Worldwide Occurrence of Sporadic *E*

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UNITED STATES DEPARTMENT OF COMMERCE • Sinclair Weeks, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

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Ernest K. Smith, Jr.

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Foreword

This Circular marks the conclusion of a general study of sporadic *E* which has been carried on for the last three years, first at Cornell on a part-time basis and since September 1954 at the National Bureau of Standards Central Radio Propagation Laboratory at Boulder, Colorado, on a full-time basis. Although the actual research described in this report was performed almost entirely at CRPL many of the techniques used grew out of the work at Cornell. In both cases the work was sponsored by the Signal Corps.

The Circular is essentially identical to the writer's Ph. D. thesis at Cornell University, which was approved there in December 1955.

A. V. Astin, *Director*.

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Abstract

This study attempts to describe sporadic E on a worldwide basis utilizing observations at high frequencies (HF) with vertical-incidence ionosphere-sounding equipments (ionosondes) and at very high frequencies (VHF) of transmissions over oblique-incidence paths. An attempt is made to evaluate some of the consequences of this description in terms of possible energy sources of sporadic E.

Ionosonde data on sporadic E must be used with extreme care due to the fact that ionosondes are not calibrated for system gain and the sporadic-E critical frequency (fEs) is power sensitive. Particular attention is therefore paid to the errors that may be introduced.

Ionosonde results are analyzed for the occurrence of fEs greater than 5 Mc. The reasons for the choice of this limiting frequency are given in some detail. Three major zones are delineated on the basis of the temporal characteristics of the sporadic E in each. The Auroral Zone is separated from the Temperate Zone, for the purposes of this study, by the 15 percent auroral isochasm. A distinct Equatorial Zone is not observed on the nighttime side of the globe, but is recognized on the daytime side within the bounds of plus and minus 10° of magnetic dip angle. Within this Equatorial Zone the customary phenomena of the Temperate Zone are found plus an additional type of sporadic E unique to the Equatorial Zone. The Es characteristics of these zones are then examined geographically for six time blocks and also temporally at a series of individual locations through "time maps".

Treatment of the vertical-incidence data differs from that of previous studies chiefly in that the sunspot-cycle variation is here found to be a second-order effect compared to the other variations in the data and is consequently averaged out. An effective increase by a factor of five in the data sample is thereby obtained. A further difference in the treatment is that full geographical variation rather than variation of sporadic E with some latitude parameter is investigated. The VHF oblique-incidence data are treated in terms of transmission loss where possible. However, a study of some three thousand reports of television reception for which transmission loss could not be computed is also included.

New effects uncovered by this study are an outcome, first, of the parallel treatment of the vertical-incidence and the VHF oblique-incidence data and, second, of taking long-term averages of the vertical-incidence data. For example, the Temperate-Zone longitude effect was first suspected through intercomparison of VHF transmission-loss probabilities for United States and Japanese paths. Inspection of the vertical-incidence data covering seven years from the worldwide network of ionosondes confirms this effect in that a well-defined maximum in sporadic E is found to exist to the south of Japan. Similarly, in the investigation of correlation between magnetic activity and sporadic E a negative correlation is found in the Temperate Zone in vertical-incidence data. However, the effects of absorption could account for the observed correlation. In the VHF band the effects of absorption become unimportant and as the negative correlation is still observed it appears that this result is real.

The Phillips frequency-dependence rule is found to work quite well for occurrence of sporadic E on vertical-incidence sounders. An example is also given where this rule is found to apply, in a reinterpreted form, to oblique-incidence data.

The results of this study point toward a terrestrial energy source for Temperate-Zone sporadic E and an extraterrestrial one for sporadic E in the Auroral Zone. In the latter area it would appear that solar corpuscles are either directly responsible for much of the sporadic E or indirectly responsible through E-region currents. The Huancayo type of daytime sporadic E appears connected to the "equatorial electrojet".

Chapter I

INTRODUCTION

A. Purpose

A vast quantity of data relating to sporadic-E transmission exists. These data come first from ionosphere sounders (vertical incidence) at over a hundred locations, and second, from monitored field-strength measurements for more than a dozen VHF paths at oblique incidence. Other sources are amateur and television listener reports. Many studies have appeared in the literature which examine sporadic E as observed at vertical incidence in detail at one location or compare sporadic E at two locations. Many of these studies will be described later on. Some analyses have been made of vertical-incidence sporadic E on a world-wide basis (e.g. Phillips [1947], Matsushita [1953] and Prechner [1955]). These analyses have been restricted to a study of how some characteristic of sporadic E varies with a latitude parameter. Considerable question has always existed as to whether vertical incidence sporadic-E data are sufficiently accurate and consistent to be useful.

This study proposes to examine the vertical-incidence data on a geographical rather than a latitude basis. An attempt to maximize the significance of the data is made by taking long term averages of recent data (1948-1954). A gauge of the reliability of the results is obtained through the internal consistency of the data both as regards their year-to-year variations and their geographic variation.

The VHF oblique-incidence data are scarcer than the ionosphere sounder data, but more reliable. These data are also much less affected by non-deviative absorption. Intercomparisons of the vertical incidence and VHF data can profitably be made. The VHF data can be used to establish points which appear probable from the vertical-incidence results; the more complete geographical distribution of the latter can be used to flesh out the VHF observations.

This study, then, is an integration of sporadic-E observations in frequency, in time, in path length and in geography. It must be classed as an exploratory study. A large number of sporadic-E characteristics will, of course, remain to be examined by this technique. As the reduction of the data is laborious an effort is made to present the reduced data in a form such that it can readily be used in other analyses.

B. A Working Definition of Sporadic E

1. Choice of a Term

There has been quite a series of terms used to cover essentially the same set of phenomena. "Abnormal E" and "nocturnal E" were perhaps the earliest chronologically, both having been used in the early thirties (e.g. Ratcliffe and White [1933], Appleton and Naismith [1933], Kirby, Berkner and Stuart [1934]). Ratcliffe and White [1934] also suggest "e layer" inasmuch as their determinations of virtual height showed that the abnormal ionization occurred at heights of 105 ± 5 km as compared to 100 to 120 km for regular E. The term "sporadic E" is found in Kirby and Judson [1935]. Each of the terms was originally an abbreviation; e.g. "abnormal E region ionization," "sporadic E region ionization," etc.

At the International Radio Propagation Conference of 1944 (see IRPL-C61), the proponents of the various terms agreed to compromise on "Es" and to discontinue the use of "sporadic E." The objections to the use of "sporadic E" are twofold. First, it is unclear from the term whether the sporadicity is temporal or geographic. Second, if it is the temporal variation which is to be considered "sporadic" how can one logically include the phenomenon observed on the magnetic equator in which a daytime transparent E-layer reflection exists which is highly regular in its time variation but is clearly not the normal E layer.

This study does have a certain responsibility towards scholarship and it seems important not to lend further support to an inappropriate term unless it is clearly established in scientific usage. The demands of scholarship would seem to dictate adherence to the expression mirroring the usage of the majority. Therefore, a study was made of the terms used in thirty papers in the field of sporadic E written by workers from six different countries. All had been published since 1951. Twenty-six of the thirty (87%) used the term "sporadic E" and eleven of these also used "Es" synonymously with "sporadic E." The writers in two of the papers (7%) used "Es" alone as recommended by the International Propagation Conference. The remaining two papers referred to the effect as "Abnormal E." A cursory inspection of usage in the published literature prior to 1944 indicated that "sporadic E" and "abnormal E" enjoyed about equal popularity, whereas now the term "sporadic E" enjoys a wide advantage over either "abnormal E" or "Es" when used in the sense intended by the 1944 conference. These results would seem to dictate "sporadic E" as the best choice and to suggest that if "Es" is to be employed it should be used synonymously with "sporadic E." This study will employ both terms and use them always interchangeably.

2. Definition

Having settled, at some length, the question of what term to use there still remains the problem of what is meant by the term sporadic E or Es. This study will adopt the following definition. By sporadic-E propagation is meant a comparatively strong and protracted transmission (several minutes to several hours) "returned" from the E region of the ionosphere by some mechanism other than the normal reflection process from the daytime regular E layer.

Five key words or phrases are underlined in this definition. In chapter III it will be found that "comparatively strong" is taken to extend down to at least 62 db below free space. "Protracted" is inserted to remove the effect of the meteoric bursts. The term "returned" is used in a specialized manner. First, it is employed in a broad sense to include a scattering mechanism if such is active. Second, an implication is intended that the return is from overhead in the vertical-incidence case and on the great-circle path for oblique-incidence transmission. However, this second condition will be stretched occasionally in the chapters that follow. The "E region" is specified instead of a height interval of 90 to 140 km, because the upper limit of the height range in the reduced Es data is subject to some variation from station to station. By eliminating only "the regular daytime E layer" this study includes the so-called "night E" or "retardation Es" seen in the auroral zone.

In wording the definition, the author has tried to make it applicable to both vertical and oblique-incidence work.

C. The Physical State of the Atmosphere in the Es Region

It is appropriate to review some of the physical properties of the region with which this study will be concerned. Table I-C-1 contains the values of temperature, pressure, density, mean molecular weight, mean free path and scale height as published by the Rocket Panel [1952] (Whipple [1954]). It should be noted, however, that the temperature values are directly proportional to the values assumed for mean molecular weight. A linear dissociation rate has been taken for O_2 in this table in the range 80-120 km and N_2 in the range 120 to 220 km. Computations by Bates and Witherspoon [1952] show that the dissociation of O_2 to O takes place in a narrow range of altitude at 100 km. In their treatment which neglects turbulent mixing it is found that in one scale height (7.3 km) centered on the height where density O_2 = density O, the ratio of these two constituents is found to change by a factor of 100. This change is 35 times greater than that used by the Rocket Panel, and although mixing will serve to reduce this gradient, still the temperatures listed for the 80 to 120 km region should not be taken too literally. It should be mentioned that the scale-height H does not depend on the value of mean molecular weight chosen because the basic rocket measurement is ambient pressure p as a function of height h and H is given by

$$\frac{d \ \ell n \ p}{dh} = \frac{-1}{H} = - \frac{gm}{kT}$$

TABLE I-C-1

Atmospheric Data
Derived from Rocket Panel Results (after Whipple [1954])

Height (Sea Level) (km)	Adopted Mol. Wt. (gm/mol.)	Temperature (^oK)	Scale Height (km)	Mean Free Path (cm)	Pressure ($\log_{10}$) (dynes/cm^2)	Density ($\log_{10}$) (gm/cm^3)
80	28.97	205.0	6.16	4.3×10^{-1}	1.094	-7.676
90	27.52	206.2	6.54	2.1	0.405	-8.389
100	26.22	217.3	7.26	9.5	-0.227	-9.065
110	25.03	233.3	8.19	38.	-0.794	-9.684
120	23.95	272.8	10.04	1.3×10^{2}	-1.273	-10.249
130	22.50	302.9	11.90	3.7×10^{2}	-1.670	-10.720
140	21.21	327.3	13.68	8.7×10^{2}	-2.009	-11.119
150	20.06	348.4	15.44	1.8×10^{3}	-2.308	-11.468
160	19.34	368.0	17.24	3.6×10^{3}	-2.574	-11.781
170	18.10	386.7	19.11	6.1×10^{3}	-2.813	-12.062
180	17.26	403.4	20.79	1.0×10^{4}	-3.030	-12.318
190	16.50	418.5	22.84	1.8×10^{4}	-3.228	-12.552
200	15.76	432.1	24.70	3.0×10^{4}	-3.411	-12.768

where g is the local acceleration of gravity, m the mean molecular weight, k is Boltzmann's constant and T is the temperature in degrees Kelvin.

1. Winds

High wind velocities in the E region have been measured by a variety of techniques such as comparison of fading patterns on spaced receivers, observation of meteor trails and velocity of sporadic-E clouds. A good review of these techniques and their results is found in Briggs and Spencer [1954]. Measured velocities are of the order of 50 m/sec.

2. The Regular E Layer

Chapman [1931] developed the basic mathematical equations for the formation of ionized layers through absorption of monochromatic radiation from the sun. He treated the case of the plane isothermal (or better constant scale height) atmosphere, but pointed out that the treatment could be extended to account for earth curvature. The expression for ionization rate q is given by

$$q = \beta \frac{dS}{dh} \cos X = 2AS_{\infty} \rho_o \exp\left[\frac{h}{H} - A\rho_o H \sec X \exp\left(-\frac{h}{H}\right) \right] \qquad \text{1-C-1}$$

where β = number of ions produced by absorption of a unity quantity of radiation

A = absorption coefficient per unit mass

S = intensity of monochromatic ionizing solar radiation

S_{∞} = S at top of atmosphere

ρ_o = density that would exist at ground level if $\rho = \rho_o \exp\ [-h/H]$ were true for all heights

h = height above ground

H = scale height

χ = solar zenith angle

Chapman assumed recombination to be the only process serving to reduce the electron density. Under this hypothesis the rate of change of electron density is given by

$$\frac{dN_e}{dt} = q - \alpha N_e^2$$

q = rate of production of ions

α = effective recombination coefficient I-C-2

Around local noon $dN_e/dt = 0$ and

$$q = \alpha N_e^2 \quad \text{(equilibrium condition)}$$

Substituting for q and solving for N_e gives

$$N_e \sim q^{\frac{1}{2}}(\chi) \quad \text{(equilibrium condition)}$$

where χ = sun's zenith angle.

Around local noon the maximum of the Chapman layer will coincide with the maximum h of ion production which in turn is obtained through differentiating (I-C-1) with respect to h and setting the right hand side equal to zero.

$$h(\chi) = H \ln (A\rho_o H \sec \chi) \qquad \text{I-C-3}$$

From (I-C-3) it is seen that the height of the level of maximum ion density of a Chapman region around midday is a function only of the solar zenith angle and is a minimum at the subsolar point.

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The E layer behaves very nearly like a pure Chapman region, at least from 0.2 N maximum up to N maximum. However, some of the recent rocket measurements have shown the region above the maximum up to the F_1 to have almost the same ion density as the maximum of the E region.

Order of magnitude values of midday electron density at the maximum and height in the E layer may be taken as $1.5 \times 10^5/cm^3$ and 110 km respectively. The electron density at the maximum in this layer as given by Allen [1948] is

$$N_e = 1.35 \times 10^5 \ (1 + 0.0097R)^{\frac{1}{2}} \ (\cos \chi)^{\frac{1}{2}}/cm^3 \qquad \text{I-C-4}$$

where R is the sunspot number and χ the solar zenith angle. Similar expressions have been given by other workers. It is seen in relation (I-C-4) that between sunspot numbers 0 and 103 the electron density of the E region maximum will increase by a factor of $\sqrt{2}$. In relation to (I-C-2) if it is assumed that $dN_e/dt << q, \alpha N^2$ (which is not unreasonable near midday), then the rate of electron production $q \sim N_e^2$. The rate of ion production, then, increases by a factor of two for an increase of R = 0 to 103. It is perhaps worth noting that by (I-C-1) the rate of ion production is directly proportional to the incident photon flux in the spectral region responsible for the E-region ionization. The flux in this spectral region (perhaps λ900 to λ1000, see below) varies by a factor of 2 in a sunspot cycle.

The recombination coefficient α for the E layer (I-C-2) is about 10^{-8} which is the order of 10^2 greater than that for the F_2 region. The explanation for this is at present uncertain.

The actual reactions involved in the production and decay of electron density in the E region expressed by relation (I-C-2) are extremely complicated. In a recent survey Bates [1954] rejects the possibility of high λ (negative ion to electron ratio) and also the attachment mechanism. He favors the following processes.

For production of E-region electrons: absorption of energy from a number of discrete bands lying within the molecular oxygen continuum followed by spontaneous ionization,

$$O_2 + h \ (\geq 12.0 \text{ eV} \leq 13.6 \text{ eV}) \ O_2' \qquad \text{I-C-5}$$

$$O_2' \rightarrow O_2^+ + e$$

For decay of E-region electron density: dissociative recombination of O_2^+,

$$O_2^+ + e \rightarrow O' + O'' \qquad \text{I-C-6}$$

where the O_2^+ is either formed directly or through charge transfer collisions,

$$O_2 + O^+ \rightarrow O_2^+ + O \qquad \text{I-C-7}$$

These mechanisms are arrived at through a process of elimination, and should be treated as the most likely production and recombination processes based on the rather scanty information currently available.

D. Energy Sources of Sporadic E

1. Solar Corpuscles

Some consensus of opinion does appear to be forming in regard to the source of energy of sporadic E in the auroral zone. It has long been appreciated that Es in this zone is correlated with magnetic activity (see for example: Appleton, Naismith and Ingram [1937]). Knecht [1952] [1956] and Heppner, Byrne and Belon [1952] have obtained correlation of Es activity with auroral forms. It has been argued (Wulf [1953]) that solar corpuscles are not the direct source of energy in aurorae but merely act as a trigger to the unstable upper atmosphere. This hypothesis is not born out by the measurements of doppler shifted hydrogen ions in auroral rays (Gartlein [1951], Meinel [1951]) and by the doppler-shift in radio echoes on 106 Mc (Bowles [1954]). If one considers the cause of magnetic activity and aurorae to be corpuscular radiation from the sun, it may also be accepted that much of auroral-zone sporadic E is due to these solar corpuscles.

Some statistics will be considered in Chapter II on the actual proportion of medium sporadic E (fEs>5Mc) attributable to this energy source in the auroral zone. It will also be demonstrated that solar corpuscles (or any other extraterrestrial phenomena) are a highly unlikely source of energy for temperate and equatorial-zone sporadic E.

2. Meteors

Early in radio work meteors were considered an agent altering the ionization in the ionosphere in a manner affecting radio communication.

Nagaoka [1929] suggested that meteors might have a "clean-up" action in supplying condensation nuclei upon which the ionic particles of the ionosphere can settle. Skellett [1931] [1932] suggested that the ionization contributed to the upper atmosphere according to the theory of Lindeman and Dobson [1923] could be substantial compared to that from other sources, in particular during meteor showers he estimated the contribution of meteors as $\frac{1}{14}$th that due to ultra-violet light in the daytime. He also correctly localized the region affected by meteors to the lower ionosphere. Schafer and Goodall [1932] suggested that the nighttime E-layer reflections were due to meteors. The results of their attempts at correlation during four meteor showers were, unfortunately, confused by magnetic activity. The ensuing years have produced a series of papers supporting meteors as a primary source of sporadic E. Unusual Es was observed during meteor showers by Mitra, Syam and Ghosh [1934] in India, Skellet [1935] in the U. S., and Appleton and Naismith [1947] in England. The latter paper in particular demonstrated that during an intense meteor shower meteors can produce Es. Meanwhile it had been discovered that if the power of a vertical-incidence sounding system or synchronized oblique-incidence system were increased so that ionospheric reflection coefficients as low as 0.001 could be noticed, a succession of short "burst" type echoes could be observed continuously. These have been discussed by a large number of authors. Eckersley [1937] and Appleton and Piddington [1938] give good descriptions of the phenomenon, while a review of the subject may be found in Dieminger [1947] [1951]. It is generally conceded that these "ionization bursts" are meteoric in origin. They are mentioned here as an associated phenomenon, not as sporadic E.

Hey and Stewart [1946] reported on meteoric reflections in the 60 - 75 Mc band and pointed out the aspect sensitivity at these frequencies. Interest in VHF meteoric reflections has been high ever since. Reference is made to Manning [1954] for a discussion and review of the work.

Pineo [1950] reported on a study at CRPL in which meteor reflections from a 27.2 Mc radar were compared to Es incidence observed on a C2 sounder. Selecting only the long duration Es echoes no correlation between the two phenomena was apparent. This experiment demonstrated quite conclusively that meteors do not furnish the principal source of energy for Es except perhaps during strong showers.

The situation at oblique incidence is much less certain. Wartime Loran work reported in the U. S. by Pierce [1946] and in England by Naismith and Bramley [1951] showed that at frequencies of 0.7 to 2 Mc returns came from a height consistently below the E layer. Naismith [1954] interpreted these results as due to the meteoric contribution at these heights and suggested that E-region echoes be divided into three categories: regular E (due to ultra-violet radiation from the sun), E_m (contribution from the meteoric E layer), and Es. Meteoric contributions to the vertical-incidence records from Slough (5-minute sweep time) are quite easily discernible. The same is, unfortunately, not the case for the current CRPL sounder, the C-3, with a nominal 15-second sweep time.

Echoes of short duration have been examined by Allen [1948] for oblique VHF paths and he found that these correlate well with the expected meteor diurnal variation (strongest in the early morning hours) whereas the Es observed over these paths did not show the same agreement. There has been considerable speculation on the extent of the meteoric contribution in ionospheric forward scatter (Bailey et al. [1952]), but there has been no definitive paper on the subject. Transmissions via meteoric reflections have been obtained in the upper H. F. band (see Villard et al. [1953]).

3. Thunderstorms

Even before sporadic E was noticed, it had been suggested by Wilson [1925] that thunderstorms might be a source of ionization in the ionosphere. He envisaged two possible mechanisms both due to the pre-lightning field of the cloud. In the first he considered the effect in the upper atmosphere of the electric moment M of the thundercloud. Taking the electric force vertically over the thundercloud as $2M/r^3$ and M of the order of 3×10^{16} e.s.u. cm, he suggested that if a conducting layer containing free electrons existed at an 80 km height these electrons might be accelerated under the influence of the field to sufficient velocities in one mean free path to cause ionization. His second mechanism consisted of so-called "run-away electrons". As high velocity electrons at sea level tend to lose energy at the rate of 10,000 volts/cm, he felt that if the field from the ground to the thundercloud exceeded this value the electrons would gain energy, and at an increasing rate, as they proceeded upwards. Many attempts have been made to measure these runaway electrons at the surface of the earth according to Chalmers (p. 139 Atmospheric Electricity, 1949) and some success has been experienced.

Appleton and Naismith [1933] treated the conducting ionosphere as a cathode, the charged thundercloud as an anode and suggested, through analogy with a vacuum tube, that ion production would be a maximum around 7 km below the conducting layer.

Another possible mechanism has been suggested by Bailey and Martyn [1934] in the course of their analysis of the Luxemburg effect. They consider that the effect of the e.m. shock wave due to lightning bolt is to produce a field in the E layer expressible in the form

$$E = AC^{-at}\sin bt. \qquad \text{I-D-1}$$

Obviously, the field of a nearby lightning bolt can modulate a radio wave in the ionosphere. Bailey and Martyn also tried to show that the field could accelerate free electrons to energies sufficient to produce further ionization through collisions which would substantially raise the existing ion densities. The authors thought their computations demonstrated this. However, Healey [1936] pointed out that an error of a factor of ten had been inadvertently introduced in one of their factors. The revised computation seemed to show that although the ion density would be increased somewhat, it would be a matter of a few percent and not constitute a substantial effect.

The actual demonstration that a correlation exists between sporadic E and thunderstorms has been a controversial process. Some measure of success has been reported by F. E. Lutkin in Appleton and Naismith [1933] and by Ratcliffe and White [1934] and most recently by Isted [1954] in England, by Colwell [1934] and Mimno [1937] in the United States and by Bhar and Syam [1937], Chatterjee [1953] and Mitra and Kunda [1954] in India. There have been no dissenting voices from India. In England, however, Appleton, Naismith, and Ingram [1937] concluded that the Appleton and Naismith [1933] correlations were suspect because the thunderstorm index used (intensity of received atmospherics) would itself be influenced by the improved propagation conditions when Es was active. Meanwhile Best, Farmer and Ratcliffe [1938] found no correlation with thunderstorms, and further, when they reworked the Ratcliffe and White [1934] data they found that upon the addition of another year's data and a slightly improved thunderstorm index the highly significant thunderstorm dependence found earlier became quite insignificant. In the United States Kirby and Judson [1935] had found no correlation.

The theory that thunderstorms provided an important source of world-wide Es was seemingly disproved by Berkner and Wells [1937] in a comparison of the incidence of blanketing and strong but non-blanketing Es as observed at Watheroo with that observed at Huancayo. They observed seventy times more Es of these varieties at Watheroo than at Huancayo. As thunderstorms are much more frequent around Huancayo, this appeared to demonstrate that thunderstorms could not play an important part in the production of strong Es. However, the weak, non-blanketing, type of Es which is a regular daytime phenomenon at Huancayo was not then included as a form of Es.

4. Winds and Turbulence

Substantial winds are known to exist at E-region heights and observations of meteor trails indicate considerable turbulence exists in this general region. Various mechanisms have been proposed to explain how this turbulence can produce blobs with the required differential of dielectric constant ($\Delta\epsilon$) from the mean (ϵ). Villars and Weisskopf [1954] sought to obtain the required $\Delta\epsilon/\epsilon$ through density fluctuations by invoking the Kolmogoroff spectrum of turbulence and introducing "observed" values of upper atmosphere turbulence velocities and scale. Recently these authors (Villars and Weisskopf [1955]) have acknowledge that the turbulence velocity (50 m/s) used for the ionospheric example in the 1953 paper was too high. As a result density fluctuations can no longer be considered an adequate explanation.

Two more promising mechanisms have been suggested by Gallet [1951] [1955]. The first considers the effect of turbulence on a region with a steep gradient of electron density with height, as in the lower part of the regular E layer. The scale of turbulence in this case determines the size of the mean square fractional deviation of dielectric constant from the average $(\frac{\Delta\epsilon}{\epsilon})^2$. The turbulent velocity need only exceed a certain minimum value in order to produce the blobs faster than they can be destroyed by recombination and diffusion. The turbulence is thus only a carrier. Villars and Weisskopf [1955] have independently arrived at this same explanation. The second mechanism postulated by Gallet [1955] is that of temperature fluctuations. If a blob is moved upwards its temperature will tend to follow the adiabatic lapse rate. If this takes place in a region of positive temperature gradient with height (as in the E region) the temperature differential between ambient and blob will be accentuated and the resultant density differential magnified.

5. Currents

Striking correlation is seen between particular types of Es and the flow of electric currents at E region heights. No reflection mechanism has been proposed. The general assumption is that the currents supply an energy source for the production and maintenance of ionization inhomogeneities which then serve as scattering sources. Matsushita [1951], Rawer [1953] and Smith [1953] have pointed out the correlation between the daytime type of sporadic E observed at Huancayo and the overhead current stream flowing around the magnetic equator. Both are regular daytime phenomena and they have the same diurnal shape. Matsushita [1951] has illustrated the similarity between the geographical behavior of the currents and the type of Es seen at Huancayo through use of Egedal's [1947] description of the daily range in the horizontal intensity of the earth's magnetic field for various stations near the magnetic equator. Singer, Maple and Bowen [1952] have determined, through rocket measurements on the magnetic equator, that the current has a mean height of 100 km corresponding to that measured for sporadic E at Huancayo.

Frequent and intense currents in the E region are also found in the auroral zone. Cases have been reported of intensification of sporadic E coincident with the passage of the E-region current system over Ithaca (Booker, private communication [1953]).

Slant Es, a type of psuedo-sporadic E which will be discussed in detail later, is seen in various parts of the world but principally in the auroral zone and on the magnetic equator. Bowles (private communication 1955) has pointed out that there is a striking time correlation between evening cases of slant Es and the appearance of a positive bay. Morning observations of slant Es show a similar correlation with the occurrence of negative bays. No correlation of Es with magnetivity activity was discernible for the four cases of slant Es observed at Maui (well off the magnetic equator).

E. The Structure of the Sporadic-E Region

Three classes of structures for the reflecting stratum have been suggested to explain the observed characteristics of sporadic E. These are: a thin horizontal layer of high electron density embedded in the regular E layer; a steep gradient in the lower or upper part of the E layer giving partial reflections by presenting a sharp boundary to the incident wave; and lastly, blobs of ionization whose electron density differs to some degree from that of the surrounding medium. Reference is made to the literature (e.g. Smith [1951]) for background material on these three classes.

1. Thin Layer

The thin layer hypothesis offers two reflection mechanisms: first, a reflection up to the plasma frequency (for vertical incidence) and second, a discontinuity reflection. The latter mechanism is the same as that for the gradient, but the physical structure is different. Several authors have computed the reflection (and transmission) coefficient versus frequency curve for special shapes of electron height distributions (e.g. Rawer [1939], Rydbeck [1948]).

2. Steep Gradient or Ledge

This structure has received some support recently from rocket measurements made coincident with a vertical radio sounding at White Sands, New Mexico. In some cases the height of the sporadic E seen on the ionogram corresponded to a ledge in the height distribution of electron density as derived from the rocket data. Seddon [1954] reported on four rocket flights above 90 km. The results of two of these flights corresponded to Es observed on the ionosonde. In the rocket flight of January 22, 1948, the electron density at 100 km rose sharply from 1.2 to 2.3 x 10^5 el./cc at which point higher measurements were obliterated. Es was observed up to 6 Mc in this case. On November 21, 1950, a steep gradient in electron density (1.3 x 10^5 el./cc , 108-109 km)was observed from the rocket measurements while Es up to 5.2 Mc showed up on the ionosonde (Jackson [1954]). Seddon observed that the only common characteristic of the two cases was the steep gradient in electron density.

3. Scattering Centers or Blobs

In an earlier survey (Smith [1951]), the author felt that the most likely E region formation responsible for temperate-zone sporadic E was a stratum containing scattering centers which differ only slightly in dielectric constant from the region in which they are embedded. At that time this mechanism had been suggested by Eckersley [1932]; Watson-Watt [1933]; Ratcliffe and Pawsey [1933]; Best, Farmer and Ratcliffe [1938]. Quantitative computations have been made by Booker [1950] and Gallet [1955].

Inhomogeneities embedded in an E region layer have also been interpreted in a somewhat different manner by Rawer [1953]. In this instance the tailing off in energy with frequency is thought to be due to the following mechanism: the plasma density of the layer itself defines the highest frequency for which unity reflection coefficient from the Es region is observed; the distribution of blobs of higher plasma densities then defines the distribution of reflected energy at higher frequencies. By this hypothesis, if energy is returned at 20 Mc, blobs of plasma densities $N = \frac{\epsilon_0 m \omega^2}{e^2} = 1.24 \times 10^4 f_{mc}{}^2 = 5 \times 10^6$ e/cc. would exist in the E region. Such high plasma densities cannot be ruled out in the auroral zones but appear highly unlikely at intermediate latitudes.

Ionization bursts and VHF forward scatter can be explained more easily than sporadic E by a scattering theory. With Es it is difficult to account for the high field strengths, the sharp height demarkation frequently observed on vertical-incidence records and the evidence of stratification.

Very interesting results, which are still largely unpublished have been obtained by Gallet [1951], [1954[, [1955]. By assuming uniform turbulence in the E region evidence is presented for intensification of the ratio $\Delta\epsilon/\epsilon$ both in the region of maximum vertical gradient in electron density (through turbulent mixing) and in the region of maximum electron density of the layer (through temperature fluctuations). This theory defines certain levels relative to the E layer maximum where sporadic E is most likely to occur, thereby affording a means of testing it by careful height determinations.

Chapter II

VERTICAL-INCIDENCE SPORADIC-E DATA

A. Introduction

This chapter is concerned with the systematization of sporadic-E critical-frequency data (fEs) as scaled from film records (ionograms) taken on vertical-incidence ionosphere-sounding equipment (hereafter referred to as ionosondes). One hundred and sixteen of these stations are listed in Appendix I for which published data are available for periods ranging from a few months to more than fifteen years in a few cases. The CRPL-F series* (formerly the IRPL-F series) have for the last ten years published monthly summaries of ionospheric data from ionosondes operated on a routine basis. The sporadic E data are given in two forms. First, the monthly median of the hourly values of sporadic-E critical frequency (fEs) at each station is reported for each hour of the day (if Es occurrence is frequent enough to provide a median value). Median values of height (h'Es) at which sporadic E is observed are similarly summarized for each hour of the day. The second presentation of monthly data offers curves showing the percent of time that the vertical critical frequency of the sporadic E exceeds 3, 5 and 7 Mc as a function of time of day at each station. Such monthly Es data

*A monthly publication of limited distribution of the National Bureau of Standards.

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as are used in this study will be drawn almost entirely from the second category. For reasons which will be considered below the major part of the vertical-incidence analysis will be in terms of percent of time for which fEs exceeds 5 Mc.

The vast majority of sporadic E recorded on ionosondes is power sensitive. The curve of the reflection coefficient versus frequency rarely drops from near unity to the neighborhood of zero in less than 0.1 Mc (the smallest frequency interval considered in routine scaling). Therefore, the Es incidence is affected by differences between ionosondes in transmitter power, receiver sensitivity,antenna patterns, duty cycles and sweep times; also, variations at different locations in interference (atmospheric and man-made) and ionospheric absorption will produce undesired changes in the observed sporadic-E incidence.

Scaling conventions are another possible source of unwanted modification in the reported sporadic-E incidence of different stations. In recent years most stations have followed conventions prescribed by CCIR and URSI but some differences still exist, notably in the auroral zone where the phenomenon becomes incredibly complex.

The critical frequency of sporadic E (fEs) is the only one of the critical frequencies regularly recorded (f_oE, f_oF_1, f_oF_2) which is power sensitive. Perhaps as a result of this fact ionospheric workers have tended to regard fEs as a pariah among its comparatively well-behaved cousins. Few attempts have been made to analyze fEs data on a world-wide basis. In fact anybody attempting such a study is in danger of being regarded as wasting his time.

The philosophy which has been adopted for this study intends to consider the sources of error which detract from the homogeneity of the data but not to prejudge results because of the possible shortcomings of the data. A basic source of trouble lies, of course, in the ionosondes. Sub-section II-A-1 considers the behavior of ionosondes in general and the C-3 in particular.

Section II-B is devoted to the appearance of sporadic E from stations operating in various parts of the world. No attempt has been made to make this section a definitive study of Es types but ionograms of some of the more distinctive types are shown and the characteristics of these types considered briefly.

Section II-C is concerned with the problems of using scaled Es data. Scaling conventions are discussed in II-C-1. Some obvious discrepancies in fEs data are considered in II-C-2, while II-C-3 contains a comparison of the relative advantages of each of the three frequency levels 3, 5 and 7 Mc as a lower limiting frequency. The utility of sporadic-E height data (h'Es) as currently scaled is considered in Section II-1.

1. <u>The Ionosonde</u>

The original vertical-incidence ionosphere-sounding device used by Breit and Tuve [1926] was a very crude piece of gear according to modern standards. It was, however, the forerunner of both the radar and the modern ionosonde. In an earlier note (Breit and Tuve [1925]) they credit W. F. G. Swann and J. G. Frayne with the plan to

". . .interrupt the continuous waves of a transmitting station and to interrupt the action of a receiving set in such a way as to have the receiver out of adjustment when the station is sending and to have it in adjustment when the station is not sending. With a suitable frequency of interruption the waves were expected to be received from the layer by the receiver even though there should be no waves directly from the transmitter." The Swann and Frayne scheme is closer to modern day radars and ionosondes than is the method actually used by Breit and Tuve.

Gregory Breit and Merle Tuve obtained the cooperation of NRL station NKF, the Westinghouse station KDKA, the RCA station WSC and the NBS station WWV. The NRL transmissions from station NKF on 70 meters were the ones from which definite indications of reflections from the ionosphere were obtained. This was attributed to the fortunate location of NKF relative to the receiving site (eight miles away) and to the fact that NKF was crystal controlled. The transmitted wave was "pulsed" simply by supplying the amplifier tubes with alternating current (500 cps) and the master oscillator with direct current. The "time on" could be varied from 1/3 to 1/5 through adjustment of the grid bias voltages. A. H. Tayler and his assistants L. A. Gephardt and L. C. Young made the arrangements for NRL. The receiving system consisted of a detector, amplifier and oscillograph. The oscillogram showed one hump corresponding to the direct transmitted pulse and then other humps corresponding to layer reflections.

The next major advance came in the introduction of sweep-frequency equipment. The first successful pulse-sweep record was obtained at the National Bureau of Standards on April 22, 1933 (Gilliland [1933]), and at the National Physical Laboratory May 20, 1933 (Naismith [1934]).

Automatic sweep-frequency (h'f) equipment which recorded photographically was the next important step. According to Wells [1940] such equipment was first developed by Messrs. L. V. Berkner, H. W. Wells and S. L. Seaton, all of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, D. C. This equipment was installed in their Huancayo Magnetic Observatory in Peru in 1937 and in 1938 at the Watheroo Magnetic Observatory in Western Australia. The equipment swept the frequency range 16 Mc to 0.516 Mc every 15 minutes.

Early work on an automatic (h'f) recorder at the National Physical Laboratory in England is described by Naismith [1934]. In 1935 he demonstrated the prototype (Naismith [1936]) of the equipment which has been operating continuously at Slough since 1943 (Naismith and Bailey [1951]). The Slough equipment sweeps 0.55 to 16.5 Mc in 5 minutes.

The National Bureau of Standards has developed four fully-automatic sweep-frequency recorders in recent years. In chronological order these are the Model C, the C-2, the C-3 and the C-4. The C-4 is still an experimental model and is specifically designed for the International Geophysical Year. The C-3 is currently in use at most CRPL stations. These instruments have a peak pulse power of about 10 kw compared to about 1/2 kw on earlier NBS equipments.

The Type C-3 ionosonde is equipped with both 16 mm and 35 mm cameras. The 35 mm camera is designed for taking the routine hourly, half-hourly or quarter-hourly records and the 16 mm for special research on rapidly changing features. The frequency sweep of 1 Mc to 25 Mc is obtained by mixing the signal from a fixed frequency oscillator (FFO) at 30 Mc with that from a variable frequency oscillator (VFO) tuning from 31 Mc to 55 Mc. At the receiver the signal returned from the ionosphere is ". . .mixed with the signal from the same VFO to produce a 30 Mc intermediate frequency. The second IF signal of 1.4 Mc is produced by the use of a fixed frequency oscillator at 28.6 Mc. The detected signal is differentiated and limited for interference control and fed to the oscilloscope units (Handbook for Automatic Ionosphere Recorder Type C-3, copyright 1951, Communications Measurements Laboratory Inc., N. Y. C.). Pulse lengths of 50μs and 100μs are available at repetition rates of 10 to 90 per second. The sweep is 7-1/2, 15 or 30 seconds and can be changed to 30, 60 and 120 seconds by installing a slower speed motor. Five time constants are available for use in the differentiating circuit. On automatic operation the receiver gain can be programmed to compensate for diurnal changes in absorption. A master clock control allows automatic records to be taken at intervals of 5, 15, 30 or 60 minutes. Both linear and logarithmic drive are available for the sweeps. Integrated receiver bandwidth in an operating C-3 is probably between 30 and 50 kc.

In normal operation the sweep time is 15 seconds and the pulse length 50μs. The gain program changes the level about four times each day and is readjusted every few months. However, a conscientious operator is at liberty to "ride" the gain manually if he so desires. Whether or not the operator does this is a question which bears on the magnetic correlation study. The author, therefore, interviewed a cross-section of station operators and found that in most cases the present gain program will not be altered to compensate for unusually high absorption or interference. The operating personnel of the CRPL stations also do the scaling of the records (which are later spot-checked in the Quality Control group). In the auroral zone where records are exceedingly complex the natural reaction of the station operator is, unfortunately, to give a shout of joy upon noting the onset of a polar blackout.

The normal antenna system which accompanies a C-3 recorder consists of two vertical broadbanded (3 wire) delta antennas placed at right angles to each other and terminated at the vertical apex with 600 Ω non-inductive resistances. The height is 68' and the base-length 130'. The characteristics of this antenna have been determined on a model range by Cones, Cottony and Watts [1950]. It was found that the polar diagram was well-behaved throughout the frequency interval of interest and that the impedance of the antenna varied between about 400 and 1000 Ω with frequency. The main objection to this standard delta has been its poor performance at the low end of the band. At 1 Mc each of the two diagonals on either delta is only one-tenth of a wavelength long. The radiation efficiency at low frequencies is correspondingly very poor.

A convenient means of increasing the radiation efficiency of the transmitting antenna at low frequencies is to increase the base-width of the delta antenna without increasing the height. In several CRPL stations this dimension has been increased from 130' to 300'. Comparison measurements (1.8 - 7 Mc) made on the 300' and 130' deltas by Cottony and Gorbaczewski (private communication) indicate that at 2.5 Mc an 8 db improvement with the large delta is realized. However, lobesplitting was seen to begin at 4.5 Mc and the small delta outperformed the large one above 5 Mc.

It is difficult to estimate the system gain of an ionosonde. To the best of the writer's knowledge no operating ionosonde has ever been calibrated for over-all system gain as a function of frequency. Also, as was mentioned above, the receiver gain setting will be varied several times during the day and in a different manner from station to station and the transmitter power output will fluctuate due to tube deterioration. Interference levels will vary with time of day, frequency, location, antenna system and receiver bandwidth. Non-deviative absorption will vary with time, location and frequency. However, an order of magnitude calculation can be made as follows

Estimated radiated field at 1 km, E_o ... 500 mv/m

Estimated minimum detectable signal E_{min} ... 5μv /m

Round trip distance to E region, d ... 220 km

Inverse distance received field intensity, $2E_o/d$ ... 4.4mv/m

Maximum dynamic range in db, $R = 20 \log \frac{E_o/d}{E_{min}} = 59$ db

This figure corresponds to a minimum detectable E-region reflection coefficient of 1.1×10^{-3}. This is certainly a high value for the low-frequency region of the sweep but is perhaps not unreasonable for frequencies above 5 Mc in quiet locations when the gain is turned up. It is interesting to note that above 5 Mc the dynamic range of the operating ionosonde is probably greater during the day than at night. The reason for this is that the receiver gain is set to overcome the effects of the daytime D-region absorption. If this absorption is, for example, 200 db at 1 Mc it is down to less than 10 db at 5 Mc. If the receiver gain is advanced 40 db over the nighttime value to compensate for this absorption, there will be a net gain at 5 Mc of 30 db in dynamic range.

B. The Appearance of Sporadic E

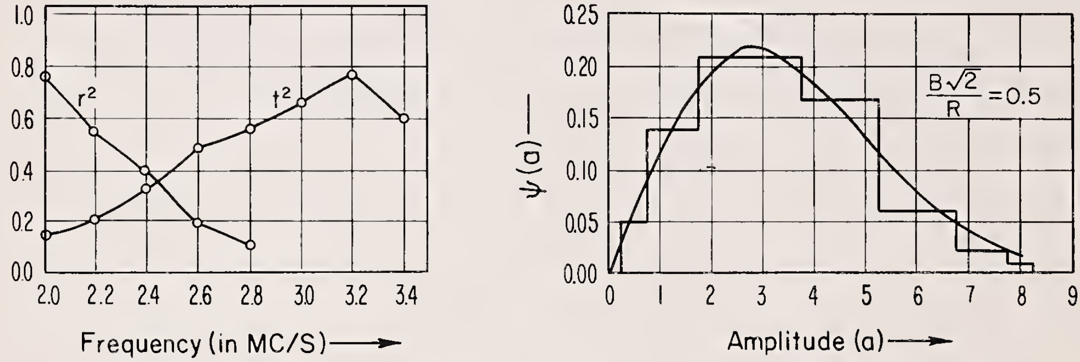
Historically speaking the term sporadic E has been developed to separate out those E region echoes not due to steady photon emission from the sun, inasmuch as once this is done the regular E layer becomes highly predictable in its time variations. It is not surprising then that many quite different types of echoes are lumped under the category of sporadic E. Research workers studying the Es echoes who have attempted to treat sporadic E as due to a single cause and having the same general structure at all places and all times have run into difficulty. As has been mentioned above it was found that the burst-type echoes observed with high-power ionosondes could logically be separated out of the category of sporadic E. Similarly it is conceded that the low-level steady component of signal observed in ionospheric forward scatter is not what is meant by sporadic E. There has also been an effort to separate out a "meteoric E layer" from the sporadic E region (Naismith [1954]).

1. Sporadic-E Types

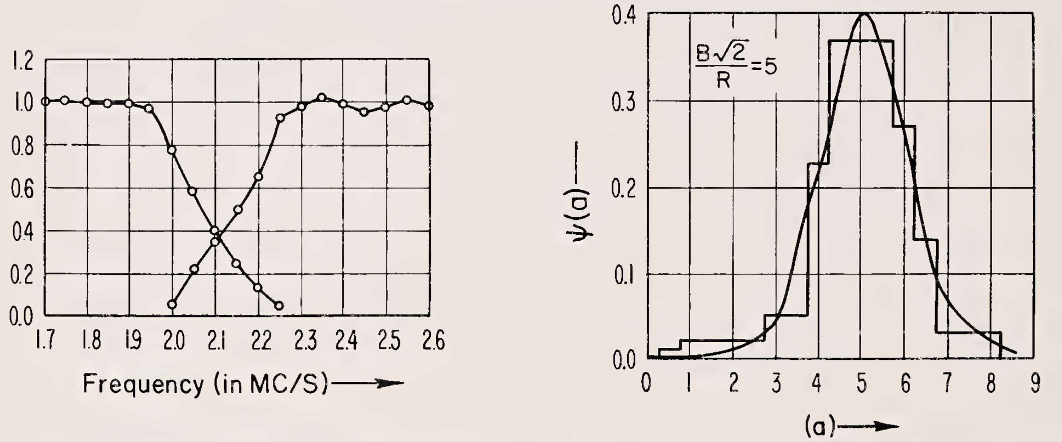
From ionograms alone it is possible to delineate certain characteristics of the echoes. If a set of characteristics appears to have distinctive temporal and geographic variations, then it is possible to define a type of sporadic E from them. Meek [1947] [1949] has made a continuing study of Es at the Canadian (auroral and sub-auroral) stations and has attempted to type the sporadic E observed at these stations. Recently Hagg and Hanson [1954] have studied Es cloud motions for this same region. Similarly McNicol and Gipps [1951] have made a type study of sporadic E for Brisbane with limited consideration of the other Australian stations. Typing based on individual station data has been tried for Kiruna, a sub-auroral station by Lindquist [1951], for Slough (north temperate zone) by Best, Farmer and Ratcliffe [1938] and by Rangarajan [1954] for Kodaikanal on the magnetic equator.

A very interesting method of studying sporadic-E characteristics has been used by Chatterjee [1953]. This method consists of simultaneously examining the amplitude distribution of returned pulses at a fixed frequency and the reflection coefficient of the sporadic E as a function of frequency. The amplitude distribution is used to estimate the proportionate contribution of the scattered and specular components in the echo after the method of Rice [1945]. The frequency variation of the reflection coefficient is then used as supporting evidence; one would expect the reflection coefficient associated with a Rayleigh distribution (expected of a scattering mechanism) to show a more gradual drop-off with frequency than one associated with a Gaussian distribution (indicative of specular reflection). Figure II-B-1 shows some of the amplitude distributions and associated reflection coefficient versus frequency curves. Certain features of the paper appear odd, such as the fact that the value of h'Es is 90 km in all the examples, and some of the techniques can be improved with modern equipment (manual reading of values at 5 second intervals to obtain the amplitude distribution); however, the experiment is an excellent one which should certainly be repeated in this country.

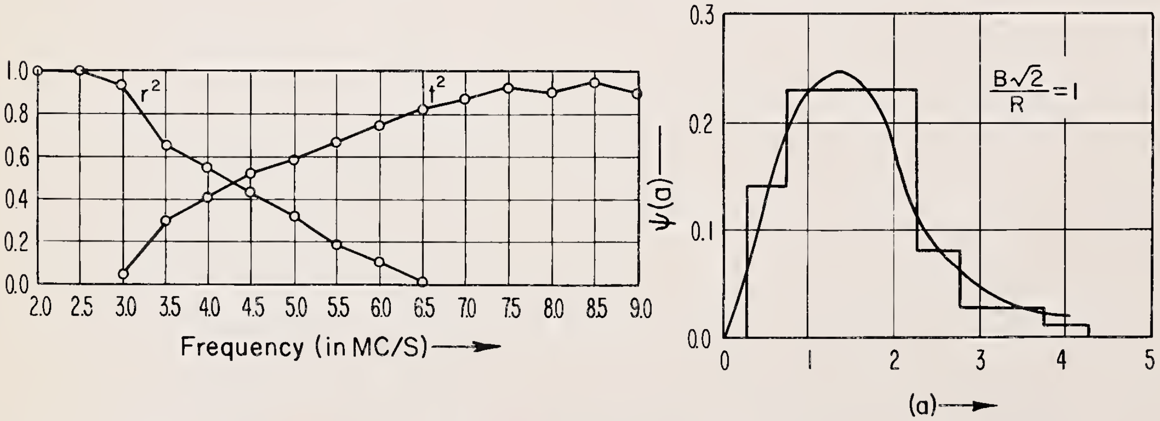
TYPICAL Es REFLECTION AND TRANSMISSION COEFFICIENTS AND ASSOCIATED AMPLITUDE DISTRIBUTIONS FOR CALCUTTA (AFTER CHATTERJEE)



(a) EARLY MORNING HOURS (0330 HR., 25 OCT. 1952



(b) IMMEDIATELY BEFORE GROUND SUNRISE (0530 HR., 4 APR. 1952)



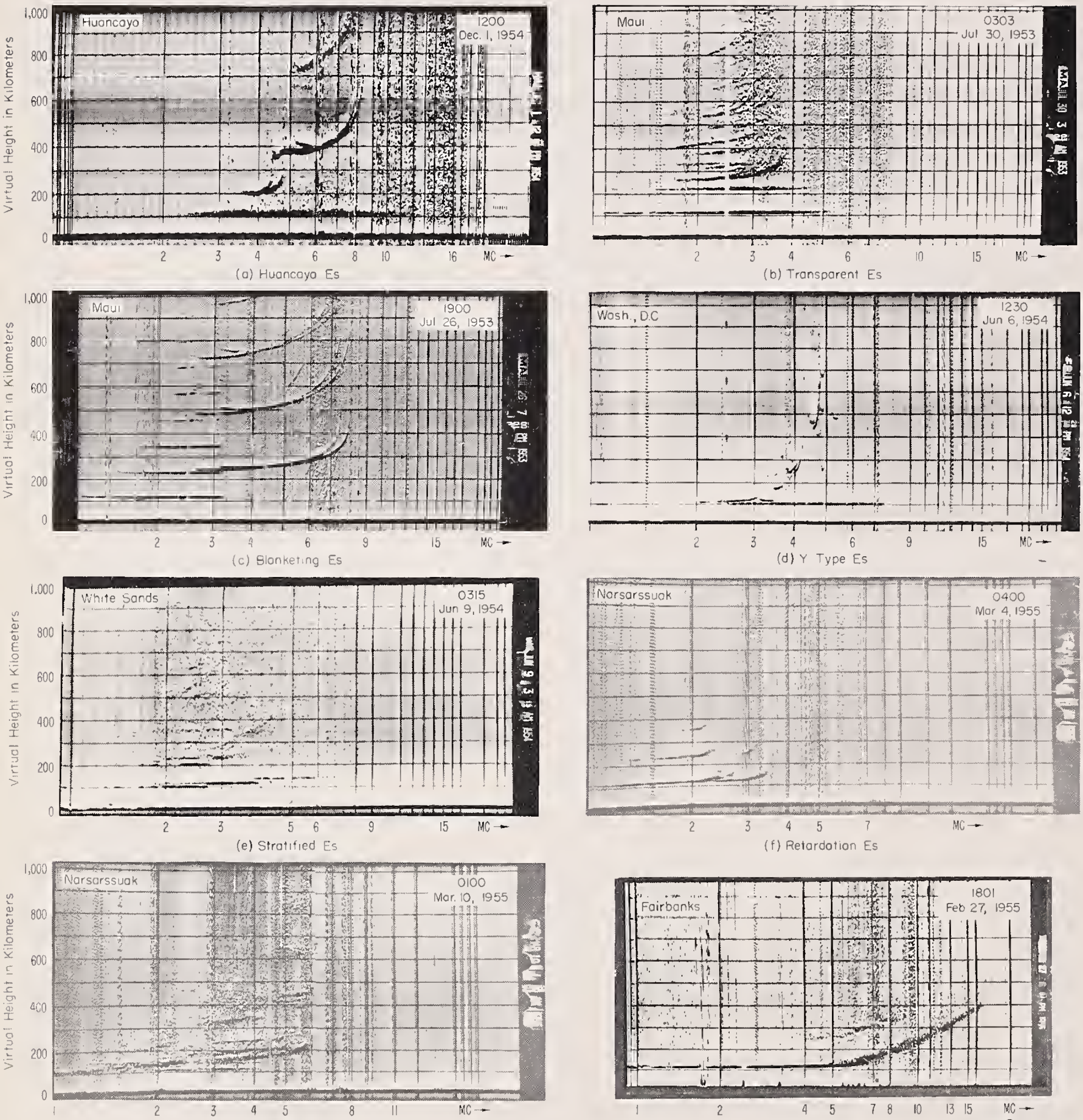
(c) AFTERNOON AND EVENING HOURS (1430 HR., 21 OCT. 1952)

Figure II-B-1

With certain sporadic-E types it is the time variation which is the definitive characteristic (e.g. sequential Es, constant height Es). However, other types can well be represented by single ionograms. Figure II-B-2 illustrates some of the classical types. It will be noticed that the typing has not been made in terms of either height (h'Es) or critical frequency (fEs). This latter sort of delineation has frequently been employed by authors in the past, but involves drawing arbitrary demarkation lines at particular heights and frequencies. There is, however, a particular type of faint trace which appears at 90 km heights in the auroral zone during a phase of magnetic storms which may legitimately be classed as a type.

a. Huancayo Es. This trace, once called "fringe E," dominates the daytime E region on Huancayo records. It is always completely transparent and without multiples. As may be seen on the map in fig. II-D-1 Huancayo is on the magnetic equator. It will be shown later that Huancayo has the highest daytime Es incidence in the world and this is due to the regular daytime occurrence of this variety of Es. Sporadic E is in some respects an unfortunate category in which to include this variety of Huancayo echo because there is nothing sporadic about it. It does, however, fall under the definition as given in Chapter I and has been recorded as sporadic E on the station sheets (from which the F series charts are compiled) for almost the last decade. This type of sporadic E has been reported from Christmas Island (Peavy [1946]) and Kodaikanal (Rangarajan [1954]) both close to the magnetic equator. Comparison of the daytime sporadic-E incidences at the several stations in North Africa where the magnetic and geomagnetic

IONOGRAMS OF SPORADIC E TYPES



(a) Huancayo Es

(b) Transparent Es

(c) Blanketing Es

(d) Y Type Es

(e) Stratified Es

(f) Retardation Es

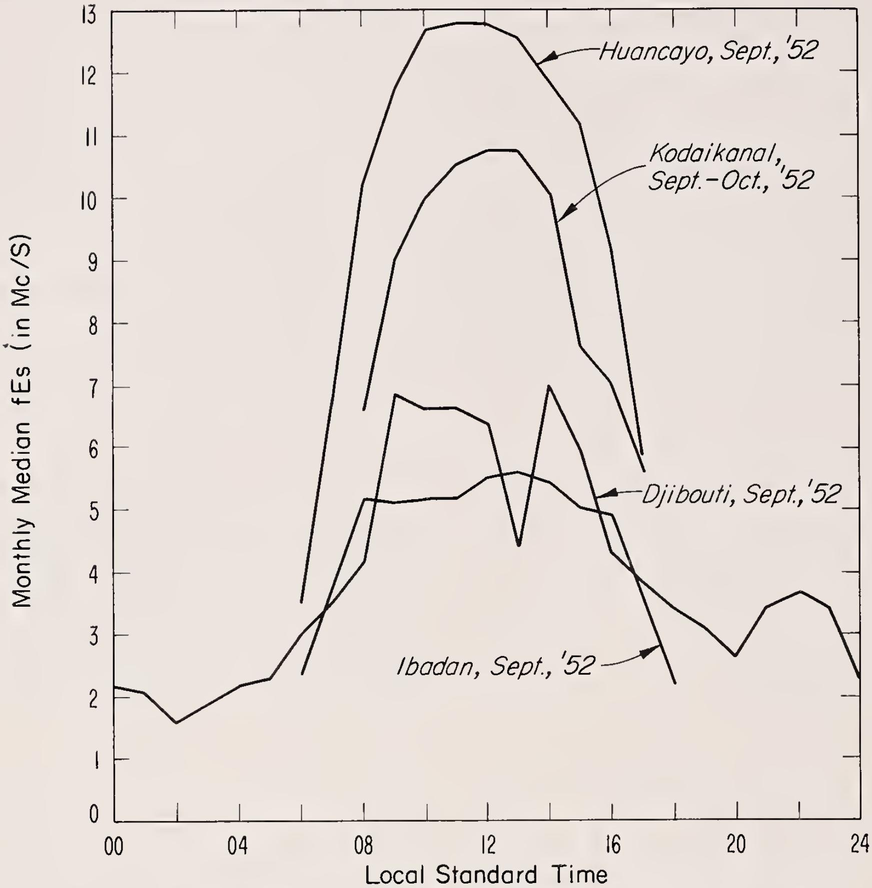
(g) Auroral Es

(h) Slant Es

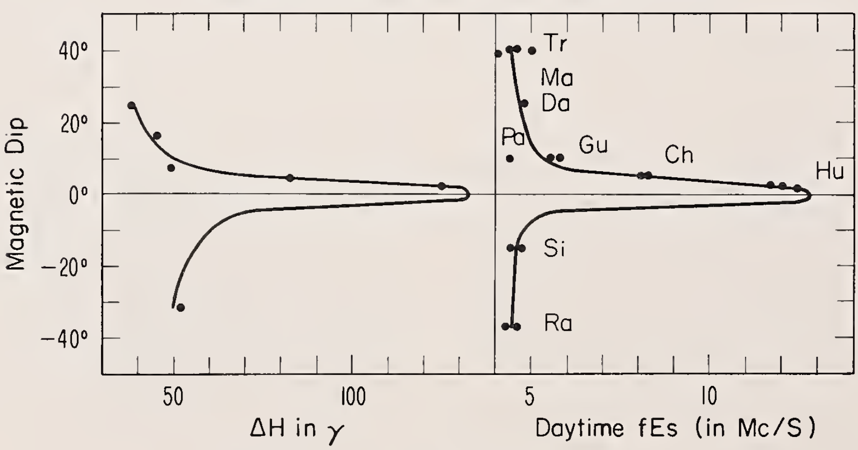
equators have their greatest separation, seems to indicate that the magnetic rather than the geomagnetic equator is followed. Matsushita [1951] has demonstrated the parallelism between noon sporadic E near the magnetic equator and the equatorial electrojet, the daytime eastward-flowing current stream. Figure II-B-3 shows the effect to be essentially limited to the region with magnetic-dip angles between plus and minus 10°, a zone on the average only 700 miles wide. Ionogram traces similar in appearance to Huancayo type sporadic E are frequently seen at other localities (e.g. the auroral zone), but never with the same diurnal consistency.

b. Transparent Es. This term has been used in the past to describe a sporadic echo which does not appear to blank out the F-region traces at all. The Huancayo type would, thus, be included in this definition so for convenience "transparent Es" will be restricted here to refer to a fairly well defined "thin layer" type of trace with no apparent blanketing effect on the F-region. This can mean, of course, that blanketing occurs at frequencies lower than the ones for which the F echoes are normally observed or that the Es reflection coefficient never does come very close to one. Several multiples may be present on nighttime records and high critical frequencies attained. Observed Es is always partially transparent in that it is theoretically impossible for any layer to go from completely blanketing to completely transparent as frequency is increased. However, it is surprising how many examples can actually be found which fit the limiting case

VARIATIONS OF SPORADIC E NEAR THE MAGNETIC EQUATOR REFLECTING THE INFLUENCE OF HUANCAYO TYPE Es



(a) DIURNAL VARIATIONS FOR STATION WITH VARIOUS VALUES MAGNETIC DIP



(b) COMPARISON OF EQUATORIAL Es WITH A MAGNETIC EFFECT (AFTER MATSUSHITA [1951])

Figure II-B-3

of transparent Es. Transparent Es seems more common in temperate latitudes and McNicol and Gipps [1951] find that the seasonal minimum for this type occurs in the winter solstice (June in Australia).

c. Blanketing Es. This type represents roughly the other extreme from the transparent variety described above. A customary definition of this type is given by requiring the blanketing frequency (f_bEs) to be greater than the highest F region critical frequency (normally f_xF_2). This definition is convenient for scaling but difficult to interpret physically as in a case where fEs = 20 Mc, f_xF_2 = 7 Mc. If $f_bEs > 7$ Mc the trace would be called "blanketing", if $f_bEs < 7$ Mc it would not. By "blanketing Es" is here meant the situation where fEs = f_bEs with the proviso that in this case fEs and f_bEs be applied separately to the O and X components. The only proposed configuration capable of giving a sharp cross-over from reflection to transmission is the thin layer. The computed cross-over frequency interval computed from coupling considerations for the E region with a scale height of 10 km is only a few kilocycles at most. However, the E region produces a distinctive cusp at the E critical on an ionogram and a much more pronounced retardation effect in the F_1 trace. The writer has never observed any retardation effects due to sporadic E in temperate latitude records. With a thin layer this observation would seem to imply a maximum semi-thickness not greater than 1 km.

d. Y type Es. This is defined as sporadic E for which the symbol Y is appropriate according to the letter symbol scheme discussed

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earlier. The symbol is appropriate only when the trace shows discontinuities as in example (d) not due to interference. It is estimated, however, that in a large number of the cases marked Y on station sheets the cause is interference and the symbol is, therefore, incorrectly used. A natural reaction is that the trace is somehow of meteoric origin as this intensity oscillation with frequency can be explained by a specular reflection from an object presenting an aperture of only a few Fresnel zones. As frequency is increased the number of zones would increase producing the observed undulating effect. With this mechanism in mind, the cases of Es shown with the symbol Y for Washington, D. C. were tabulated. The diurnal distribution of these cases is seen in figure II-B-4. The maximum incidence is later in the day than the classical meteoric maximum at 0600 Local Time but is not in bad agreement with recent determinations of the diurnal maximum of sporadic meteors. The regular evening secondary maximum in sporadic E has disappeared completely and the location of the minimum at this time is in agreement with the possibility of a meteoric mechanism.

e. Stratified Es. The international symbol H (stratified within the layer) is used to describe records such as (e) of figure II-B-2 in normal scaling practice. At CRPL if the previous or following records indicate that all or all but one of the traces are obliques, the symbol H is not felt to be appropriate inasmuch as more than one stratified layer is not thereby indicated. As a general rule, when they can be identified, oblique traces are not considered in scaling fEs and h'Es.

TEMPORAL VARIATIONS OF Y TYPE Es AT WASHINGTON, D.C.

Total Occurrences 1949-1954

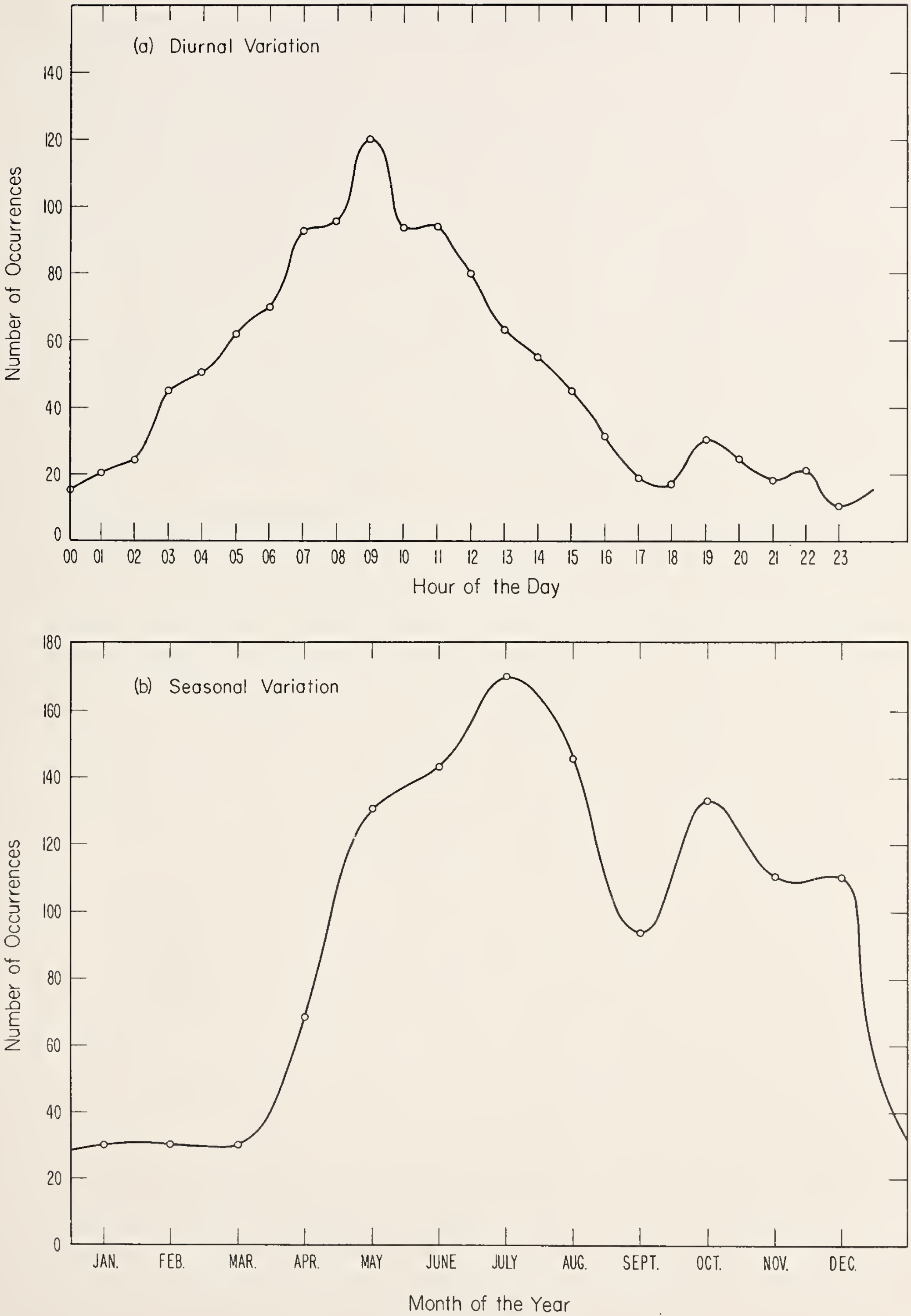

Figure II-B-4

Stratified Es is not so much a type of sporadic E as the situation of simultaneous occurrence of several traces which is not uncommon. It is included here in order to describe what is seen in individual records.

It is interesting to note that the theory of Gallet [1955] predicts three strata of Es layers in the case of homogeneous turbulence in a Chapman region. Also, that Helliwell [1954] has found certain preferred heights of Es for Stanford.

f. Retardation Es. This type of Es is an indication that sporadic E can at times have considerable thickness. It appears to be strictly an auroral-zone phenomenon and can be broken down into two varieties. The first variety is indistinguishable on an ionogram from regular E except that it occurs mostly at night. The Canadians (who see the most of it) have called this variety "night-E" (Meek [1947]) and do not consider it a type of Es. The following characteristics are attributed to night E (Hanson, Hagg and Fowle [1953]).

1. There is a definite cusp on both the E and the F2 layer traces defining the critical frequency.
2. There is complete blanketing of the F2 layer up to the critical frequency and complete penetration of the ordinary wave beyond it unless sporadic E is also present.
3. The extraordinary trace appears frequently and the z trace is also commonly seen.
4. There is generally more spread near the critical frequency than is the case with the normal E layer.

5. The critical frequency often varies rapidly; changes of 1.0 Mc or more in a few minutes sometimes occur. Values of the f_oE may be anywhere from 1.0 Mc to 4.5 Mc or more.

The same authors find night E to be exclusively an auroral zone phenomenon but do not find any direct hour to hour correlation with aurora or other ionospheric phenomena.

The second type of retardation Es does not blanket the F region. It may, therefore, be due to a localized cloud (or clouds) of ionization.

An interesting study of sporadic-E types of Kiruna, Sweden has been made by Lindquist [1951]. This station sees about half the number of aurorae as at the maximum of the auroral zone and correspondingly gets some temperate zone Es with the auroral types. Lindquist separated out three types of sporadic E. These were: E-1 (Es with virtual height 75 to 100 km), N-1 (retardation Es) and N-s (isolated patches of ionization). He found that N-1 "... appears similar to regular E except thicker...often shows complicated splitting near retardation frequency...occurrence frequency correlates closely with magnetic activity." The diurnal and seasonal variations of this retardation type of Es as compared to the remaining Es at Kiruna are shown in figure II-B-5. It seems that type N-1 also includes a certain amount of "auroral E" (see below). At any event, at Kiruna type N-1 is seen in figure II-B-5 to have time variations which will later be shown to be characteristic of auroral zone stations whereas the remaining sporadic E has temperate

TEMPORAL VARIATIONS OF A RETARDATION TYPE Es AT KIRUNA (AFTER LINDQUIST)

N1...."appears similar to regular E except appears thicker..."

E1.... Es with virtual height 75-100 km

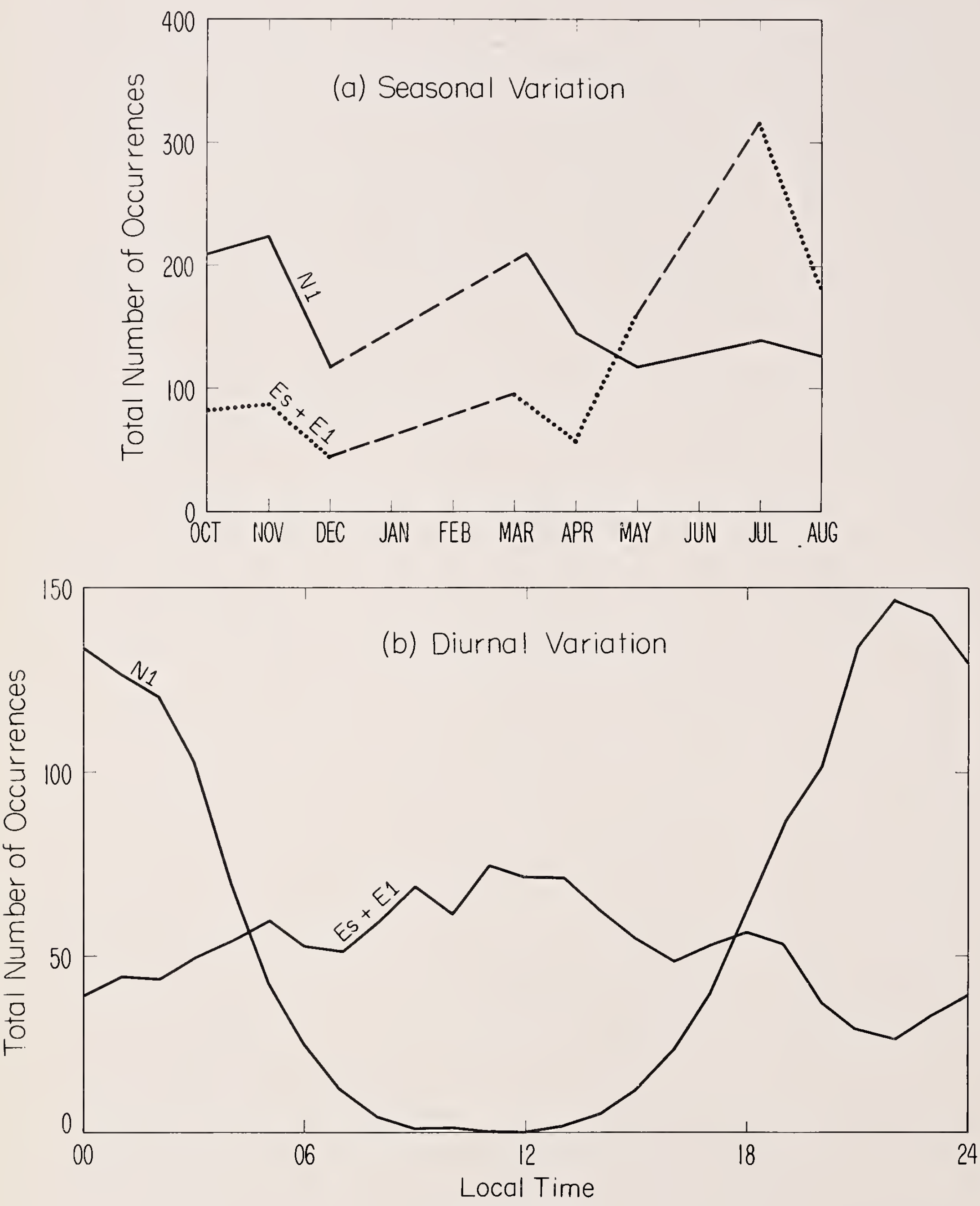

Figure II-B-5

latitude temporal characteristics.

g. Auroral Es. The association of sporadic E with visual aurora has been demonstrated by Knecht [1951] [1956]. The record shown in g of figure II-B-2 is of the type seen at the maximum of the auroral zone for aurora not quite overhead. For actual overhead aurora the trace is more likely to extend out to frequencies of 10 to 15 Mc at a constant height of slightly over 100 km. The gradually rising Es trace shown in II-B-2(g) is a type not seen outside of the auroral zone.

The intensity of the echo makes it difficult to credit an explanation in terms of increasing obliquity with frequency. The association of the echo with other than overhead aurora would seem, however, to point in this direction.

h. Slant Es. This peculiar trace is observed in its most intense form in the auroral zone where it is associated with auroral flutter. K. L. Bowles (private communication) has shown that in the evening for College, Alaska, it occurs shortly after the onset of a positive bay, in the morning hours after a negative bay.

A weaker form of slant Es is seen at Huancayo on the magnetic equator. Four cases examined showed the same time relationship to magnetic bays as had been observed at College. Four periods of slant Es at Maui showed no relationship with magnetic disturbance. As both College, Alaska and Huancayo are on belts of heavy E-region currents and Maui is not, some relationship with currents may be indicated.

The auroral type of slant Es usually appears to be taking off from the end of a stretch of sporadic E. At low latitudes the slant trace appears to emanate from the E-region critical frequency.

A study of slant Es based on a possible scattering mechanism is found in the appendix of this report.

i. Sequential Es. The most amazing aspect about sequential Es is that so little attention has been paid to it so far. The name "sequential Es" appears to be due to McNicol and Gipps [1951] who use the term to describe a very common Es phenomenon at Brisbane, Australia. The trace first appears around 4 Mc and a height of 140 to 210 km and then decreases in virtual height and increases in critical frequency until a height of 100 to 110 km is reached. This process normally takes several hours to run its course. The regular time sequence of events is what is referred to in the name. Members of the staff at CRPL have been aware for years that this type shows up on the records from almost all of the CRPL stations from the equator to arctic and is the dominant daytime Es type at a low-latitude station such as San Juan, Puerto Rico. S. Matsushita, a guest worker at CRPL from Japan is currently studying this phenomenon and has uncovered many interesting features. These are described in an internal report of the High Altitude Observatory (Matsushita [1955]).

An example of sequential Es is seen in the Maui ionograms in figure II-B-6. The sequence starts at 1400 with a trace at about 145 km. The height decreases steadily until reaching 114 km at 1700 hr. Partial blanketing of the F region occurs from 1500 hr.

A SERIES OF IONOGRAMS FROM MAUI
SHOWING A SEQUENTIAL Es DEVELOPMENT

July 14, 1953
Time: 150° W.

Frequency in Mc

Figure II-B-6

onward and multiples are also increasingly present. Both of these facts make it impossible to explain the apparent decrease in virtual height in terms of an oblique echo. The steady descent of the Es stratum would seem to be real. It will be noticed in figure II-B-6 that although the sequential Es traces show a high degree of blanketing action no retardation due to the Es layer can be seen. The early development of sequential Es is not well illustrated in figure II-B-6. The sequence was chosen to demonstrate that the downward motion is real.

C. Considerations in the Use of Scaled Data

There are various aspects which need to be considered before using the sporadic-E data which is reported from the regular stations. As may be seen from the ionograms of figures II-B-2 and II-B-6, it is patently impossible to describe the sporadic-E traces observed with a few numbers or symbols. Various writers have used different terms to describe the Es characteristics they observe and others have meant different things by the same terms. Section II-C-1 traces some of the history of the terms used and points out sources of the differences in scaling practice which still exist. Distributions of scaled data are examined in section II-C-2 to see what light can be shed on scaling errors. Finally in section II-C-3 the pros and cons of the three readily available limiting frequencies are considered relative to their use in this study.

1. Scaling Conventions and Practices

This discussion will be limited to sweep-frequency equipments (h',f) first introduced in the middle thirties. The main problem has always centered around the measure of the maximum frequency of sporadic E. Berkner and Wells [1937] in their comparison of sporadic E at Huancayo and Watheroo used the highest frequency of the first Es multiple (two round trips). Using this definition of Es they observed seventy times more sporadic E at Watheroo than at Huancayo. If they had used the highest frequency excursion of the Es echo itself they would certainly have found more sporadic E at Huancayo, at least during the daytime. This is due to the fact that the Huancayo type Es (figure II-B-2[a]) shows no multiples when recorded on standard equipment. Best, Farmer and Ratcliffe [1938] considered the maximum excursion of the Es echo together with penetration frequency of the Es layer (lowest frequency at which F echoes are observed) and noted that the former was more variable than the latter.

The first concerted attempt at international standardization of techniques and practices took place in May and June 1944 when the International Radio Propagation Conference* was held at the National Bureau of Standards in Washington, D. C. It was attended by representatives of the armed forces and propagation laboratories of Australia, Great Britain, New Zealand and the United States. The conference made the following recommendations which concern sporadic-E measurements. Almost no important changes have been made since. The following is taken from the Conference Report IRPL-C61, p. 38:

"It is recommended that, for the present, the various laboratories should report, in addition to the normal E-layer critical frequency, the highest frequency at which other echoes are observed from the approximate height of the E layer. The frequency shall be denoted by the symbol fEs, it being understood that, where ordinary and extraordinary components are identifiable, the ordinary wave frequency shall be recorded.

"This frequency should be reported regularly by each observatory on an hourly basis. Where it is considered practicable at the observatories, the monthly median value of this frequency, and also the percentage of occurrences of fEs at each hour throughout the month should also be reported on the monthly summary sheet.

---

*See IRPL-C61 "Report of International Propagation Conference," issued June 1944, National Bureau of Standards, Washington, D. C.

"It is recommended that "Es" be used instead of "sporadic E" or "abnormal E."

"It is agreed that there are two other characteristics of the Es layer which may have operational significance and that further study of these characteristics is necessary to determine their usefulness.

"These characteristics are:

1. "Blanketing" frequency (f^{b}_{Es}), which is defined as the frequency at which the Es is first penetrated as indicated by the return of an echo from a higher layer.

2. "Multiple" frequency (f^{m}_{Es}), which is defined as the highest frequency at which the first multiple from the Es layer is observed. It is desirable that measurements of this characteristic be accompanied by an indication of the power radiated vertically by the transmitter and the receiver sensitivity throughout the frequency range. Reporting of one or both of these frequencies will be at the discretion of each laboratory."

Certain descriptive symbols were recommended for use in connection with the tabulated hourly values. Those pertaining to the interpretation of sporadic E are:

B or b = Characteristic not measurable because of loss of trace due to absorption either partial or complete.

C or c = Characteristic not measurable due to loss of trace due to equipment failure or interference.

D or d = Characteristic higher than upper limit of recorder.

E or e = Characteristic less than lower limit of recorder.

H or h = Stratification observed within the region.

Data tabulations in the IRPL-F series (later CRPL-F series) were made to agree with these recommendations within the following year.

The Fifth Meeting of the International Radio Consultative Committee (CCIR), Stockholm, 1948 reviewed the symbols and terminology situation as regards the scaling of ionograms. They defined*:

"fEs = Highest frequency on which echoes of the sporadic type are observed from the E layer (see Remark 2)

"Remark 2: Understanding of the processes which give rise to sporadic-E reflections is still largely lacking. There have been cases reported in which sufficient retardation, and also change in echo intensity, has been observed to suggest the possibility of using such symbols as f_oEs and f_xEs. When this resolution is not possible it is customary to regard fEs as equivalent to f_oEs."

This position straddled the fence as regards whether the highest frequency at which sporadic E is observed or the highest frequency for the ordinary wave should be scaled. It may be mentioned that at mid-latitudes this distinction will make very little difference. The virtual height of the E layer was also defined separately to be (Ibid. p. 6):

"h'Es = Minimum virtual height of sporadic echoes from the E layer"

Several more descriptive symbols pertinent to the use of Es data were added to the previous listing (Ibid. p. 10):

M, S and T (or m, s, and t) describe reasons for loss of data.

Y or y = Es trace intermittent in frequency range.

These symbols became effective in the CRPL-F series beginning January 1949.

---

*Document No. 293 E, 29 July 1948, pp. 6, 7; CCIR Vth Meeting, Stockholm 1948.

The Sixth Meeting of CCIR in Geneva in 1951 again reviewed symbols and terminology and redefined fEs to restrict the possible height range. (CRPL -F89, p. 3). Note that the ambiguity in whether fEs refers to the highest frequency at which any Es trace is observed or highest frequency of the ordinary component has disappeared.

"fEs = Highest frequency on which echoes of the sporadic type are observed from the lower part of the E layer.

fE2s = Highest frequency on which echoes of the sporadic type are observed from the upper part of the E layer; the distinction between the upper and lower parts of the E layer is purely one of apparent virtual height (apparent range of echo) and should be based on station experience; 140 km has been chosen by some stations to represent this distinction.

fbEs = The lowest frequency at which echoes from the F region are observed when sporadic echoes from any height in the E layer are of the intense or blanketing type.

These recommendations became effective in data of the CRPL-F series beginning with that reported for January 1952. These same recommendations were maintained in effect through 1954 (the last year of interest to this study).

Although stations in other countries appear to follow the latest recommendations of the international conferences scrupulously, there is still a certain freedom of action possible. For instance, the British recognize the CCIR distinction between "Es" and "E2s." However, when reporting "fEs" data both of the above categories are included. In practice this makes almost no difference. Also, the Canadians, as has been pointed out before, do not consider blanketing retardation Es to be a form of sporadic E but choose to include it with regular E on their data sheets.

2. Some Discrepancies and Irregularities in Data from Ionosondes.

It is convenient to divide this discussion into two categories: irregularities in function of the frequency of sweep and irregularities in function of time. Irregularities in terms of frequency are illustrated in figure II-C-1 which shows the distribution of sporadic E (fEs $\geq$ 3 Mc) at Washington, D. C. for the year 1952. The distributions are shown separately for day and night to bring out the effect of daytime absorption. If the number of cases of Es is mentally summed for one megacycle intervals in fEs it is seen that a fairly smooth decay with frequency would be obtained. There is a suggestion of an abnormal peak around 7 Mc. However, within the one megacycle intervals the distribution is far from uniform. There are several possible reasons for this non-uniformity. It will be noticed in figure II-B-2 that the C-3 ionogram has frequency markers at one megacycle intervals above 2 Mc. These coincide with the peaks of fEs occurrence seen in figure II-C-1. A second possible explanation is the psychological preference which the scaler may have toward integer values, half integer, fifth integer, etc. The third possibility is other station interference; and a fourth non-linearities in system gain. The periodicity of one megacycle must needs be attributed to one of the first two possibilities. The two latter ones undoubtedly have an effect in a showing of the over-all distribution. A study of the

DISTRIBUTION OF fEs WITH FREQUENCY FOR WASHINGTON, D.C.

Data for Calendar Year 1952

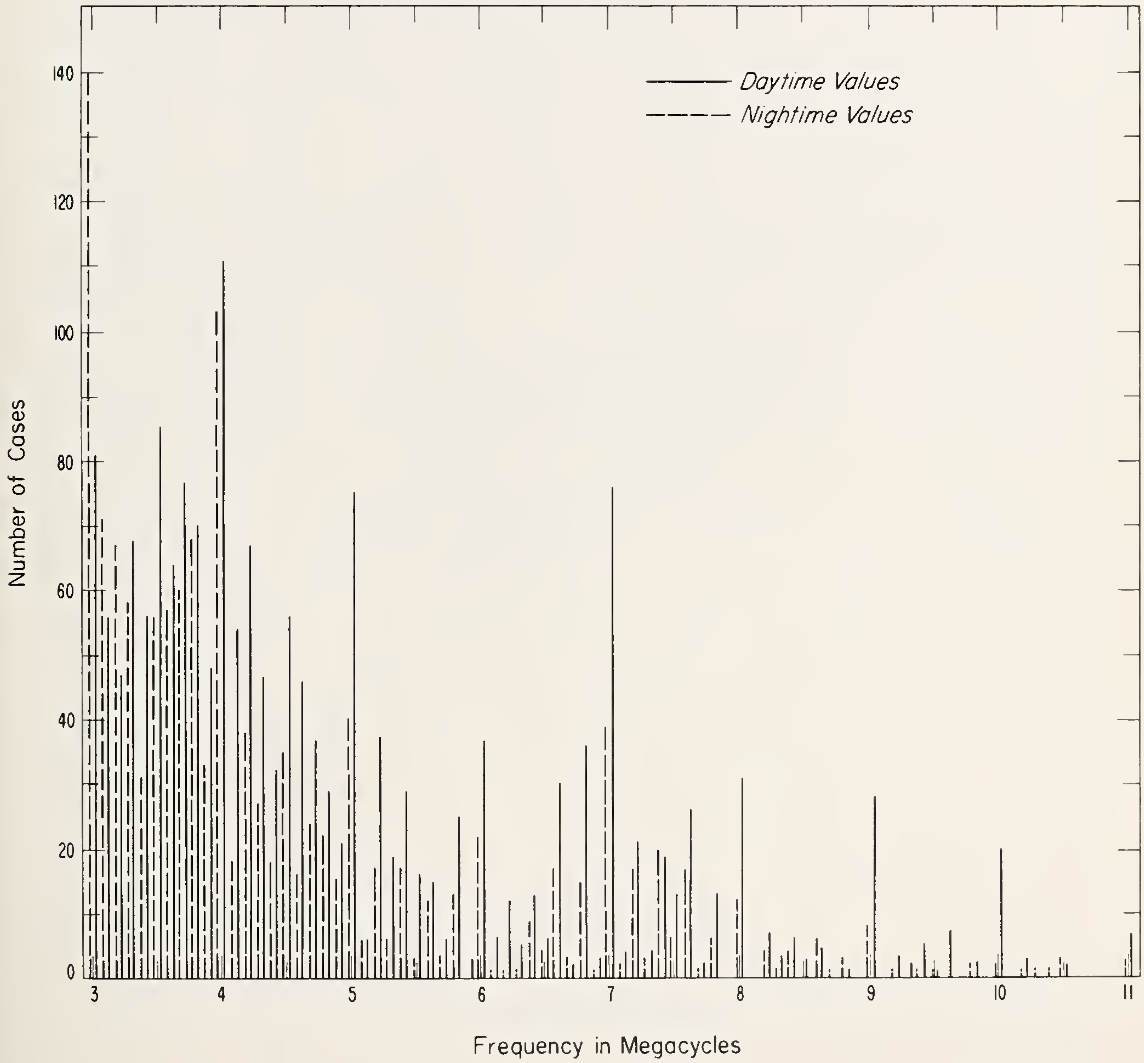

Figure II-C-1

CUMULATIVE DISTRIBUTION OF fEs
WITH FREQUENCY FOR WASHINGTON, D.C.
DATA FOR CALENDAR YEAR 1952

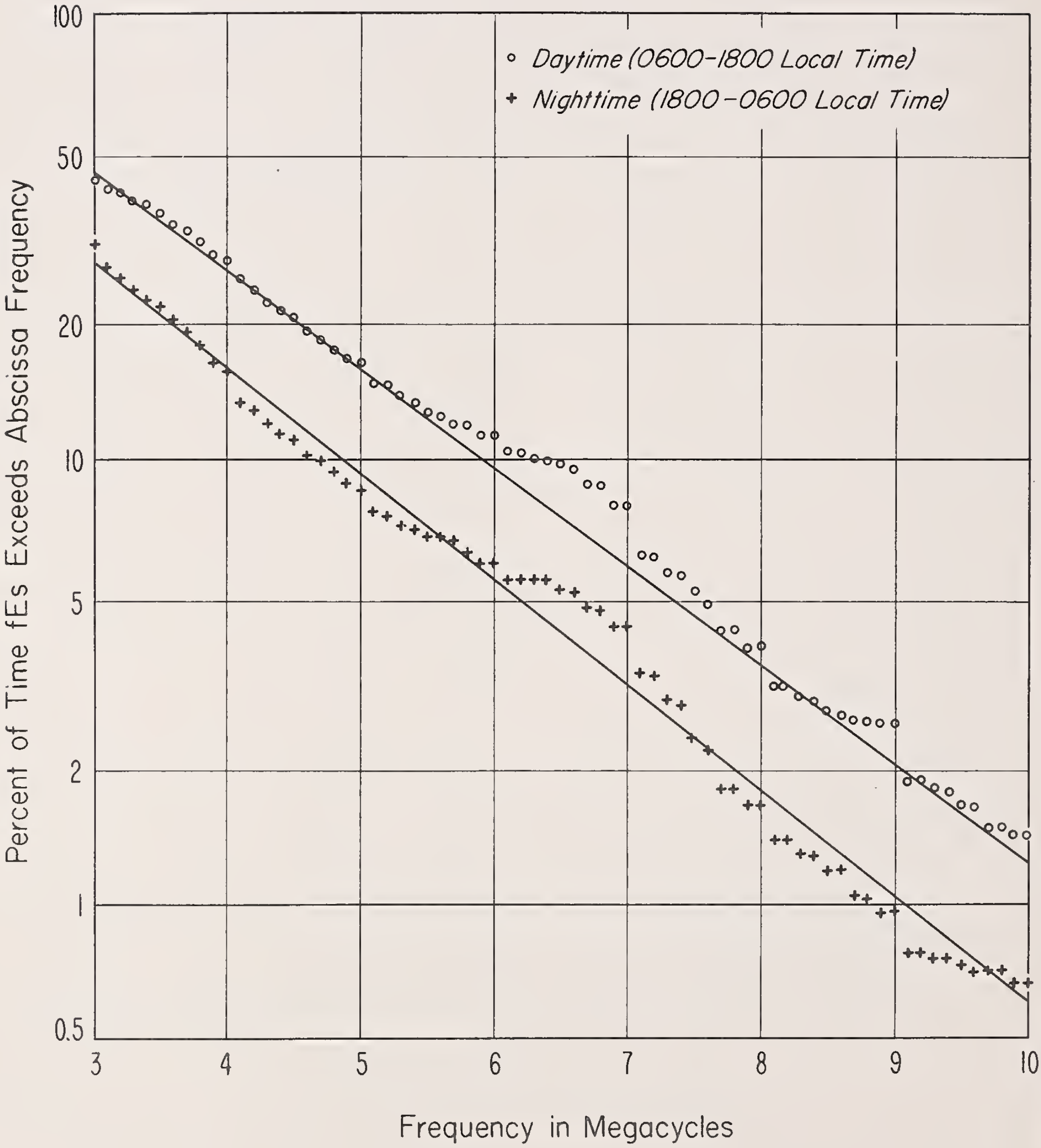

Figure II-C-2

frequency distribution of fEs and f min F in Japan by Uyeda, Miya and Kobayashi [1952] revealed that other station interference was more important than gain variations in accounting for irregularities in the spectral distributions. Fortunately, this study is interested not in values of fEs recorded at a particular frequency but in all values above that frequency, i.e. the cumulative distribution (ogive) of values. Ogives for the two distributions of figure II-C-1 are seen in figure II-C-2, and it is reassuring to note that the irregularities now look much less serious. This semi-logarithmic plot in figure II-C-2 is one which will give an almost straight line distribution of Es as M. L. Phillips [1947] has shown.

A similar plot for Slough, England is seen in figure II-C-3 for four months in 1953 covering the summer maximum. The character of this plot is seen to be quite different from that for Washington. With the exception of 5 Mc the preference for integer values is not nearly so apparent. A broad peak does seem to exist between 9 and 10 Mc which may well be due to variations in overall gain in the equipment. The ogive for this distribution is given in figure II-C-4. Again it is seen that the cumulative distribution is not seriously affected by the irregularities in the frequency distribution itself.

The time irregularities for reasons other than the sporadic E itself can be due to equipmental changes or variations in interference or to the effects of D- layer absorption. A rather unusual example of the former is found in the change during the spring of 1951 from a locally made ionosonde to a C-3 at Baton Rouge, La, a

DISTRIBUTION OF fEs WITH FREQUENCY FOR SLOUGH, ENGLAND

May, June, July and August 1952

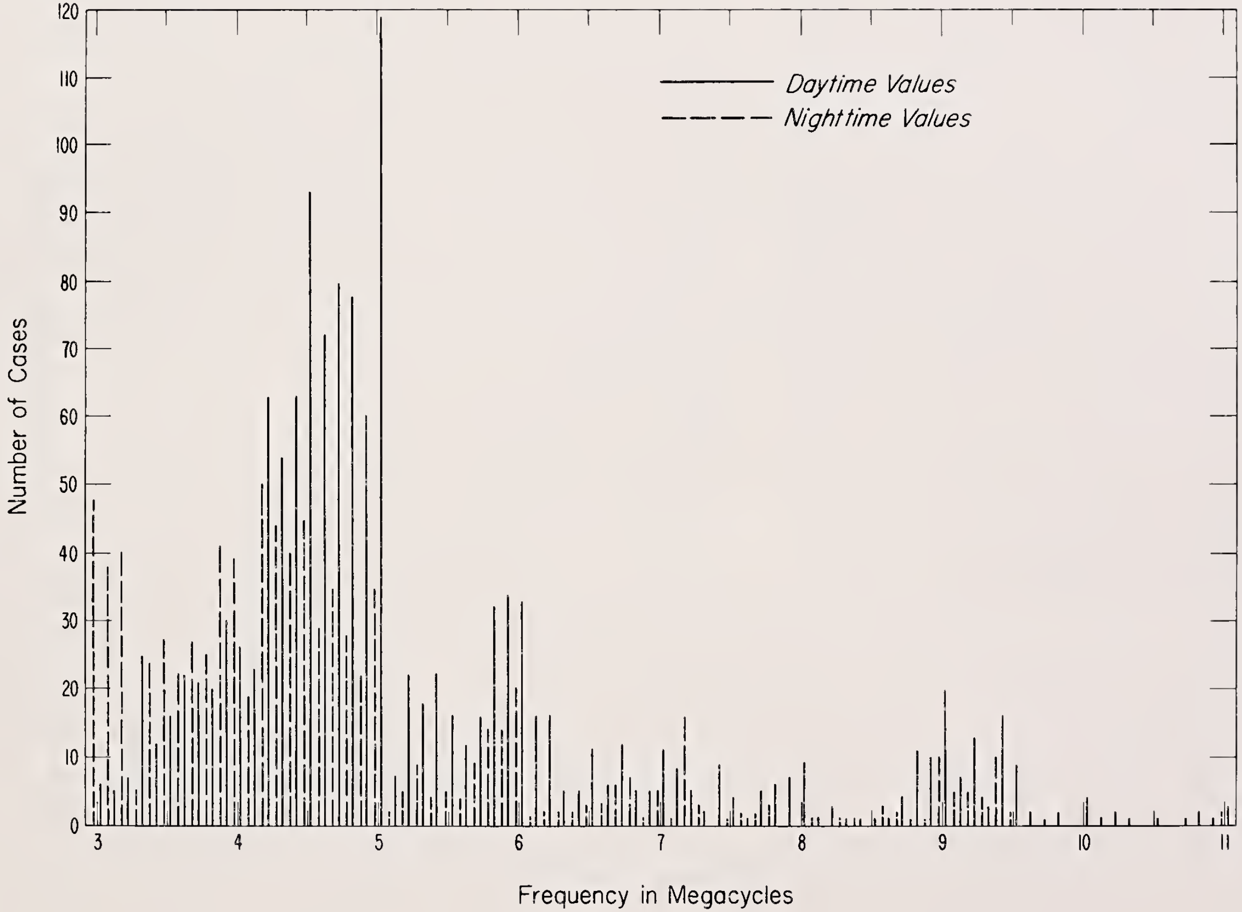

Figure II-C-3

CUMULATIVE DISTRIBUTION OF fEs
WITH FREQUENCY FOR SLOUGH, ENGLAND
MAY, JUNE, JULY AND AUGUST 1952

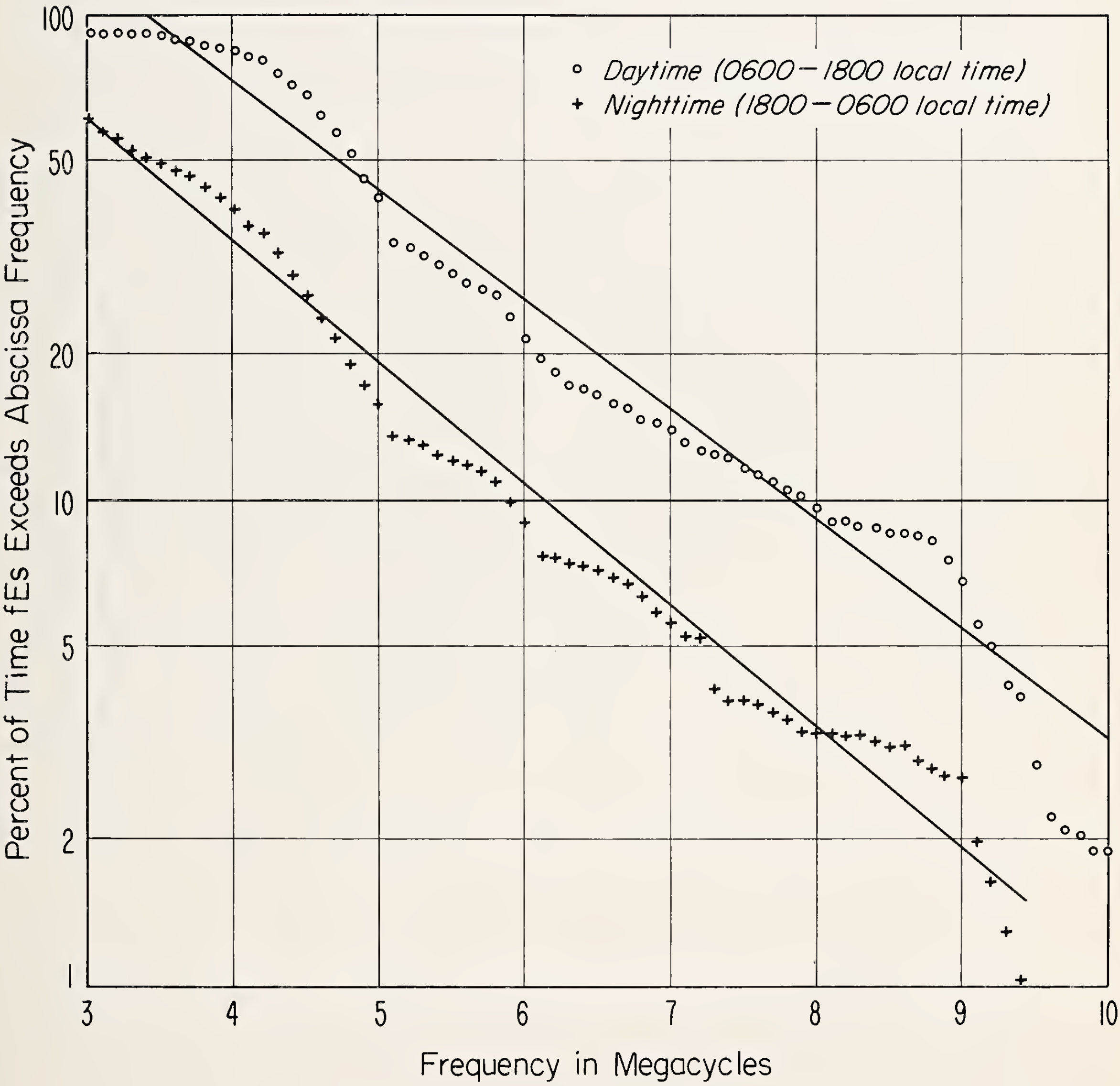

Figure II-C-4

station no longer on contract with CRPL. Comparing the summer maximum of 1951 to that for 1950 in figure II-C-5 it can be seen that on the 3 and 5 Mc limiting frequencies about 1.5 times more sporadic E was observed at the peak during 1951 and about 2.5 times more for the 7 Mc limiting frequency. The sporadic E observed for the entire years 1950 through 1952, however, reveals that the over-all increase was greater than that for the peak months.

Frequency in Mc	Percent of Year Es Observed 1950	1951	1952
3	18.2	44.0	39.4
5	6.9	19.4	25.3
7	1.4	7.3	8.2

It is also apparent that the relative augmentation increases with frequency as it is two times at 3 Mc, four times at 5 Mc and 6 times at 7 Mc. Baton Rouge is the most striking case which the writer has encountered, but it does show what can happen.

A case can be made for throwing out routine ionosonde Es data if factors for which one cannot correct produce variations of the order shown for Baton Rouge. It is perhaps worth reiterating the philosophy employed in this study. This philosophy is to let the degree of internal consistency of data itself, arrived at through consideration of data from many locations and over long periods of time, determine the reliance put on the final product. The internal consistency is statistical in nature and not determined by the few cases with obviously large irregularities.

AN EXTREME EXAMPLE OF Es INCIDENCE AFFECTED BY EQUIPMENT CHANGE

Baton Rouge, La.

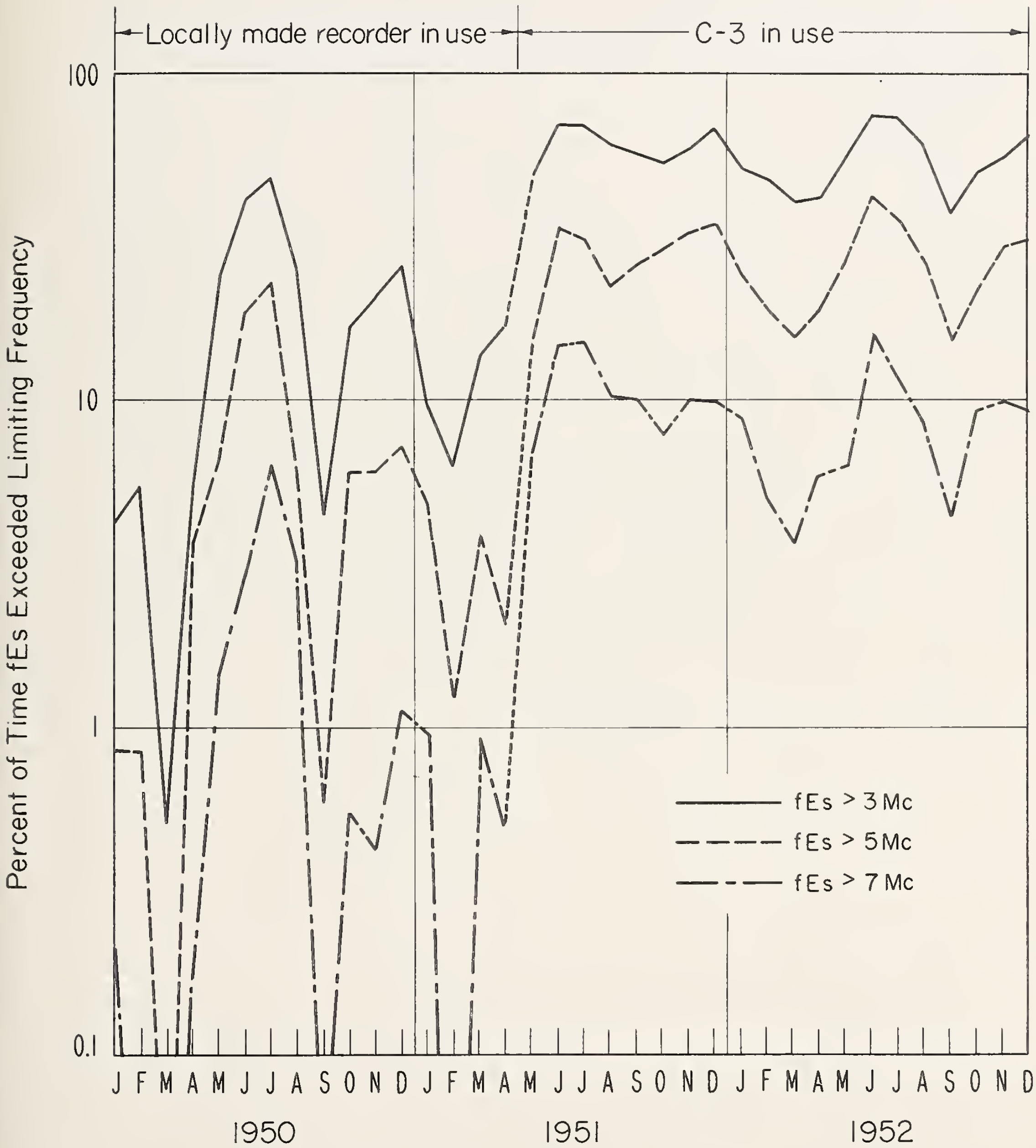

Figure II-C-5

Daytime absorption produces a diurnal and seasonal irregularity in the Es incidence for which it is difficult to correct for several reasons. The first, and least important, is the unpredictable part of the attenuation due to absorption. A second is that the receiver gain setting is changed several times each day and in a manner which varies with the season and station and for which a record is not kept. A third problem is that even if the first two difficulties are resolved a quantitative correction cannot be made unless the system gain for vertical transmission is known as a function of frequency. About all that can be said with certainty is to reiterate the statement that inasmuch as the over-all system gain of the ionosonde is increased during the daytime (and is not importantly a function of frequency) and the effect of absorption decreases rapidly with frequency, Es reflection coefficients must be higher at low frequencies to be just observable in the daytime but may be lower at high frequencies.

3. The Choice of Limiting Frequency

The percent of each hour of the month for which the Es critical frequency (fEs) at the reporting stations is observed to exceed 3, 5, and 7 Mc has been given in the CRPL-F series for over ten years. These percents may be interpreted as ones which would be attributed to sporadic E for fixed-frequency transmission circuits operating at 3.1, 5.1 and 7.1 Mc at vertical incidence. The system gains would be those of the ionosonde for these frequencies. As seen in figures II-C-1 and II-C-3 there is often a preference for the integer values (e.g. more cases of fEs = 5.0 Mc are found than for fEs = 4.9 Mc or fEs = 5.1 Mc). Therefore, the fixed-frequency equivalent of the category "fEs exceeds 5 Mc" is probably nearer 5.2 to 5.3 Mc than 5.1 Mc. A much better scaling convention would be to add one-half of the cases observed at say 5.0 Mc to the ones used to determine the percents of "fEs > 5 Mc." If done this way, the distributions of fEs could be considered continuous functions. At the same time the preference for integer values would be balanced out. However, this definition is not the one which has been used, so the existing definition must be used. The ratio of the percents arrived at using the two definitions will rarely differ from unity by more than 10%.

As mentioned before, the median values of fEs (when such can be obtained) are also available. However, unless one is interested in the highest frequency which can be supported by sporadic E for 50% of the time the median is not what is needed. For interference computations the distribution of Es percents for a fixed frequency is more meaningful than a distribution of frequencies at a fixed percent (even if the value in question were 10% instead of 50%).

The choice then may be limited to the distributions of percents of time for which sporadic E exceeds the limiting frequencies of 3, 5 and 7 Mc. The 3 Mc limiting frequency is often used, and serves to maximize the data sample. This level has, however, the following disadvantages:

a. The effects of absorption are so great that meaningful results cannot be obtained if they are ignored, unless attention is restricted to the nighttime.

b. Masking by the regular E region can attain frequencies in excess of 4 Mc (see section IC). A plot of the diurnal variation of Es values normally reveals a bite out of the midday region as is illustrated in figure II-C-6 for Washington, D. C.

c. The existing difference in scaling practice regarding "night E" (see "Retardation Es" in section II-B) is important at 3 Mc for auroral stations.

d. Possible saturation effects will be more serious at this frequency than for either of the other two. This is simply because the percentage occurrence of Es at 3 Mc is necessarily higher than that for either 5 Mc or 7 Mc. By "saturation effect" is meant the non-linearity between "number of occurrences" and "percent of time" when 100 percent is approached due to the increased probability of two or more events occurring simultaneously in the same time interval. To the extent to which sporadic E behaves as a true random variable, its actual occurrence related to its percent of time occurrence may be represented by the curve in figure II-C-7. The mathematical model used here requires the computation of the number of boxes out of 100 boxes total which will contain at least one coin in terms of the number of coins thrown (N). The coin is assumed to have an equal chance of

DIURNAL PLOT OF fEs DISTRIBUTION
ILLUSTRATING BITE TAKEN OUT BY DAYTIME E LAYER
WASHINGTON, D.C., JUNE 1952

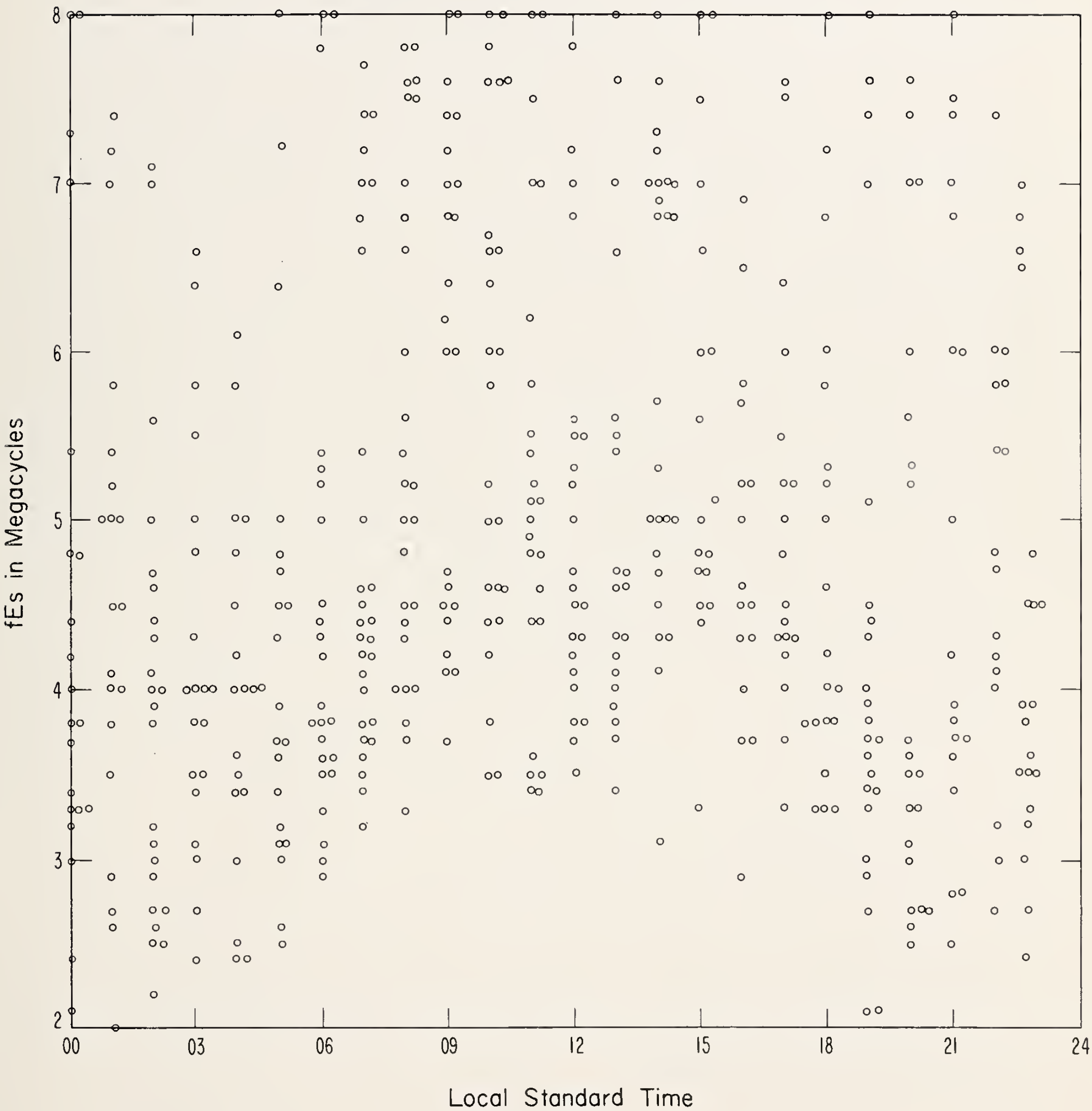

Figure II-C-6

landing in any box for each throw. As can be seen, below about 25%, the percent of time may be considered linearly related to the number of events while above 50% the non-linearity has become very marked.

e. The advantage of the large data sample is to some extent neutralized by the fact that the relative variations in time and location are less at 3 Mc than at 5 or 7 Mc. This effect is illustrated by the seasonal variations of sporadic E for the three frequencies in figure II-C-5.

At the 5 Mc level the absorption in db will be down by more than a factor of two from the 3 Mc level. Masking by the regular E-layer will not exist. A spot check of five years of Ft. Chimo data revealed that the critical frequencies of " night E" exceeded 5 Mc only 0.33% of the time. This is in keeping with the definition of night E which states that it cannot be distinguished from regular E traces except by time of day. As regular E criticals do not exceed 5 Mc, it follows that night E criticals should not either. Saturation effects will be down at 5 Mc, but not always negligible. Temporal and geographical variations will be relatively greater than at 3 Mc, but less than 7 Mc.

The 7 Mc level has all the advantages listed for 5 Mc in greater degree, but the size of the data sample has decreased to a point where the problem of statistical significance appears to have overridden the advantages.

THE SATURATION EFFECT FOR RANDOM Es

$$P = 100\left[1-(0.99)^N\right]$$

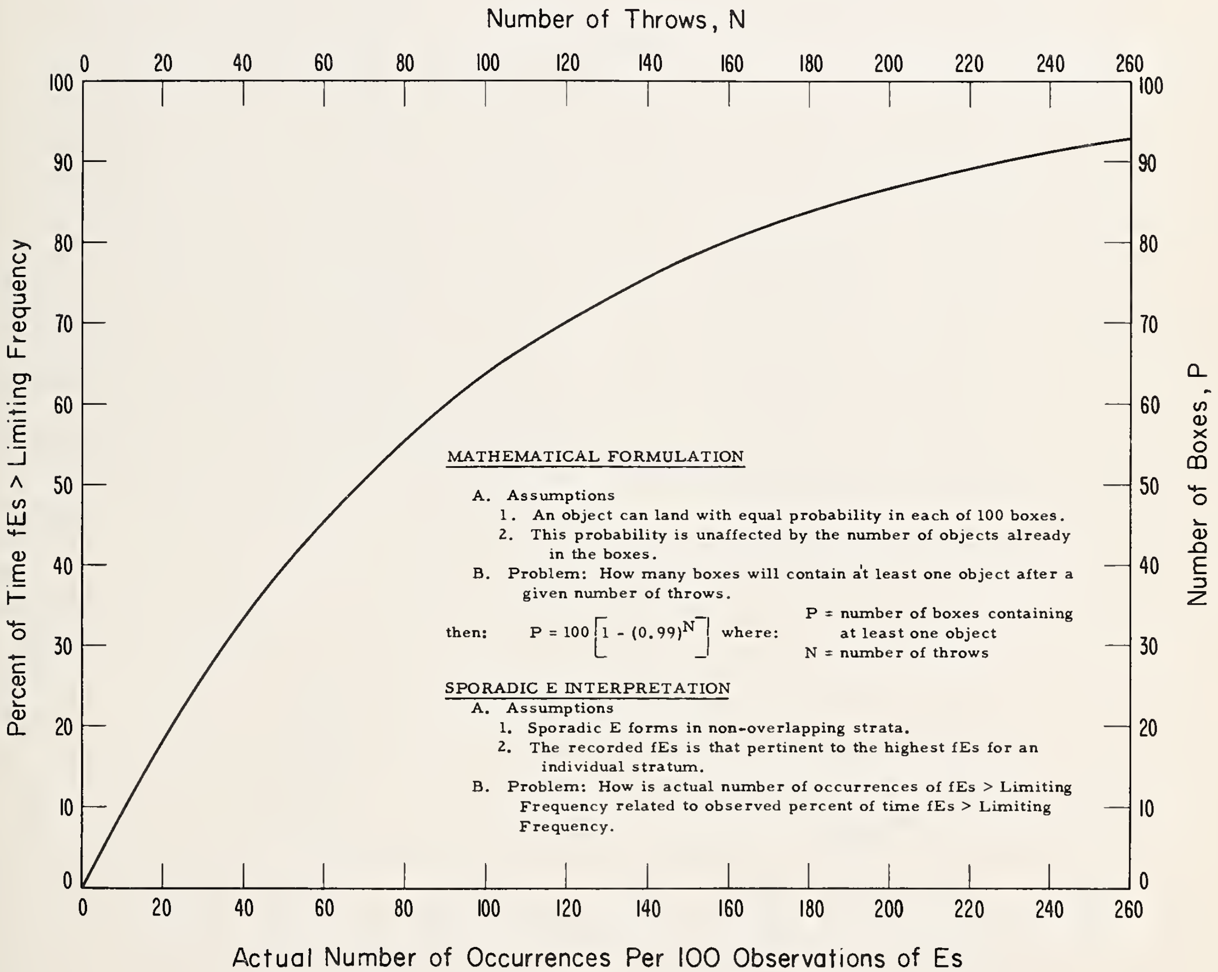

Figure II-C-7

The writer started his analysis at the 7 Mc level (Smith [1951]) which is not bad for such things as the diurnal variation of Es average over the year or the seasonal variation for all hours of the day. The 5 Mc level was resorted to when it became necessary to determine the diurnal variation for a particular month and seasonal variation for a given hour of the day. A visual demonstration of this limitation at 7 Mc is given in figure II-C-8 which shows a map of the temporal variations at Washington, D. C for two years for each frequency level. The percents of occurrence of Es are represented through the contour levels.

TIME MAPS OF Es INCIDENCE FOR THREE LIMITING FREQUENCIES
WASHINGTON, D. C.

Contours Represent Percent of Time fEs > Limiting Frequency

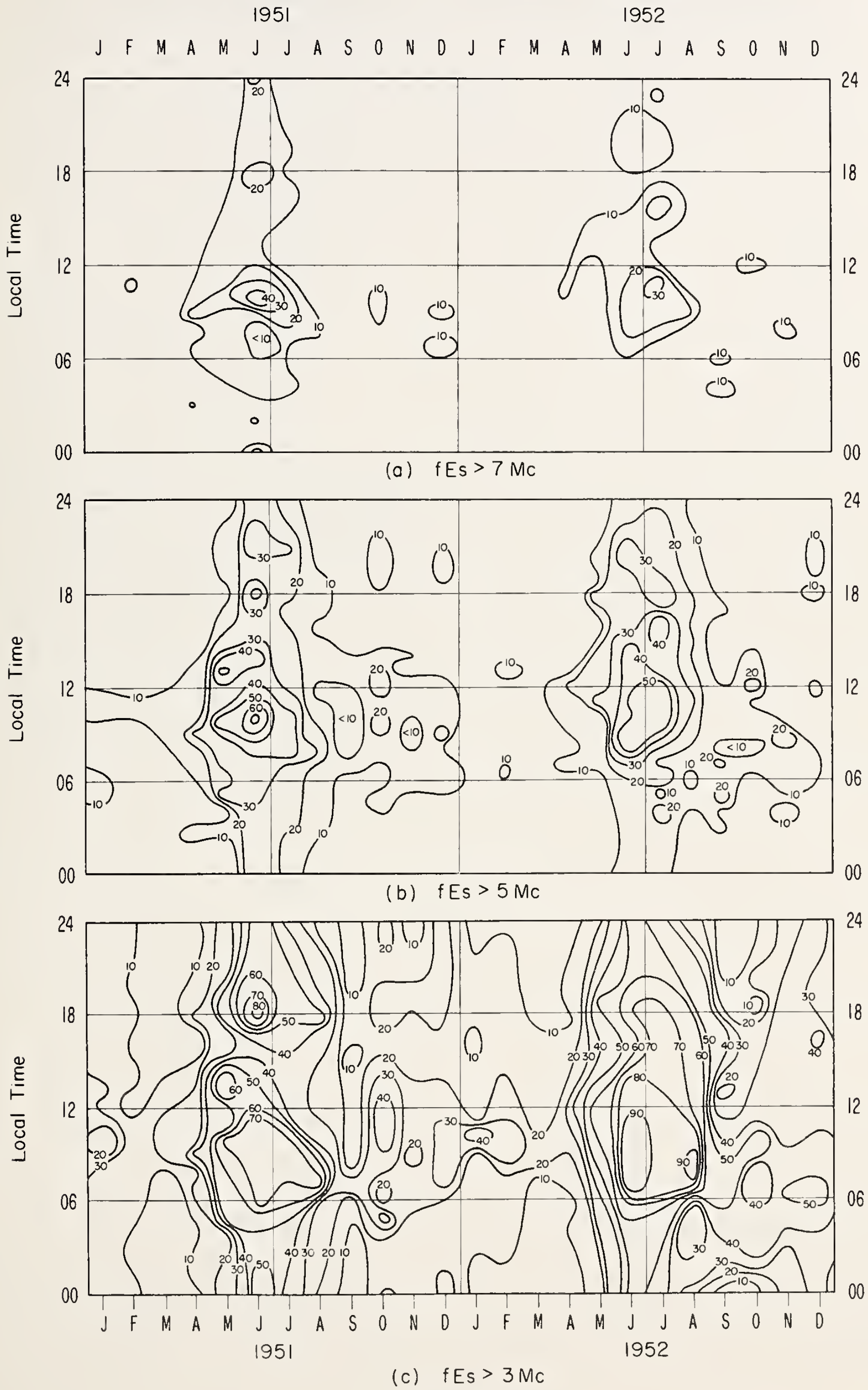

Figure II-C-8

D. The Major Sporadic-E Zones

Scientists and communication engineers have appreciated for some time that sporadic E can appear very different in different areas of the world. Characteristics of Es seen in the equatorial zone, the temperate zone and the auroral zone have been described by Tremellen and Cox [1947] and Matsushita [1953]. Considerable variation exists inside these zones, but our current understanding of sporadic E is not sufficient to increase the number of zones.

It is appropriate at this point to define some of the terms which will be used and point out the common misconceptions concerning them. By "magnetic equator" will be meant the line at which the magnetic dip I = 0 at a height of 100 km. In practice it will be assumed that the dip equator charted for 1945 by Vestine et al. [1947] and derived from the first six spherical harmonics of the earth's magnetic field is a close enough approximation to this. The word "geomagnetic" will always be used to refer to the axial dipole component of the field. Thus, on figure II-D-1 (world in geomagnetic coordinates) the "geomagnetic equator" is the horizontal line marked 0°. The "magnetic equator" is the dashed line which is seen to deviate from the geomagnetic equator by as much as 15°.

It is also frequently assumed that the auroral isochasms (lines of equal observed frequency of aurora) are concentric to the

WORLD IN GEOMAGNETIC COORDINATE SHOWING AURORAL ISOCHASMS AND MAGNETIC (DIP) EQUATOR

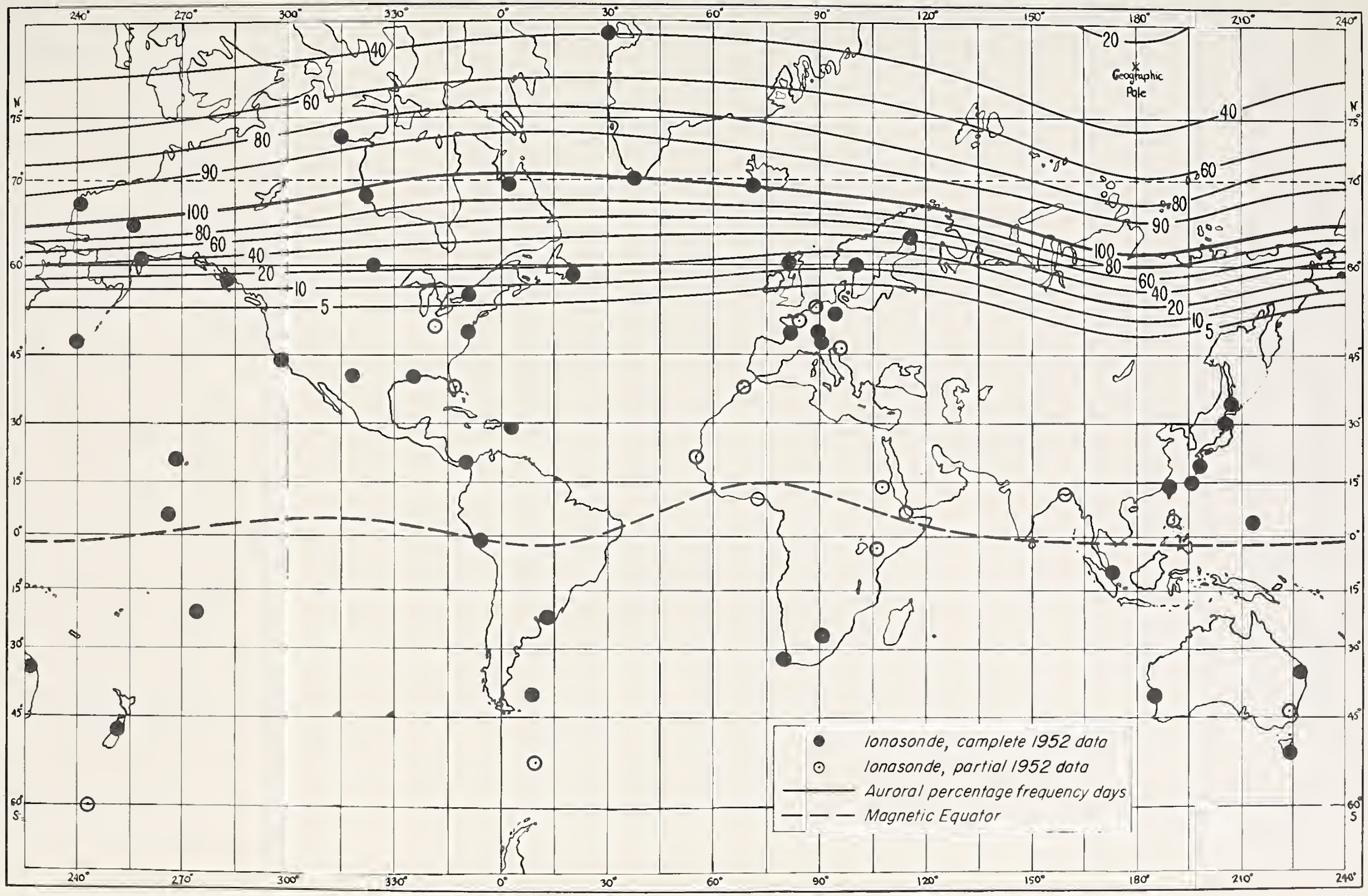

Figure II-D-I

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geomagnetic axis of the earth. If this were so the isochasms (as given by Vestine [1944]) would appear as straight horizontal lines on figure II-D-1. The isochasms obviously do not do this. In fact at the auroral maximum (100% auroral frequency) the line exhibits an excursion of almost 10^{o} in geomagnetic latitude. It can be argued that these excursions of the isochasms are due to inhomogeneities in the data sample and that more and better data would reveal the isochasms to be co-axial with the dipole axis. However, Vestine (private communication, 1955) feels that the excursions are probably real. Auroral isochasms for the southern auroral zone have been drawn by Vestine and Snyder [1945], but are based on much less data than those for the northern hemisphere.

The auroral isochasms shown in figure II-D-1 will be treated as though they are invariant in time. This, of course, is not the case. Gartlein and Moore [1951] have demonstrated that a seasonal effect exists over North America which, though barely noticeable near the auroral maximum, becomes pronounced as one moves southward. Seasonally, aurorae show maxima at the equinoxes and minima at the solstices. The same paper shows a year-to-year variation which is not markedly related to the sunspot cycle. The outer isochasms will show a seasonal ebb and flow. From the Gartlein and Moore study, however, one may infer that this seasonal variation will not affect the isochasms of auroral-percent-frequency greater than about fifteen percent.

1. Equatorial Zone -The work of Matsushita [1951] will be used to define this zone. Figure II-B-3(b) presents a plot of daytime Es

versus magnetic-dip. It is seen that this equatorial increase in Es is bounded on the south by the dip $I = -10^{\circ}$ and on the north by $I = +10^{\circ}$. Examination of ionograms of equatorial stations reveals that the daytime rise in sporadic E around the magnetic equator is due to the "Huancayo type" of sporadic E described in section II-B. The correlation of this Es type with the equatorial electroject (Chapman [1951]) which flows on the daylight side of the earth is good. However, it is not known with certainty that either the equatorial electrojet or the Huancayo type of Es completely girds the earth. Nor is it certain that either are maximum exactly at the line defined by $I = 0^{\circ}$. It will be assumed for the purposes of this study that the Huancayo type Es occurs in this zone independently of the normal sporadic E and that its percent occurrence above 5 Mc is given geographically by

$$P = P_{Hu} \cos (9I) \text{ for } -10^{\circ} \leq I \leq +10^{\circ} \qquad \text{II-D-1}$$

where: P = percent occurrence of Huancayo type E

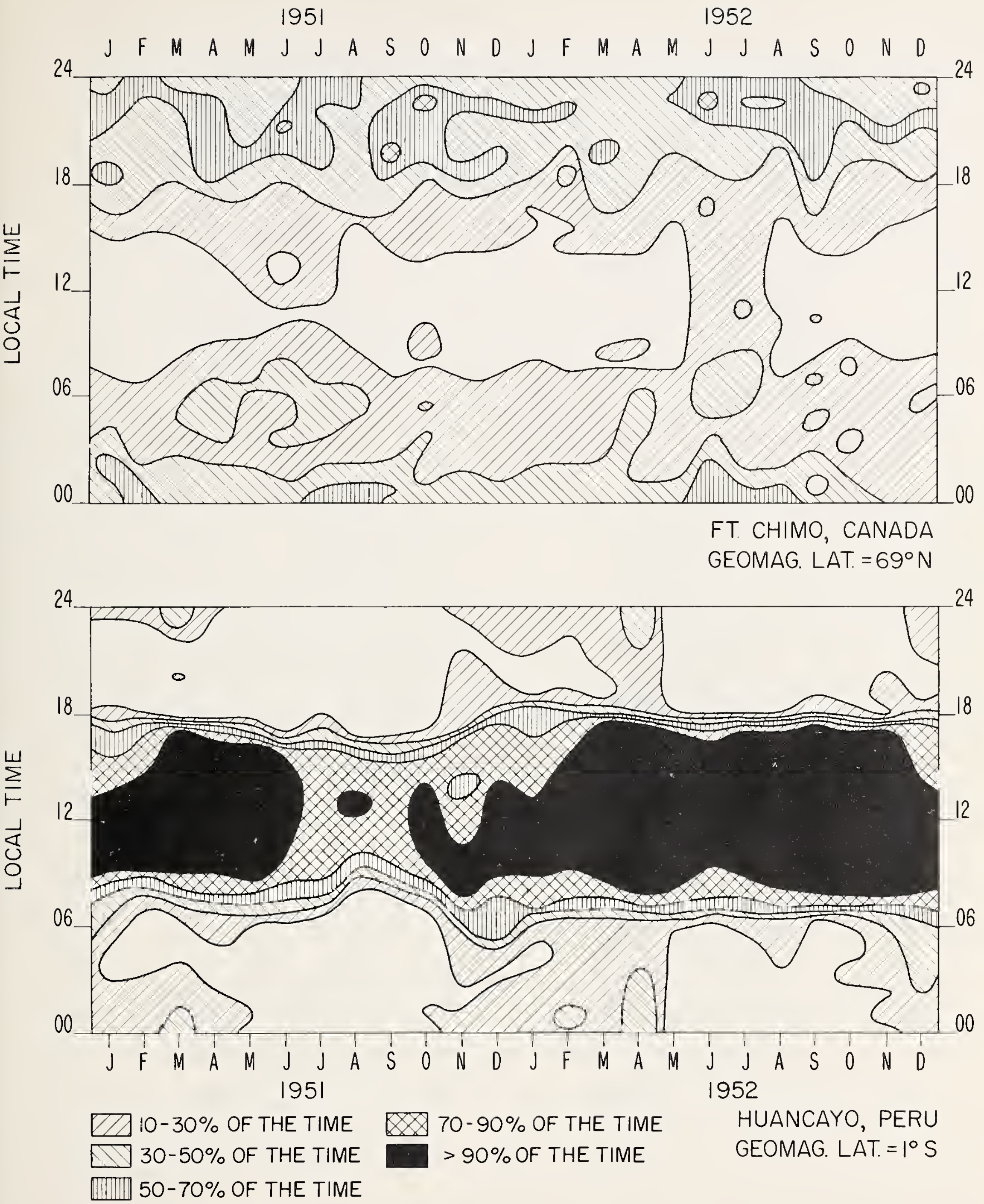
P_{Hu} = observed percent occurrence of this type at Huancayo, Peru

I = magnetic dip in degrees.

It is interesting to contrast the temporal variations of Es as observed at such stations as Huancayo and Kodaikanal on the magnetic equator with those for stations at the maximum of the Auroral Zone. Both represent areas of frequent intense E-region current flow, the former in the daytime and the latter mostly at night. The "time maps" in figure II-D-2 illustrate this comparison for Ft. Chimo, on the auroral maximum and Huancayo, Peru, on the magnetic equator. The diurnal variation is seen to be the dominant time variation for both stations. However, the diurnal variations at the two stations are in almost exact antiphase; at Huancayo Es is almost exclusively a daytime phenomenon whereas at Ft. Chimo it occurs almost entirely at night. Moreover, during most of the daylight hours fEs at Huancayo is seen to exceed 5 Mc more than 90% of the time. Stations on the magnetic equator are the only ones for which Es occurrence of 90% or greater have been recorded at this frequency level.

Very little seasonal variation can be detected at Huancayo, but at Kodaikanal, Rangarajan [1954] reports quite a substantial variation. Relation II-D-1 is consequently far from perfect at all points on the magnetic equator.

2. Temperate Zone - This zone is easily the largest of the three from the standpoint of geographical area. It extends continuously between the North and South Auroral Zones inasmuch as the Equatorial Zone is considered to be overlaid on top of it and not to affect it. The temporal variations of sporadic E in this zone are in marked contrast with those of both the Equatorial Zone and the Auroral Zone. This contrast is illustrated by the time maps in figure II-D-3. The temporal pattern of Es at Washington, D. C., a High Temperate Zone station, is seen to be dominated by the seasonal rather than diurnal variation as is the case in the Auroral and Equatorial Zones. There is a well defined seasonal



COMPARISON AURORAL ZONE TO MAGNETIC EQUATOR Es

fEs > 5 Mc

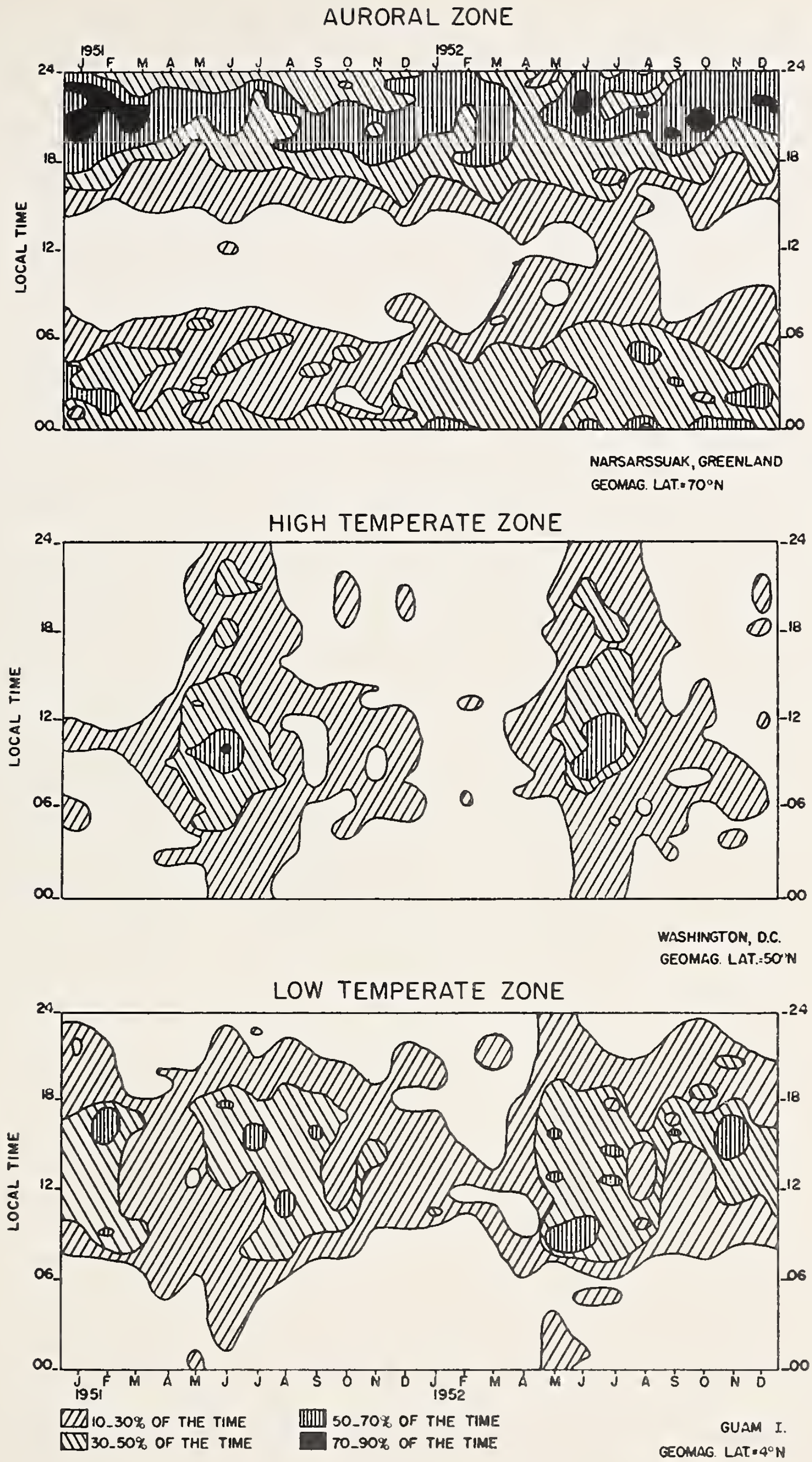
Figure II-D-2

maximum in the neighborhood of the June solstice and a more poorly defined secondary maximum around the December solstice in the northern hemisphere (Phillips [1948])and the minima occur at the equinoxes. These variations become naturally less pronounced as the geographical equator is approached and reverse in the southern hemisphere. As a rule there is more Es in the daytime than at night. The diurnal maximum falls around 10:00 a.m. local time, a secondary maximum is frequently apparent in the vicinity of 6:00 p.m. and the diurnal minimum is normally around 4:00 a.m.

3. Auroral Zone - Time maps for stations on the auroral maximum are presented in the top charts of figure II-D-2 (Ft. Chimo) and figure II-D-3 (Narsarssuak). It has already been pointed out that the diurnal variation is the dominant one and that little seasonal variation is in evidence at the auroral maximum. The diurnal maximum is seen to be a few hours before midnight for both Ft. Chimo and Narsarssuak, however it will be seen later that as one moves westward to Fairbanks, Alaska the maximum shifts to after midnight. The diurnal minimum appears to be at midday.

4. Demarkation Line Between Auroral and Temperate Zones

The dividing line between the Auroral Zone and the Temperate Zone is not easy to draw. Figure II-D-3 illustrates the fact that not only are the time variations at the maximum of the Auroral Zone quite different from those of the North Temperate Zone, but they are mutually exclusive, i.e. there is no question of one distribution blanketing the effects of the other. The writer has found no quantitative study of the transition from one zone to



COMPARISON: AURORAL ZONE TO TEMPERATE ZONE Es

fEs > 5 MC

Figure II-D-3

the other in the literature. In fact no quantitative information appears to exist as to what geographical parameters are important in determining the behavior of sporadic E in either region. The current CRPL-D series Es predictions assume an Es dependence on geomagnetic latitude. It will be seen in the course of this analysis that geomagnetic latitude is not a very good choice for either zone. However, if a single latitude parameter must be used the geomagnetic has a slight edge over the geographic in that it serves better to determine observed Es behavior in the Auroral Zone.

A direct way of examining how the transition takes place is to consider the variation in some quantitative measure of the distinctive features of Es in each zone. As a measure of the seasonal variation which is so striking in the Temperate Zone let us consider the ratio of the percent of time occurrence of sporadic E at the 5 Mc level for the solstitial months (June, July, December and January) to that for the equinoctial ones (March, April, September and October). The Auroral-Zone characteristics may be demonstrated either through the ratio of nighttime to daytime sporadic-E incidence for fEs > 5 Mc averaged over the year ($\overline{N}/\overline{D}$) or by considering the total nighttime incidence $\overline{N}$. Nighttime is defined as 1800 to 0600 local time and daytime 0600-1800 local time. These data were scaled from the monthly charts giving percent Es occurrence above the limiting frequencies of 3, 5 and 7 Mc for the various reporting stations of the world. As all these Es data are to be considered in twelve hour groups, a scaling shortcut has been used. It was found possible to visually integrate the area under the curves in 12 hour groups through use of a transparent overlay with guide lines on it. The mean scaling error for a single measurement of one to two percentage points becomes negligible in any of the connections in which these data will be used in this study.

An exploratory study of 1952 Es data (Smith [1955]) indicates that, for this particular year at any rate, the demarkation line can be appropriately drawn at the isochasm of 15% auroral occurrence. The correctness of this dividing line is brought out in the bottom chart of figure II-D-4 (nighttime, 1952) where it is seen that the dots, representing Temperate Zone stations, and the crosses, Auroral Zone stations, appear to behave as two separate distributions. The same is true of night-to-day ratio in the top chart of figure II-D-5. The most spectacular division is obtained through the solstice-to-equinox ratio shown in the lower chart of figure II-D-5. The seasonal variation, as reflected in this ratio, is seen to rise steadily with geomagnetic latitude up to 60°, but then to be sharply smothered as the Auroral Zone is reached. Again the 15% auroral isochasm serves to divide the two distributions.

Correlations of two Auroral Zone Es features ($\overline{N}$, $\overline{N}/\overline{D}$) and auroral percent-frequency days are seen in the first two charts of figure II-D-6. A better correlation is obtained by using a different measure of Auroral Zone Es through taking the product of the nighttime incidence and the night-to-day ratio. The correlation of this measure ($\overline{N}^2/\overline{D}$) with auroral percent frequency days appears in the right-hand chart. The product of two Es character

OCCURRENCE OF SPORADIC E IN NORTHERN HEMISPHERE fEs > 5 Mc, 1952

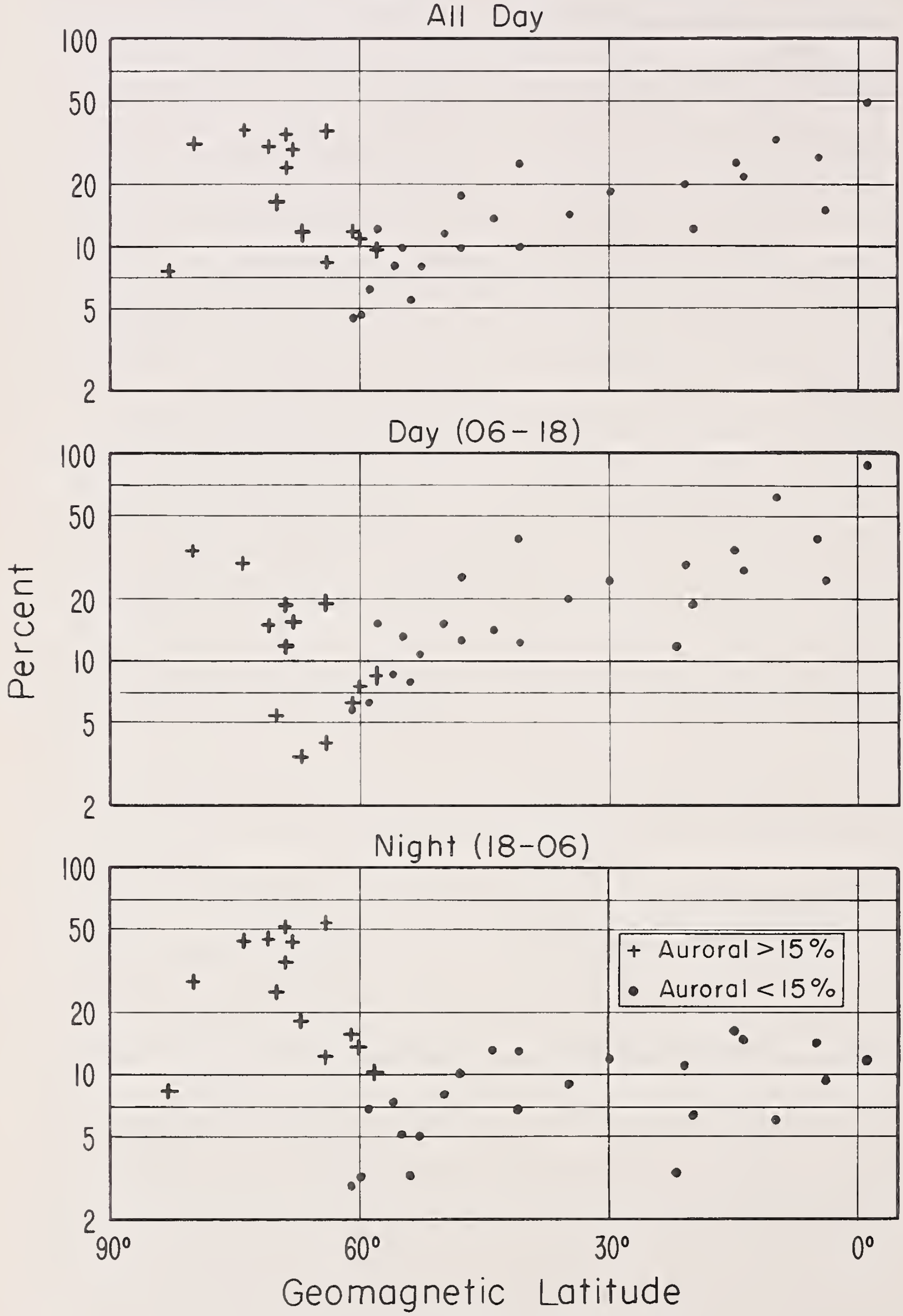


Figure II-D-4

figures, both of which maximize in the Auroral Zone is certainly as suitable a measure of Es Auroral Zone behavior as either of the two original character figures themselves. The tight correlation obtained in the right-hand chart of figure II-D-6 implies auroral control of Es behavior down to the region where the points begin to scatter. The points representing stations located in areas of more than 15% aurorae are seen to be just above the dispersion region, so again the demarkation line is seen to be appropriate.

The linear correlation coefficients pertinent to the plotted values on figure II-D-6 are as follows:

$\overline{N}$ and Auroral Percent Frequency Days; correlation coefficient = 0.63

$\overline{N}/\overline{D}$ and Auroral Percent Frequency Days; correlation coefficient = 0.75

$\overline{N}^2/\overline{D}$ and Auroral Percent Frequency Days; correlation coefficient = 0.92

The explanation of this improved correlation is uncertain. One possibility is that the effect of increasing the system gain of an ionosonde would be to raise $\overline{N}$ but lower $\overline{N}/\overline{D}$. The product of the two figures would then be less affected by variations in the gain of the equipments than either of the factors themselves. By this argument the improved correlation is to be attributed to a compensation of the variation in gain between equipments. That this is probably not the most important reason is suggested by the fact that stations north of the auroral maximum appear systematically high on the $\overline{N}$ chart and systematically low in the $\overline{N}/\overline{D}$ chart in N figure II-D-6. Later it will be seen that a longitude effect appears

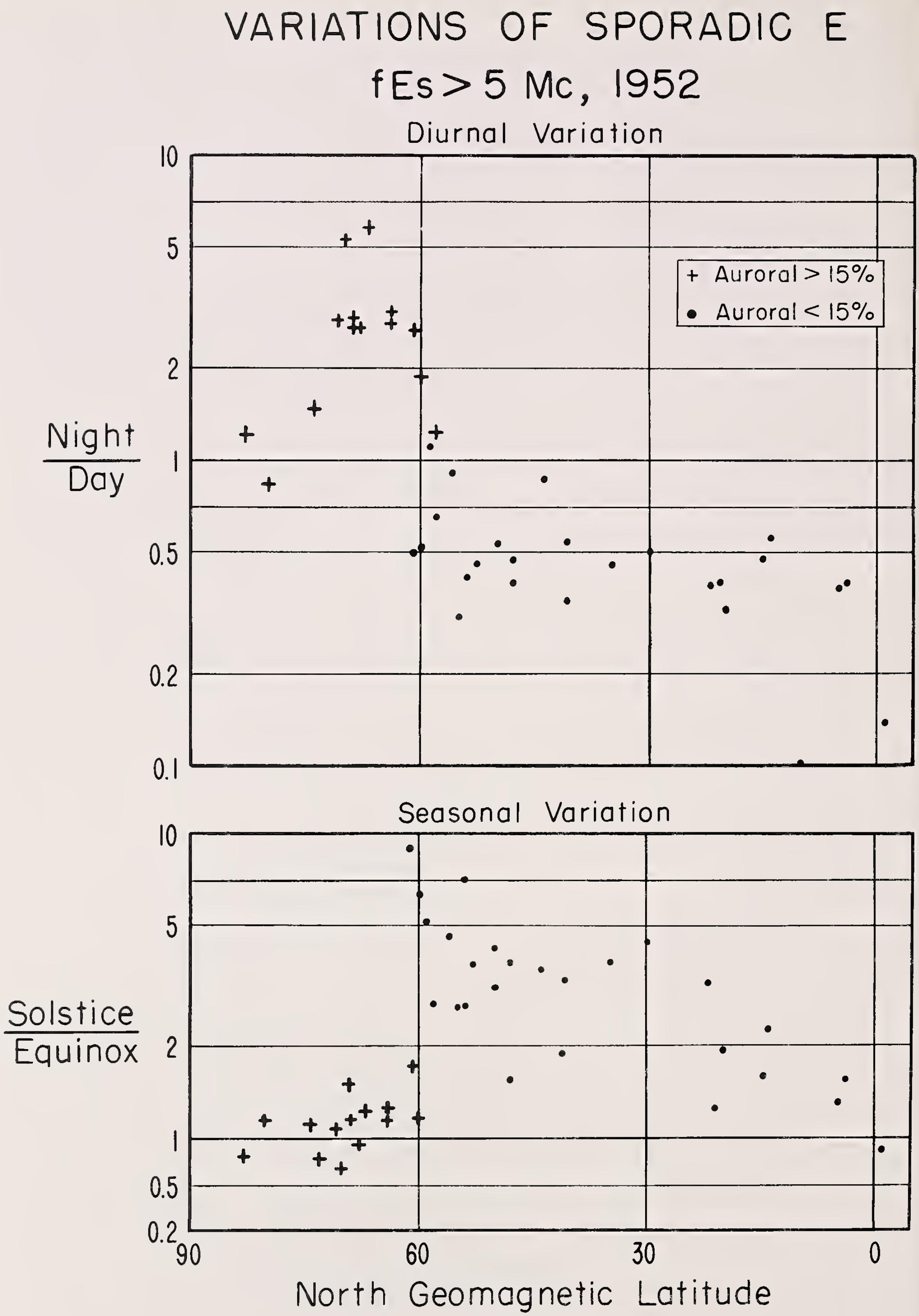

VARIATIONS OF SPORADIC E
fEs > 5 Mc, 1952
Diurnal Variation
10
5
2
1
0.5
0.2
0.1
Night / Day
+ Auroral > 15%
• Auroral < 15%
Seasonal Variation
10
5
2
1
0.5
0.2
Solstice / Equinox
90
60
30
0
North Geomagnetic Latitude

Figure II-D-5

COMPARISON OF SPORADIC E INCIDENCE ABOVE 5 MC WITH AURORAL PERCENTAGE FREQUENCY DAYS

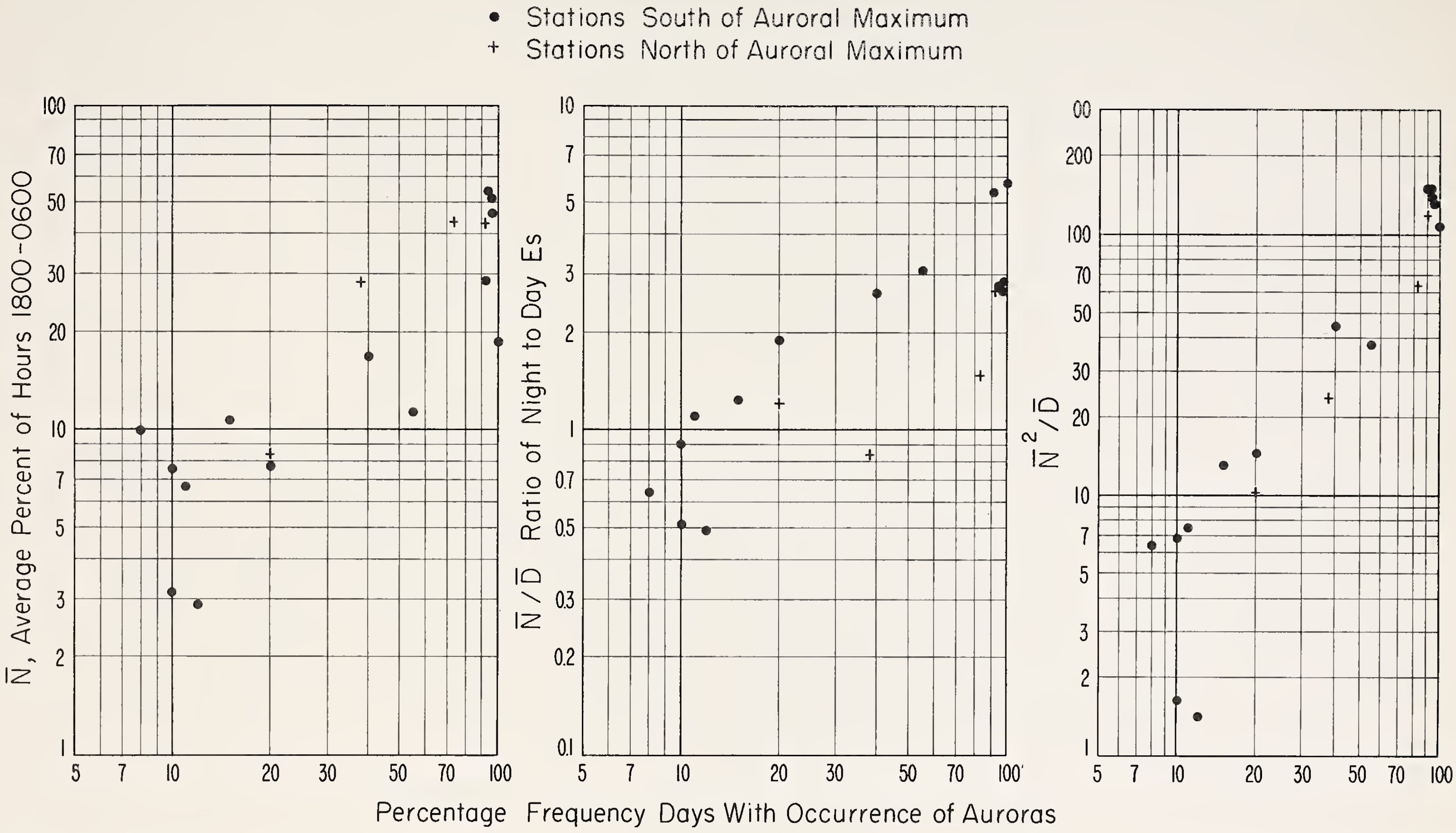


Figure II-D-6

also to contribute.

It is interesting to note that the separation of Auroral and Temperate-Zone stations achieved for 1952 by the 15% auroral isochasm could not be accomplished by using a parallel of geomagnetic latitude, say 60°. This is readily apparent in figures II-D-4, II-D-5 and II-D-6.

The actual period which will be considered in this study is the seven year interval from 1948 through 1954. The peak of sunspot activity occurred in 1947 (Zurich number = 151.5) and the minimum in 1954 so that this period represents the declining part of the cycle and encompasses a full range of sunspot numbers. A map showing ionosphere sounding stations for which data are available is seen in figure II-D-7. A listing of the geographical and geomagnetic coordinates of these same stations is found in table II-D-1. The code numbers listed opposite the stations in this table are used to identify these stations in certain of the charts which follow. Stations are included in this study for which two or more calendar years of data are available. A listing of stations utilized and the time intervals involved for each appears in figure II-D-8. The E. I and W zones mentioned on this figure are the conventional ones shown in figure II-D-9.

To transfer the results obtained for 1952 to the period 1948 to 1954, it is necessary to investigate the year to year variations of the two character figures: $\overline{N}/\overline{D}$ and the solstice-to-equinox ratio for the stations in the cross-over region. This is presented for stations lying between the 5% and 49% isochasms in figure II-D-10. In both cases, the yearly values of the character figures have been plotted on a logarithmic scale. The value for the year 1951 is taken as a reference level. The original curves plotted on paper with a logarithmic ordinate scale are then transferred off after setting the 1951 level arbitrarily to unity. As an interval on a logarithmic scale defines a ratio which is unaffected by translation, this method conserves the ratios between yearly values when presented in the normalized form of figure II-D-10. In cases where there is no value for 1951, the value for the year nearest 1951 has been set equal to unity.

The scatter of values in figure II-D-10 is high. However, if one examines the median values shown for each year it becomes apparent that for these stations in the cross-over region the Es incidence for the year 1952 was characterized by weak Temperate Zone and strong Auroral Zone influence relative to the mean of the period 1948-1954. This is a rather surprising result and is perhaps related to the high index of magnetic activity for the 1951-1952 period which will be discussed later.

The effect of the greater penetration into temperate latitudes of the Auroral Zone influence in 1952 than for the average of the period will mean that the Es observed at the 15% auroral isochasm will, on the average, show more temperate influence than is demonstrated in figure II-D-5. This fact is born out in figures II-D-11 and II-D-12 where the night-to-day ratio and solstice-to-

IONOSPHERE SOUNDING STATIONS

Past and Present Data Stations of CRPL - F Series

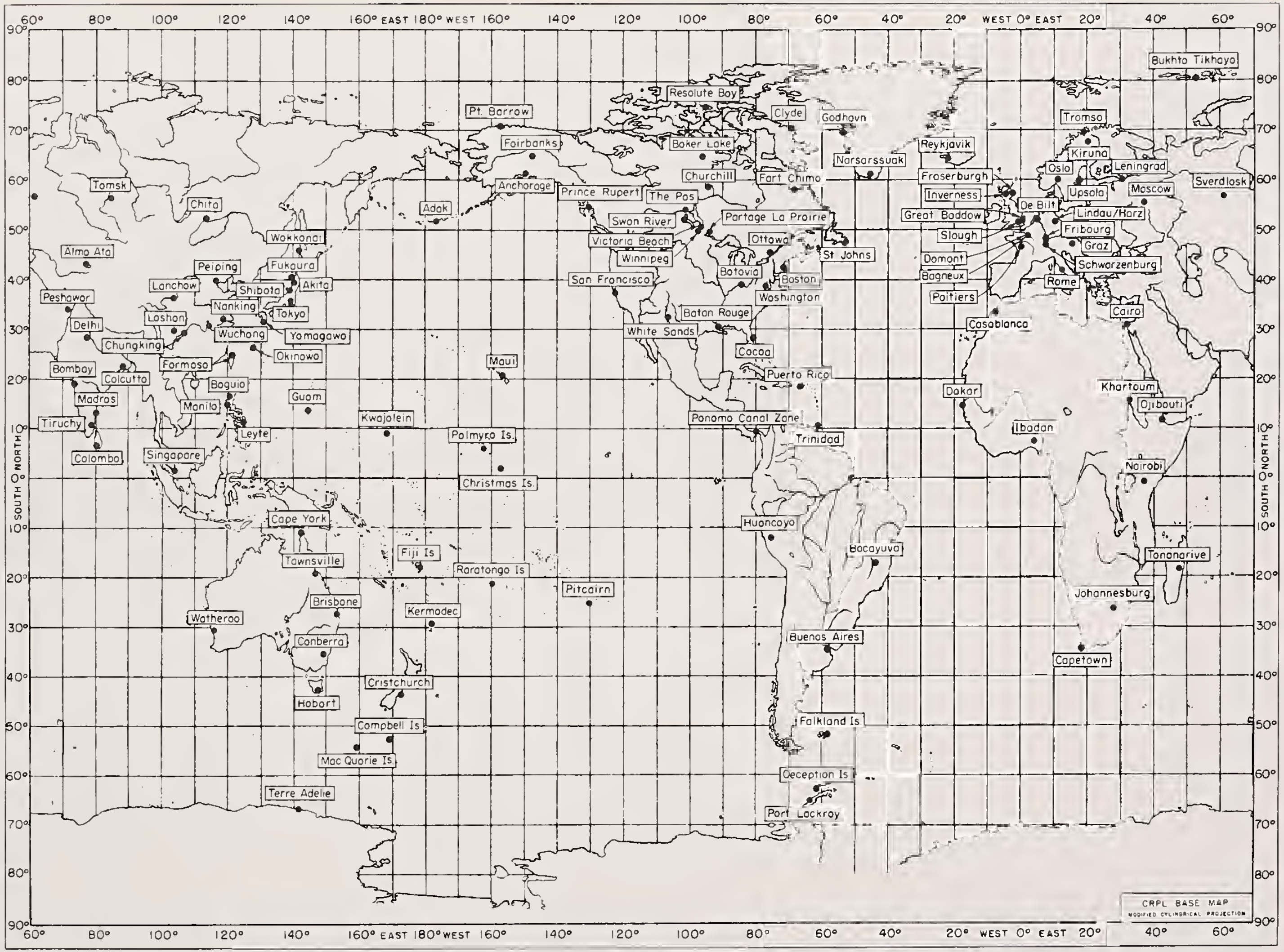


Figure II -D-7

STATIONS AND TIME PERIODS USED IN STUDY

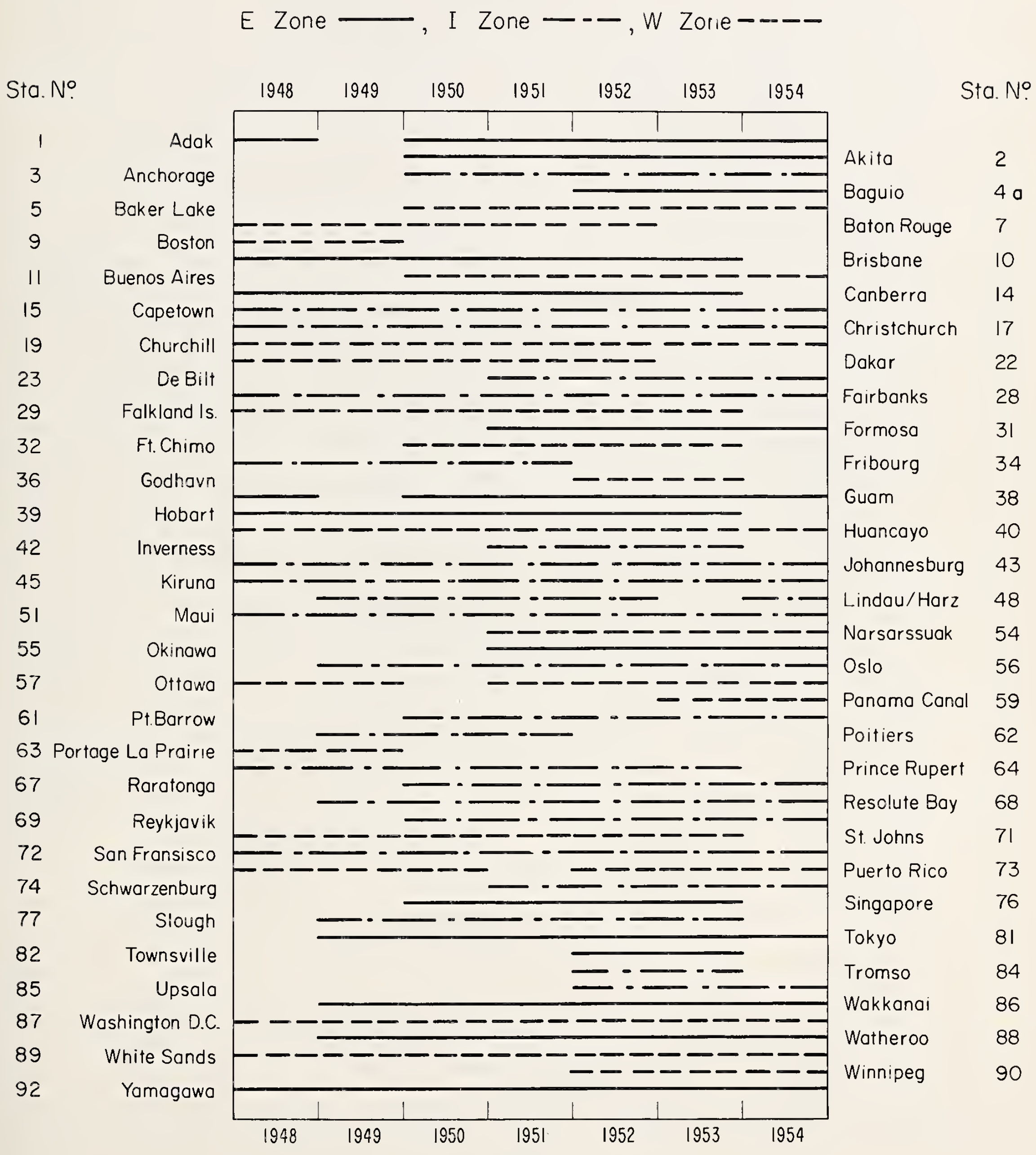


Figure II-D-8

WORLD MAP SHOWING ZONES COVERED BY CRPL - D SERIES PREDICTIONS

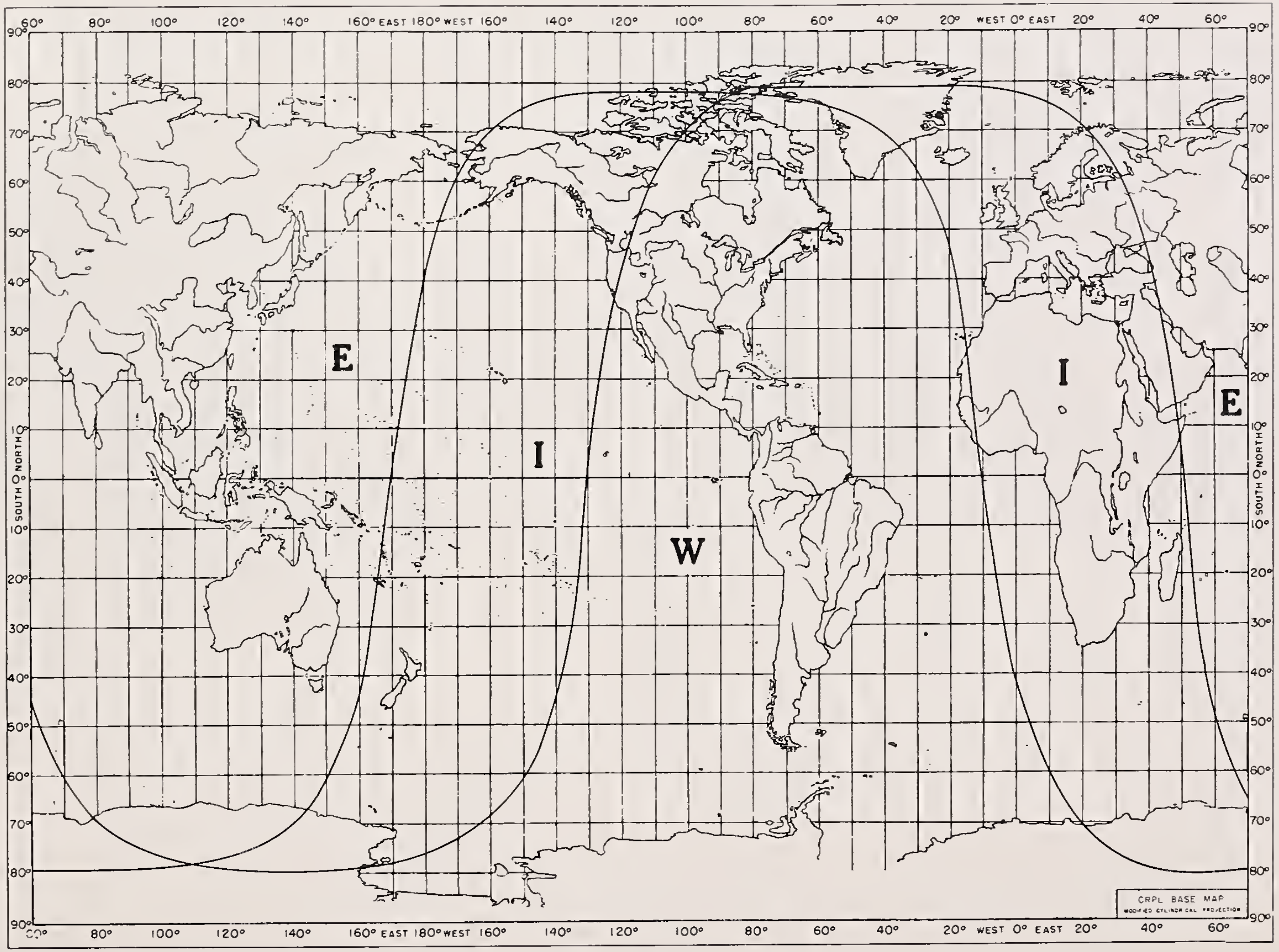


Figure II-D-9

YEAR TO YEAR VARIATION OF AURORAL AND TEMPERATE Es CHARACTERISTICS AT SELECTED STATIONS

Stations at Location with Percent Auroral Frequency = 5 to 49

fEs > 5 Mc

Annual Values Normalized to those for 1951

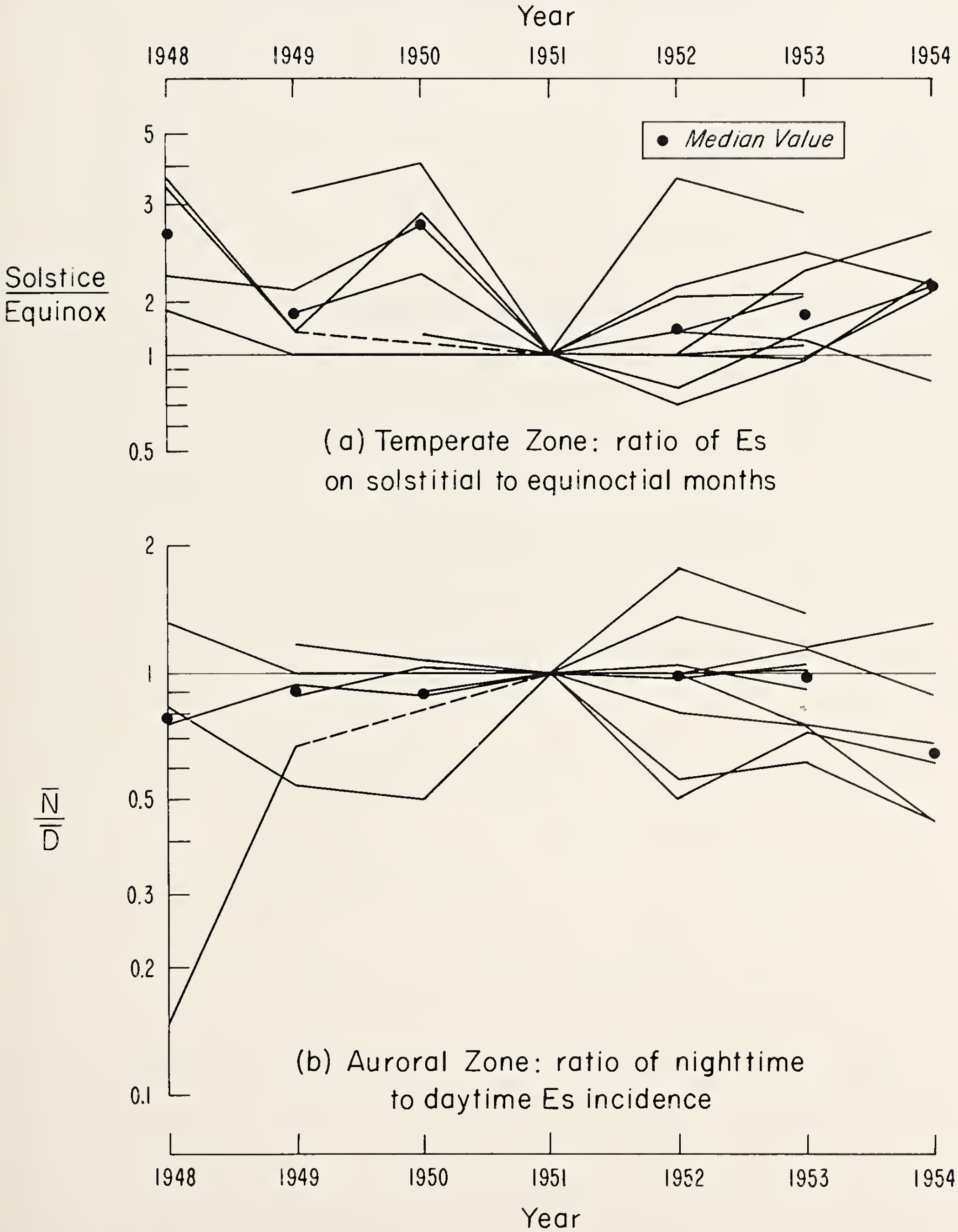


Figure II-D-10

equinox ratio respectively for the seven year period are plotted as a function of geomagnetic latitude. The ordinate scales in these two figures are effectively comparable to those of figure II-D-5. The linear scale is used here in order to make the mean deviations of the plotted values easier to interpret. It is seen in figure II-D-12 that although the Es characteristics of the two zones now have a gradual transition from Temperate to Auroral behavior, still the 15% isochasm is a satisfactory dividing line.

The Auroral Zone correlations corresponding to those of figure II-D-6 but this time for the seven year period are given in figure II-D-13. As before it is seen that quite a good correlation for both $\overline{N}/\overline{D}$ and $\overline{N}$ with auroral-percent frequency days is obtained but that a better one exists for $\overline{N}^2/\overline{D}$. The linear correlation coefficients of the mean values shown in figure II-D-13 are as follows:

1. $\log_{10} \overline{N}$ and $\log_{10}$ (auroral % frequency days)...r = 0.89

2. $\log_{10} (\overline{N}/\overline{D})$ and $\log_{10}$ (auroral % frequency days) ...r = 0.91

3. $\log_{10} (\overline{N}^2/\overline{D})$ and $\log_{10}$ (auroral % frequency days)...r = 0.96

These correlation coefficients are not directly comparable to those given for figure II-D-6 as this set refers to a correlation of the logarithms of the quantities and the earlier set to the correlation of the quantities themselves. It might be pointed out that the logarithmic correlation is the one the eye attempts to make for either plot.

THE NIGHT TO DAY RATIO OF Es INCIDENCE AS A FUNCTION
OF GEOMAGNETIC LATITUDE
fEs > 5 MC   1948 – 1954

Ranges Shown Are Mean Deviations
Night = 1800 – 0600 Local Time, Day = 0600 – 1800 Local Time

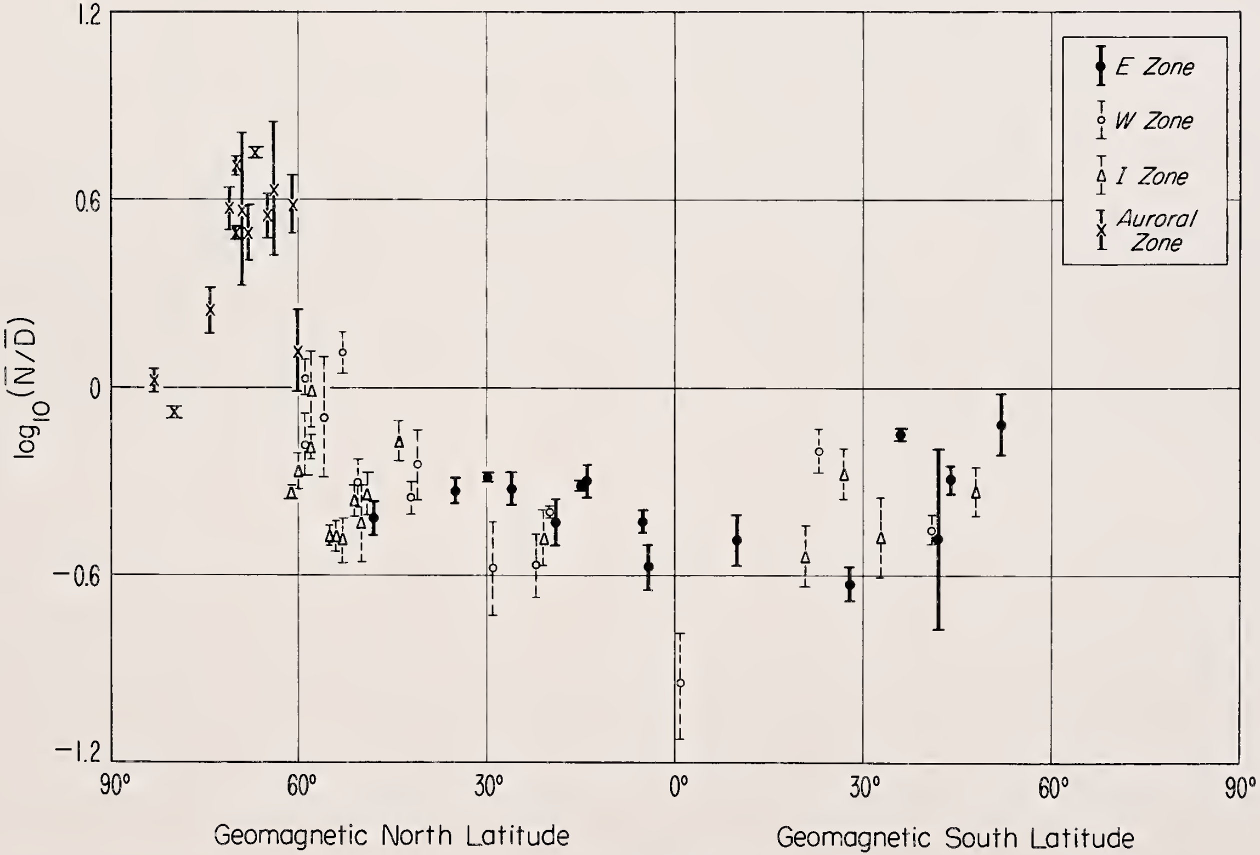


Figure II-D-11

THE SOLSTICE TO EQUINOX RATIO OF Es INCIDENCE AS A FUNCTION OF GEOMAGNETIC LATITUDE

fEs > 5 MC   1948 - 1954

Ranges Shown Are Mean Deviations

Solstitial Months = June, July, December and January

Equinoctial Months = September, October, March and April

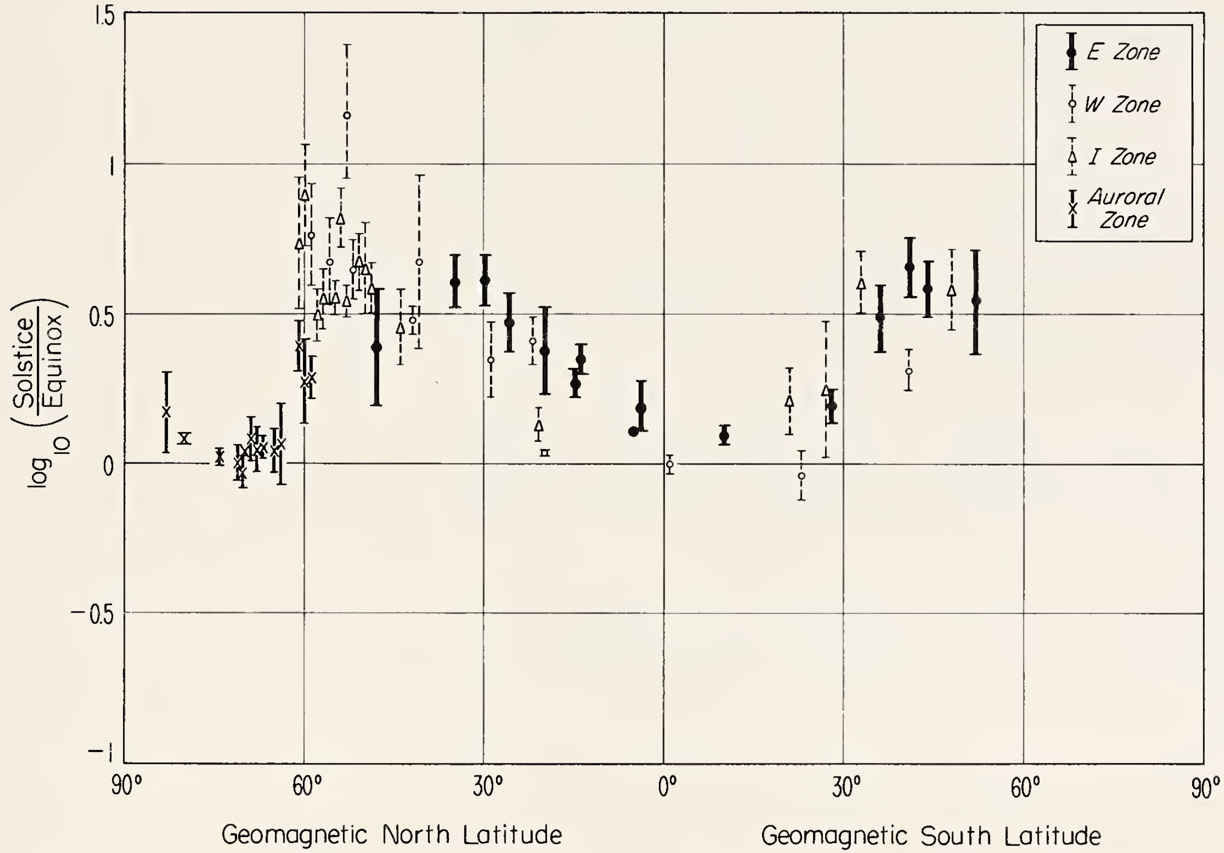


Figure II-D-12

CORRELATION OF Es CHARACTER FIGURES: $\bar{N}/\bar{D}$, $\bar{N}$, $\bar{N}^2/\bar{D}$
WITH AURORAL PERCENT FREQUENCY DAYS

fEs > 5Mc, 1948-1954

Ranges Are Mean Deviations of Annual Values

- ∘ Location; North of Auroral Maximum
- • Location; South of Auroral Maximum

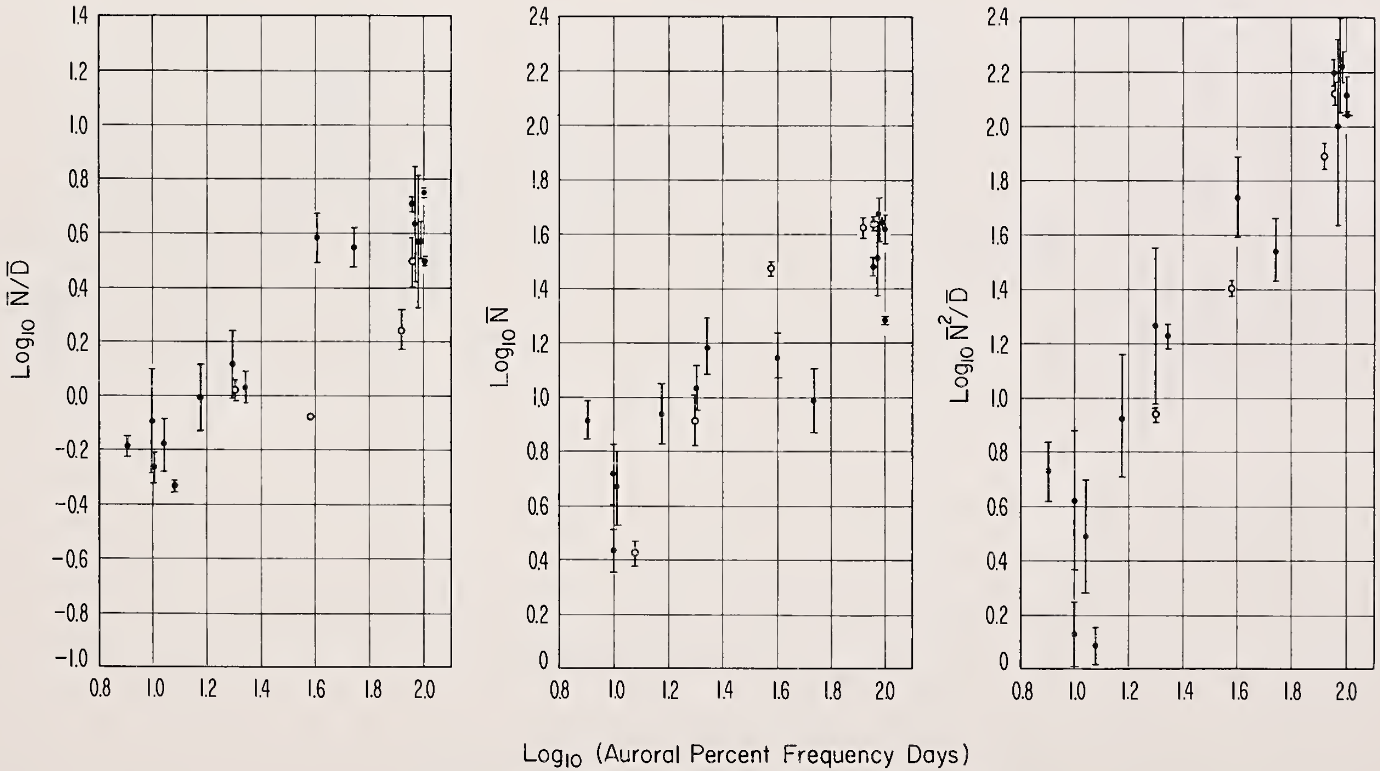


Figure II-D-13

TABLE II-D-1

List of Ionosondes

Station Number	Station	Geographic Lat.	Geographic Long.	Geomagnetic Lat.	Geomagnetic Long.
1	Adak, Alaska	51.9°N	176.6°W	48°N	240°E
2	Akita, Japan	39.7°N	140.1°E	30°N	205°E
3	Anchorage, Alaska	61.2°N	149.9°W	61°N	258°E
3a	Alma Atta, USSR	43.2°N	76.9°E	33°N	150°E
4	Bagneux, France	48.8°N	2.3°E	52°N	84°E
4a	Baguio, P. I.	16.4°N	120.6°E	5°N	190°E
5	Baker Lake	64.3°N	96.0°W	74°N	315°E
6	Batavia, Ohio	39.1°N	84.1°W	51°N	341°E
7	Baton Rouge, Louisiana	30.5°N	91.2°W	41°N	335°E
8a	Bocayuva, Brazil	17.1°S	43.8°W	6°S	24°E
8	Bombay, India	19.0°N	73.0°E	10°N	144°E
9	Boston, Massachusetts	42.4°N	71.2°W	53°N	358°E
10	Brisbane, Australia	27.5°S	153.0°E	36°S	227°E
11	Buenos Aires, Argentina	34.5°S	58.5°W	23°S	13°E
11a	Bukta Tikhaya, USSR	80.3°N	52.8°E	71°N	153°E
11b	Cairo, Egypt	30.6°N	31.9°E	29°N	107°E
12	Calcutta, India	22.6°N	88.4°E	12°N	159°E
13	Campbell Is.	52.5°S	169.2°E	57°S	253°E
14	Canberra, Australia	35.3°S	149.0°E	44°S	224°E
15	Capetown, U. of S. A.	34.2°S	18.3°E	33°S	80°E
15a	Cape York, Australia	11.0°S	142.4 E	21°S	213°E
16	Casablanca, Morocco	33.6°N	7.6°W	39°N	69°E
16a	Chita, USSR	52.0°N	113.5°E	41°N	182°E
17	Christchurch, N. Z.	43.6°S	172.7°E	48°S	252°E
17a	Christmas Is.	1.9°N	157.3°W	2°N	271°E
18	Chungking, China	29.4°N	106.8°E	18°N	176°E
19	Churchill, Canada	58.8°N	94.2°W	69°N	322°E
20	Cocoa, Fl°rida	28.2°N	80.6°W	39 N	347°E
21	Clyde, Baffin Island	70.5°N	68.6°W	81°N	360°E
21a	Colombo, Ceylon	6.6°N	80.0°E	3°S	149°E

(Table II-D-1 Continued)

Station Number	Station	Geographic Lat.	Geographic Long.	Geomagnetic Lat.	Geomagnetic Long.
22	Dakar, French West Africa	14.6°N	17.4°W	22°N	55°E
23	DeBilt, Holland	52.1°N	5.2°E	54°N	89°E
24	Deception Is.	63.0°S	60.7°W	52°S	6°E
25	Delhi, India	28.6°N	77.1°E	19°N	149°E
26	Djibouti, Fr. Som.	11.5°N	43.1°E	7°N	114°E
27	Domont, Fr.	49.0°N	2.3°E	52°N	84°E
28	Fairbanks, Alaska	64.9°N	147.8°W	64°N	256°E
29	Falkland Is.	51.7°S	57.8°W	41°S	9°E
30	Fiji Island	18.0°S	178.2°E	22°S	251°E
31	Formosa	25.0°N	121.5°E	14°N	189°E
32	Fort Chimo, Can.	58.1°N	68.3°W	69°N	2°E
33	Fraserburgh, Scotland	57.6°N	2.1°W	60°N	86°E
34	Fribourg, Germany	48.1°N	7.8°E	50°N	90°E
35	Fukaura, Japan	40.6°N	139.9°E	31°N	205°E
36	Godhavn, Greenland	69.2°N	53.5°W	80°N	30°E
37	Graz, Austria	47.1°N	15.4°E	47°N	96°E
37a	Great Baddow, England	51.7°N	0.5°E	55°N	84°E
38	Guam Is.	13.6°N	144.9°E	4°N	213°E
39	Hobart, Tas.	42.8°S	147.4°E	52°S	224°E
40	Huancayo, Peru	12.0°S	75.3°W	1°S	354°E
41	Ibadan, Nig.	7.4°N	4.0°E	10°N	75°E
42	Inverness, Scotland	57.4°N	4.2°W	61°N	84°E
43	Johannesburg, U. of S. A.	26.2°S	28.1°E	27°S	91°E
43a	Kermadec Is.	29.3°S	177.9°W	32°S	258°E
44	Khartoum, Sudan	15.6°N	32.6°E	14°N	104°E
45	Kiruna, Sweden	67.8°N	20.5°E	64°N	116°E
45a	Kwajalein, Atoll	9.0°N	168.0°E	3°N	236°E
46	Lanchow, China	36.1°N	103.8°E	25°N	174°E
46a	Leningrad, USSR	60.0°N	30.3°E	56°N	117°E
47	Leyte, P. I.	11.0°N	125.0°E	0°	194°E
48	Lindau/Harz, Germany	51.6°N	10.1°E	53°N	94°E
48a	Loshan, China	29.5°N	103.7°E	19°N	174°E
49	MacQuarie Is.	54.5°S	159.0°E	60°S	243°E
50	Madras, India	13.0°N	80.2°E	3°N	150°E
50a	Manila, P. I.	14.6°N	120.0°E	4°N	190°E
51	Maui, Hawaii	20.8°N	156.5°W	21°N	268°E
51a	Moscow, USSR	55.5°N	37.3°E	51°N	121°E
52	Nairobi, Kenya	1.0°S	37.0°E	4°S	105°E
53	Nanking, China	32.1°N	119.0°E	21°N	187°E

(Table II-D-1 Continued)

Station Number	Station	Geographic Lat.	Geographic Long.	Geomagnetic Lat.	Geomagnetic Long.
54	Narsarssuak, Greenland	61.2°N	45.4°W	71°N	37°E
55	Okinawa Is.	26.3°N	127.8°E	15°N	196°E
56	Oslo, Norway	60.0°N	11.0°E	60°N	100°E
57	Ottawa, Can.	45.4°N	75.7°W	56°N	351°E
58	Palmyra Is.	5.9°N	162.2°W	6°N	266°E
59	Panama Canal	9.4°N	79.9°W	20°N	348°E
60	Peiping, China	39.9°N	116.4°E	29°N	184°E
60a	Peshawar, India	34.0°N	71.5°E	25°N	145°E
60b	Pitcairn Is.	25.0°S	130.0°W	19°S	303°E
61	Pt. Barrow, Alaska	71.3°N	156.8°W	68°N	241°E
62	Poitiers, France	46.6°N	0.3°E	50°N	82°E
63	Portage La Prairie, Canada	49.9°N	98.3°W	59°N	322°E
64	Prince Rupert, Canada	54.3°N	130.3°W	58°N	283°E
65	Port Lockroy	64.8°S	63.5°W	54°S	9°E
66	Puerto Rico, W. I.	18.5°N	67.2°W	29°N	2°E
67	Rarotonga Is.	21.3°S	159.8°W	21°S	274°E
68	Resolute Bay, Canada	74.7°N	94.9°W	83°N	287°E
69	Reykjavik, Iceland	64.1°N	21.8°W	70°N	71°E
70	Rome, Italy	41.9°N	12.5°E	42°N	92°E
71	St. Johns, Newfoundland	47.6°N	52.7°W	59°N	21°E
72	San Francisco, California	37.4°N	122.2°W	44°N	298°E
73	San Juan, Puerto Rico	18.4°N	66.0°W	29°N	3°E
74	Schwarzenburg, Swit.	46.8°N	7.3°E	48°N	88°E
75	Shibata, Japan	38.0°N	139.3°E	28°N	205°E
76	Singapore	1.3°N	103.8°E	10°S	173°E
77	Slough, England	51.5°N	0.6°W	55°N	83°E
77a	Sverdlosk, USSR	56.7°N	61.1°E	49°N	141°E
77b	Swan River, Manitoba	52.1°N	101.2°W	61°N	318°E
78	Tananarive, Madagascar	18.8°S	47.8°E	24°S	112°E
79	Terre Adelie	66.8°S	141.4°E	75°S	232°E
79a	The Pas, Manitoba	54.0°N	101.0°W	63°N	317°E
80	Tiruchy, India	10.8°N	78.8°E	1°N	149°E
81	Tokyo, Japan	35.7°N	139.5°E	26°N	206°E
81a	Tomsk, USSR	56.5°N	84.9°E	45°N	160°E
82	Townsville, Australia	19.4°S	146.5°E	28°S	218°E
83	Trinidad, B. W. I.	10.6°N	61.2°W	22°N	9°E
84	Tromso, Norway	69.7°N	19.0°E	67°N	117°E

(Table II-D-1 Continued)

Station Number	Station	Geographic Lat.	Geographic Long.	Geomagnetic Lat.	Geomagnetic Long.
85	Upsala, Sweden	59.8°N	17.6°E	58°N	106°E
85a	Byrd Expedition, U. S. S. Canistea	66 °S	105 °W	56°S	335°E
85b	Victoria Beach, Canada	50.8°N	96.5°W	61°N	324°E
86	Wakkanai, Japan	45.4°N	141.7°E	35°N	207°E
87	Washington, D. C.	38.7°N	77.1°W	50°N	351°E
88	Watheroo, Aust.	30.3°S	115.9°E	41°S	185°E
89	White Sands, N. M.	32.3°N	106.5°W	41°N	318°E
90	Winnipeg, Canada	49.9°N	97.4°W	60°N	323°E
91	Wuchang, China	30.6°N	114.4°E	20°N	183°E
92	Yamagawa, Japan	31.2°N	130.6°E	20°N	198°E

E. Year-to-Year Variation

Many workers have investigated the problem of the dependence of sporadic E on the sunspot cycle, but at this writing the question must be considered largely unresolved. From a theoretical point of view it would be surprising if all the manifestations of Es were independent of the sunspot cycle. There are several reasons for this. One is that such E-region structures as might produce Es such as gradients, thin layers, blobs produced through turbulence all rely in some degree on the ambient ionization of the E region and this appears to vary by approximately $\sqrt{2}$ between high and low sunspot numbers. Also, later in this chapter it will be shown that Es occurrence in the different zones shows various degrees of dependence on magnetic activity which in turn is correlated (particularly if an appropriate phase angle is introduced) with the sunspot cycle (Chapman and Bartels, Geomagnetism p. 368 [1940]). Mrs. Phillips [1947] examining the occurrence of fEs > 3 Mc found a negative sunspot cycle correlation at Washington, D. C. for the period 1935 to 1946 and suggested an explanation in terms of the mean heliographic latitude of the sunspots. McNicol and Gipps [1951] examined Es at Brisbane, Australia for the period 1943 to 1949 and could find no evidence of correlation with sunspot cycle. Smith [1951] considering the occurrence of fEs > 7 Mc noted that the total sporadic E recorded at five U. S.

stations increased steadily during the three year period 1948-1950 indicative of a negative correlation. Peterson [1954] examining Es on a world-wide basis (apparently just for fEs > 3 Mc) found twice as much sporadic E for periods of low sunspot number.

A comparison of the year-to-year variations at six stations for the three limiting frequency levels (fEs > 3 Mc, 5 Mc, 7 Mc) is shown in figure II-E-1. The year-to-year variation is seen to become more extreme as one progresses to higher limiting frequencies. Also, it is interesting to note that for White Sands the annual values of fEs exceeding the 3 and 5 Mc level would indicate a positive correlation with sunspot cycle, whereas the 7 Mc level would be commensurate with a negative one.

The year-to-year variations in occurrence of fEs > 5 Mc for the forty-one stations considered in this study are shown in figure II-E-2. The same technique has been employed in normalizing the values to those for 1951 as has been described above in connection with the plots in figure II-D-10. It is seen that the yearly median values for each group of curves are surprisingly close to unity. The only variation of the medians from unity which might possibly be considered significant in view of the wide scatter of the individual station variations is the rise from 1948 to 1949. As the mean annual Zurich sunspot numbers for these two years are 136.2 and 134.7 respectively, a difference of 1.1%, the variation can hardly be attributed to a sunspot-cycle dependence.

It is possible to take either of two positions regarding the wide year-to-year variation exhibited by an individual station. The

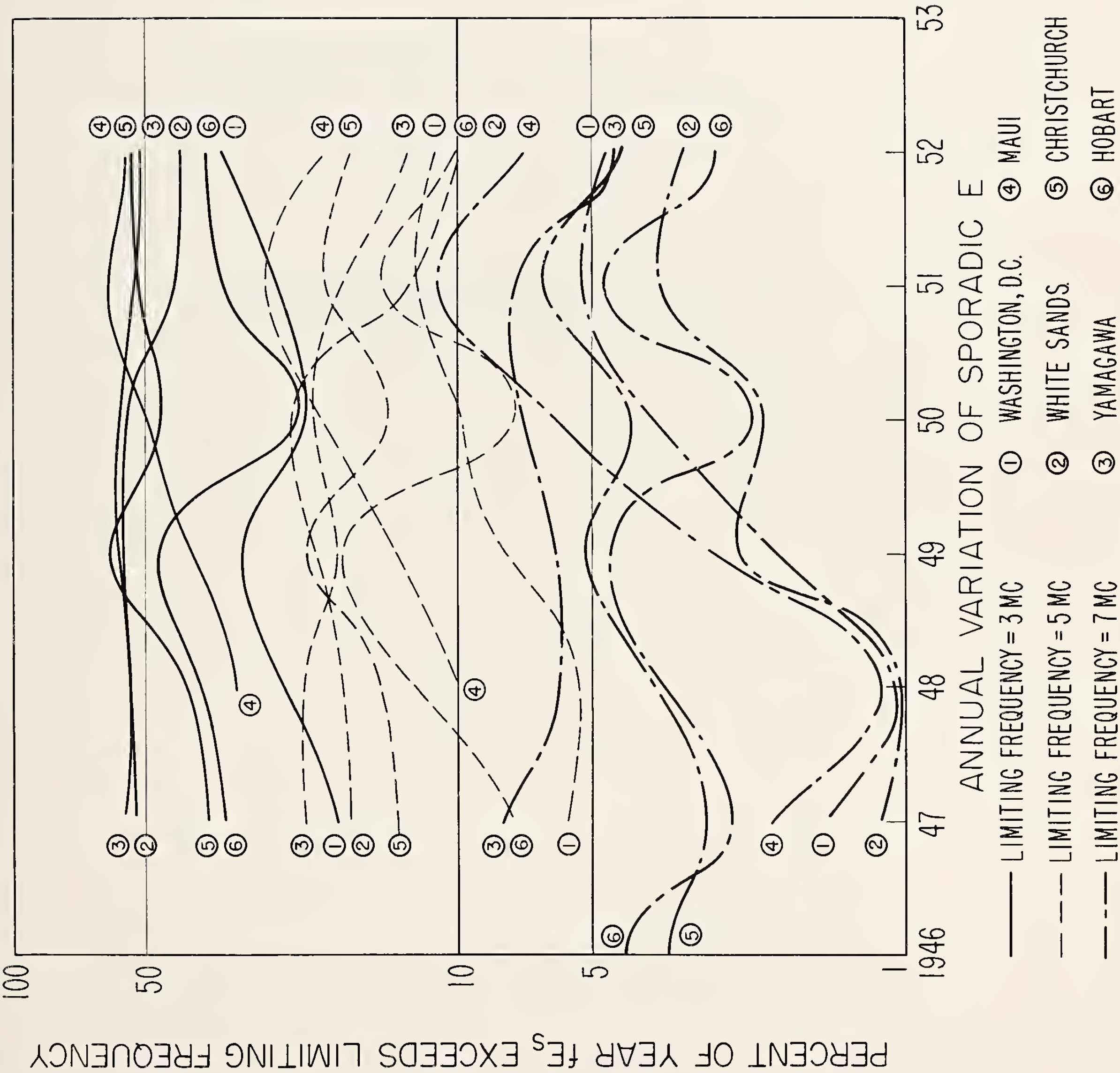

ANNUAL VARIATION OF SPORADIC E
PERCENT OF YEAR f_{E_s} EXCEEDS LIMITING FREQUENCY
100
50
10
5
1
1946
47
48
49
50
51
52
53
LIMITING FREQUENCY = 3 MC
LIMITING FREQUENCY = 5 MC
LIMITING FREQUENCY = 7 MC
① WASHINGTON, D.C.
② WHITE SANDS
③ YAMAGAWA
④ MAUI
⑤ CHRISTCHURCH
⑥ HOBART

Figure II-E-1

ANNUAL VARIATION BY ZONES OF fEs > 5 MC
RELATIVE TO THE 1951 OCCURRENCE FOR EACH STATION

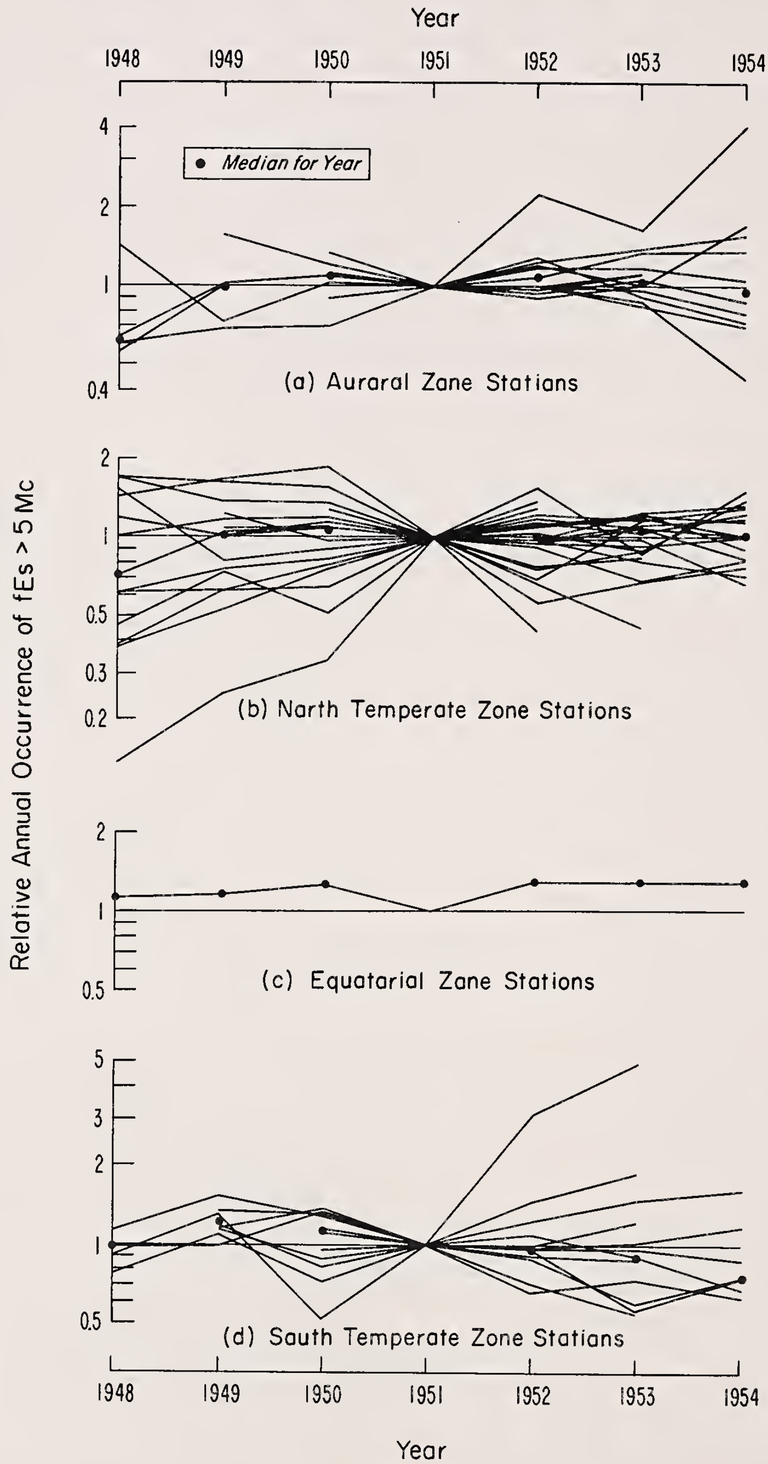


Figure II-E-2

first is to suppose that the variation is due to malfunctioning of the ionosonde. If this is the case, then the highest recorded yearly values should be used. The second position is to attribute the variation to the sporadicity of the phenomenon coupled with equipment variations. In this case it is more logical to use the means of the observed annual values (if no cyclic dependence can be established). This latter position is the one taken here. The mean is then to be interpreted as the expectation of occurrence of fEs >5 Mc for any given year under conditions of average performance from an ionosonde in average condition.

409475 O - 57 - 8

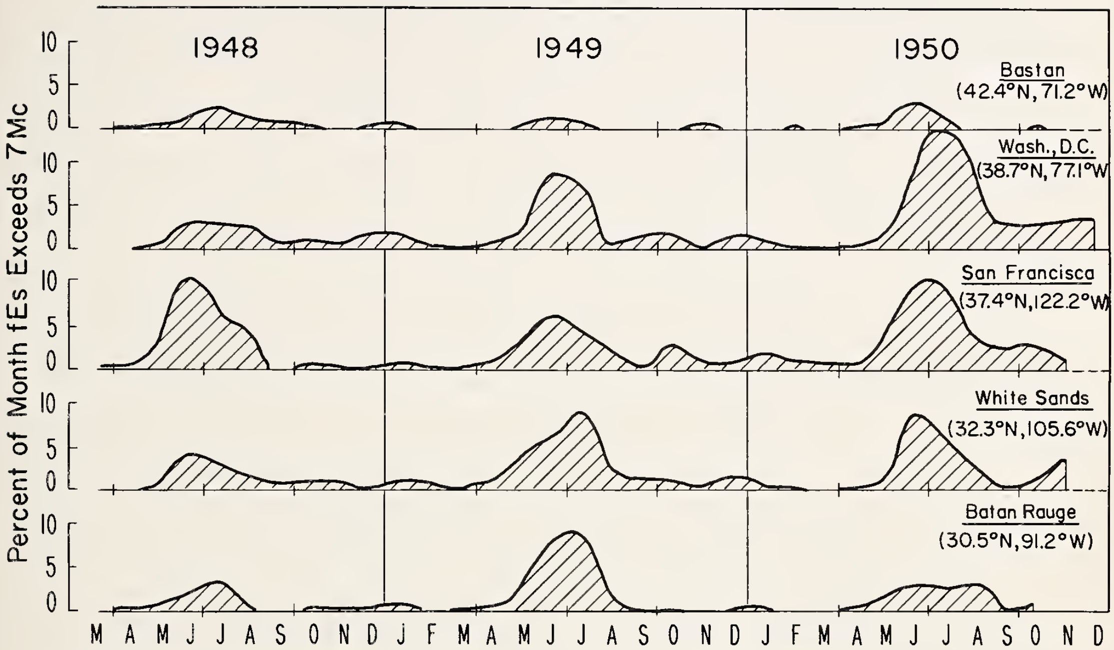
F. Presentations of Temporal and Geographic Variations in Occurrence of fEs > 5 Mc

One indication of the truly sporadic nature of Es in space as well as time is the improvement obtained in the distinctness of its time variations when the data sample is increased. An example of this improvement is found in Smith [1951] reproduced in figure II-F-1, where it is seen that the seasonal curve of all recorded cases of fEs > 7 Mc for five U. S. stations is smoother and more systematic than that for any individual station. A similar technique is employed in this study and is applied to time as well as space averaging. It was seen in the last section that the ionosonde data taken as a whole exhibits little indication of any systematic variation in the year-to-year occurrence of fEs > 5 Mc for the period 1948-1954. True, there was evidence presented of a shifting boundary between the Auroral and Temperate Zones and this fact will be hidden in the analysis to follow, but by and large little will be lost through averaging the seven years of data under consideration. The order will be to first display the geographical variations of Es through the occurrence of fEs > 5 Mc for forty-one Temperate-Zone and fifteen Auroral-Zone stations for various time blocks; then to consider the time variations at seventeen strategically located stations through time maps of the type employed earlier in this chapter.

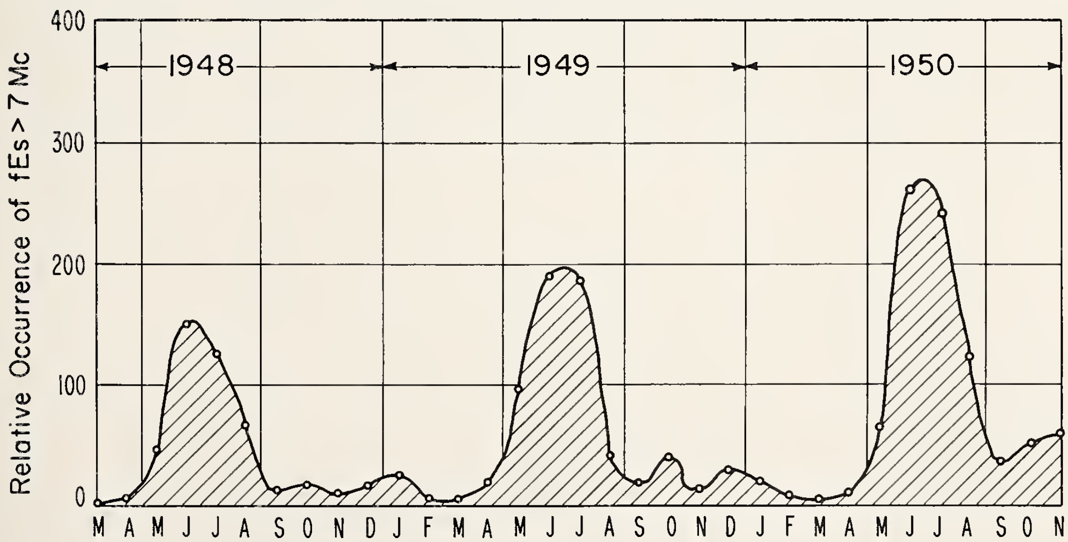
1. Geographic Variations

The displays of Es incidence for the Auroral Zone and for the Temperate Zone are kept separate in the presentations of this

IMPROVED CLARITY OF TRENDS OBTAINED BY INCREASED DATA SAMPLE ILLUSTRATED THROUGH FIVE U.S. STATIONS, fEs > 7Mc



(a) Seasonal Variation in Sporadic E For Five U.S. Stations



(b) Seasonal Variation in Sporadic E in the U.S.
(Composite of the five stations in (a) above).

Figure II-F-1

section. There are several reasons for this. In the first place, the behavior of Es in the two zones is quite different and secondly, there is considerable disparity in the reliability of the final curves for the two zones. Also the Auroral-Zone data are somewhat better presented on polar maps. The six time blocks for which data are given on geographical displays are, however, the same. These time blocks are as follows:

#1 June Solstice, Daytime = May, June, July and August 0600-1800 L. T.

#2 June Solstice, Nighttime = May, June, July and August 1800-0600 L. T.

#3 December Solstice, Daytime = November, December, January and February, 0600-1800 L. T.

#4 December Solstice, Nighttime = November, December, January and February, 1800-0600 L. T.

#5 Equinox, Daytime = March, April, September and October, 0600-1800 L. T.

#6 Equinox, Nighttime = March, April, September and October, 1800-0600 L. T.

The number of years involved for any particular station are those shown in figure II-D-8. The 5 Mc limiting frequency is used throughout.

a. Temperate Zone. One of the most interesting aspects of the Temperate-Zone analysis has been the uncovering of a marked longitude variation in this zone. This effect is not so apparent when yearly means of the data are considered so it is not too surprising that the effect has not been noted before. The Temperate-Zone presentations consist of two series of data displays. The first series is made up of seven figures each containing the mean values and mean deviations of the seven yearly values of the occurrence of fEs > 5 Mc as a function of both geomagnetic and geographic latitude for a particular time period. The first figure gives the mean yearly Es incidence, the other six are for the six time blocks. An indication is given on these charts of the longitude zone (E, I or W) to which the station belongs for the Temperate Zone stations. The main purpose of this first series is to make available the mean deviations of the data for use in connection with the second series of figures. This second series consist of seven maps which give the geographical variations of Es for the same time periods as before.

The latitude variation of the mean annual occurrence of fEs > 5 Mc is seen in figure II-F-2. There is some indication that E-zone sporadic E is more frequent than W, but the effect is not marked. However, for time block #1 (June Solstice, Daytime), seen in figure II-F-3, the greater Es incidence in the E zone cannot be denied. Examination of the distributions for time block #2 through #6 in figure II-F-4 through II-F-8, respectively shows that the same E-zone dominance occurs in time block #2 (June Solstice, Nighttime), but the situation is reversed for time blocks #3 and #4 (December Solstice, Day and Night, respectively) and non-existent for time blocks #5 and #6 (Equinox, Day and Night). Four of the stations in the E zone belong to the Japanese chain and it might be argued that this longitude effect is due to different equipment and perhaps scaling procedures. However, many stations outside Japanese jurisdiction such as Formosa, Okinawa, Guam and

MEAN YEARLY Es OCCURRENCE VS LATITUDE
TEMPERATE ZONE
fEs > 5 MC 1948 - 1954

Ranges Shown Are Mean Deviations

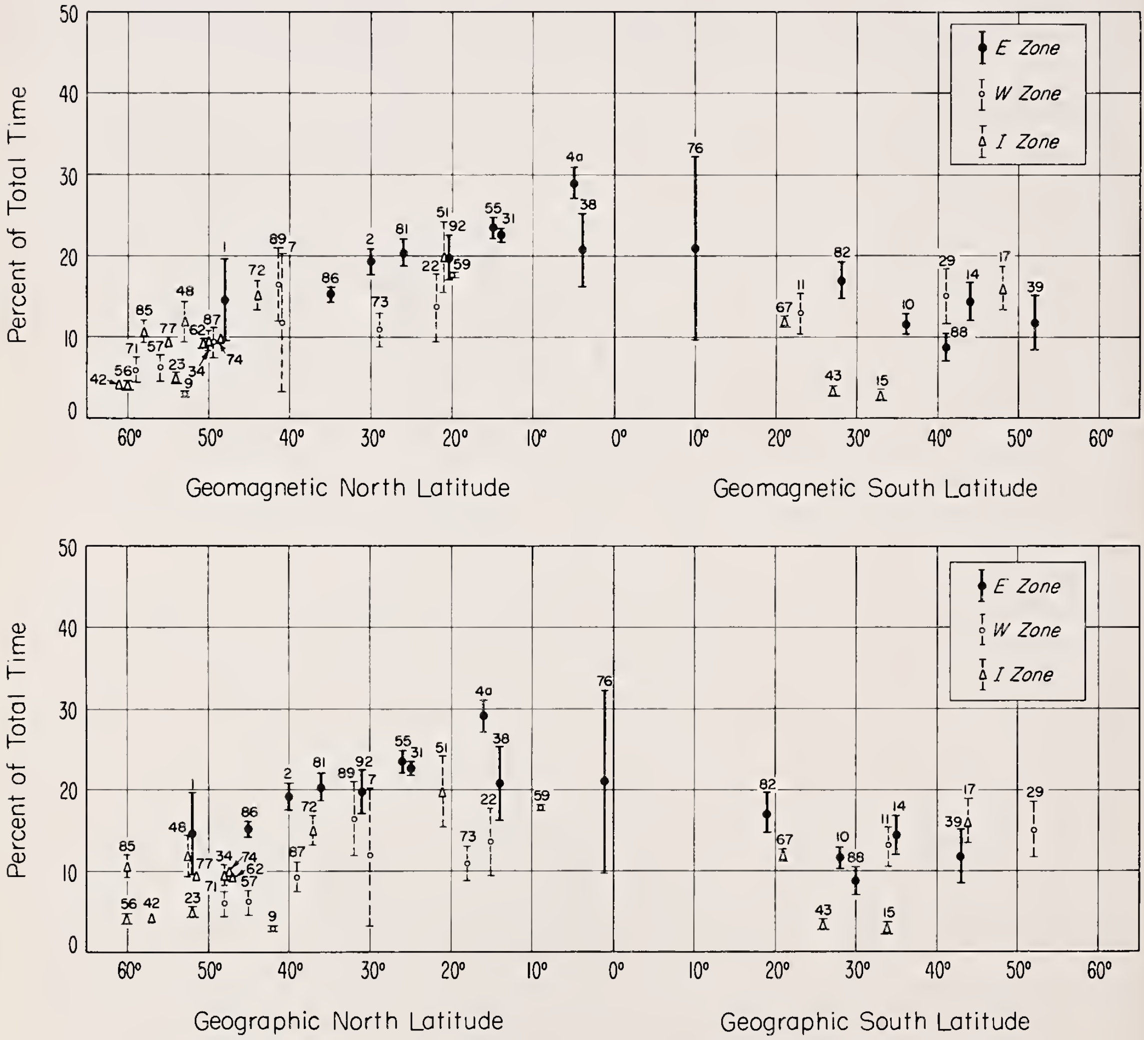


Figure II-F-2

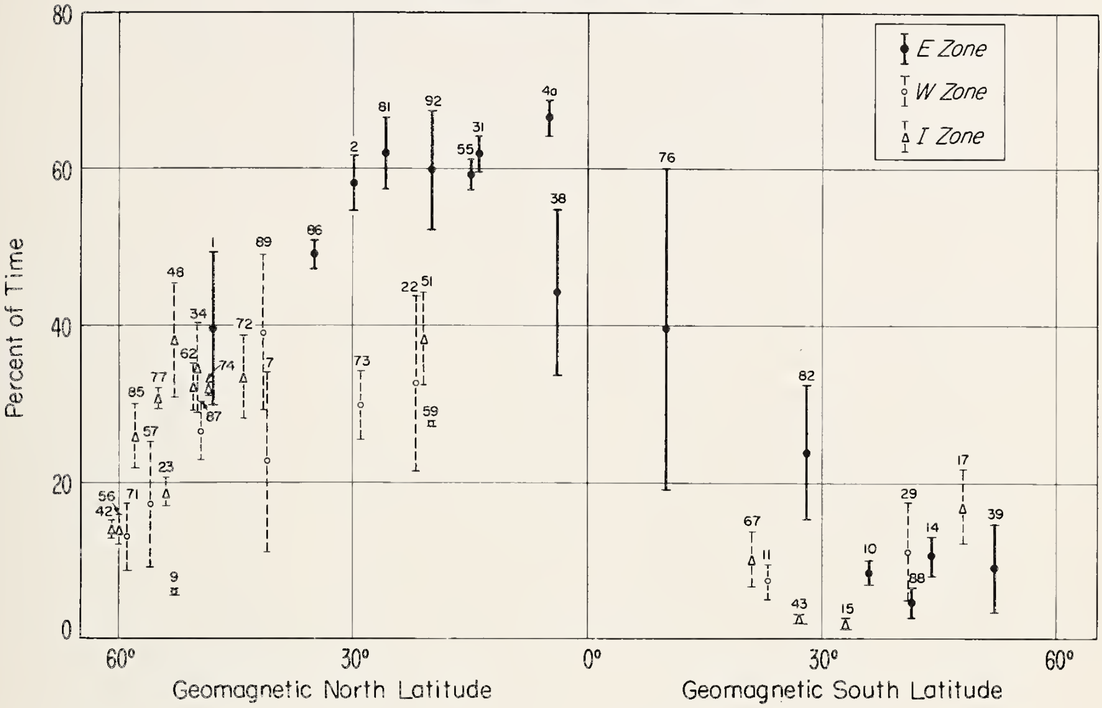
N° I, JUNE SOLSTICE, DAYTIME

Es OCCURRENCE VS LATITUDE – TEMPERATE ZONE

May, June, July and August; 0600 – 1800 Local Time

fEs > 5 Mc 1948 - 1954

Ranges Are Mean Deviations



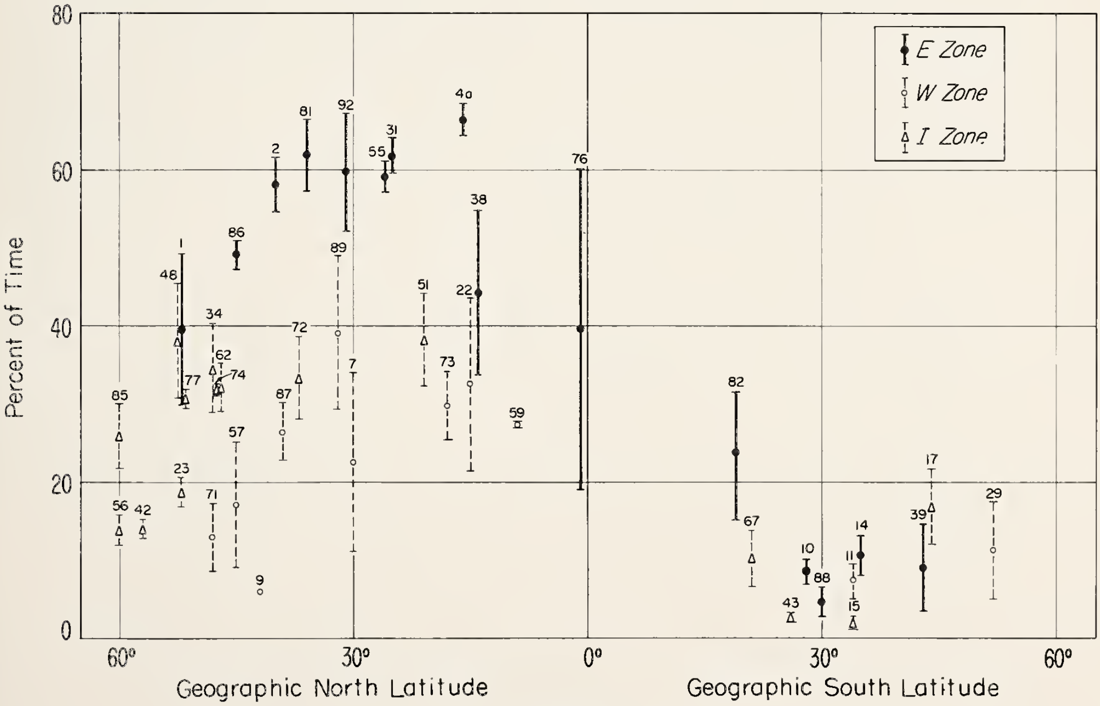


Figure II-F-3

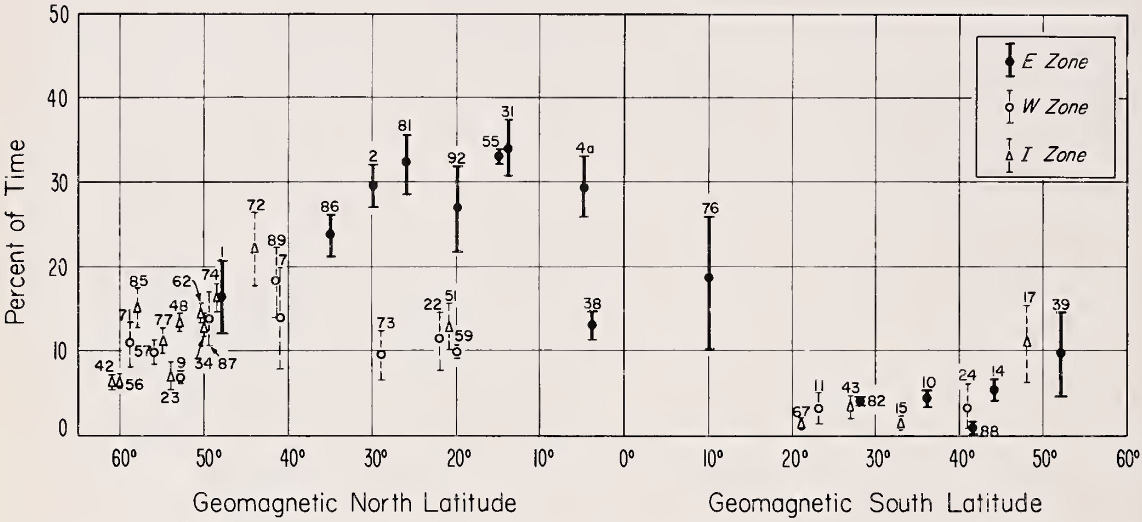
N° 2, JUNE SOLSTICE, NIGHTTIME

Es OCCURRENCE VS LATITUDE – TEMPERATE ZONE

May, June, July and August; 0600–1800 Local Time

fEs > 5 Mc, 1948–1954

Ranges Are Mean Deviations



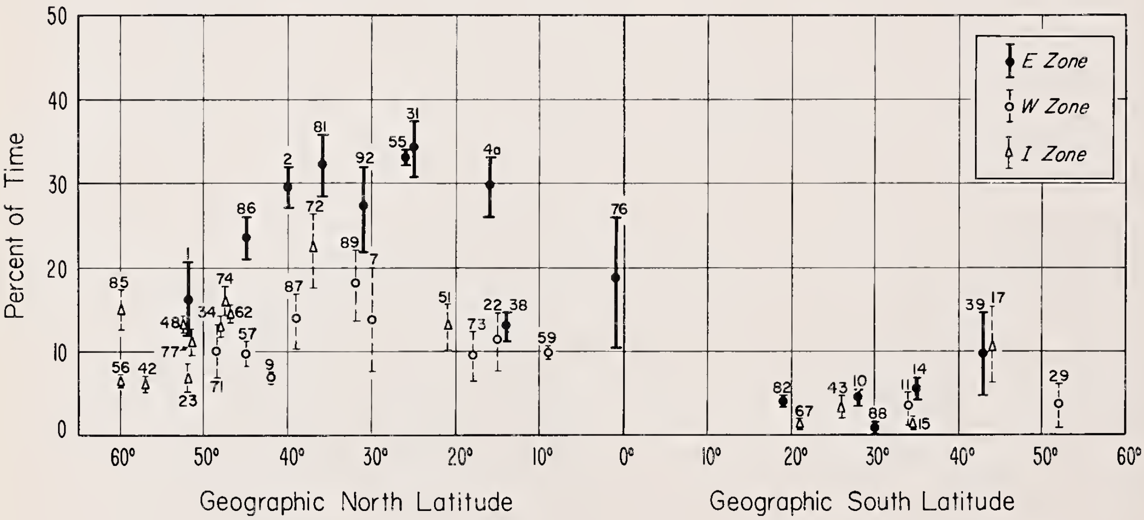


Figure II-F-4

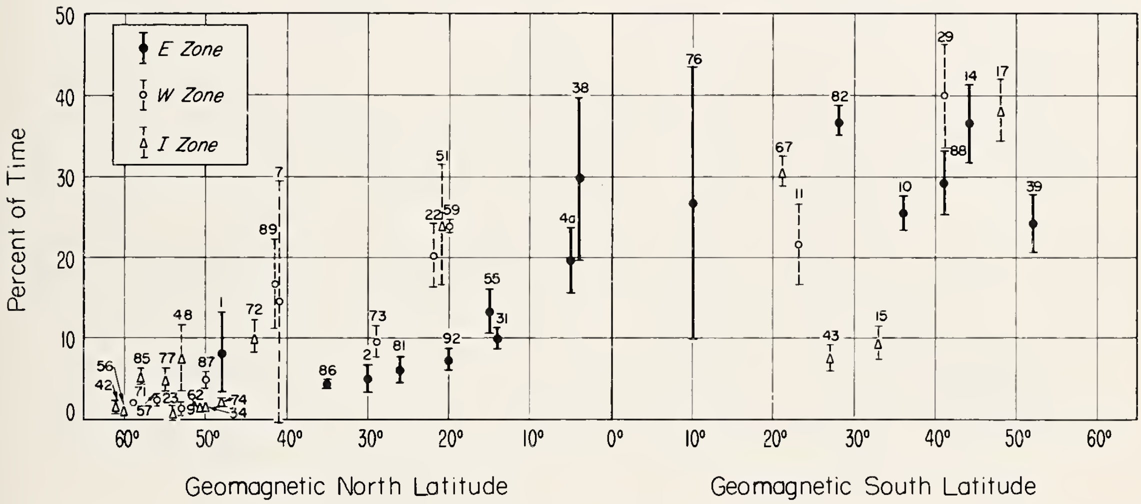
Nº 3, DECEMBER SOLSTICE, DAYTIME

Es OCCURRENCE VS LATITUDE - TEMPERATE ZONE

November, December, January and February; 0600 - 1800 Local Time

fEs > 5 Mc 1948 - 1954

Ranges Are Mean Deviations



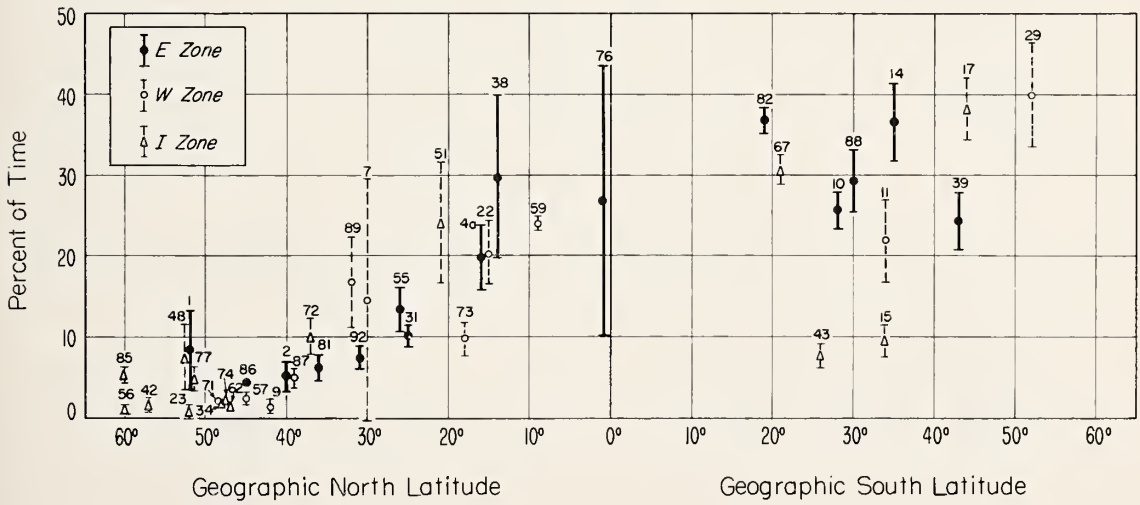


Figure II-F-5

Nº 4 DECEMBER SOLSTICE, NIGHTTIME

Es OCCURENCE VS LATITUDE - TEMPERATE ZONE

November, December, January and February; 1800 - 0600 Local Time

fEs > 5 Mc, 1948 - 1954

Ranges are Mean Deviations

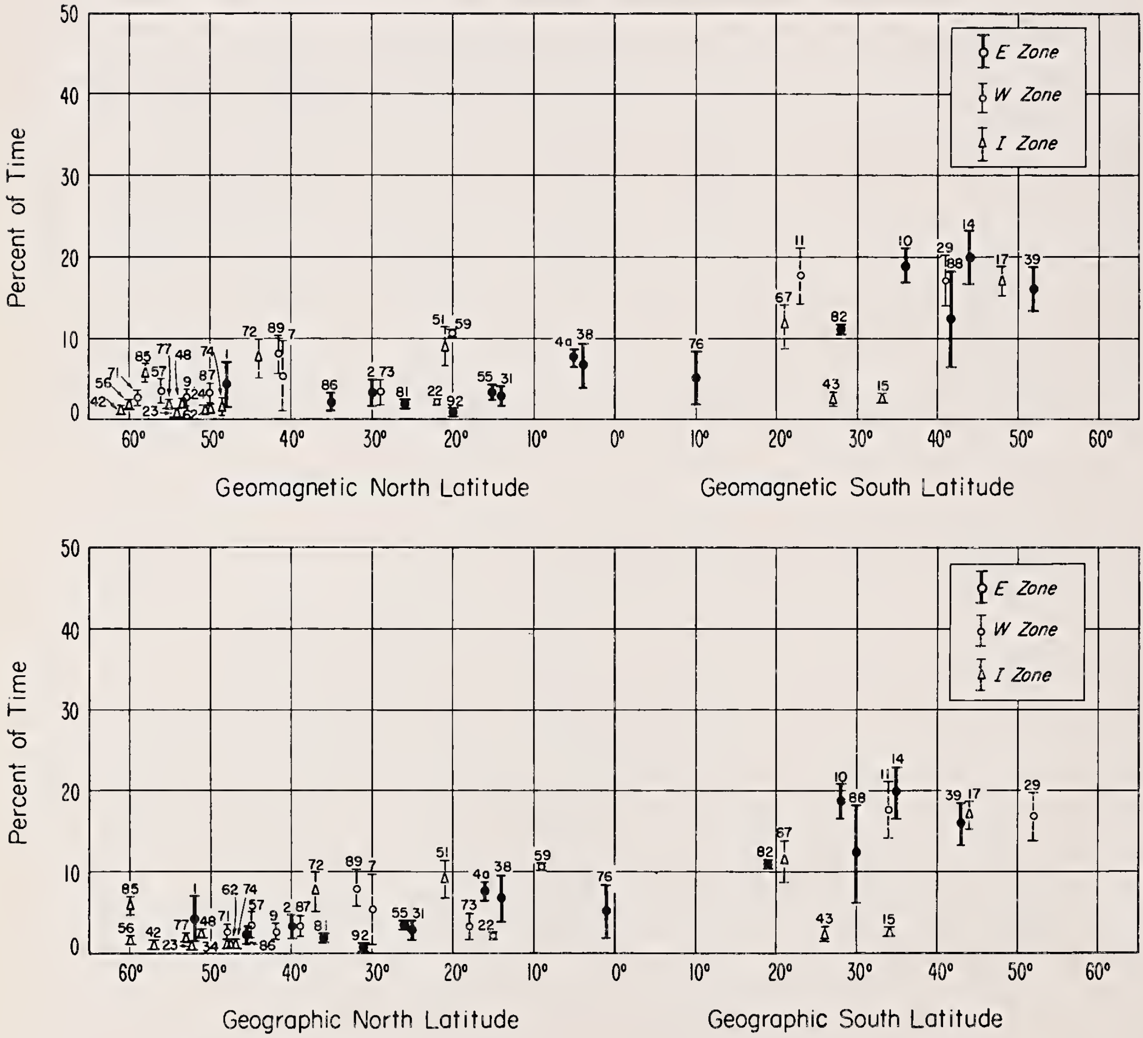


Figure II-F-6

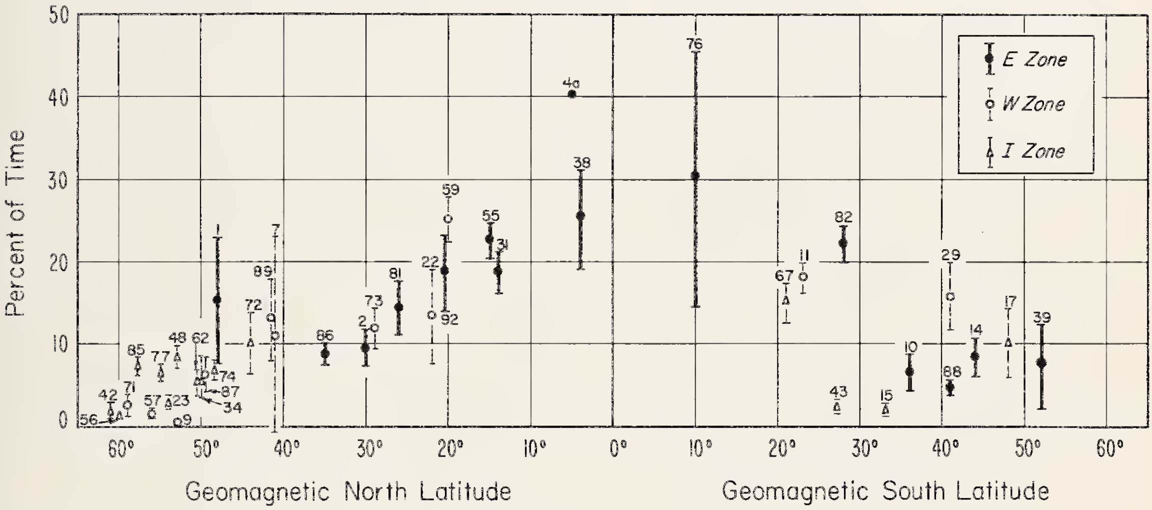
N° 5, EQUINOX, DAYTIME

Es OCCURRENCE VS LATITUDE – TEMPERATE ZONE

March, April, September and October; 0600–1800 Local Time

fEs > 5 Mc, 1948–1954

Ranges Are Mean Deviations



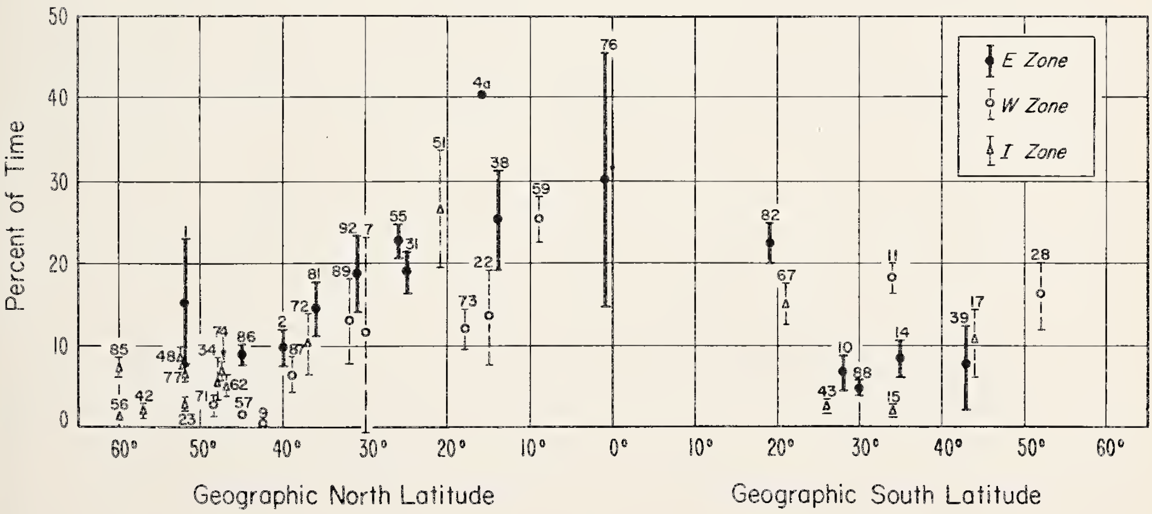


Figure II–F–7

N° 6 EQUINOX, NIGHTTIME

Es OCCURENCE VS LATITUDE – TEMPERATE ZONE

March, April, September and October; 1800–0600 Local Time

fEs > 5 Mc, 1948 – 1954

Ranges are Mean Deviations

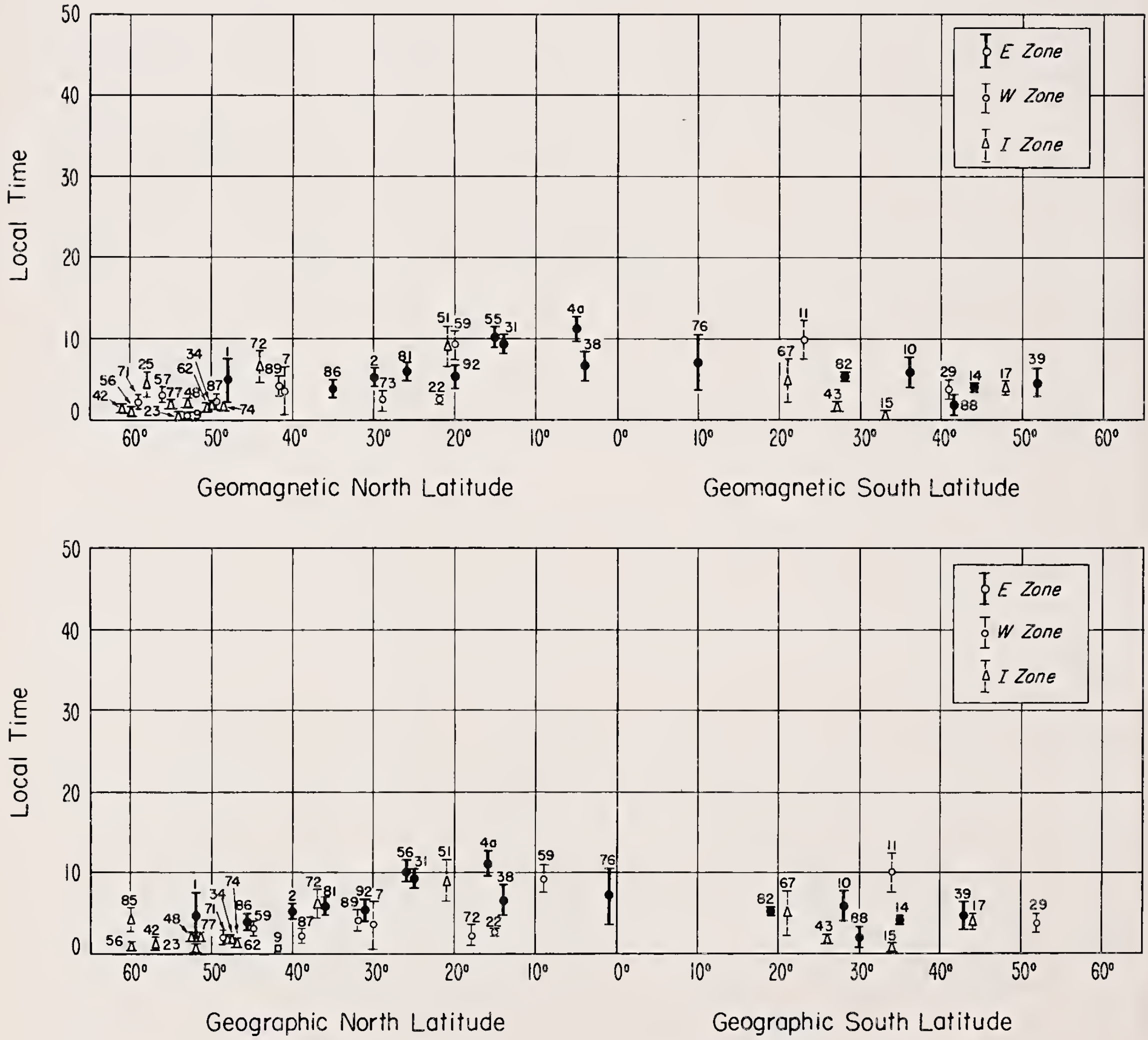


Figure II-F-8

Baguio exhibit Es occurrences which blend smoothly into those of the Japanese group. As most of these latter stations are U. S. owned and operated, this argument is very difficult to support.

The second series of Es occurrence displays is seen in figures II-F-9 through II-F-15. These figures each contain a world map showing the geographical variation of the recorded incidence of fEs $>$ 5 Mc; first, for all year and, then, for the time blocks. The order is by ascending time-block numbers as before.

The area covered by the North and South Temperate Zones has been blocked off at the 15 percent isochasm. The position of this isochasm for the North Auroral Zone is taken from Vestine [1944], that for the Southern Auroral Zone from Vestine and Snyder [1945].

The Equatorial Zone which is shown blocked off on the Daytime maps (figures II-F-9, II-F-10, II-F-12, II-F-14) is defined to be bounded by the lines of magnetic dip equal to plus and minus 10° as suggested by the work of Egedal [1947] and Matsushita [1951]. The geographic positions of these lines are taken from Vestine et al. [1947].

Generally speaking the Temperate-Zone occurrence of fEs $>$ 5 Mc is complementary in the northern and southern hemispheres with respect to seasons. That is, where the seasonal maximum in the northern hemisphere falls in the month of June or July, that for the southern hemisphere occurs during December or January. This complementary behavior will be more appropriately illustrated through time maps later in this section. Figures

MAP SHOWING PERCENT OF YEAR fEs EXCEEDS 5MC IN THE TEMPERATE ZONE

Auroral Zone = Region of > 15% Auroras
Equatorial Zone = Region of Magnetic Dip Between ± 10°

Data Years: 1948 – 1954

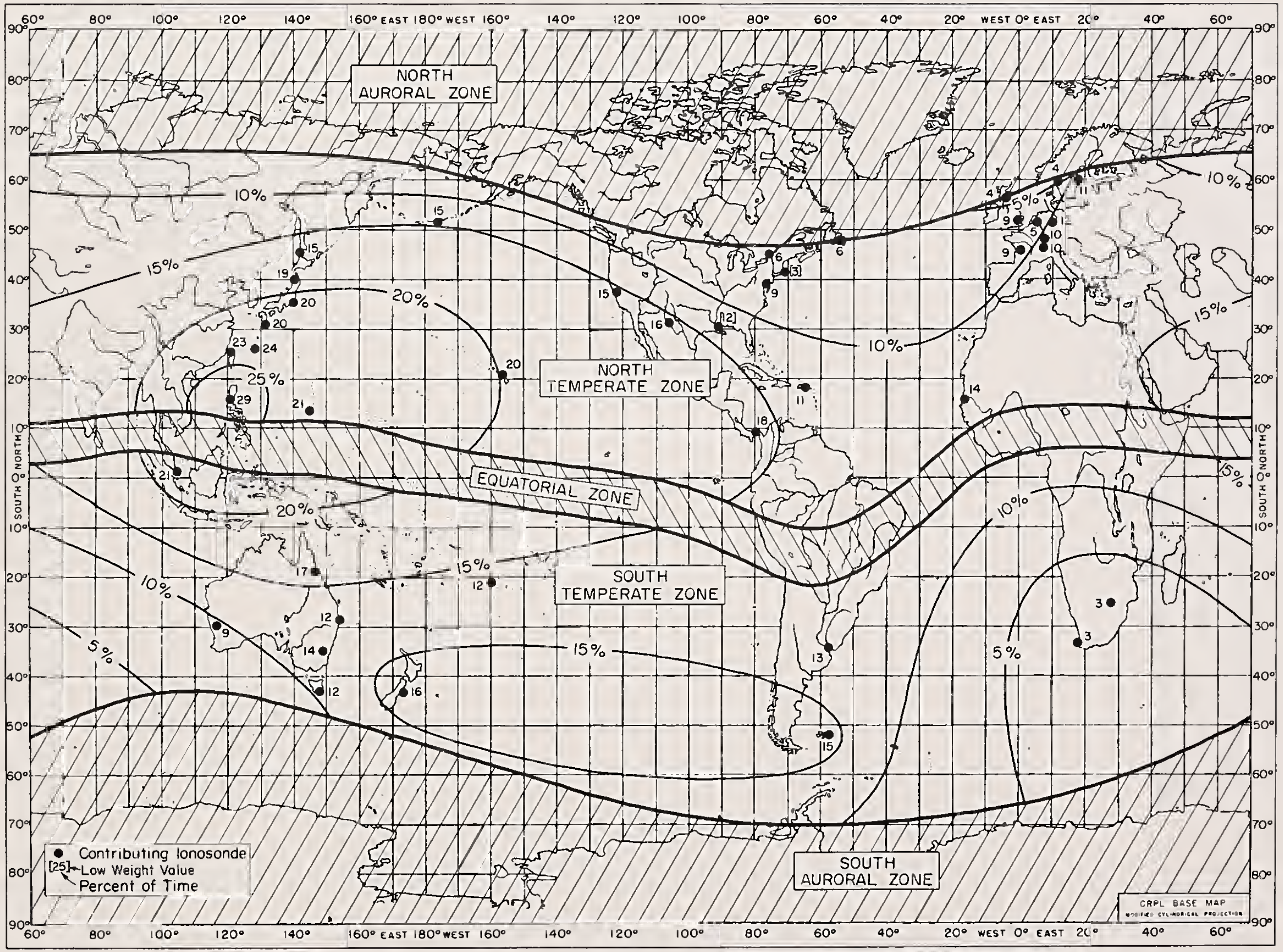


Figure II-F-9

Nº I JUNE SOLSTICE, DAYTIME

MAP OF TEMPERATE ZONE Es OCCURRENCE

May, June, July and August; 0600 - 1800 Local Time

fEs > 5 Mc, 1948 - 1954

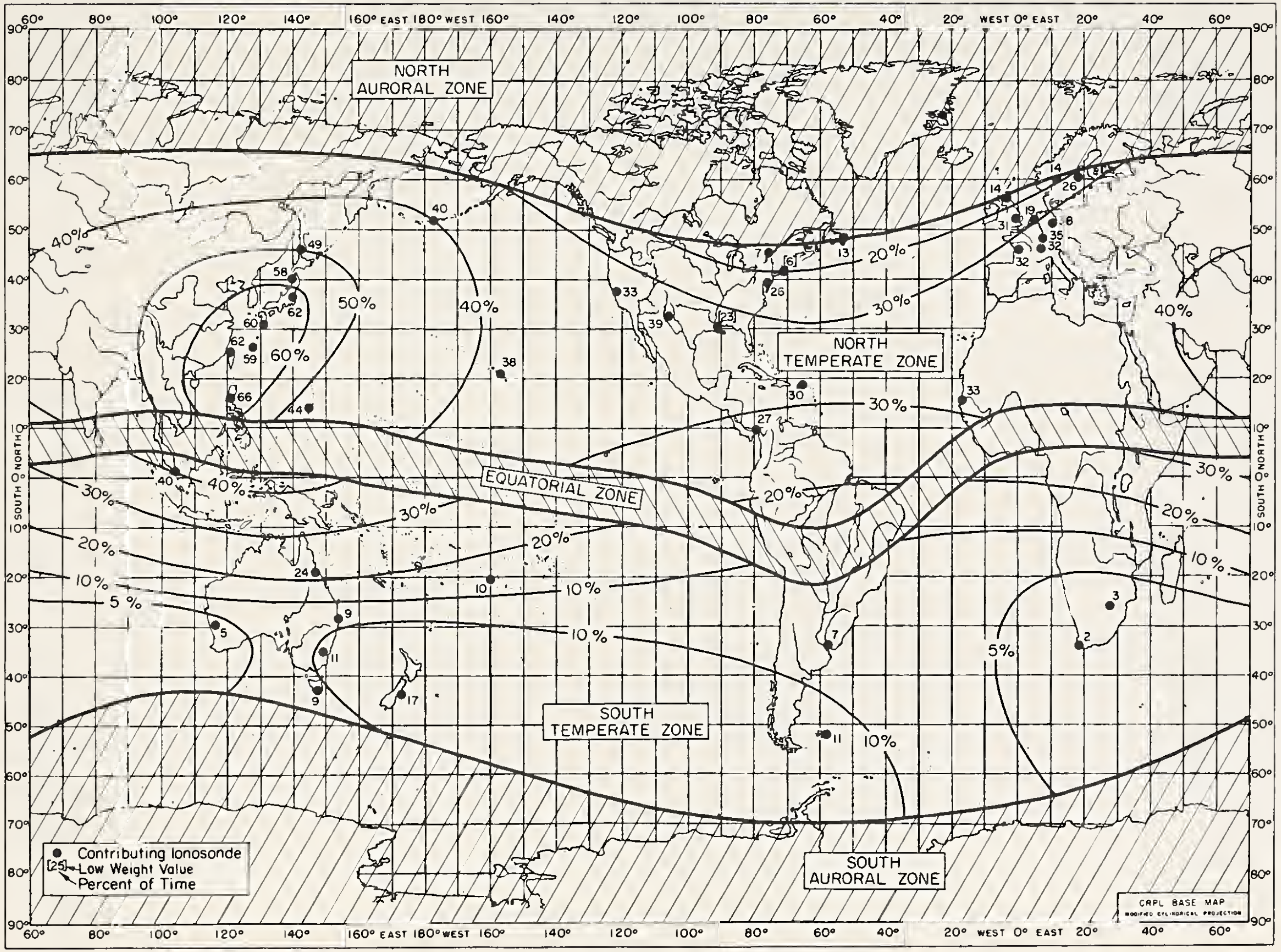


Figure II-F-10

Nº 2, JUNE SOLSTICE, NIGHTTIME
MAP OF TEMPERATE ZONE Es OCCURRENCE
May, June, July and August; 1800–0600 Local Time
fEs > 5 Mc, 1948 - 1954

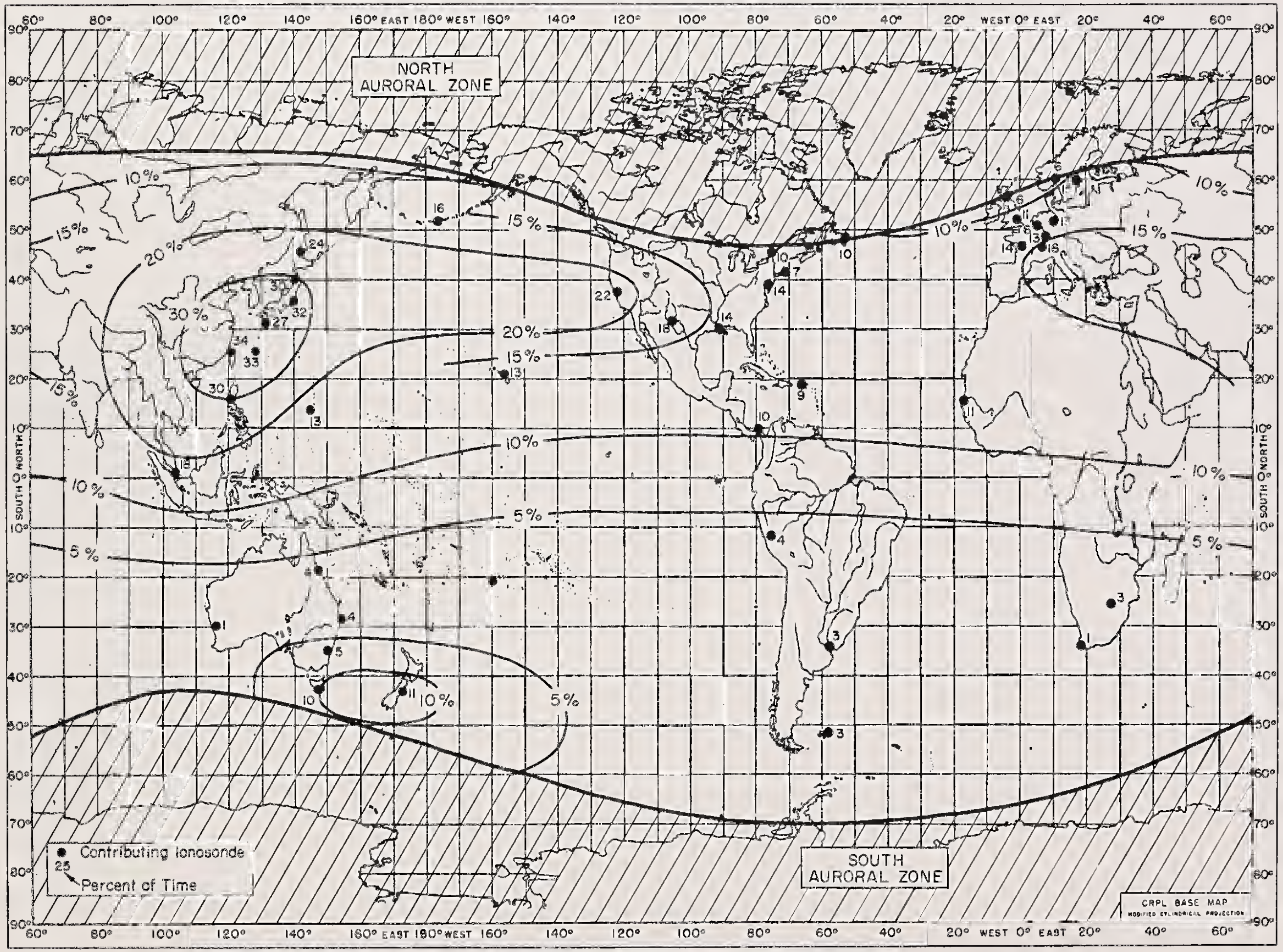


Figure II-F-11

Nº 3, DECEMBER SOLSTICE, DAYTIME

MAP OF TEMPERATE ZONE Es OCCURRENCE

November, December, January and February; 0600 – 1800 Local Time

fEs > 5 Mc, 1948 – 1954

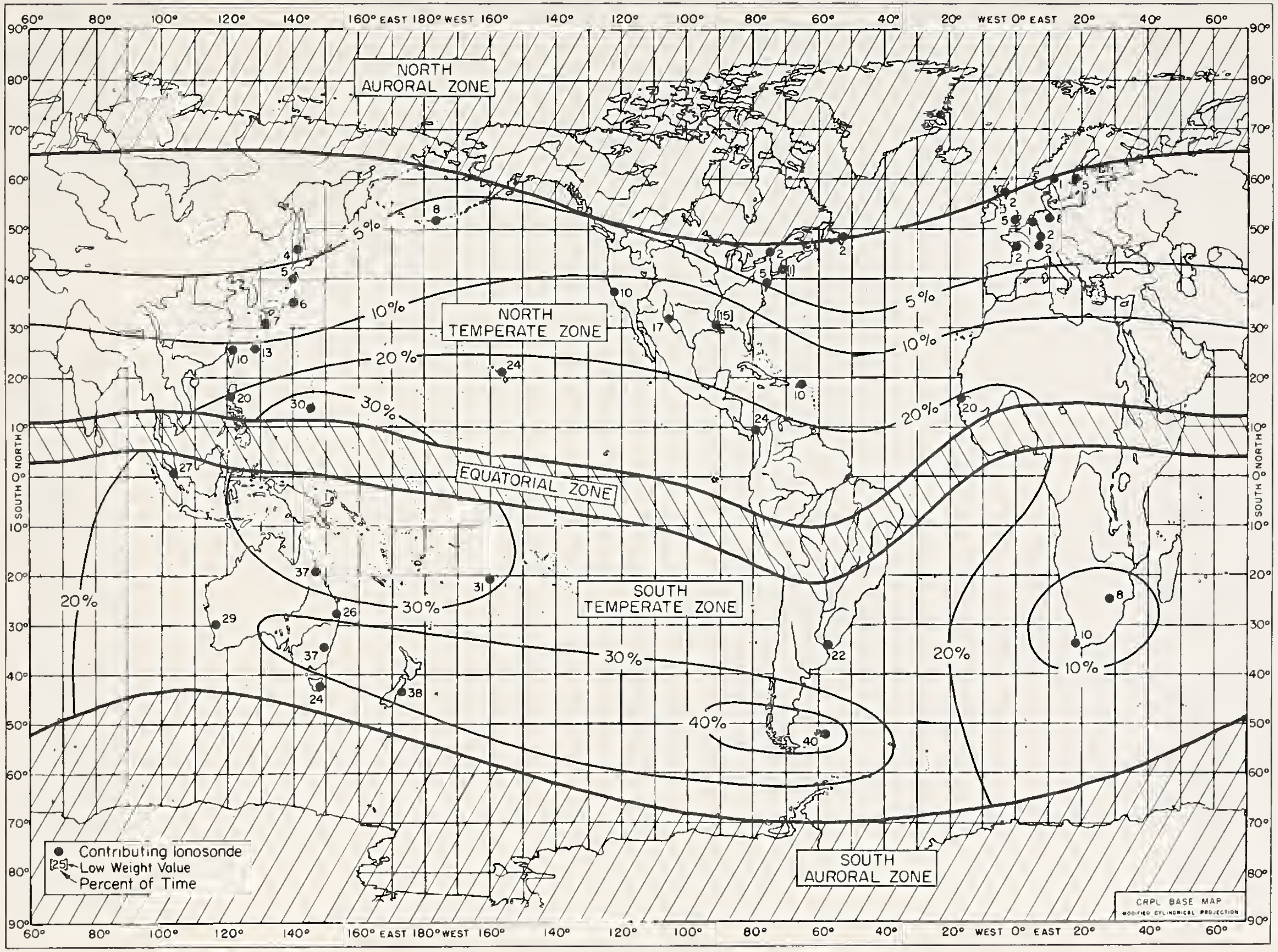


Figure II-F-12

Nº 4, DECEMBER SOLSTICE, NIGHTTIME

MAP OF TEMPERATE ZONE Es OCCURRENCE

November, December, January and February; 1800 - 0600 Local Time

fEs > 5 Mc, 1948 - 1954

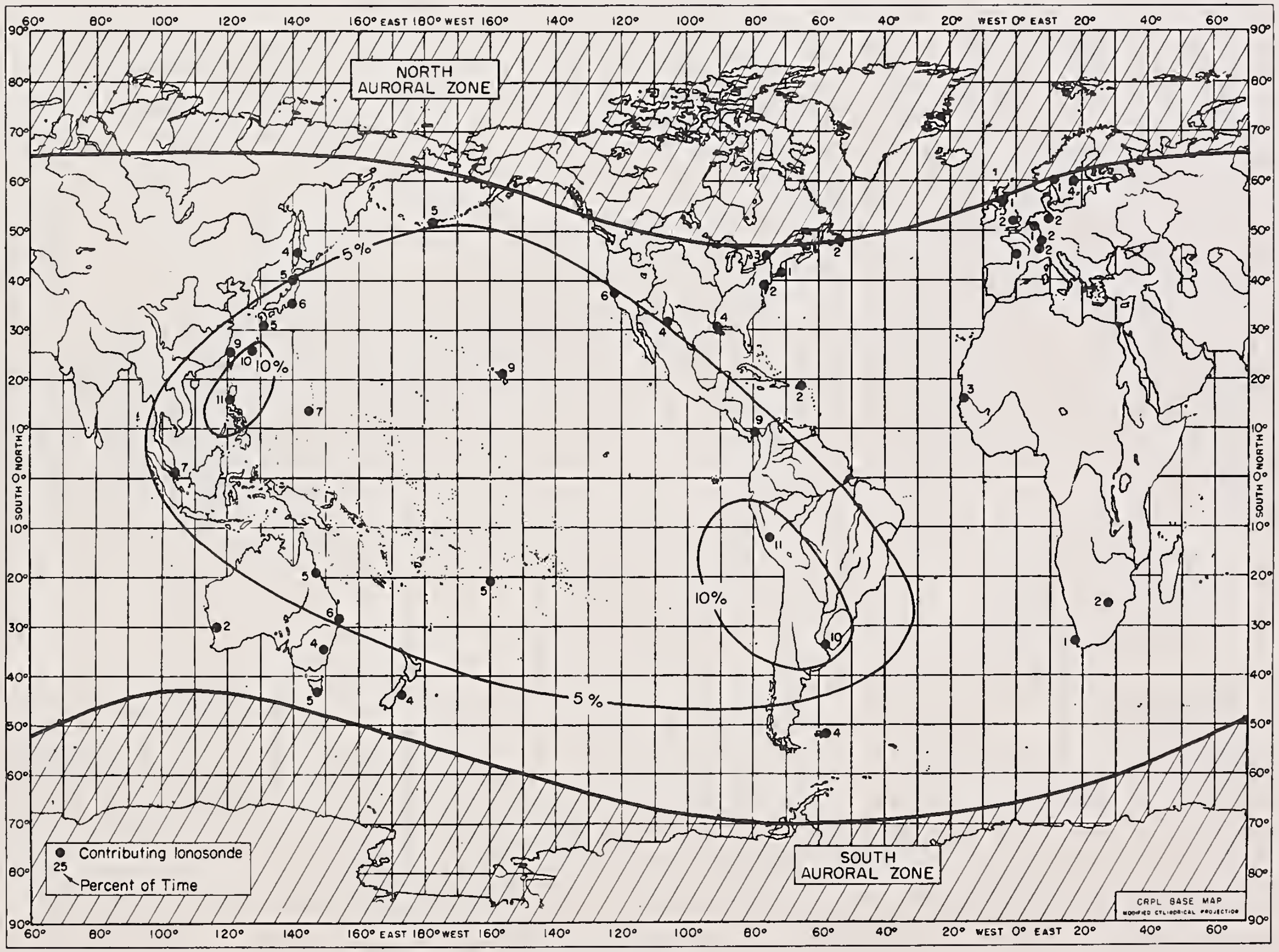


Figure II-F-13

Nº 5, EQUINOX, DAYTIME

MAP OF TEMPERATE ZONE Es OCCURRENCE

March, April, September and October; 0600 - 1800 Local Time

f Es > 5 Mc, 1948 - 1954

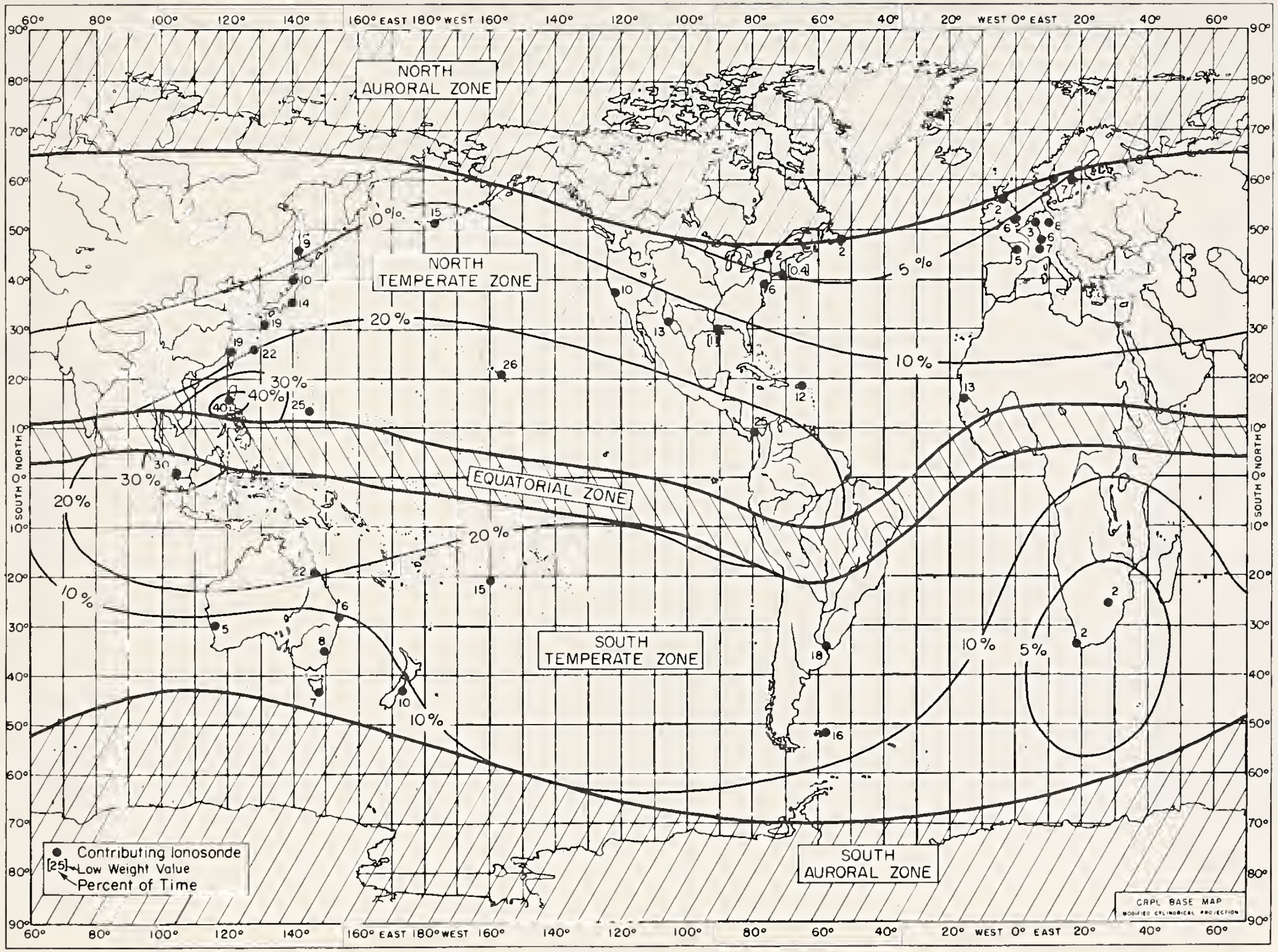


Figure II-F-14

Nº 6, EQUINOX, NIGHTTIME

MAP OF TEMPERATE ZONE Es OCCURRENCE

March, April, September and October; 1800 – 0600 Local Time

fEs > 5 Mc, 1948 – 1954

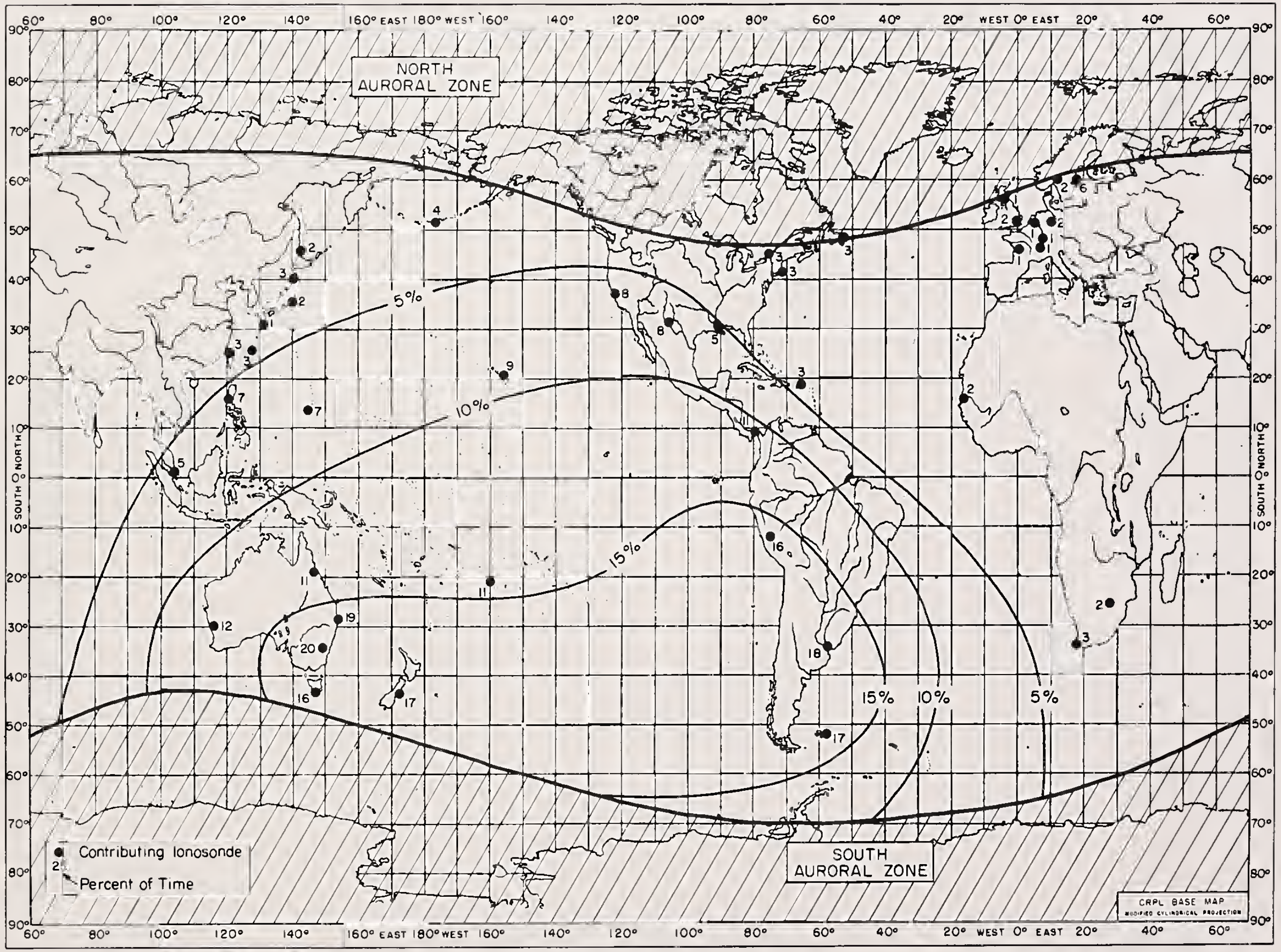


Figure II -F-15

II-F-10 and II-F-11 portray the Temperate-Zone longitude effect in its most striking form. An area in the neighborhood and to the south of Japan is seen to contain a well-defined maximum in June-Solstice Es incidence. The peak is roughly a factor of two higher than that for the comparable latitude in the W zone. A second feature is the "low" which shows up in South Africa for almost all time blocks. Only two stations are available in this area, but their results are mutually compatible. A low in the horizontal intensity H of the earth's magnetic field does occur in this same region.

b. Auroral Zone. The fifteen Auroral-Zone stations with data periods which meet the requirements of this study are all in the northern hemisphere. Sporadic-E occurrence in the Southern Auroral Zone can, therefore, only be ascertained through analogy with the Northern Zone. As the contours of equal-Es occurrence which have been drawn for the northern Auroral Zone are on pretty shaky footing over a large part of the Zone, their transferal to the Southern Auroral Zone hardly seems warranted.

The mean values and mean deviation of the annual values are given for yearly occurrence of Es in figure II-F-16 and for the six time blocks in figure II-F-17. Auroral-percent-frequency days have been plotted on the abscissa in each case.

A polar map of the Northern Auroral Zone showing the fifteen data stations and three reference isochasms is given in figure II-F-18. It is seen that a great circle can be drawn through the north geographic pole such that all fifteen data stations are on one side of it. As a result, Es behavior on the Siberian side of the pole can only be guessed at through extrapolation of trends and some assumption of symmetry.

Contours of the mean yearly percent occurrence of fEs > 5 Mc for the Auroral Zone are shown in figure II-F-19. These are overlaid on a geographic coordinate system. The data stations are spotted and the mean Es occurrence value for each station is also shown. Es occurrence for the six time blocks is given in similar plots on the three following figures (figure II-F-20 to II-F-22). An attempt has been made to draw the contours on the basis of the mean values shown on each map but guided also by the close correlations observed between Es behavior and auroral percent frequency days and a feeling that the two sides of the geographical distributions are probably rather symmetrical.

The most striking feature of all of these curves is the high incidence of Auroral-Zone Es over northern Canada and Greenland as compared to Siberia. It is quite possible that a secondary geographical maximum may occur which is not reflected in these data at all, but on the basis of what is available here a factor of about three-to-one in occurrence of fEs > 5 Mc appears to exist between the Canadian and Siberian sections of the line of auroral maximum.

MEAN YEARLY OCCURRENCE OF SPORADIC E IN THE AURORAL ZONE 1948-1954; fEs > 5 Mc

Ranges are Mean Deviations

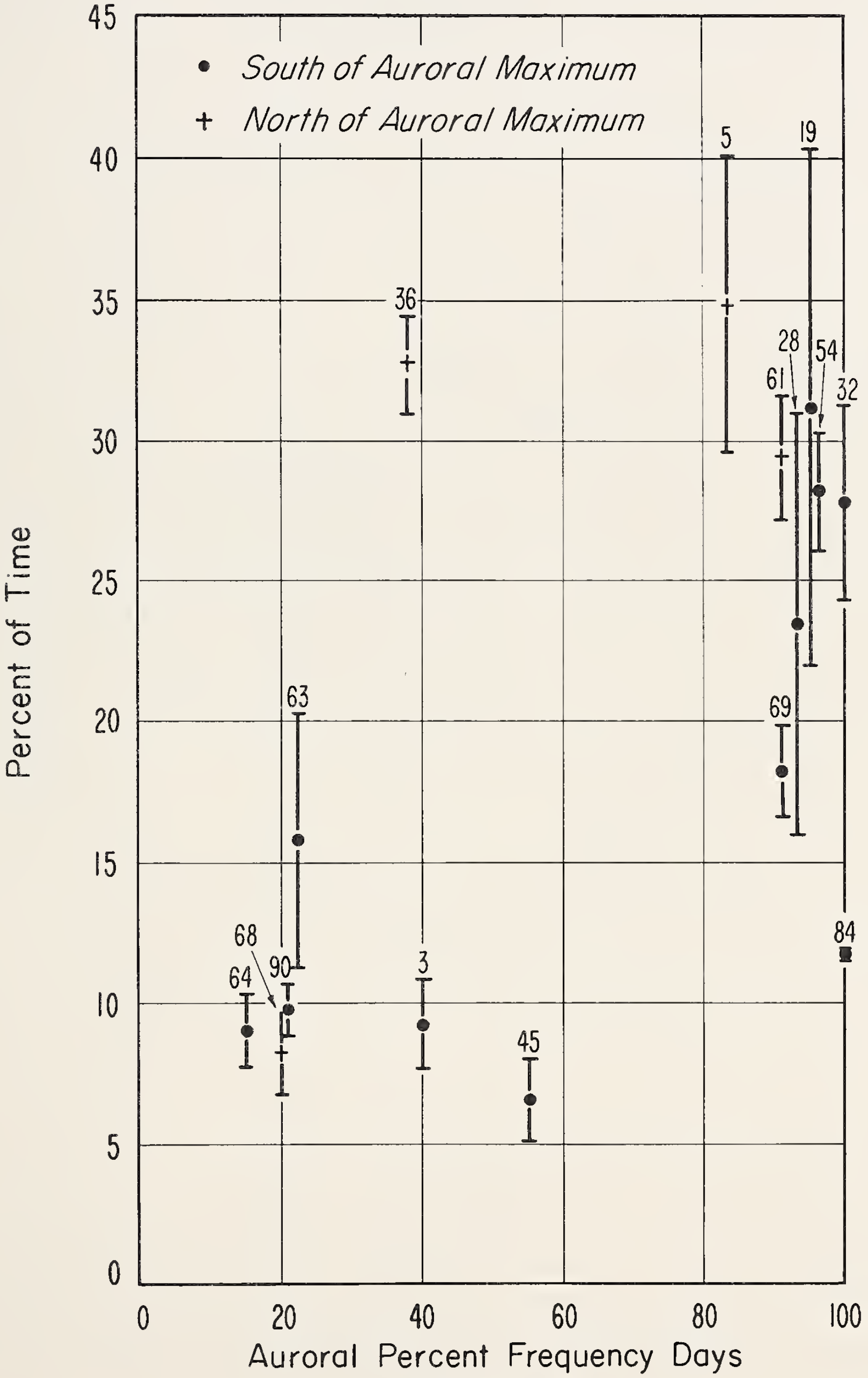


Figure II-F-16

OCCURRENCE OF SPORADIC E DURING SIX TIME BLOCKS IN THE AURORAL ZONE

1948-1954, fEs > 5 Mc, Ranges Are Mean Deviations

• South of Auroral Maximum, ◦ North of Auroral Maximum

—— W Zone, - - - I Zone

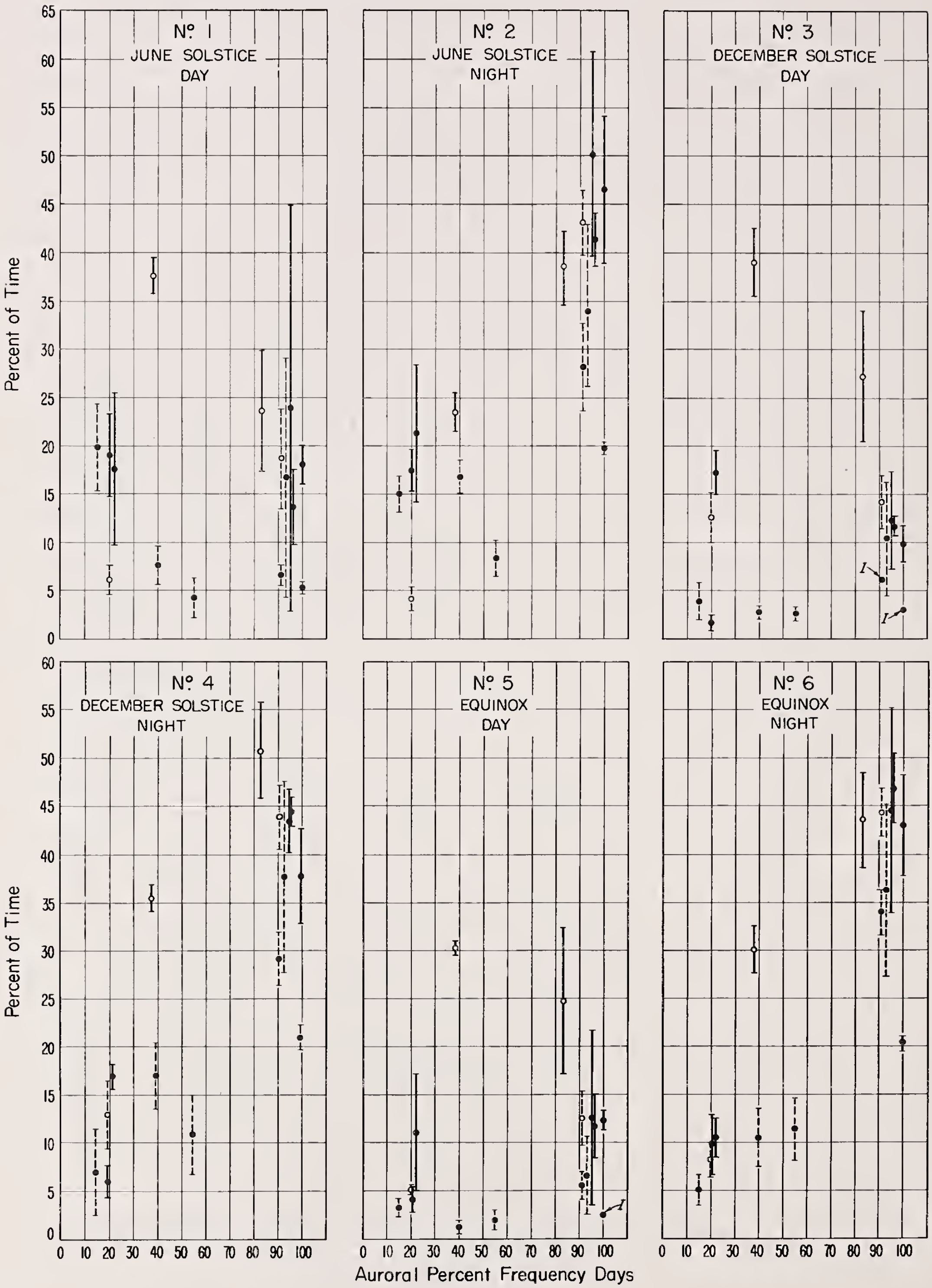
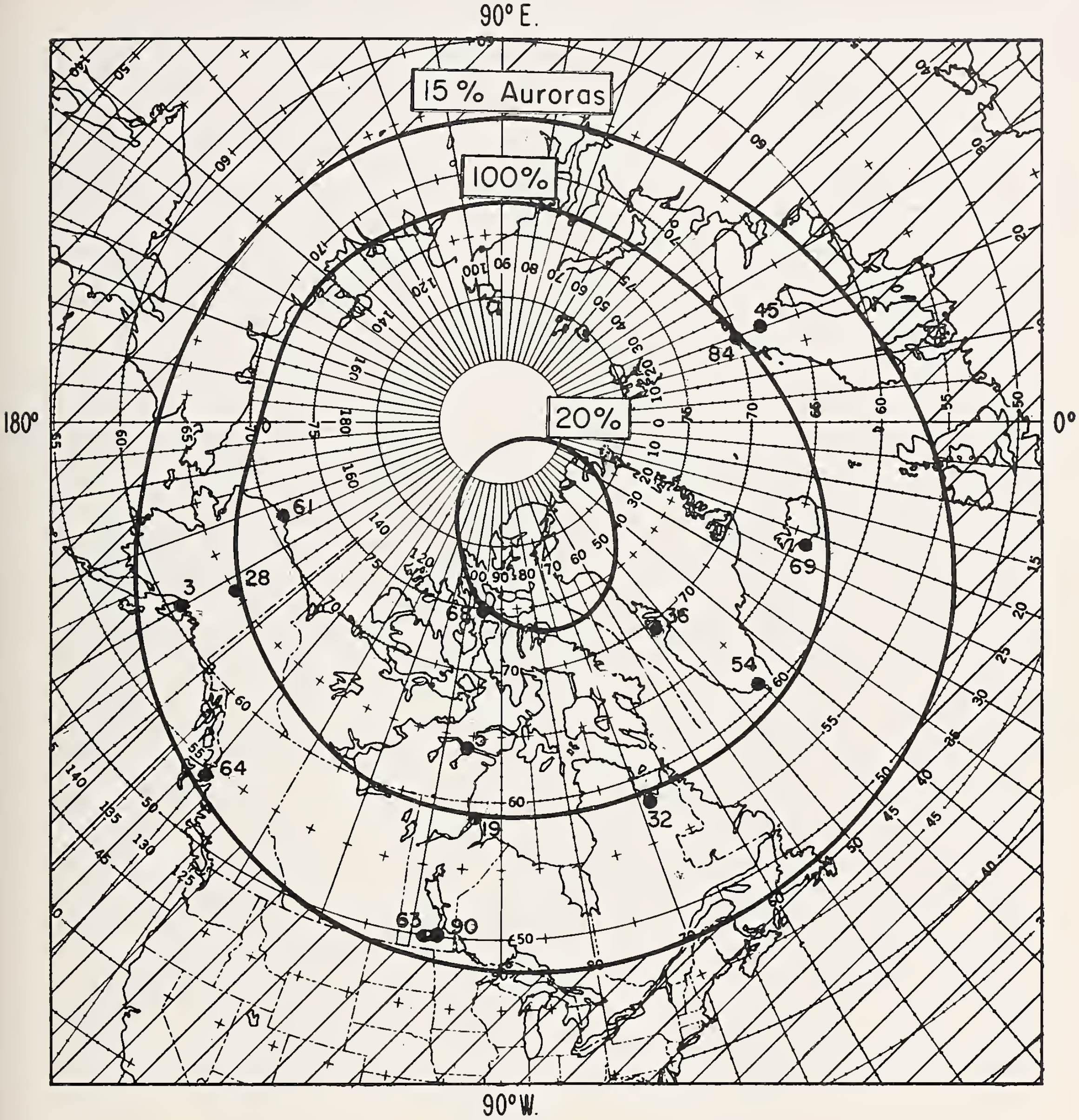


Figure II-F-17

POLAR MAP OF AURORAL ZONE SHOWING STATION LOCATIONS



3 = Anchorage
5 = Baker Lake
19 = Churchill
28 = Fairbanks
32 = Fort Chimo
36 = Godhavn
45 = Kiruna
54 = Narsarssuak
61 = Pt. Barrow
63 = Portage La Prairie
64 = Prince Rupert
68 = Resolute Bay
69 = Reykjavik
84 = Tromso
90 = Winnepeg

Figure II-F-18

MEAN ANNUAL Es OCCURRENCE IN THE AURORAL ZONE
fEs > 5 Mc; 1948-1954

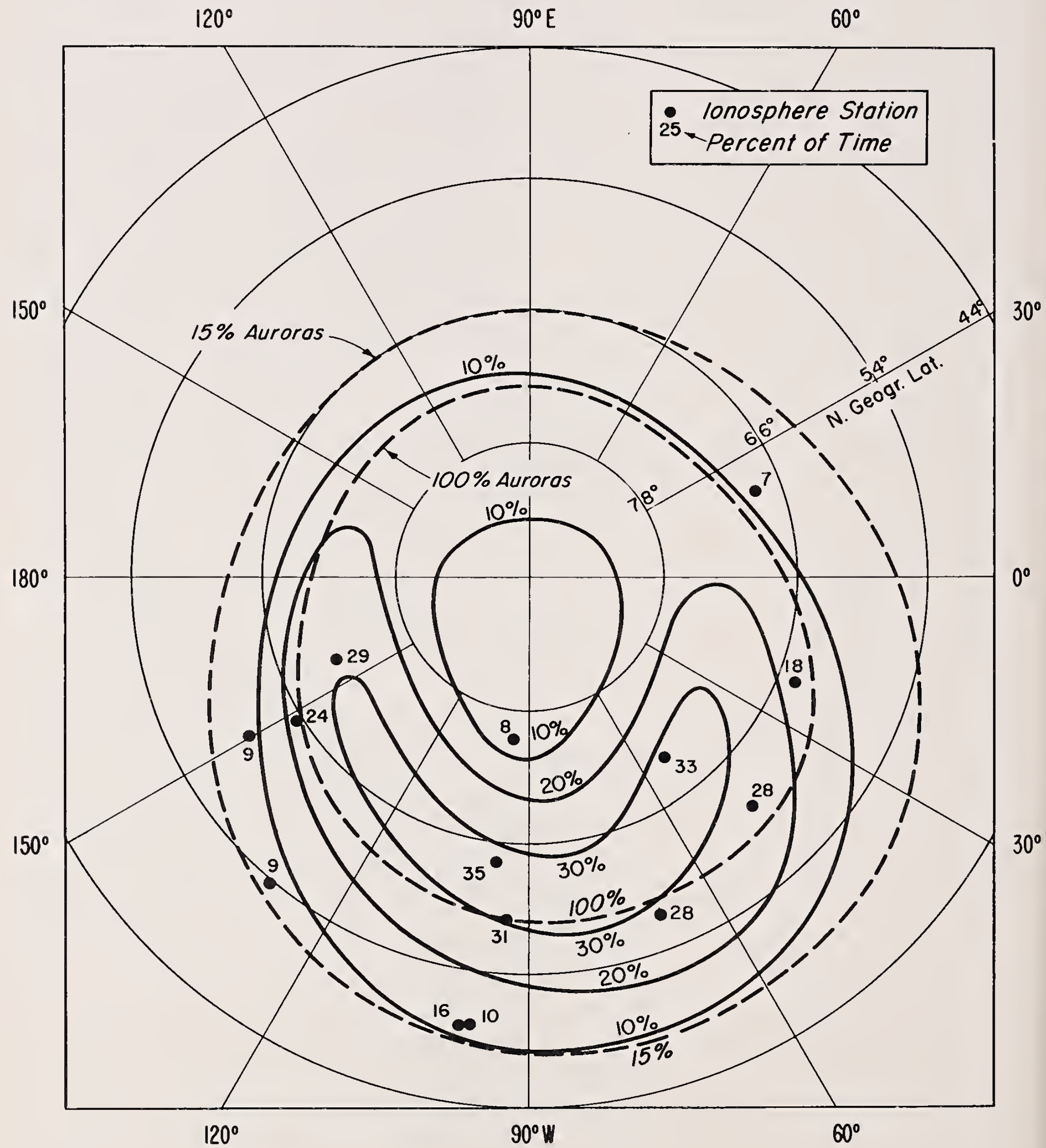


Figure II-F-19

AURORAL ZONE Es OCCURRENCE
JUNE SOLSTICE
MAY, JUNE, JULY AND AUGUST
fEs > 5 MC; 1948 - 1954

No. 1 DAYTIME (0600-1800 L.T.) — No. 2 NIGHTTIME (1800-0600 L.T.)

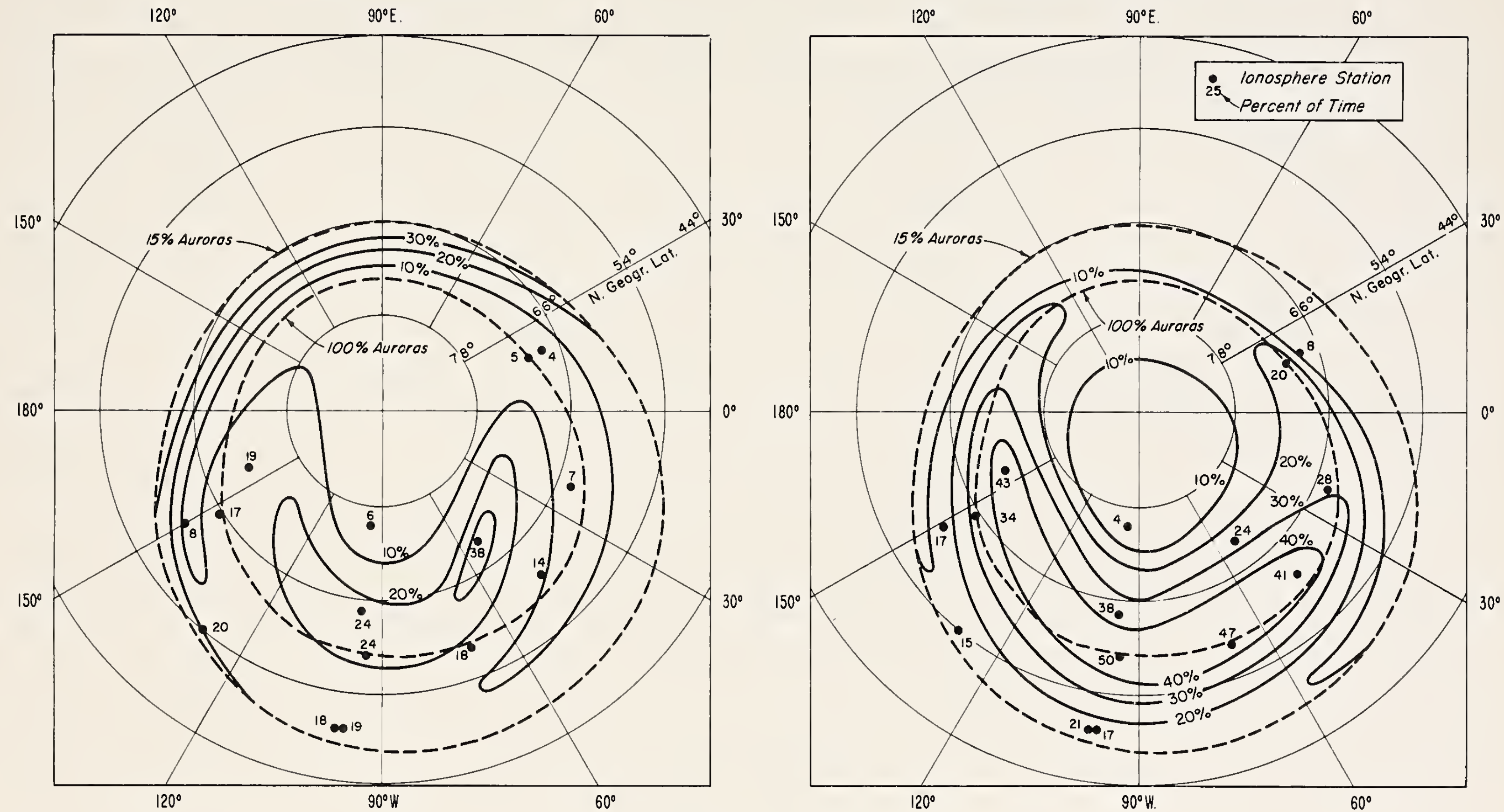


Figure II-F-20

AURORAL ZONE Es OCCURRENCE
DECEMBER SOLSTICE
NOVEMBER, DECEMBER, JANUARY AND FEBRUARY
fEs > 5 Mc; 1948-1954

N° 3 DAYTIME (0600-1800 L.T.) | N° 4 NIGHTTIME (1800-0600 L.T.)

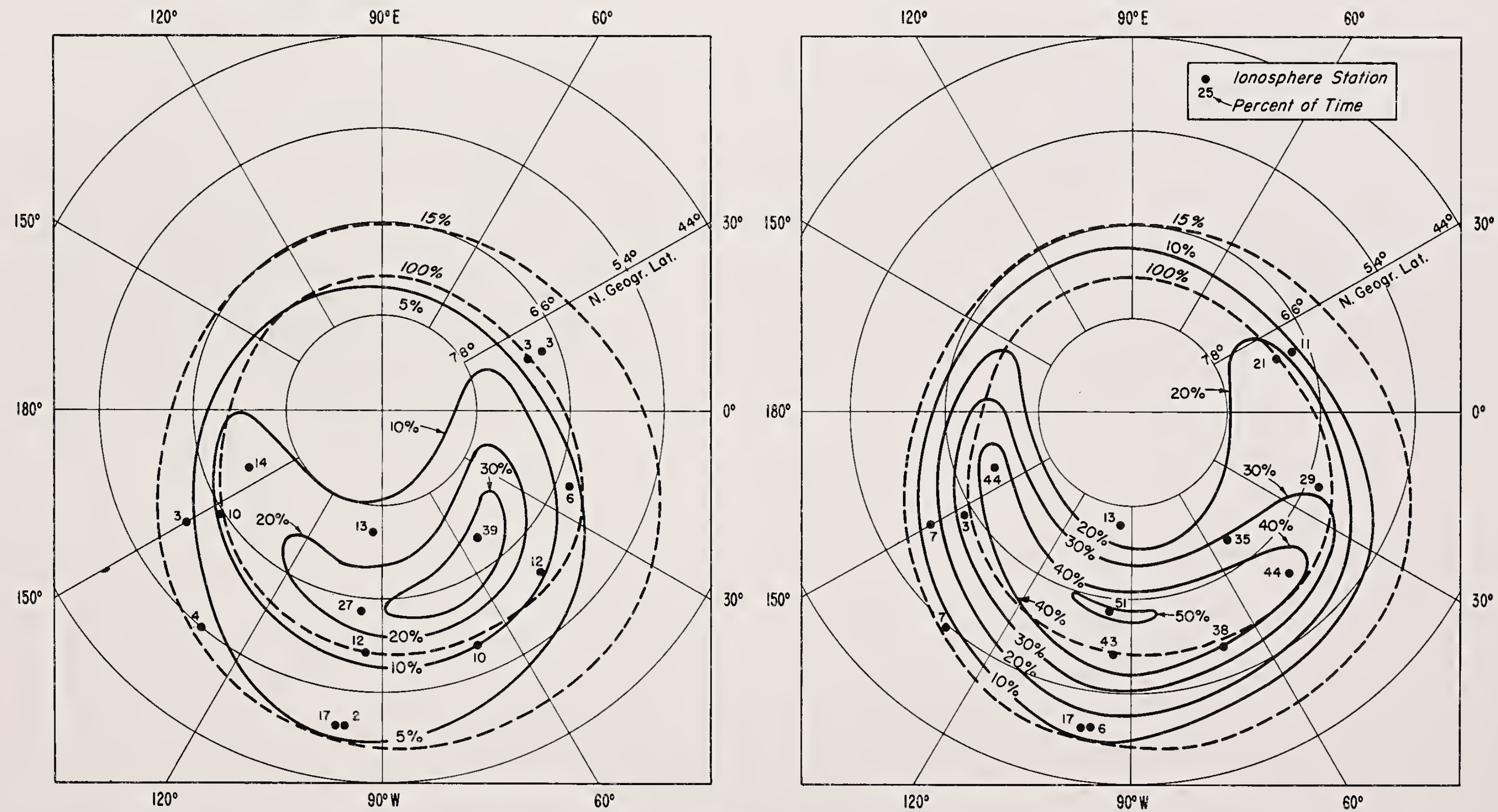
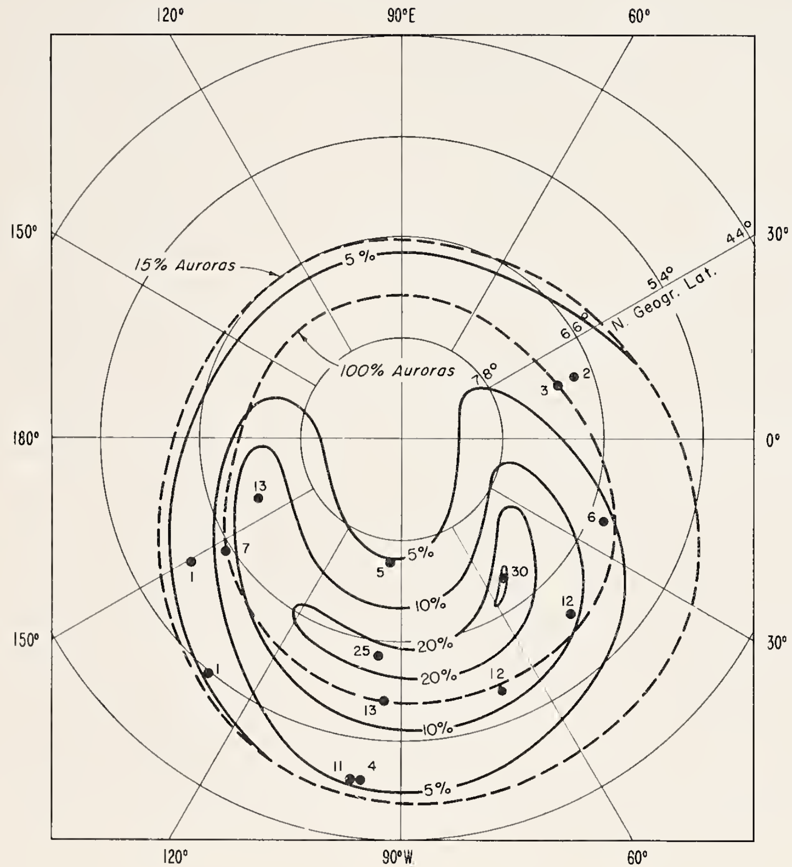


Figure II-F-21

AURORAL ZONE Es OCCURRENCE
EQUINOX
MARCH, APRIL, SEPTEMBER AND OCTOBER
fEs > 5 MC; 1948 - 1954

N° 5 DAYTIME (0600-1800 L.T.)



N° 6 NIGHTTIME (1800-0600 L.T.)

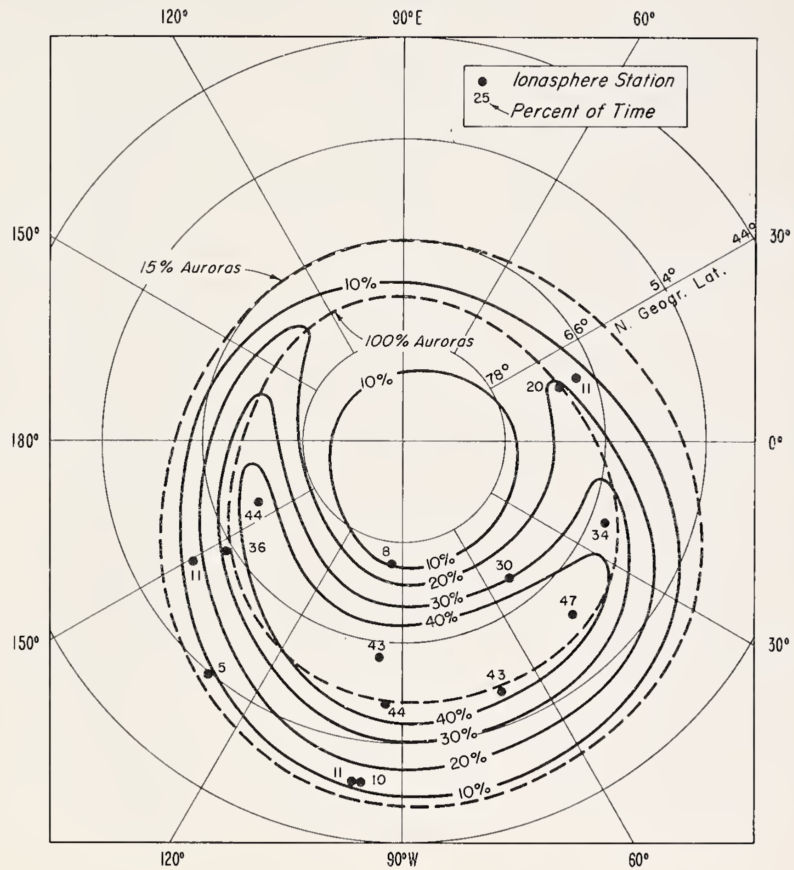


Figure II -F-22

2. Temporal Variations at Selected Location. The time-block displays above give continuous geographic distributions for six fixed time intervals. The time maps, on the other hand, present a continuous time distribution for a single location. Five dimensions are needed for a sensible display of both simultaneously (i.e. geographical latitude and longitude, time of day, time of year and percent occurrence of sporadic E at a particular frequency). One solution would be to present a map for each hour of the day for each month of the year, a total of 288 maps. This is clearly out of the question. The approach here is to present time maps representing mean Es occurrence for the period 1948-1954 for seventeen selected locations. These stations of which eight are in the North Temperate Zone, four in the South Temperate Zone, four in the North Auroral Zone and one in the Equatorial Zone have been selected out of the fifty-seven stations considered in the time block analysis on the basis of two criteria: first, do they appropriately sample the geographic areas to be covered and, second, do they appear to exhibit normal Es behavior compared to their adjacent stations.

The time map of the Equatorial Zone station is seen in figure II-F-23. Although this station, Huancayo, Peru, is in the southern hemisphere, the seasonal effect is small and the abscissa scale is left reading from January through December. The seasonal scale on the other southern hemisphere stations (figure II-F-26) has been altered to read from July through June in order to illustrate

MEAN TEMPORAL VARIATIONS OF SPORADIC E
HUANCAYO, PERU
fEs > 5 Mc, 1948-1954

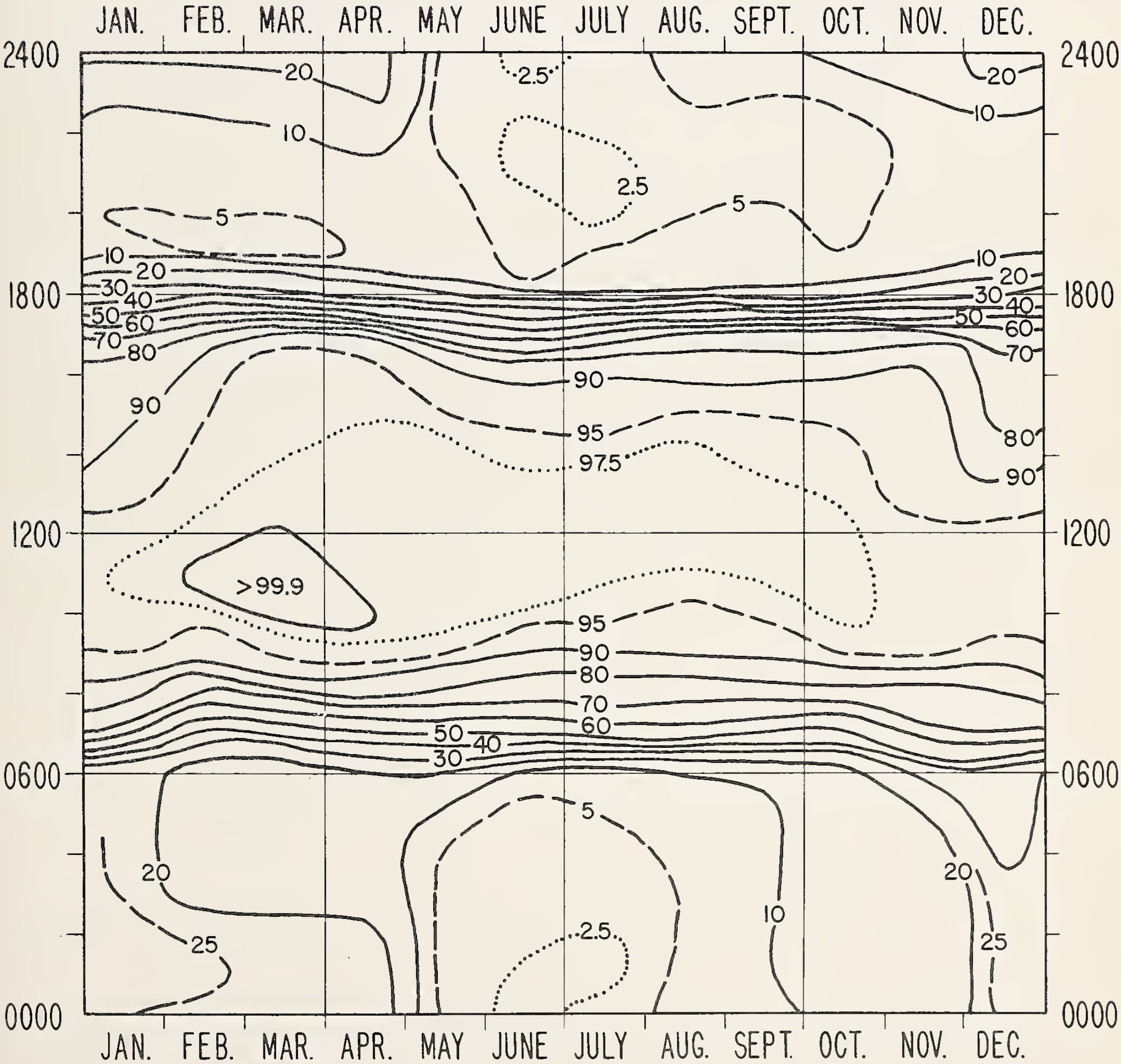


Figure II-F-23

the six month phase difference in Es between the hemispheres.

Time maps of Es at four high latitude stations in the North Temperate Zone are seen in figure II-F-24. The pronounced daytime summer maximum is the dominant feature in all of these stations. The secondary evening summer peak does not show up too consistently. Note, for instance, that it is not so apparent at Adak as it is at the other stations which belies the sometimes-heard hypothesis that this peak is a feature of stations of high geomagnetic latitude.

Four lower-latitude stations of the North Temperate Zone are shown in figure II-F-25. The two Japanese stations, Yamagawa and Wakkanai are seen to have quite similar time characteristics which appear most closely allied to those for Adak despite the wide differences in geographic and geomagnetic latitudes. San Juan, Puerto Rico shows an unusually late midday maximum which is possibly related to the high incidence of sequential Es observed at this station. The time map for Maui is seen to be quite different from that for Yamagawa, although the stations differ by only 1° in geomagnetic latitude (10.4° in geographic latitude) which seems to show that the longitude variations noted earlier are in form as well as in degree.

The southern hemisphere stations found in figure II-F-26 all show a maximum incidence in daytime of the southern summer (December, January and February) and the abscissa scale has been plotted so that direct comparison with the northern hemisphere

TEMPORAL VARIATIONS IN Es AT FOUR STATIONS IN THE HIGH NORTH TEMPERATE ZONE

fEs > 5 Mc

CONTOURS ARE PERCENTS OF TIME

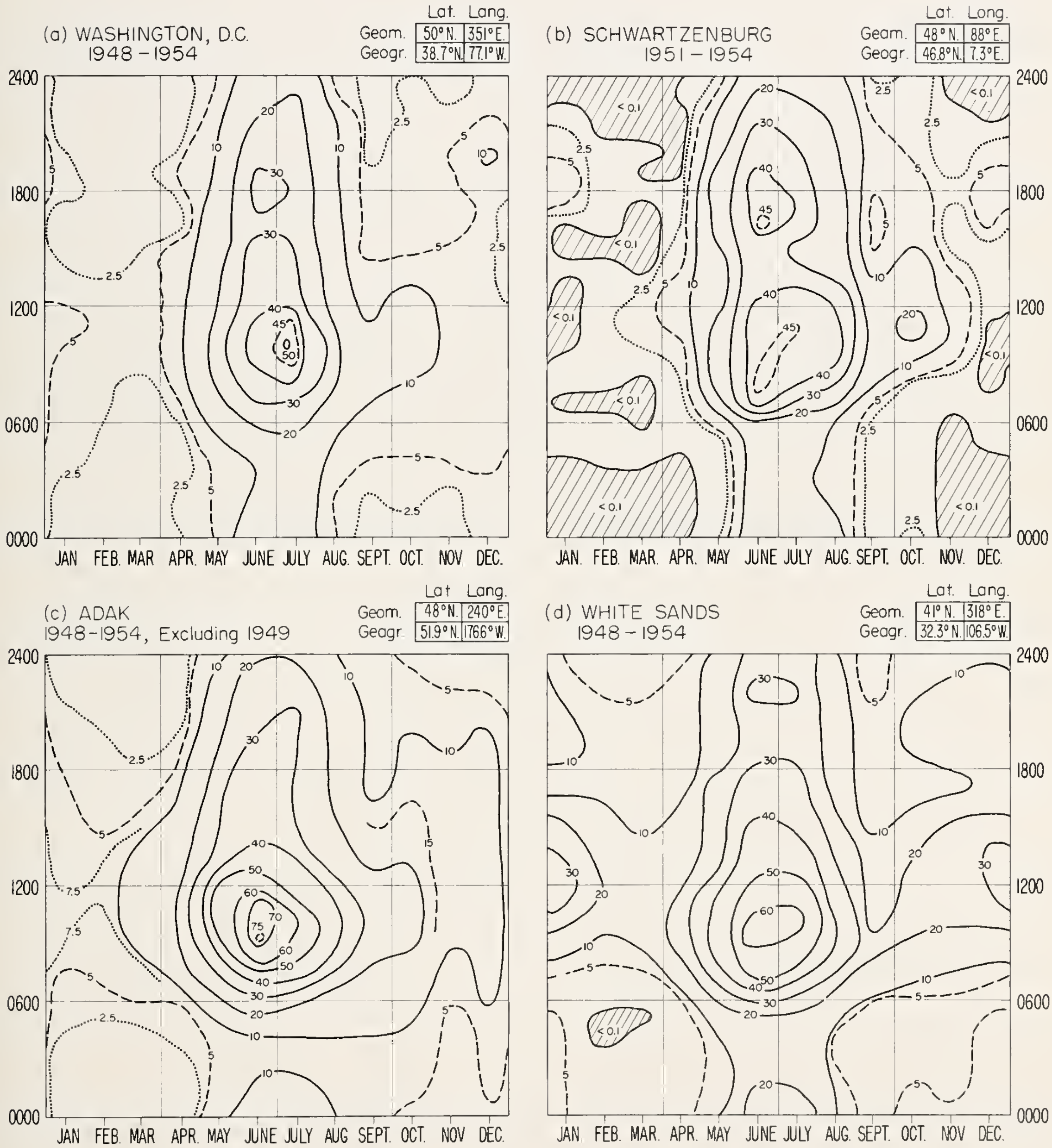


Figure II -F-24

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TEMPORAL VARIATIONS IN Es AT FOUR STATIONS IN THE LOW NORTH TEMPERATE ZONE

fEs > 5Mc

CONTOURS ARE PERCENTS OF TIME

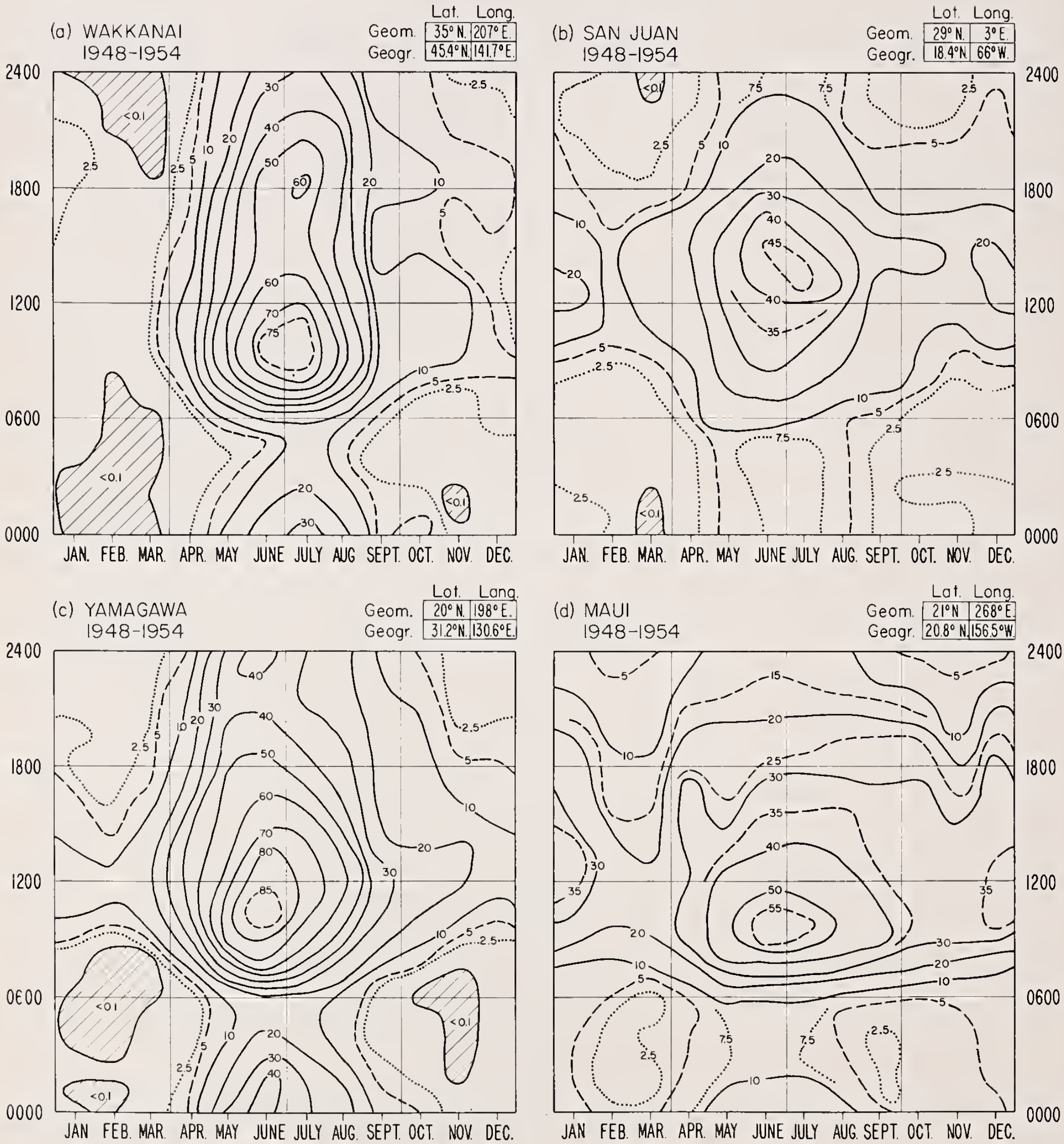


Figure II-F-25

TEMPORAL VARIATIONS IN Es AT FOUR STATIONS IN THE SOUTH TEMPERATE ZONE

fEs > 5 Mc

(Note: Seasonal Scale Starts With July)

CONTOURS ARE PERCENTS OF TIME

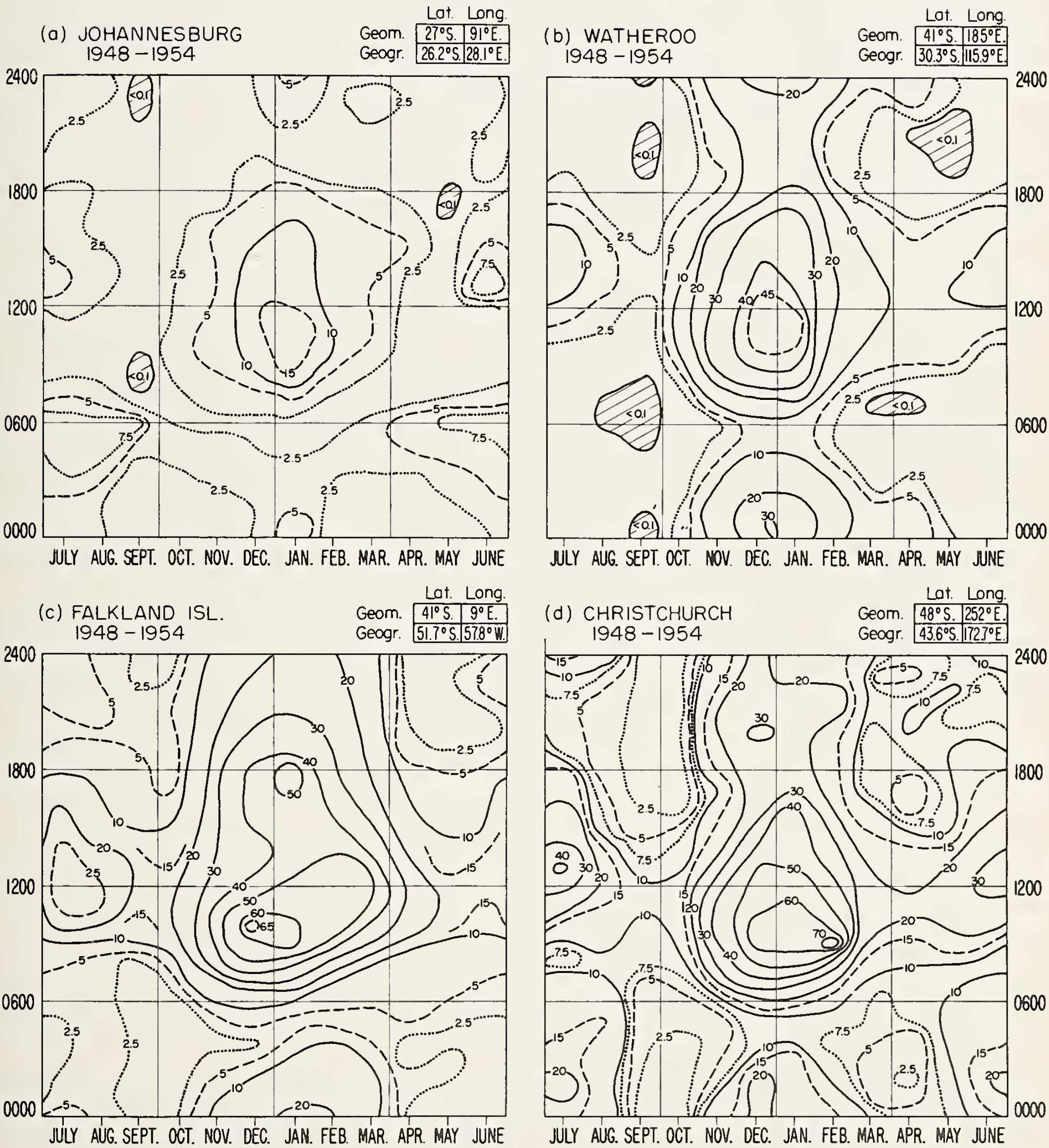


Figure II-F-26

stations is possible. Most of these stations show a better developed winter secondary maximum (June and July) than do the northern stations and this maximum is seen to peak about three hours later than the corresponding primary maximum. Johannesburg and Watheroo are especially interesting in that both stations show a peak in December and January around midnight. Johannesburg also shows a high incidence of Es around 0500 in local winter. A somewhat similar peak is in evidence at Christchurch, but at about three hours earlier.

The time maps for the four Auroral-Zone stations (figure II-F-27) portray some of the uncertainties one is faced with in this area. Well-defined trends are seen at Fairbanks and Narsarssuak, but neither the map for Resolute Bay nor the one for Kiruna is likely to inspire confidence with regard to the reliability of their time trends. Resolute Bay, well to the north of the auroral maximum, shows a rather well developed late morning maximum in November and December somewhat reminiscent of the southern Temperate Zone but more probably related to the secondary seasonal peak which is thought to occur at the winter solstice. Of the other three stations, two, Narsarssuak and Fairbanks, show very similar distributions, but, whereas, the diurnal maximum at Narsarssuak is in the neighborhood of 2200 local time, that at Fairbanks is between 0200 and 0300. This difference would seem to indicate a longitude shift in the peak along the maximum of the auroral zone.

TEMPORAL VARIATIONS IN Es AT FOUR STATIONS IN THE NORTH AURORAL ZONE

fEs > 5 Mc

CONTOURS ARE PERCENTS OF TIME

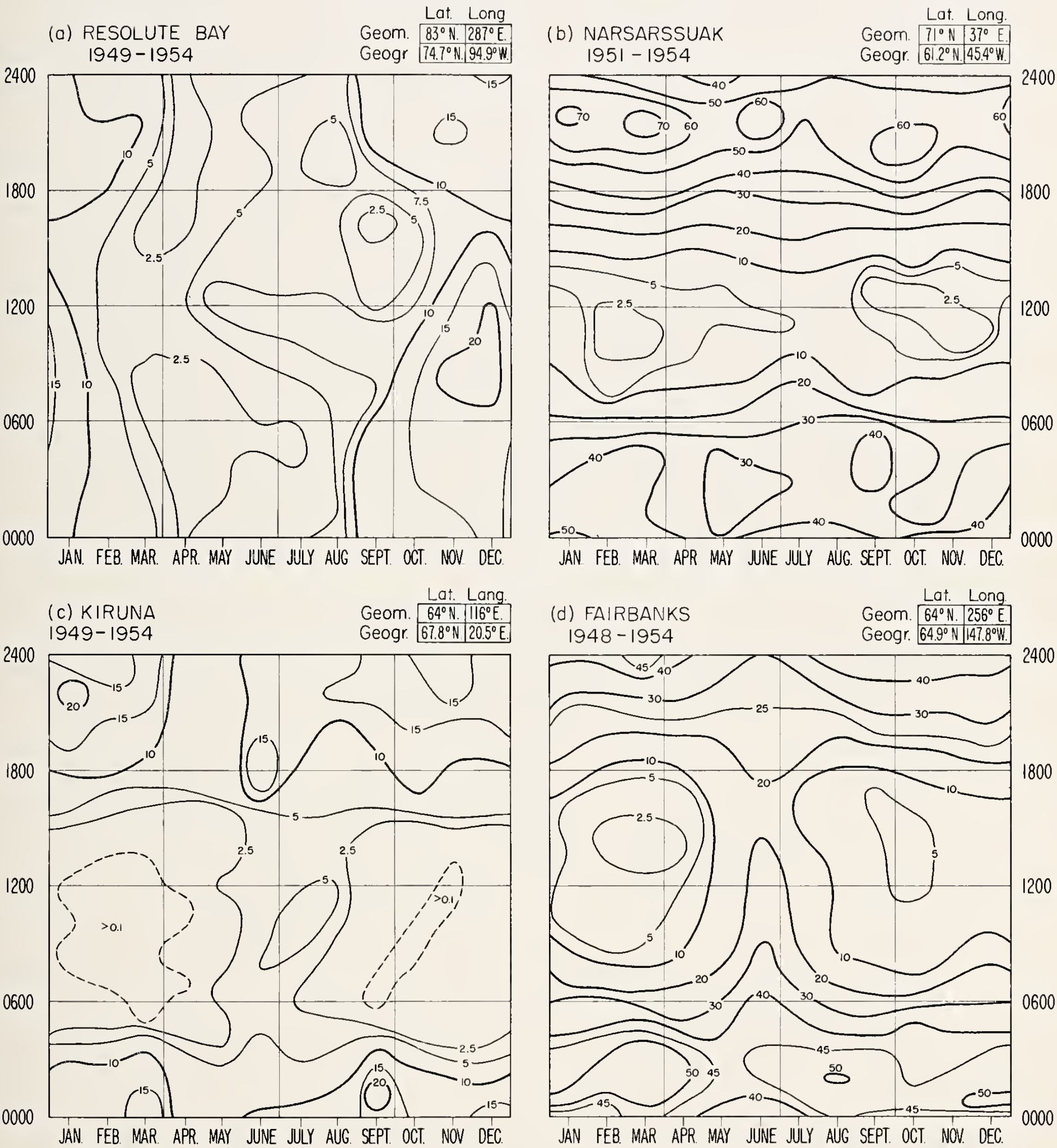


Figure II -F-27

G. Frequency Dependence of Vertical-Incidence Es

1. The Phillips Frequency-Dependence Rule

A logarithmic relation for the frequency dependence of sporadic E has been in use at the National Bureau of Standards since 1943 (see for example: IRPL Radio Propagation Conditions Issue of October 14, 1943, pp. 3, 4; Issue of February 14, 1944, pp. 3, 4). It appears in the published literature in Phillips [1947]. The relation takes the form of

$$\log_{10} P = a + bf \qquad \text{II-G-1}$$

where: P = probability of occurrence of fEs > f

f= the frequency in megacycles

a, b = adjustable constants

without loss of generality this equation may also be written:

$$\log_{10} \left(\frac{P_1}{P_2}\right) = b (f_1 - f_2) \qquad \text{II-G-2}$$

where: P_1 P_2 refer to the probability of occurrence of fEs above the frequencies f_1, f_2 respectively.

The relation II-G-2 represents the difference of two cases of II-G-1. For the special case $a \ll bf$ a simple quotient relation may also be written which contains no arbitrary constants

$$\frac{\log_{10} P_1}{\log_{10} P_2} = \frac{f_1}{f_2} \text{ (for } a = 0 \text{)} \qquad \text{II-G-3}$$

2. Variations in Frequency Dependence.

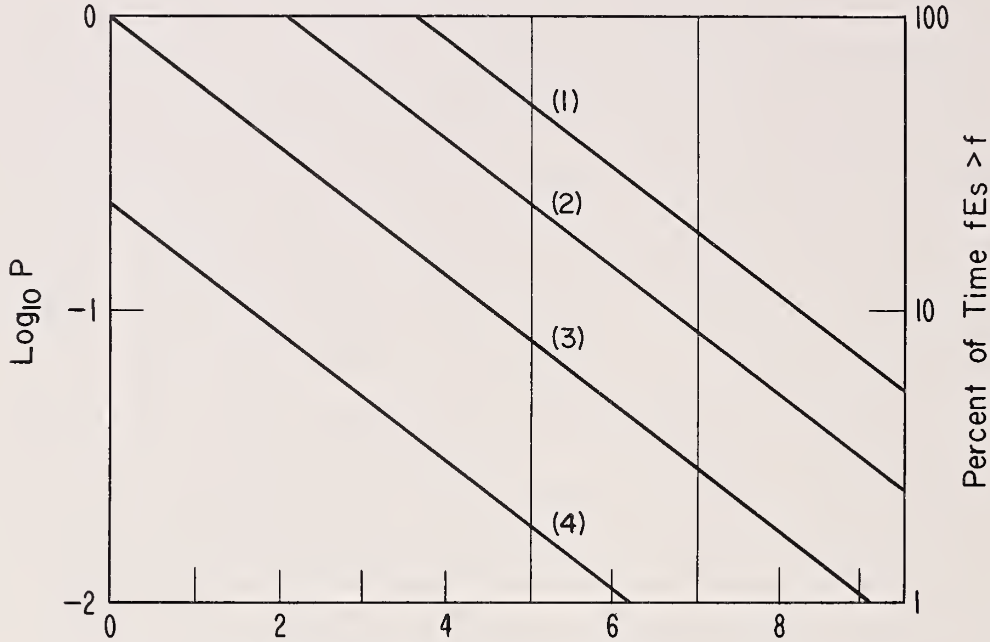
Relation II-G-1 is the equation of a straight line on a linear plot of log P vs. f or on a semi-logarithmic plot of P vs. f such as in figure II-C-2 and II-C-4. As can be seen from these figures the straight line is not too bad a representation. There are many interesting implications of relation II-G-1 which merit consideration, for example, can a linear coordinate transformation reduce "a" effectively to 0. This possibility can be investigated by exploring the connection between the slope "b" in relations II-G-1 and II-G-2 and the occurrence of fEs above some frequency, say 5 Mc. Two possible idealized situations are portrayed in figure II-G-1. In (a) is seen the case for the slope "b" a constant. In this situation the ratio of Es observed on two curves is a constant with respect to the abscissa frequency. In figure II-G-1 (a) although "b" is constant, "a" must be able to vary. In (b) of figure II-G-1 is seen the system of straight lines contained implicitly in relation II-G-3 where the constant "a" has been set equal to zero.

The ordinate values at 5 Mc of the numbered curves are the same at 5 Mc for the two families of curves in figure II-G-2. However, the differences between the two families are seen to become increasingly greater as one considers higher and higher frequencies.

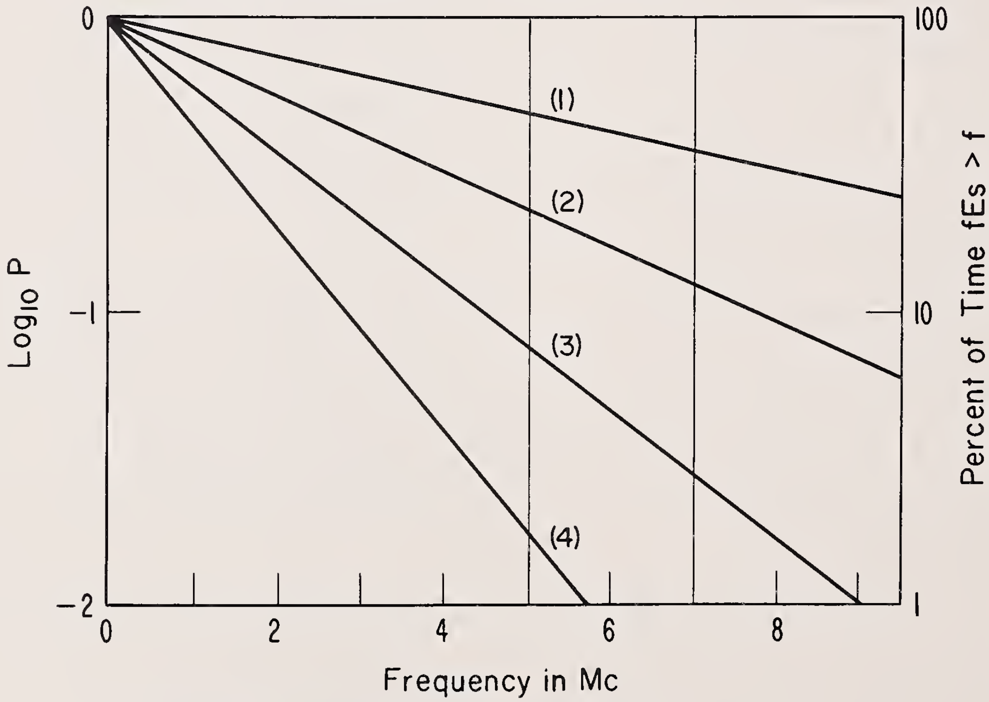
It is apparent in figure II-G-1 that in order to distinguish between two such sets of curves as shown in (a) and (b) it is

IDEALIZED VARIATION IN THE FREQUENCY DEPENDENCE OF Es WITH CHANGES IN OVERALL LEVEL

$\text{Log}_{10} P = a + bf$



(a) Parallel Distribution (b = Constant)



(b) Lines Radiating From Origin (a = 0)

Figure II-G-1

necessary to consider the variations of Es occurrence simultaneously at two frequencies (e.g. 5 Mc and 7 Mc as shown).

A general case of a radial distribution, for which (b) in figure II-G-1 is a special case, is shown in figure II-G-2. The point (f_o, y_o) is not restricted to the lower right-hand quadrant of the f, y plane. In practice, it will tend to fall in the upper right-hand quadrant and in the interval $0 < f < 4$. The radiant itself is a mathematical not a physical entity, i. e. the radials cannot be followed towards the radiant in practice to frequencies less than about 4 Mc.

It will be noted in figure II-G-2 that the horizontal cross-hatching identifies one pair of similar triangles and the vertical cross-hatching another pair. By relating corresponding sides, one may write

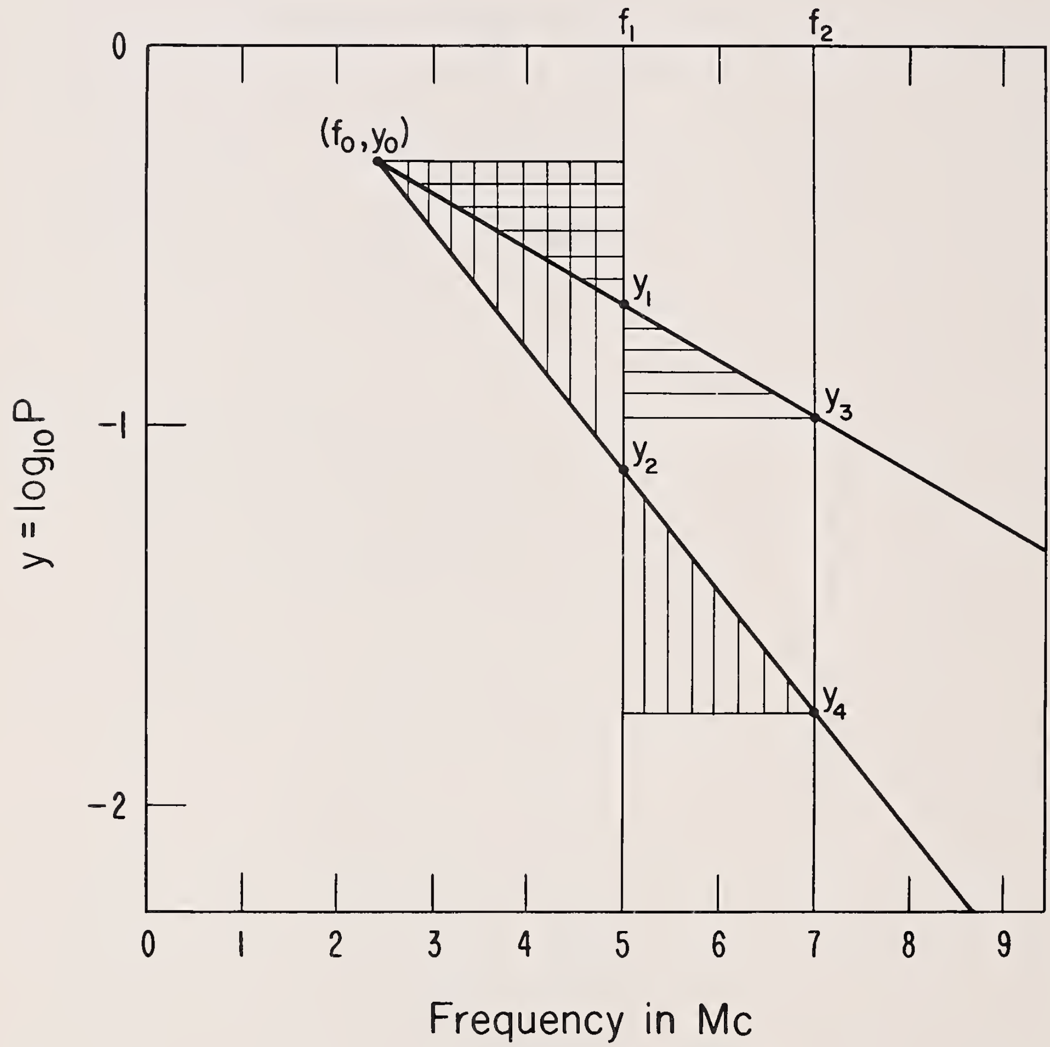
$$\frac{y_1 - y_3}{y_1 - y_o} = \frac{y_2 - y_4}{y_2 - y_o} = \frac{f_2 - f_1}{f_o - f_1} = \text{constant} \qquad \text{II-G-4}$$

where: $y = \log_{10} P$

The constant of II-G-4 depends only on the position of the radiant (f_o, y_o) and the sampling frequencies f_1, f_2. As the radial lines shown are not restricted in any way it follows that relation II-G-4 will hold for all the radials intersecting the lines $f = f_1$ and $f = f_2$. Relation II-G-4 reduces to zero for a parallel set of lines such as those shown in figure II-G-1 (a) which corresponds to the radiant (f_o, y_o) at infinity.

If one writes $\Delta y_1 = y_3 - y_1$, $\Delta y_2 = y_4 - y_2$, and $\Delta f = f_2 - f_1$

GEOMETRICAL CONSTRUCTION DEMONSTRATING CONDITION FULFILLED BY RADIAL LINES



$$\text{Radial Condition: } \frac{y_1 - y_3}{y_1 - y_0} = \frac{y_2 - y_4}{y_2 - y_0} = \frac{f_2 - f_1}{f_0 - f_1} = \text{Constant}$$

Figure II-G-2

relation II-G-4 may be written:

$$\frac{\Delta y_1}{y_1 - y_o} = \frac{\Delta y_2}{y_2 - y_o} = \frac{\Delta f}{f_1 - f_o} = \text{constant}$$

or

$$\frac{\Delta y}{y - y_o} = c = \frac{\Delta f}{f_1 - f_o} \qquad \text{II-G-5}$$

where: Δy = difference in the logarithms of the probabilities of occurrence of Es at two frequencies.

y = logarithm of the probability of occurrence of Es at the lower frequency

Δf = difference of two sampling frequencies in Mc.

f_o, y_o = coordinates of the radiant.

Relation II-G-5, which expresses the condition that the family of lines in the f,y plane radiate from a point, also defines a straight line ($\Delta y = cy - cy_o$) in the Δy, y plane. As Δf and f_1 will be known, this line will uniquely determine the radiant point f_o, y_o. For $y_o = 0$ the line will pass through the origin on the Δy, y plane and the slope "c" of this line will determine the corresponding intercept on the frequency axis of the y, f plane ($f_o - f_1 = \Delta f/c$). For $y_o = 0$ the radiant may be determined from the slope and the intercept of the line with the Δy axis.

a. Seasonal Variation . One of the best defined and perhaps the most important regular variation which can be studied is the seasonal one.

Six representative stations have been selected and the occurrence of fEs > 5 Mc and fEs > 7 Mc tabulated for each month of the period 1948-1954. The percent of time for the seven years during which Es exceeded these two frequencies has been obtained for each of the twelve calendar months. Thus, $\Delta f = 7 - 5 = 2$ Mc. As $\Delta y = \log_{10} P_1/P_2$, one then obtains from relation II-G-2 that $b = \Delta y/2$.

Figure II-G-3 displays the b, y plots of mean monthly values for the six stations. For the three stations portrayed at the top: Yamagawa, Christchurch and White Sands, it is possible to fit straight lines to the distributions down to y = -1 with little dispersion. This interval of fit is fortunately the one of most interest. The radiant points contained implicitly in the three straight lines appearing in figure II-G-3 may be found by determining the slopes from the b values at the y = 0, and - 1 intercepts and then determining the point of intersection of the two lines on the y, f plane. These two lines are defined by the two values of the slopes and their respective passages through the points (f = 5, y = 0) and (f = 5, y = -1). The pertinent values are given as follows:

Location	at y = 0	at y = -1	Radiant Point		
	b	b	f_o	$\log_{10}P$	P
Yamagawa	- .052	- .46	2.6Mc	.125	1.32
Christchurch	- .06	- .39	2.00	.184	1.53
White Sands	- .13	- .445	1.83	.42	2.6

Of the three remaining stations the Maui and Narsarssuak

RATIO OF Es OBSERVED ON 5 AND 7 MC AS A FUNCTION OF 5 MC Es

Meon Monthly Volues for Period 1948 - 1954

Numbers Refer to Months in Chronologicol Order

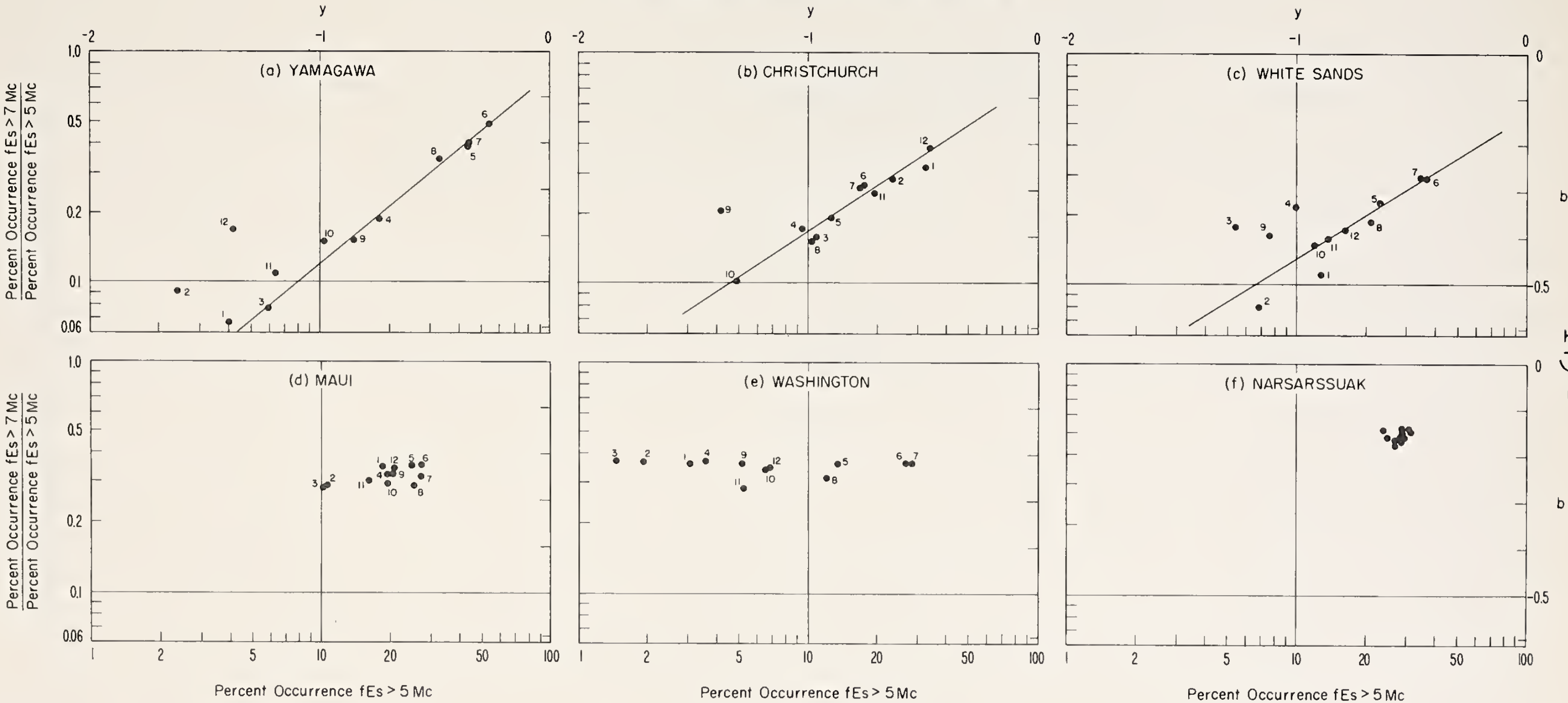


Figure II-G-3

distributions show too small month-to-month excursions in y to enable one to say much about them. Washington shows wide excursions in y but almost none in b. The best fitting straight line would be almost exactly horizontal indicating a radiant at infinity.

b. Sunspot-Cycle Variations. Roughly speaking, an idea of the influence of sporadic E on oblique-incidence transmission over 700 to 1400 mile paths may be obtained by multiplying the observed vertical critical frequencies of fEs by five as suggested by the secant rule. The 5 Mc observations considered in this study then become pertinent to 25 Mc oblique transmissions. The effect of b, the proportionality constant of relations II-G-1 and II-G-2, on the expected Es occurrence at other frequencies is demonstrated in figure II-G-4. An occurrence of 30% for fEs > 5 Mc has been used as a reference. From figure II-G-3, it can be seen that values for b of - 0.1 to - 0.6 are not uncommon in practice. At double the observing frequency (10 Mc for vertical incidence, 50 Mc for oblique) it is seen that more than a factor of 100 difference in occurrence of Es is obtained depending on which value is used. It is important, therefore, that the appropriate value of b is used.

In an early study of the variation of b at Washington, D. C. (IRPL Radio Propagation Conditions, issued 14 February 1944, p. 4) the following variation of this quantity with season and sunspot cycle is noted:

> "...For observations made at Washington, the constant of proportionality varies at sunspot minimum from about - 0.3 for months near both summer and winter solstices to about

THE EFFECT OF DIFFERENT VALUES OF THE FREQUENCY DEPENDENCE FACTOR b ON EXPECTED Es OCCURRENCE

30 Percent Occurrence fEs > 5 Mc Used For Reference

$$\log \frac{P_1}{P_2} = b(f_1 - f_2)$$

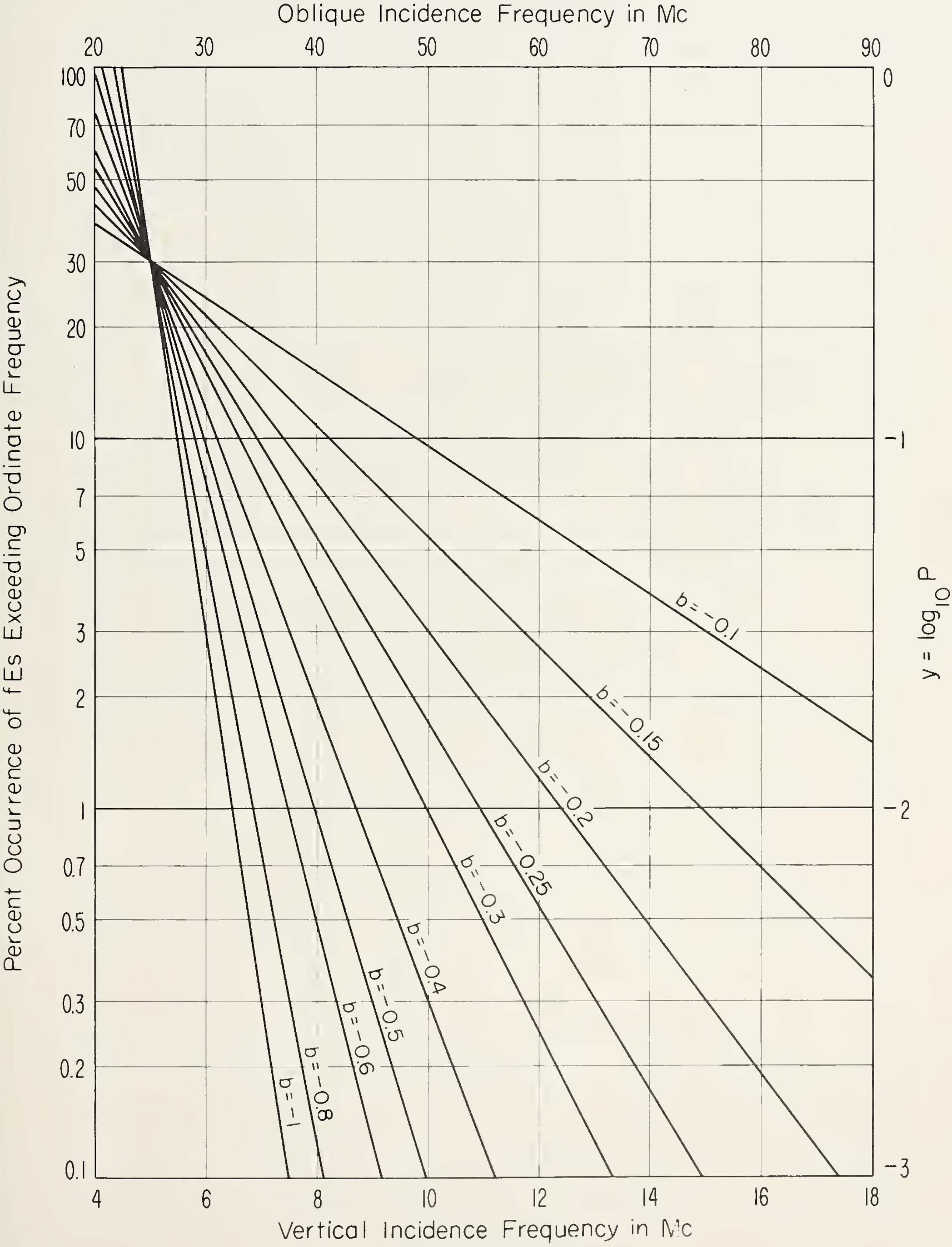


Figure II-G-4

- 0.7 for months near the equinoctial periods, these values varying respectively, between about - 0.1 and - 0.3 at sunspot maximum..."

The variation of the average yearly value of b during the period 1948-1954 for the same six stations as above is shown in figure II-G-5. The three U. S. operated stations, Washington, White Sands and Maui, show an increase in b up to 1951 after which a plateau appears to be reached. All three of these stations shifted from the model A or the C-2 ionosonde to the C-3 in the period 1950-1951. In the case of White Sands, the change in b occurred concommitant with the change to the C-3 in April of 1951. The non-United States stations, Christchurch, Yamagawa, and Narsarssuak, do not appear to show any systematic variation with sunspot cycle.

It is interesting to note that if equipment improvement is discounted, the sunspot dependence would be just opposite to the earlier observation referred to above for Washington. This fact lends support to the position that no regular variation of b with sunspot cycle can yet be considered established.

VARIATIONS IN OBSERVED VALUES OF THE FREQUENCY DEPENDENCE FACTOR "b" DURING 1948–1954

Comparison of Occurrence fEs > 7Mc to fEs > 5Mc

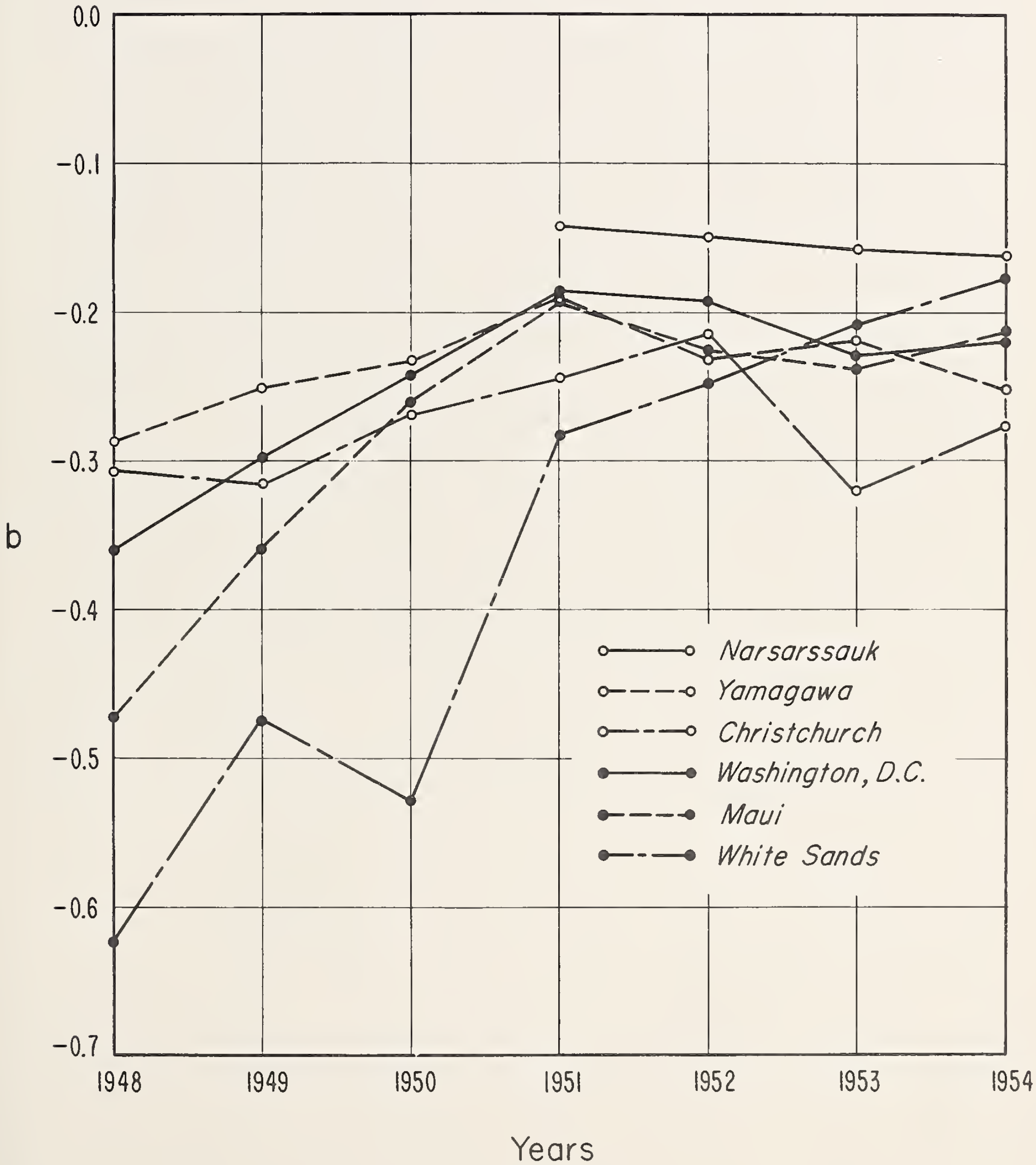


Figure II-G-5

H. Magnetic Activity and Sporadic E

The influence of solar corpuscles in producing sporadic E has been reviewed in chapter I. Magnetic activity is discussed in some detail in Appendix I and the reader is referred to this review for definitions and the history of the principal measures of the phenomenon. Suffice to say here that most magneticians believe that magnetic activity is a product of the incidence upon the upper atmosphere of charged particles from the sun (see for example Bartels and Johnston [1939]). If this conception of magnetic activity is correct, then a study of the relationship of Es and magnetic activity is also a study of the influence (perhaps indirect) of charged solar corpuscles on sporadic E.

A comparison of sporadic-E incidence observed on magnetically quiet days to that observed on disturbed days is described in 1 of this section. An analysis of magnetic activity during the period 1948-1954 is given in 2. The significance of the results of 1 and 2 from the point of view of radio communications is not easy to assess from the results of the method used in this study which compares one-sixth of the days of the year to another one-sixth of the days. A possible use to communications is indicated by the results, but the proper determination of the applicability of the correlation of magnetic activity and sporadic E will be left for a future study.

1. Es Occurrence on Magnetically Quiet and Disturbed Days.

Auroral-Zone sporadic E taken as a whole has long been known to be positively correlated to magnetic activity. In the Temperate Zone, however, most authors do not consider any marked association of Es with magnetic activity to exist. This latter opinion is at variance with the findings of this study.

A very simple method is used to portray the degree of magnetic effect on Es. The distributions of Es (with frequency and hour of the day) for the five magnetically-quiet days of each month are compared with the distributions obtained for the five magnetically-disturbed days. The distributions are reduced from the hourly values of fEs on the magnetically-selected days for a basic period of one year for each station considered. Figure II-H-1 compares the total Es recorded on magnetically-disturbed to magnetically-quiet days during the year 1951 for each hour of the day at three stations. The station examined in the top histogram, Ft. Chimo, is on the maximum of the Auroral Zone. Es there is seen to occur more frequently on the disturbed than on the quiet day as expected. The second chart is for Washington, D. C., a high temperate-latitude station. Es at this location is observed to be consistently more frequent on magnetically quiet than disturbed days. In the histogram at the bottom of figure II-H-1, the Es occurrence at Puerto Rico, a low temperate-latitude station, is seen to be independent of magnetic activity.

The comparison for more intense sporadic E is shown in figure II-H-2. It differs from figure II-H-1 in that only the

SPORADIC E INCIDENCE ON MAGNETICALLY SELECTED QUIET AND DISTURBED DAYS TOTAL Es

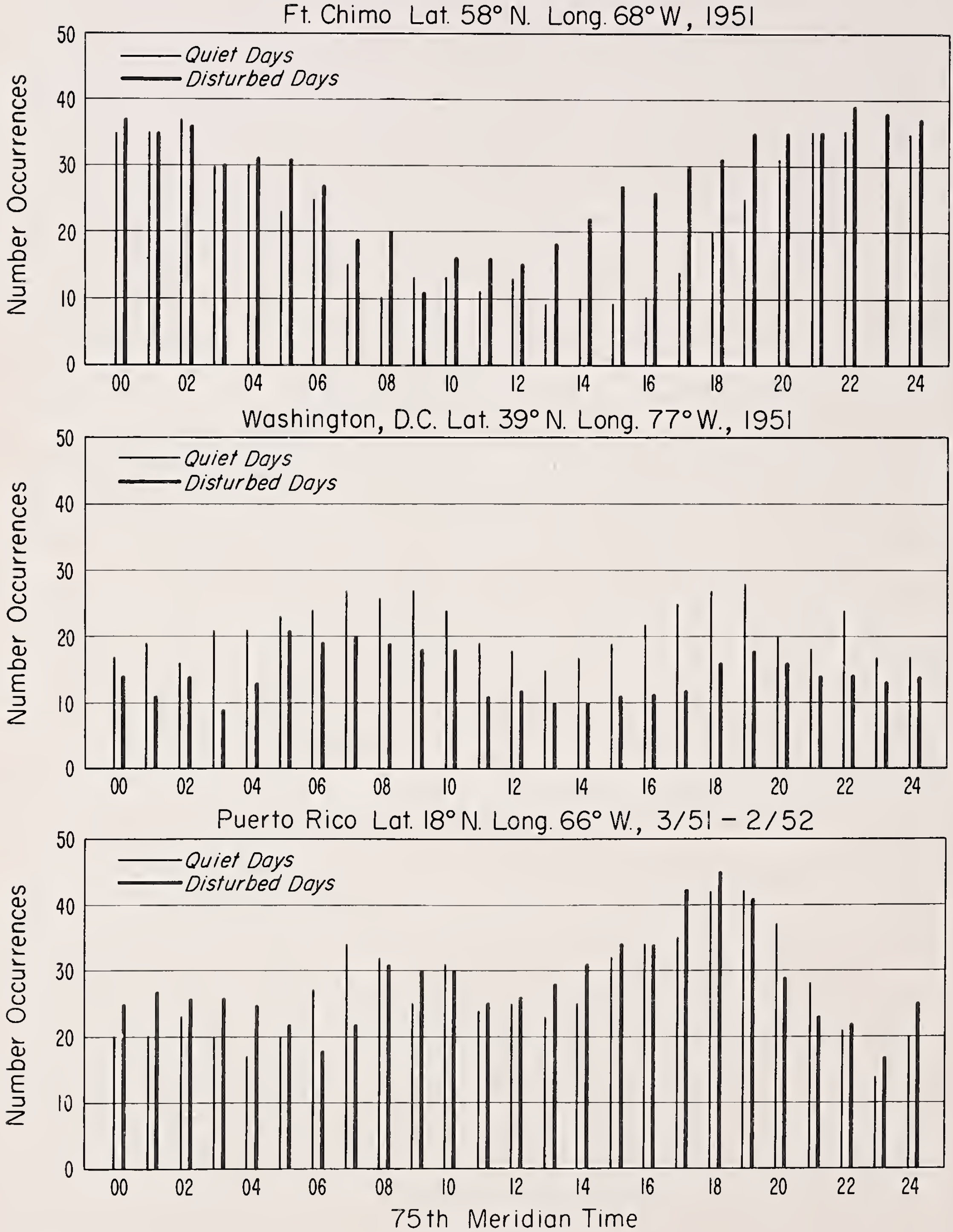


Figure II-H-1

SPORADIC E INCIDENCE ON MAGNETICALLY SELECTED QUIET AND DISTURBED DAYS

f Es > 4.95 Mc

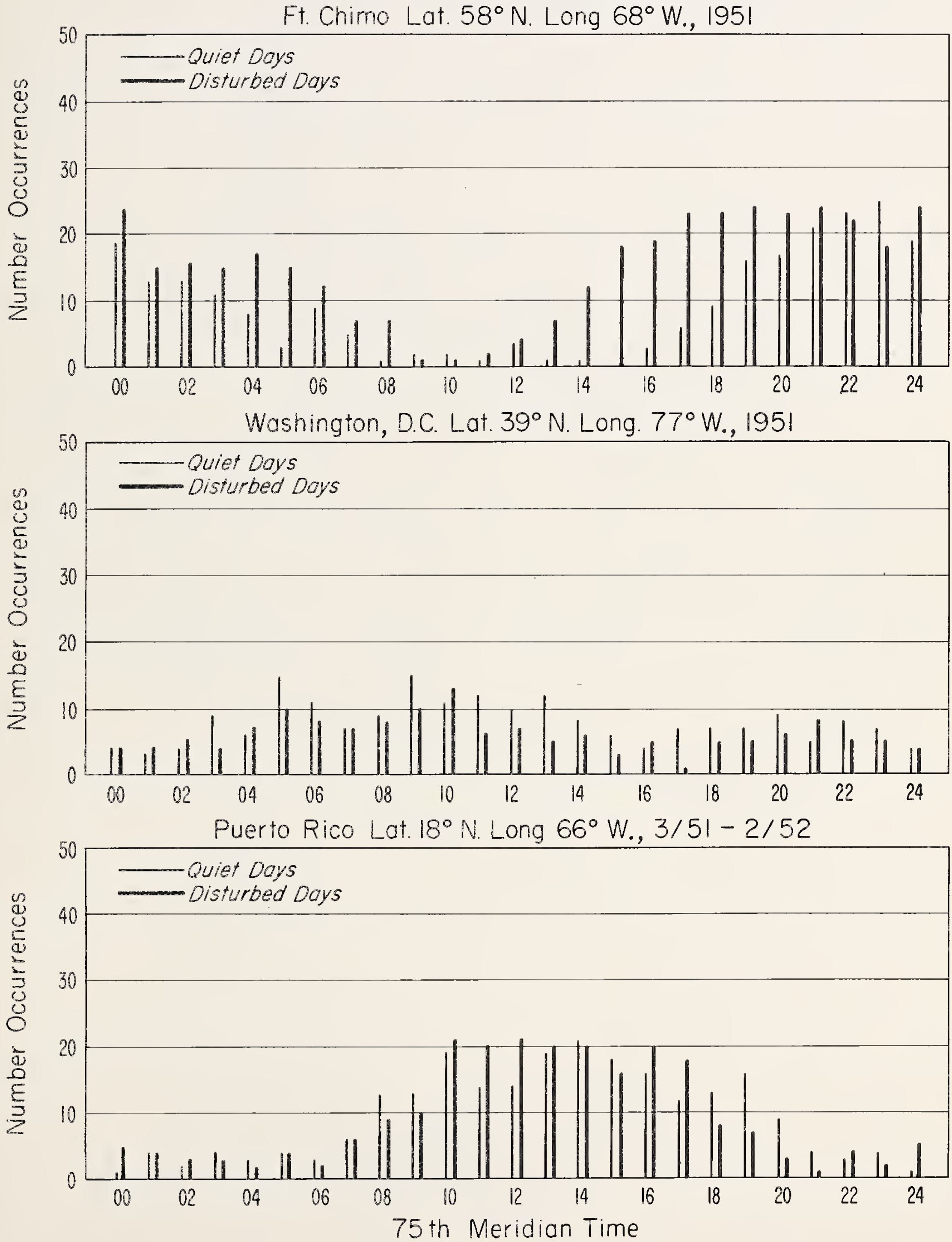


Figure II-H-2

recorded values of Es with critical frequency greater than 5 Mc are considered. It is interesting to note that at Ft. Chimo the preponderance of Es on disturbed days is greater than before, at Washington the quiet days show more Es than the disturbed days, but not quite so strikingly, while at Puerto Rico there is still no magnetic effect apparent.

In order to obtain an adequate statistical sample in a critical frequency presentation, it is desirable to lump the data for all hours of the day together. Figure II-H-3 shows the occurrence of sporadic E criticals in each half-megacycle frequency unit during the magnetically quiet and disturbed days for the same three stations. The peaks and irregularities shown in this histogram (in accordance with the discussion in section II-C) pretty certainly have little to do with Es but rather represent variations in system gain in the ionosonde and in intensity of incoming interference.

The cumulative distributions of the data of figure II-H-3 are shown in figure II-H-4. It is noteworthy that the Phillips Rule (Phillips [1947]) which states that a straight line will fit an Es distribution plotted as in figure II-H-4 appears to fit Es recorded on magnetically quiet and disturbed days individually. Also worthy of note is the fact that at Ft. Chimo the proportion of Es observed on disturbed days goes up with increasing frequency. This fact is also observed at Washington, but the data sample becomes too small to ascertain if Es observed on disturbed days ever becomes greater than that observed on quiet days as higher

DISTRIBUTIONS OF Es ON MAGNETICALLY SELECTED DAYS BY CRITICAL FREQUENCY

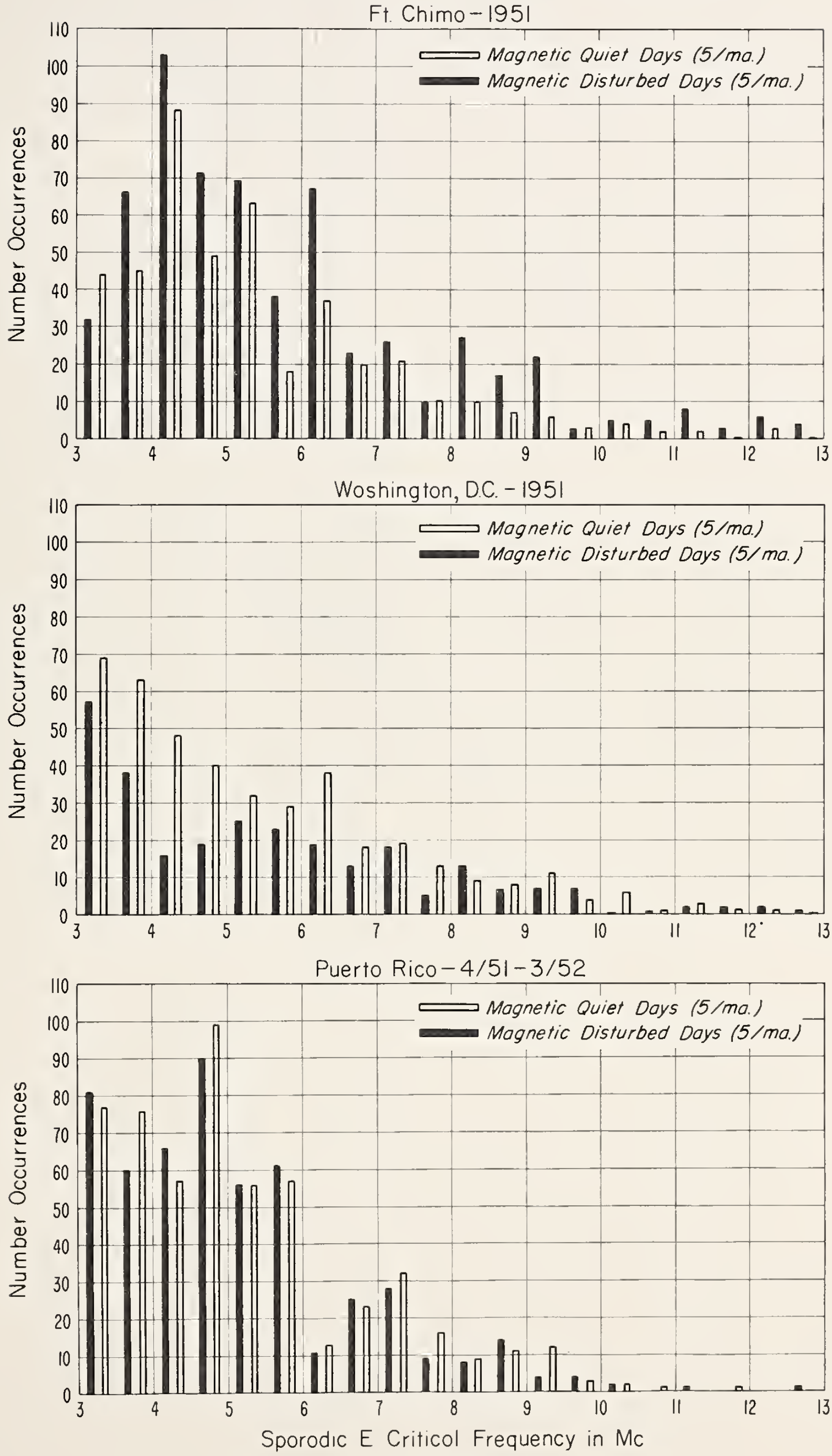


Figure II-H-3

CUMULATIVE DISTRIBUTIONS OF SPORADIC E ON MAGNETICALLY SELECTED DAYS

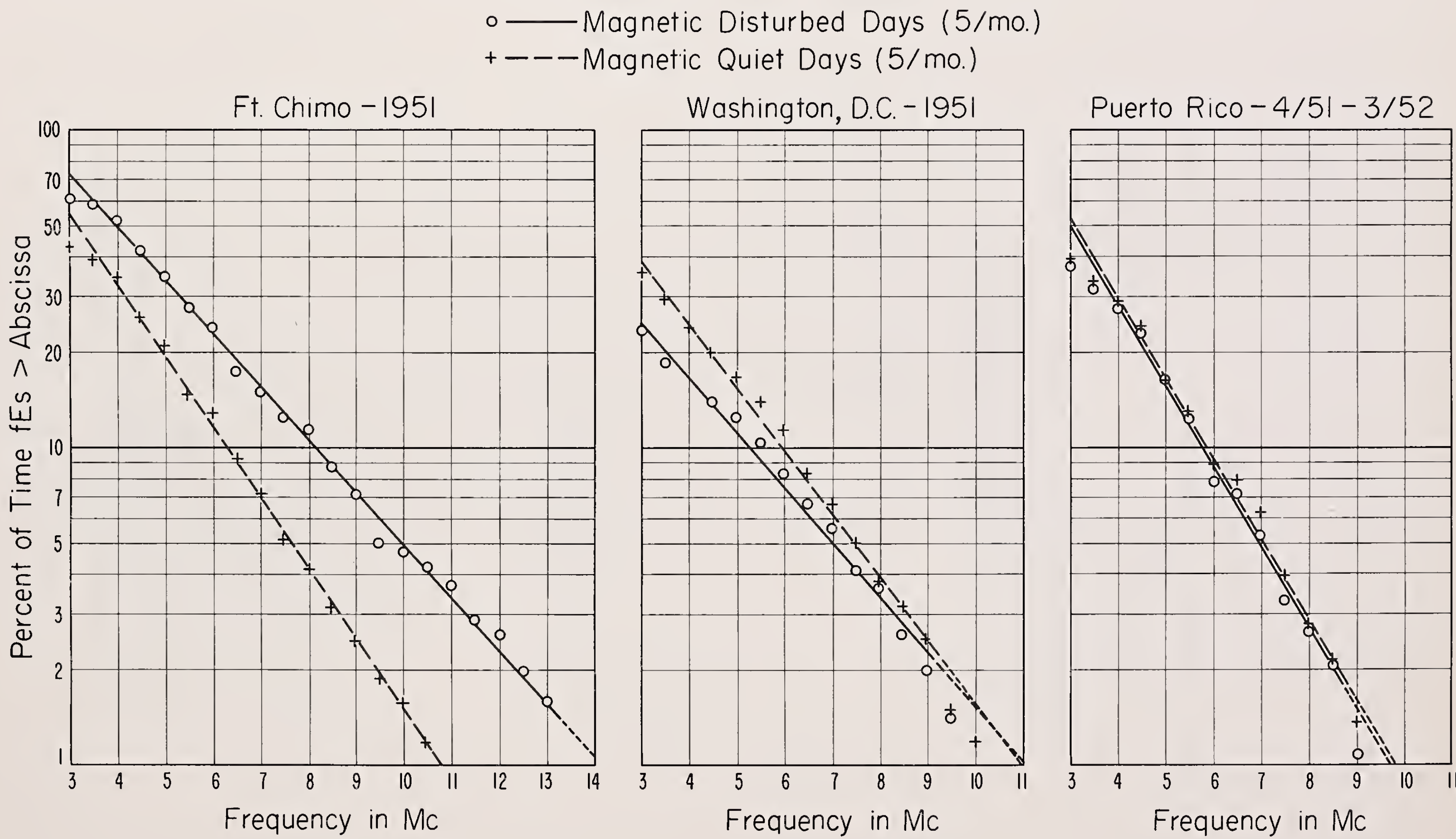


Figure II-H-4

frequencies are considered. It will be shown in the next chapter that this does not appear to be the case.

Figure II-H-5 presents a summary of the findings on the influence of magnetic activity on Es for the stations examined for the year 1951. It has proven very difficult to fill the blank area between 60° and 70° north geomagnetic latitude. This is due to the prevalence of polar blackouts in this interval (Agy [1954]). The scaling convention used has been that if a magnetically-selected disturbed Greenwich day contains more than two hours rendered unusable because of total absorption, that day is discarded and one day is also discarded from the quiet group for the month. This convention leads to the rejection of essentially all days for this latitude interval. Figure II-H-5 does illustrate that in the Auroral Zone more Es is observed on magnetically disturbed days, whereas in the high Temperate Zone (30° to 60° N. geomagnetic latitude) more Es is observed on magnetically quiet days. The situation below about 20° (shown in dashed line) is not clear at present.

It is difficult in a study of this nature to combat the argument that the results obtained are due not to a variation of Es but to one in non-deviative absorption. For instance, the negative correlation found for temperate latitudes could be completely invalidated if high absorption were found to possess a strong positive correlation with magnetic activity in this zone. The following quote from a recent comprehensive account of non-deviative absorption over England by Appleton and Piggott

A MAGNETIC EFFECT ON SPORADIC E
1951 DATA

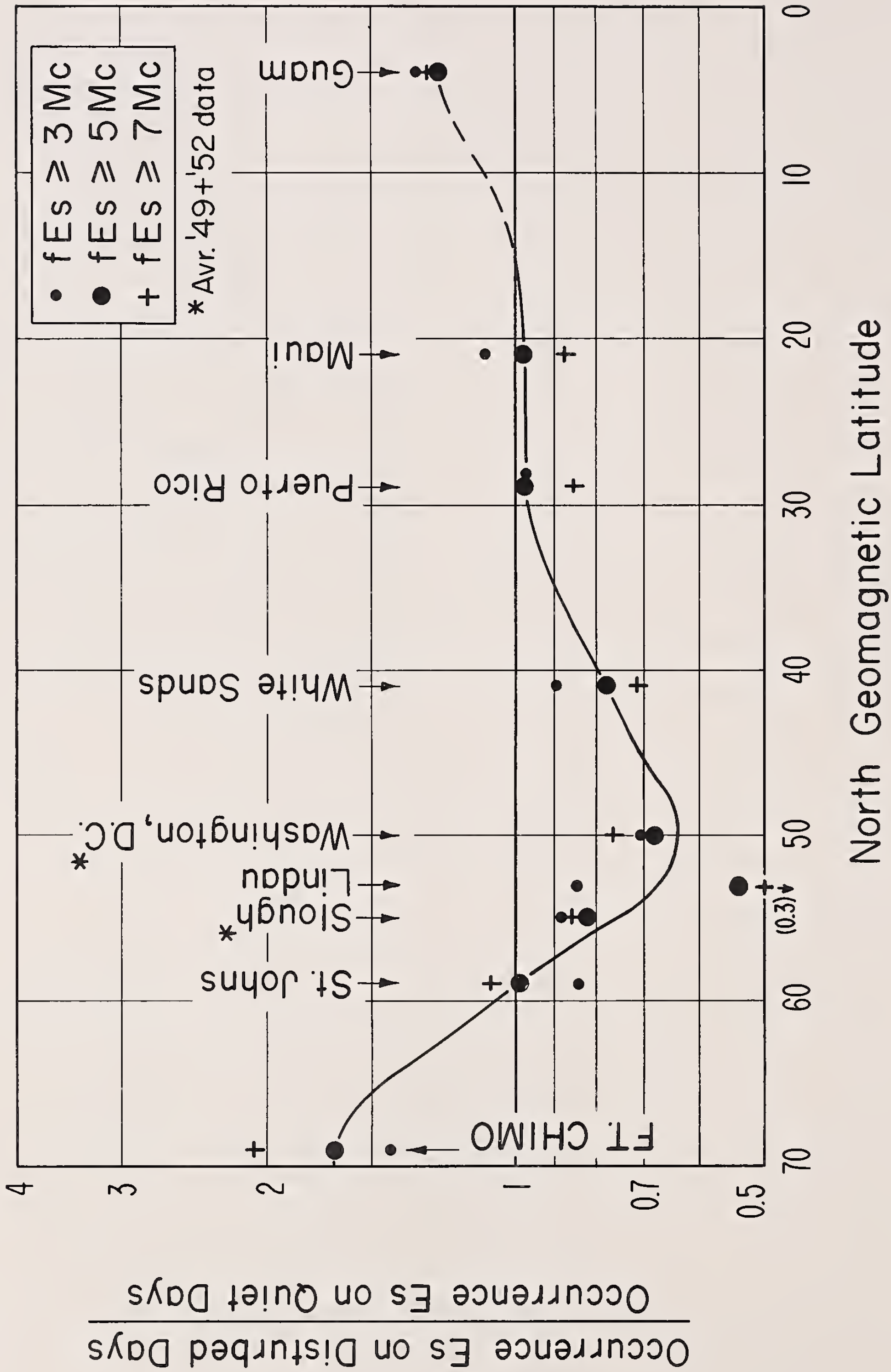


Figure II-H-5

[1954] shows this to be an unlikely explanation.

"We have also sought to find if days of high absorption and periods of magnetic activity are connected, but have found no correlation. However, we have noticed that sequences of days of high absorption often cease with the onset of a magnetic storm. Selecting the five magnetically quiet days for the winter months we find that these are associated with high absorption 1.2 times as frequently as would be expected by chance."

A similar result has been obtained by Beynon and Davies [1954], again for England.

In the Auroral Zone the known increase in blackouts during active overhead aurorae will serve to accentuate the results shown here for the magnetic effect in this zone.

The negative correlation of Es with magnetic activity indicated here for the North Temperate Zone is re-examined in the next chapter where a study of long-distance television reception (TV-DX) is made. As the same negative correlation is found for these sporadic-E transmissions which concern frequencies above 54 Mc where the effects of absorption are reduced to neglibible proportions the negative correlation would appear to be real.

It is important in a study of this nature to investigate whether or not a phase lag exists between magnetic activity and sporadic E. As the correlation procedure used here is a very crude one only a rough determination of phase is practical. The method employed is to determine the cumulative distribution curve of fEs occurrence for the sixty days in a year immediately preceding the sixty magnetically-selected quiet days. The process is repeated for the sixty days immediately following the quiet days. The whole process is then repeated in connection with the sixty disturbed days. These distributions are now compared with the ones for the quiet and disturbed days themselves. Such a comparison for Washington D. C., 1951 data, is seen in figure II-H-6. The day immediately before the quiet day (Q-1) is seen to be little different from the quiet day (Q) itself. Q-1 shows lower Es occurrence for values of the abscissa frequency under a 5 Mc and higher occurrence for values over 9 Mc, D+1 is substantially lower at almost all frequencies. For the day preceding the disturbed days (D-1) the cumulative distribution is seen to be higher than that for D at both ends of the spectrum, whereas, D+1 is lower for the high frequencies. This variation with spectral region makes interpretation difficult. The results for D-1, D and D+1 are what one might expect if a negative correlation exists between Es and magnetic activity and also if the effects of a magnetic storm take some time to wear off. The quiet day distributions seem to imply that for sporadic E, Q-1 is about as "quiet" as Q and considerably more "quiet" than Q+1, or that Es leads magnetic activity somewhat in this regard.

Another aspect which needs to be considered is the year-to-year variation of the correlation. Figure II-H-7(a) contains a frequency presentation of the ratios of the ogives for quiet and disturbed days for four years at Washington, D. C. As can be seen in (b) of this figure a considerable spread of sunspot num-

CUMULATIVE DISTRIBUTIONS OF Es IN THE NEIGHBORHOOD OF MAGNETICALLY SELECTED DAYS
WASHINGTON, D.C. 1951

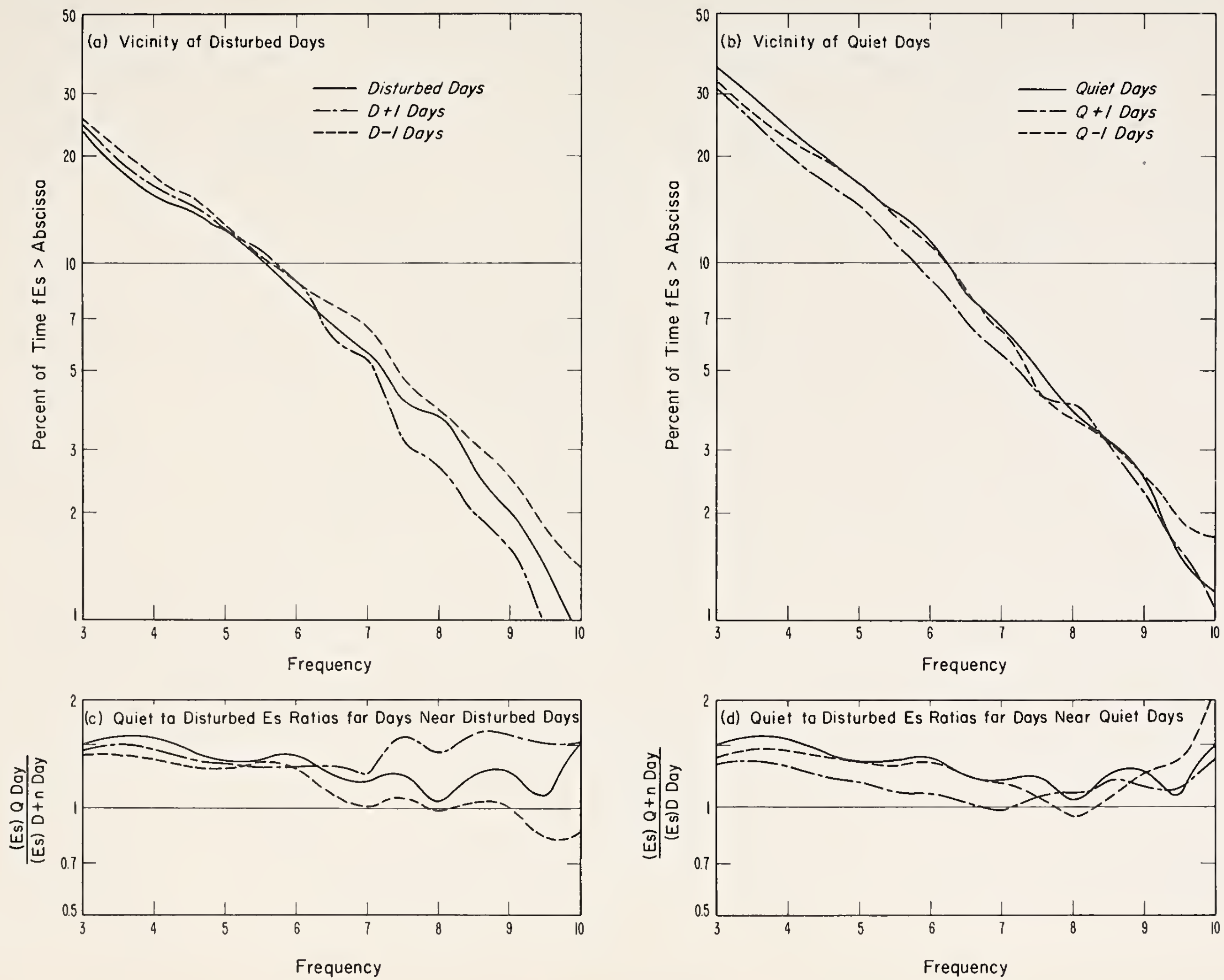
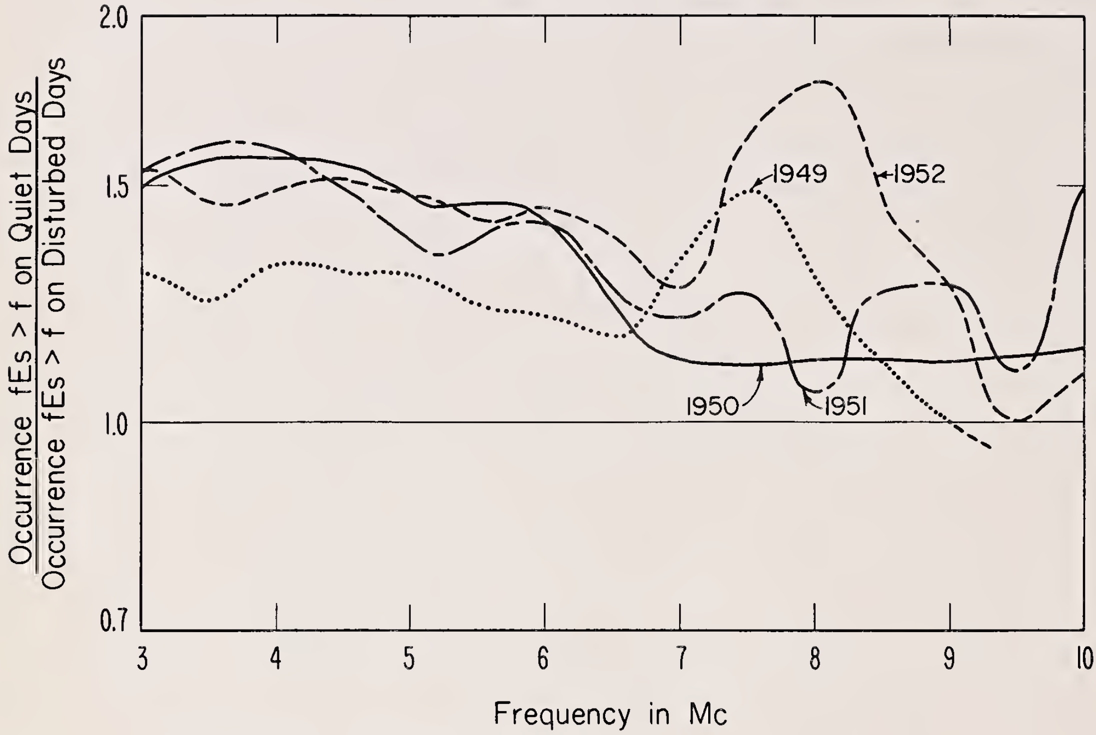
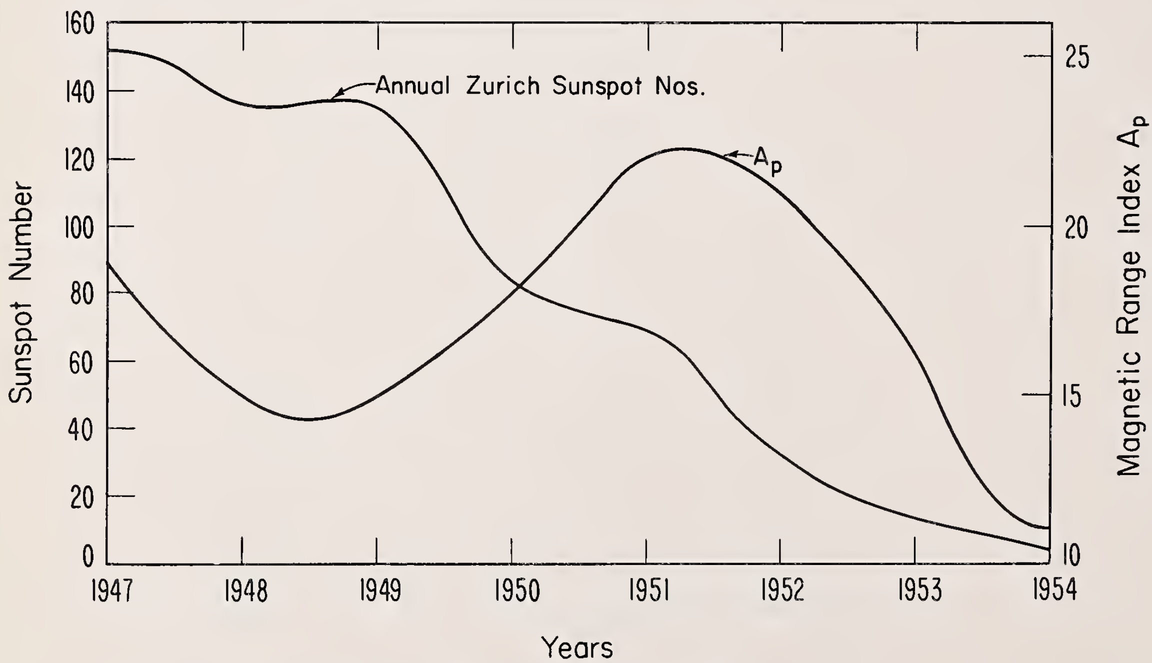


Figure II-H-6

MAGNETIC EFFECT ON Es FOR VARIOUS YEARS AT WASHINGTON, D.C.



(a) Sporadic E at Washington, D.C.



(b) Mean Sunspot and Magnetic Activity Figures

Figure II-H-7

bers is represented as well as magnetic figures and still no drastic change in the ratios is discernible between 1949 and 1952.

2. Magnetic Activity During the Period 1948-1954.

It is interesting to consider how magnetic activity has varied on the international quiet and disturbed days throughout the period 1948-1954 which covers the declining half of a sunspot cycle. Figure II-H-8 gives the values of A_p (the equivalent range index) during this period for the quiet and disturbed days of each month. The reader is referred to Appendix I for a description of how this magnetic selection of days is made. It is seen that, although the highest individual values of Ap appear during the years 1948-1949 (a period near sunspot maximum), the highest levels of magnetic activity occurred in 1951-1952. The statistical lag during certain sunspot cycles of magnetic activity behind sunspot number has frequently been noted in the past, however, a better understanding of this lag is given in a recent study by Newton and Milson [1954] where an analysis of magnetic storms shows that great magnetic storms and small ones characterized by sudden commencement did occur most frequently at the peak of the sunspot cycle. On the other hand, small magnetic storms without sudden commencement reached their greatest occurrence frequency two to three years after the peak of the sunspot cycle. These features can be seen to be in general agreement with the distribution of Ap values for the quiet and disturbed days shown in figure II-H-8.

VARIATION OF MAGNETIC ACTIVITY
FOR THE INTERNATIONAL QUIET AND DISTURBED DAYS
1948 – 1954

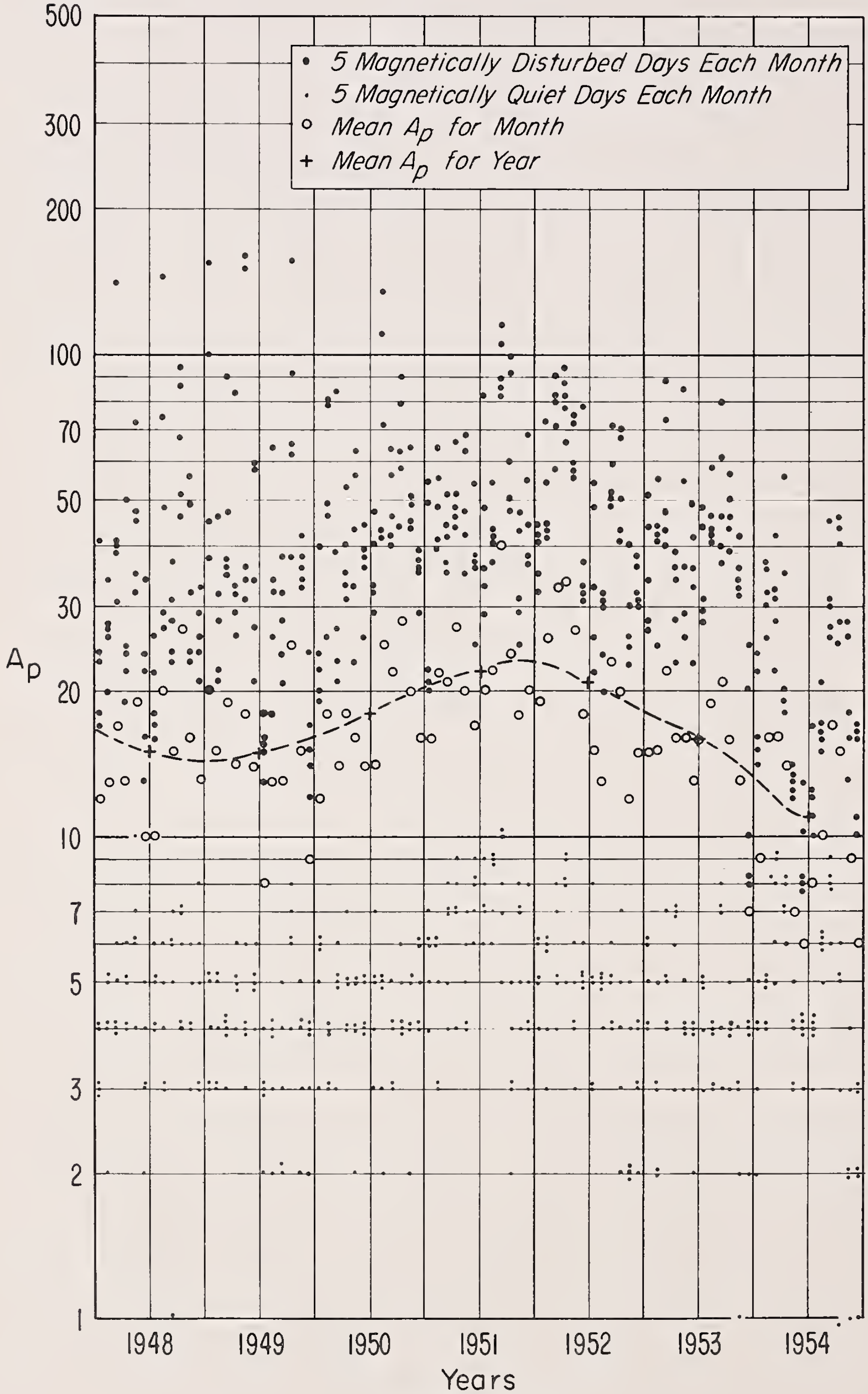


Figure II - H - 8

A legitimate question in connection with the preceding analysis of Es on the magnetically quiet and disturbed days is how does one know that for a quiet month the Ap value for a disturbed day may not be less than the Ap values for quiet days during a disturbed month. Examination of figure II-H-8 reveals that only after December 1953 is there any overlapping of Ap values for the two sets of days. Prior to that time, the Ap values for the disturbed days are observed to be all higher than those for the quiet days.

The seasonal variation of magnetic activity during the 1948-1954 period is shown in figure II-H-9. It is seen that, as is the case with auroral activity, magnetic activity is high during the equinoctial periods and low in the solstitial ones. This is exactly opposite to the seasonal variation of Temperate-Zone sporadic E and, therefore, agrees well with the negative correlation found for most of this zone.

One of the first indications which early observers had that magnetic activity was subject to solar control was the 27-day recurrence tendency which magnetic activity exhibits. The superposed-epoch diagram of figure II-H-10 illustrates this recurrence tendency in the selected quiet and disturbed days. A quantitative representation of this tendency is obtained through the Chree diagrams (Chree [1912]) seen in figures II-H-11 and II-H-12.

The solid curves may be interpreted as probabilities by dividing the ordinate scales by 420. Both quiet and disturbed days are seen to exhibit a 27-day recurrence tendency. The mean

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SEASONAL VARIATION OF MAGNETIC ACTIVITY
1948-1954

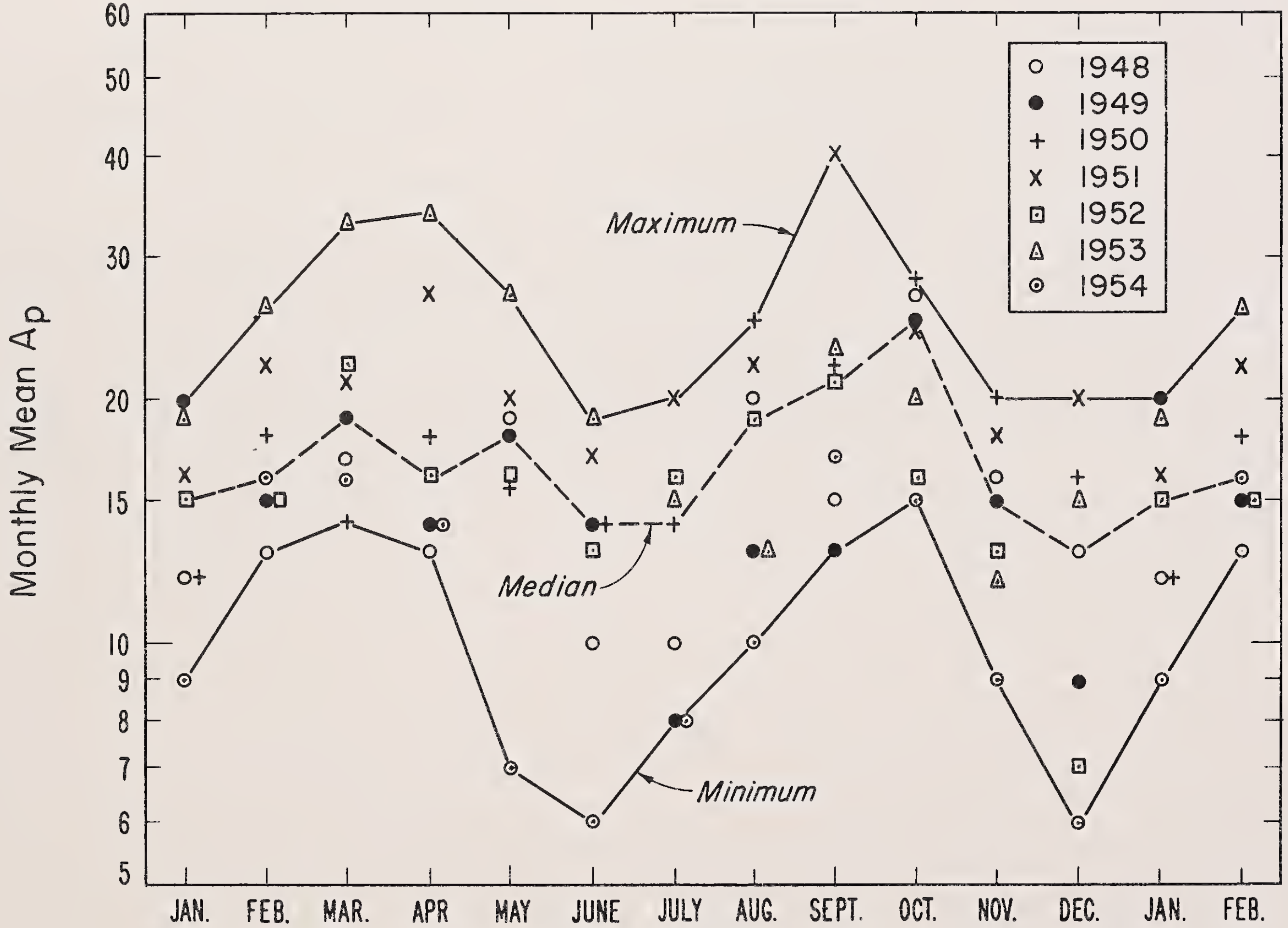

Figure II-H-9

27-DAY RECURRENCES IN MAGNETICALLY SELECTED QUIET AND DISTURBED DAYS
1948 – 1954

○ QUIET DAYS (5 per month)
● DISTURBED DAYS (5 per month)

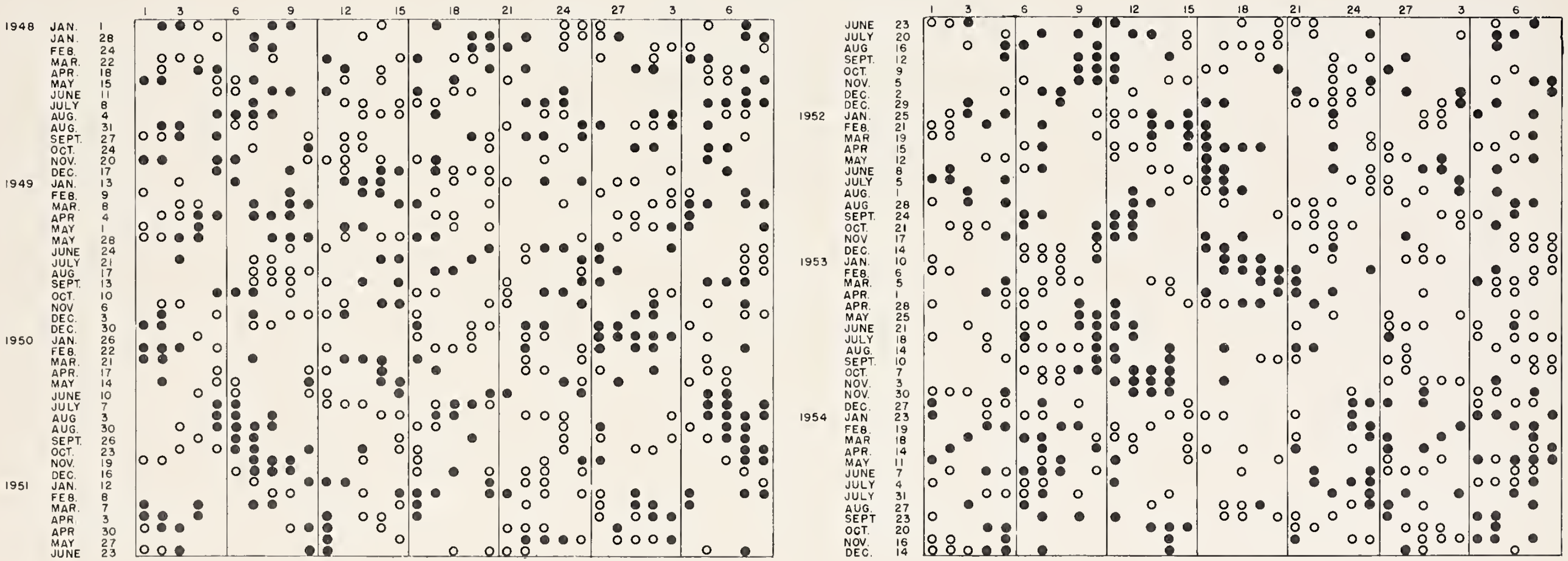

Figure II-H-10

27-DAY RECURRENCE TENDENCY IN MAGNETICALLY SELECTED DISTURBED DAYS 1948-1954

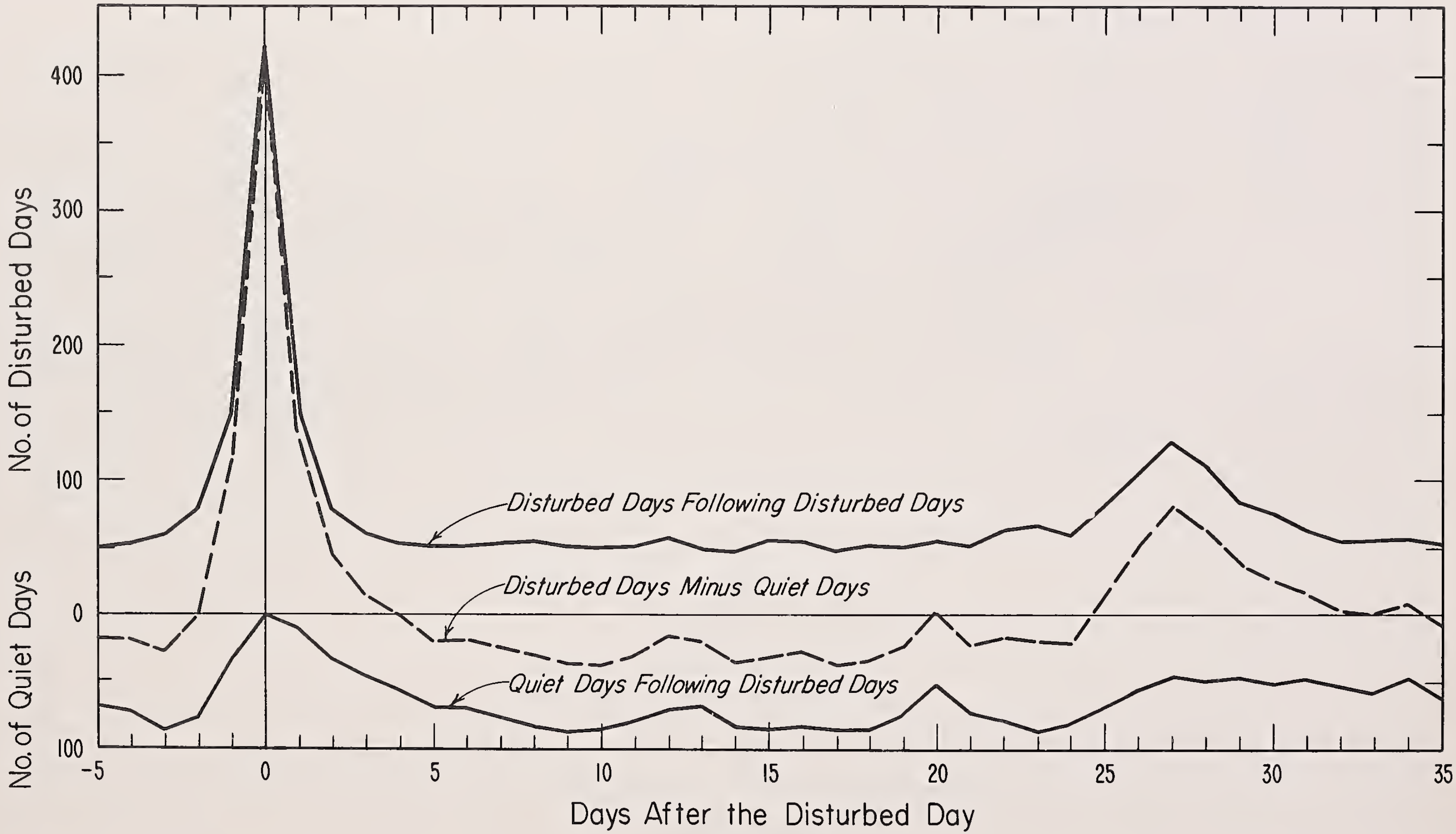

Figure II-H-11

27 - DAY RECURRENCE TENDENCY IN MAGNETICALLY SELECTED QUIET DAYS 1948–1954

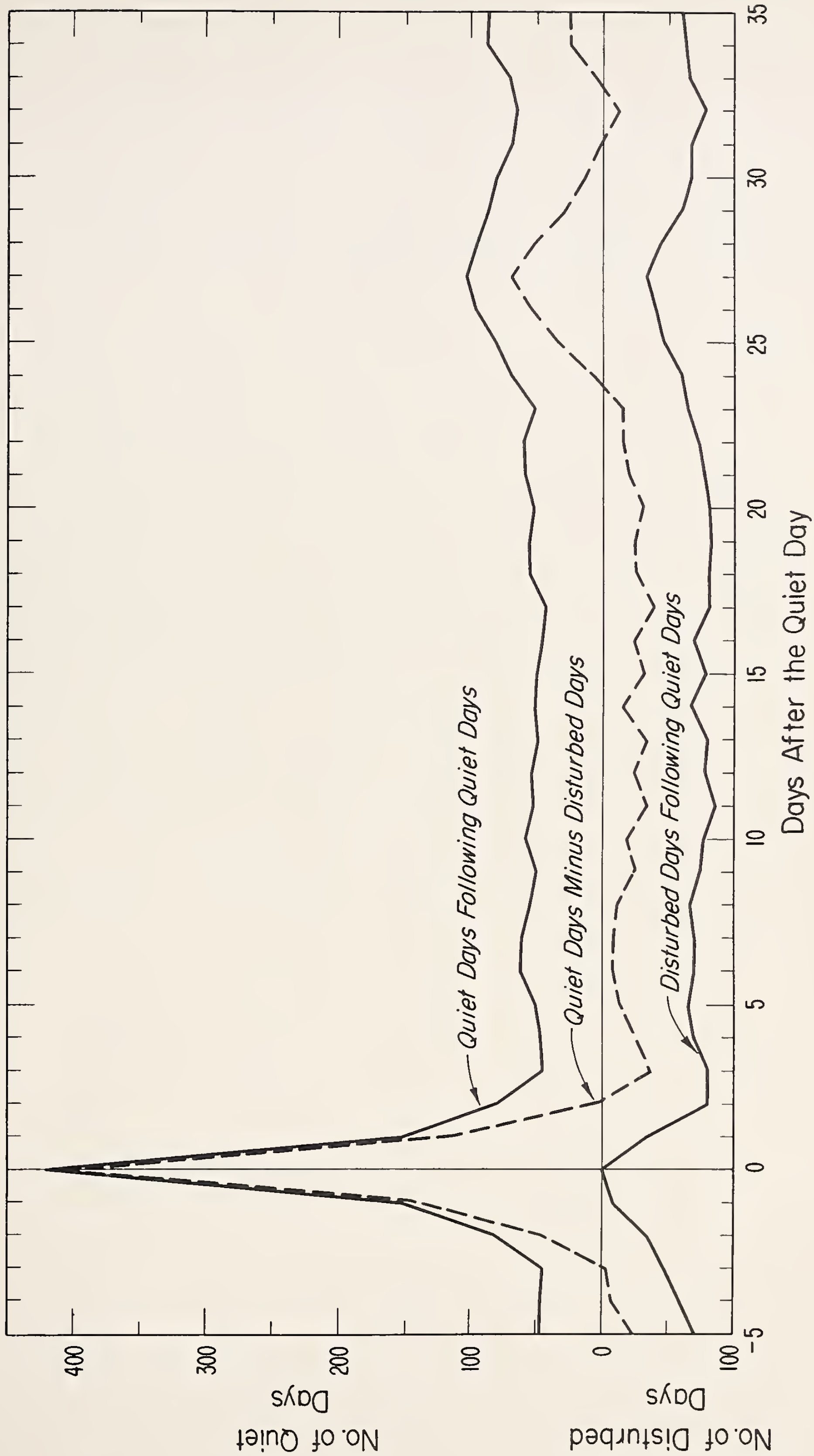

Figure II-H-12

probabilities over the 1948-1954 period of observing quiet, disturbed or intermediate days 27 days after a quiet or disturbed day can be tabulated from figures 4 and 5 as follows:

27 days following type of day shown	Probabilities		
	Disturbed Days	Quiet Days	Intermediate
Disturbed Days	0.30	0.11	0.59
Quiet Days	0.08	0.25	0.67

The variation of the 27-day recurrence tendency with year during the 1948-1954 period is seen in figure II-H-13. This tendency appears markedly stronger during 1952-1953 than either before or after. This peak is somewhat later than the maximum in the level of magnetic activity seen in figure II-H-8.

VARIATION IN THE 27-DAY RECURRENCE TENDENCY IN MAGNETIC ACTIVITY

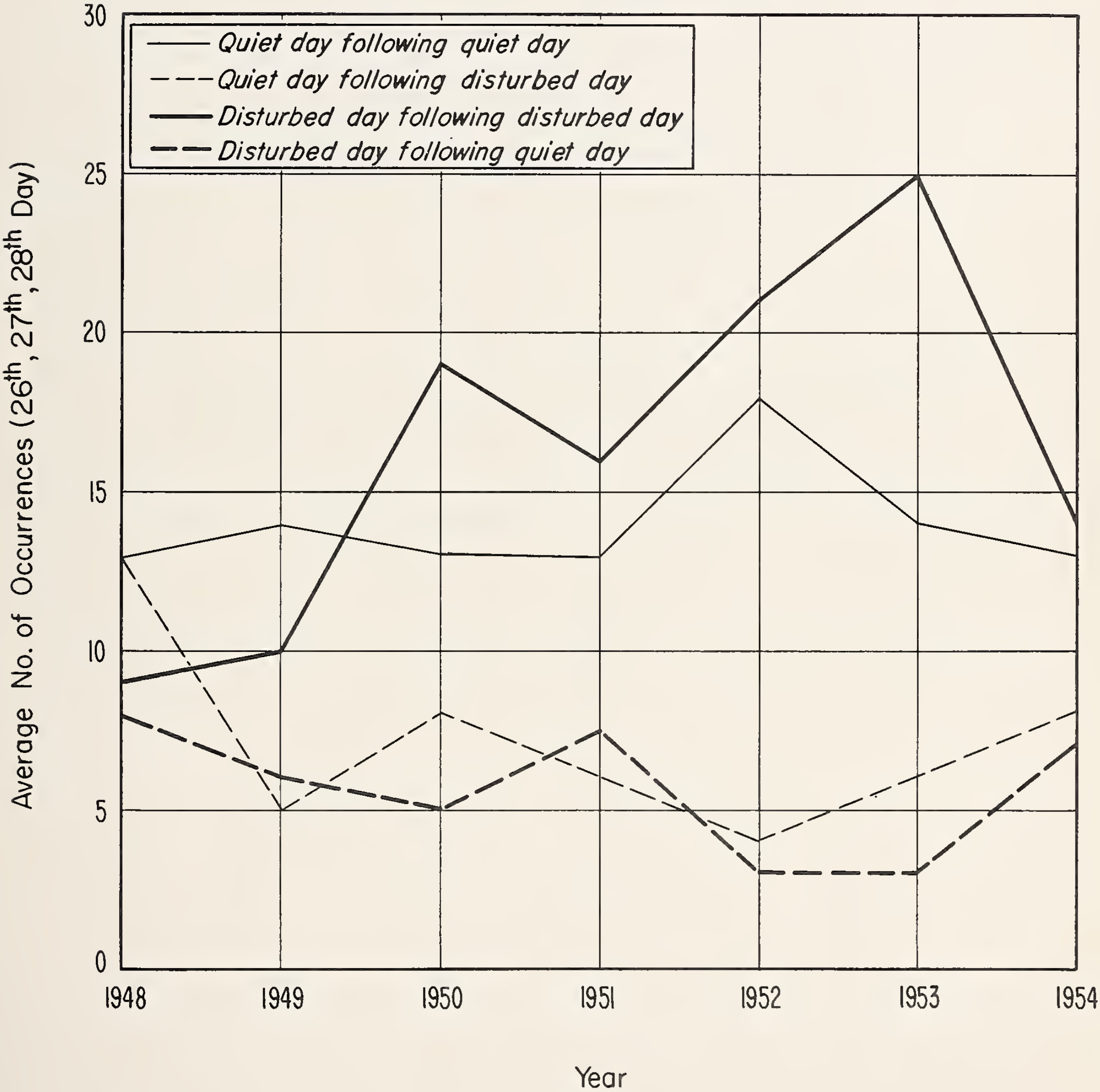

Figure II-H-13

I. A Study of the Height of Occurrence of Es

The measurement of the virtual height of the ionospheric layers is not considered to be very accurate or very important. By international convention most routine stations only record virtual height to the nearest 10 km. By definition the virtual height is the lowest height at which the echo is observed for the layer in question. For most cases of sporadic E the virtual height will not vary with frequency and this recorded value is the one of interest. For the regular E-layer the virtual height of maximum ionization will be about 10 km, (somewhat more than one scale-height) above the recorded value of h'E.

1. Determinations of the Height of the Regular E Layer.

In a study of sporadic-E height it is of interest to know how these heights stand relative to the regular-E layer. One is led, therefore, to take an interest in the height of the regular-E layer. Chapman theory predicts minimum height of the E layer to occur at the location of the sub-solar point and at local noon (or shortly thereafter) at all locations.

The variation of h'E on a typical day (Mar. 3) at Washington, D. C. is shown in figure II-I-I as a function of the sun's zenith angle X. The values obtained to the nearest 10 km for routine reporting are compared with measurements of the same film made on a Tele-Reader. These latter values appear through the courtesy of Roger Gallet. The implication of these data is that there appears considerable justification for routine measurement of h'E to

VARIATION IN THE HEIGHT OF THE REGULAR E LAYER WITH THE SUN'S ZENITH ANGLE

March 3, 1955 Washington, D.C.

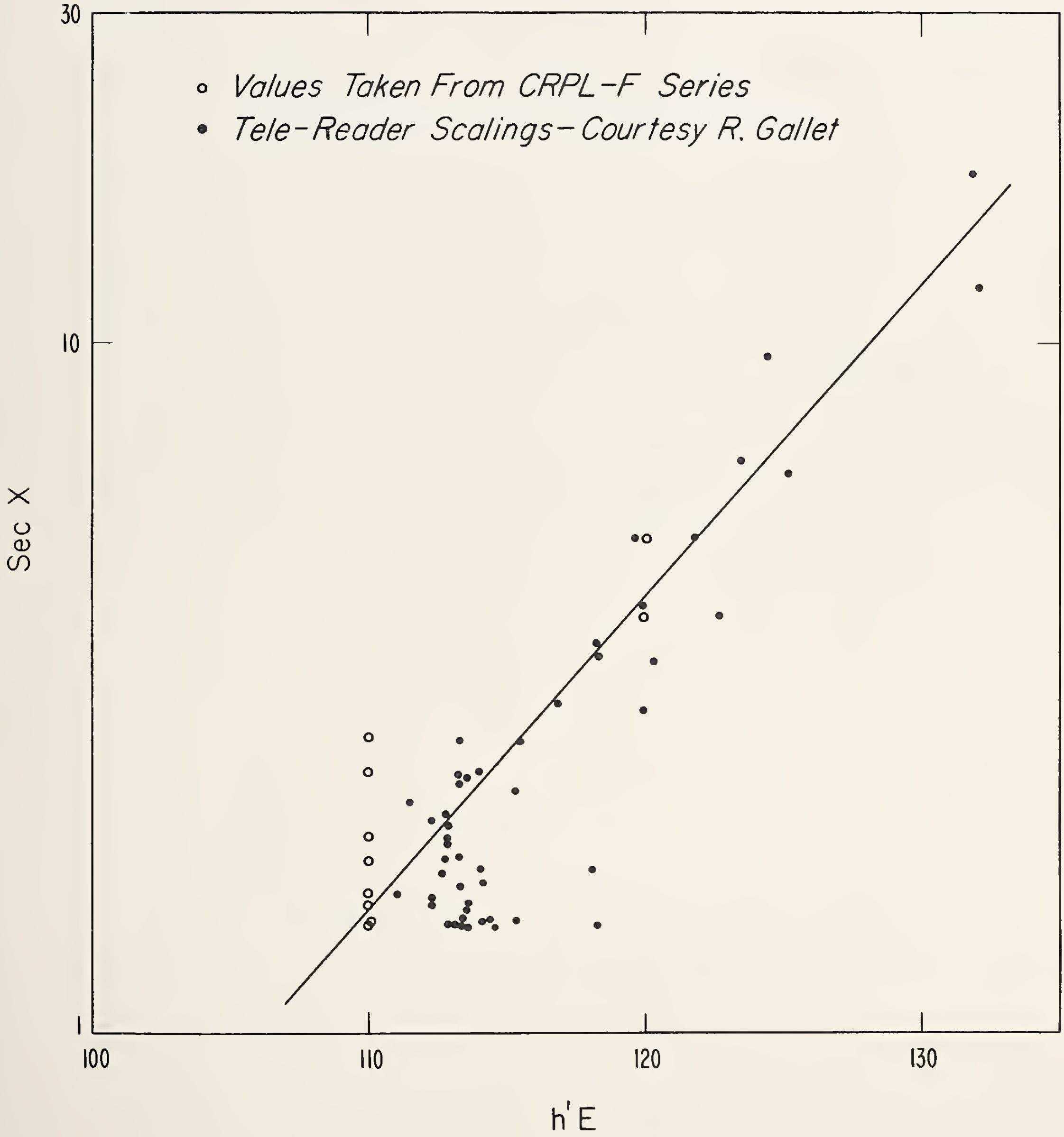

Figure II-1-1

perhaps 1 km instead of 10km.

The opposite impression is obtained when one plots the variation of noon h'E as a function of geographic latitude. Shown in figure II-I-2 are the monthly median values of noontime h'E for reporting stations during the months of June,September and December 1952. The situation for June is particularly disconcerting inasmuch as h'E appears more like a maximum than a minimum at the sub-solar point (20° to 22° North). In fact, December is the only month shown for which the height distribution appears to agree even approximately, with prediction. It is quite possible that as June is the month of maximum Es in the northern hemisphere, many of the low values for the latitudes 30° - 60° N. can be attributed to Es contamination. The principal purpose served by figure II-I-2 is to cast doubt on the recorded values of h'E. If the trouble with these h'E values is Es contamination, then the same inconsistencies need not show up in the sporadic-E height determinations (h'Es). On the other hand, if the trouble lies in equipment malfunctioning or in preconceived notions on the part of the persons doing the scaling as to what the layer height should be, the same errors would be reflected in the h'Es data.

2. <u>The Distribution of Observed Heights of Es Occurrence</u>.

One conclusion stemming from the consideration of regular E-region heights in the previous section is that short-term variations at a given station are probably the most reliable of the height characteristics which can be obtained from these data. For this reason this study of h'Es will be restricted to a consideration

LATITUDE DISTRIBUTION OF MONTHLY MEDIAN VALUES OF h'E
Source: CRPL-F Series 1948-1954

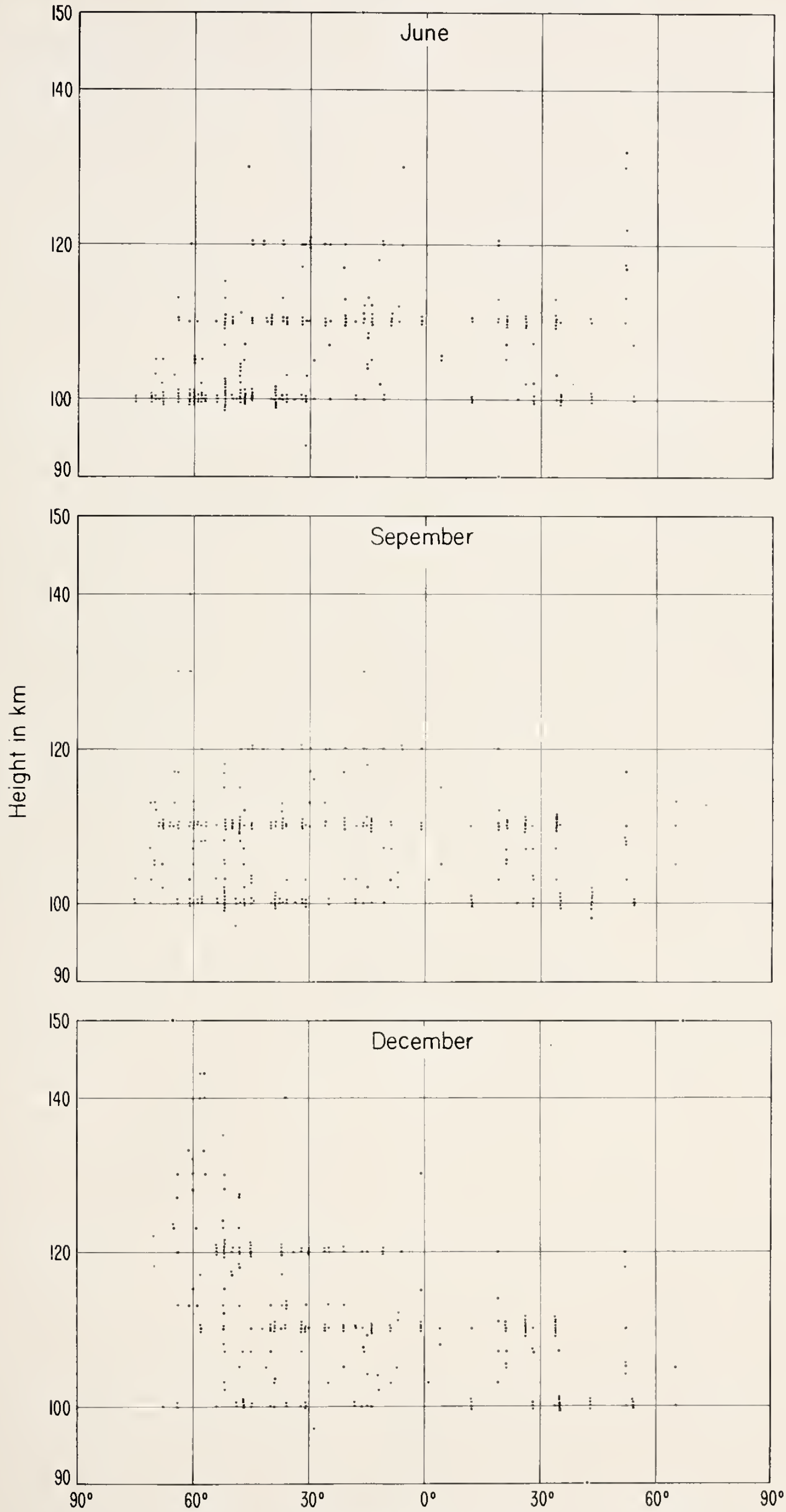

Figure II-1-2

of the variation of diurnal distributions at several stations. As is seen in section II-F for the North Temperate Zone, the peak in yearly occurrence of sporadic E will fall around the summer solstice. In order to see if the diurnal height distribution is different during this solstitial maximum from that for the remainder of the year, the diurnal plots are averaged for the months of May - August and for September - April.

For the single case of Washington, D. C. values of h'Es the diurnal distributions have been summed for the two blocks of months over a period of seven years (1948-1954). These distributions are presented in virtual height vs. time of day plots (similar to those used by R. A. Helliwell, e. g. Helliwell [1954]) in figure II-I-3. The interpretation of these charts is best explained by describing their construction. For each case of sporadic E shown on the station report sheets as having a critical frequency equal to or greater than 5 Mc (fEs $\geq$ 5 Mc) the value of the height (h'Es) is taken. These values for each 10 km height interval are now summed for each hour of the day for the period in question. The sums are entered on the appropriate points of a height vs. time of day chart giving a field of numbers. Contours are now drawn by linear interpolation between these numbers and then smoothed to take out random variations. This procedure is not ideal. For instance if a count of 100 is found for 100 km and 0 for 90 km, linear interpolation will give contours of 75 at 97.5 km, 50 at 95 km and 25 at 92.5 km. However, any measurement of h'Es between 85 and 95 km would have been included in the

Es HEIGHT DISTRIBUTIONS AT WASHINGTON, D.C.

fEs ≥ 5 Mc 1948 - 1954

Contours Are Relative Occurrence of Es

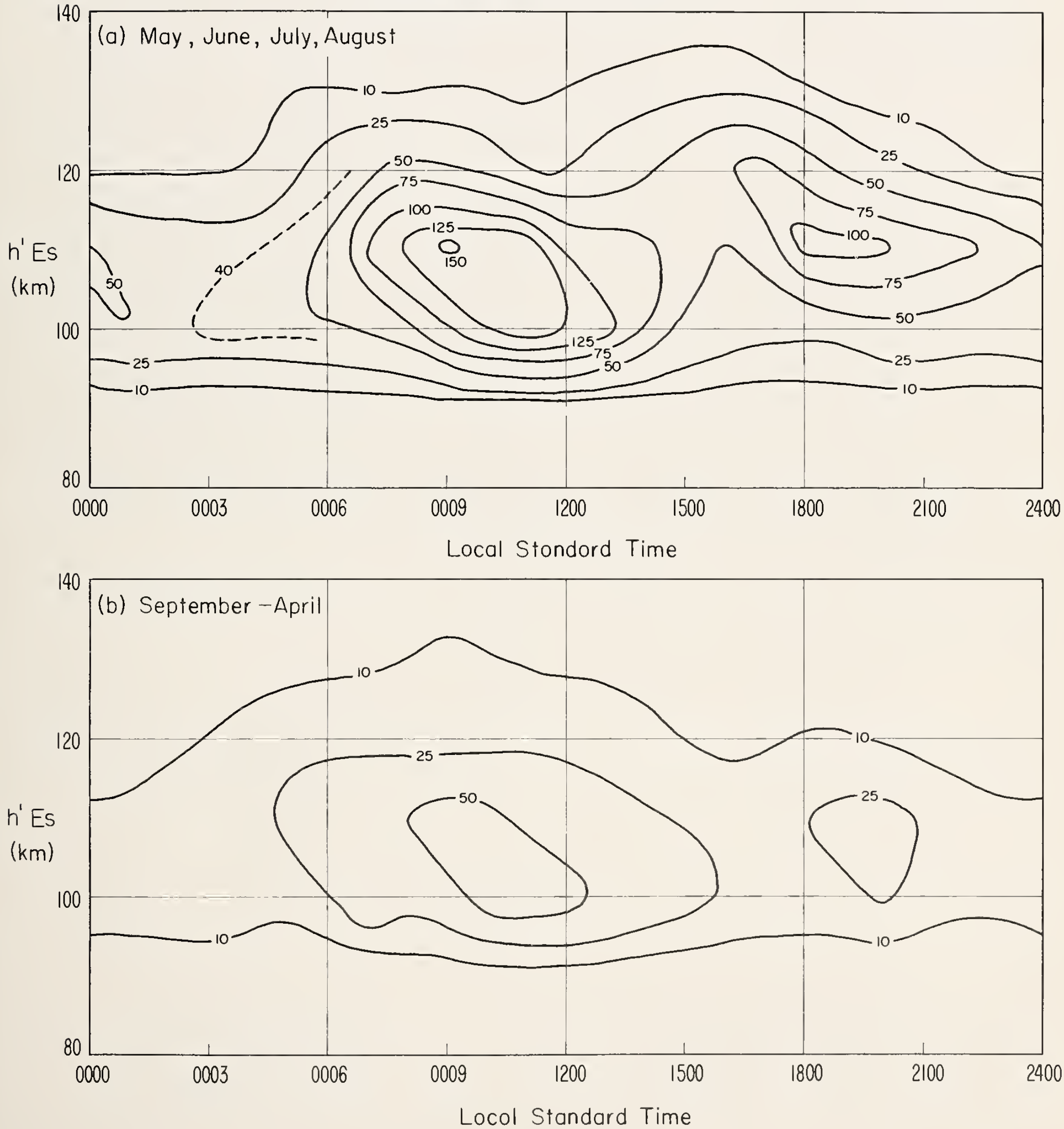

Figure II-1-3

90 km figure and this is zero. A 25 contour at 92.5 km, therefore, seems somewhat surprising. It is necessary to add that the contour value represents the number of cases of h'Es which fall within 5 km of the contour location. This statement assumes that the values given for each 10 km height are evenly distributed throughout the height interval.

An interesting feature of the Washington, D. C. Es height distributions of figure II-I-3 is the separateness of the morning and evening maxima. Both show a tendency to decrease in height with time, but in the evening maximum this tendency is more pronounced. Matsushita [1955] has suggested that this evening maximum be due to sequential Es and this hypothesis appears supported by the evidence of decreasing height from 1700 to 2000 local time. The average hourly height at Washington lies between 105 and 115 km for both time periods so that the choice of 110 km seems appropriate in this area.

In figure II-I-4 are seen charts of the height distributions of five stations during 1952. Ft. Chimo, at the peak of the auroral incidence and Huancayo, on the magnetic equator, appear relatively insensitive to season. The three intermediate stations show quite a bit of variation. At White Sands and Maui mean heights are somewhat higher for the summer months while at Guam a peculiar dorsal-fin like appendage makes its appearance. At both Guam and Maui a downward descent of the distributions can be detected which again may be related to sequential Es.

Es HEIGHT DISTRIBUTIONS AT FIVE STATIONS FOR 1952

$fEs \geq 5$ Mc

Contours Are Relative Occurrence of Es

MAY, JUNE, JULY, AUGUST | JAN. – APR., SEPT. – DEC.

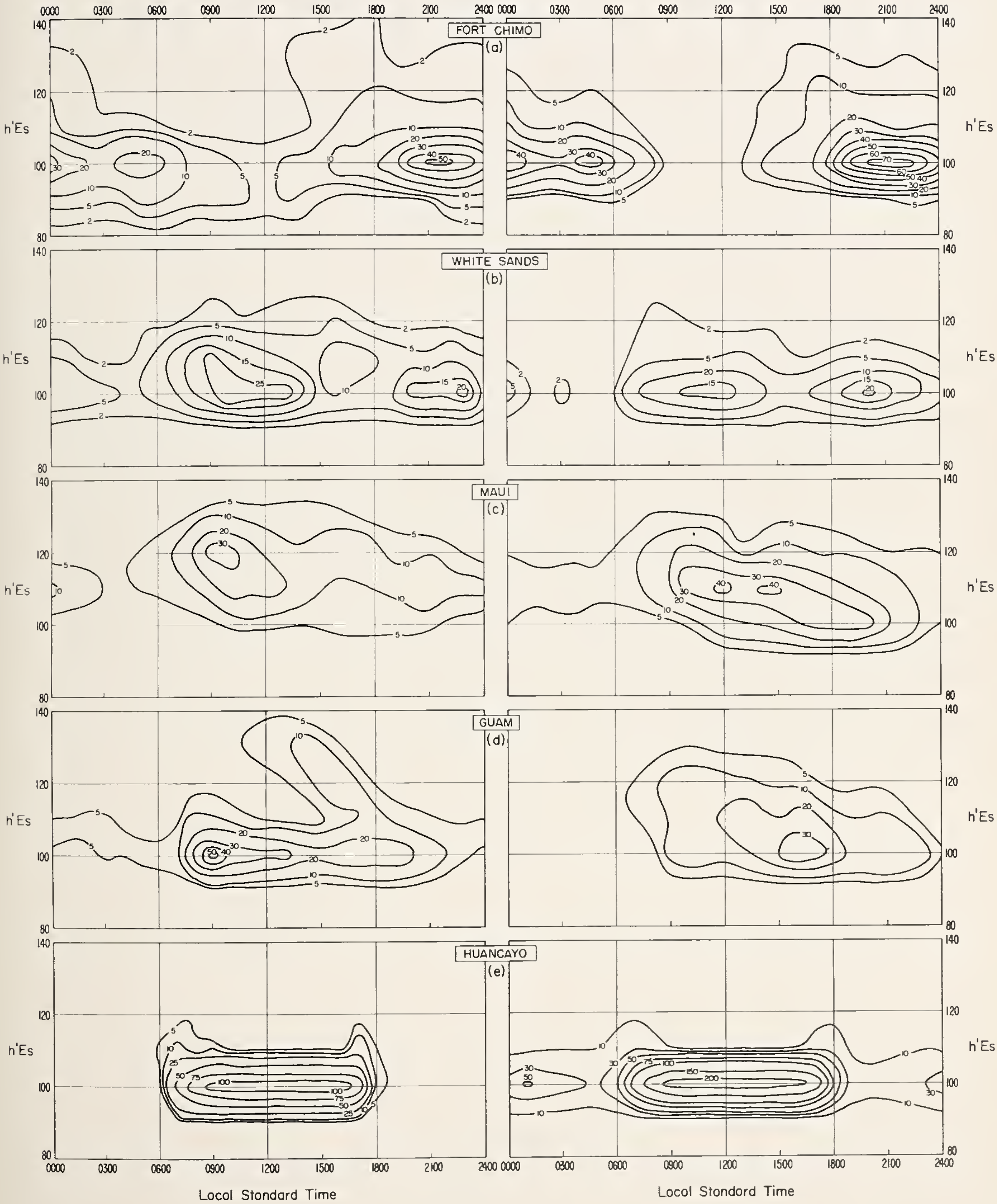

Figure II-1-4

Chapter III

SPORADIC-E PROPAGATION IN THE VHF BAND

A. Introduction

In this chapter, consideration will be given to several types of VHF sporadic-E data. All Es data at these frequencies have the common advantage that non-deviative absorption becomes a second-order consideration. The first type considered in section B, is made up of reports of long distance receptions of VHF television stations (TV-DX reports). Almost 99% of these reports concern the low-band TV channels at frequencies of 54-88 Mc and the vast majority of the reports for this band are certainly of sporadic-E propagation. Considerable question exists regarding the highband reports. Evidence presented in section B indicates that most if not all of these reports do not reflect sporadic-E propagation. Two properties of sporadic E are especially appropriate to treat through TV-DX reports. These are the distribution of VHF Es propagation as a function of distance and the effect of magnetic activity on intense sporadic E.

A second general type of data is made up of published or about to be published data on sporadic-E field strengths over VHF circuits. These data represent the most quantitative

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sporadic-E measures considered in this study and, therefore, have certain obvious advantages. A further advantage is that they closely represent actual operational conditions about which Es information is most needed by engineers.

The advantages of the panoramic point of view are illustrated through the results of this chapter. The negative correlation of Es at high-temperate latitudes with magnetic activity was first noticed in the ionosonde data in the HF band. To establish this property, however, it is necessary to go to higher frequencies in order to get away from the effects of non-deviative absorption. An analysis is correspondingly made in section B with the receptions of low-band TV stations. On the other hand, the longitude effect in sporadic E was first noticed when a comparison was made of VHF sporadic-E data for the United States and Japan. Very limited geographical area could be considered at these frequencies, and the actual fleshing out of the effect is accomplished with vertical-incidence data in chapter II.

It is very difficult to determine whether or not sporadic E obeys the secant law. Indications are that it does to a first approximation (Smith [1951] fig. 23), (Wieder, Sulzer and White [1952]), (Kono, Uesugi, Hirai, and Abe [1954]). There are several reasons why it is hard to make a definitive test. Listing these we find:

1. Sporadic E exists in many forms. Results from one test at a particular locality and period can not necessarily be extended to other areas and different times.

2. The height of reflection, h_o, enters into the determination of the angle of incidence, i_o, on the reflecting or scattering stratum and this height information is rarely available.

3. Sporadic E is known to be power sensitive and in varying degrees (Chatterjee [1952]). Ionosonde data are not available in terms of effective reflection coefficient so that no quantitative basis for comparison exists when these data are related to a certain level in "db below free-space" for an oblique transmission path.

Perhaps the best evidence of the general applicability of the secant law is given indirectly by Kono et al. [1954] (described in greater detail in section C below) where received fields are predicted to $\pm$ 5 db for long-term probabilities through a semi-empirical expression which contains f cos i_o as the sole variable.

If one ignores tropospheric refraction at the regions near the terminals of the path, the appropriate factor relating oblique to vertical incidence critical frequency may be computed from the expression:

$$\left(\frac{f}{f_c}\right)^2 = \frac{4\left(h_o + \frac{D^2}{8R}\right)^2 + D^2}{4\left(h_o + \frac{D^2}{8R}\right)^2} \qquad \text{III-A-1}$$

This relation (Mitra [1952] p. 268) is just geometry plus the secant law. It includes the approximation for small Θ, $\cos\Theta \sim 1 - \frac{\Theta^2}{2}$. The variation of the secant factor as a function of distance is seen in figure III-A-1 as computed by relation

MUF FACTOR FOR THIN IONIZED LAYERS
TROPOSPHERIC REFRACTION NOT CONSIDERED

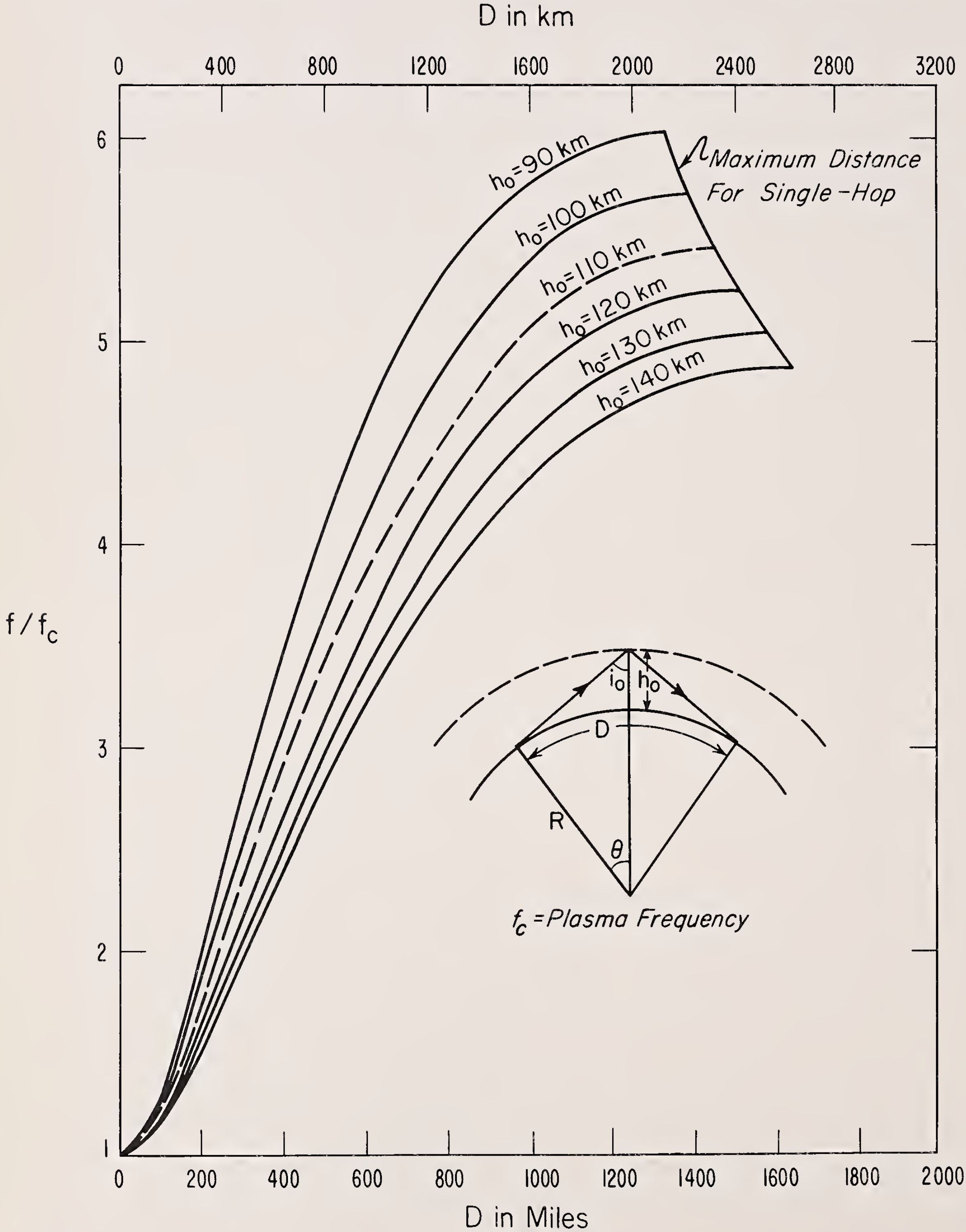

Figure III-A-I

III-A-1. It was shown in chapter II that 110 km is the most common height and this height is assumed below except where statement is made to the contrary.

B. Receptions of TV Stations at Distances Over 400 Miles During the Period 1951-1953

In an earlier work (Smith [1951]) an analysis was made of TV-DX reports for the year 1950 submitted to Radio-Electronics magazine. 456 reports of receptions of television stations at distances of greater than 200 miles were reduced in this study. Even with this small statistical sample it was possible to demonstrate that sporadic-E propagation was responsible for most of the reports for distances greater than 500 miles and tropospheric propagation involving distances less than 500 miles. The range from four to five hundred miles appeared, however, as a transitional region. It was also possible to show for reports in the distance grouping assigned to sporadic E that the number of reports per station was greatest for channel 2 and decreased monotonically to channel 6 as would be expected for sporadic-E propagation. Quite good coincidences were found between times of reported TV-DX and appearance of sporadic E on the vertical incidence sounder for the few instances when the midpoints of the transmission paths for TV-DX reports happened to fall near ionosondes. Maps of the transmission path midpoints for particular days were used to illustrate the fact that sometimes the midpoints formed a tight cluster as would be expected for an Es cloud whereas at other times the midpoints appeared well dispersed.

Recently E. P. Tilton, on behalf of Radio Electronics, loaned the author the file of reports for 1951, 1952 and 1953.

These have been reduced in a manner identical with the author's earlier study. However, there are 2819 reports in this collection compared to 456 in the earlier study. This is a statistically much better sample but also involves a factor of six times more work for any given aspect of study than the earlier sample did. It has been necessary, therefore, to restrict the areas investigated to conform with certain objectives. The results outlined in the preceding paragraph are ones which will not be repeated in this study because of probably diminishing returns. On the other hand certain results of the earlier study were questionable because of the small data sample. In addition, developments since the 1951 study have brought up the possibility of a magnetic-activity correlation (not considered earlier). For these reasons the following specific points will be considered here.

1. The 1950 TV-DX data covered a period of only 4 1/2 months so that no meaningful seasonal distribution of reports could be given. The current study encompasses data for a continuous period of 33 months so that the seasonal variation may now be described over almost a three year period.

2. The distribution of reports by distance considered in the 1951 study showed a peculiar double maximum with peaks at 780 and 1030 miles. It was suspected at the time that this might be due to the small sample. With a larger sample it is now of interest to see if the double peak does smooth out.

3. In the earlier study of 1950 data only one high-band (174-216 Mc) report was found of reception at a distance of more

than 400 miles. In the 1951-1953 period there have been 35 such reports. This group of reports is examined to see whether or not it shows the characteristics of sporadic-E propagation.

4. In the North Temperate Zones, the area pertinent to this study, sporadic E as observed on ionosondes appears negatively correlated with magnetic activity. It can be argued that this negative correlation is due not to sporadic E but to a positive correlation of non-deviative absorption and magnetic activity. This argument although not supported by recent absorption studies (e.g. Appleton and Piggott [1954]) is, nevertheless, almost impossible to counter. However, at the frequencies of interest in low-band television (54-88 Mc) absorption no longer plays a significant role. If the negative correlation still exists in these data the absorption argument may be successfully surmounted. As it is considered established that reports for distances less than 400 miles are largely tropospheric and therefore not of interest here, this study concerns itself only with reports for distances of 400 miles or greater.

1. <u>Seasonal Variation in TV-DX Reports</u>.

As mentioned above, the TV-DX reports for 1950 analyzed earlier (Smith [1951]) covered a period of only 4 1/2 months contrasted to 33 months for the current study (January 1951 to September 1953). The seasonal distribution of these data is of interest as it can not only serve to determine the responsible transmission mechanism to be sporadic E but can also be used to help ascertain if the sporadic E is of the Temperate-Zone or Auroral-Zone variety. Figure III-B-1 is a plot of the number of reports received for each month during this period. The result is strikingly similar to the seasonal distribution shown in the light line for sporadic E (fEs > 7 Mc) observed at vertical incidence. In order to obtain a vertical-incidence sporadic-E seasonal distribution representative of the same area of the TV-DX reports, an average was taken of the occurrence of Es at Washington, D. C. and White Sands. The dominant characteristics of the Temperate-Zone seasonal variation in sporadic E, namely, the pronounced primary maximum centered around the summer solstice, a small secondary maximum around the winter solstice and minimum at the equinoxes, are seen clearly in figure III-B-1. Figure III-B-2 is a display of the same information as III-B-1 but broken down channel by channel. The general seasonal curve is seen to be very closely the same for all five low-band channels. The most striking feature of these curves is perhaps the steady rise of the maximum value during the three years for channel 2 contrasted to the stationary maximum on channel 4. The uneven distribution of reports among the channels appears in the expected decreasing order when plotted on a "per station" basis as has been shown by Smith [1951] and Tilton [1951], [1954].

2. Distribution of DX reports by Distance.

In general it has not been possible to combine the results of the study of 1950 TV-DX data with the 1951-1953 results. The original reports have long since been returned to Radio-Electronics

DISTRIBUTION OF TV-DX REPORTS BY MONTHS
COMPARED TO PERCENT OF TIME fEs > 7MC

Low Band Stations Only

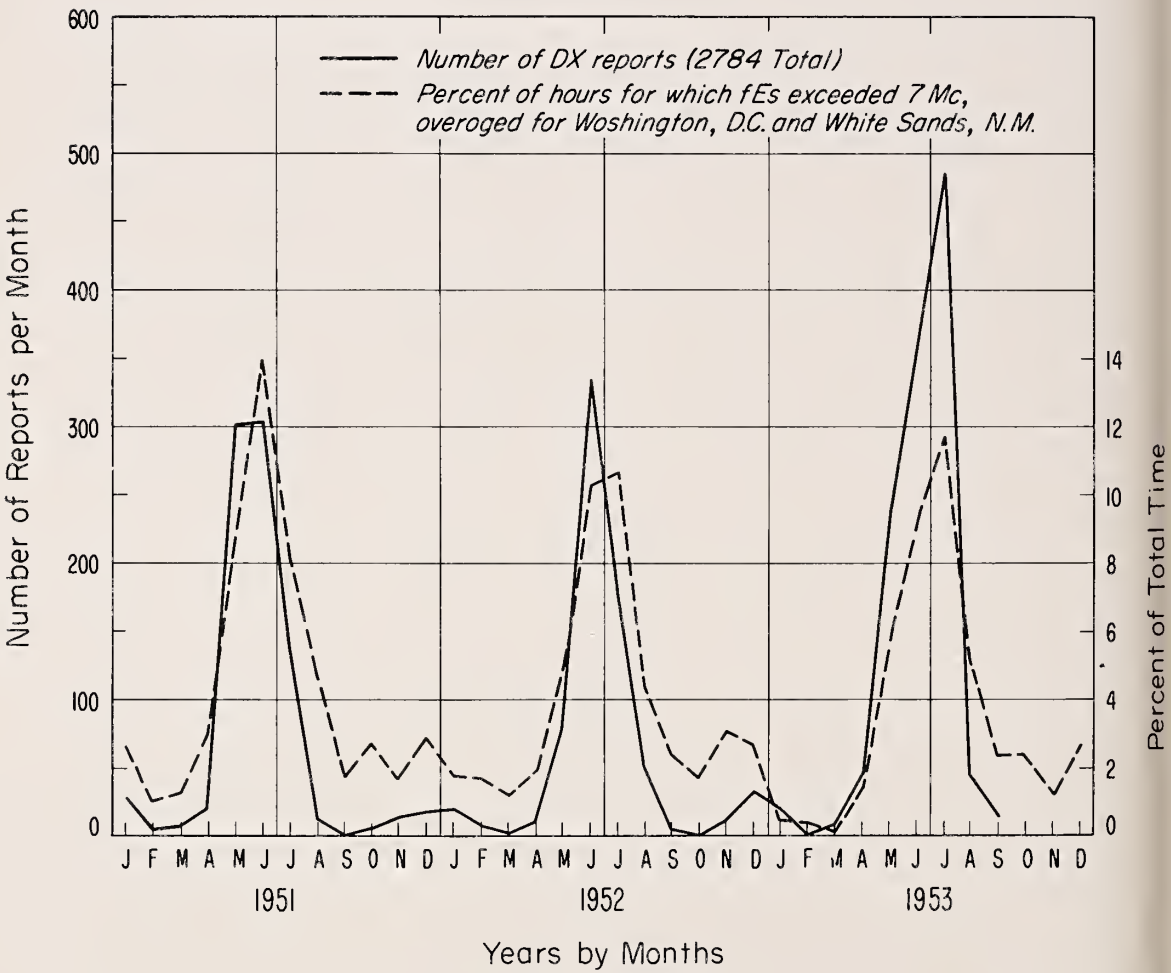

Figure III-B-1

DISTRIBUTION OF TV-DX REPORTS BY MONTHS FOR EACH LOW-BAND CHANNEL

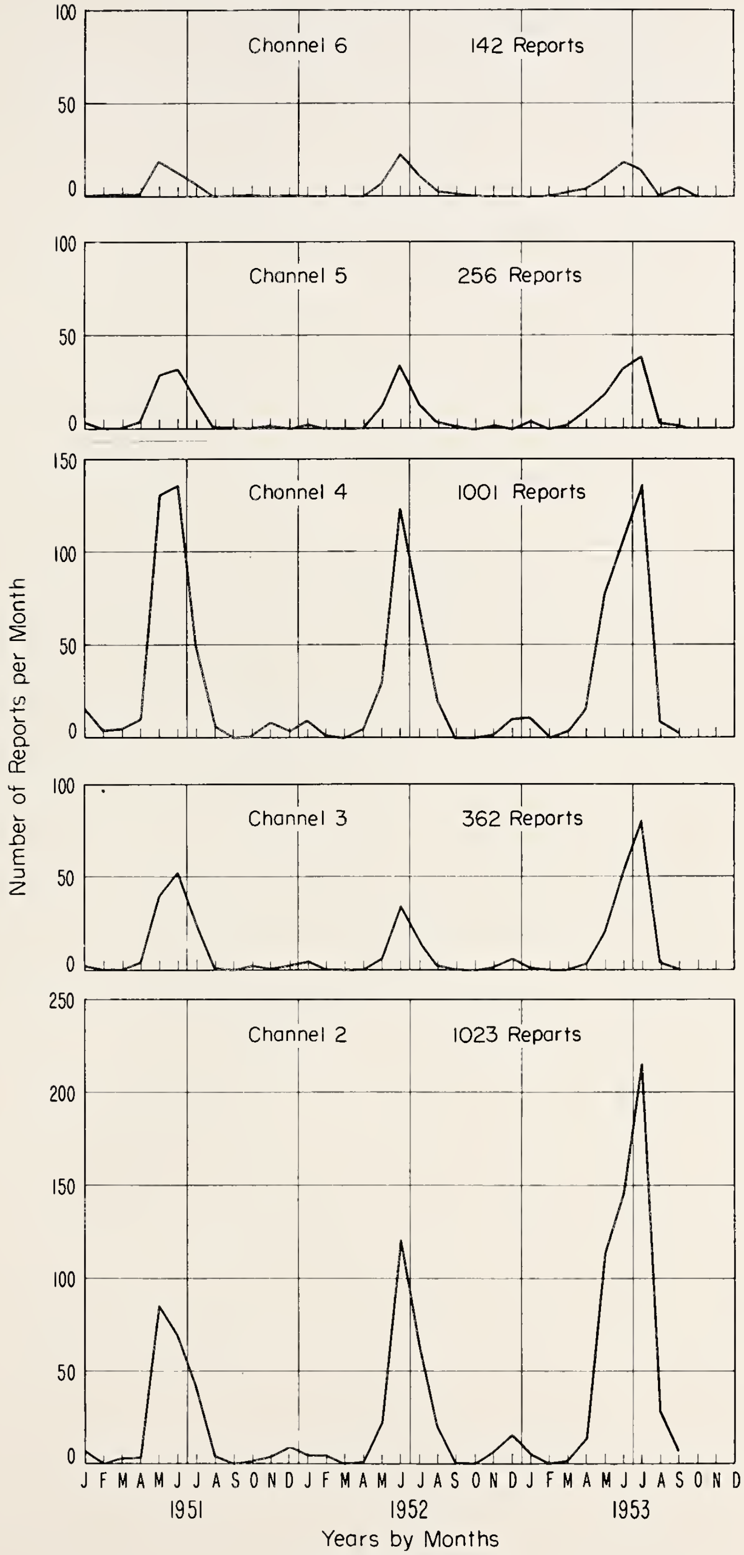

Figure III-B-2

and the 3 X 5 cards giving the statistics of each report for this period have been discarded. The analysis of 1950 data (Smith [1951]) concerned itself with reports of receptions from 200 miles up, whereas the current study is for distances beyond 400 miles. The histogram showing the number of reports in fifty-mile intervals is, however, one place where the 1950 data can be added directly to the data for the three later years. Thus, the histograms in figure III-B-3 and III-B-4 contain the 1950 reports but are the only places in this study where the 1950 data are included in the presentations of data. Figure III-B-3 is, perhaps, the best reduction of these reports to use for purposes of computing the interference potentialities of a group of stations,(with low receiving and high transmitting antennas) uniformly distributed geographically and operating in the 54 to 88 Mc region. That there may be geographical bias in figure III-B-3 is illustrated by figure III-B-4 where the reports of receptions of U. S. stations and foreign stations are shown separately. The histogram of U. S. reports appears skewed towards shorter distances (as would be expected due to the geographical boundaries of the country), whereas the reports from foreign stations are undoubtedly skewed in the direction of greater distances. A few of the foreign reports were of Canadian and Mexican stations situated on the U. S. border, but the majority were reception of Cuban stations and others were of Mexico City.

The distance distributions of reports by channel are seen in figure III-B-5 for the low-band channels. It is seen that the

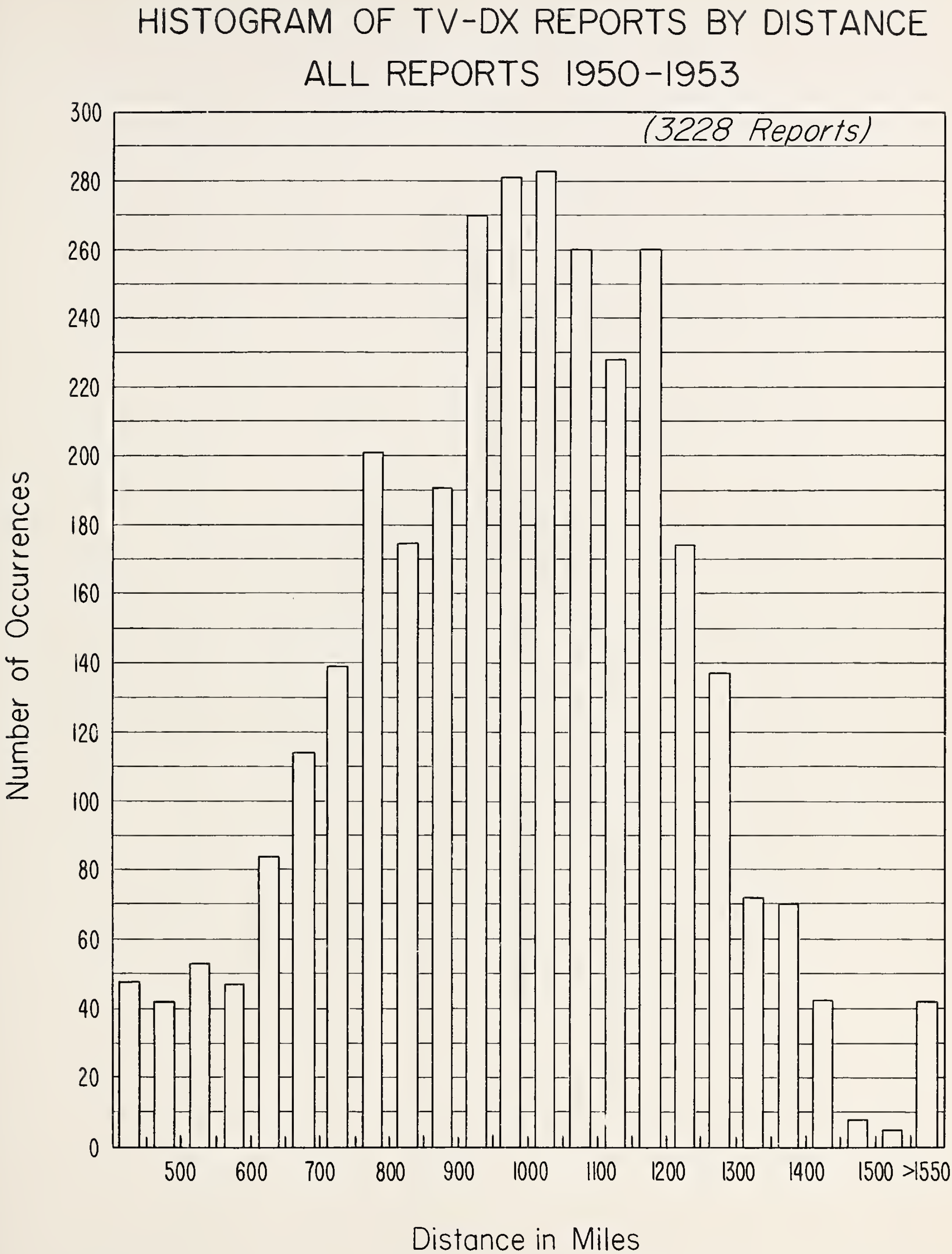

Figure III-B-3

HISTOGRAMS OF TV-DX REPORTS
FOR (a) U.S. AND (b) FOREIGN STATIONS
IN FUNCTION OF DISTANCE
1950-1953

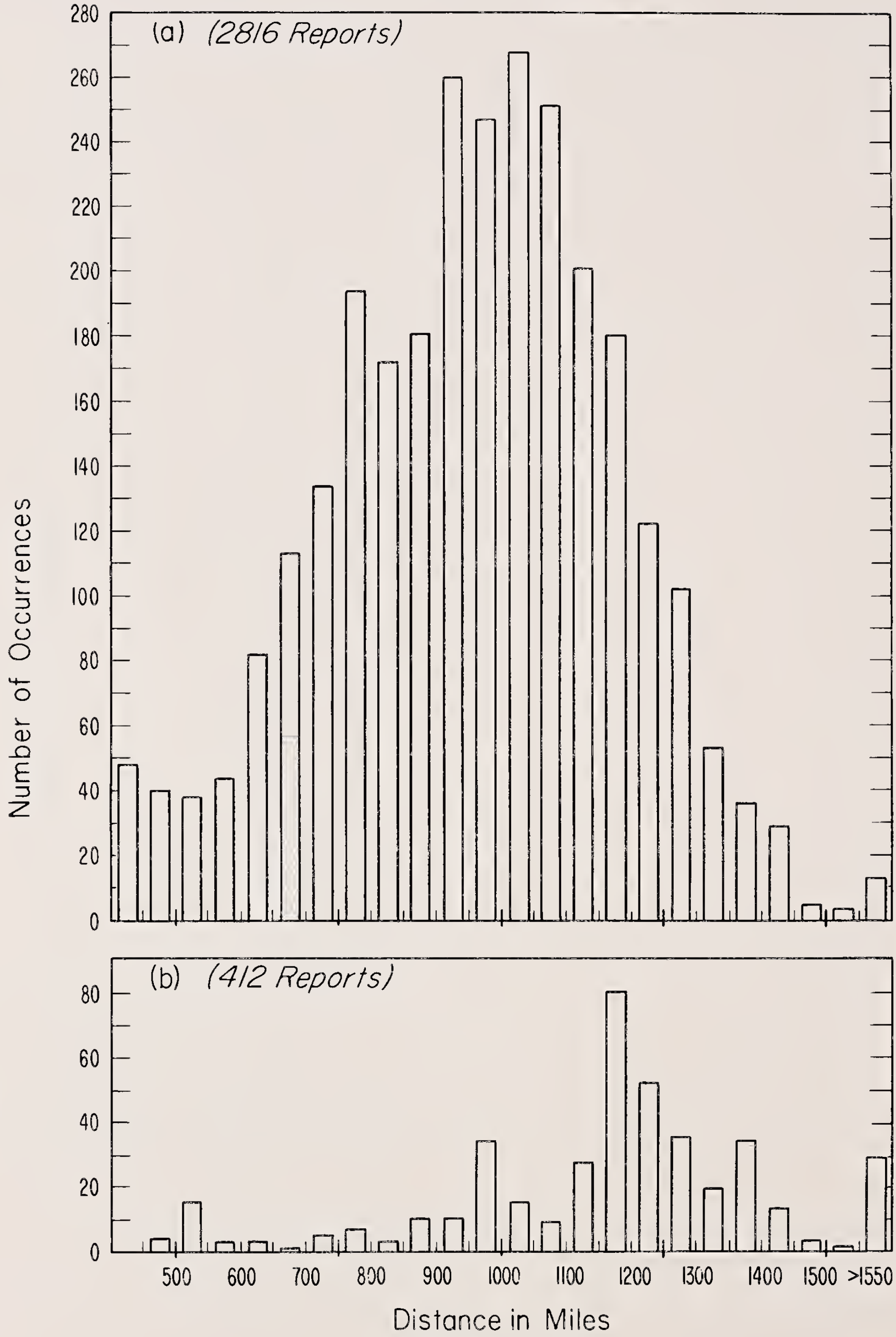

Figure III-B-4

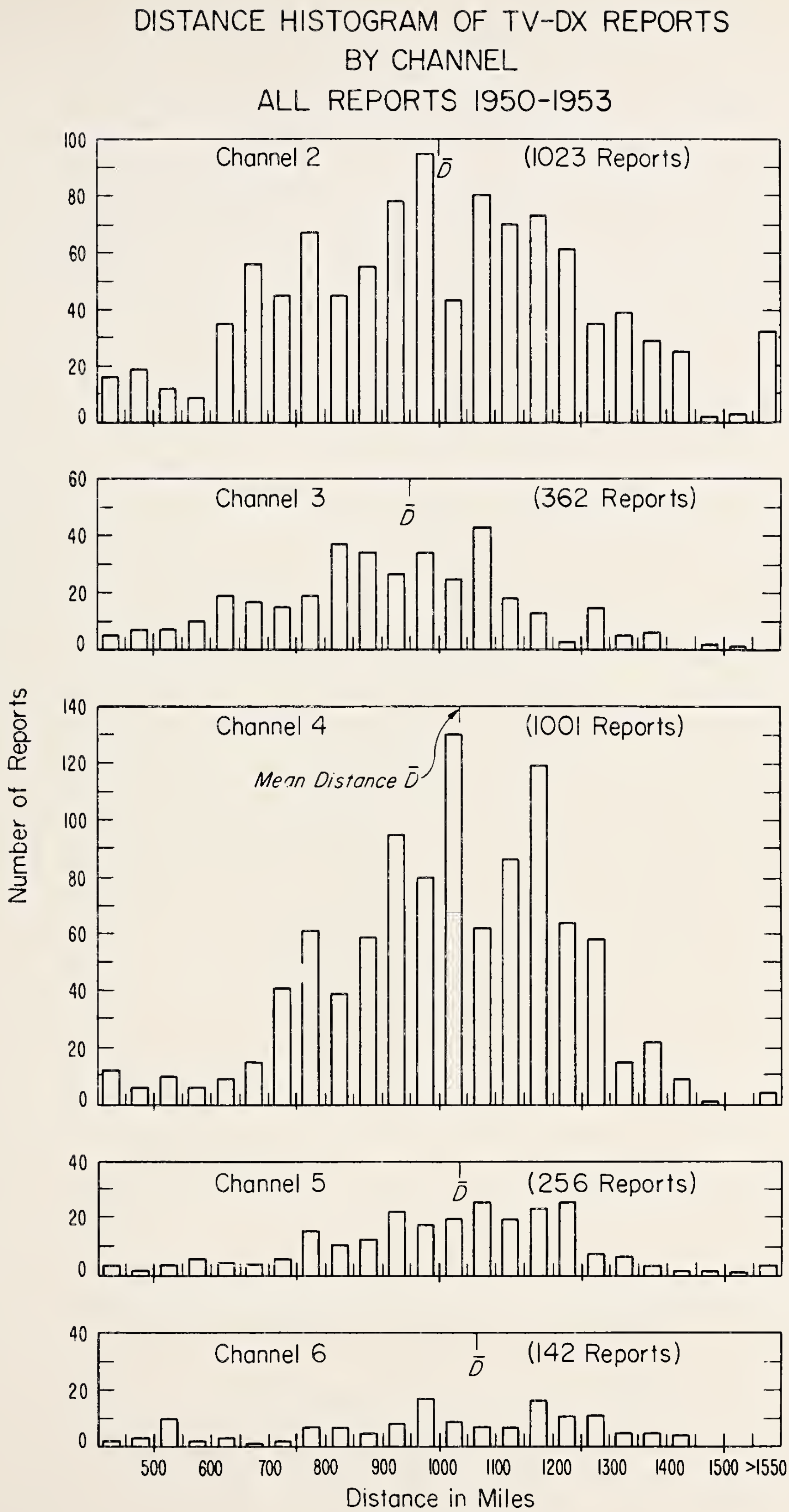

Figure III-B-5

general shape of the distributions are very similar. A tendency is noticeable for reports to be more numerous at distances greater than 1000 miles for the higher channels. The mean distances for reports between 600 and 1400 miles (the maximum distance for 1 - hop Es propagation) bear out this observation. This displacement with frequency is not unexpected for two reasons. First, if the secant law has any bearing, a given patch of sporadic E will have a shorter skip distance for the lower frequency. Second, if transmitting and receiving antenna heights are roughly the same for all channels, the higher channels will have more favorable patterns at low radiation angles than will the lower ones.

If one is interested, for instance, in the extent of interference by sporadic-E propagation to be expected between two VHF stations when their separation is increased from 400 to 1400 miles the representations in figures III-B-3, 4 and 5 are not quite what are needed. The reason is that the area of each annular ring considered in the histograms increases as the distance increases. Simple geometrical considerations show that this increase is proportional to the radius vector to the center of the interval. Figure III-B-6 presents the same data as figure III-B-3 but the number of reports in each interval has been divided by the mean distance of the interval, thus taking out the effect of increasing area with distance.

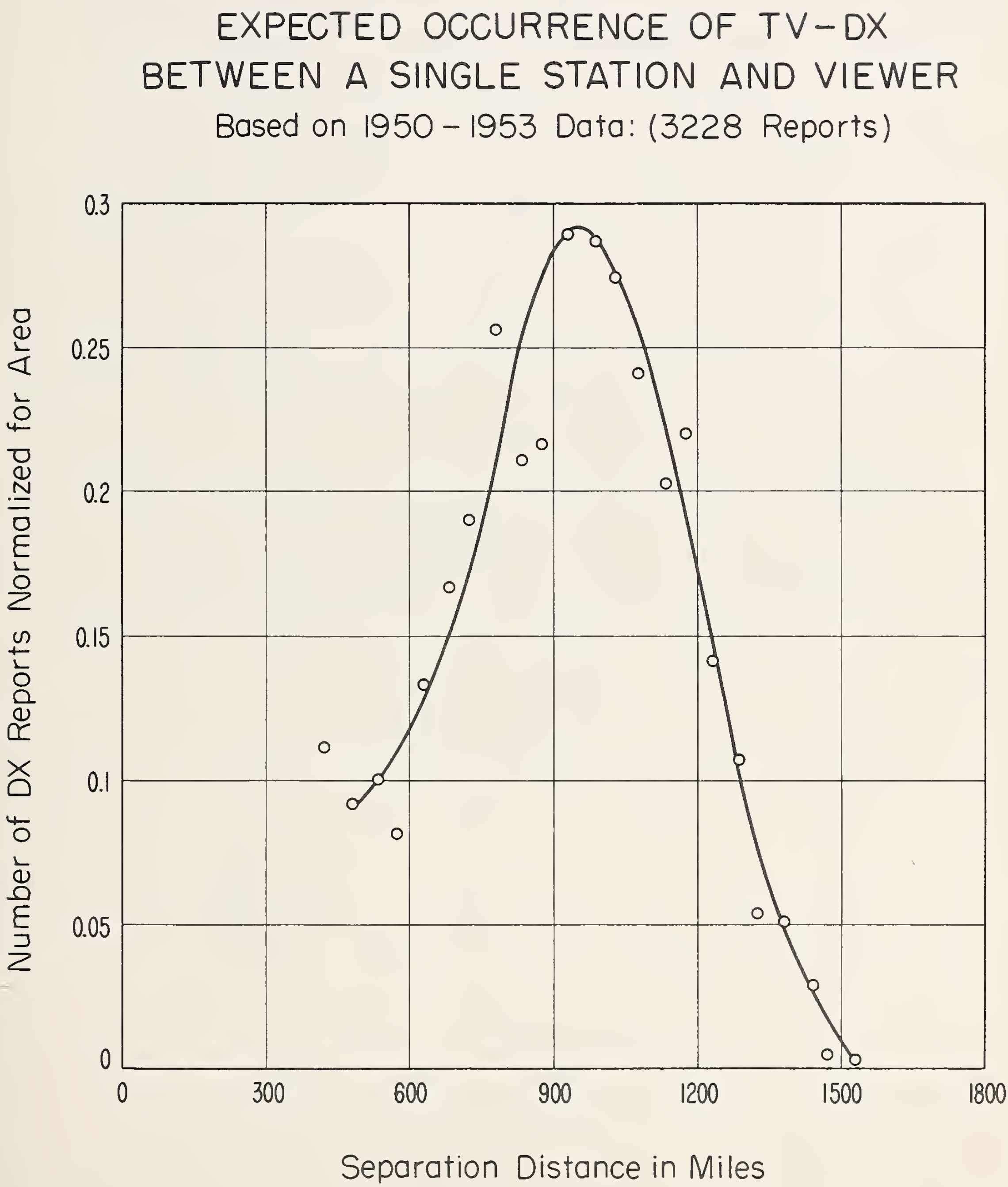

Figure III-B-6

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3. Characteristics of the High-Band Reports.

Thirty-five reports is not a very significant sample statistically when used in the manner which will be employed here, but it is a vast improvement over the single report available earlier. Figure III-B-7 shows the distribution of the thirty-five reports by month compared to a mean curve for the low-band reports (a) and their distribution by distance (b). It has been demonstrated earlier that one of the characteristics of sporadic E is the intensification of its time distributions as frequency is increased. For the low-band stations 90% of the reports fall in the months of May, June, July and August, whereas only 60% of the high-band reports occur in this period. In the distance histogram the general effect is that of a monotonically decreasing function, and there is no tendency to peak around 1000 miles as would be expected of sporadic E. The distance histogram, with the possible exception of three reports for distances greater than 900 miles, is what would be expected for tropospheric propagation and the seasonal distribution lends some support to this conclusion. Ten out of the thirty-five reports are seen to be for dominantly overwater paths (probable duct propagation). This is much higher percent than for the low-band reports. Of the three reports for distances greater than 900 miles, two are for January and the third for July (and a distance of 1795 miles). January is not a probably month for intense sporadic E. July is a probable month, but 1795 miles (Los Angeles to Indianapolis) is a highly improbable distance.

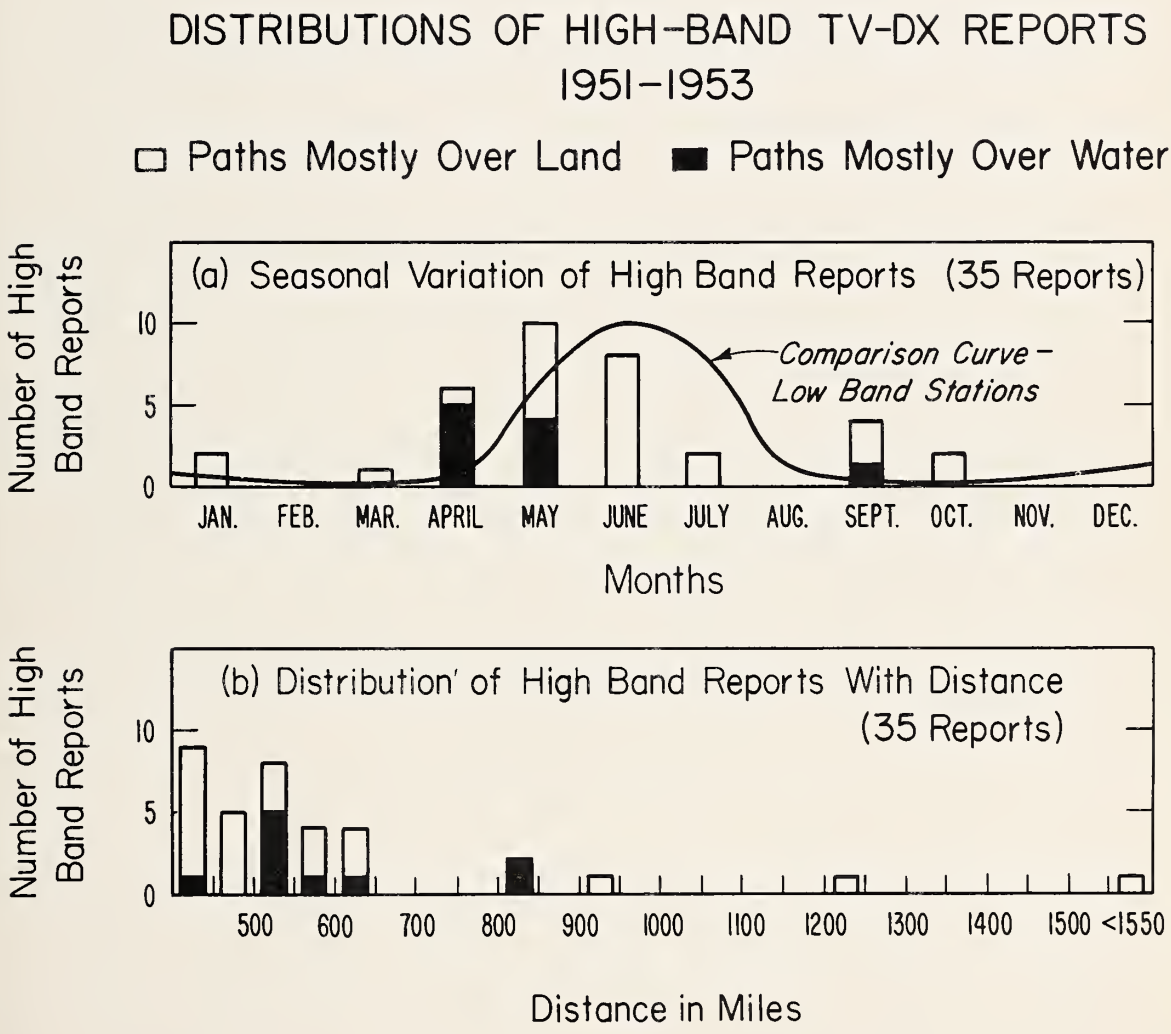

Figure III-B-7

The conclusion is, therefore, that there is still no real evidence of reception of high-band television stations via sporadic E.

4. TV-DX and Magnetic Activity.

The occurrence of reports is displayed on a 27-day recurrence diagram of the type introduced by Bartels [1934] for the three year period of record in figure III-B-8. The figure has an additional property that it contains the day-by-day record of TV-DX activity, thereby eliminating the necessity of reproducing this separately. It is seen from figure III-B-8 that the sporadic-E season is so short that 27-day recurrence is difficult to establish. Superposed epoch diagrams of the Chree [1912] variety were constructed for the summer months to test recurrence of days with more than 5 reports and those with more than 20. Not even a suggestion of a recurrence tendency at 27 days could be found in the 5 report or more analysis. The 20 report analysis suffered from a small data sample but did show a small peak at 26 days and a smaller one at 30 days. The conclusion would have to be that no strong recurrence tendency is observed in these data.

A straight correlation of the number of reports for a given day against Ap(the magnetic equivalent-daily-amplitude index) produces a widely-dispersed scatter diagram. A semblance of order may be made out of this by computing the average number of reports per day for a series of Ap intervals. Such an ordering is seen in figure III-B-9. An effort has been made here to divide the points

DISPLAY OF TV-DX REPORTS ON 27-DAY RECURRENCE DIAGRAM

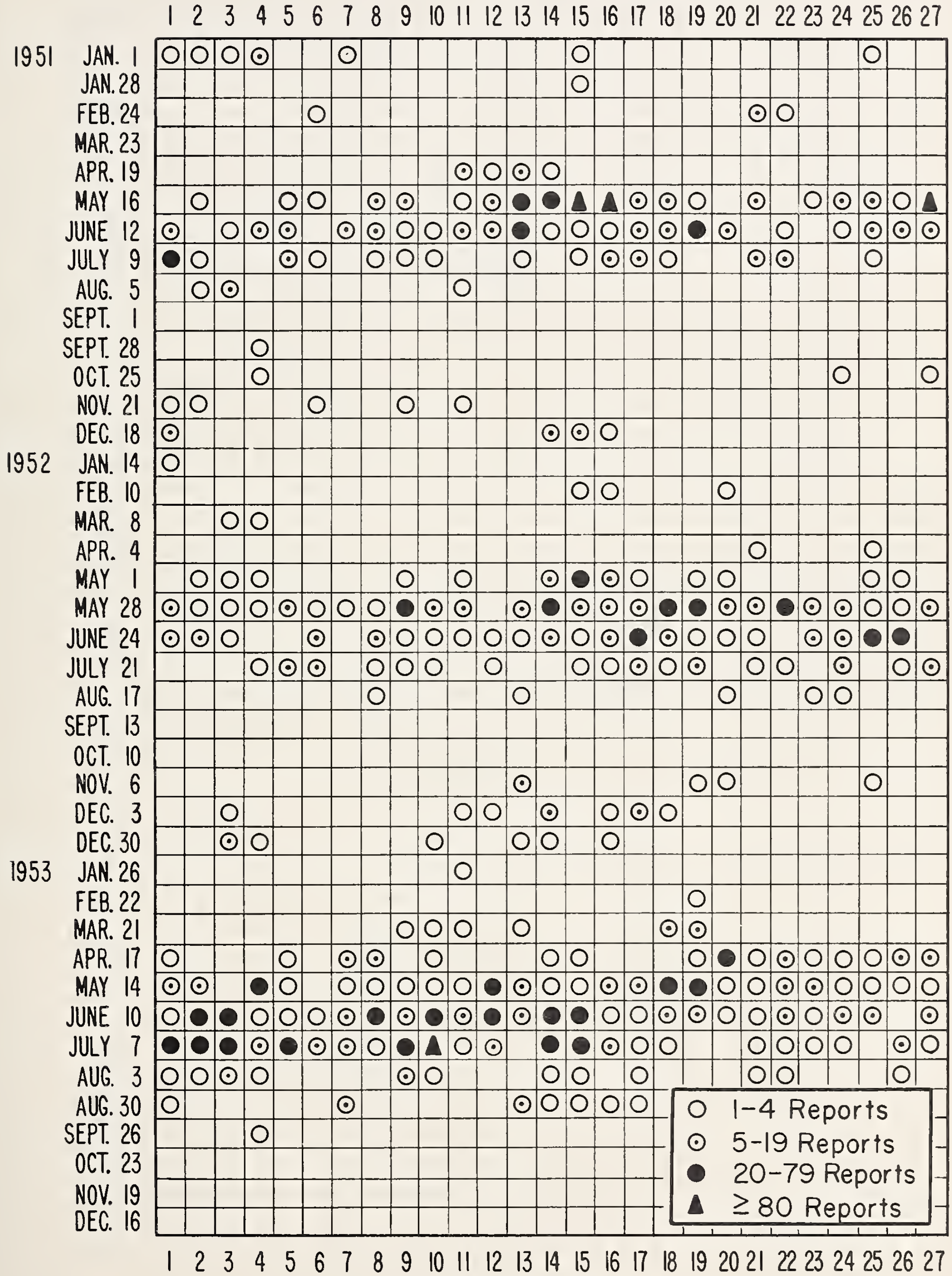

Figure III-B-8

TV - DX FOR MAGNETICALLY QUIET, INTERMEDIATE AND DISTURBED DAYS 1951 – 1953

Distances Greater than 400 Miles; Channels 2–6

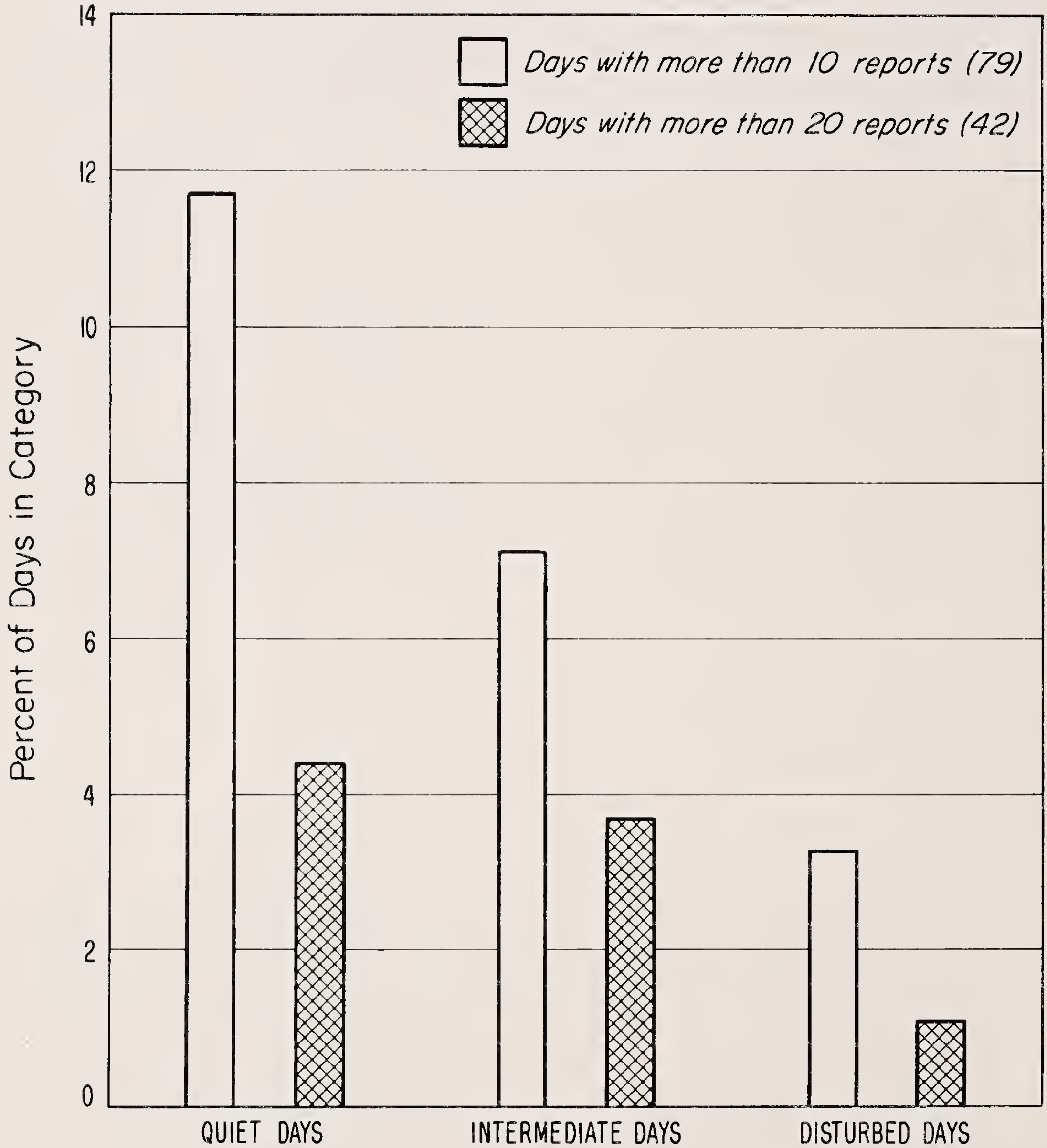

Figure III -B-9

into four equal groups (consistent with the grouping of Ap by octaves). It is seen that more than three times as many reports occur, on the average on days for Ap ≤ 7 than on days where Ap ≥ 31. However, we know that magnetic activity tends to be higher in the equinoxes than during the solstices (see section II-H-2), whereas sporadic E behaves in just the opposite manner. It can be argued that the anti-correlation indicated by figure III-B-9 can be explained by the two seasonal distributions being out of phase and that no day-to-day anti-correlation need exist. If this were the case it would be expected that the quiet and disturbed days within a given month would show almost no difference in mean number of reports. An organization of the data by quiet and disturbed days appears below.

	Magnetically Quiet Days		Magnetically Disturbed Days	
	Number of Days with Reports	Number of Reports	Number of Days with Reports	Number of Reports
1951	14	108	12	43
1952	16	151	14	78
1953	20	326	19	113
	50	585	45	234

It is noteworthy that for each of the three years at least two times as many reports occurred on quiet as on disturbed days and the average for the three years is 2 1/2 times as many for the quiet days. The number of "days with reports" is only slightly different for the two categories, but this is not surprising when one notes on figure III-B-8 that during the Es season there are reports on almost all days, while there are very few reports out of the season.

It is also possible to investigate the percent of quiet and disturbed days with more than a given number of reports. This is done in figure III-B-10 for days with more than 10 and 20 reports.

For the ten-report level it is seen that a differential of more than 3 1/2: 1 exists for the quiet-to-disturbed day ratio. The days of intermediate magnetic character take a position appropriately midway between the other two. A ratio of 4:1 exists at the 20 report/day level, but here the intermediate days are more like the quiet.

Three rather different tests each indicate quite markedly that a negative correlation with magnetic activity exists for TV-DX at least for the period of 1951-1953. Nondeviative absorption expressed in db varies inversely as the square of the frequency. 10 db of absorption at 5 Mc would result in only 0.1 db at 50 Mc for the same path. True the paths here are oblique compared to the vertical transmission through the absorption layer considered in chapter II, but the increased time spent in the absorption layer is such as to increase the absorption by not more than 5 times. The resulting effect of daytime absorption, for instance, on a TV-DX transmission will still be under 1 db, which is certainly a negligible effect. It seems inescapable then to conclude that the negative correlation is real. Also, if real for these frequencies, the findings at vertical incidence seem strongly supported.

DISTRIBUTION OF TV-DX REPORTS BY MAGNETIC ACTIVITY FIGURE A_p
MAY - AUGUST
1951 - 1953

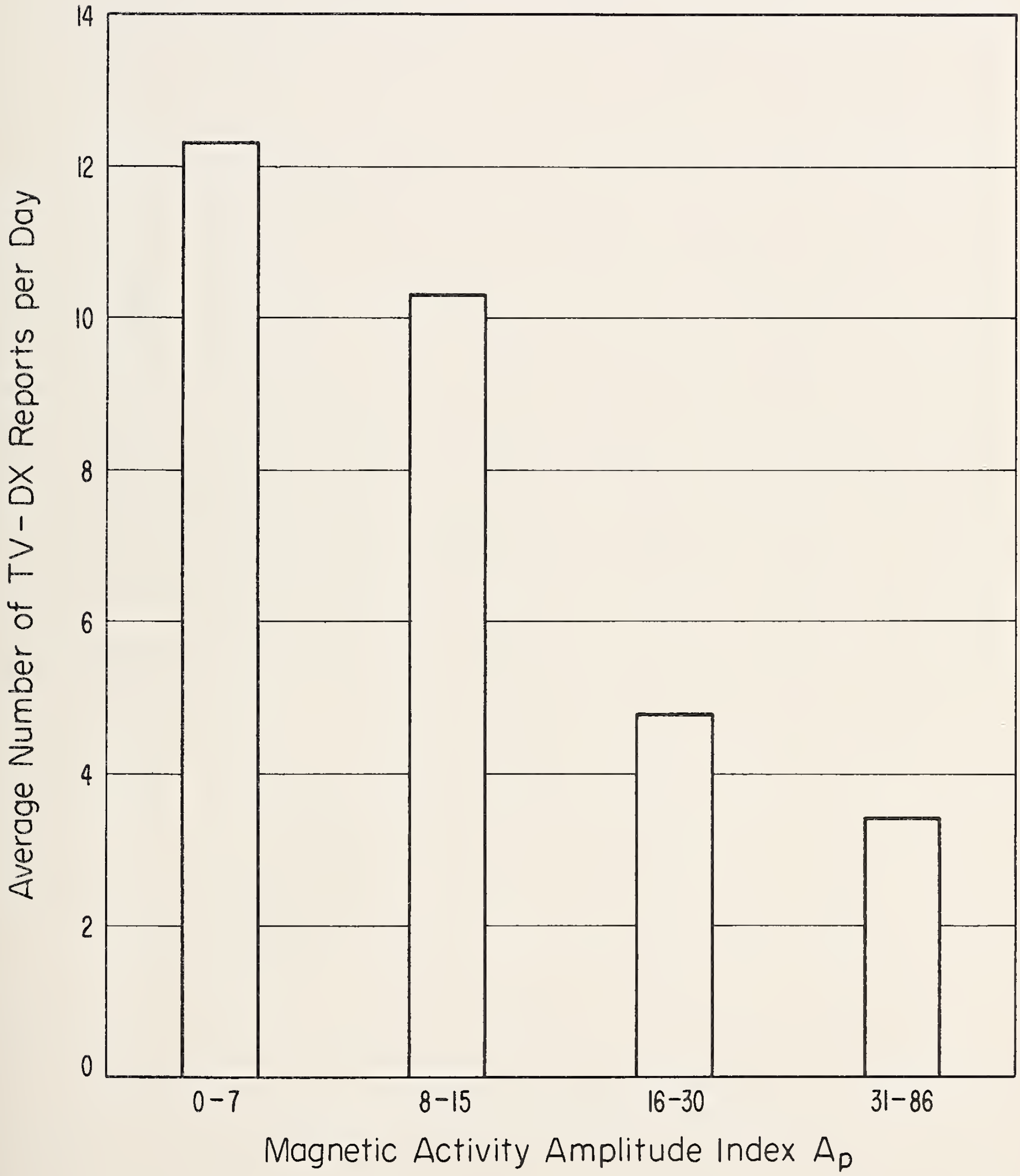

Figure III-B-10

a. Similar Tests Applied to Dyce's Data. In a recent study by Dyce (R. B. Dyce Ph.D. Thesis, June 1955) a day-by-day presentation of sporadic E recorded at 50 Mc over an 800 mile path from Sterling to Ithaca (his Fig. 26) is given. These data cover about 79% of the days for a 31 month stretch from March 27, 1952 to October 17, 1954. Sporadic-E occurrence in this period is divided into four categories: no. Es, 0-4.9, 5-19.9,> 20. The numbers for the boundaries of the categories apparently represent a weighted per-cent-of-the-day during which Es was observed. The method used by Dyce to distinguish Es from other modes is an interesting one. Unfortunately, the method is such that comparisons between his data and others on a quantitative basis are difficult.

One striking feature of the 27 day recurrence diagram given by Dyce (his fig. 26) is the strong recurrence tendency in the summer of 1954. This was a period of very low magnetic activity as may be seen in fig. II-H-8. Also, it was not a period of strong recurrence tendency as is seen in fig. II-H-10 and II-H-13. Other than the fact that the entire summer of 1954 was magnetically quiet (mean A_p for June, July, August = 8), the groups of days showing strong 27-day recurrence in percent of Es do not appear to exhibit any other magnetic abnormalities.

The nearest vertical-incidence station to the midpoint of the Cedar Rapids to Sterling path is Washington, D. C. If one considers the number of hours fEs $\geq$ 5, 10 Mc it is found that the day-to-day similarity is quite strong but that the differences are in the direction such as to diminish the 27-day recurrence tendency in the vertical-incidence data. The conclusion seems to be that the strong recurrence tendency exhibited in the summer of 1954 by the Dyce data is largely fortuitous.

C. Monitored VHF Field Strength Data

1. Survey of Available Data.

This section deals with the rather scanty amount of recorded Es field strengths in the VHF band. Three groups of data are described below.

a. The FCC Data. These data are contained in a series of reports* released by the FCC in connection with the reallocation of the FM band after World War II. They represent measurements of received field intensities from WGTR Paxton, Massachusetts (44.3 Mc, 340 kw) made at a series of FCC monitoring stations in the period 1943 through 1945. In the reports referred to, the data have been reduced to time distributions of received field strength. The inverse-distance field ($\frac{2E_o}{d}$) is given for reference in each case.

The distances involved ranged from 720 to 1370 miles, thus bracketting the zone of maximum Es (see section B). The FCC data used in this study are summarized in Table III-C-1.

b. The Japanese Data. An excellently designed experiment from the communications engineering point of view was carried out in Japan in the summer of 1952 (Kono et al. [1954]). One-hundred-watt transmitters operating on 31.55, 43.85 and 65.82 Mc were installed at Hiraiso in north-central Honshu. Seven receiving sites were located to the southeast at distances of 302 to 674 miles. Vertical

*Report on VHF Field Strength Measurements 1943 - 1944" FCC Docket No. 6651, Exhibit 4, Sept. 28, 1944; "Measurements of Sporadic E Field Intensities," FCC, 14100

Source of Es Transmission Loss Data Used in This Report

Transmitter				Receiver			Source of Data
Location	Power	Frequency	Assumed Operating Hours	Location	Miles Distance	Period	
Paxton, Mass. (WGTR)	340 kw	44.3 Mc	0600-2400	Allegan, Mich.	720	Sep.'43-Aug.'44	Ref. 1
				Atlanta, Ga.	900	"	"
				Grand Island, Neb.	1370	"	"
				Montgomery, Ala	1040	Jun.-Aug.'45	"
Hiraiso, Japan	100 w	31.55 Mc	0000-2400	Osaka	302	Jun.-Aug.'52	Ref. 2
				Mt. Gyosei	316	"	"
				Kochi	447	"	"
				Mt. Ishigatake	524	"	"
				Yamagawa	674	"	"
Hiraiso, Japan	100 w	43.85 Mc	0000-2400	Osaka	302	"	"
				Kochi	447	"	"
				Nobeoka	570	"	"
				Yamagawa	674	"	"
Hiraiso, Japan	100 w	65.82 Mc	0000-2400	Osaka	302	"	"
				Kochi	447	"	"
				Nobeoka	570	"	"
				Yamagawa	674	"	"

TABLE III-C-1

incidence sporadic-E data from the Kokubunji and Yamagawa ionsondes were coordinated with the VHF results. Noise figure and bandwidth specifications of the receivers are not given in the Kono et al. [1954] paper, but the statement is made that signal levels less than -40 db relative to free-space were subject to noise contamination (the 35 db advantage in transmitter power makes the FCC data useful to lower levels.) Not all of the receiving sites obtained useful results on all three frequencies as may be seen from table III-C-1. The measurements were made during the months of June, July and August 1952. There is no mention in the Kono paper of the number of hours of operation per day so it is assumed that continuous measurements were made.

c. The Forward-Scatter Data. Some of the VHF ionospheric forward-scatter data has now been declassified and D. K. Bailey was kind enough to give the author pre-publication copies of the illustrations pertinent to sporadic-E transmission. These illustrations have now appeared in a paper in the October 1955 issue of Proc. IRE by D. K. Bailey, R. Bateman and R. C. Kirby.

The level of the forward-scatter signal on the Cedar Rapids - Sterling path (1243 km, 49.80 Mc) is of the order of -100 db relative to the free-space signal level and the receiver noise-level is down around - 140 db.

The recording equipment in use until very recently saturated at -62 db (1 millivolt across the 600 ohms open-circuited receiving rhombic). Sporadic-E propagation was said to exist when the recorder saturated in a high signal period of 12 minutes or more, but the length of time accredited to sporadic E then included the rise time from the normal signal level and also the decay time back to normal signal level. This additional time is in part counterbalanced by the 12 minute minimum (to discriminate against long-duration meteor echoes.) Bailey*, however, feels that the overall effect is to magnify the actual durations of sporadic E relative to the -62 db level. For the Cedar Rapids-Sterling link on 49.80 Mc reduced Es data are available for the period March 1951 through December 1954. The number of hours of Es transmission for each month during this period is seen in figure III-C-1 (a), and the diurnal variation for 1952 in (b) of the same figure.

2. <u>The Modified Frequency-Dependence Formula.</u>

The Japanese data give, for the first time, a coherent series of VHF sporadic-E field-strength measurements on three well-separated frequencies. The frequency-dependence of sporadic E in the VHF band can, therefore, be examined. It is seen in table III-C-1 that data are available for only three of the receiving sites on all three frequencies. These are: Osaka (302 miles from the transmitters at Hiraiso), Kochi (447 miles) and Yamagawa (674 miles). It was pointed out in the previous section that for TV-DX reports on the low-band (54-88 Mc) a preponderance of the reports are not due to sporadic-E propagation until a distance of 500 miles is attained. For this reason, of the three receiving stations,

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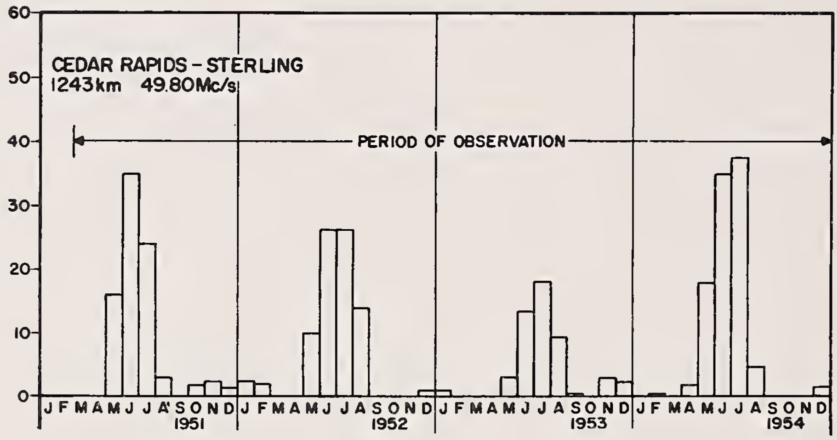
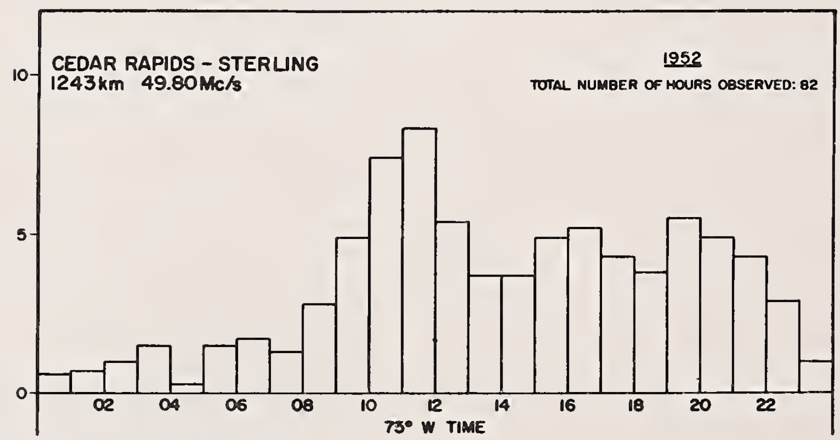
*D. K. Bailey - private communication, August 17, 1955.

Es OBSERVED ON AN IONOSPHERIC FORWARD SCATTER LINK

(After Bateman, Bailey and Kirby [1955])



(a) Annual Variation



(b) Diurnal Variation

Figure III-C-1

Yamagawa at a distance of 674 miles should give most nearly pure sporadic E on all three frequencies. The three transmitting frequencies were 31.55, 43.85 and 65.82 Mc.

Mrs. Phillips [1943], [1944], [1947] derived an expression from ionosonde data which expresses the probability of occurrence of sporadic E capable of supporting a signal at any given frequency at vertical incidence. This expression which has been discussed in II-B, has the form:

$$\log P = a + bf \qquad \text{(III-C-1)}$$

where: f = frequency in megacycles

a, b = adjustable constants

P = probability that fEs > f.

If the assumption is made that a = o, then III-C-1 can be written as a simple proportionality:

$$\frac{\log P_1}{\log P_2} = \frac{f_1}{f_2} \quad \text{where } P_1, P_2 = \text{probabilities} \qquad \text{(III-C-2)}$$

f_1, f_2 = frequencies.

This relation contains no arbitrary constants. As it does contain the assumption that a = o (III-C-2) will be a good approximation of (III-C-1) only for $|a| \ll |bf|$.

When expression (III-C-1) is applied to ionosonde data, the question of what transmission path attenuation is actually involved does not enter explicity. Also, inasmuch as ionosondes are not calibrated for this quantity, all that can be done is to make an educated guess as to what the transmission attenuation is for any given value of fEs. A reasonable "order of magnitude" approximation would be that the weakest Es return which can be detected

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on the ionosonde represents the same value of reflection coefficient at all frequencies. This is demonstrably untrue at low frequencies where the radiation efficiency of the antennas is low, but should not be too bad above about 5 Mc. A constant reflection coefficient at oblique incidence would result in a constant received field-strength level in decibels relative to the free-space level. If relation (III-C-2) is applied to the observed percent occurrences at 43.85 Mc for Yamagawa the expected occurrence probabilities may be plotted for all other frequencies. These predicted values are expressed by the solid lines in figure III-C-2. The observed values at 31.55, 43.85 and 65.82 Mc are connected by the dashed lines. It is interesting to note that there is no systematic deviation between the observed and predicted values.*

3. <u>The Discrepancy Between the U. S. and Japanese Data</u>.

a. <u>The Concept of Basic Transmission Loss</u>. It is useful to introduce "transmission loss" (Norton [1953]) at this point. Basic Transmission Loss, L_b, is defined as the loss in decibels that would be experienced if the system used perfectly conducting isotropic transmitting and receiving antennas. Mathematically

$$L_b = 20 \log_{10} d + 20 \log_{10} f + A + 36.58 \qquad \text{(III-C-3)}$$

---

* The point of concurrency for the solid lines of figure III-C-1 is the origin rather than the offset point found for monthly variation of ionosonde data at Yamagawa in section II-G.

COMPARISON OF PREDICTED FIELD INTENSITY WITH THAT OBSERVED AT YAMAGAWA

Prediction Relation: $f_1 \log P_2 = f_2 \log P_1$

Observed Level Probabilities at 43.85 Mc Were Used as Reference

Yamagawa Data Normalized to Represent Full Year 1952

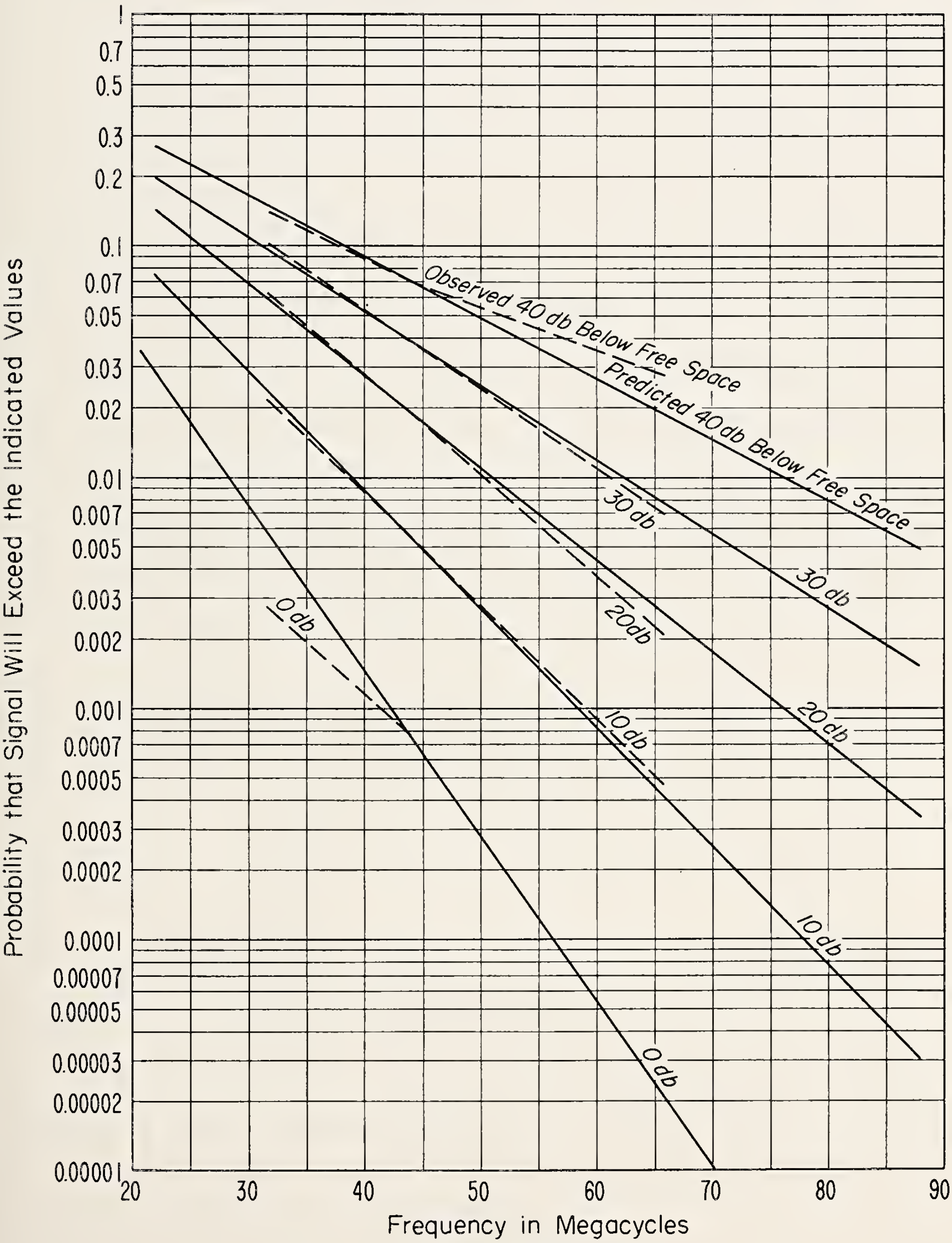

Figure III-C-2

where: d = distance in miles

f = frequency in Mc

A = propagation path attenuation in db relative to the free-space value.

The constant, 36.58, is fixed by the reference antenna and the units used for d and f. "Basic Transmission Loss" has the advantage over "db relative to free space" in that it expresses the inverse-distance attenuation and also the decreasing aperture of the antenna (with dimensions fixed in wavelength) with frequency.

b. Normalizing Procedure. It will be noticed in the table above that with the exception of the Cedar Rapids-Sterling data, none of the measurements of sporadic-E transmission loss were made for a full day over a period as long as a year. The FCC data which are mostly for a year's duration were taken only 18 hours per day. The Japanese data which are assumed to be 24 hours per day, on the other hand, are limited to three summer months. To make these data more readily usable and also to put them all on a comparable base, they have been normalized, in each case, to a full year. The FCC data in normalized form refer to what would probably have been observed during the period September 1943 through August 1944 for a 24-hour day. The normalized Japanese data apply correspondingly to the calendar year 1952. No effort has been made to reduce the three sets of data to a common year, as this involves a possible error of a greater order of magnitude.

The normalizing procedure assumes that the seasonal or diurnal distribution of sporadic E observed over the oblique VHF path is proportional to that obtained for fEs > 7 Mc on the nearest vertical-incidence ionosphere sounder for the period in question. The Washington, D. C. ionosphere sounder results as published in the CRPL -F series were used for the FCC paths. Data from the Yamagawa sounder was employed for the Japanese paths.

We may define:

P_1 = probability that the transmission loss is less than a given level for the year September 1943 - August 1944,

r_1 = measured fraction of the time that transmission loss is less than a given level for June, July and August, 1944 06-24 hours in the United States,

r_2 = measured fraction of the time that transmission loss is less than a given level for September 1943 through August 1944 in 06-24 hours in the U. S.

Then for the FCC paths where Washington, D. C. data are used:

$$P_1 = 0.250\ r_1 \qquad \text{(III-C-4)}$$

$$P_1 = 0.782\ r_2$$

Correspondingly for the Japanese paths let

P_2 = probability that the transmission loss is less than a given level for the calendar year 1952.

r_3 = measured fraction of the time that transmission loss is less than a given level during June, July and August, 1952, in Japan.

Then, when the Yamagawa sounder data are used:

$$P_2 = 0.391\ r_3 \qquad \text{(III-C-6)}$$

c. Comparisons of the Data. The data, all normalized to a yearly base, are presented in figures III-C-3, 4 and 5. In figure III-C-3, the Japanese data are given for 31.55 Mc, the transmission frequency whereas the FCC and Cedar Rapids-Sterling measurements have been adjusted from 49.8 to 32 Mc through relation (III-C-2). Similarly in figure III-C-4 the Japanese data are shown for the transmission frequency 43.85 Mc, the FCC's for 44.3 Mc (the operating frequency of WGTF) and the Cedar Rapids-Sterling values adjusted from 49.80 to 44 Mc. Finally in figure III-C-5 both sets of U. S. data are extrapolated to 66 Mc and the Japanese measurements made at 65.82 Mc appear as recorded at that frequency. The dotted lines labelled tropospheric forward scatter are theoretical values. They appear through the courtesy of P. L. Rice and K. A. Norton, and have been added to give a visual estimate of possible tropospheric contamination.

The saturation level of the recorder for the Cedar Rapids-Sterling path corresponds to 62 db below the free-space level (A = 62 in III-C-3). These measurements, therefore, give only one point on each of the three figures. The Japanese data, as was pointed out above do not extend below -40 db relative to free space.

Figure III-C-4 compares the three sets of data most directly i.e. involves the smallest extrapolations from the frequency at which the data were recorded. It is seen that levels for the Japanese data range from 25 db higher than the FCC for a probability of occurrence of 0.0005 (0.05% of the time) to 35 db

SPORADIC E BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 32 MC

The Labels on the Curves Refer to the Probability, p,
During a Period of One Year that the Observed
Basic Transmission Loss will be Less than the Ordinate Values

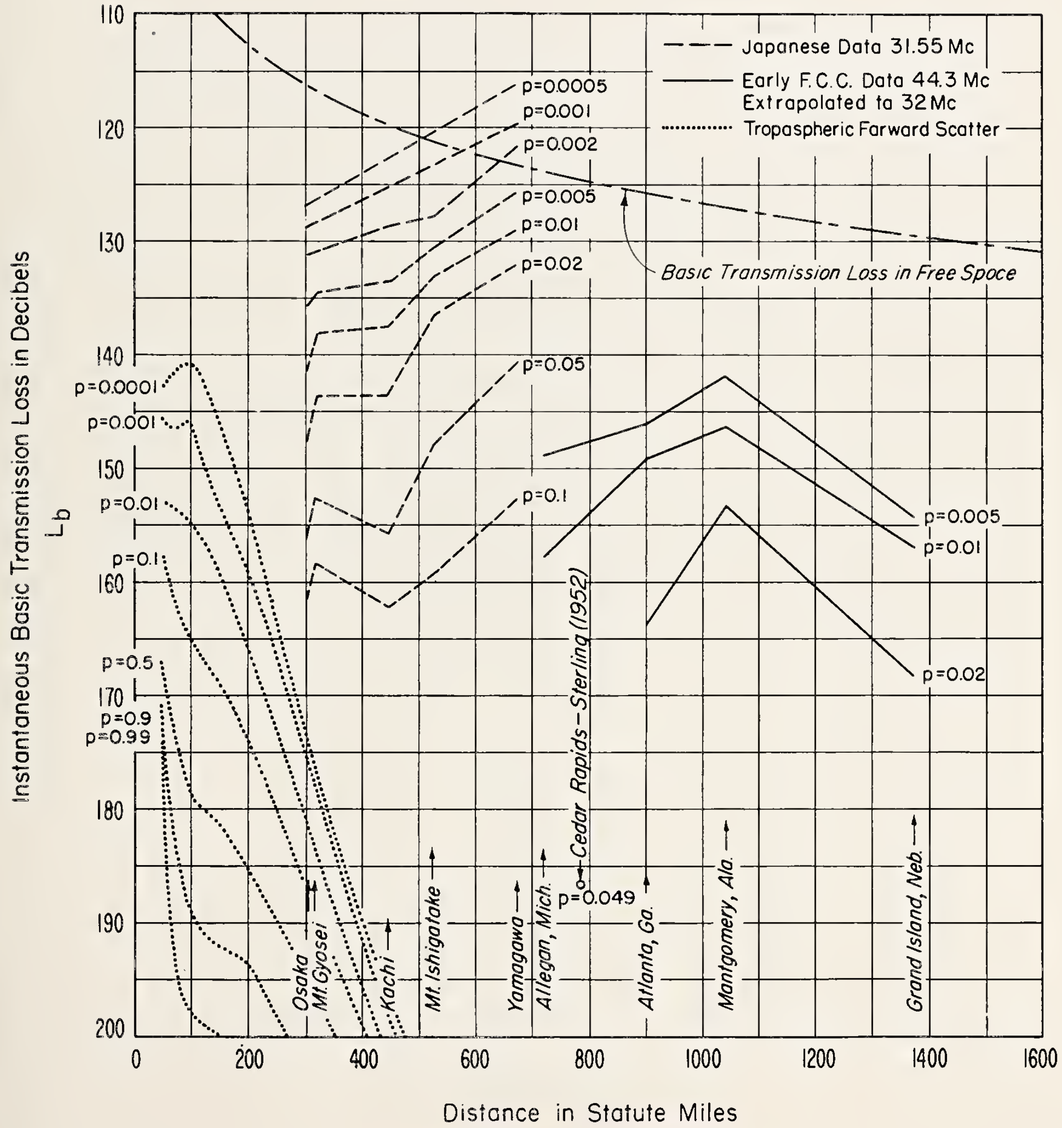

Figure III-C-3

SPORADIC E BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 44 MC

The Labels on the Curves Refer to the Probability, p,
During a Period of One Year that the Observed
Basic Transmission Loss will be Less than the Ordinate Values

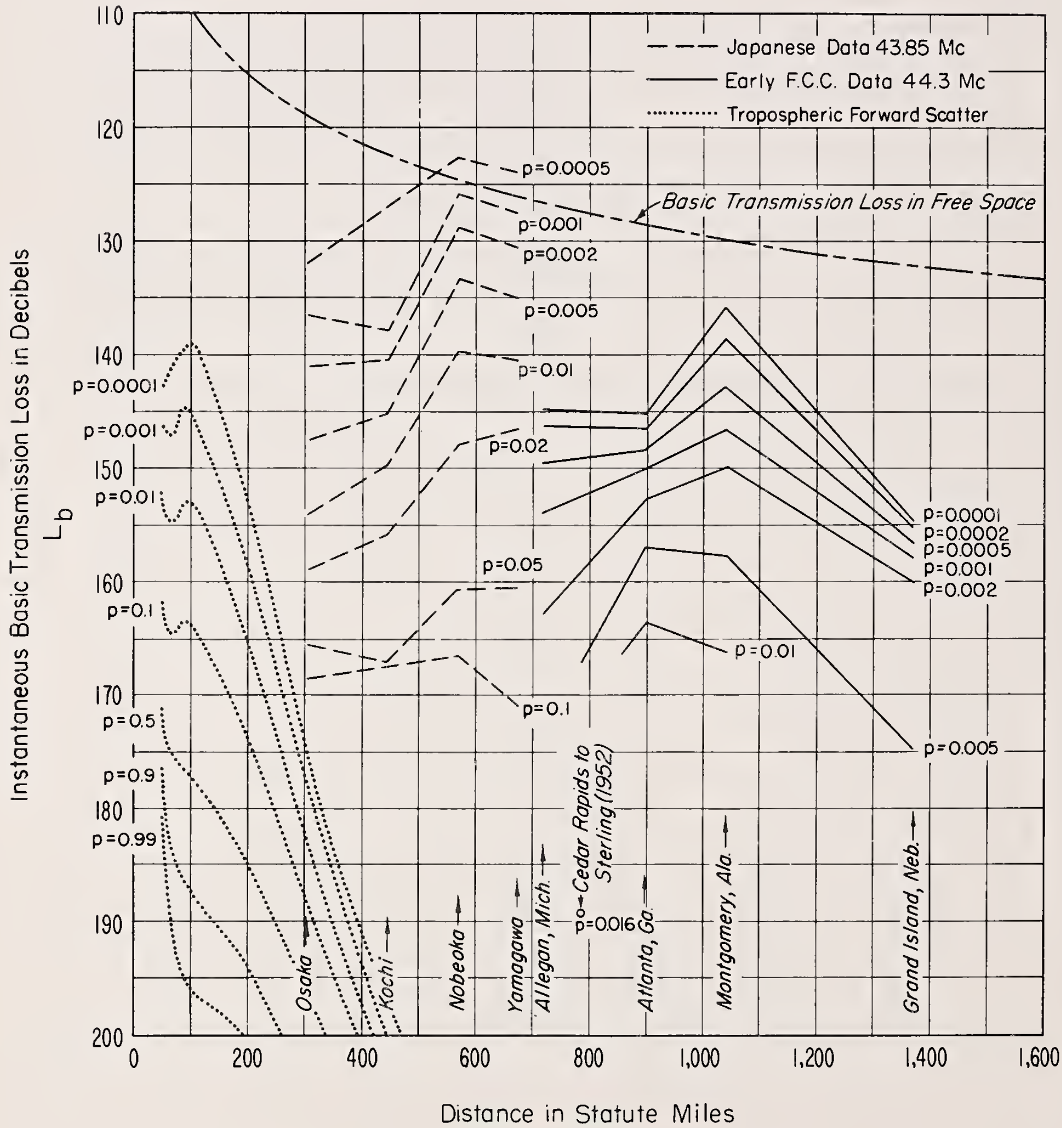

Figure III-C-4

SPORADIC E BASIC TRANSMISSION LOSS VERSUS DISTANCE AT 66 MC

The Labels on the Curves Refer to the Probability, p, During a Period of One Year that the Observed Basic Transmission Loss will be Less than the Ordinate Values

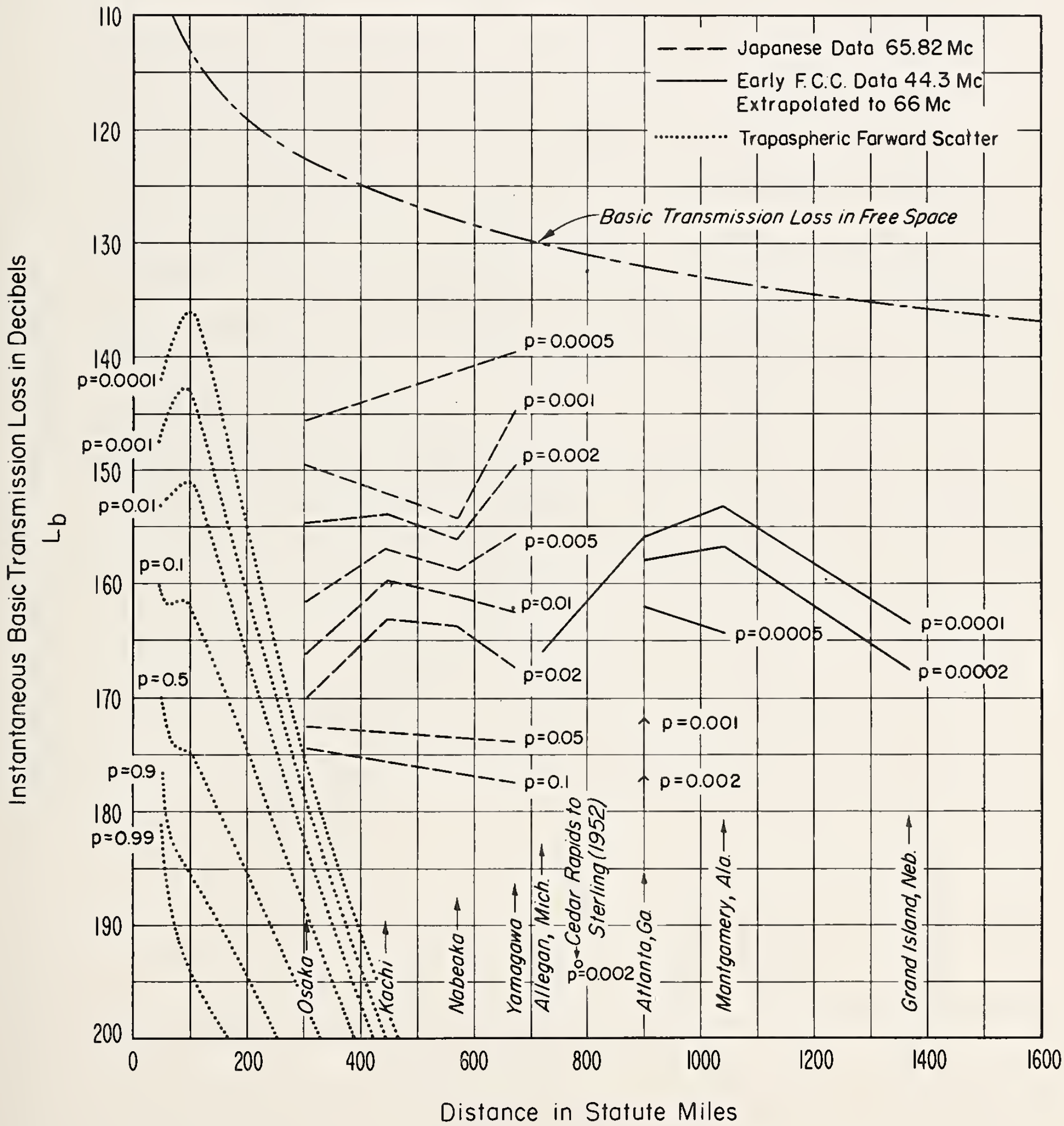

Figure III-C-5

higher at a probability of 0.005 (0.5% of the time). For a fixed level of transmission loss, if one mentally extrapolates the two sets of curves to 700 miles it is seen that at the level L_b = 145 db Es propagation occurs 160 times more frequently in Japan than in the U. S. At L_b = 170 db the figure is down to about 20 times.

It must be pointed out that the FCC data (shown in the solid curves) are referred to year 1944 and the Japanese to 1952. However, the Cedar Rapids-Sterling data shown are for 1952 and, as may be seen in figure III-C-5, demonstrate that the Es levels were perhaps even lower in 1952 than in 1944. It, therefore, seems probable that the differences shown are real and represent a true longitude effect.

The author submitted a copy of this comparison to Mr. Kono and asked him to review it for possible misuse of the Japanese results. Mr. Kono replied that he found no error in the methods and calculations and suspected the longitude effect to be real.

Further support for the VHF longitude effect is found in the similar effect derived from vertical-incidence data in Chapter II.

Chapter IV

CONCLUSIONS

A. The Correspondence of Sporadic E at Vertical and Oblique Incidence

It is probable that sporadic E observed on an oblique incidence path can be related only statistically to the sporadic E observed on an ionosonde at the midpoint of the path. By this is meant that the instantaneous correlation between the two sets of observations is probably not good. This is perhaps due to off-path transmission at oblique incidence.

1. The NBS Oblique-Incidence Experiment.

In the NBS Oblique-Incidence Experiment (reported by Wieder, Sulzer and Wright [1953]) two synchronized ionosondes, modified C-3 equipments, were located at Sterling, Virginia and St. Louis respectively, a separation of about 1150 km. A regular C-3 was placed at the path mid-point near Batavia, Ohio. Four days of records (May 14-15 and June 11-12, 1952) were analyzed for sporadic E. The ratios of the Es critical frequencies observed simultaneously on the oblique and vertical incidence records was found to vary from three to eight. This ratio appeared to depend somewhat on the value of h'Es observed at the mid-point ionosonde but the statistical significance of this connection was low. Reciprocity for the east-to-west and west-to-east transmissions of Es critical frequencies was good but by no means perfect. The report pointed out that for the situation in question the secant law can be properly applied only to the O-wave and that the O and X components can rarely be distinguished in the Es traces on either the vertical or oblique records.

2. The Japanese Experiment.

A description of this work (Kono, Uesugi, Hirai and Abe [1954]) has already been given in section III-C, but consideration was restricted to the oblique-incidence results. Vertical-incidence sounders were available at roughly the two ends of the oblique path. It is not unreasonable to assume that a sounder at the mid-point of a path would record sporadic E with characteristics intermediate to those observed at the two terminal ionosondes. The distributions at these terminal ionosondes (Kokubunji and Yamagawa) are given in figure IV-A-1. The four curves labeled Odb.....-30db below free space show the probabilities at which these levels were observed to occur for the Hiraiso to Yamagawa path (674 mi.) on 31.55 Mc, 43.85 Mc. and 65.82 Mc and for the Hiraiso to Osaka path (302 mi.) on 31.55 Mc. The remaining line represents the predicted sporadic-E occurrence using the methods of section II-G applied to the Kokubunji and Yamagawa ionosondes. The value used for the frequency dependence factor b is calculated from the mean difference of Es occurrence at the 5 Mc and 7 Mc level for the two ionosondes.

It is interesting to note that this derived frequency dependence corresponds very closely to the level given by the oblique incidence data for - 15 db below free space. (The corresponding figure over a U. S. path in 1945 is -21 db.) The values actually observed at vertical incidence (solid lines) do not appear to show the same form of frequency dependence at all. The remarkable implication of these facts is that it appears preferable to derive b from the occurrence levels of fEs> 5 Mc and fEs > 7 Mc if one is interested in oblique-incidence Es than to determine the actual occurrence of fEs above the frequency in question.

A further implication of figure IV-A-1 is that only unity reflection coefficients can be detected when the ionosonde sweep frequency has reached 15 Mc. This conclusion assumes the equivalence of vertical and oblique-incidence Es. As the writer has no information on the ionosondes used at Kokubunji or Yamagawa further speculation is hardly justified. If the equipments had been C-3 recorders, which should be at their best around 15 Mc, one would be tempted to use figure IV-A-1 to indicate that oblique-incidence Es does not have the same frequency behavior (assuming the secant law) that is observed for Es on vertical-incidence equipments.

For want of more complete data it is suggested that the vertical-incidence data of Chapter II be related to the level of 20 db below free space when converted by the secant law for use in connection with oblique-incidence transmission. The result is derived from data for summertime 1952 in Japan and the year 1945 in the U. S. It is probably more directly applicable in the

COMPARISON OF VERTICAL AND OBLIQUE INCIDENCE FREQUENCY DEPENDENCE FOR SPORADIC E
SUMMER 1952
Data Taken From Kono et al. [1954]
Secant Law Assumed

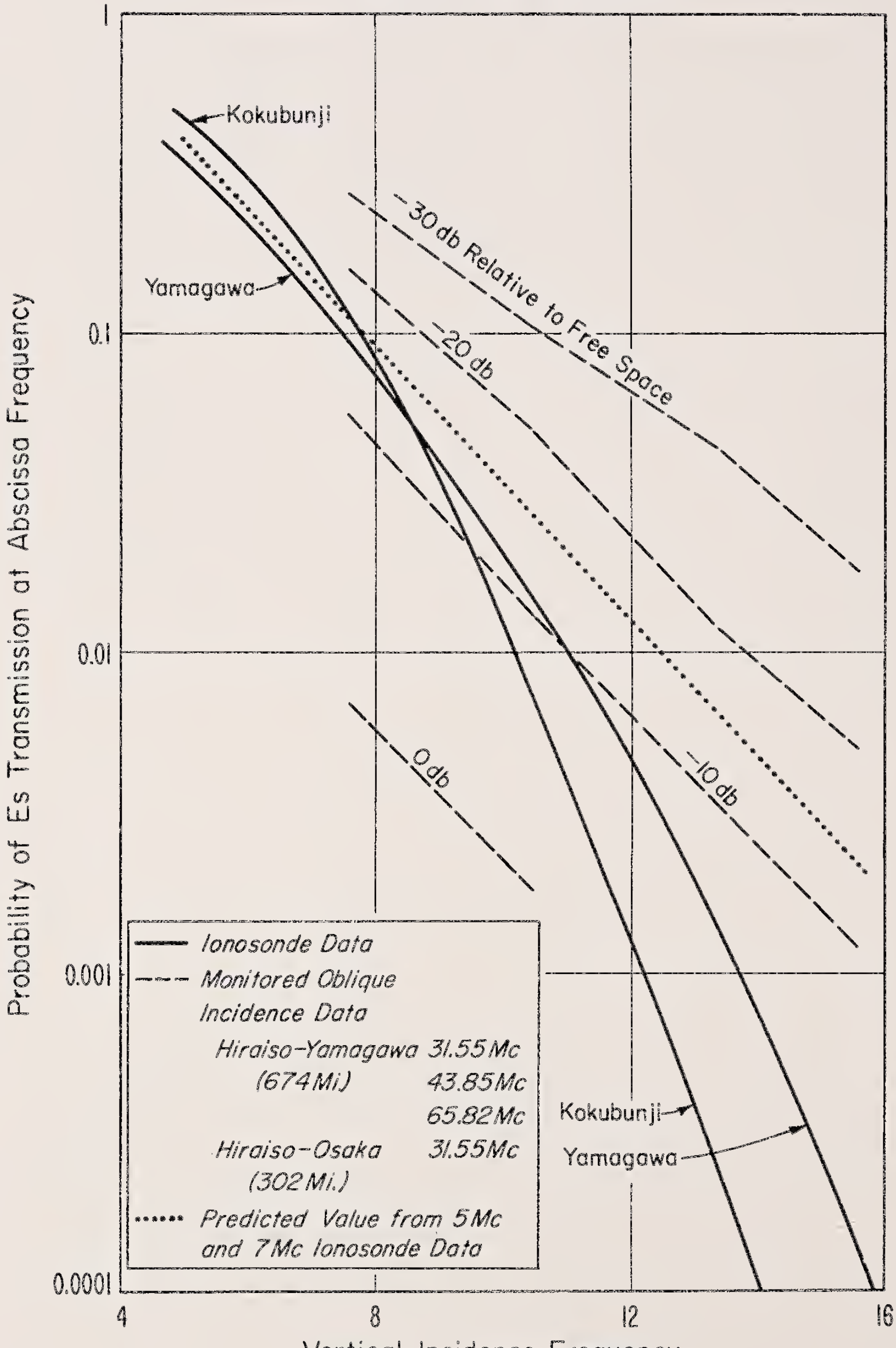

Figure IV-A-1

Temperate Zone than in the Auroral Zone and is probably subject to diurnal and seasonal variations.

B. Reconsideration of Energy Sources for Sporadic E

Up to now the emphasis has been on the description of sporadic E at vertical and oblique incidence and not on the interpretation of the findings. This description is, of course, the main purpose of this study, however, it is appropriate in this last chapter to consider the implication of some of these results on our knowledge of the possible energy sources of sporadic E.

The following section considers the probable importance of the various sources of energy for sporadic E. This consideration is made on the basis of the results of the current study added to the body of pertinent existing knowledge. The conclusions of this survey are tabulated in Table IV-B-1.

It will be assumed in the discussion to follow that the observed sporadic E will show time variation patterns which can be related to those of the energy source. It is probable that this assumption is correct, but it is easy to create models where it would not be. For example if some sort of reservoir for energy exists in the upper atmosphere, this reservoir would shield the sporadic E from variations in the energy source. Alternatively a catalytic agent may be present whose time variations may, for practical purposes, completely overshadow those of the actual source of the energy.

1. Solar Corpuscles

The high correlation found between sporadic E in the Auroral Zone and auroral-percent-frequency-days and also magnetic activity indicates that most sporadic E ($fEs > 5$ Mc) near the 100% isochasm is associated with aurorae and perhaps hence with solar corpuscles. A surprising disagreement is presented by the marked seasonal variation in the forward-scatter Es data. The situation is quite otherwise in the High Temperate Zone. Here negative correlation with magnetic activity exists and the sporadic-E peaks occur during the solstices whereas magnetic activity and aurorae both have equinoctial peaks at these latitudes. The diurnal variation of sporadic E in this zone is also completely different from those for magnetic activity and aurorae. At lower latitudes in the Temperate Zone, none of these characteristics which speak against a solar corpuscular source are so marked but the evidence is still against this source. The Es geographical peak around Japan during the summer months is difficult to explain on a corpuscular basis although this peak bears a faint resemblence to the geographical one found for cosmic rays.

In the Equatorial Zone the two striking characteristics of the Huancayo type Es are that it is a daylight phenomenon and that it exists in a very narrow geographical belt near the magnetic equator. This belt would be one which charged solar particles would shun; and for neutral particles it is difficult to see why their incidence on the earth should be restricted to either the daylight side or to a narrow belt.

2. Meteors

The seasonal variation of total meteor incidence upon the earth, shower and sporadic, is not too dissimilar to that observed for sporadic E in the North Temperate Zone. However, Temperate-Zone sporadic E shifts in phase by six months when one moves to the Southern Temperate Zone (see section II-F) whereas meteoric incidence is probably not greatly changed. It will be observed in the time maps of section II-F that most of the periods of essentially zero sporadic E fall in the early morning hours when meteoric activity should be high. Similarly the Temperate-Zone diurnal Es minimum is regularly during the early morning hours when meteoric activity is high, also the evening maximum occurs at a time when meteoric activity should be at a minimum.

For meteors to be the sole agent of sporadic E on a world-wide basis it would be necessary that latitude variation in Es be gradual and that no systematic longitude variation exist. These characteristics are not observed in sporadic E so that meteors cannot be considered an important direct source of energy. It is, however, quite possible that during an intense shower meteors do create an effect which is indistinguishable from sporadic E as has been shown by Appleton and Naismith [1947].

If meteoric particles provide a ground level of sporadic E and the more conspicuous characteristics of the phenomenon are overlaid upon this, then the meteoric features would be expected to be most apparent for areas of low sporadic E. An area of this nature exists in South Africa as was seen in Chapter II. The time variations for Johannesburg (figure II-F-26), a station in this area, do not appear any more meteoric in character than do those for stations in areas of higher annual Es occurrence. This argument indicates that probably no important percentage of the sporadic E observed at 5 Mc is due to meteors.

3. Thunderstorms

The case for thunderstorms as an energy source is a mixed one. The dominant seasonal variation exhibited by stations in the Temperate Zone coupled with the 180° phase shift as the equator is crossed is highly suggestive of a terrestrial energy source. Thunderstorms have a local summer maximum, as does Es, and the 180° phase shift between the hemispheres is thus automatically achieved. Indian scientists have maintained for twenty years that close correlation exists (in India) between thunderstorms and sporadic E. The literature, as reviewed in Chapter I, is well-stocked with possible explanations of how thunderstorms can produce the necessary ionization to account for Es.

On the negative side is the lack of day-to-day correlations between thunderstorms and Es, at least which have stood up through the years, outside of India. Also a comparison of a map of thunderstorm days (courtesy Atmospheric Noise Project, CRPL) shows little correspondence with the geographical variations of sporadic E presented in section II-F. Especially difficult to explain is the high thunderstorm count in South Africa, the area with apparently the world's lowest Es occurrence. A less serious point is that the Californian coast experiences very few thunderstorms compared to, say, New Mexico and yet the occurrence of sporadic E at San Francisco is about the same as that at White Sands. These examples are by no means isolated. If one ignores

"Huancayo Es" (see section II-B-1) the comparison of first multiple Es at Huancayo and Watheroo by Berkner and Wells [1937] can still be invoked to show that Temperate Zone Es is not directly related to the incidence of thunderstorms.

It may be that "thunderstorm count" per se is not the measure which should be compared to Es. For example, it may be only the discharges upward to the ionosphere which cause sporadic E. The earth-ionosphere potential is thought to be controlled by the world-wide thunderstorm activity, but the details of these potential variations are not well-known. Also the import of the results announced by Isted [1953], [1954] of a connection between bursts of signal over VHF paths and lightning has not been assessed.

The mean potential difference between the earth and the ionosphere is 4×10^5 volts, but the atmospheric leakage currents are such that this potential difference would decay to negligible proportions in a matter of tens of minutes if the charge separation were not continually replenished. This replenishment is thought to be supplied by terrestrial storms in the lower atmosphere particularly those over Africa and South America (Chalmers [1949]). It is instructive to compute the total value of this steady leakage which flows downward through the atmosphere. A mean value of the columnar resistance (the resistance of a 1 cm^2 column extending from the ground to the ionosphere) may be obtained from data given by Chalmers (loc. cit.).

mean columnar resistance, $r = 2 \times 10^{21}$ ohms/cm^2

area of earth, $a = 5 \times 10^{18}$ cm^2

total resistance of atmosphere, $R = r/a = 400$ ohms

potential of ionosphere relative to earth, $v = 4 \times 10^5$ volts

total leakage current = V/R = 1000 amperes.

If the charging sources are quite localized, this current of the order of 1000 amperes will flow over extended geographical areas both in the ionosphere and on the earth. One might wonder, therefore, why it is not picked up on magnetograms. However, the current system in the upper atmosphere necessary to produce even the S_q (solar quiet day) variation is 89,000 amperes in June and 62,000 amperes at the equinoxes (Mitra [1952], p. 374). The leakage current is, therefore, pretty well overshadowed by the S_q current. As this S_q current is thought to flow in the D or E region (Matsushita - private communication) there seems little likelihood of the leakage current playing an important role in sporadic E except in the vicinity of the thunderstorms.

4. Winds and Turbulence

Very little is known of the variation of the E-region wind-systems with latitude, height and time so that the point by point comparison of the type made between Es and thunderstorm count is not possible with winds. Winds do have the same general advantage as do thunderstorms that they too are a terrestrial energy source. If winds supply the energy then the mechanisms of Gallet [1955] may be invoked to explain the observations.

5. Currents

E-region currents are an available mechanism for sporadic E in the Auroral Zone and in the Equatorial Zone. In the Temperate Zone the negative correlation or lack of correlation between Es and magnetic activity limits the possibilities to the S_q current. Matsushita [1955] offers an ingeneous explanation for sequential Es which involves the S_q current, but for the most part the very regularity of this current speaks against it. Some other factor must be brought in to explain the sporadicity of Es.

In the Equatorial Zone the geographical and temporal simultaneity of the equatorial electrojet and·Huancayo type Es favors this current as the energy source.

TABLE IV-B-1

Tabulation of Es Energy Sources by Zone

ZONE	Possible Sources of Energy					
	SOLAR Corpuscles	Meteors	Thunderstorms	Winds and Turbulence	Currents	Other
Auroral	<u>probable</u> (perhaps indirect)	<u>improbable</u>	<u>improbable</u>	<u>improbable</u>	<u>possible</u> (difficult to separate from corpuscles)	<u>possible</u>
Temperate	<u>improbable</u> (except during intense magnetic storms)	<u>improbable</u> (except during intense meteor showers)	<u>possible</u> (but indirectly for most areas)	<u>possible</u>	<u>possible</u> contributing factor in sequential Es	<u>possible</u>
Equatorial (Huancayo type Es)	<u>improbable</u>	<u>improbable</u>	<u>improbable</u>	<u>possible</u>	<u>probable</u>	<u>possible</u>

APPENDIX I GEOMAGNETIC-ACTIVITY FIGURES

Geomagnetic Activity

Geomagnetic activity is defined as the frequency and intensity of magnetic disturbance (roughly, the irregular part of the variation of the three magnetic elements on a magnetogram) and is thought to indicate the influx of solar corpuscular radiation on the earth. The first widely adopted measure was the magnetic character figure C, a qualitative measure. In recent years the most used index of magnetic activity, at least in connection with ionospheric studies, has been the three-hour-range index K, a quantitative measure proportional to the logarithm of the range of the irregular part of the field. This K index was originally developed to fulfill a need in ionospheric radio research (Bartels, Heck and Johnston -1939]) A new index A has recently been offered as a substitute for the K index and it might be well to discuss the reasons for the change, along with a background to the International quiet and disturbed days. These latter are used frequently in the text.

The C Figures

The C figure has been in use since 1906 and is obtained at a given station as follows. The records for the three magnetic elements are examined for each Greenwich day and the day is assigned one of the three digits: 0 (quiet), 1 (average or moderately disturbed) or 2 (disturbed). The average of the C figures from the various observatories is then taken at a central office (DeBilt, Holland). This average carried to one decimal point is the international magnetic character figure Ci. A daily planetary character figure Cp has been proposed by Bartels (IATME Bulletin 12f - 1952). Cp is, however, a world average to be derived from the three-hour-range indices K and so becomes a quantitative measure. A recent proposal to the International Association of Terrestrial Magnetism and Electricity to replace Ci by Cp was dropped (IATME Bul. 12f, p. 4, 1952).

A difference in terminology regarding the C figures is found between the early and recent literature. In references before 1944 (e.g. Chapman and Bartels, Geomagnetism, Oxford, 1940; Johnson [1943] the international magnetic character figure was called C (now called Ci) and the classification of days into 0, 1 or 2 at individual observatories was not given a letter designation.

The K indices

The K index as provisionally adopted by the International Association of Terrestrial Magnetism and Electricity in September 1939 (Bartels, Heck and Johnson [1940]) was to work as follows. Each contributing observatory was to assign to each three-hour interval beginning 0 hr., 3 hr.,...Greenwich time one of the integers 0 to 9 as a range index K. This was to be done on a quantitative basis. The actual ranges of magnetic variation involved for each integer value of K would, of course, vary from observatory to observatory. Certain Geomagnetic time variations were considered.

Non-K Variations

Sq... the solar daily variation on quiet days;

L.... the lunar daily variation;

Dma.. that after effect of the disturbance-field which consists of a general change in level of the curves well after the actual disturbance has subsided.

This left the following variations contributing to K.

K Variations

D.... the regular fluctuations during disturbance;

Dm... the mean effect of the disturbance-field as manifested in changes throughout the three-hour interval, except Dma;

S_D... the disturbance daily variations including that part of Dm called the non-cyclic variation on disturbed days.

Niemegk in Potsdam was used for the pilot model. The K scale for Niemegk is:

K = 0 1 2 3 4 5 6 7 8 9

R = ..5..10..20..40..70..120.200.330.500. γ

where R defines the range of the most disturbed element during the three hour interval. The above scale means: all ranges less than 5γ define K = 0, those from 5γ up to 10γ define K = 1 and so on. It will be noticed that the scale proceeds by multiples of 2 up through K = 4 and then somewhat more gradually for the remainder of its course.

To arrive at the K scale for a different observatory the procedure was roughly to count downward in the ordered range indices for a substantial period until the same number of entries was reached as for those having K values of 5 to 9 at Niemegk for the same period. The value of R corresponding to this last ordered entry is now defined as the upper limit for K = 4 at the new station (corresponding to R = 70 γ at Niemegk. The K scale for the new station is now assigned range values so that it differs everywhere from the Niemegk scale in this same ratio. This works out in practice so that about the same number of intervals show K =0 , 1, ... etc. as for Niemegk.

Most stations exhibit local characteristics and as the geographical distribution of observatories is far from uniform these local characteristics show up to some extent in K. A standardizing process has been developed (Mitra, The Upper Atmosphere, 2nd Ed., p. 363, The Asiatic Society, 1952) whereby the individual station K indices may be freed from these local features. The resulting "standardized" K index is Ks. Ks values are available from 11 observatories between geomagnetic latitudes of 47 and 63 degrees. The three-hour geomagnetic planetary index Kp is the average of the eleven Ks indices.

The A Index

A need has been felt in recent years to express "magnetic activity" in some linear scale in addition to the quasi-logarithmic scale for K. The need is particularly felt when time periods need to be averaged.

A three-hourly planetary equivalent amplitude ap is related to Kp as follows:

Kp =	0o	0+	1-	1o	1+	2-	2o	2+	3-	3o	3+	4-	4o	4+
ap=	0	2	3	4	5	6	7	9	12	15	18	22	27	32
Kp =	5-	5o	5-	6-	6o	6+	7-	7o	7+	8-	8o	8+	9-	9+
ap =	39	48	56	67	80	94	111	132	154	179	207	236	300	400

Ap, the equivalent daily amplitude, is the average of the eight ap values per day.

To obtain the local equivalent amplitude ak from the K value at a station the following table is used.

K =	0	1	2	3	4	5	6	7	8	9
ak =	0	3	7	15	27	48	80	140	240	400

Ak is the daily average of the eight values of ak and is thus the local equivalent of Ap.

A daily index B had been suggested by Bartels, Heck and Johnston [1939] but does not appear to be in use today. B is derived from the world-wide average of the K indices by converting each of these three-hour averages into equivalent ranges, taking the daily average of the eight ranges, and reconverting this range average back into the quasi-logarithmic scale of the K index. Thus, although B is not a linear index it has many of the advantages of the A index and is related to it through a simple conversion table.

International Quiet and Disturbed Days

The selection of the five magnetically quietest and the five magnetically most disturbed days each month has been made since

1906. Up to World-War II this selection was made on the basis of international magnetic character figure C (now Ci) through simply arranging these values for each month in decreasing order. The days with the five highest C values were then the five disturbed days for the month, the five days with the lowest C values were designated the five international quiet days for the month. During World-War II the number of contributing observatories was cut almost in half (from 61 to 33) and the accuracy of the C-derived selection of days was correspondingly reduced. At the same time ionospheric radio research was going forward with high priority and researchers in this field needed an accurate designation of the days badly. At first an attempt was made to bolster the data used in the selection through inclusion of the more precise and quantitative K figures (Johnston- [1942]). About a year later (Johnston- [1943]) the proposal appeared on which the present selection is based. This proposal was to examine the fifteen quietest days each month and the seven most disturbed in terms of five criteria. These were:

1. the international magnetic character figure C;
2. the daily index B;
3. the sum of the eight values of the three-hour range index Km (a mean value analogous to Kw):
4. the maximum value of Km for the day;
5. the sum of the squares of the eight values of Km.

The days are ranked by each criterion, then the ranks are summed. The resulting ranking is used to determine the ten quiet days in order of rank and the five disturbed days. In the scheme now in use, criteria 1. and 2. have been discarded and Kp, the planetary index, substituted for Km (see for example CRPL-F130, p. 12, June 1955).

APPENDIX II A NOTE ON SLANT Es

Slant Es is a very interesting anomaly. It generally takes the form of a faint trace slanting diagonally upwards with a slight upward curvature on the ionogram record. Characteristically it will appear to emerge from an Es trace at a height of 110 km and a frequency of perhaps 5 Mc and continue upward to say 400 km at a frequency of perhaps 14 Mc. It is seen primarily in the arctic close to the maximum of the auroral zone. At College, Alaska it has been associated most frequently with glows to the north (Heppner, Byrne and Belon [1952]). Cases have also been observed at mid-latitude stations (Adak, Maui) and on the magnetic equator (Huancayo). Examples of slant Es are illustrated in the ionograms of figs. Ap II-1 and A-II-2.

An explanation of this phenomenon is offered here and a comparison made of this explanation with the other ones which the author has encountered. If the explanation is correct it has an interesting bearing on ionospheric forward scattering, in that it offers an independent determination of the height of the scattering layer.

The mode of propagation invoked here is an extension (or perhaps better, a compression) of a mode invoked by D. K. Bailey (CRPL Colloquim, March, 1955) to explain the nose on oblique-incidence h'f records. Bailey suggested two scatter mechanisms, an asymmetrical single-scatter case (fig. Ap II-3 a) and a symmetrical double-scatter case (fig. Ap II-3b).

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SLANT Es AT COLLEGE, ALASKA

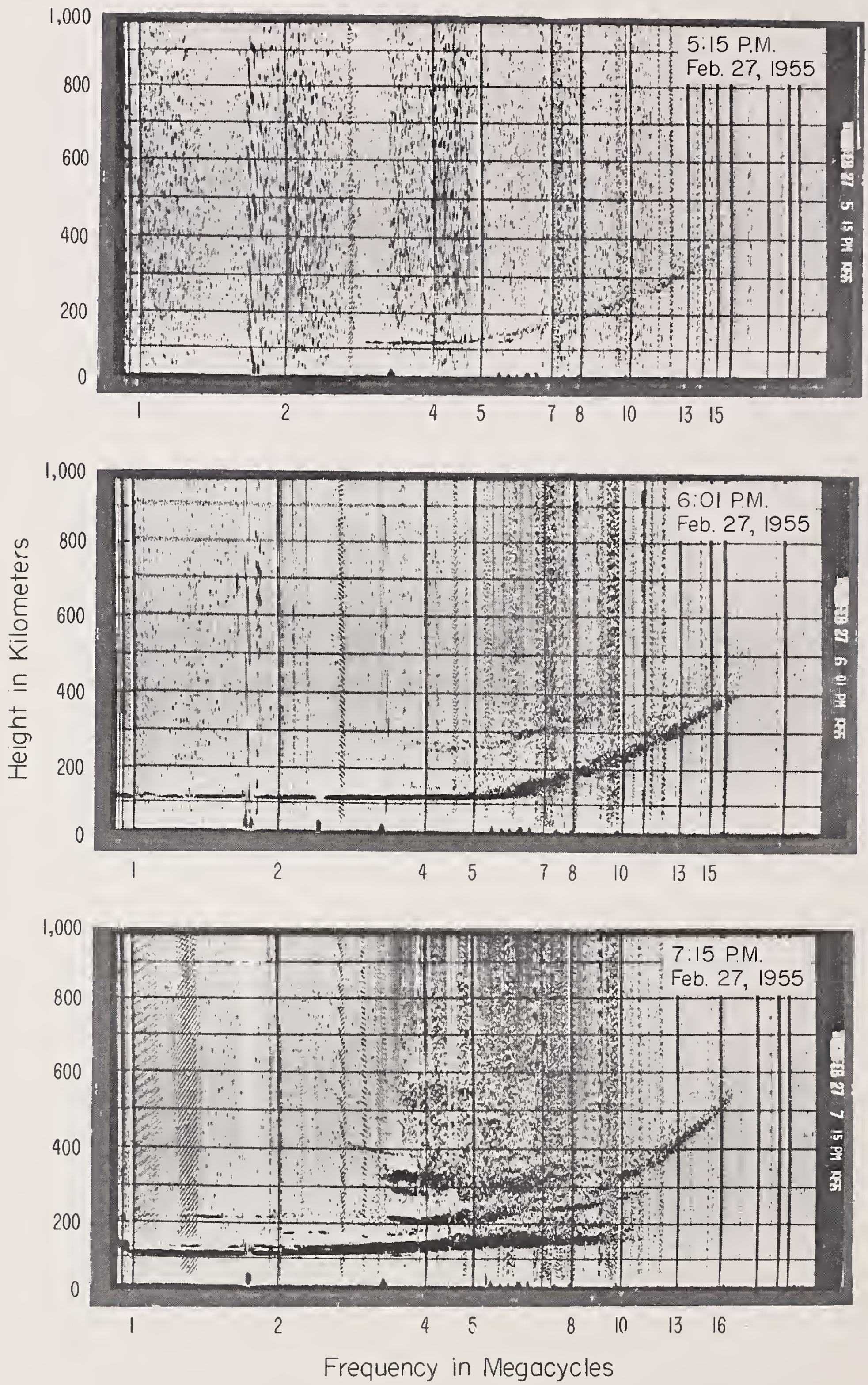
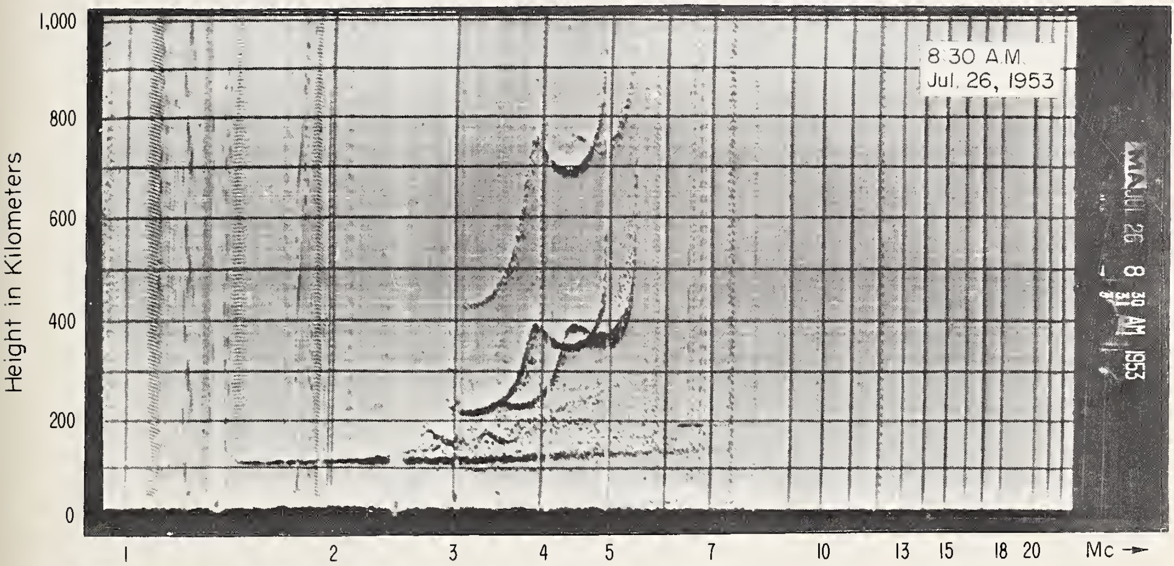
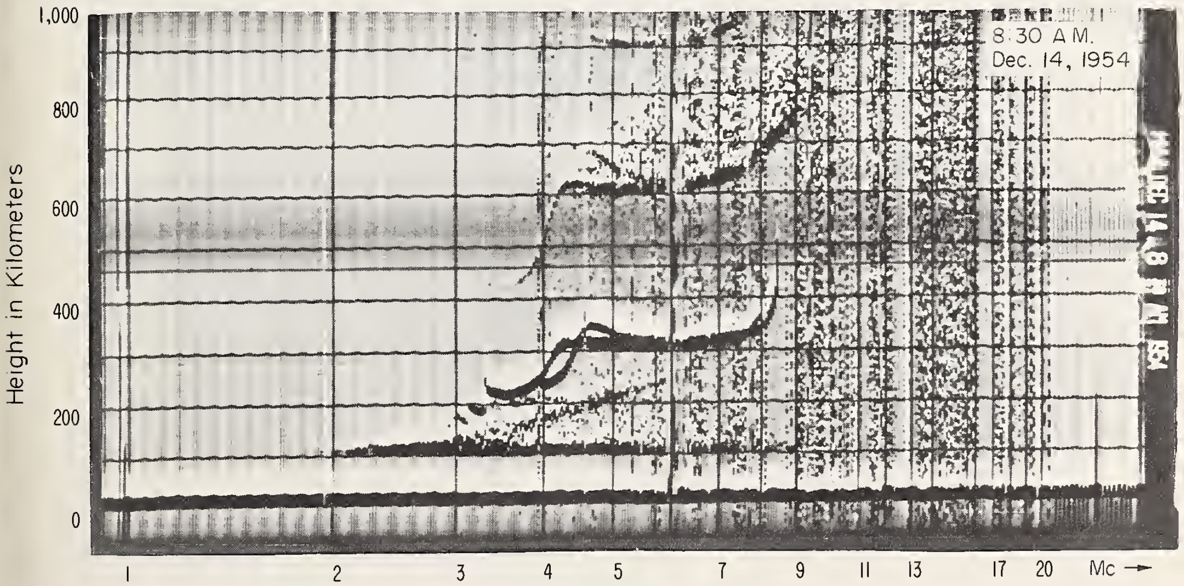


Figure Ap II-1

NON AURORAL SLANT Es



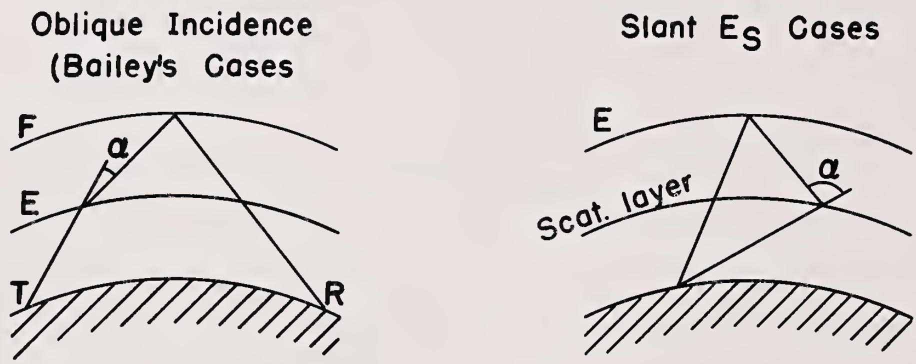
(a) Maui, Hawaii



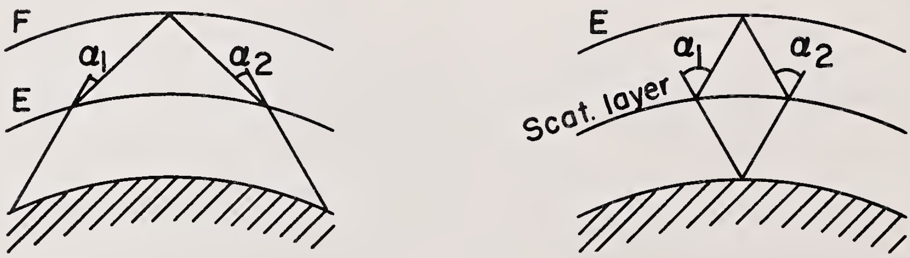
(b) Huancayo, Peru

Figure Ap II -2

PROPOSED MODES OF PROPAGATION TO EXPLAIN SLANT E_S



a) Single Scatter Cases



b) Double Scatter Cases
(for symmetrical double scatter $\alpha_1 = \alpha_2$)

Figure Ap II-3

Let us now assume that slant Es is due to energy propagated in annular rings around the location of the ionosphere sounder at a height of 80 km by the single-scatter* or double-scatter mechanisms. Let us further postulate an Es layer 10 to 40 km above the scattering layer with a fairly well-defined critical frequency. If one now applies the secant law to compute the maximum frequency which will be transmitted by the Es layer as a function of the apparent range (one half total distance), a curve is defined for any given set of parameters (fEs, h'Es, and h scat.) which corresponds with the lower edge of the observed slant-Es traces. These curves are given in figure Ap II-4 for single or asymmetrical scatter and in Ap II-5 for double or symmetrical scatter. Three combinations of scattering height and height of the reflecting layer have been taken. With the first number designating the height of the scattering layer in km and the second number that of the reflecting height, the three combinations are 80-100, 90-100, and 80-120. The computations were based on plane earth for the original study, but as a final check one curve was computed on a curved earth basis. This shows up as a dotted line in the middle chart of figure Ap II-4. As can be seen, the difference does not become important until apparent heights of 400 km or so reached. The average maximum apparent height of the thirty-one cases which are considered here is just over 300 km. The curves in figure Ap II-4 and 5 are

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* The single-scatter case is analogous to Eckersley "1F Mode" (1) applied here to the E region and the scattering region below it.

FAMILIES OF THEORETICAL SLANT Es CURVES ASSUMING A SINGLE SCATTERING MECHANISM AND PLANE EARTH

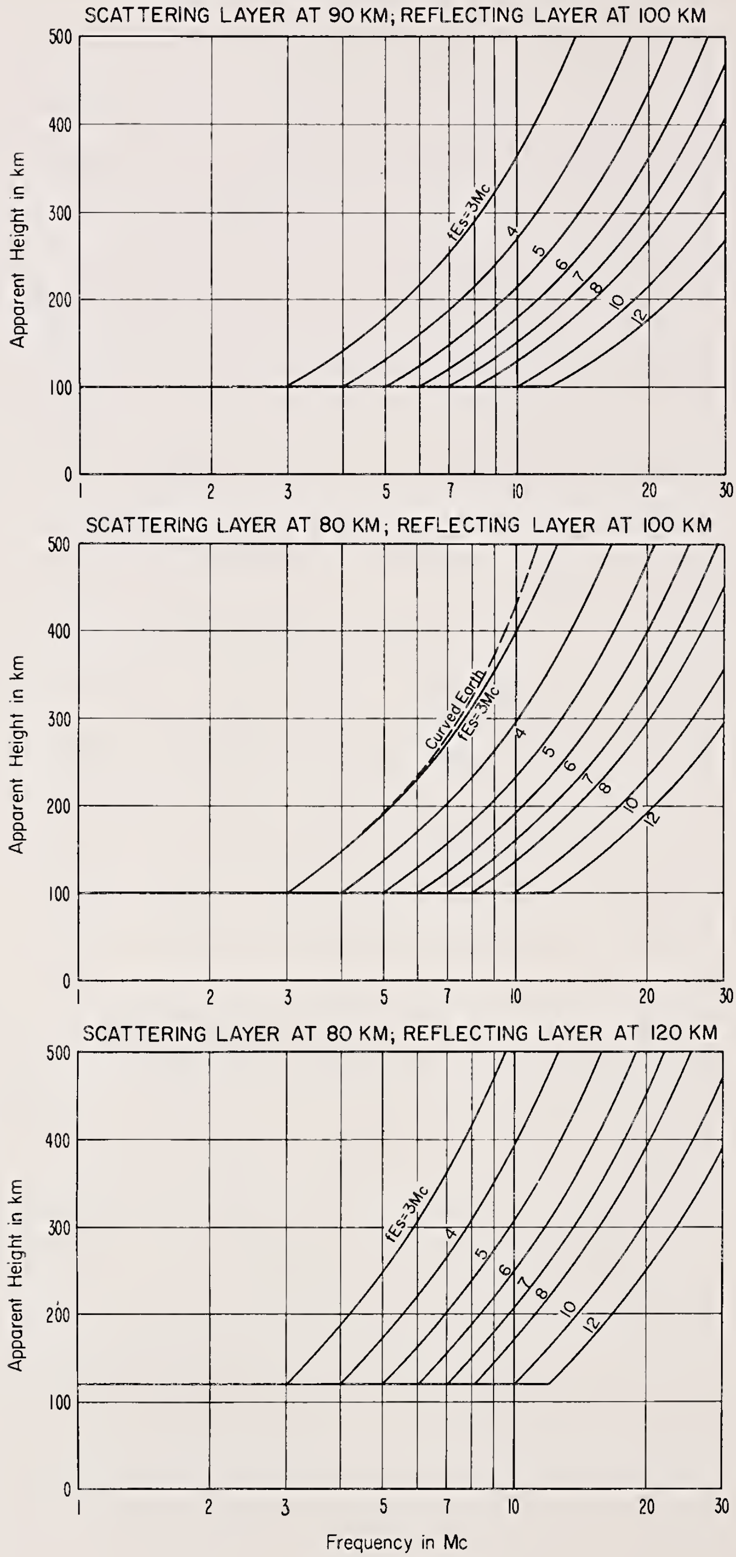


Figure Ap II -4

FAMILIES OF THEORETICAL SLANT Es CURVES ASSUMING A SYMMETRICAL DOUBLE SCATTERING MECHANISM AND PLANE EARTH

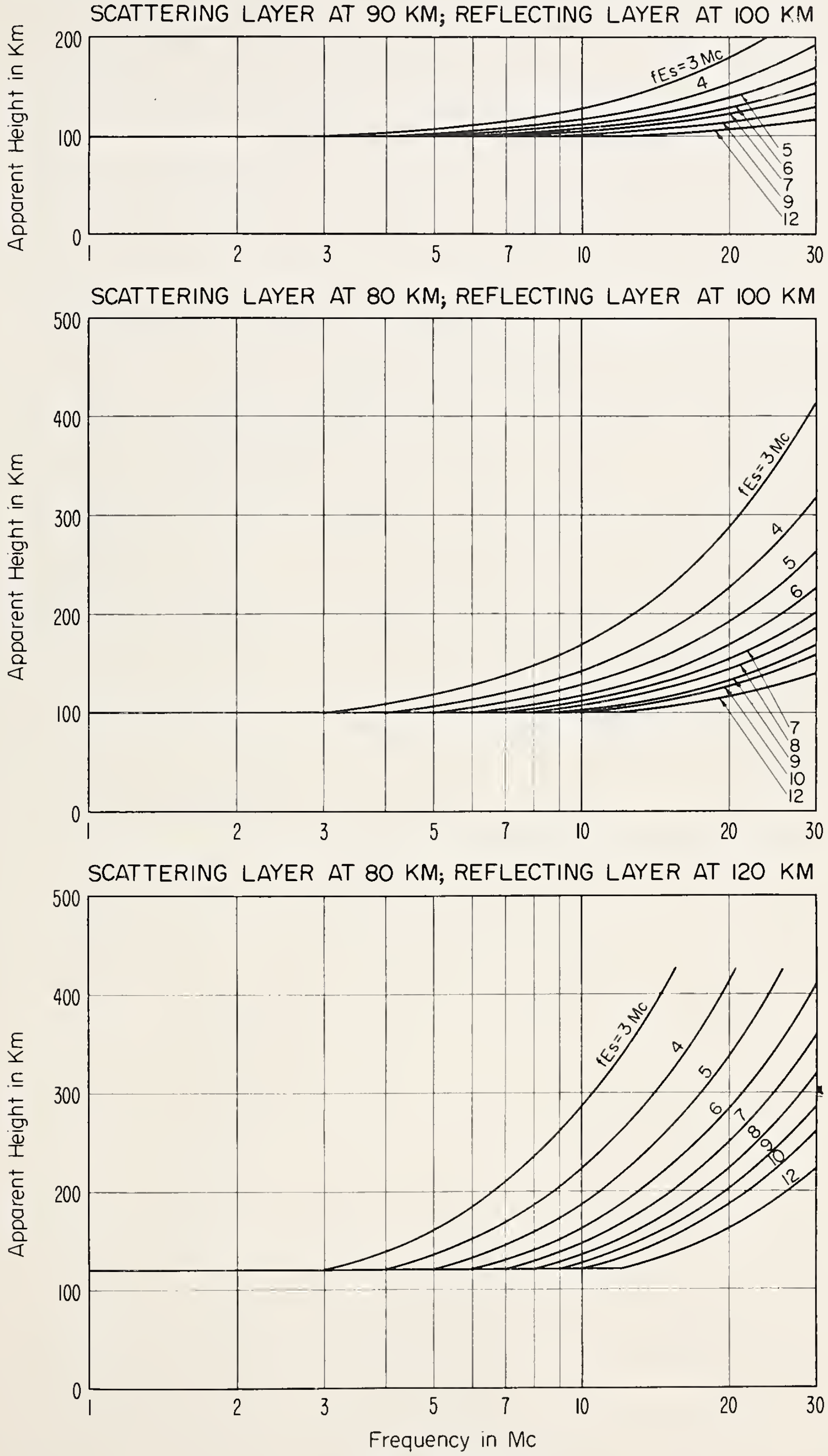


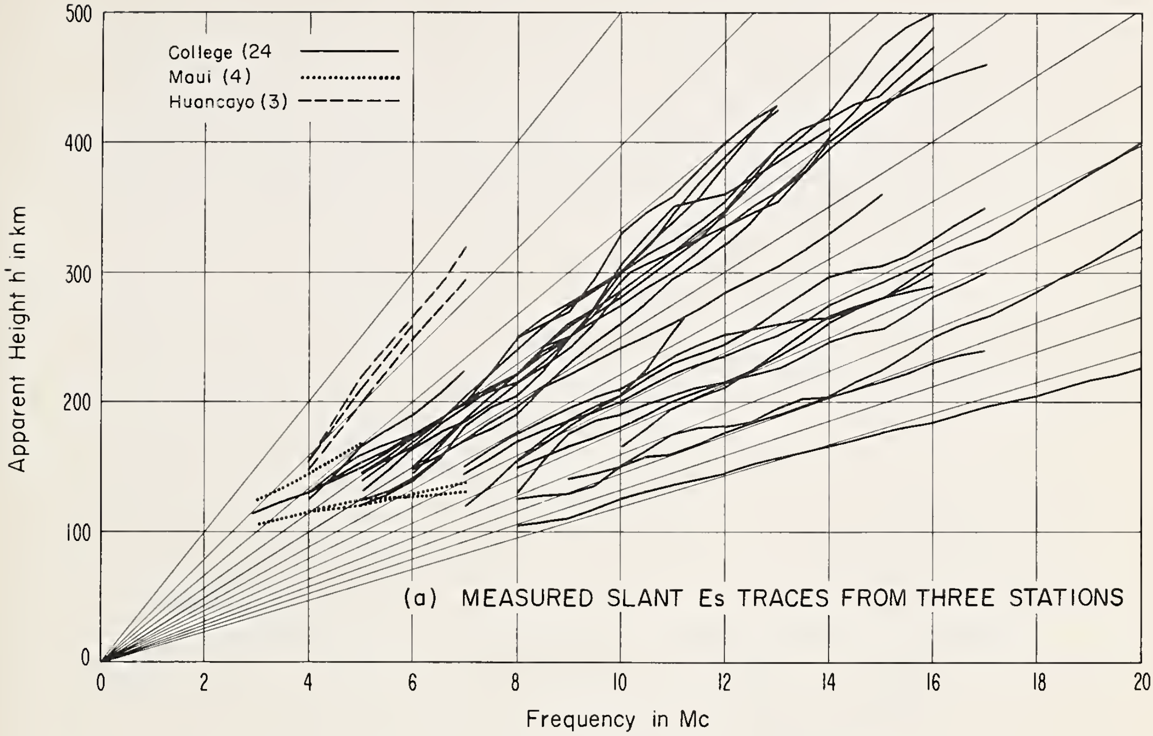
Figure Ap II -5

presented on a semi-log basis for visual comparison with the linear height versus logarithmic frequency scale of the normal h'f ionogram.

The most convincing demonstration of the applicability of the theoretical curves would be to overlay the three sets over the observed data. This is hardly practical, so a somewhat different approach is used to accomplish the same thing. A characteristic of sporadic E which has been noted previously at CRPL (mentioned to the author by Vaughn Agy) is that if apparent height vs. frequency data are plotted on a linear base, the slant Es traces appear roughly as straight lines radiating from the origin. The cases analyzed here are plotted in this manner in figure Ap II-6 (a) while in figure Ap II-6 (b) the theoretical scatter curves for fEs = 3 Mc are shown to the same scale. The same radial reference lines appear for comparison in both charts. It is seen that a scattering curve can in general be found which will fit any of the observed slant Es curves.

It is a delicate matter to explain why the scattered intensity is greatest along a computed curve which defines the maximum frequency supported by this scatter-reflection mode. The two most serious questions may be stated as follows. First, why is not the inside of the slant Es trace filled in at any particular height for all lower frequencies down to the point where non-deviative absorption becomes serious. Second, for apparent heights of 400 km or so, the scattering angle (fig. Ap II-3) is approaching 180°. Why then is not backscatter the dominant mode? To answer these questions it is necessary to resort to a form of ionospheric "focusing" such as

LINEAR REPRESENTATION OF MEASURED AND COMPUTED SLANT Es CURVES



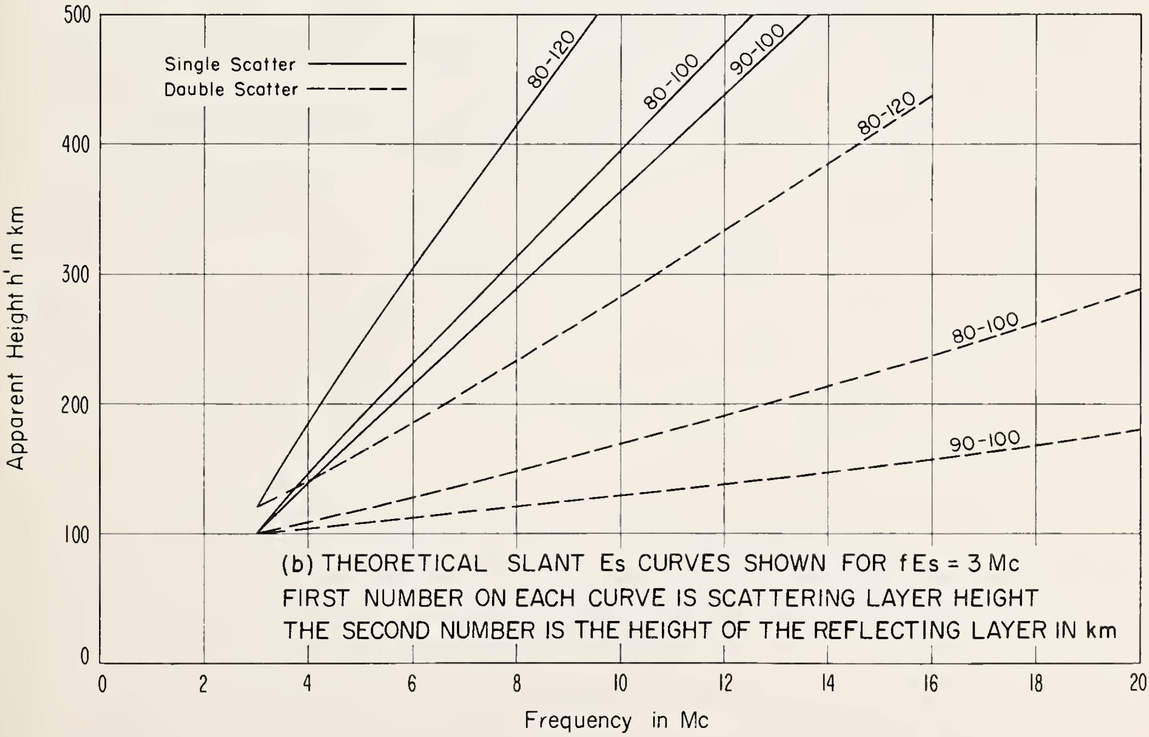


Figure ApII-6

described by Eckersley [1932], and more recently by Peterson [1947] and Dieminger [1950]. To invoke such "focusing" it is necessary to require that the Es (or E) layer have sufficient thickness that the transmission curve for an oblique path is not a horizontal line dying off gradually at the critical frequency as often seen at vertical incidence. This is, of course, frequently observed in the Auroral Zone in retardation Es. The "focusing" is now due to the fact that the outside edge of the slant Es trace corresponds to the caustic of the transmission curves in a similar manner as that computed by Dieminger (figure A-II-7) to explain a ground-scatter case. It would be theoretically possible to obtain quantitative values for the amplitudes, but as there are no similar quantitative measurements of slant Es available, such computations have not been performed as yet.

One unexplained phenomenon in auroral stations is the case where a heavy Es trace will appear at 105 km at 2 Mc and rise to perhaps 130 to 140 km at 6 Mc, with a slope appropriate to double-scatter; from 6 Mc a steep but faint slant Es trace will continue, which will fit a single-scatter curve. However, the necessary fEs to explain the first leg of the curve will be perhaps 1.5 Mc, that for the second part typically around 5.5 Mc. Sometimes the scattering height implicit in the two slopes is the same, sometimes not.

There are also cases of unexpected support for the scattering mechanism. At College there are examples where the slope of the slant Es provides a good fit to a single-scatter

APPLICATION OF CAUSTIC FOCUSING TO SLANT E_S THROUGH ANALOGY TO DIEMINGER'S GROUND SCATTER CASE

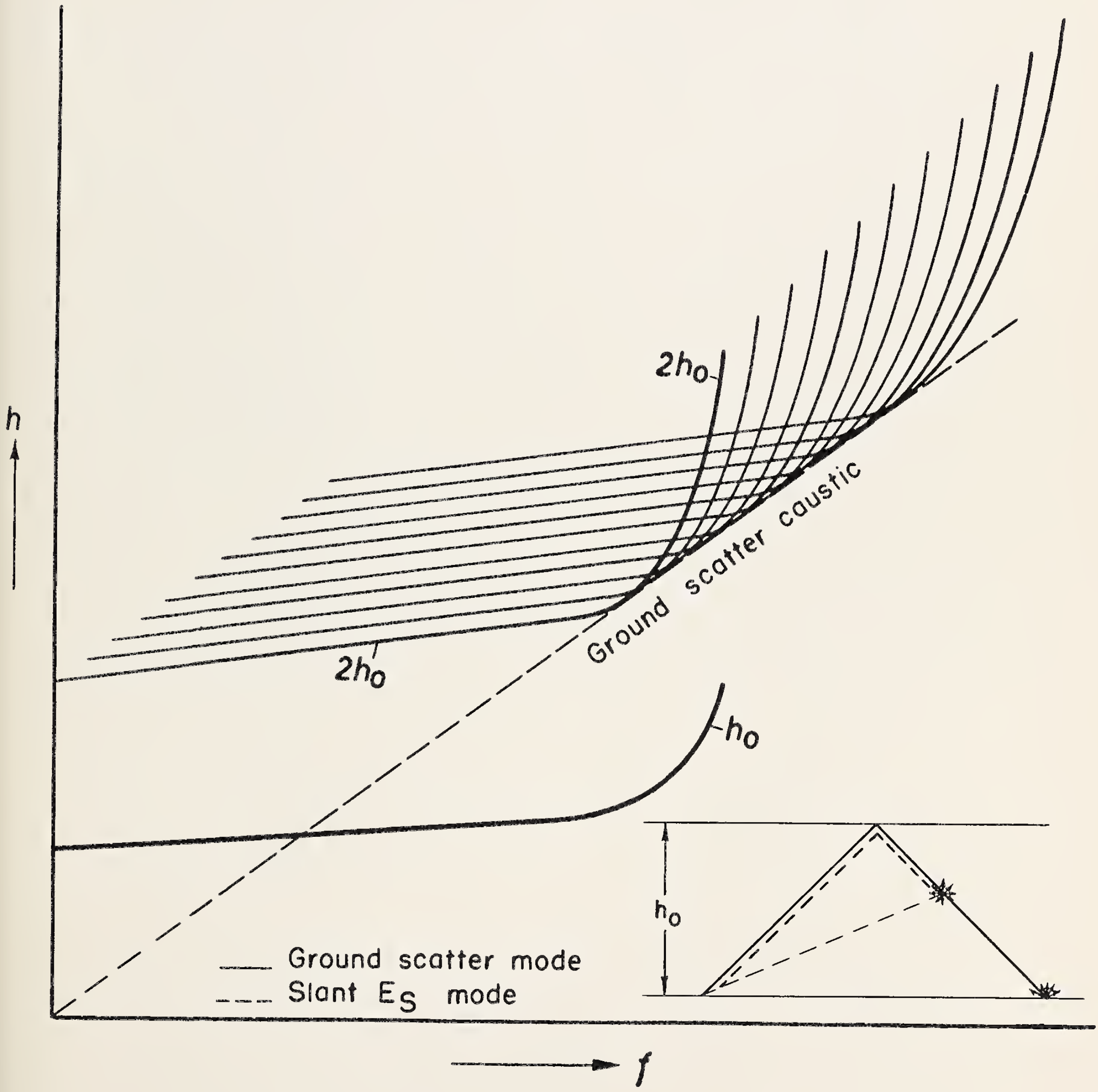


Figure Ap II-7

curve for a scattering layer at 90 km, and on the record a faint Es layer could be observed at 90 km. At Maui (fig. Ap II-2 see record for 0830, July 26, 1953) there is a case where two slant traces appear. Fitting the steeper of these to single-scatter, a scattering-layer height of 95 $\pm$ 3 km and fEs = 1.7 $\pm$ 0.5 Mc was found. Fitting the second slant trace to the double-scatter curves results in a scattering-layer height of 95 $\pm$ 3 km with a critical frequency this time of 2. $\pm$ 0.3 Mc.

Several other explanations have at one time or another been advanced to explain slant Es, but as far as could be found they have not been published. It is, therefore, difficult to give credit to the proper source. With the explanation proposed in this appendix as number 4, the various explanations are as follows:

1. Reflections from auroral rays at E layer heights. In the VHF band the normality condition would apply strictly, but at low frequencies one would expect reflection from directly overhead.

2. Ground-scatter via E layer as described by Dieminger[3].

3. An oblique backscatter path going to E then to in-homogeneities located below the E layer and then back along the same path.

4. Single and double forward scatter around annular rings from a scattering layer up to an E or Es layer.

The two main objections to the auroral mechanism are: first, slant Es has been observed at Adak, Maui and also Huancayo, locations all well removed from the auroral zone, and second, on the linear h'f plot of figure Ap II-6 80% of the cases appear to radiate as straight lines from the origin (f = const. x h). This would seem to imply a mechanism depending on the secant law, and auroral reflection does not.

Dieminger's ground-scatter mechanism explains a trace originating at an apparent height corresponding to 2h'E. We did find at least one case of this, but it is the exception and not the rule. It is interesting to speculate on why one does not observe this type of slant trace all the time.

The third explanation is difficult to counter because it is so similar to the scatter mechanism of (4). One objection to it is that one must postulate a porous, blobby layer lying below the E region in order to let the rays pass through the layer for their initial reflection. Once having postulated this, it appears that one would get a stronger signal from this layer by the forward-scatter mechanism of (4) than by the back-scatter mechanism of (3). It is true that the back-scatter mechanism involves two reflections from the E or Es layer contrasted to one for the forward-scatter mechanism and, inasmuch as ionosphere "focusing" is invoked in mechanism (4) without ascertaining the degree, it can not be said with certainty that (4) will supply higher fields than will (3). Another objection to (3) is that the trace originates at a range h' = h'Es + $\triangle$h where $\triangle$h is the difference in height between the scattering layer and the reflecting layer. As slant Es normally appears to come directly off the Es layer, explanation (3) permits only a very small separation between the scattering and reflecting layers.

The height of the scattering layer postulated by the forward-scatter mechanism may be obtained from the measured curves through comparison with the theoretical curves of figures Ap II-4 and 5. These heights for College, Alaska are shown with their estimated probable errors in figure Ap II-8.

The error ranges shown in figure Ap II-8 are rather subjective in nature and it has been pointed out to the writer by D. K. Bailey that the height resolution afforded by this method is poor. H. G. Booker (private communication) has further pointed out that the scattering and reflection levels could be the same without affecting either the observed linear relationship of frequency and virtual height (figure Ap II-6 (a)) or the applicability of caustic focusing.

An interesting extension of the fourth explanation listed has been suggested by D. K. Bailey and applies to the auroral zone slant Es. Let us postulate that the scattering layer active in slant Es in the auroral zone is cause by an influx of solar corpuscles spiralling down the lines of magnetic force. The scattering centers thus generated would be expected to be non-isotropic in their properties. One might consider these scattering centers to be very much elongated blobs oriented along the lines of magnetic force. These blobs will then have many of the same properties as meteor trails in their reflection characteristics. For geometrical reasons the important contribution from a horizontal scattering stratum can be shown to come from a crescent shaped area

SCATTERING LAYER HEIGHTS DEDUCED FROM SLANT Es

Single Scatter Mode Assumed
College, Alaska: April and December, 1954

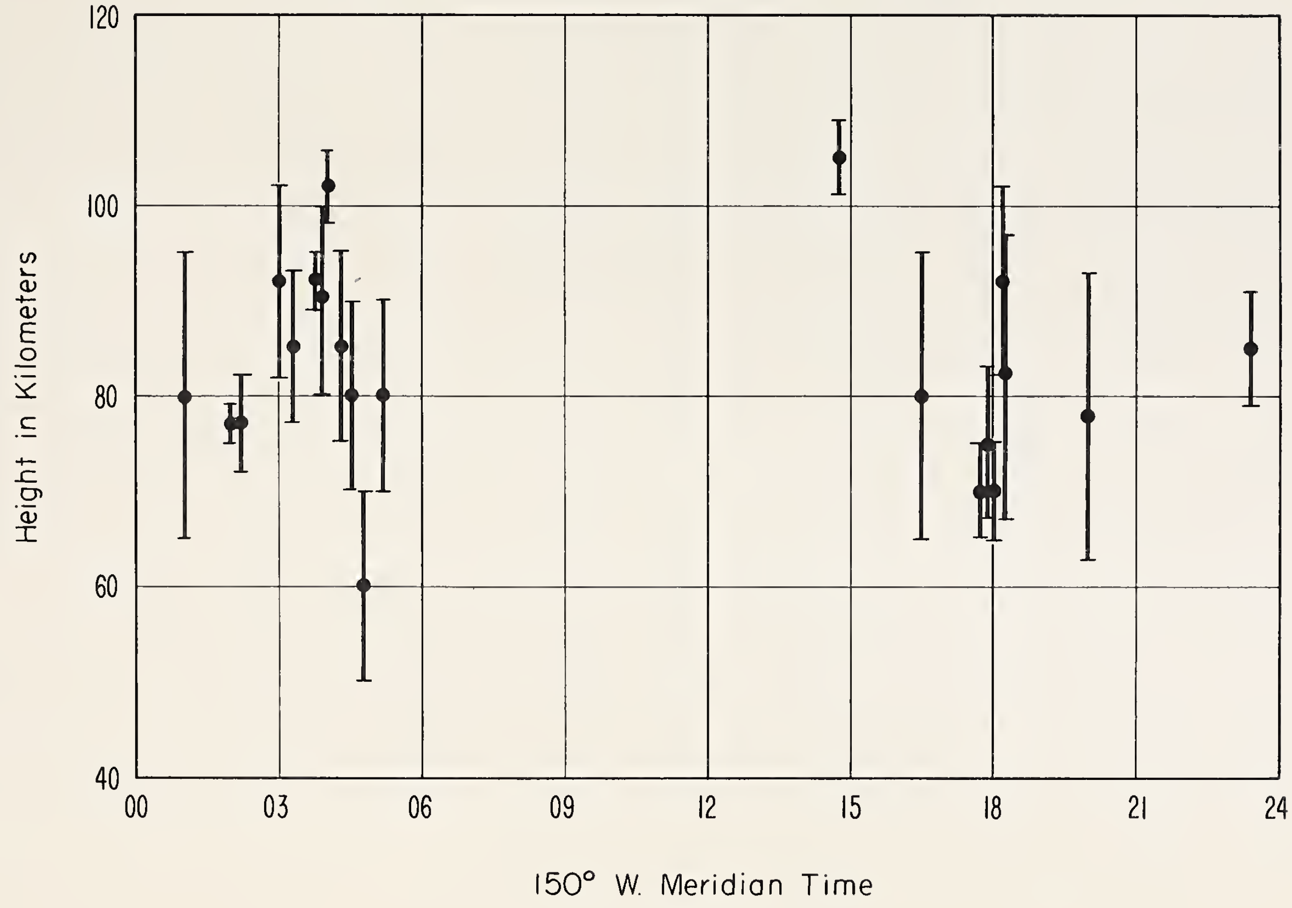


Figure Ap II-8

centered about the geomagnetic axis south of the station. This same type of formation might be expected to produce auroral flutter over certain radio circuits.

Acknowledgment. The writer initially thought that the double symmetrical scatter case was the only mechanism which could be used for slant Es. He showed these curves to R. W. Knecht and D. K. Bailey both of whom independently suggested that the single-scatter mechanism could also be used. Ionogram scaling was performed jointly by Knecht and the writer. Vaughn Agy suggested the linear presentation of figure Ap II-6.

APPENDIX III MAGNETIC LATITUDE DERIVED FROM THE DIP ANGLE

Geomagnetic coordinates, which may be obtained by simply rotating the geographic coordinate system 11.4° to the geomagnetic poles, have many advantages. For instance, the terms latitude and longitude may properly be employed. Latitude refers to the angular distance of a point on a sphere above or below an equatorial plane; longitude is the angle between the standard meridian plane and one passing through the point of interest. A further advantage is that the geomagnetic dip, total intensity, horizontal intensity, etc. may be uniquely defined in terms of the geomagnetic latitude alone.

Scientists engaged in ionospheric propagation studies have found added reason to employ geomagnetic rather than observed values in that at a sufficiently great distance from the earth the dipole field alone is important. It is interesting to investigate how far up it is necessary to go before the dipole term is the only important one. An easy way to do this is to consider the geographic location of the magnetic equator at the meridian of Greenwich as a function of height above the earth. The magnetic equator in this connection is defined to occur at the location where the magnetic vertical intensity is zero. This location may be found by graphical interpolation between the values given at 10° intervals for the vertical intensity at various heights (Vestine et al.[1947]).

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The meridian chosen here happens to be one where the geomagnetic and the surface dip equator experience their greatest separation and, thus, provides a good cross-section at which to perform this test. Figure Ap. III-1 shows that the magnetic equator obtained from the Hydrographic Office Maps (or the first six harmonies referred to the surface) is a better choice than the geomagnetic equator up to a height of 3600 km.

If one is primarily interested in the dip at ionospheric heights it is, therefore, worth-while to redefine the latitude index to take into account the observed variations in the dip. This may be simply done as follows. Geomagnetic latitude Λ is related to the geomagnetic dip I by

$$\Lambda = \tan^{-1}(1/2 \tan I) \qquad \text{Ap III-1}$$

Let us define a magnetic latitude Λ' which bears this same relation to the magnetic dip I'.

Hence

$$\Lambda' = \tan^{-1}(1/2 \tan I') \qquad \text{Ap III-2}$$

The use of the term latitude is no longer correct by the definition given above, but is retained because of its analogy to geomagnetic latitude. A map of the world showing this magnetic latitude in 10° intervals is given in figure Ap III-2 along with the dip I' in 10° intervals. The heavy solid curves are lines of constant

VARIATION OF REGIONAL MAGNETIC ANOMALY WITH HEIGHT

Geographic Longitude =0°
Source–Hydrographic Office Map for 1945 and CIW 580

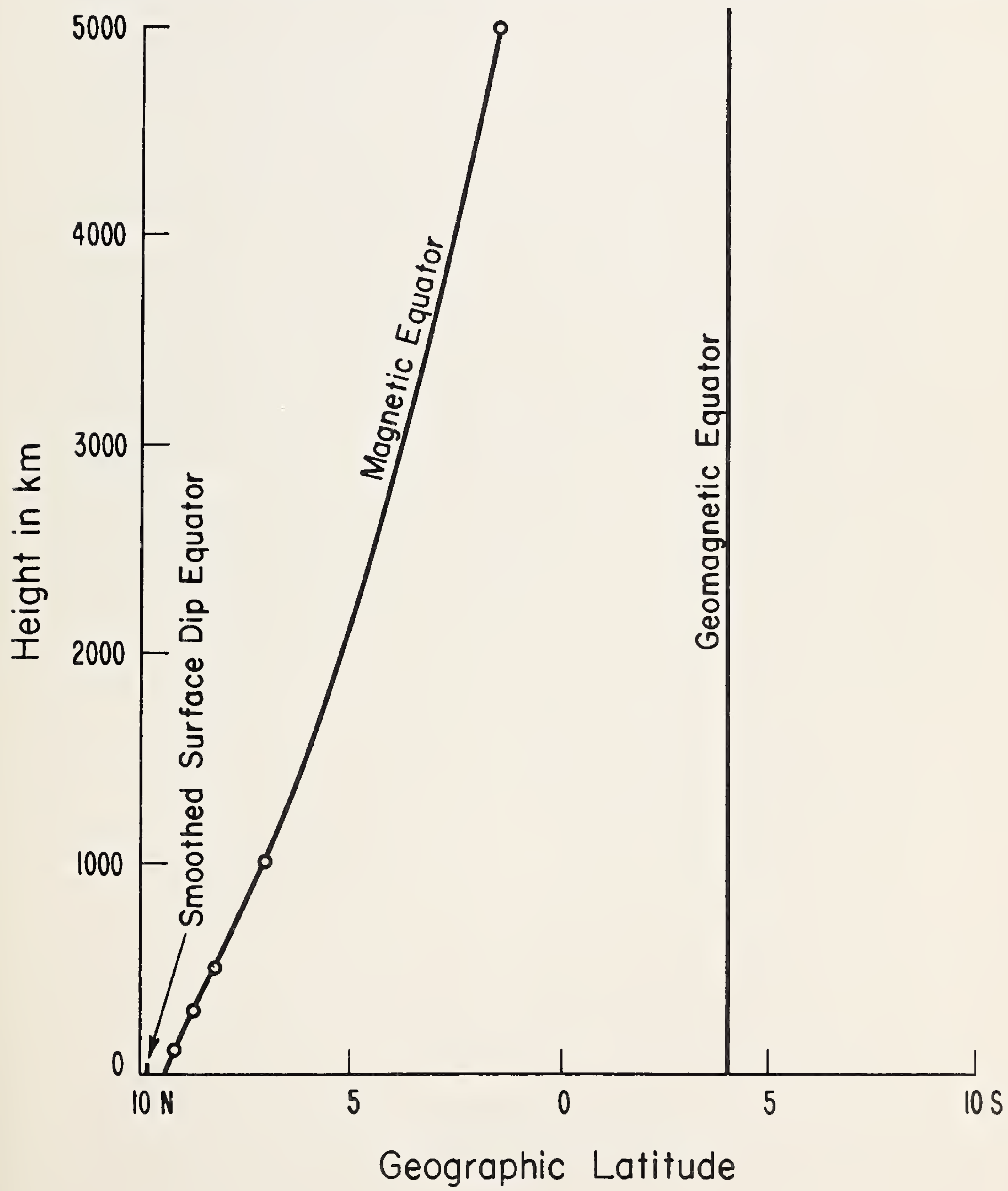


Figure Ap III-1

difference between magnetic latitude Λ' and geographic latitude. They can be used to delineate longitude zones corresponding to the E, I and W zones associated with geomagnetic coordinates.

A word of caution should be reiterated here. As soon as one departs from the geomagnetic coordinate system, it is no longer possible to derive the gyro-frequency, for instance, from the latitude. The total magnetic intensity, the quantity of interest for the gyro-frequency, can and does vary in a different manner than does the magnetic dip. This is demonstrated in figure Ap III-3 where the magnetic total intensity for 1945, is shown. The magnetic horizontal intensity is seen in figure Ap III-4. As mentioned in Chapter II the world-wide distribution of horizontal intensity does bear a resemblance to the distribution of Temperate Zone sporadic E as seen in figure II-F-9, Figures Ap III-3 and Ap III-4 are both taken from Vestine et al [1947] and represent the sum of the first six spherical harmonics of the earth's field. In practice they differ very little from the smoothed surface values given in the Hydrographic Office Charts.

MAGNETIC LATITUDE DERIVED FROM THE MAGNETIC DIP

Source: DTM 580 and Hydrographic Office Map of Dip for 1945

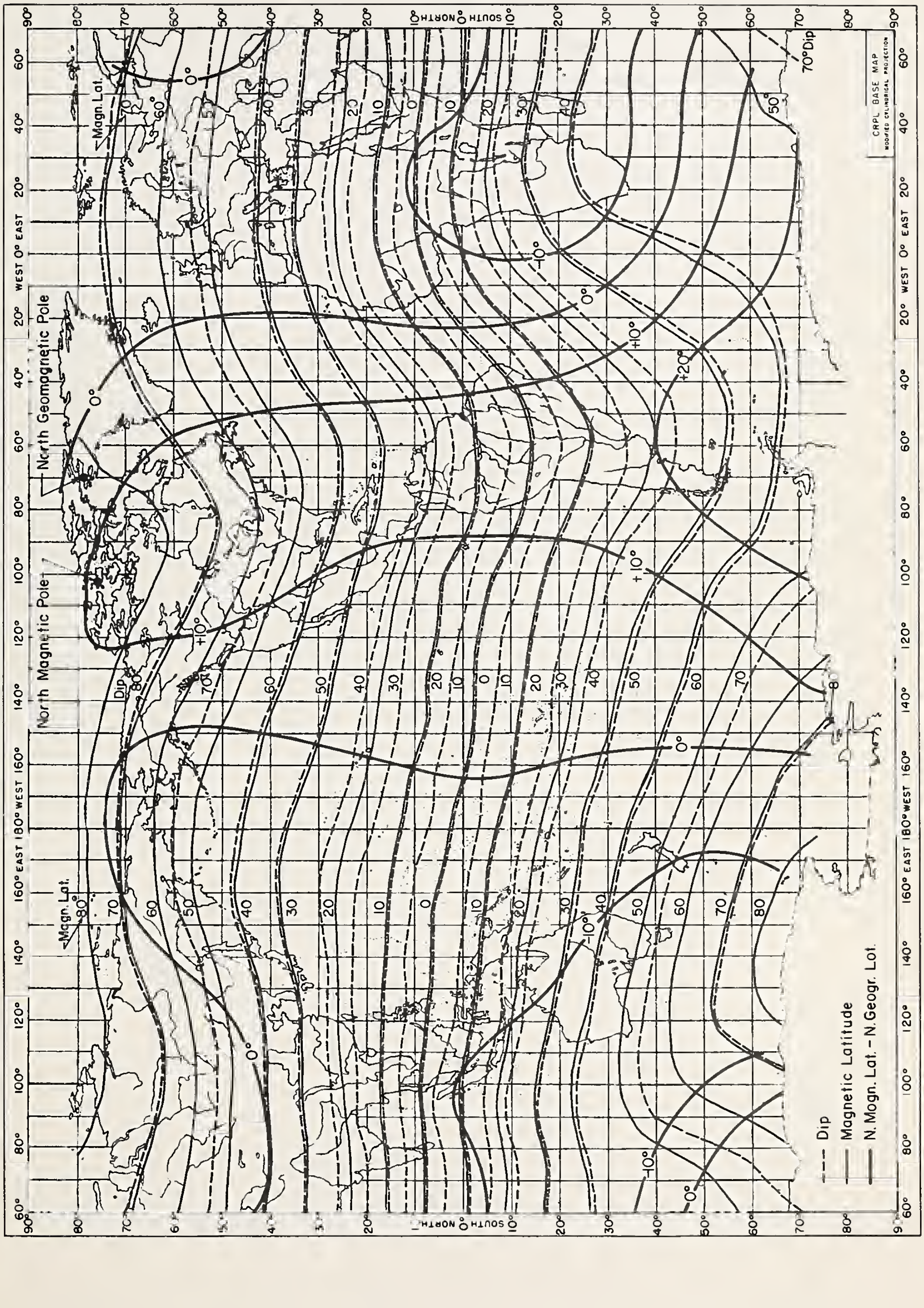
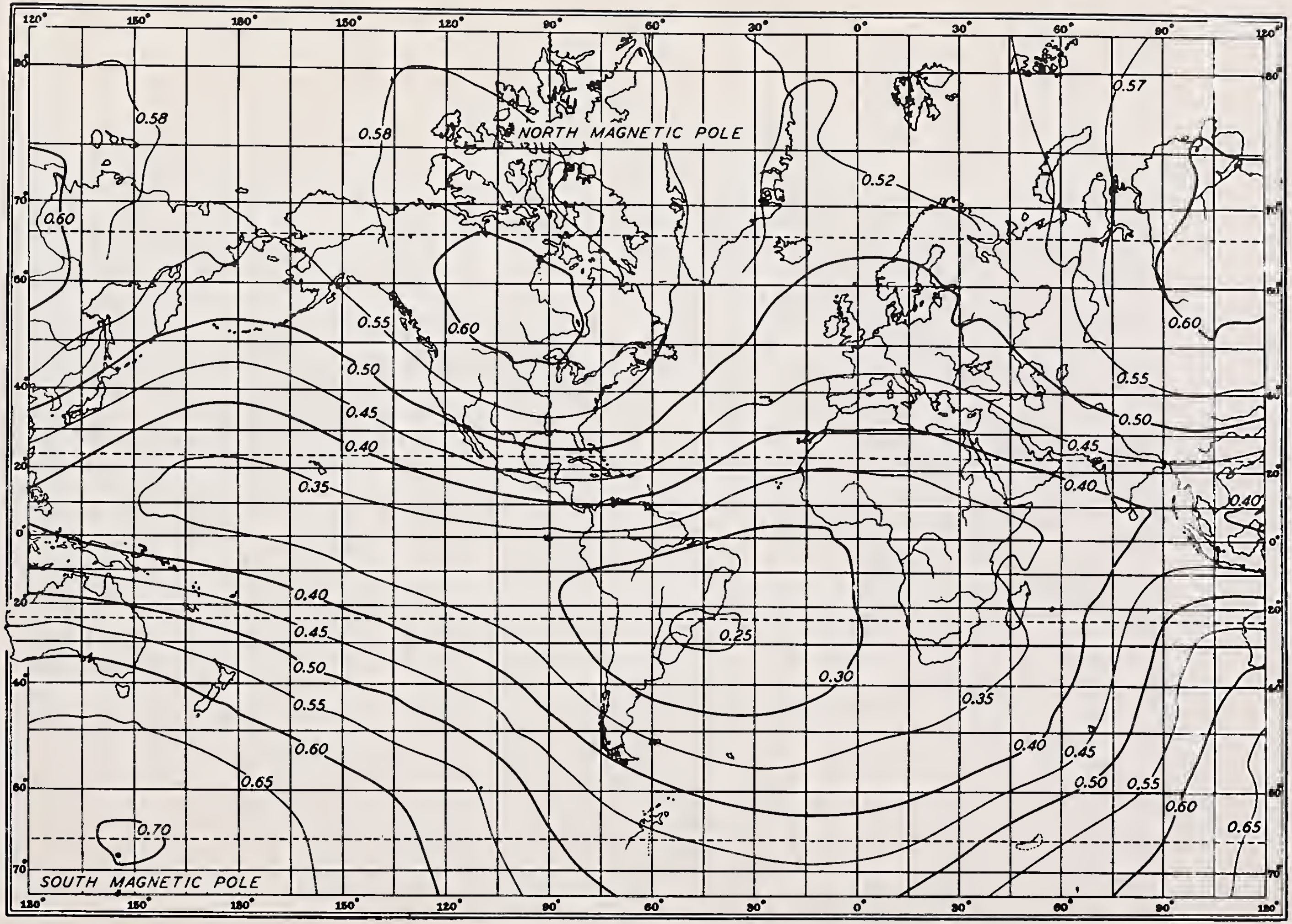
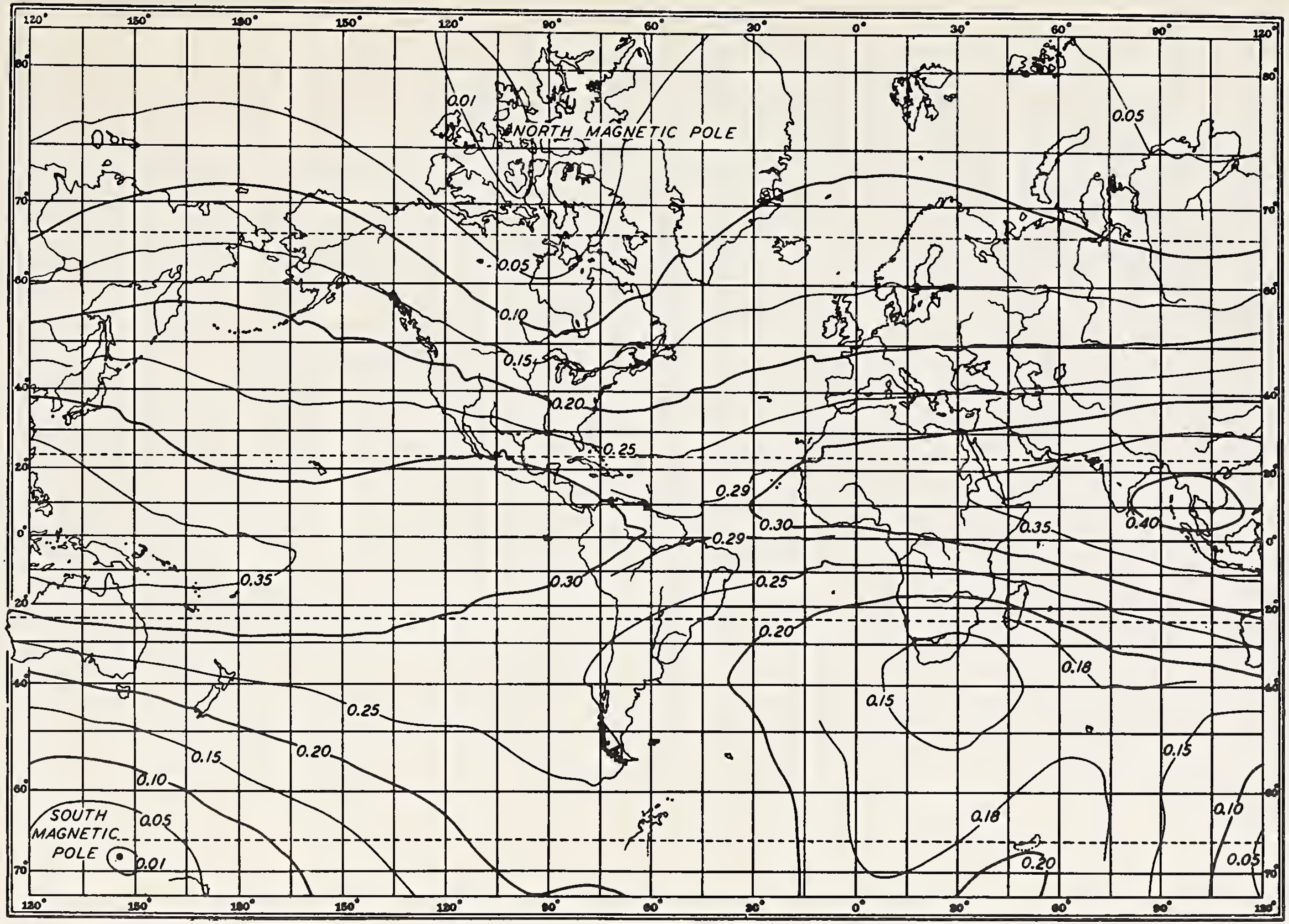


Figure Ap III-2



MAGNETIC TOTAL INTENSITY IN CGS-UNITS FOR 1945

Figure Ap III - 3



MAGNETIC HORIZONTAL INTENSITY IN CGS-UNITS FOR 1945

Figure Ap III-4

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