paragraph will generally be justified.

Finally, it must be noted in Fig. 5 that the enhancement of the spread-*F* occurrence probability at Tokyo and Akita predominated much on the 13th only, but not so largely on other stormy days (on the 4th and 22nd). This may be due to the difference of the times at which these magnetic storms began, as well as the difference of the magnitude of the storms. In this connection, our

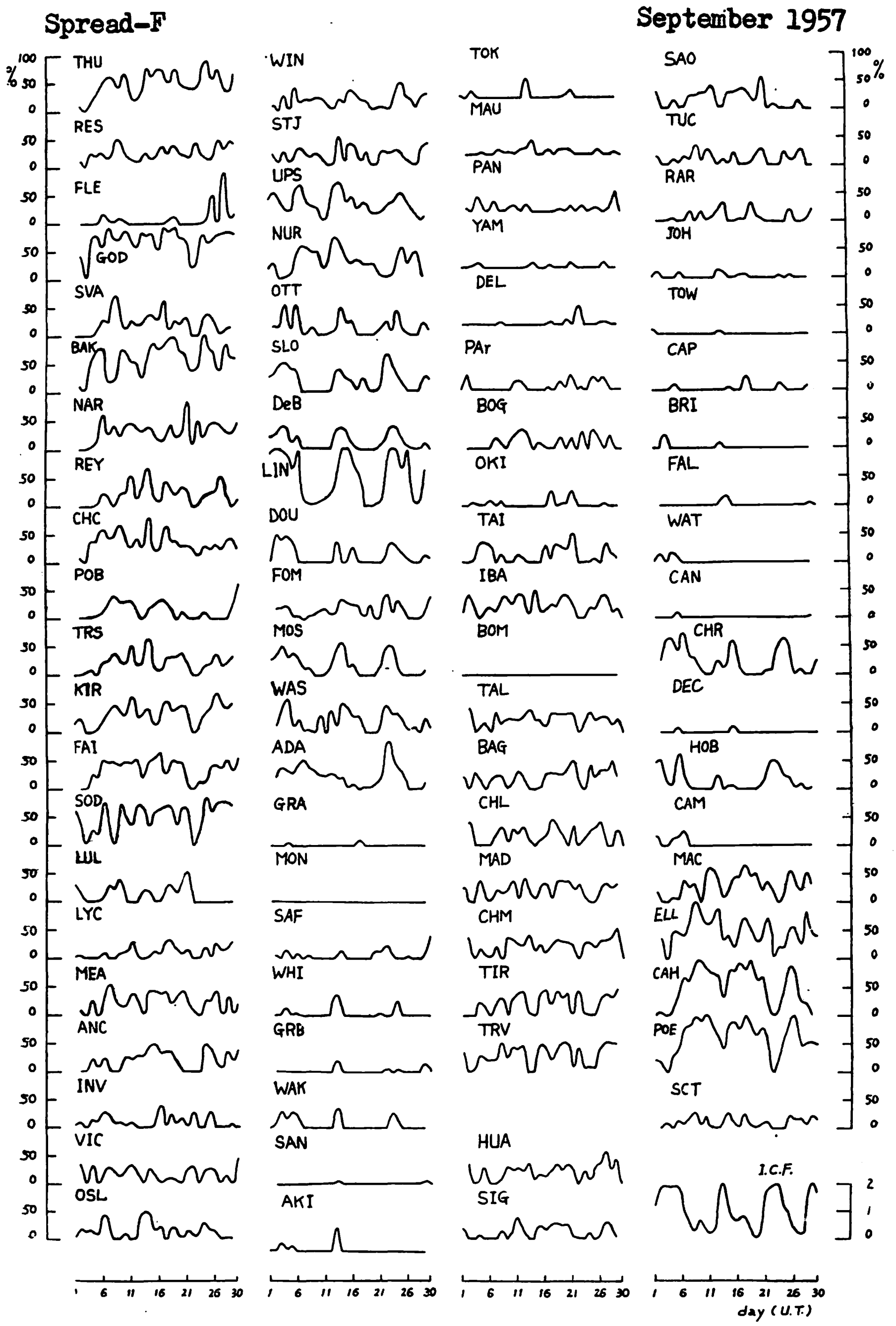


Fig. 5. Day-to-day variations in the occurrence probability of spread-*F* in September, 1957.

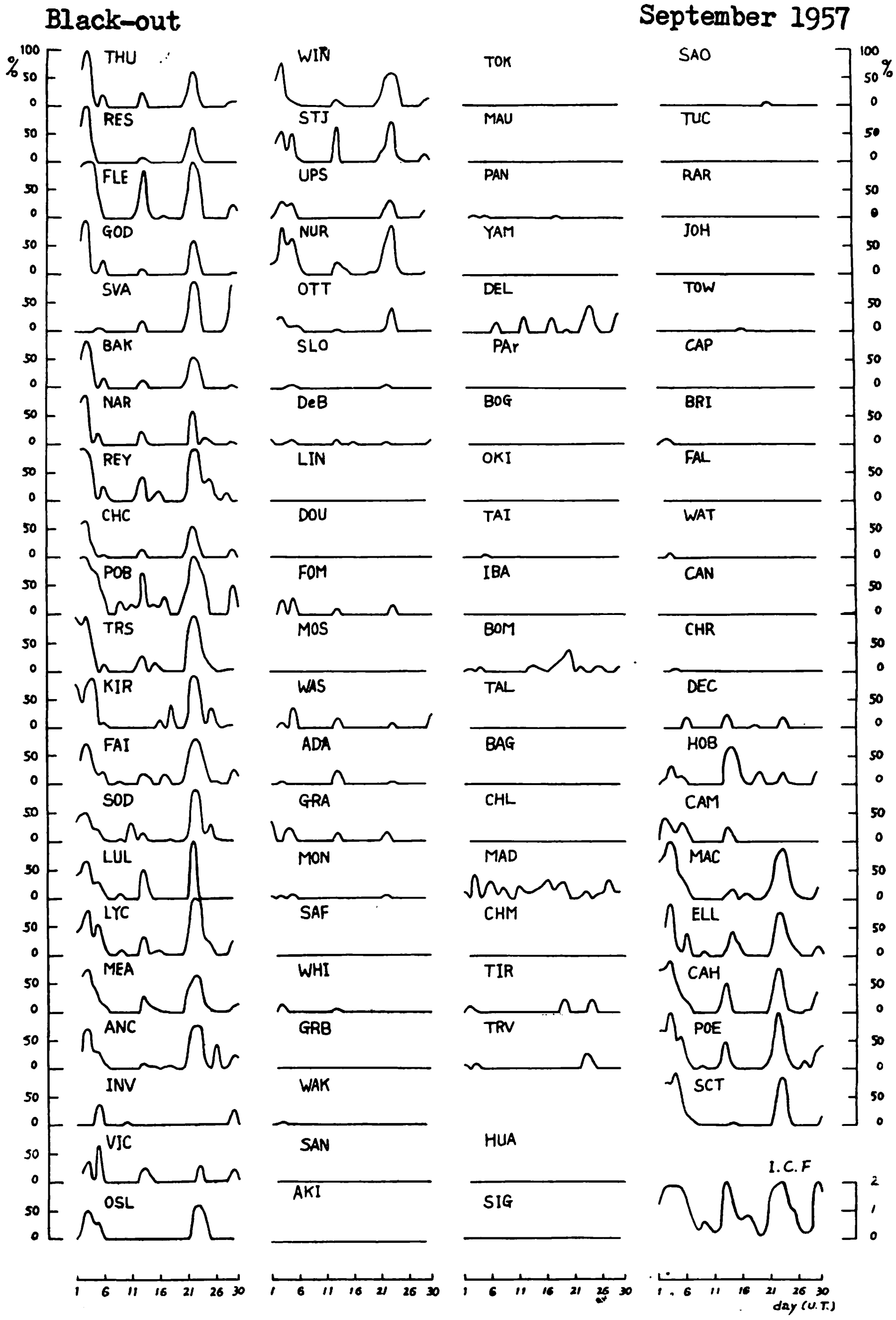


Fig. 6. Day-to-day variations in the occurrence probability of "black-out" in September, 1957.

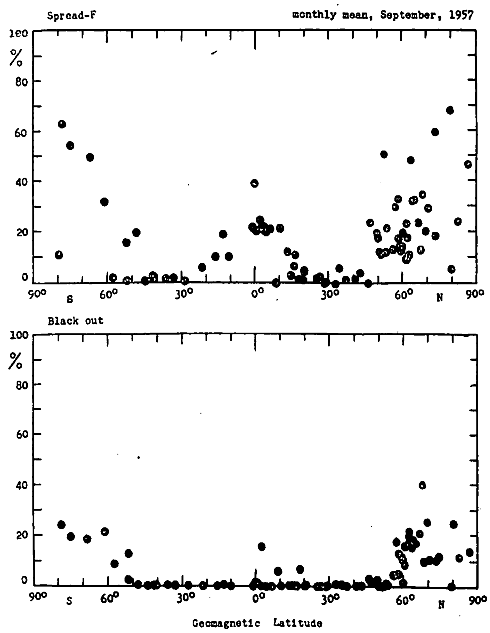


Fig. 7. (a) Latitudinal distribution of the occurrence probability of spread-*F* and "black-out". The average state in September, 1957.

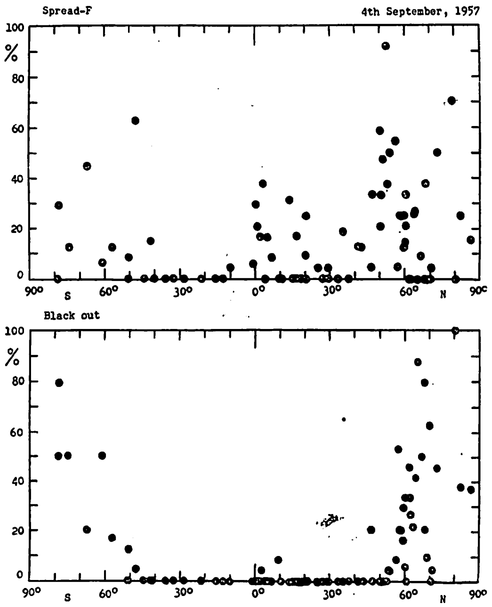


Fig. 7. (b) The state on the 4th of September, 1957.

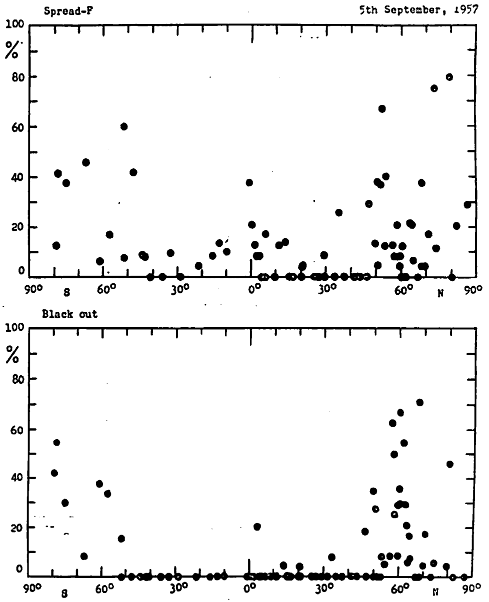


Fig. 7. (c) The state on the 5th of September, 1957.

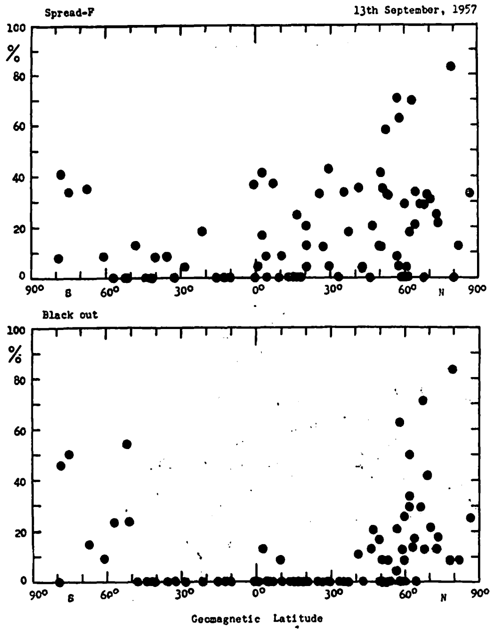


Fig. 7. (d) The state on the 13th of September, 1957.

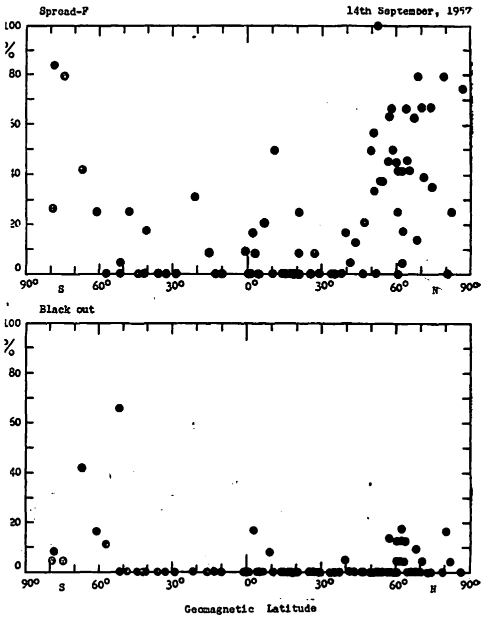


Fig. 7. (e) The state on the 14th of September, 1957.

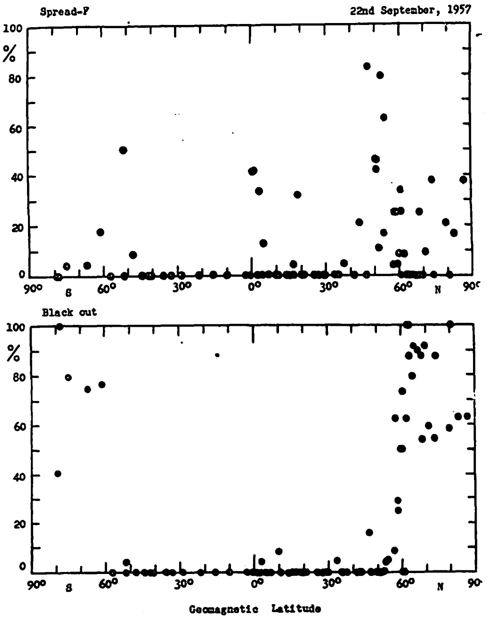


Fig. 7. (f) The state on the 22nd of September, 1957.

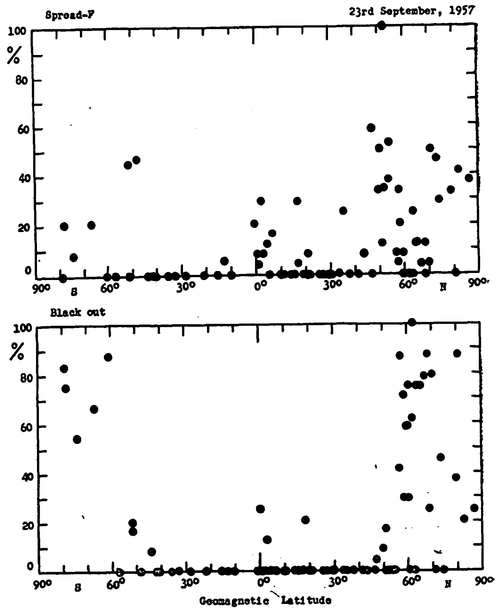


Fig. 7. (g) The state on the 23rd of September, 1957

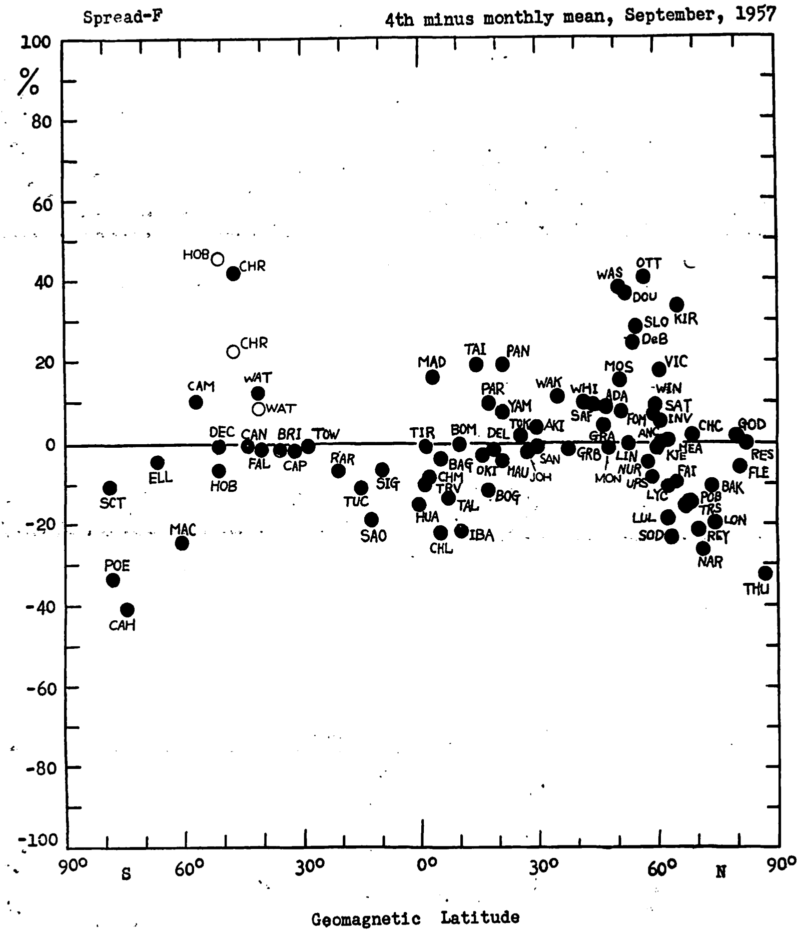


Fig. 8. (a) Latitudinal distribution of the difference between the occurrence probability of spread-*F* on the 4th of September, 1957, and its monthly mean. The white circles indicate the difference between that on the 5th and the monthly mean.

attention must be given to the fact that the time when the storm began on the 11th of February, 1958, was 01 h 26 m in universal time, and was nearly equal to the time of beginning of the storm on the 13th of September, 1957, (00 h 45 m). It is very interesting to see that in these two magnetic storms the spread-*F* occurrence probability at Tokyo and Akita increased considerably, while in two other storm the probability did not increase so largely, the latter two occurring at nearly the same local time (13 h 00 m on the 4th and 13 h 44 m on the 22nd), quite different from the former two storms. And in the

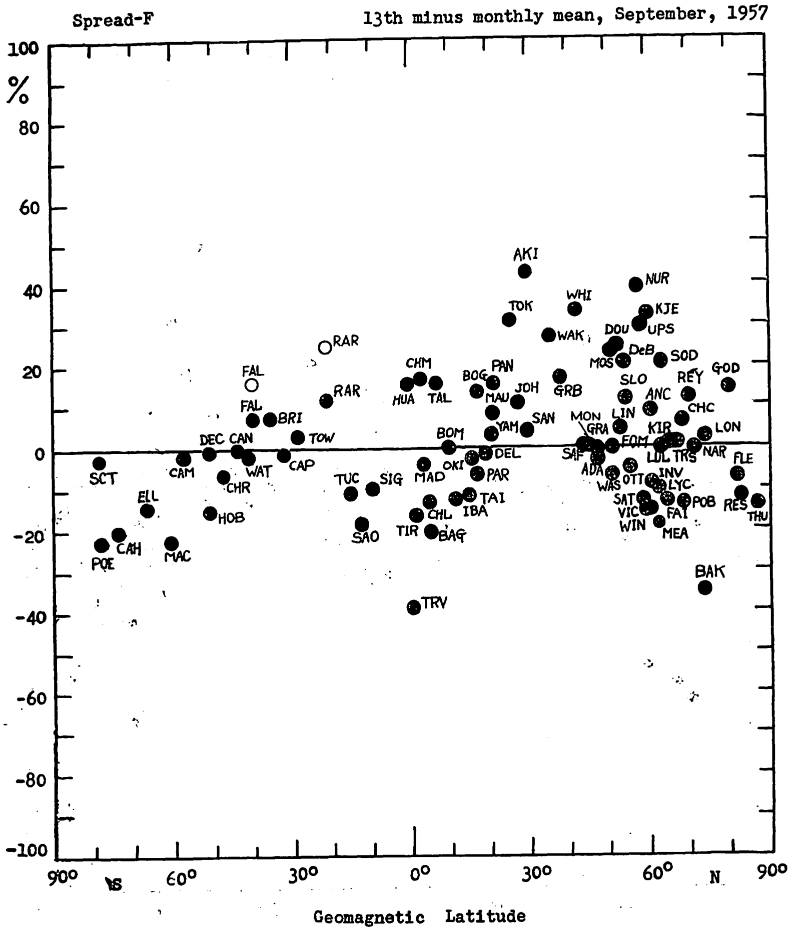


Fig. 8. (b) Latitudinal distribution of the difference between the occurrence probability of spread-*F* on the 13th of September, 1957, and its monthly mean. The white circles indicate the difference between that on the 14th and the monthly mean.

latter two storms, the enhancement of the occurrence probability can be seen most clearly at stations in Europe such as Slough in England and Doubres in Belgium (See Fig. 5).

Thus, it may be concluded that when the *SC* occurs during the daytime, the spread-*F* appears at the night following, while when it occurs at night, the occurrence of spread-*F* is not so appreciable at the night and the following at stations in the middle latitudes. This may be due to the fact that the effect of charged particles impinging the upper atmosphere accompanying with the severe

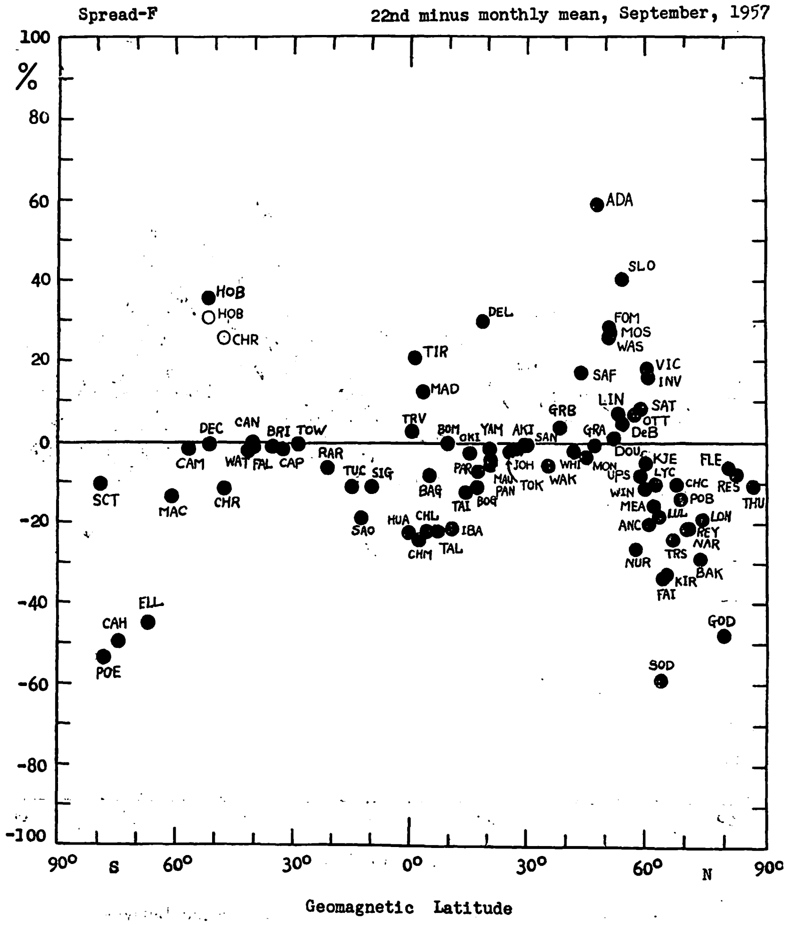


Fig. 8. (c) Latitudinal distribution of the difference between the occurrence probability of spread-*F* on the 22nd of September, 1957, and its monthly mean. The white circles indicate the difference between that on the 23rd and the monthly mean.

magnetic storms reaches the middle latitudes after a half day or so from the beginning of the storm.

3. Concluding Remarks

The results obtained in the present investigation may be summarized in the following conclusions:

(1) The correlation between the occurrence probability of spread-F and the geomagnetic activity is strongly negative at latitudes lower than 20°, while it is strongly positive at latitudes between 20° and 60°, and at latitudes higher than 60° it becomes negative again.

(2) The negative correlation at lower latitudes may suggest that the spread-F that occured at lower latitudes is due to the development of turbulent motions of ionized gas in the magnetic fields (see also the discussion in Part I), while the positive correlation at higher latitudes may suggest that the spread-F that occurred at higher latitudes is attributed to the entry of charged particles into the earth's upper atmosphere, although at very high latitudes (>60°) the spread-F can not be observed on the ground because of the occurrence of " black-out ", thus changing the correlation to the negative again.

(3) In severe magnetic storms, the occurrence probability of spread-F is much enhanced at middle latitudes, while it is much reduced at higher latitudes. At lower latitudes the effect of magnetic storm is not so appreciable as at higher latitudes. It seems likely that the enhancement of the probability at middle latitudes occurs somewhat later in the Southern hemisphere than in the Northern hemisphere.

(4) The change in the effect of magnetic storms with the latitude may well be explained by the consideration that the critical level of penetrating of charged particles into the earth's upper atmosphere rises gradually with the descent of latitude. At high latitudes, the ionization by impinging charged particles can occur in D or E regions, which may produce the " black-out ". At middle latitudes, the charged particles can not reach these lower levels but the F region, resulting in the enhancement of the spread-F occurrence probability. At lower latitudes, the charged particles can not reach even the F region, thus the effect will not be observed.

(5) The enhancement of the occurrence probability of spread-F at stations in the middle latitudes at the time of severe magnetic storms depends upon the time at which the magnetic storm begins as well as the magnitude of the storm. When large magnetic storm occurs at daylight hours, the spread-F tends to appear at the night following, but when it occurs at night, the spread-F is rather hard to appear at that and the following nights.

Acknowledgments

The present study has beed carried out as a part of ionosphere research programs in the Radio Research Laboratories, and the author wishes to express his thanks to Dr. H. Uyeda, Dr. Y. Aono, vice-directors of the Laboratories, and Dr. T. Yonezawa, chief of the Radio Physics Laboratory for their hospitality and financial support given the author.

The author's cordial thanks are given to members of the Ionosphere and

Space Research Committee in Japan for their valuable discussions, particularly to Prof. T. Nagata of Tokyo University and Prof. K. Maeda of Kyoto University.

The author is also indebted to Dr. D. F. Martyn in Australia who had a chance to visit Japan recently for his interest and valuable suggestions.

The author expresses his appreciation to all members at the observatories listed in Table 1 for the supply of available data. The author's acknowledgment is also made to Mr. M. Kimura for his aid given in carrying on troublesome numerical calculations.

References

Booker, H. G., 1957, Polar Atmosphere Symposium, Part II, Pergamon Press, p. 52.
Booker, H. G. and Wells, H. W., 1938, Terr. Mag., **43**, 249.
Bullough, K. and Kaiser, T. R., 1955, J. Atmosph. Terr. Phys., **6**, 198.
Dagg, M., 1957 a, J. Atmosph, Terr. Phys., **11**, 133.
1957 b, J. Atmosph. Terr. Phys., **11**, 139.
Dungey, J. W., 1958, Cosmic Electrodynamics, Cambridge Univ. Press. p. 167.
Kasuya, I., Katano, S., and Taguchi, S., 1955, J. Radio Res. Labors., **2**, 329.
Lehnert, B., 1955, Proc. Roy. Soc. Series A, **233**, 299.
Lyon, A. J., Skinner, N. J., and Wright, R. W., 1958, Nature, **181**, 1724.
Martyn, D. F., 1959, Proc. I. R. E., **47**, 147.
McNicol, R. W. E. and Webster, H. G., 1956, Aust. J. Phys., **9**, 272.
McNicol. R. W. E., Webster, H. G., and Bowman, G. G., 1956, Aust. J. Phys., **9**, 247.
Osborne, B. W., 1951, J. Atmosph. Terr. Phys., **2**, 66.
Reber, G., 1954, J. Geophys. Res., **59**, 445.
1956, J. Geophys. Res., **61**, 157.
Singleton, D. G., 1957, Aust. J. Phys., **10**, 60.
Webster, H. G., 1958, Aust. J. Phys., **11**, 322.
Wells, H. W., 1954, J. Geophys. Res., **59**, 273.