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THE SPORADIC E LAYER (OR Es) OVER AHMEDABAD

I. INTRODUCTION

Besides the regular solar controlled normal E layer, reflections from about the same height of transient character, sometimes rapidly varying in amplitude, and sometimes strong and persistent are observed (1) at or near the level of the maximum electron density of the E layer, (2) at the lower boundary of the E layer and (3) below the base of the E layer on frequencies sometimes much higher than E critical frequency. It was also noted by many observers (Appleton & Naismith 1940, Best et al 1938, McNicol & Gipps 1951, Berkner & Wells 1937 and so on) that the reflections from a height usually near hpE, seen as a tail from the cusp of foE was strongly reflecting and of a blanketing type and more or less solar controlled. The other two types were found to be partially reflecting, partially transmitting and became more and more transparent at higher frequencies. Their occurrences and changes in ion-density were found to be irregular. Radio communication at frequencies exceeding the m.u.f.'s of F2 layer and as high as 50 Mc/s and more (Appleton & Beynon 1953, Bailey et al 1952) has been possible over paths of 1500 km using Es reflections in summer. The causes of ionization of such layers are not fully known, but many have been suggested.

a. Solar Control

Appleton and Naismith (1940) showed that in temperate
latitudes, Es which occurs at or slightly below the level of
maximum ionization of the E layer was in general more intense
and frequent during day and stronger in summer. Occasions
when intense Es was observed during night were rare. From the
radio observations during the second polar year 1932-33 at
Tromso (49.7°N, 18.9°E), Appleton and his co-workers (1937)
found maximum occurrence and intensity of Es at midnight when
magnetic activity and auroral displays were also maxima. A
second small peak at noon was also noticed, giving evidence of
solar control. At Slough (51.5°N, 0.6°W), however, they found
noon maximum and no relation to magnetic activity. Naismith
(1954) and Rangarajan (1954) at Kodaikanal (10.2°N, 77°E) also
reported solar control of Es. Berkner and Wells (1937) found
that the occurrence of Es at Huancayo (12°S, 75.3°W) and
Watheroo (30.3°S, 116°E) were least frequent near the sunspot
maximum period. Kotadia (1956) reported that the intense type
of Es at Ahmedabad (23°N, 72.6°E) showed dependence on solar
altitude.

b. **Meteors and Es**

Reflections from below the base of the E layer have
often been observed. Eckersley (1929) working at frequency of
6.2 Mc/s observed scattered echoes in the skip zone, probably
from Es clouds. Schafer and Goodall (1932), and Skellet (1935),
found increased abnormalities in the E layer during periods of
meteoric showers at frequencies of 1.6 - 6.4 Mc/s. Mitra et
al (1935) showed an effect of meteoric showers on Es. Bursts
of ionization giving transient echoes were observed by
Appleton et al (1937), and Appleton and Piddington (1938) at frequencies ranging from 2.0 to 8.8 Mc/s. Appleton and Naismith (1947) found that the diurnal and seasonal variations of occurrences of bursts of ionization on 27 Mc/s showed correlation with sporadic meteors (peak at 06 hr, minimum at 18 hr; maximum in summer, but not symmetrical fall in following months). Strong evidence proving the close correlation of sporadic ionization with meteors was presented by Hey and others (1946, 1947) in their observations during the great Giacobinid shower of 10 October 1946, using a frequency of 60 Mc/s and by Lovell and others (1947) who employed 72 Mc/s for radio detection of meteors. Neuzil (1955) has shown good correlation of Es activity with the known recurring meteor showers. Dieminger (1952) from the records of Lindau (51.5°N, 10.1°E) attributed nighttime echoes at 95 km to meteoric dust ionization. Lastly, Lovell (1956) attributed individual daytime maxima of transient echoes in summer to the influence of meteor streams.

In the light of all these positive evidences of meteoric ionization in the E region (at heights below the level of normal E layer), there are also reports showing no correlation between meteors and Es ionization. McNicol and Gipps (1951) and later Thomas (1956) at Brisbane (27.5°S, 153°E) and Rangarajan (1954) at Kodaikanal did not find any change in Es intensity or occurrence during meteor showers, nor nighttime Es conform to incidence of sporadic meteors. The diurnal variation in the occurrence of sporadic E echoes at Japanese
stations show two maxima, one near sunrise and the other near sunset, which does not agree with the diurnal variation of sporadic meteors. These observational facts, therefore, pose a question:

"Do meteors contribute to sporadic E layer ionization in low latitudes?"

Some evidence is presented in the following sections to show that meteors do contribute to Es ionization at Ahmedabad (23°02′N, 72°38′E).

C. Thunderstorms and Es Ionization

Although Appleton and Naismith (1933) established a high correlation coefficient (0.75) between abnormal Es ionization and thunderstorm character figure, Best, Farmer and Ratcliffe (1938) did not confirm such correlation by a closer analysis of data. Berkner and Wells (1937) did not find any effect of thunderstorms at Huancayo (12°S) in spite of the fact that they are greatly prevalent there. Similarly thunderstorms do not seem to show any effect on Es at Kodaikanal (10.2°N). Bhar and Syam (1937) and Mitra and Kundu (1956) presented definite evidence for the effect of thunderstorms on Es. Isted (1954, 1955) showed that thunder-clouds which discharge upwards contribute largely to long duration bursts of Es ionization. At Ahmedabad, Rastogi (1957) found close connection between isolated thunderstorms in the non-monsoon seasons and Es ionization. Both Dr. Rastogi and the author have noted many instances of dense and low-lying clouds accompanied by large thunders and lightning discharges towards
the ground during the monsoon season at Ahmedabad (June-September), without showing any sign of producing or contributing to Es ionization. It appears, therefore, that only high-lying clouds discharging upwards might affect the Es layer.

d. Magnetic Activity and Es

It is now well-known that Es-ionization in the auroral zone is associated with magnetic storms and auroral displays. At Tromso, however, Appleton et al (1937) did not observe Es during severe magnetic disturbances and at Slough they could not find any effect of magnetic storms on Es. At Ibadan, Skinner and Wright (1957) found that low fEs was generally found on days of high magnetic activity. From the day-to-day analysis of mean fEs and occurrences of Es, at Slough by Naismith (1954) and at Kodaikanal by Rangarajan (1954), it was not possible to get any correspondence between magnetic activity and Es. At Ahmedabad, Es ionization has been found to be enhanced during some of the magnetic storms, and ionograms showing this effect are reproduced.

e. Geomorphology of Es

We know now that midnight fEs is maximum in the auroral zone and midday fEs is maximum at the magnetic equator. Matsushita (1952) showed that there exists a narrow equatorial zone of daytime Es corresponding to the electrojet or the narrow band of large diurnal variation of the earth's horizontal magnetic field (Egedal 1948). From the foregoing discussion,
it will be clear that there are many ionizing agents which produce Es; these include solar wave-radiation, meteors, thunderstorms and particles which cause magnetic storms, and all these factors will not be equally effective in different latitudes. The agent which is effective in a particular zone of latitudes will produce a type of Es which may be different in character from another type of Es caused by some other agent in another zone of latitudes. The common practice of comparing the highest frequency $f_{Es}$ irrespective of the type of Es or their heights, rather leads to confusing interpretation.

In the following sections, the diurnal, seasonal and annual variations of Es at Ahmedabad taken as a whole (all types taken together) are discussed considering $f_{0}Es$, Es occurrences when $f_{x}Es$ is greater than 3, 5 and 7 Mc/s, when Es is of the blanketing type and when it takes the form of Es-scatter. Next, the characteristics of each type of Es are described with presentation of illustrative ionograms and the dependence of the top frequency $f_{x}Es$ on receiver sensitivity or transmitter power is elucidated. Then an attempt is made to correlate one of the types of Es with meteoric showers. A few examples of the effect of magnetic storms on Es are also given.

II - METHOD OF ANALYSIS OF ES DATA

In the C.R.P.L. F-series publication of ionospheric data, information is available of the highest frequency of reflection from the sporadic E layer and of the percentage occurrences of Es when this frequency is greater than 3, 5
7 Mc/s, without any consideration of the height at which the reflection takes place. The above treatment of data gives the sum total of the different types of Es, which may have different causes for their ionization.

It is known that the reflectivity of the Es layer generally decreases with increasing frequency of the exploring radio wave and the highest frequency fEs depends on the power of the transmitted pulse, the directivity and gain of the antenna and the sensitivity of the receiver. Moreover, all these factors vary with frequency and the recording equipment used at various places differs in one or more of these respects. So a quantitative comparison in terms of absolute results obtained at different stations becomes difficult. Nevertheless, for a particular place, it is possible to study the relative diurnal and seasonal variations of the sporadic layer. The classification of Es with fEs greater than the above-mentioned limiting frequencies in a way helps to compare its characteristics at different places fairly reasonably.

In a previous analysis of Es data at Ahmedabad for the period 1953-54 (Kotadia 1956), the top frequency fEs was considered as a measure of Es ionization and the monthly medians were based on the data of those days only on which Es was recorded in the ionograms. According to the recommendation of the Special Committee for World-wide Ionospheric Soundings appointed by the U.R.S.I./A.G.I. "Es has to be regarded as present all throughout the day and instead of fEs, foEs should be scaled to bring homogeneity with other ionospheric parameters."
foEs should be taken as "less than the lower limit of the transmitter frequency" at night and "equal to foEs" during daytime if Es trace is not observed in the ionograms. The Es trace generally does not show group retardation near its end and therefore top frequency foEs should be taken as fxEs. foEs is determined by the relation foEs = fxEs - fH/2 where fH is the gyromagnetic frequency". At Ahmedabad, the difference between fxEs and foEs for the lower Es's is usually found to be 0.7 Mc/s and it is 0.65 Mc/s for higher Es's. Although the Es trace is found to remain at a constant height throughout the range of frequencies, clear indication of the ordinary and extraordinary waves is obtainable from the strength of the reflection and also sometimes from the break in the trace at foEs. An h'-f record at 15 hr on 15-10-1957 in Figure 6 shows the above characteristic from which foEs could be read distinctly.

In view of the above recommendations for scaling Es parameters, our data were re-examined for all the months from January 1954 to May 1957 (Since June 1957, the above recommendations have been followed under the I.G.Y. programme). It may be stated that the characteristics of Es described in our earlier paper for 1953-54 have very little by adopting the new procedure, owing to the fact that the frequency of occurrence of Es was high in those years. As regards classification of Es according to types, our previous terminology has been modified so as to be in agreement with the international recommendation.

III - DIURNAL, SEASONAL AND ANNUAL VARIATIONS OF Es (ALL TYPES INCLUDED)

An analysis of the data of 29759 hours of observation
over the period of four years (1954-57) is made here; Es was recorded as a distinct trace on 20705 occasions out of the above hours. In the treatment of data for Es occurrences having $f_xE_s$ greater than the limiting frequencies, only those hours in which an Es trace was visibly recorded were taken into account for finding percentages. The total percentage occurrence of Es (all types included) for each year is given in Table I. In the same table are also given the mean yearly values of $f_oE_s$ at noon and midnight. For convenience, the occurrences of different types of Es classified according to international recommendations, are also summarised.

3.1 **Diurnal variation of occurrence of Es (irrespective of type)**

3.1a $f_xE_s > 3 \text{Mc/s}$

A compact picture of the diurnal variations of Es through the half sunspot cycle 1954-57 is given in Fig. 1, wherein the percentage occurrences of Es with different limiting frequencies are plotted for January, April, July and October and annual averages of these characteristics are given at the bottom of the figure. It will be seen that there is a tendency for Es with the lowest limiting frequency (i.e. with $f_xE_s > 3 \text{Mc/s}$) to show two maxima, one near sunrise and another near sunset, and minima at about 14 hr and 00 hr. There are large changes from season to season and year to year. In the summer months, it is difficult to make out clearly the morning and evening maxima. Even the variations for the same month of
Fig. 1: Diurnal variation of the occurrence of Es (all types included) at Ahmedabad when fxEs was greater than 3, 5 and 7 Mc/s in January, April, July and October of 1954 to 1957; annual mean variations are also shown.

different years do not remain similar. On the average, however, the annual mean variation shows clearly two maxima, one at 07-08 hr and another at 18 hr. The large daytime increase in Es activity during 1955 resulted in a type of variation in which the morning and evening maxima were not clearly distinguishable.
3.1-b  \( f\times E < 5 \) Mc/s

Unlike the diurnal variation of occurrence of \( f\times E > 3 \) Mc/s, that of \( f\times E > 5 \) Mc/s shows a tendency to be maximum at 10-11 hr after which it gradually falls. In summer and the following months till about the end of the year, there is a large percentage of days on which \( E_s \) is maintained until late afternoon hours. At night the intensity of \( E_s \) falls down, but on some rare occasions, \( f\times E \) exceeds 10 Mc/s.

3.1-c  \( f\times E > 7 \) Mc/s

The variations are more or less similar to those of \( f\times E > 5 \) Mc/s, but the occurrences are less frequent and are more symmetrically distributed around noon. In summer and the autumnal equinox months, intense \( E_s \) is found in the afternoon hours also. The annual average diurnal variation shows that \( E_s \) with high ionization is mainly a daytime feature.

From the above description of the diurnal variations of occurrence of \( E_s \) with increasing limiting frequencies, it is concluded that the intense ionization is under solar control and a weak ionization is superposed on this which gives rise to the morning and evening maxima. The evening peak is strengthened by the continuance of intense daytime \( E_s \) till late in the afternoon, as seen from the average characteristics in 1957. But usually the morning peak for weak ionization is more prominent. The fact that intense \( E_s \) has most frequent occurrence at 10-11 hr is significant because Appleton and Lyon (1955) have shown that the rate of increase in normal \( E \) ionization is slowed...
down below that expected from Chapman's theory in the above time interval and these authors attribute this slowing down to vertical drift. The causes of the 07-08 hr and 17-18 hr peaks for Es's with $f_x E_s > 3 \text{ Mc/s}$ is discussed later.

3.2 Seasonal and annual variations of occurrences of Es

3.2-a $f_x E_s > 3 \text{ Mc/s}$

The percentage occurrence in a month is calculated by dividing the total occurrence in the month by the total number of observations available. In Fig. 2 are shown the seasonal variations of occurrence of Es having different limiting frequencies for the period April 1953-December 1957. It is found that the occurrences are most frequent in summer having a peak value in July. There is, however, another sub-maximum observed in winter for $f_x E_s > 3 \text{ Mc/s}$. In 1955, the variation

![Fig. 2: Seasonal changes in the occurrence of Es (all types included) at Ahmedabad from April 1953 to December 1957 when $f_x E_s$ was greater than 3.5 and 7 Mc/s.](image-url)
did not show appreciable decrease in the equinoxes after the summer months, as it did in 1953 and 1954. The occurrences were high in years of low sunspot activity and maximum in 1955 and then they decreased with increase in sunspot activity.

3.2-b & c \( f_x E_s > 5 \) and \( > 7 \text{ Mc/s} \)

In contrast to the variations of Es whenever \( f_x E_s > 3 \text{ Mc/s} \), those with higher frequencies only show more or less symmetrical seasonal variation having a pronounced maximum in mid-summer. This means that a weaker type of Es ionisation which has two peak occurrences in summer and winter is superposed on the summer maximum intense type of Es to give a pronounced maximum in summer and another small maximum in winter for all values of \( f_x E_s \). Thus it is seen that the intense type of Es shows a solar control both from the seasonal variation and also from the diurnal variations discussed in Section 3.1. Particularly of interest to radio communication is the large percentage of intense type of Es in summer. In 1955, intense type of Es occurred in summer nearly 4 times as often as in winter. It remains to be seen why the weaker type of Es has two maxima in the seasonal variation.

IV. DIURNAL AND SEASONAL VARIATIONS OF \( f_0 E_s \)

4.1 Diurnal variation of \( f_0 E_s \)

\( f_0 E_s \) is the measure of ionisation density in the sporadic E layer. The analysis of \( f_0 E_s \) given in this section
does not refer to any one type of Es layer but the highest frequency is taken irrespective of the type of sporadics found in the height range 95-135 km. The procedure of finding monthly medians is on the lines recommended by the Special Committee on Worldwide Ionosphere Soundings (see Information Bulletin No.99, URSI, September-October 1956). It will be shown later that the two lower types of Es contribute most to the foEs variations shown here.

In Fig. 3 are plotted median foEs for January, April, July and October from 1954 to 1957. It will be seen that while the daytime foEs more or less follows the solar zenith distance, it undergoes some fluctuations in the evening. The intensity of ionization reached its maximum in July 1955 when nighttime ionization was also maintained at a high level.

Fig. 3: - Diurnal variation of foEs in January, April, July and October and mean of all months at Ahmedabad, 1954-57.
There is some indication that foEs passes through a maximum before noon during times of low sunspot activity. In years of high solar activity 1956-57, daytime variation of foEs is similar to that of foE. This is apparently because Es was not observed distinctly as a separate trace in these years and under such circumstances foEs was taken to be equal to foE. From the annual averages shown at the bottom, it could be seen that the night-time foEs is nearly constant and not much change has taken place with change in solar activity, although on some special occasions, large fluctuations were noticed.

4.2 Seasonal variation of noon and midnight foEs

From Fig. 4a, it will be seen that noon foEs has a sharp peak in the summer months, while falls rapidly on either

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Fig. 4: Seasonal variation of (a) noon and midnight foEs (b) occurrence of blanketing type of Es and (c) occurrence of Es-scatter at Ahmedabad in 1954 to 1957.
side. It recorded the highest median value of 6.3 Mc/s in July 1955, while in 1957, noon foEs was the same as noon foE. Midnight foEs is also maximum in summer but it is not so sharp as noon foEs. The variation is also not symmetrical around summer, the tendency being to show high values in the months following summer. It may be remembered that most of the meteor showers occur in the latter half of the year.

V. BLANKETING TYPE OF ES

5.1 Diurnal variation

On some days, the sporadic E layer is so dense that it blankets the higher regions or totally reflects the radio waves up to a certain value of the radio frequency. The occurrences of such Es are shown in Fig. 5, which shows clearly that blanketing Es is an afternoon phenomenon. Comparing this variation with that of fxEs > 5 and > 7 Mc/s of Fig. 1, one finds that although they show maxima at midday, blanketing takes place in the afternoon hours. No doubt, blanketing Es has a noon-time high value in summer also, but the effects in afternoon and evening are more pronounced. In the annual averages, we find the variation to have a peak at 17-18 hrs, the hour being earlier in low sunspot years.

Blanketing Es is practically absent in winter and equinoxes, excepting in the winter of 1955 and autumn of 1957. We shall see later that while noon-time blanketing is due to one type of Es, the evening one is due to another
type of Es.

Fig. 5: Diurnal variation of occurrence of blanketing type of Es at Ahmedabad in January, April, July and October and mean of all months in 1954-57.

5.2 Seasonal variation

Refering back to Fig. 4b, one finds that the blanketing effect is primarily a summer feature, and this happened to be high also in September-October 1957. On the average, there is not much change found with increasing sunspot number, though some increase was recorded in 1957.

VI. Es-SHATTER ECHOS

6.1 Diurnal variation

Spread and patchy types of echoes appear sometimes
as a result of reflections from different scattering centres in the vicinity of the main reflecting point in Es. This scatter is due to irregularities in the structure of Es clouds or it may be due to diffusion of ionization after its production. The diurnal variations of the appearance of such scattered echoes at Ahmedabad are shown in Fig. 6 for different seasons and years. The first point to be noted from this figure is that Es scatter begins to increase after sunset and remains a nighttime phenomenon. In low sunspot years, when Es is more frequent Es-scatter is observed during daytime also and more so in summer. An interesting point is the difference in times of peak occurrences of F2 scatter and Es scatter, although both happen to be nighttime
features. Whereas F2 scatter had a peak at 03 hr in 1954-55, Es-scatter had a peak at about midnight. In the equinoxes of 1956-57, F2-scatter had a peak at 22-23 hr, and Es-scatter had it after midnight. The diurnal variation of Es-scatter does not show that the scatter echoes are more frequent in the second half of the night. It will be later shown that the above variation agrees with that of one of the types of Es, viz. the Esf type, and the scatter is increased when two lower types occur simultaneously.

6:2 Seasonal variation

The seasonal changes in Es-scatter show maximum occurrences in summer and they were practically nil in 1957 (Fig. 4c). The above type of variation is also similar to that of Esf. The conclusion which can be derived from Es-scatter-variations is that the Esf is associated with or embedded in the normal E layer and has a cloud-like structure which rapidly changes in shape after the disappearance of the normal E layer, while the weaker type of Es which neither produces blanketing nor much scatter is a thin layer.

VII. NOTE ON SOME GAIN-RUN RECORDS OF ES

Thomas and others (1956) showed by taking observations at reduced receiver gains that the top frequency f_xEs and the blanketing frequency f_bEs for the two types Esl and Esc occurring at Brisbane were independent of receiver gain, or in other words, f_xEs and f_bEs for these two types of Es were not affected by the sensitivity of the receiver. In another
note (1957) they have shown that the above two frequencies are also independent of the transmitter power. It will be seen from the records reproduced in Fig. 9 that the end frequencies are reduced in the repeated reflections, because of the reduced transmitted power after each back-reflection from the ground, thus proving that the top frequency does depend on the power of the transmitted pulse. We reproduce two gain-run records in Fig. 7 one taken on 13 October 1957 for Esc and the other taken on 26 October 1957 for Esl and Esf simultaneously.

Fig. 7: - h'-f records of Ahmedabad at intervals of 1 minute taken with increased attenuation in the I.F. stage of the receiver to show the dependence of fEs on the sensitivity of the receiver.

The records of Esc were repeated at interval of 1 minute with the receiver gain reduced approximately from 5 db to 15 db. One can see that the top frequency in the first reflection is not affected by reducing the gain of the receiver except for its own time-variation. The trace ends abruptly in all cases and does not get fainter towards the end even though
the sensitivity of the receiver is reduced. But there is a
general decrease in the strength of the echoes and the top
frequency in the second reflection is not the same as in the
first reflection. Recording of an echo will be possible till
the same end frequency if the pulse-power is strong enough to
produce a recordable amplitude of the echo even after changing
the receiver-gain. The reduction in top-frequency usually
believed to be due to the factors already mentioned is only a
matter of convention, because how can the maximum ionization
density be changed simply by changing the exploring methods?
Photographic film or paper may not be sensitive enough to
give visible record of very low strength of received echo.
Thus the highest frequency may not always be a true figure
for maximum ionization density.

From the record of 26 October 1957 in Fig. 7, in
which the first record at 1631 hr is without any added
attenuation and the second record at 1632 hr is with an
attenuation of about 12 db, it can be seen that while the
end frequency of the stronger reflection is not affected, that
of fainter and higher Es has gone down at reduced gain of the
receiver. The scattered echoes are also reduced down.

The highest frequency of the Es record also depends
on the structure of the sporadic i.e. whether it is a strongly
reflecting or partially reflecting type. Usually the cusp-type
of Es is a strongly reflecting type and its f_xEs is less
affected than that of the other types by changing the receiver
gain or transmitter power.
Yet another example of the effect of a change in the power of the transmitted pulse is given in Fig. 8, in which hourly ionograms from 1500 to 1900 hr on 15 October 1957 are reproduced. It may be noticed that the end frequency of the strongly reflected cusp-type Esc layer at 1700 hr has remained the same in all its multiple reflections, while that of the low Es1 has fallen even in the 2nd reflection. At 1900 hr when the Esc has taken the form of thick Esf the end frequency in the multiples has progressively decreased. This evidence proves that the Esc which gives strong reflection throughout its range of frequencies is not affected in its end frequency by reduction in the transmitter power, whereas the partially reflecting layers do show changes in their end frequencies.

**Fig. 8:** Ionograms of Ahmedabad on 15 October 1957 showing 
(1) break at foEs in the trace of Es1 (2) development of strong Esc, (3) top frequency of Esc unchanged in repeated reflections and (4) sharp Esc echoes changing to broad Esf echoes.
VIII - CLASSIFICATION OF ES ACCORDING TO TYPES

We have noted earlier that different types of Es occur at different places. Examples of Es recorded at some stations have been published in the Annals of the I.G.Y., Vol. III - (Fig. 93a at White Sands; Fig. 141 et seq. on pages 112 and 113 at Maui; and Figs. 107 and 142 at Point Barrow). In Fig. 9 are reproduced some ionograms which show the various types of Es obtained at Ahmedabad. The author (1956) had described earlier the characteristics of three main types of Es for the year 1953-1954, a sunspot minimum.

Fig. 9: Typical h'-f records of Ahmedabad showing different types of Es.
Record No. 1 was taken on a day of Quadrantid meteor shower. The time taken to sweep each band of frequencies is one minute. It shows the long-enduring diffused and scattered reflections, the intensity of scatter falling at higher frequencies, probably due to decreasing sensitivity of the receiver at higher frequencies and reduced power of the transmitted pulse. The reflection starts at about 110 km, comes down to 100 km and again rises to 110 km. In the 2nd multiple, however, only the reflection from a higher level is repeated.

No. 2 of Fig. 7 gives a sharply defined echo at a constant height of 100 km, well below the lower boundary of the normal E layer. This is called Esl (Es low).

No. 3 shows a strongly reflecting layer whose trace comes out as a tail from the cusp of foE and is then maintained at a constant height of about 117 km. It has blanketed all the higher regions, while the Esl type in record Nos. 1 and 2 did not produce much blanketing. The cusp-type Es is termed Esc (Es cusp).

Records 4, 6 and 7 give flat, thick reflections till the end without any indication of group retardation. The subscript 2 means that there were more than one reflection from the layer. No. 4 shows a strongly reflecting or blanketing Es, No. 6 shows both low and flat types of Es simultaneously and No. 7 has recorded a weak interrupted echo at a height of 160 km besides the main lower reflection from flat type of Es. This flat type of Es is termed as Esf (Es flat). Most of the records
reproduced in Fig. 9 were taken in summer except the one on 3rd January 1955.

Normally, the occurrence of blanketing Es is more frequent in summer at Ahmedabad.

Record No. 5 shows a type of Es reflection, typical of equatorial conditions. A patchy reflection throughout the range of frequencies and a broad scattered echo at the end are the main features. In spite of the fact that the top frequency exceeds 15 Mc/s, blanketing takes place only up to 5.4 Mc/s. Such Es echoes are usually found at the equator and hence the layer is called Esq or Equatorial type of Es (Es equatorial). This type of Es is very much less frequent at Ahmedabad and is observed on some days of magnetic storms. The record given here was taken on 27 July 1956 when two solar flares occurred, which were associated with fade-outs and were followed by intense Esc and then by Esq.

A common point to be noted from all these records is: In the repeated reflections, the frequency increases at the lower end of the traces while it decreases at the upper end of the traces; i.e. the lower frequencies are more absorbed on repeated reflection and the end frequencies get feebler by repetition. Another feature is that, in spite of the strongly reflecting and highly ionised Es layer during daytime, more than two multiples are rarely observed; but during night and morning, even though the Es layer is less dense and partially reflecting, repeated reflections and N-echoes fill up the whole of the
height range on the time-base. The daytime reduction in the number of multiple is probably due to absorption by the D layer.

IX - DESCRIPTION OF THE VARIOUS TYPES OF Es

9.1 The low or Esl type

This type of Es is recorded at a constant height throughout its range of frequencies; the height is usually 95-100 km. It gives sharp reflection which ends abruptly at its top frequency. It has weak ionization, and is in a thin layer. Generally it is of the partially reflecting, transmitting type. When it is clear of the daytime E layer or Esf, the trace of Esl is sometimes interrupted. There is no group retardation or magnet-ionic splitting. On some occasions, it is found that the latter part of Esl trace is weak and that the initial part is strong with a sharp change at a frequency which is its ordinary wave critical frequency. The difference between fo and fo of Esl has been found to be 0.7 Mc/s from the records of Ahmedabad. The record at 15 hr in Fig. 9 illustrates the above fact. Moreover this Esl appears to have formed as a result of drift from the normal E layer, because at 14 hr the Esl was not present. From many other records taken at 15 mt. intervals, it has been observed that the Esl is frequently evolved as a stratification from the E layer in the afternoon hours.

9.2 The flat or Esf type

This type of Es is usually observed as a trace in
continuation of the normal E layer. The record shows a flat in the height range 105-115 km till near the end frequency, but sometimes shows a small rise in height at the end. The echo from Esf is thick and often spread. Magneto-ionic components are not distinguishable. Because of its association with the E layer, some solar control is noticeable in its diurnal and seasonal variations. The trace of Esf is rarely interrupted. The density of Esf is such as to make it more reflecting than Esl. It is often evolved out of Esc in the evening or persists as a remnant of the daytime E layer. During night, Esf has a tendency to split into more than one stratum. Helliwell et al (1951) have shown the possibility of nighttime splitting of the E layer into discrete stratifications. Peiffer and Mitra (1955) explained the experimental results on night-time E layer by vertical drift.

9.3 The cusp or Esc type

This type is recognised by the trace emerging out of the cusp of the E layer in the form of a tail, which, after initial group retardation, is maintained at a constant height at or near the level of maximum ionization in the normal E layer i.e. in the height range 115-125 km. This type is evolved in sequence from the E2 layer by the latter's downward movement. In doing so, the layer becomes thinner with sharp-gradient and gives very strong reflections, invariably blanketing the higher regions. Although the record is maintained at a constant height, the two magnetoionic components are always found to be distinctly recorded. Because of its
evolution in a sequence from the E2 layer, it has been called E2s or Ess in some earlier publications. Seddon et al (1954 a, b) found from rocket observations that Es had a steep gradient of ionization near E maximum. Probably their observations refer to the cusp-type of Es. Some records of this sequence can be seen in Fig. 9 of the last section, and from Fig. 9 of a previous paper by the author, a reprint of which is appended. This Esc when recorded above the height of E maximum is now called Esh but the origin of this is also the E2 layer. In summer, during day-time, Esc cannot be distinguished from Esf, and when they combine, they produce a strongly blanketing type of Esf layer. The difference between $f_x$Esc and $f_0$Esc (or Esh) is usually found to be 0.65 Mc/s at Ahmedabad. Esc or Esh is mainly a daytime phenomenon.

X - DIURNAL, SEASONAL AND ANNUAL VARIATIONS OF THE OCCURRENCES OF Esl, Esf AND Esc LAYERS.

We have already discussed the general characteristics of the Es layer as a whole in Sections III to VI and now propose to explain these as due to the sum of the effects of Esl, Esf and Esc.

10.1 Diurnal Variations

These are shown in Fig. 10. The diurnal variations of Esl and Esf are generally complementary of each other. The occurrence of Esf is minimum at about 14 hr and maximum in the early morning. The Esl is most frequent in the late afternoon or evening hours. Any increase of Esl is accompanied
Fig. 10: Diurnal variation of occurrence of Esl, Esf and Esc (including Esh) types of sporadic E layers at Ahmedabad in January, April, July and October and mean of all months in 1954 - 1957.
by fall in Esf and vice versa. On the other hand, Esc is predominantly an evening phenomenon. The peaks in Esl and Esf follow the peaks of Esc and Esh, that of Esl follows Esf. This suggests that Esl is formed by drift of ionization from the normal E layer and from Esf which is embedded in the E layer. The ionization left in Esf after sunset is partly the remnant of daytime E and partly drifted from Esc. The prominent evening maximum observed in the occurrence of E of all types with fxEs > 3 Mc/s is thus due to the combination of occurrences of all the three types. The daytime maximum in the occurrence of Es with fxEs > 5 Mc/s and > 7 Mc/s is more attributed to Esf than to Esl. Another peak of foEs which is seen in the evening is due to the cusp type of Es. In general, the nature of variation in a particular month for each type of Es remains the same, although the solar activity changes. The morning peak near sunrise in the totality of Es seems to be related to Esf. In 1955, Esl was more frequently observed during daytime. The peak of occurrence of Esc is most pronounced in October.

10.2 Simultaneous occurrence of Esl and Esf

Normally one would expect that the two lower Es's would occur at the time when the downward drift from a higher level is a maximum. Fig. 11 shows that almost in every month the peak occurrence of Esl and Esf is round about sunset time. In 1955, the simultaneous occurrence of Esl and Esf was frequent even during daytime and some cause other than drift might have been responsible. In the variation of all Es
10.3 Seasonal Variations

The monthly mean occurrences of different types of Es are shown in Fig. 12. It is found that while Esf is maximum in summer, Esl has two maxima in summer and in winter. Esl is least frequent in March-April throughout the whole period. The Esc occurrence is least in winter and most frequent in summer. Comparing the seasonal variations of occurrence of Es as a whole for $f$Es > 3 Mc/s with those of Esf and Esl, one concludes...
Fig. 12: Seasonal variation of the occurrence of different types of Es at Ahmedabad from 1954 to 1957.

that Esf is more responsible for the summer maximum and Es1 for the winter maximum. The variation of intense Es at frequencies > 5 and > 7 Mc/s is accounted for by the combination of Esf and Esc. Es1 should be considered as a class with weak ionization, and the other two with intense ionization. Esf is more a solar-controlled occurrence. However, the overall seasonal variation is not quite symmetrical after the summer months. Does this mean that one of the sources of ionization of Es1 is meteors? It is known that most of the major meteor showers take place in summer and in the second half of the year. The large daytime increases in Es1 during 1955 suggests that meteors (sporadic as well as showers) might have been very active in this period to produce ionization at Ahmedabad. The percentage of Esh or Esc are very low compared to those of Es1 and Esf, and the overall seasonal variation of Es may be treated as being due to the contribution by the latter two types.
10.4 **Annual Variation**

The mean yearly occurrences of different types of Es, of those with different limiting frequencies, of blanketing Es and of Es-scatter are given in Table I. The mean noon and midnight values of foEs are also tabulated for each year, along with the mean Zurich sunspot number.

**Table I - Mean yearly Es Characteristics.**

<table>
<thead>
<tr>
<th>Type of Es</th>
<th>Percent Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1954</td>
</tr>
<tr>
<td>(All types included)</td>
<td></td>
</tr>
<tr>
<td>All values of fxEs</td>
<td>68</td>
</tr>
<tr>
<td>with fxEs &gt; 3 Mc/s</td>
<td>53</td>
</tr>
<tr>
<td>&quot; &quot; &gt; 5 Mc/s</td>
<td>31</td>
</tr>
<tr>
<td>&quot; &quot; &gt; 7 Mc/s</td>
<td>13</td>
</tr>
<tr>
<td>Type Esl</td>
<td>26</td>
</tr>
<tr>
<td>&quot; Esf</td>
<td>45</td>
</tr>
<tr>
<td>&quot; Esc</td>
<td>7</td>
</tr>
<tr>
<td>&quot; Esh</td>
<td>8</td>
</tr>
</tbody>
</table>

| Esl Esf occurring simultaneously | 7 | 15 | 9 | 4 |

| Blanketing Es | 6 | 7 | 4 | 8 |

| Scatter-Es | 13 | 10 | 11 | 6 |

| Noon foEs (Mc/s) | 3.6 | 4.0 | 4.0 | 4.2 |
| Midnight foEs (Mc/s) | 1.65 | 2.2 | 2.14 | 1.7 |

| Zurich sunspot No. | 43 | 38 | 139 | 190 |
It will be seen from the above table that the maximum occurrences of Esf and Esl are found in 1955, a year on the rising side of sunspot cycle. No marked change is observable in the occurrences of Esc and Esh and their contribution is very much less than of Esl and Esf. No correlation with sunspot number can be established, although Es is less frequent in high sunspot years. While the mean noon foEs rose to a maximum value in 1957 in a nearly the same way as noon foE, midnight foEs was maximum in 1955.

II - METEORS AND E\textsubscript{s} IONIZATION

There is no longer any doubt that Es ionization can be caused by impact of meteors, particularly in temperate and high latitudes; about Es ionization in low latitudes, there is however still some doubt. In the previous sections, we have seen that the daytime diurnal variation of Es in summer and the seasonal variation of Esl at Ahmedabad does in a way suggest some connection with sporadic meteors and meteor showers. It should be remembered that in the first half of the night large Es ionization is left over from the daytime normal E as well as from the other higher sporadic layers. Unless the contribution from the higher layers in the E region is removed, the comparison of Es occurrences in different parts of the night for detecting meteoric effects has very little meaning. One thing is certain that maintenance of appreciable Es in the second half of the night (Esf or Esl) must be due to some ionizing agent other than the drifted or a remnant ionization in the first half of the night. Direct evidence to prove that there is definite
contribution by meteors can only be achieved by observing changes in Es ionization during some of the major meteor showers. We give below some of our results obtained during a few meteor showers mentioned in Table II.

Table II - Details of Meteor showers during which Es-observations are described.

<table>
<thead>
<tr>
<th>Name of Meteor shower</th>
<th>Day of maximum</th>
<th>Radiant Coord.</th>
<th>Hourly Rate</th>
<th>Time of Transit GMT, hr</th>
<th>Time of marked rise in foEs GMT, hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrantids</td>
<td>Jan. 3-4</td>
<td>23°, 52°</td>
<td>35</td>
<td>08-09</td>
<td>08 - 09</td>
</tr>
<tr>
<td>Arietids</td>
<td>June 8</td>
<td>44°, 22.6°</td>
<td>60</td>
<td>08-10</td>
<td>09</td>
</tr>
<tr>
<td>α-Orionids</td>
<td>July 12-13</td>
<td>87°, 11°</td>
<td>50</td>
<td>04-08</td>
<td>04-08</td>
</tr>
<tr>
<td>ω-geminids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>λ-geminids</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perseids</td>
<td>Aug 10-14</td>
<td>47°, 58°</td>
<td>50</td>
<td>04-05</td>
<td>04</td>
</tr>
<tr>
<td>Geminids</td>
<td>Dec 13-14</td>
<td>113°, 32°</td>
<td>60</td>
<td>00</td>
<td>Doubtful (22-00)</td>
</tr>
</tbody>
</table>

The above particulars which are averages over a long period are taken from the book "Radio Astronomy", Chapter V, by Lovell, Bernard, and Clegg J.A., 1952. Data of hourly rates of meteors were obtained from the Jodrell Bank Experimental Station, Manchester, and the laboratory is much indebted to the authorities of this station. Let us now compare these meteor data with our observations of fEs at Ahmedabad.

11.1 Quadrantids, January 3-4, 1956

The results are plotted in Fig. 13. It is noticed that
Fig. 13: Relation of Es ionization at Ahmedabad and Yamagawa to hourly rate of meteor incidence at Manchester on 3-4 January 1956, a day of quadrantid meteor shower.

... 

the peak activity of meteor incidence and rise in $f_{Es}$ coincide with each other. A record of increased $f_{Es}$ ionization at 04 hr GMT on January 3, 1955 was reproduced in Fig. 7 which coincided with a large increase in meteoric activity. The height of such an ionization usually varies from 100 to 105 km, which is quite in agreement with the idea of meteoric impact. At Yamagawa also, the effect of meteor showers is noticeable.

11.2 Aristids June 8, 1956

Ionograms repeated at intervals of 15 minutes are reproduced in Fig. 14 to illustrate the effect of the above meteor shower. It may be seen that $f_{Es}$ shot up to more than 15 Mc/s at 1400 hr (75° EMT) which is also the time of peak meteoric activity. The frequency came down in the next 15 minutes, but now the reflection is broad and diffused. At
Fig. 14: Ionograms of Ahmedabad on 8 June 1956 showing large and short period increase of fEs during the Arietids meteor shower. Note the broad and diffused echoes after the peak of meteoric activity.

1430 hr patchiness of the echo became pronounced and fEs later continuously decreased, going down to less than 6 Mc/s at 1515 hr when the reflection became sharp and thin. So this high production of ionization was sustained only for a short duration of at the most half an hour, and this took place at a height of 100 km. It should be noted that the intensity of ionization was so strong that frequencies upto 10 Mc/s were blanketed and the reappearance of echoes from higher layers began after the lower Es ionization had diffused out. Rise in height at the end of the trace is possibly due to oblique reflection from the drifting cloud.
11.3 **Orionids, Geminids and Geminids, on July 12-13**

The effect of above meteor showers of July 12-13, 1953 and 1955 on fEs is clearly seen from the plots of Figs. 15 and 16. The peaks in hourly rates of meteors and fEs very nicely agree in time with each other. From Fig. 15, meteor-effect on Es is also noticeable at Yamagawa. Increased Es ionization produced blanketing of the higher regions, and the height remained at 100 km during peak activity. It is curious to find that although the hourly rate of meteor hardly reached 15, the increase in Es ionization was extremely large and in excess of $2.5 \times 10^6$ electrons / c.c. during peak meteor activity. This is found so almost in all cases of daytime meteor showers.

**Fig. 15**: Relation of Es-ionization at Ahmedabad and Yamagawa to meteors recorded at Manchester on 12-13 July 1953.

**Fig. 16**: Relation of Es-ionization at Ahmedabad to meteors recorded at Manchester on 12-13 July 1955.
11.4 Perseids, August 12-13, 1956

The rate of meteor incidence of Perseids is larger than that on July 12-13. In Fig. 17 are plotted fEs at Ahmedabad and Yamagawa and meteor rates at Manchester. Here also the peaks in both the parameters at 0400 hr GMT on 12-8-1956 coincide with each other, but the increase in fEs is not so high as that observed on July 12-13 above.

Fig. 17: Relation of Es-ionization at Ahmedabad

(1) to meteors recorded at Manchester during the Perseids shower of 12-13 August 1956, and

(2) also to the magnetic storm of 11 August 1956.

On the next day, however, they do not exactly agree in time. The increase in fEs on the night of 11-8-1956 at Ahmedabad followed an SC type magnetic storm which commenced at 0043 hr GMT. Other instances of h'-f records for Es associated with magnetic storms are given later.
11.5 **Geminids, December 13-14, 1953 and 1956.**

The Geminids give the hourly rate of meteors largest of all showers and this is a night time incidence. The observations of fEs during this shower are shown in Fig. 18. Peak rate of meteor fall was as high as 100 per hr on the 13th and 60 per hr on 14th at 00 hr GMT. Inspite of this, there is no marked rise in fEs at Ahmedabad either in 1953 or 1956. In 1954, fEs data were missing and nothing of any interest could be found in 1955. There are large fluctuations in fEs as seen in Fig. 18 and some of the peaks in fEs do coincide with those of meteors. In any case, this big night-time shower produced negligible effect on Es as compared to smaller daytime showers.

![Fig. 18](image)

**Fig. 18:** Changes in fEs at Ahmedabad compared with those of hourly rate of meteors of Manchester on 13-14 December 1953 and 1956.
All the above instances thus furnish definite affirmative evidence in reply to the question posed earlier "Do meteors contribute to Es Ionization in low latitudes?"

XII - MAGNETIC STORMS AND CHANGES IN Es

12.1 We had seen earlier that although the diurnal variation of Es intensity and occurrence is roughly parallel to the variation of the earth's horizontal magnetic field in auroral latitudes, Es was not found during magnetic disturbances (Appleton et al 1937). Near the geomagnetic equator, Skinner and Wright (1957) showed opposite relation between Es and magnetic activity and at Kodaikanal no correlation could be found between these. A day-to-day analysis of mean fEs and total occurrence of Es was made at Ahmedabad for 1953, but no definite conclusion could be reached to establish relation between SK and Es. From an examination of some individual cases of SC type magnetic storms, it was found that not all storms were accompanied by increased Es ionization, although during the main phase of the storm there were many instances when it was recorded. An example of changes in fEs following a storm on 11 August 1956 has already been given in Fig. 17. Echoes in scattered form at Es level as well as above 125 km were observed.

12.2 Magnetic storm of 30 August 1957.

This commenced at 0020 hr 75° EMT. Strong scattered Es echoes followed from 0130 hr and lasted till 0330 hr. Although the Es echoes were very much scattered, there was very little evidence for its producing F2-scatter in the range of frequencies
at which Es was recorded. The effect of the storm on F2 seemed to have begun at 0245 hr after which the layer was raised up to great heights. In Fig. 19, it is seen that fEs was very much increased during daytime on 30.8.57, though it was not a day of high meteoric activity.

Fig. 19: High values of fEs were recorded on the day following the commencement of a magnetic storm on the previous night. Meteors at Manchester did not show any significant change on this day.

12.3 Magnetic storm of 4 September 1957.

This commenced at 1800 hr. The effect on Es and F2 is illustrated by ionograms in Fig. 3 of Chapter II. At 2200 hr Es-ionization reached its minimum. A faint echo at 150 km is seen at 2215 hr and at 2230 hr echoes from scattering clouds appeared at about 210 km and those at normal level increased in strength and they got still stronger in the next 15 minutes.
No evidence of spread F due to Es is noticeable. Plots of foF2 and hpF2 are given in Fig. 18 of Chapter IV.

12.4 **Magnetic storm of 29 September 1957.**

A severe storm commenced at 0515 hr on 29-9-57 on the night of 29/30-9-57 at 0130 hr scatter echoes at 200 km were recorded as seen from Fig. 15 of Chapter II and they were observed till 0230 hr. Sporadic reflections again reappeared at 130 km at 0400 hr. A curious phenomenon was observed after 05 hr when sporadic reflections were observed at 160 km (Fig. 20) and they drifted down to normal Es level which finally merged into sharp reflection from the E layer at 0630 hr.

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**Fig. 20:** h'f records of Ahmedabad on the night of 29-30 September 1957 showing appearance of scattered sporadic echoes at heights 170 km - 200 km during a severe magnetic storm.

See also Fig. 15 in Chapter II for sporadic echoes at 160-200 km.
Such sporadic echoes at high levels are normally not observed at Ahmedabad, but they were found to be specially associated with magnetic disturbances in the earlier stages. It is not evident from these records that the ionization might have drifted down from the F2 layer. The parallel trace of F2 record at 0400 might have been due to scattering by Es layer.

In summary, it may be stated that there is no definite evidence of increased Es ionization during increased magnetic activity in general, barring some few special cases.