Dissertation

on

STUDIES IN THE PHYSICS OF THE IONOSPHERE

presented

by

R. G. RASTOGI

for

the degree of

DOCTOR OF PHILOSOPHY

of

THE GUJARAT UNIVERSITY

October 1956

043



B1661

PHYSICAL RESEARCH LABORATORY
Ahmedabad

P R E F A C E

The thesis embodies some of the investigations carried out at the Physical Research Laboratory, Ahmedabad, during the period 1953-1956. The ionospheric section of the laboratory is maintained with financial assistance from the Council of Scientific and Industrial Research (India). The author has been working in the Section since its start.

The special observations at Ahmedabad discussed in this thesis and the relevant calculations were all made by the author. The field-strength measurements made during solar eclipse were made with the assistance of the author's colleagues and this is acknowledged in the appropriate places. Acknowledgements to sources from which additional information has been taken are given in the references.

Dr. U.D.Desai, Reader in Electronics, rendered great help of the installation of the ionospheric recorder. Thanks are also due to Mr. K.M.Kotadia who has been associated in the maintenance of the ionospheric station.

I am indebted to Professor K.R.Ramanathan for his keen interest and guidance during the investigations.

R G Rastogi

R. G. RASTOGI.

Countersigned

K R Ramanathan

14/10/56

C O N T E N T S

Chapter

I. Intermediate layers of ionisation between the E and F1 layers of the ionosphere over Ahmedabad (23°N, 72.6°E).

II. On high multiple reflections and other abnormalities observed in the P'-f records.

III. On the solar control of the E and F1 layers of the ionosphere - Variations of k and n with latitude and with sunspot number.

IV. A study of the noon critical frequencies of the E and F1 layers of the ionosphere.

V. Solar eclipses and the ionosphere.

VI. Thunderstorm and sporadic E layer ionisation.

CHAPTER I

INTERMEDIATE LAYERS OF IONISATION BETWEEN THE E AND F_1 LAYERS OF THE IONOSPHERE.

CHAPTER I

INTERMEDIATE LAYERS OF IONISATION BETWEEN THE E AND F1 LAYERS OF THE IONOSPHERE OVER AHMEDABAD (23°, 72.6°E)

CONTENTS

		Page
	Introduction with reprints of two papers by the author.	
	(i) Intermediate layers.....over Ahmedabad.	
	(ii) Two types of development of the E2 layer at Ahmedabad.	
I.	Development of the intermediate layers in the morning hours.	3
II.	Formation of E2 from F1.	8
III.	General characteristics of the E1 and E2 layers of the ionosphere.	17
	(1) Determination of the true height of an ionospheric layer.	18
	(2) Occurrence of E1 and E2 layers.	23
	(3) Critical frequencies and heights of E1 and E2 layers.	25
	(4) Critical frequencies and sunspot activity.	30
	(5) Solar control of E1 and E2 layers.	32
IV.	Intense E2 layer.	38
V.	Night E2 layer.	43
VI.	E2 and sporadic E.	48
VII.	Origin of E1 and E2 layers.	55
	References - Tables	

Reprinted from the "Proceedings of the Indian Academy of Sciences," Vol. XL 1954

INTERMEDIATE LAYERS OF IONISATION BETWEEN THE E AND F_1 LAYERS OF THE IONOSPHERE OVER AHMEDABAD (23° N, 72° 6 E)

BY

R. G. RASTOGI

Reprinted from "The Proceedings of the Indian Academy of Sciences", Vol. XL, No. 4, Sec. A, 1954

INTERMEDIATE LAYERS OF IONISATION BETWEEN THE E AND F_1 LAYERS OF THE IONOSPHERE OVER AHMEDABAD (23° N, 72°·6 E)

BY R. G. RASTOGI

(Physical Research Laboratory, Ahmedabad)

Received September 9, 1954

(Communicated by Dr. K. R. Ramanathan)

INTRODUCTION

THE existence of an ionised layer intermediate between the two main layers E and F_1 was first reported by Schafer and Goodall,[1] and shortly afterwards by Appleton,[2] and by Ratcliffe and White.[3] Similar observations were later reported by Gilliland,[4] and by Lung.[5] This intermediate layer, now called E_2, was generally observed during morning and evening hours[2] and mainly in the winter months.[5] A more detailed study of this layer has been made by Becker and Dieminger.[6, 8] They found that the E_2 layer occurred regularly; it had an average virtual height of 130–140 km. The layer also showed evidence of magneto-ionic splitting. Becker and Dieminger suggested that the ionisation of the layer might be due either to neutral corpuscles or to a small range of frequencies of ultra-violet radiation from the sun. Commission III of the U.R.S.I. on 'Ionosphere and Propagation' in their recommendation to the 1948 General Assembly at Stockholm made the following remark,[7] "In the event that clear stratification is evident within the regular E layer, and a second critical frequency is observed, it is increasingly common practice to refer to the upper critical frequencies as f_0E_2 and f_xE_2 and the minimum virtual height as $h'E_2$." Becker and Dieminger in their second paper have concluded that the E_2 layer should be considered as a continuous thin homogeneous layer.

Leiv Harang[9] in 1937 noted two stratifications between the E and F_1 layers. Soon after the ionospheric station at Ahmedabad was established in 1953, it was noticed that between the E and F_1 layers, there were often two regular ionisation steps indicating discrete ionised layers. An example of such an occurrence is shown in Fig. 1.

Symbols used.—Throughout this paper, we shall indicate the normal E layer simply as the E layer, and the two intermediate layers as E_1 and E_2.

the upper one being called E_2. The ordinary wave critical frequencies for the E, E_1, E_2 and F_1 layers will be indicated by f_0E, f_0E_1, f_0E_2 and f_0F_1 and the minimum virtual heights by $h'E$, $h'E_1$, $h'E_2$ and $h'F_1$. This would be consistent with the recommendations of U.R.S.I.[7]

Frequencies of Occurrence of the Layers

E_1 and E_2 layers are most clearly seen shortly after sunrise. During evening hours they are less clear owing to interference and absorption. They are least clear during the noon hours, presumably due to absorption. Fig. 2 gives the percentage frequencies of occasions on which these layers could be observed in February, March and April 1953.

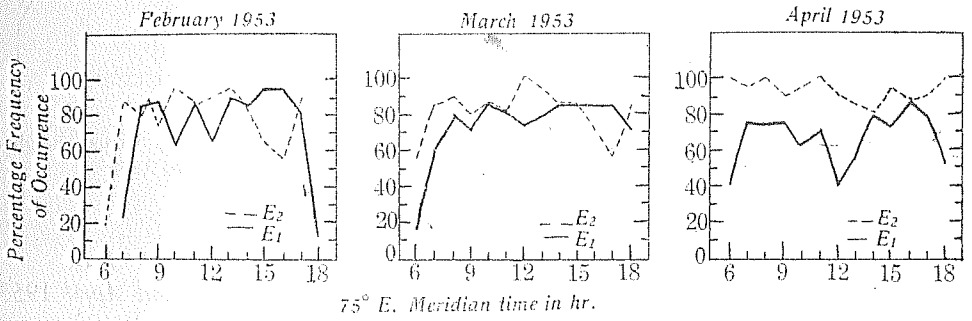


Fig. 2. Frequencies of occurrence of the E_1 and E_2 Layers during February, March and April 1953.

Critical Frequencies of the Layers

Both E_1 and E_2 layers show magnetic splitting similar to the normal E layer. The extraordinary components of E_1 and E_2 are recorded as weak reflections except in the morning and evening hours. Fig. 3 shows a P'-*f* record in which the extraordinary components are clearly visible.

The observed critical frequencies indicate that the E_1 and E_2 layers are almost as regular as the main layers E and F_1. Moreover the scatter of the values of f_0E_1 and f_0E_2 is of the same order of magnitude as the scatter of f_0E and f_0F_1. On the average, f_0E_1 is only slightly larger (0·2 Mc/s) than the corresponding f_0E, and the average difference between f_0E_2 and f_0E_1 is 0·6 Mc/s.

Table I gives the median values of the critical frequencies of the layers E, E_1, E_2 and F_1 for the months of February, March and April 1953. The values are plotted in Fig. 4. The figure shows that similar to the normal layers, E_1 and E_2 also follow the sun's altitude.

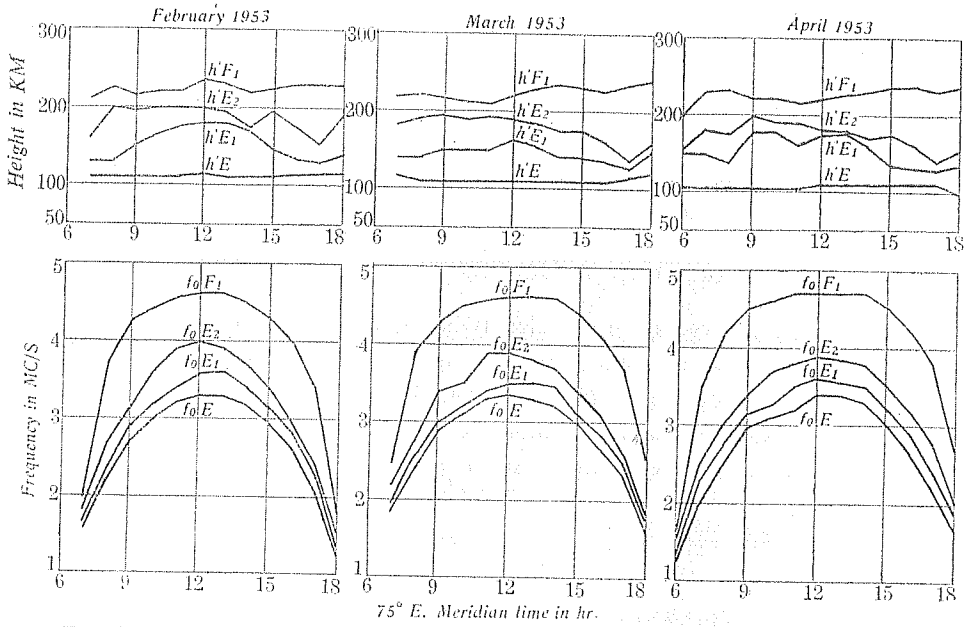


FIG. 4. Curves showing the median values of the critical frequencies and virtual heights of E, E_1, E_2 and F_1 layers during the months of February, March and April 1953.

TABLE I

Monthly median values of the critical frequencies (in Mc/s) of E, E_1, E_2 and F_1 layers during the months of February, March and April 1953

Hours 75° E.M.T.	February				March				April			
	f_0E	f_0E_1	f_0E_2	f_0F_1	f_0E	f_0E_1	f_0E_2	f_0F_1	f_0E	f_0E_1	f_0E_2	f_0F_1
6	..	..	1·15	..	..	..	1·1	..	1·25	1·3	1·6	..
7	1·6	1·65	1·8	1·95	1·9	1·95	2·2	2·45	2·0	2·3	2·5	3·5
8	2·2	2·35	2·65	3·7	2·4	2·55	2·75	3·9	2·5	2·75	3·05	4·2
9	2·7	2·9	3·1	4·25	2·9	3·0	3·4	4·3	3·0	3·25	3·45	4·5
10	3·0	3·15	3·6	4·4	3·1	3·2	3·5	4·5	3·1	3·25	3·7	4·6
11	3·1	3·4	3·9	4·55	3·3	3·4	3·9	4·55	3·2	3·5	3·8	4·7
12	3·2	3·6	4·0	4·6	3·35	3·5	3·9	4·6	3·4	3·6	3·9	4·7
13	3·2	3·6	3·9	4·6	3·3	3·5	3·8	4·6	3·4	3·55	3·85	4·7
14	3·1	3·4	3·7	4·5	3·2	3·45	3·7	4·6	3·3	3·5	3·8	4·7
15	2·95	3·15	3·4	4·3	3·0	3·1	3·4	4·4	3·0	3·2	3·5	4·5
16	2·65	2·85	2·95	4·0	2·65	2·85	3·1	4·1	2·65	2·9	3·15	4·2
17	2·0	2·25	2·4	3·4	2·3	2·55	2·6	3·7	2·2	2·4	2·8	3·8
18	..	...	1·55	..	..	1·6	1·8	2·5	1·7	1·9	2·0	2·7

The critical frequencies of these intermediate layers obey approximately the law

$$f_0 = k \cos^n Z,$$

where Z is the sun's zenith distance and k and n are constants. Fig. 5 shows the graph of the critical frequencies of E, E_1, E_2 and F_1 layers against cos Z for the month of March 1953. The values of k and n are given in Table II.

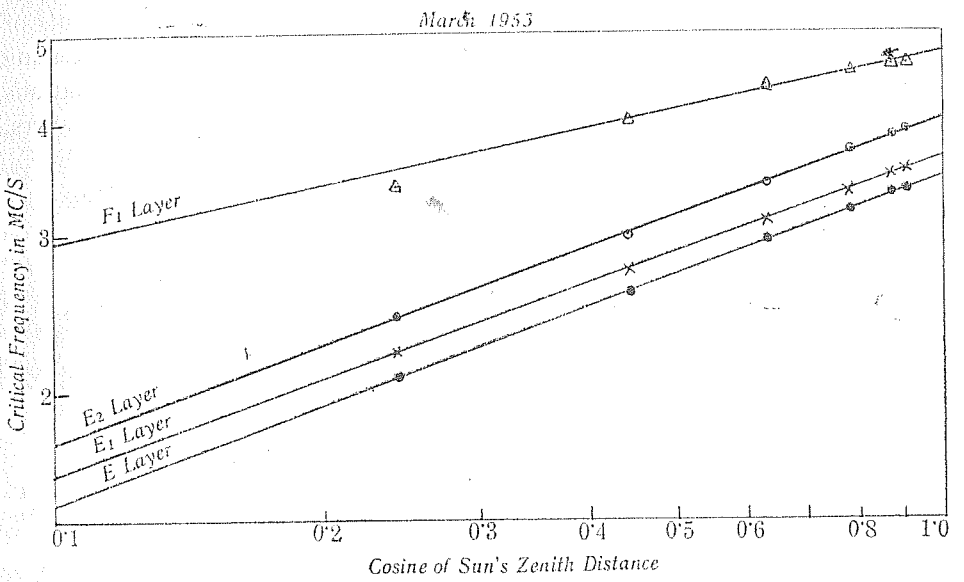


FIG. 5. Graph of critical frequency *versus* cos Z for the layers E, E_1, E_2 and F_1 during the month of March 1953.

TABLE II

Values of k *and* n *for E, E_1, E_2 and F_1 layers during the months of February, March and April* 1953

Layer	February		March		April	
	k	*n*	*k*	*n*	*k*	*n*
E ..	3·5	0·35	3·5	0·37	3·4	0·41
E_1 ..	3·9	0·38	3·6	0·35	3·6	0·38
E_2 ..	4·3	0·41	4·1	0·39	3·9	0·36
F_1 ..	4·8	0·22	4·7	0·21	4·8	0·20

If the ionisation followed a simple Chapman Law, the constant n would be 0·25, whereas the observed values are near 0·38 for E, E_1 and E_2 layers and near 0·21 for the F_1 layer.

VIRTUAL HEIGHTS OF THE LAYERS

As regards the heights of these layers, the individual observations of the virtual height are rather widely scattered. The observed virtual heights of E_1 and E_2 layers are usually considerably greater than the true heights of reflection due to the proximity of the critical frequencies of the underlying layers. Consequently the values of $h'E_1$ and $h'E_2$ show large variations depending upon the nearness of the critical frequencies of the lower layers. Table III gives the median values of the minimum virtual heights of E, E_1, E_2 and F_1 layers for the months of February, March and April 1953.

TABLE III

Median values of the minimum virtual heights of E, E_1, E_2 and F_1 layers during the months of February, March and April 1953

Hours 75° E.M.T.	February				March				April			
	$h'E$ km.	$h'E_1$ km.	$h'E_2$ km.	$h'F_1$ km.	$h'E$ km.	$h'E_1$ km.	$h'E_2$ km.	$h'F_1$ km.	$h'E$ km.	$h'E_1$ km.	$h'E_2$ km.	$h'F_1$ km.
6	..	..	160	..	..	..	170	..	105	150	155	..
7	110	130	160	210	115	140	180	220	105	150	180	230
8	110	130	200	225	110	140	190	220	105	138	175	230
9	110	150	195	215	110	150	195	215	105	175	200	220
10	110	165	200	220	110	150	190	210	105	185	190	220
11	110	175	200	220	110	150	195	210	105	160	190	215
12	115	180	200	235	110	165	190	220	110	180	175	220
13	110	180	195	230	110	155	185	230	110	180	180	225
14	110	170	175	220	110	140	175	233	110	160	170	230
15	110	145	195	225	110	140	175	230	110	135	175	235
16	115	135	175	230	110	135	160	225	110	130	160	235
17	115	130	155	230	115	125	135	235	110	130	140	230
18	..	..	190	..	..	150	160	240	100	130	150	235

True Heights of the Layers

The true height of the ionisation maximum of a layer can be determined with the help of Booker and Seaton's formula[10]

$$h' = h_m + \mathrm{T}\,\phi\,(f/f_c)$$

where h' is the virtual height of reflection for a wave of frequency f, h_m the height of ionisation maximum, T the semi-thickness of the layer and ϕ is a function defined by

$$\phi\left(\frac{f}{f_c}\right) = \frac{1}{2}\,\frac{f}{f_c}\log_e\left|\frac{f_c+f}{f_c-f}\right| - 1$$

where f_c is the critical frequency of the layer. If another layer lies just above the height of maximum ionisation of the lower layer then the group retardation of a wave ($f > f_c$) penetrating the lower layer is given by

$$\Delta h' = \mathrm{T}\,\phi\left(\frac{f}{f_c}\right)$$

But if the upper layer overlaps the lower layer below its ionisation maximum then the group retardation by the lower layer is given by a formula given by Ratcliffe.[11]

$$\Delta h' = \mathrm{T}\,(f/f_c)\log_e\left\{\frac{1+f/f_c}{\sqrt{1-(f_B/f_c)^2}+\sqrt{(f/f_c)^2-(f_B/f_c)^2}}\right\}$$

where f_c is the critical frequency of the lower layer and f_B is the frequency at which the reflections start from the upper layer. Thus h_m and T of a layer can be determined by fitting the observed P′–f curve with the standard P′–f curves drawn on a transparent sheet according to the above formula [Ratcliffe's method[11]]. The values of h' are plotted against [Appleton and Beynon's method[12]] and the slope of the straight line passing through the points gives T, and its intercept on the h' axis gives h_m.

Such a determination of true height is often not possible for these intermediate layers due to the very short trace of P′–f curve which is visible, or the frequent overlapping of the layers, or the presence of scattered E or sporadic E reflections. The heights of these layers on a number of days were determined by Ratcliffe's method. The values were verified by Appleton and Beynon's method. Table IV gives the results of such determination from a few clear P′–f records.

The true heights of E_2 layer were calculated to which the above method could be applied, from all records of March 1953 and Table V gives the mean values of the true heights of E and E_2 layers during March 1953.

TABLE IV

Virtual and true heights of E, E_1 and E_2 layers on some individual days

Date (1953)	Time 75° E.M.T. hr.	E Layer			E_1 Layer			E_2 Layer		
		h' (km.)	h_m (km.)	T (km.)	h' (km.)	h_m (km.)	T (km.)	h' (km.)	h_m (km)	T (km.)
12th February ..	0800	100	112	5	128	125	18	155	145	<5
13th February ..	0800	115	113	10	130	118	22	150	130	8
2nd March ..	1600	110	114	10	132	120	18	150	140	<5
12th March ..	1100	115	106	25	155	120	10	140	135	<5
1st April ..	0800	120	118	20	152	122	10	170	155	<5
16th April ..	0700	112	110	12	130	126	22	160	150	<5

TABLE V

Mean true heights of ionisation maximum of normal E and E_2 layers during March 1953

Time 75° E.M.T. Hr.	E Layer			E_2 Layer		
	No. of occasions	h_m (km.)	T (km.)	No. of occasions	h_m (km.)	T (km.)
06	..	..	..	5	160	15
07	8	116	12	7	159	15
08	8	113	10	4	142	15
09	6	107	11	6	155	10
10	8	109	22	7	134	5
11	7	110	24	11	148	< 5
12	11	112	18	7	142	< 5
13	11	112	20	9	137	< 5
14	9	112	26	14	139	< 5
15	15	116	20	14	141	< 5
16	18	116	17	15	140	< 5
17	10	120	15	14	127	< 5
18	..	..	..	8	135	< 5

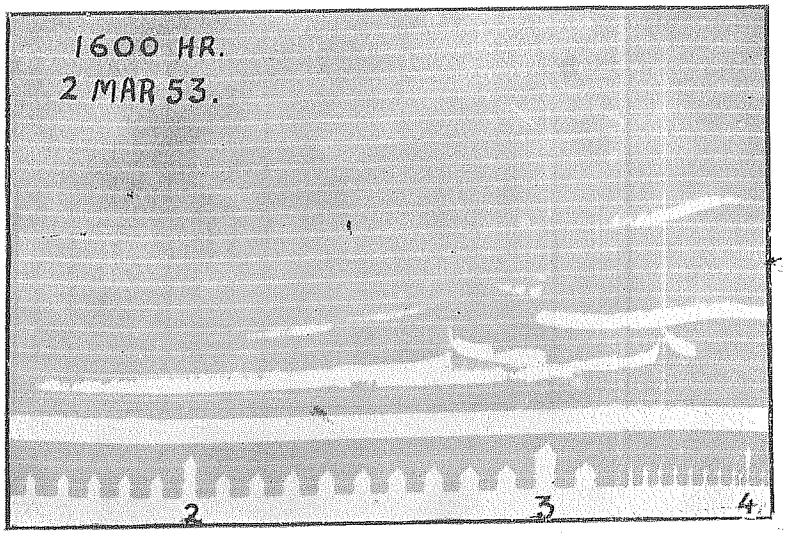


FIG. 1

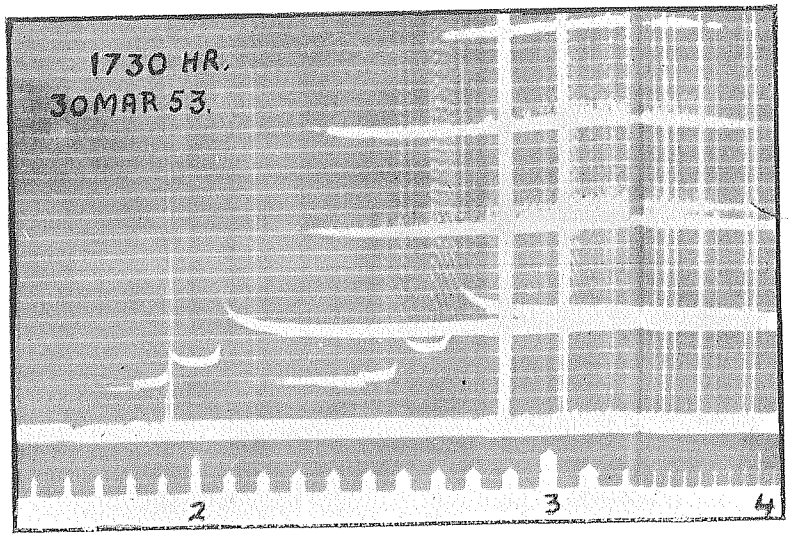


FIG. 3

FIG. 1. P′-*f* record taken at 1600 hr. 75° East Meridian Time on 2nd March 1953. Two intermediate layers between main E and F_1 layers can be clearly seen, particularly in the second curve.

FIG. 3. P′-*f* record taken at 1730 hr. 75° East Meridian Time on 30th March 1953. Ordinary as well as extraordinary components of E, E_1 and E_2 layers are clearly visible.

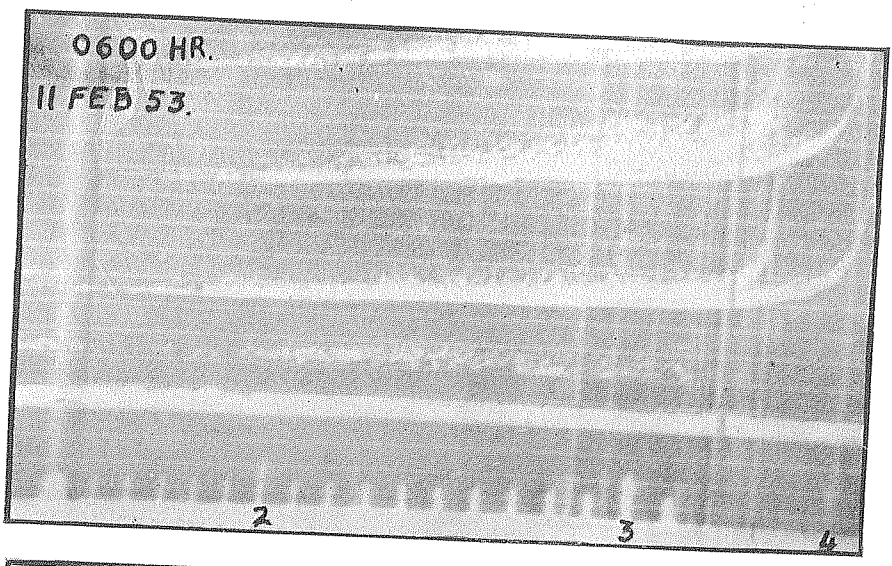


FIG. 6*a*

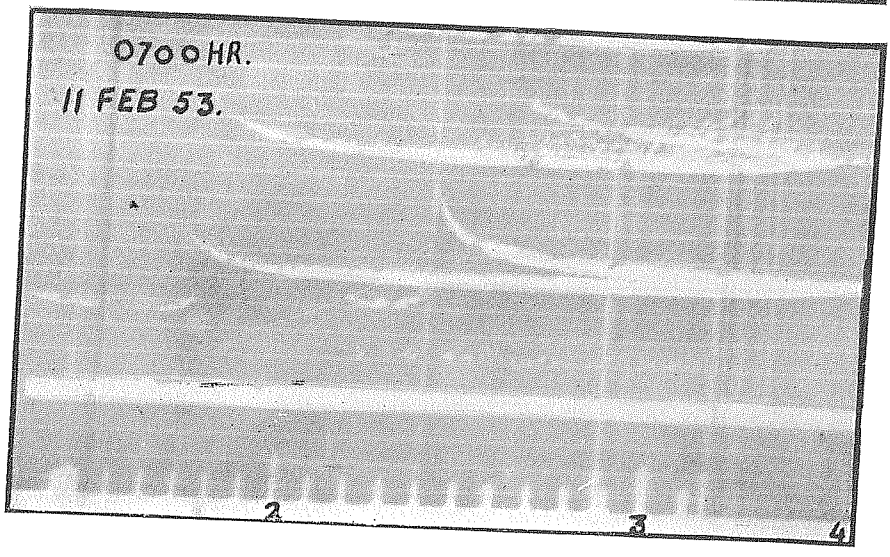


FIG. 6*b*

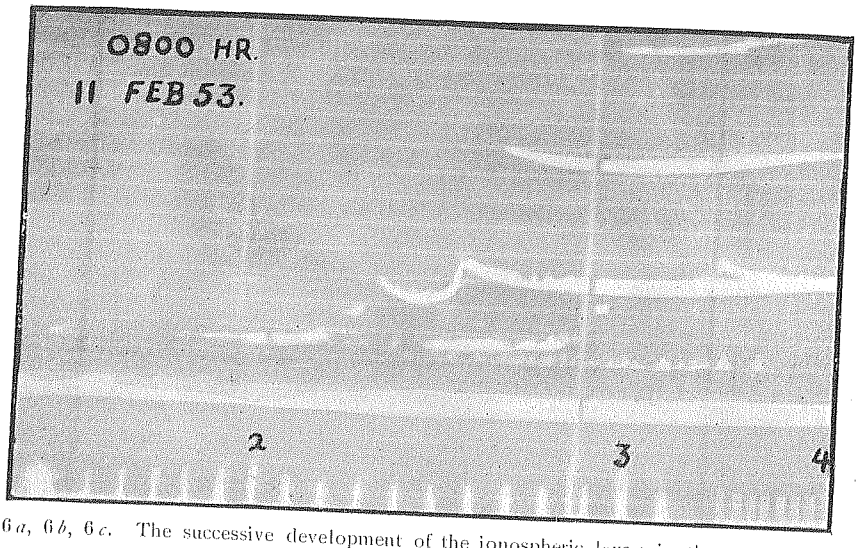


FIG. 6*c*

FIGS. 6*a*, 6*b*, 6*c*. The successive development of the ionospheric layers in the morning hours on 11th February 1953.

On the average, the E_2 layer occurs at a height of about 140 km.; it is a very sharp layer having a semi-thickness less than 5 km., while normal E occurs at the height of about 115 km. and has an average semi-thickness of 18 km. E_1 occurs at the height of 120 to 130 km. and is of about the same thickness as the E layer.

After sunrise, the E_2 layer is the one to appear first and E_1 and E layers develop later. From the observations taken at intervals of 5 min. in the morning hours during another season, it was found that E_2 layer developed approximately 10–20 min. before the appearance of the E layer. The F_1 layer becomes distinguishable from the general F layer only about an hour after the appearance of the E_2 layer. It appears that as the sun's altitude increases and the sun's rays illuminate the lower strata of the atmosphere, the ionospheric layers develop successively. Fig. 6 illustrates the development of these layers on 11th February 1953.

There have recently been a few determinations of the electron concentrations in the ionosphere with the aid of rockets. Seddon[13] obtained on 29th September 1949 a value of electron density for the E layer $1{\cdot}6\times10^5$ electrons per c.c. at a height of 107 km., and for the E_2 layer $2{\cdot}2\times10^5$ electrons per c.c. at 142 km. The usual ionospheric P′–*f* record obtained during the rocket firing showed the virtual height of the E_2 layer to be 215 km. In the diagram given by Seddon there is also a secondary maximum of electron concentration at about 120 km. The data obtained by J. R. Lien and collaborators[14] on 26th June 1953 gave for the normal E layer $1{\cdot}3\times10^5$ electrons per cm.^{3} at a height of 110 km. and for the E_2 layer 2×10^5 electrons per cm.^{3} at a height exceeding 130 km. The diagram given by the authors shows a third intermediate maximum at 120 km. with electron density lower than that of either the normal E layer or of the E_2 layer. Bering's[15] data obtained on 15th Dec. 1952 gave for the normal E layer a charge density of $1{\cdot}0\times10^5$ per cm.^{3} at a height of 103 km. The next higher layer appeared at 123 km. with a charge density nearly the same as that of the normal E layer and a third maximum at 156 km. with $1{\cdot}4\times10^5$ per cm.^{3} The electron density maxima between the main layers E and F_1 as obtained by rocket data thus correspond reasonably well with the two layers E_1 and E_2 regularly observed at Ahmedabad.

It seems to be of importance to maintain systematic records of the appearance, critical frequencies and other characteristics of the E_2 and E_1 layers. A more extended study of the phenomenon has been undertaken by the author.

SUMMARY

Between the main layers E and F_1 of the ionosphere over Ahmedabad, two intermediate layers occur regularly having virtual heights of 125 and 140 km. They also show the characteristic magneto-ionic splitting. The critical frequencies of these layers follow the position of the sun according to the law $f_0 = k \cos^n Z$, n neing near about 0·38. Minimum virtual heights of these layers have been shown to be very misleading due to the proximity of the lower layers. The true height and the thickness have been determined for some cases. The true heights of these layers correspond well with the heights of ionisation maxima in the ionosphere determined with the aid of rockets.

ACKNOWLEDGEMENT

I am very grateful to Dr. K. R. Ramanathan, for his continuous encouragement and kind guidance in the work, and to Dr. U. D. Desai for his valuable help during the installation of the ionospheric station. The Council of Scientific and Industrial Research (India), is supporting the Ionospheric Station with financial assistance.

REFERENCES

1. Schafer, J. P. and Goodall, W. M. — *Nature*, 1933, **131**, 804.
2. Appleton, E. V. .. — *Ibid.*, 1933, **131**, 872.
3. Ratcliffe, J. A. and White, E. L. C. — *Ibid.*, 1933, **131**, 873.
4. Gilliland, T. R. .. — *Proc. Inst. Radio Engr.*, 1935, **23**, 1076.
5. Lung, H. L. .. — *U.R.S.I. Proc. Eighth General Assembly*, held in Stockholm, 1949, 250.
6. Becker, W. and Dieminger, W. — *Naturwissenschaften*, 1950, 37, 90.
7. *U.R.S.I. Information Bulletin on Terminology and Symbols*, Commission III on Ionosphere and Propagation, 1949, 10.
8. Becker, W. and Dieminger, W. — "U.R.S.I. Mixed Commission on Ionosphere," *Proc. Second Meeting*, held in Brussels, 1950, 126.
9. Harang, L. .. — *Terr. Mag. and Atmos. Elect.*, 1937, **42**, 68.
10. Booker, H. G. and Seaton, S. L. — *Phys. Rev.*, 1940, **57**, 87.
11. Ratcliffe, J. A. .. — *J. Geophy. Res.*, 1951, **56**, 463.
12. Appleton, E. V. and Beynon, W. S. G. — *Proc. Phys. Soc.*, 1940, **52**, 518.
13. Seddon, J. C. .. — *J. Geophy. Res.*, 1953, **58**, 323.
14. Lien, J. R., Marcou, R. J., Ulwick, J. C., Aarons, J. and Mc Morrow, D. R. — *Rocket Exploration of the Upper Atmosphere*, Pergamon Press Ltd., London, 1954, 232.
15. Bering, W. W. .. — *Ibid.*, 1954, 272.

Two types of development of the E2 layer at Ahmedabad.

Soon after the installation of the ionospheric recorder at Ahmedabad in January, 1953, it was noticed that the P'-f records showed kinks in the reflection traces characteristic of a maximum ionization between the normal E and F1 layers of the ionosphere. An examination of these records showed that they were due to two intermediate layers (called E1 and E2) having heights of maximum ionization at about 125 km and 140 km. These layers showed the properties of normal ionospheric layers formed by photoionization by solar radiation. An account of them has been published(RASTOGI, 1954).

BECKER and DIEMINGER (1950a,b) have described the occurrence of an E_2 layer at Lindau. They concluded that the E2 layer was a continuous thin homogeneous layer and that it might be caused either by short-wave radiation or neutral corpuscles from the sun.

A different sequence of formation of an ionised layer at about 140 km has been described by McNICOL and GIPPS(1951). This layer separated out from F1 and formed an "E2" layer having properties similar to those of E and F1. McNICOL and GIPPS designated this layer as Ess. SKINNER, BROWN and WRIGHT (1954) described a similar formation of an E2 layer from a ridge in the F1 layer at Ibadan. Recently SAHA and RAY (1955) have reported the

occurrence of and E_2 layer at Calcutta. According to them, the E2 layer first appears as a ridge in F1. It then moves downwards and merges with the E layer. The phenomenon was most usually observed at about 1300 local mean time. As the features of the E2 layer have been carefully watched during the last three years at Ahmedabad, which has about the same latitude as Calcutta, a summary of our observations at Ahmedabad may be of interest.

The E2 layer at Ahmedabad first appears in the morning before ground sunrise. It shows itself first as a group retardation in the F reflection, then weak echoes appear from a layer below F, and these subsequently get stronger. The E2 layer develops after the F2 is affected by sunrise, but before the appearance of the E layer. Both the ordinary and extraordinary components of reflection from E2 are regularly observed. With increasing altitude of the sun, the ionization of the layer increases. These facts show that the E2 layer is formed by photoionization by solar radiation just like the other normal ionospheric layers. However, the formation of E2 is often accompanied by the development of one more layer between it and the normal E.

Fig.1 illustrates the development of these intermediate layers in the morning hours on 6 November 1954. The times of sunrise (75^0 E.M.T.) at different heights on that day are given below:

Height	Time of sunrise
200 km	0520
100 km	0536
0 km	0621

At 0545 there existed only the F2 layer; the record shows the extraordinary trace only. At 0600 the F2 critical frequencies had increased due to sunrise at these levels; both the ordinary and extraordinary traces are clearly recorded, and the extraordinary trace shows group retardation at 1.8 Mc/s. At 0615 the extraordinary component of E2 reflection appears at a virtual height of 150 km, with the critical frequency of 2.2 Mc/s. At 0630 both the ordinary and extraordinary traces of E2 are clear, f_oE2 being 1.8 Mc/s and h'E2 130 km. At 0645 the extraordinary components of E2 shows group retardation due to a lower layer at 2.2 Mc/s. At 0700 the extraordinary component of E1 has become quite clear, and there is also evidence of group retardation at 1.8 Mc/s. At 0715 both the ordinary and extraordinary components of E1 and E2 are clearly recorded.

Occasionally, with the growth of the E layer, the virtual height of the E2 layer increases to join the F1 layer or form a ridge in it. This happens at about 11 L.M.T. It then becomes difficult to distinguish the E2 layer from the ridge in F1. The ridge in F1 later breaks from F1 towards the E layer, with the formation of a separate layer. The virtual height of this separated E2 continues to decrease after breaking from the F1 layer. The ordinary and extraordinary

components can be seen separately. The critical frequencies generally increase if the breaking occurs much beforenoon, and decrease if the phenomena occurs at about noon or in the afternoon. This again indicates a solar control of the E2 layer. By evening the layer comes down to about 120 km and merges with E or Es. The ordinary and extraordinary critical frequencies can be distinguished by the start of the F1 trace. On evenings when there is not much Es, the E2 layer can be followed till it disappears with decrease in solar altitude. The Calcutta observers say that the merging of the E2 layer is followed by the formation of sporadic E ionisation.

Fig.2 illustrates the formation of the E2 layer from a ridge in F1 on 20 October 1954. At 0800 E2 was at 125 km and its critical frequency 2.8 Mc/s. By 0915 f_0E2 has increased to 3.2 Mc/s and h'E2 to 165 km. After this stage, E2 almost joined up with the F1 trace and appeared as a ridge in the F1 layer. Later, this ridge in F1 again broke to form an E2 layer, and its virtual height decreased with time. At 1145 there again appeared a ridge (as a slight break in the virtual height, but more in the amplitude of the trace) in F1. At 1200 this ridge broke from F1 and formed an E2 layer. The virtual height of E2 continually decreased, till at 1600 this descended to the height of the normally layer and merged with sporadic E. This phenomena too is generally accompanied with the appearance of a layer E1 between E2 and the normal E layer.

It has been also observed that on certain nights there exists a layer at about 150 km, showing characteristic group retardation near its critical frequencies.

SUMMARY OF THE OBSERVATIONS AT AHMEDABAD

The sequence of phenomena leading to the separation of the E2 layer in the morning hours after high level sunrise indicates the presence of certain atmospheric consequence in the neighbourhood of 150 km which are photo-ionized by the solar radiation. Further, the frequent appearance of a stratified ionized layer at 150 km during night indicates that there exists a sensitive and stable region for the formation of an ionized layer atabout 150 km over the tropics.

ACKNOWLEDGEMENT : The work described is part of the programme of ionospheric research carried out in this laboratory with financial assistance from the Council of Scientific and Industrial Research (India). The author is indebted to Professor K.R.Ramanathan for his keen interest and guidance.

REFERENCES

Becker, W., and Dieminger W.	1950	Naturwissenschaften, 37, 90
Becker, W., and Dieminger W.	1950	U.R.S.I., Proc. Commission on Ionosphere. Second Meeting held at Brussels. p.126.
McNicol, R.W.E. and Gipps C.D.L.	1951	J.Geophys.Res.56,24.

Rastogi, R.G.	1954	Proc.Ind.Acad.Sci.40, 158.
Saha, A.K. and Ray, S.	1955	J.Atmosph.Terr.Phys. 7, 107.
Skinner, N.J., Brown, R.A. and Wright, R.W.	1954	J.Atmosph.Terr.Phys. 5, 95.

****

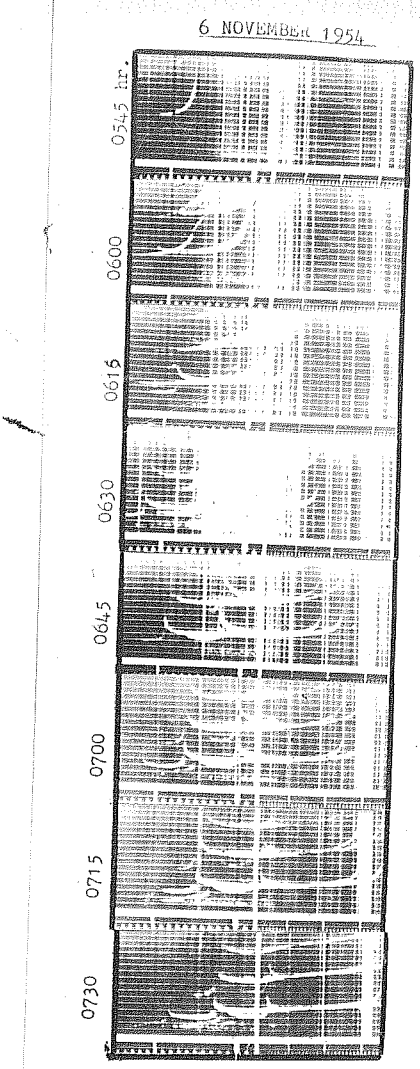


FIGURE 1

20 OCTOBER 1954

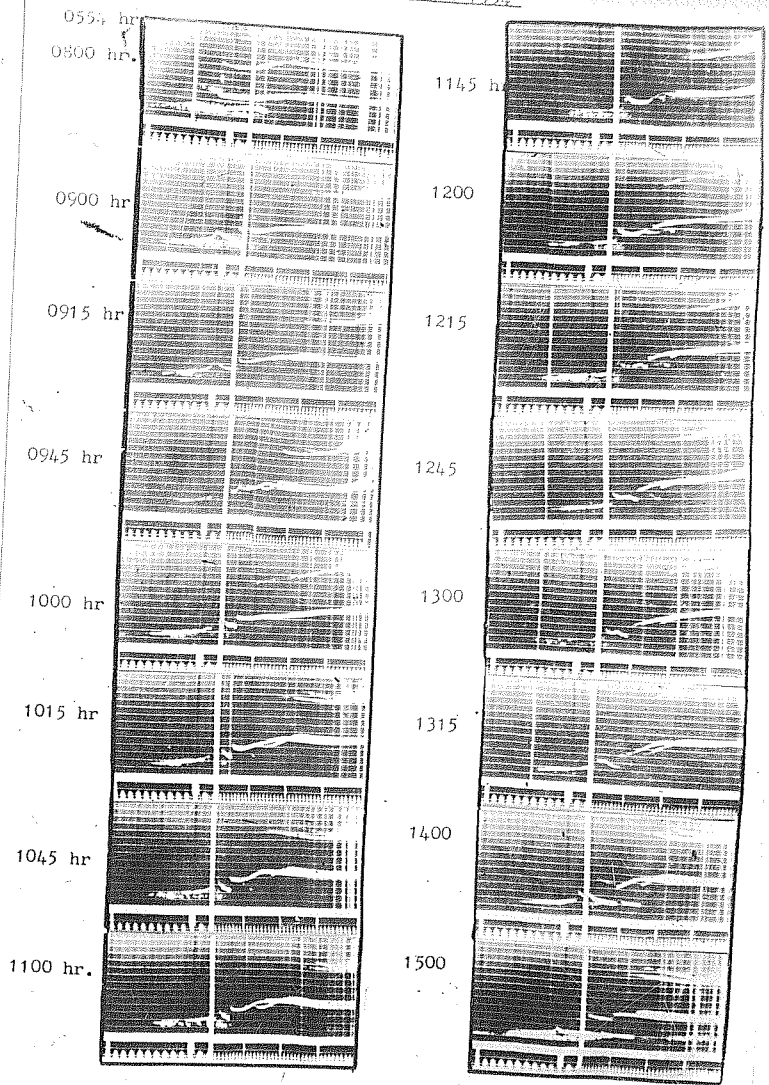


FIGURE- 2

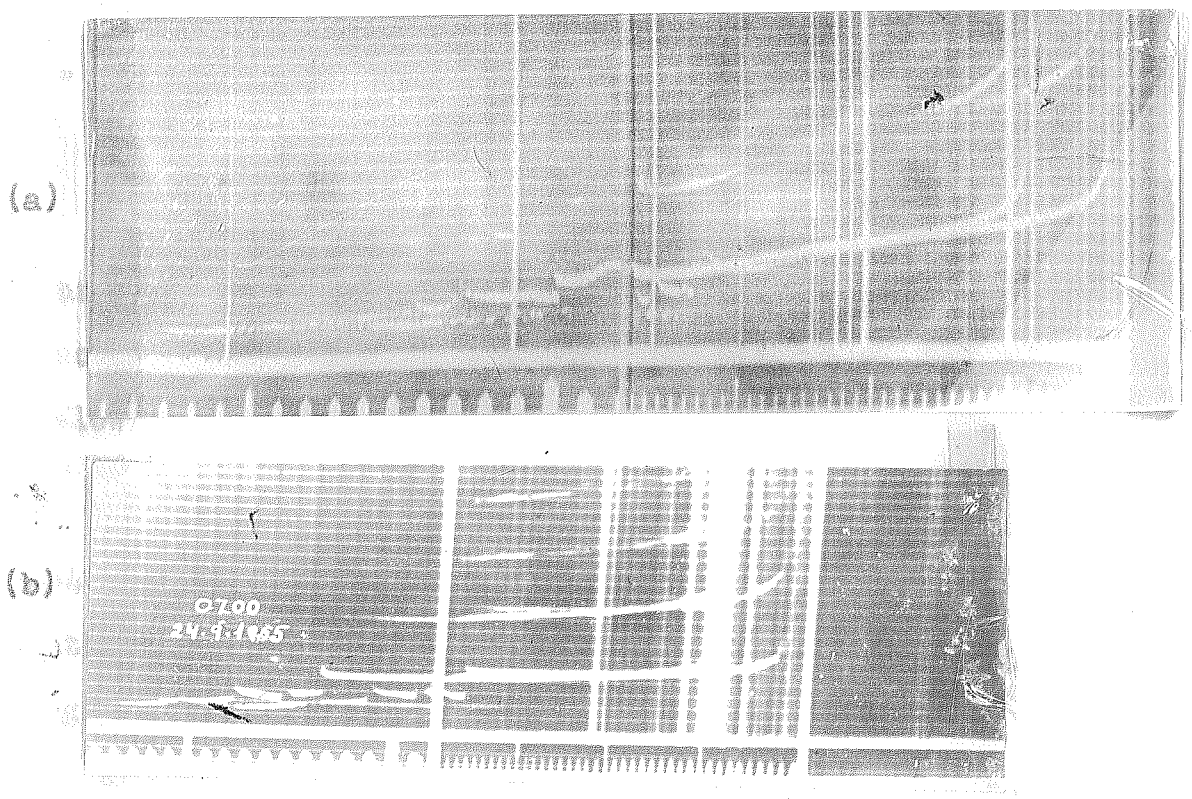
Fig. 2

Intermediate Layers of Ionisation between E and F1 layers of the Ionosphere.

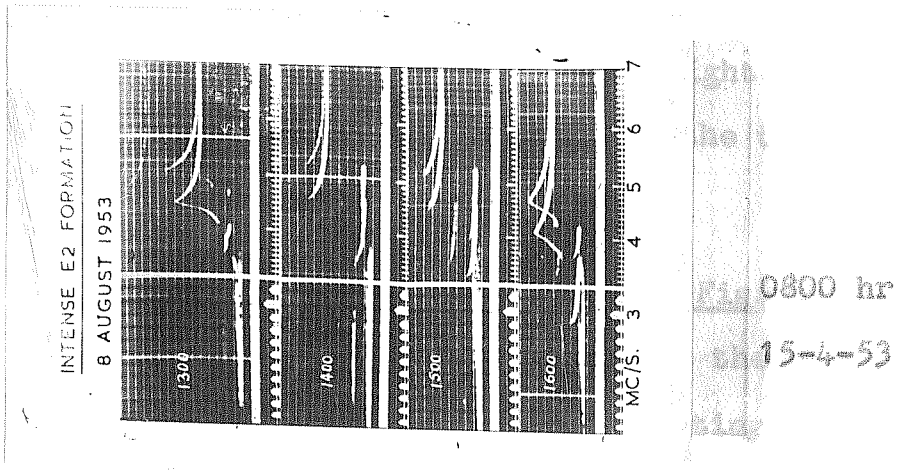
Shortly after a Union Radio Ionospheric Recorder of the British N.P.L. type was installed at Ahmedabad, it was found that the height of the echoes did not vary continuously with frequency for reflections between the E and F1 layers. At times, the record presented a complicated P'-f pattern, suggesting a number of ionisation maxima in that region. A few such records are shown in Fig. 1. An examination of these records showed that two of these layers between E and F1 occurred regularly.

The regular occurrence of these intermediate layers of ionisation between the E and F1 layers of the ionosphere over Ahmedabad, called E1 and E2, has been reported and discussed in two previous papers[1,2].

The present paper contains further studies in the same subject, particularly the development of the layers in the morning, forenoon and occasionally at night, and the relation of these layers to Es. The data regarding these layers collected at Ahmedabad during 1953 to 1955 have been statistically analysed and discussed.



P'-f records showing several intermediate layers between normal E and F1 layers. Note both ordinary and extraordinary component traces for each of these layers.



P'-f record showing a complicated ionisation distribution between E and F1 layers.

Fig. 1

I. Development of the Intermediate Layers in the morning hours.

The development of these layers at the time of sunrise was studied with the help ofshort interval P'-f records. Some examples of these observations are described below.

Observations on August 21, 1953 (Fig. 2) :- At 0540, 0545 and 0550 hr only F2 traces were recorded together with strong Es; f_0F2 was increasing with time. At 0555 the beginning of the F2 traces showed group retardation; this was clearer on the extraordinary component. This indicated the existence at that time of a lower ionised region (E2), though the reflections from it were too weak to be recorded. At 0605 group retardation was quite clear on both the o and x components. E2 was recorded at 0615 at a height of about 150 km. By 0630 both the components of all the three layers E, E1 and E2 were clearly seen.

Observations on September 11, 1953 (Fig. 3) :- The record at 0550 hr showed group retardation at the beginning of the F2 traces at 1.2 and 1.95 Mc/s, indicating the presence of an underlying layer E2. At 0555 weak reflection at 150 km was recorded and f_xE2 had increased to 2.15 Mc/s. At 0600 the x component of E2 showed group retardation at the beginning of its trace due to a still lower layer (E1). At 0605 the lower layer, E1, was evident at 130 km. At 0625 all the three

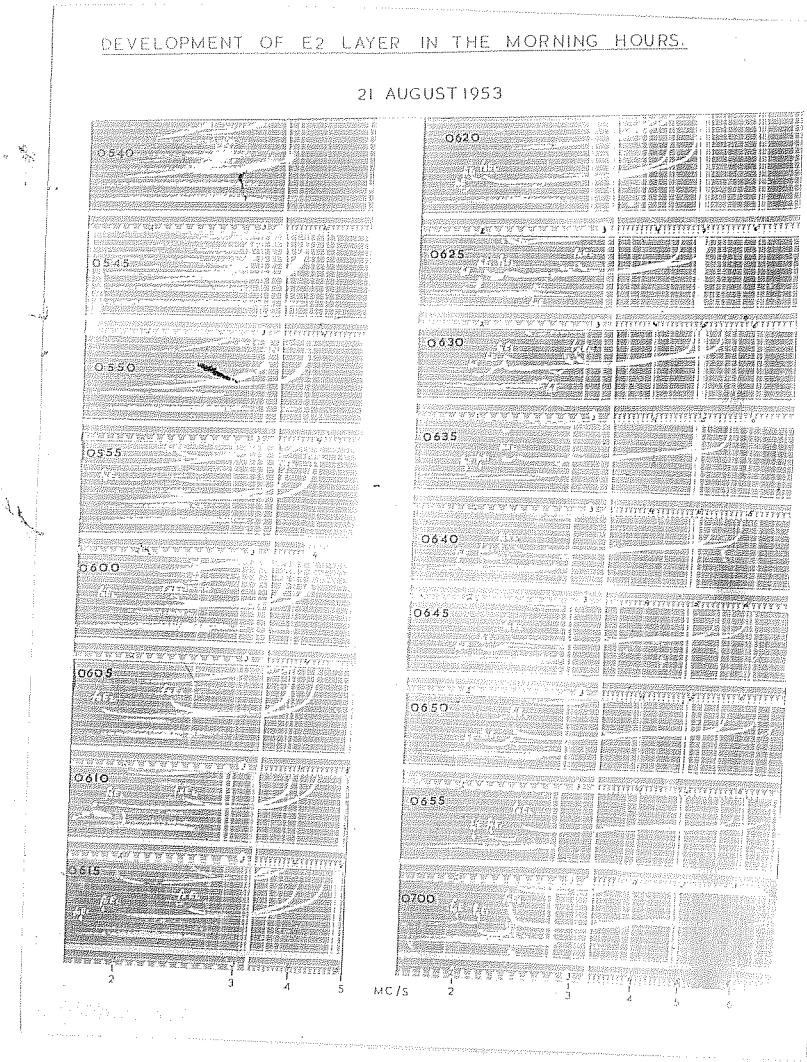


Fig. 2 P'-f records taken at short intervals on August 21, 1953 showing the development of E1 and E2 layers in the morning hours.

DEVELOPMENT OF IONOSPHERIC LAYERS WITH SUNRISE (AHMEDABAD)

11 SEPTEMBER 1953.

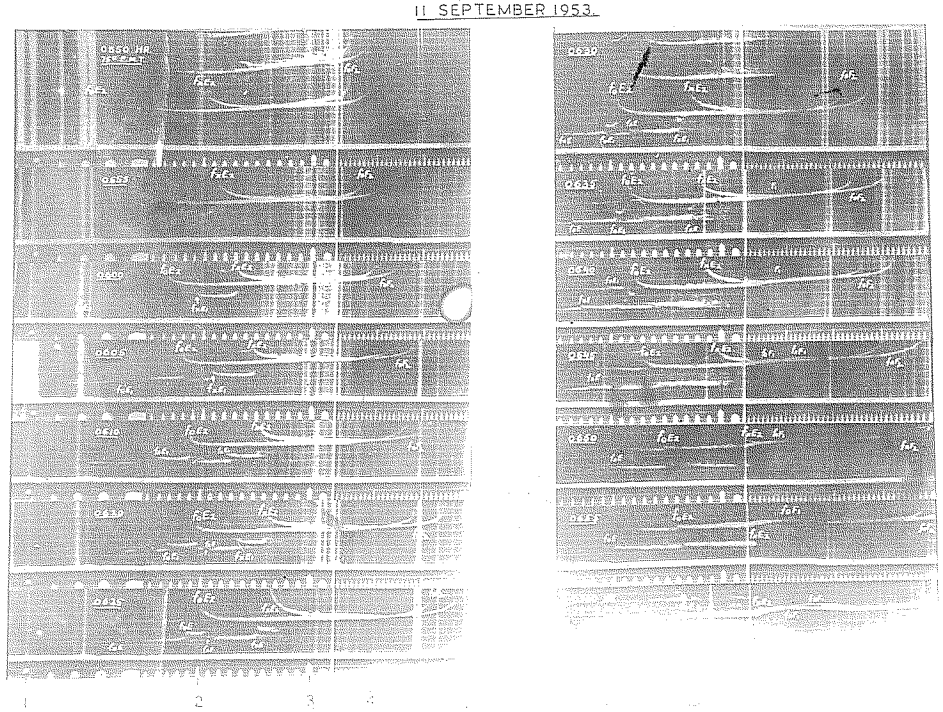


Fig. 3 P'-f records taken at short intervals on September 11, 1953 showing the development of E1 and E2 layers in the morning hours.

layers E, E1 and E2 were quite clear. The later P'-f records showed the development of these layers. At 0640 however, the E1 trace merged with Es reflections. The group retardation in F1 due to E2 first decreased and then vanished by 0655. F1 showed development from a very flat cusp on the F2 trace at 0635 to a clear cusp at 0700. The variation of critical frequencies with time is shown in Fig. 4.

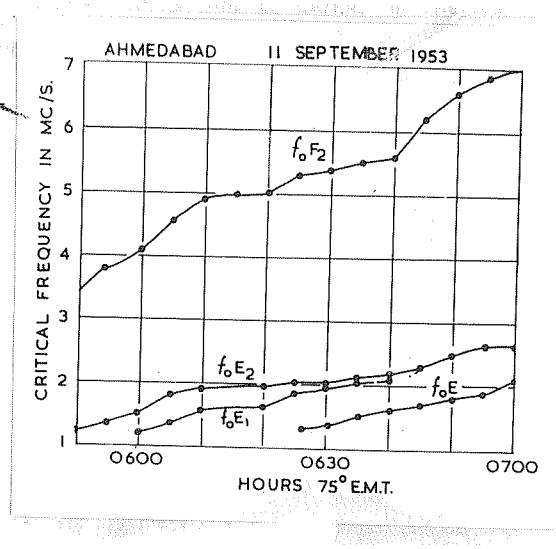
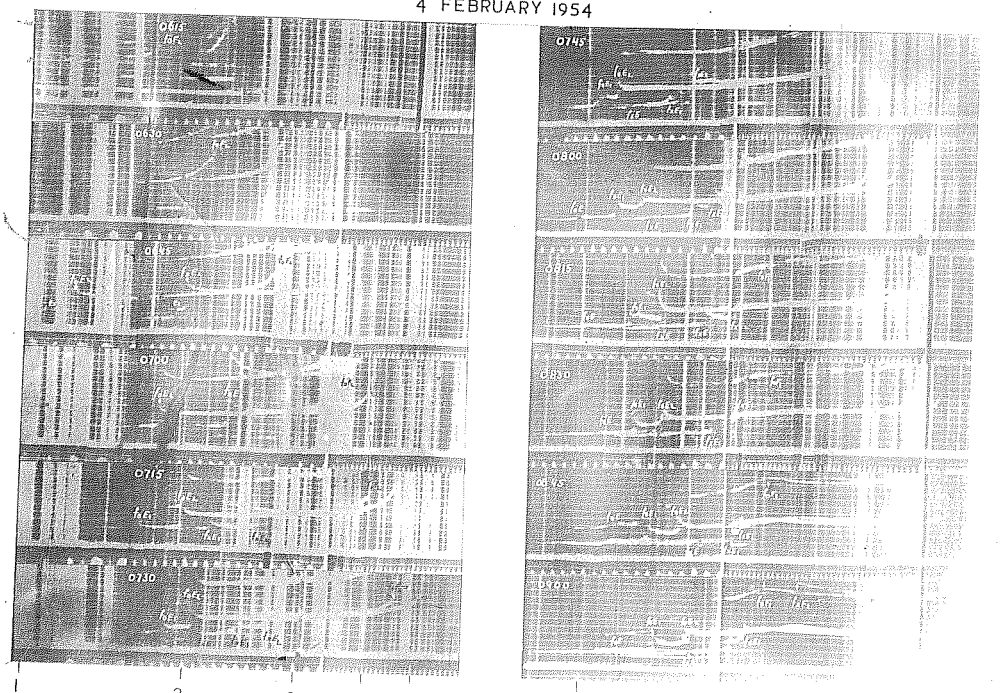


Fig. 4.

Observations on February 4, 1954 (Fig. 5) :- At 0615 hr F2 was recorded together with strong Es. At 0630 the critical frequencies of E2 increased due to the effect of sunrise at that level, and the beginning of x component of F2 reflections showed slight group retardation. At 0645 group retardations in F2 were clearer and E2 traces were recorded at a virtual height of 150 km with $f_oE2 = 1.15$ Mc/s.

DEVELOPMENT OF E1 AND E2 LAYERS IN THE MORNING HOURS.

4 FEBRUARY 1954



This document is the property of the United States Government. It is loaned to your agency; in that it is disclosed it is not to be distributed outside your agency, and its contents not to be disclosed to any unauthorized person.

At 0715 the beginning of E2 showed group retardation at 1.4 Mc/s due to underlying E1 layer. E1 became clearer at 0730 with a virtual height of 130 km and f_oE1 = 1.8 Mc/s. At 0800 the record showed the o and x components of all the three E, E1 and E2 layers clearly. The critical frequencies of all these layers increased with time as the solar altitude increased.

Observations on February 11, 1956 :- The variation of the critical frequencies of the ionosperic layers in the morning hours on 11 February 1956 are shown in Fig. 6.

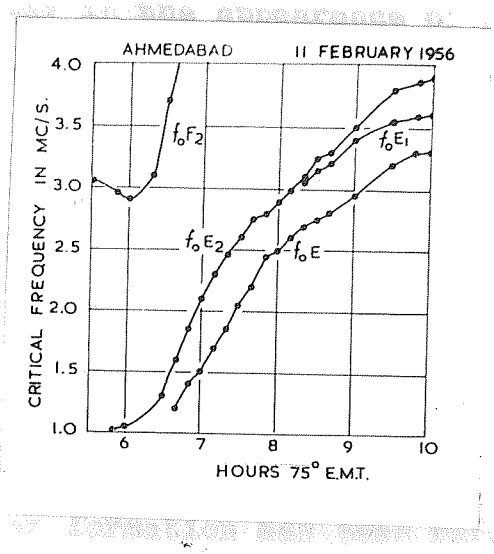


Fig. 6.

Similar short period observations were taken in different months. The times when the E2 layer was just visible on the records are shown in Fig. 7. It will be seen that E2 first appears about 30 minutes after the sun

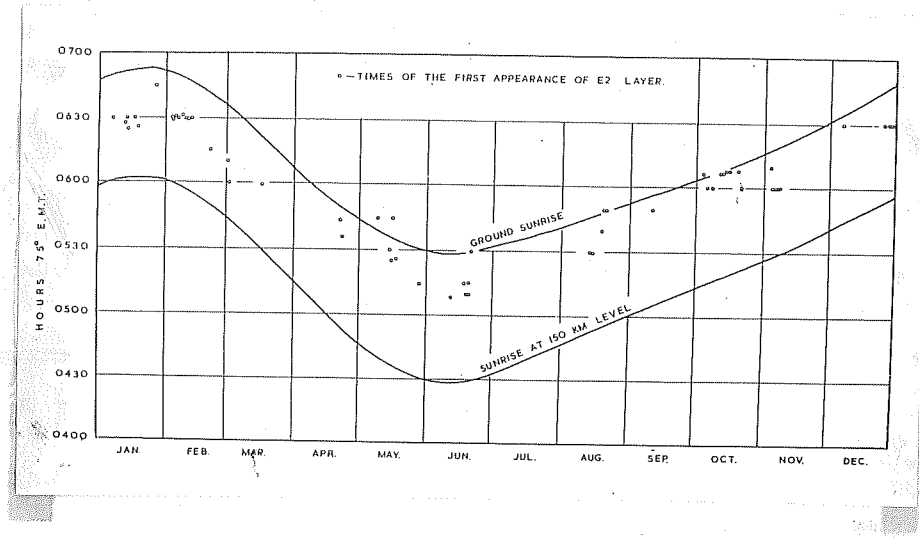


Fig. 7.

risen at 150 km and generally before it rises at the ground. The apparant delay in the appearance of E2 after sunrise at 150 km may be due to instrumental limitation in recording reflections of very low frequency and intensity.

II. Formation of E2 from F1.

A sequence of formation of E2, different from the early morning development was described by McMicol and Gipps.[3] A stratification in the F1 layer led to the formation of an E2 layer. Similar formation has been reported by other workers viz. Rivault[4] at Poitiers, Haubert[5] at Casablanca, Skinner, Brown and Wright[6] at Ibadan and Saha and Ray[7] at Calcutta. The development of E2 out of a ledge in F1 is a common occurrence in the afternoon hours at Ahmedabad and has been described in a note by Rastogi[2]. A few examples are described below.

Observations on October 15, 1954 (Fig. 8) : At 0610 hr all the layers were evident in the P'-f record. At 0620 the critical frequencies of these layers had slightly increased. At 0630 the F1 trace showed a kink; this was more clear in the second order reflection. The ledge became quite clear at 0650. The changes in the F1 traces and the critical frequencies between 0630 and 0930 are worthy of note. At 0930 and 0950 there was a ledge in F1 which broke

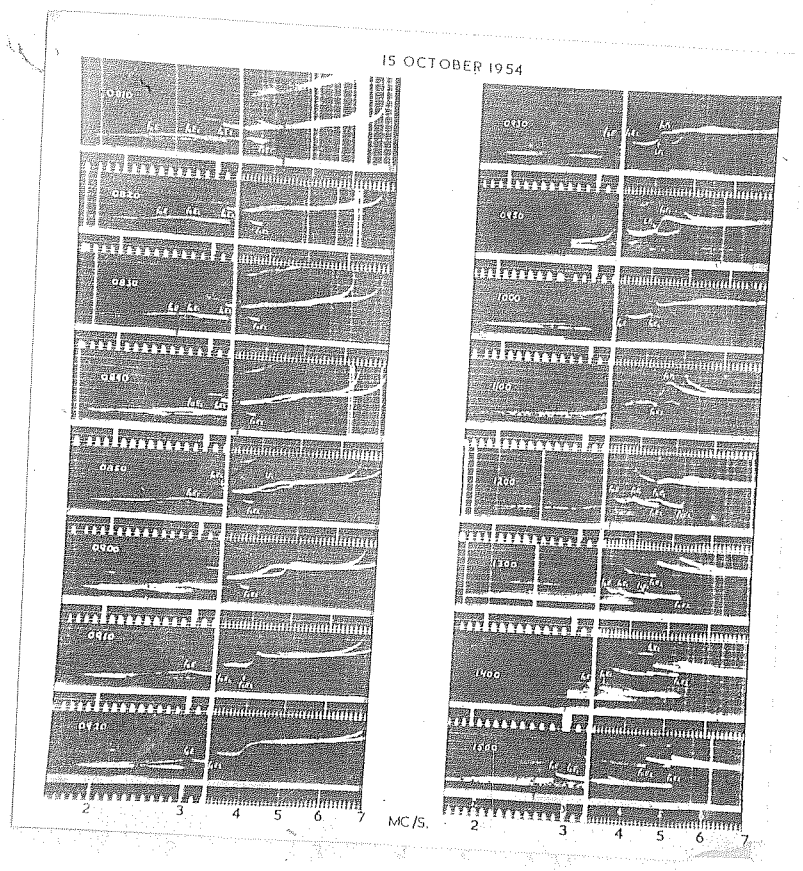


Fig. 8.

at 1000 to form E2 layer. At 1200 both E1 and E2 were quite clear. The later records show that the E2 layer descended slowly to 125 km at 1500.

Observations on August 20, 1955 (Fig. 9) : - At 0800 hr the F1 layer was quite clear, but the ordinary components of E and E2 were mixed up with sporadic E reflections. They could however, be extrapolated from the corresponding extraordinary traces. At 0900, f_0E2 was 3.2 Mc/s and F1 showed a ledge. At 1000 the F1 layer was highly distorted and at 1100, it broke up to form an E2. At 1200, the E2 descended and all the four layers E, E1, E2 and F1 were seen clearly.

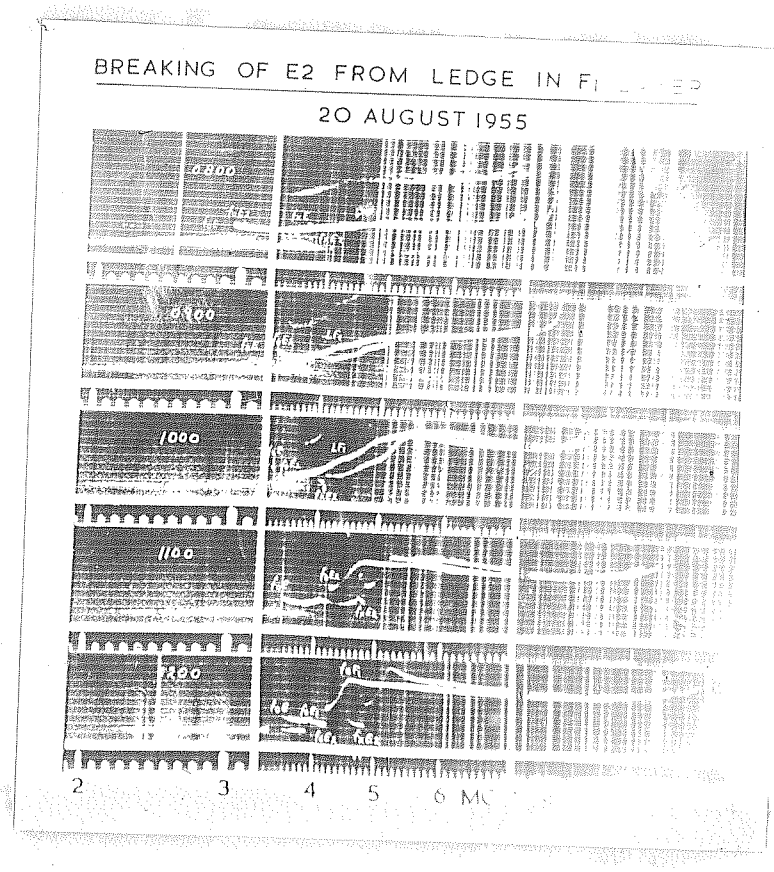


Fig. 9.

Observations on February 18, 1955 (Fig. 10) :- At 1000 hr E, E2, and F1 are clearly recorded with their ordinary component critical frequencies at 3.1, 3.4 and 4.3 Mc/s. The virtual heights of E2 and F1 were not very different. At 1100, f_0E increased to 3.25 Mc/s and E2 almost joined F1 forming a short of ledge in F1. At 1200, E2 formed a cusp at the bottom of F1 and at 1300, it detached itself from F1. This example shows that at about 10-11 hr the morning E2 sometimes joins F1 and later detaches itself from F1 to form the afternoon type of E2.



Observations on August 15, 1953 (Fig. 11) :- At 0740 all the layers E, E1, E2 and F1 were clear. At 0800, E2 joined F1 giving rise to a long extended F1 trace. At 0820, F1 showed a slight kink. At 0830, E2 and F1 began to separate and

between 0840-0950 E2 was separated from F1 though the traces were joined. Note that the virtual height of F1 was very low during the period; at 0900 h'F1 was only 180 km. This type shows itself occasionally a few hours before noon, E2 joins up with F1 due to a lowering of F1 layer, and later detaches itself from F1.

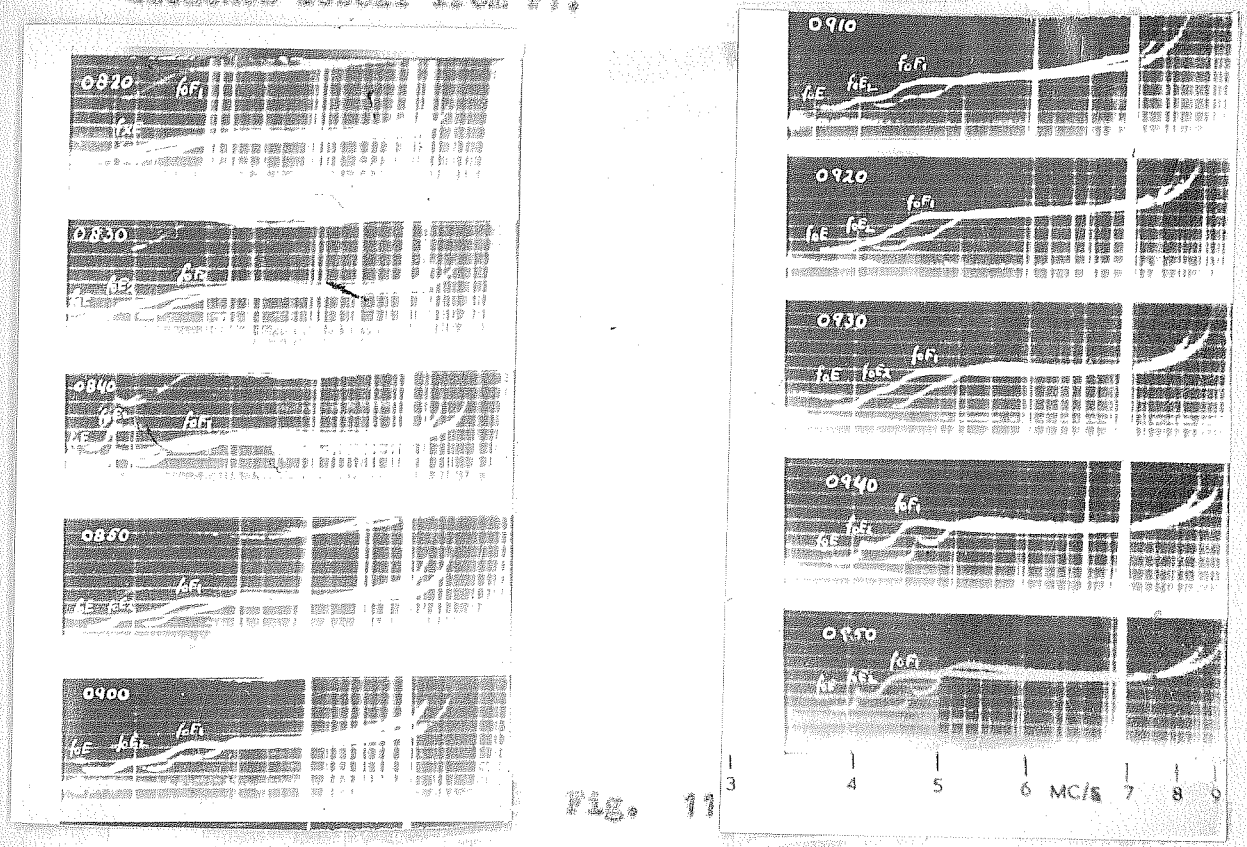


Fig. 11

Observations on December 12, 1958 (Fig. 12) :- At 0800 and 0815 hr the traces due to E, E1 and E2 were clearly recorded. At 0830, E2 had joined up with F1. At 0945 a ledge appeared in F1 and became more evident later. At 1130, it broke from F1 to form E2. From 1145, the records show the development of E1 and E2 layers. The difference between f_0E2 and f_0E1 decreased progressively and at 1415 they had merged. Later only E and E2 remained. Fig. 13 shows the variation of the critical frequencies and the virtual heights of these

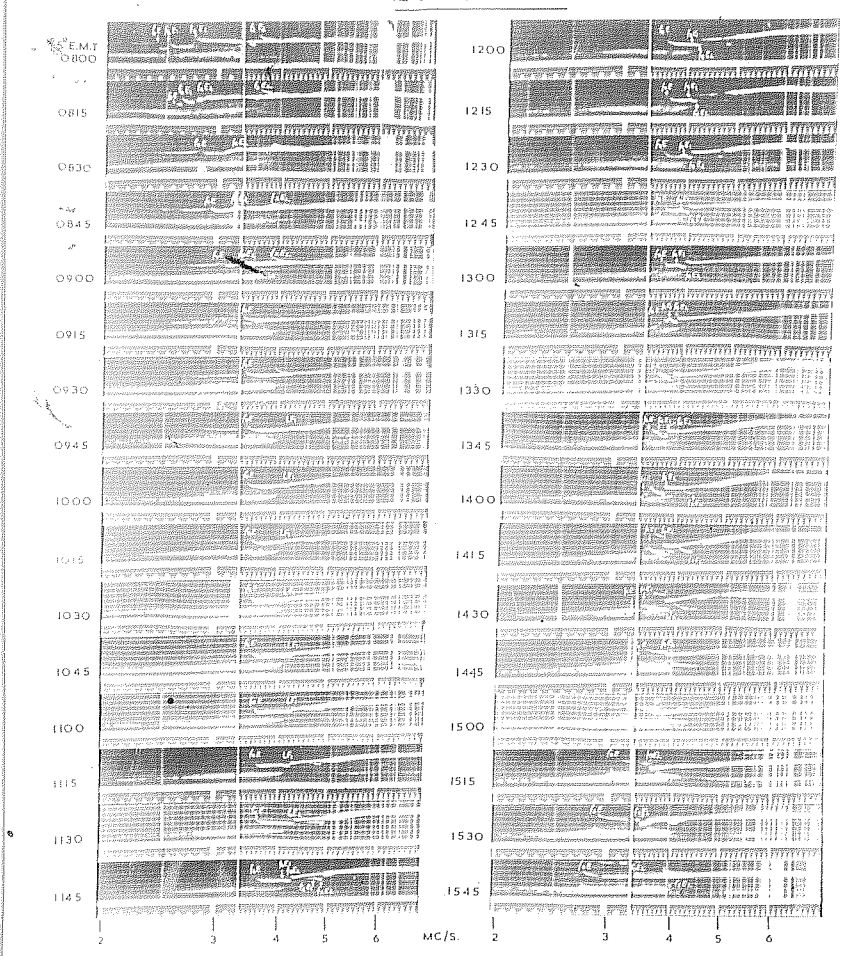


Fig. 12.

P'-f records on 12 December 1955 showing the progress of E1 and E2 layers during the course of the day.

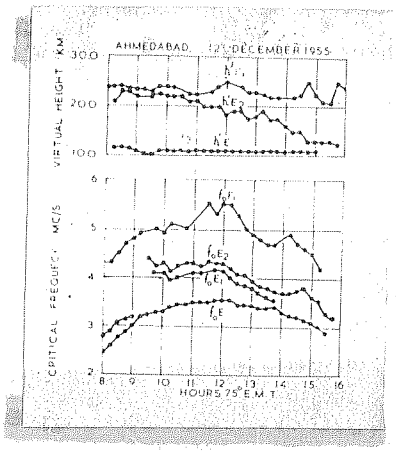


Fig. 13.

layers. At about 0910, there was very little difference between h'E2 and h'F1 and E2 was hardly distinguishable.

Fig. 14 shows the variation of the occurrence of ledge F1 at different hours of the day for each of the months

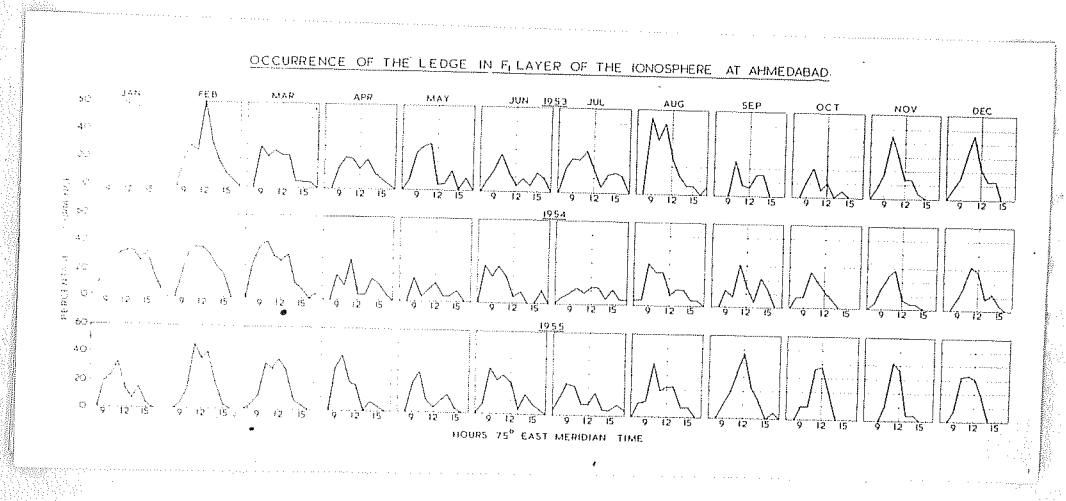
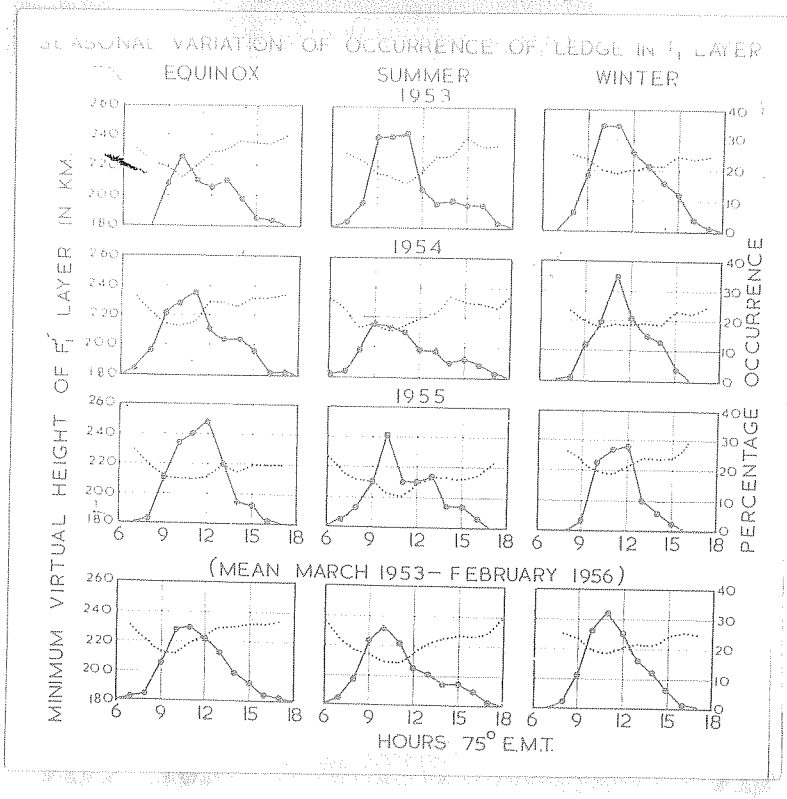


Fig. 14.

February 1953 to December 1955. One can see that the maximum frequency of ledge formation in F1 in most of the months is

at about 1000-1100. During winter, and to a less degree in equinoctial months, the occurrence of a ledge in F1 has only one maximum. During summer, the maximum is flatter and there is a tendency for a secondary maximum in the afternoon hours. Fig. 15 shows the diurnal variation of the occurrence of ledge F1 in different seasons of the years 1953 to 1955, these are compared with the corresponding variation of the minimum virtual height of the F1 layer. From the figure,



full line curve — ledge F_1 occurrence
dotted line curve — min. virtual height of F_1

Fig. 15.

one notes that ledges in F1 are more frequent when the height of F1 layer is lowest. The time of maximum occurrence of ledge F1 is at a later hour in winter than in summer.

Fig. 16 shows the annual mean diurnal variation of ledge F1 occurrence for 1953, 1954 and 1955. There does not appear any significant difference in the average frequency of occurrence at any hour or of the hour of maximum occurrence in different years. In order to see if the occurrence of ledge F1, has any seasonal variation related to E2 and F1 layers, the 0900 to 1200 hours mean values of frequency of occurrence of ledge F1, and the minimum virtual height of E2 and F1 layers are plotted in Fig. 17. The figure indicates

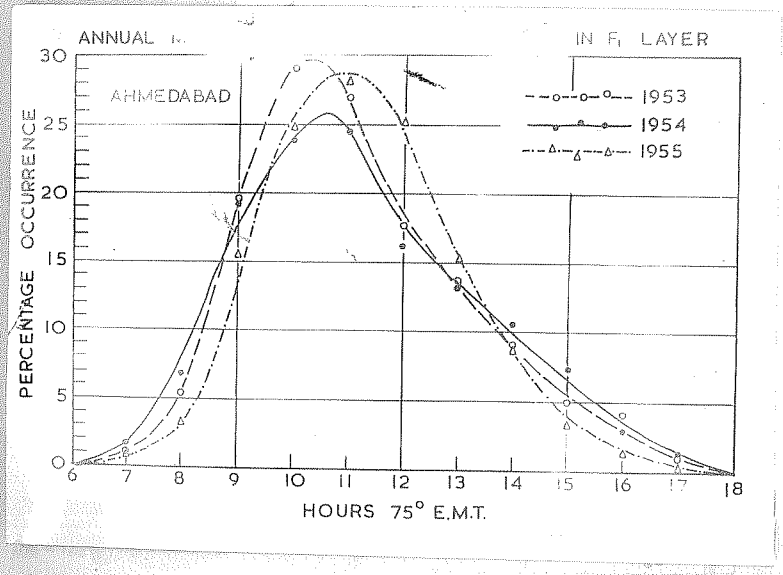


Fig. 16.

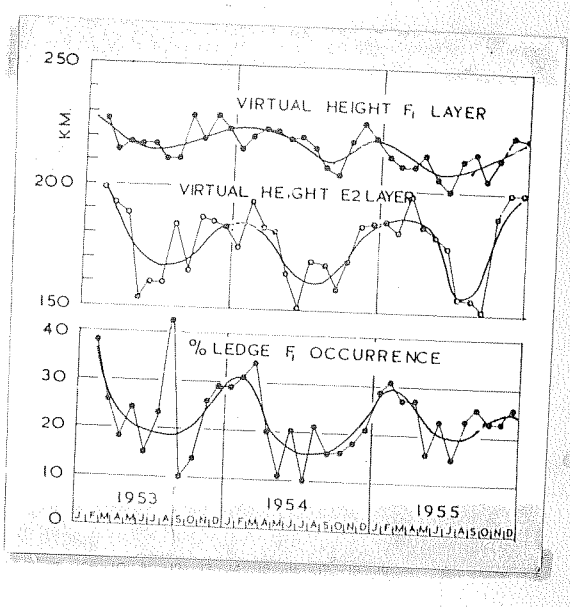


Fig. 17.

that ledge F1, on the average occurred more frequently during winter than during summer. h'E2 is minimum during summer months. h'F1 shows little variation from month to month and there is some indication that it is minimum in summer months. The occurrence of ledge F1 follows h'E2 quite well. There is more probability of ledge F1 occurring when the difference

between the heights of E2 and F1 layers is small.

III. General Characteristics of the E1 and E2 Layers of the Ionosphere.

Fig. 18 shows a mass plot of critical frequencies and virtual heights of E, E1, E2 and F1 layers during the month of March 1953. It is clear from the figure that all

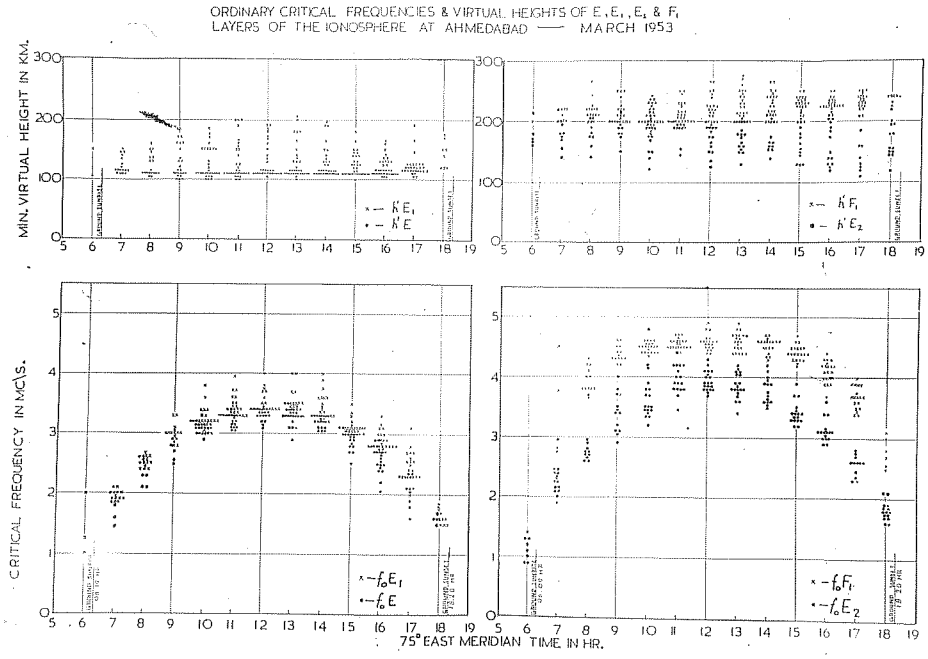


FIG 4

Fig. 18.

these layers approximately follow Chapman's relation i.e. the critical frequencies are maximum at about noon. The points indicating the minimum virtual heights of E1 and E2 show more scatter than those of E and F1 layers. It should be remembered

that the virtual heights of E1 and E2 are very much affected by the proximity of their critical frequencies of those of E and F1. It was considered desirable to calculate the true heights of these layers, and calculations were therefore made of the true heights, of ionisation maximum and of the semi-thicknesses of the layers in a few individual cases when the records were clear. The method of calculation is briefly described below.

(1) Determination of the true height of an ionospheric layer :- The quantity usually measured by vertical incidence ionospheric sounding is the equivalent path P'. Appleton[8] has shown that P' for the ordinary ray propagated inside the layer with parabolic distribution of ionisation and of semi-thickness y_m, for a wave of radio frequency f is given by

$$P' = y_m \frac{f}{f_c} \log_e \frac{f_c + f}{f_c - f}$$

where f_c is the critical frequency of the layer. Appleton and Beynon[9] have shown that the equivalent height of reflection h' is given by

$$h' = h_o + \frac{y_m f}{2 f_c} \log_e \frac{f_c + f}{f_c - f}$$

where h_o is the height of the base of the layer.

They pointed out that the relation between h' and

$$\frac{1}{2}\,\frac{f}{f_c}\,\log_e\frac{f_o + f}{f_c - f}$$

is linear and the slope of the straight line obtained by plotting these two quantities gives y_m.

Booker and Seaton[10] gave the same relation in a more convenient form. They showed that the virtual height h' of reflection of a pulse of a frequency f f_c from a layer of semi-thickness T and height of maximum electron density h_m is given by

$$h' = h_m + T.\ \phi(f/f_c)$$

the function $\phi(f/f_c)$ is given by

$$\phi(f/f_c) = \frac{1}{2}\,\frac{f}{f_c}\,\log_e\frac{f_o + f}{f_c - f} - 1$$

If another layer lies just above the height of maximum ionisation of the lower layer then the group retardation of a wave f f_c penetrating the layer is given by

$$h' = T.\ \phi(f/f_c)$$

Ratcliffe[11] has given a rapid method to determine h_m and T of a layer by comparing the observed P'-f curve with the standard curves drawn with various values of parameters according to the above equations. He has further shown that if the upper layer overlaps a lower one below the level of maximum ionisation then the group retardation by the

lower layer is given by the formula

$$h' = T.(f/f_c).\log_e \frac{1 + f/f_c}{1 - (f_B/f_c)^2 + (f/f_c)^2 - (f_B/f_c)^2}$$

where f_c is the critical frequency of the lower layer and f_B is the frequency at which the reflections start from the upper layer.

To determine h_m and T of E1 and E2 layers, the P'-f curves were translated on a semi-logarithmic graph paper (f in log scale and P' in linear scale). The redrawn P'-f curves were compared with standard P'-f curves drawn on a transparent film sheet. The use of a logarithmic scale for frequency enables the same standard curves to be used for any critical frequency. The traces of E1 and E2 were corrected for group retardation due to the lower layer before comparing them with standard curves. The values of h_m and T were later checked by determining them by Booker and Seaton's method.

Fig. 19(a) shows the P'-f curves at 1100 hour on February 5, 1953. Fig. 19(b) shows the corrected P'-f traces

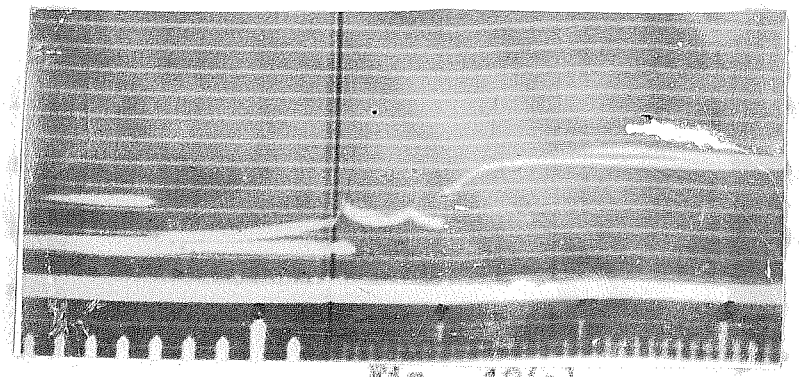


Fig. 19(a)

Fig. 19(b)

and the distribution of electron density in these layers. It is to be noted that whereas h'E2 was 160 km, h_mF2 was only 138 km. Similarly h'E1 was about 165 km but h_mE1 was only 132 km. It further shows that h'E1 may at times be greater than h'E2 whereas the true heights of these layers are otherwise.

In Table 1 are given the values of minimum virtual heights, true heights and the semi-thicknesses of E, E1 and E2 layers on a few individual days. One can see that there is not much difference between h'E and h_mE because E is the lowest layer. The maximum discrepancy occurs in E1 because f_oE1 is very close to f_oE and E1 is

Table 1.

Virtual and true heights of E, E1 and E2 layers on some individual days.

Date 1953	Time 75° E.M.T.	E Layer h' km	E Layer h_m km	E Layer T km	E1 Layer h' km	E1 Layer h_m km	E1 Layer T km	E2 Layer h' km	E2 Layer h_m km	E2 Layer T km
Feb. 12	0800	100	112	5	128	125	18	155	145	<5
	0900	110	112	20	165	150	10	150	150	<5
13	0800	115	113	10	130	118	22	150	130	8
Mar. 2	1600	110	114	10	132	120	18	150	140	<5
5	1700	120	114	18	165	138	22	160	140	<5
12	1100	110	106	25	160	120	10	145	135	<5
16	1300	115	110	5	130	115	10	130	120	<5
22	0900	105	110	8	170	160	18	200	180	<5
31	0800	110	114	10	160	134	20	180	155	<5
	1600	110	115	10	135	130	10	200	165	<5
Apr. 1	0800	120	118	20	152	122	10	170	155	<5
16	0700	112	110	12	130	126	22	160	150	<5

comparatively thick. On the average, the normal E layer occurs at the height of about 115 km and has a thickness of 18 km. E1 occurs at the height of 120-130 km and is of about the same thickness as E. E2 occurs at a height of 140-145 km and is generally a sharp thin layer with a semi-thickness of less than 5 km.

Fig. 20 shows two clear examples of F'-f records where E2 is apparently lower than E1.

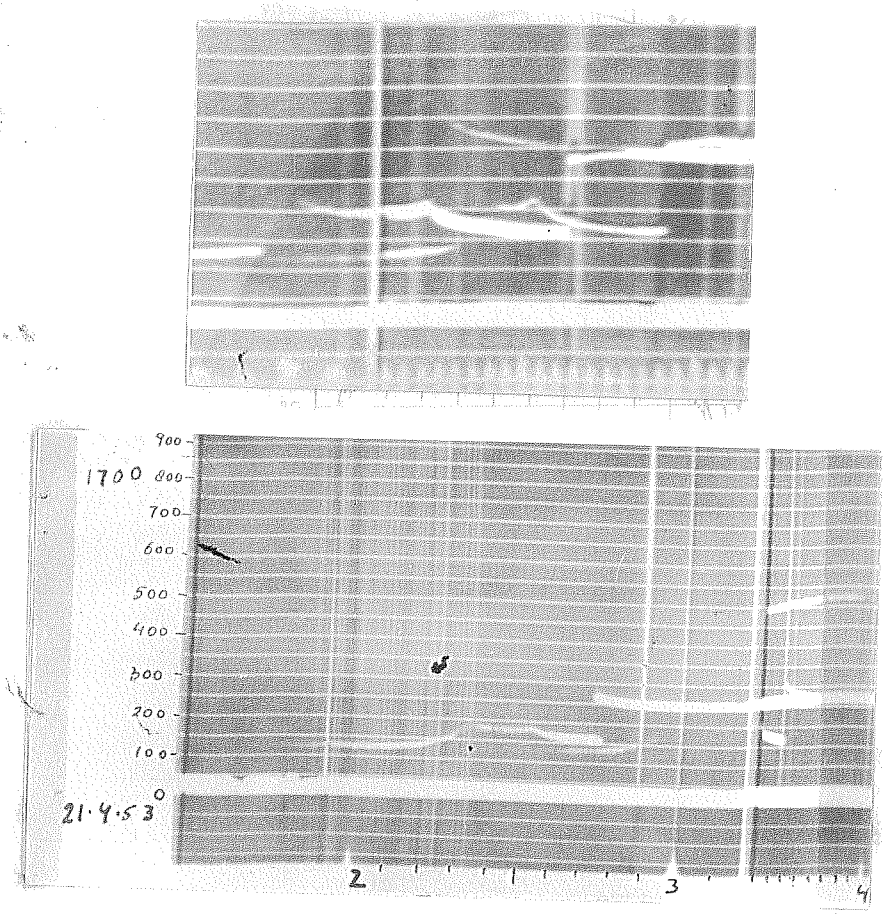


Fig. 20.

(2) Occurrence of E1 and E2 layers.:- In Fig. 21 are plotted the total number of occurrences of E1 and E2 layers at each hour during the years 1953, 1954 and 1955. The total number of days on which observations were available at the corresponding hours in the whole year are also shown for comparison. During 1954 and 1955, E2 was observed at noon on about 230 days and E1 on 150 days, while the total number of days on which records were available were about 300. In 1953, E2 was observed on only 190 days

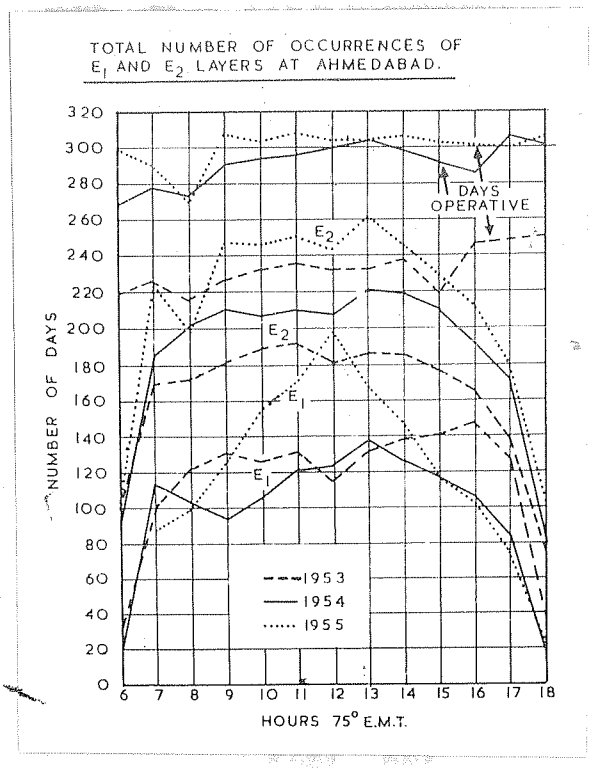


Fig. 21.

and E1 on 120 days, the number of days operating in that year were also fewer due to equipment failure. One must remember that critical frequencies of E1 and E2 were not observable on many occasions because the traces were either blanketed by Es or were merged with Es. The observations had to be excluded when E1 and E2 were not seen due to blanketing, or interference or too much absorption. The times when E1 or E2 was not distinguishable were thus determined and the percentage occurrence of these layers at each hour during the whole month calculated. In Fig. 22 are plotted annual mean percentage frequency occurrence of E1 and E2 layers at each hour of the day. On the average E2 was observed on 95% and E1 on 65% of times.

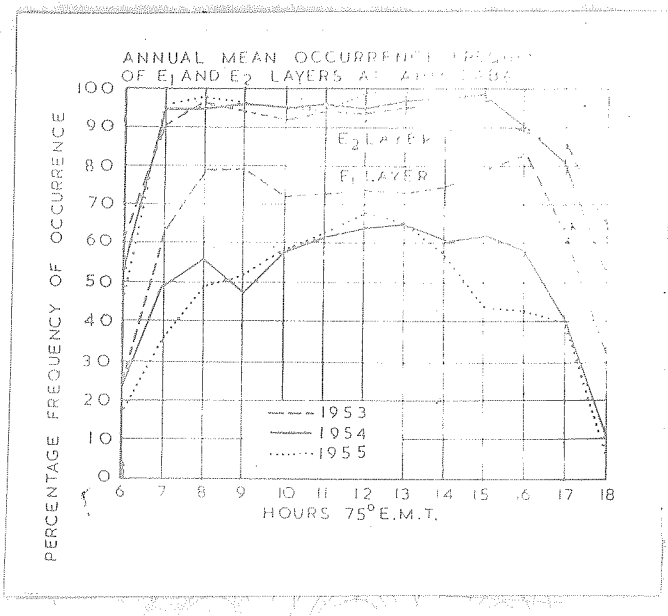


Fig. 22.

(3) Critical frequencies and heights of E1 and E2 layers :- The critical frequencies of E1 and E2 layers show the same diurnal variation as the normal E and F1 layers. The frequencies increase after sunrise with a maximum at about noon and again decrease with the lowering of the sun. Fig. 23 shows the diurnal variation of the critical frequencies of E, E1, E2 and F1 in different seasons of the years 1953 to 1955. Fig. 24 shows the annual mean diurnal variation of f_0E, f_0E1 and f_0E2. One can see that critical frequencies of these layers were lower in 1954 than in 1953 and had increased in 1955. We know that the sunspot activity was also minimum in 1954 and was greater in 1955 than in 1953. The ionisation of these layers thus appears to vary with the solar activity.

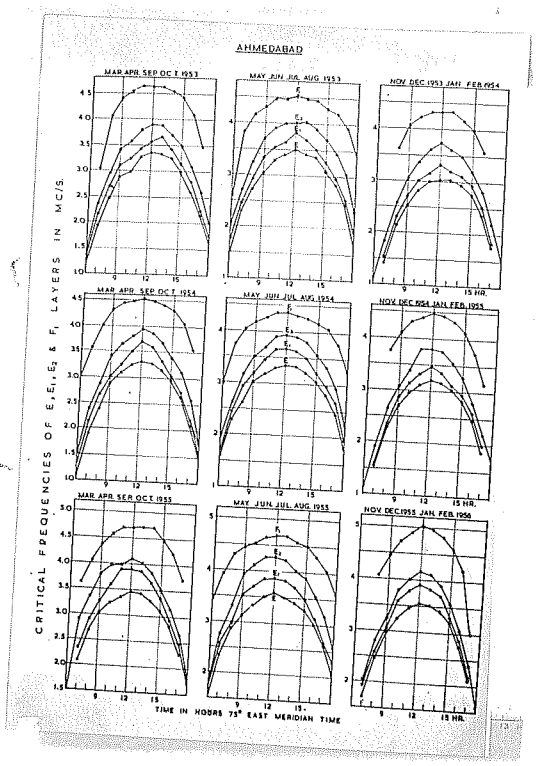

AHMEDABAD
MAR APR SEP OCT 1953
MAY JUN JUL AUG 1953
NOV DEC 1953 JAN FEB 1954
MAR APR SEP OCT 1954
MAY JUN JUL AUG 1954
NOV DEC 1954 JAN FEB 1955
MAR APR SEP OCT 1955
MAY JUN JUL AUG 1955
NOV DEC 1955 JAN FEB 1956
CRITICAL FREQUENCIES OF E, E1, E2 & F1 LAYERS IN MC/S.
TIME IN HOURS 75° EAST MERIDIAN TIME
15 HR.

Fig. 23.

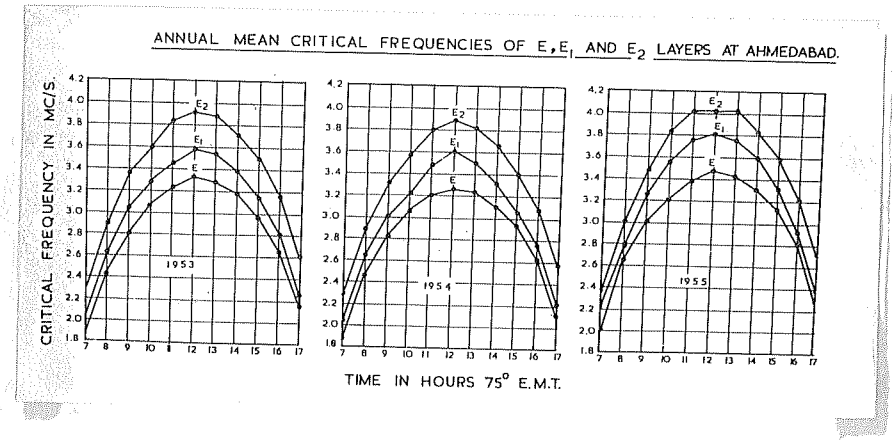

ANNUAL MEAN CRITICAL FREQUENCIES OF E, E1 AND E2 LAYERS AT AHMEDABAD.
CRITICAL FREQUENCY IN MC/S.
1953
1954
1955
TIME IN HOURS 75° E.M.T.

Fig. 24

In Fig. 25 are shown the diurnal variations of h'E1 and h'E2 for the different seasons of the years 1953 to 1955. In Fig. 26 the annual means for each year are plotted. Virtual heights increase soon after sunrise, reach a maximum well before noon and later decrease progressively till sunset. One can see from the diagrams that in general h'E2 is greater than h'E1 in the forenoon hours but in the afternoon hours it is lower than h'E1. As explained

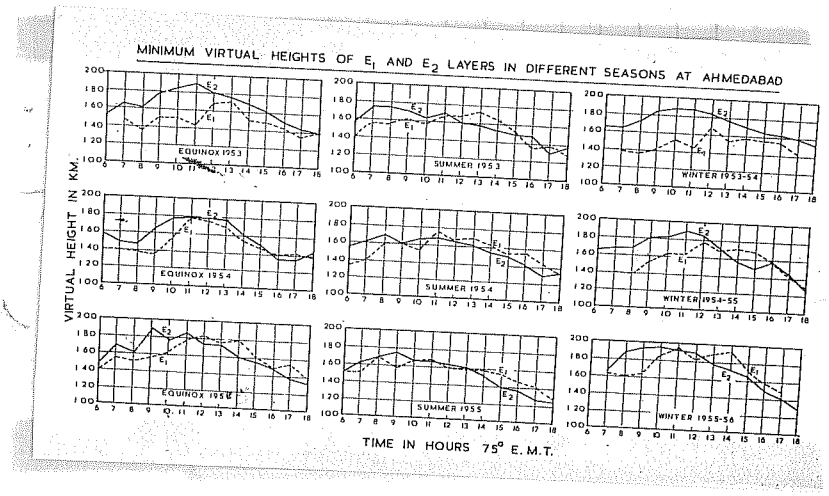
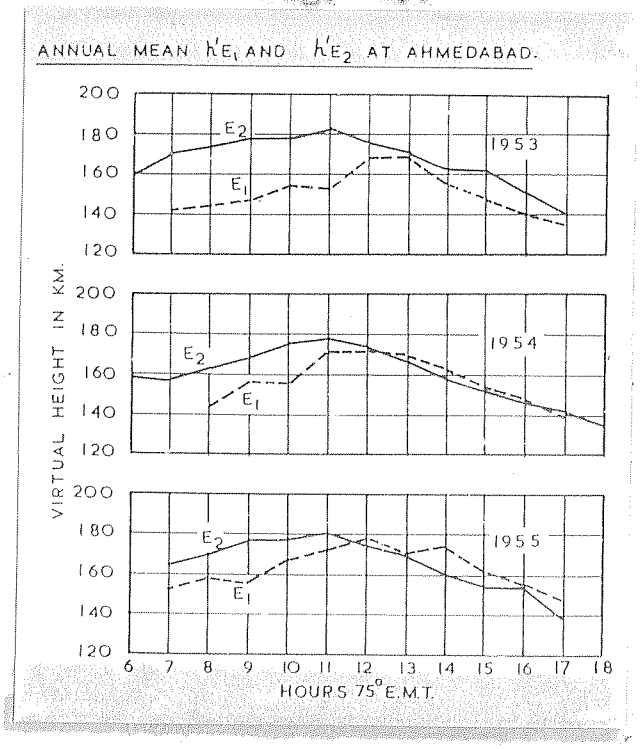


Fig. 25.



earlier this is due to extreme thinness of the E2 layer in the afternoon hours. In Fig. 27 are shown the annual mean diurnal variation of f_0F1 and h'F1. It can be seen from

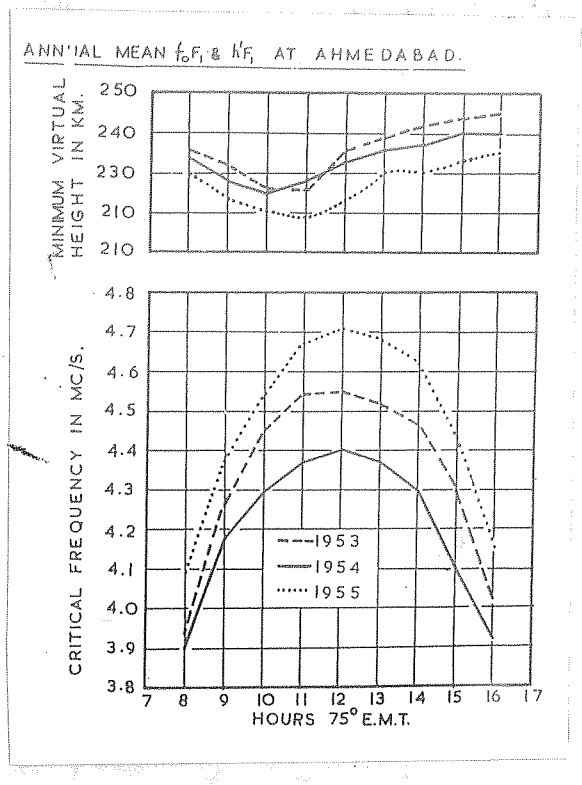


Fig. 27.

the figure that h'F1 is not symmetrical about noon but is a minimum at 10-11 hr and is higher in the afternoon than in the forenoon hours for the same solar altitude. In order to study the seasonal variation of these layers, monthly mean noon critical frequencies of the layers are plotted in Fig. 28. One can see that the critical frequencies of E, E1 and E2 show maxima in summer and minima in winter whereas f_0F1 shows two maxima one in each equinox and two minima one in each solstice. f_0E1 and f_0E2 thus follow solar zenith

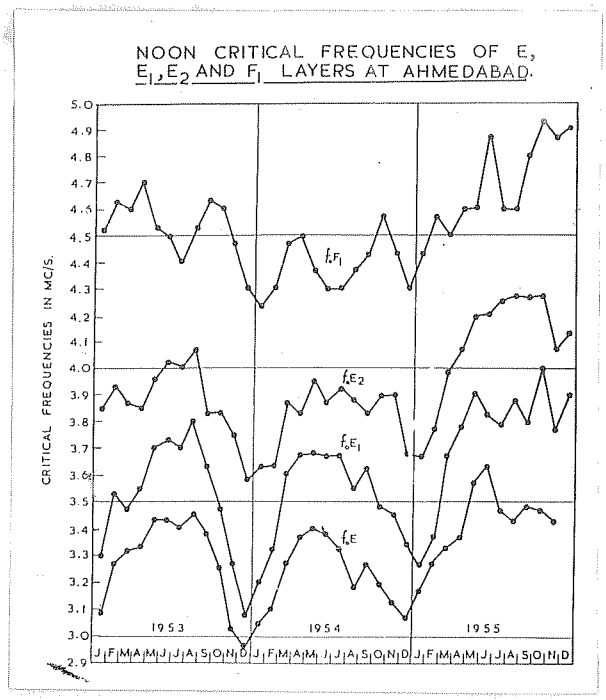


Fig. 28.

distance just as f_0E but f_0F1 is influenced by other perturbations. In Fig. 29 are plotted the monthly mean noon h'E, h'E1, h'E2 and h'F1. h'F1 does not show any

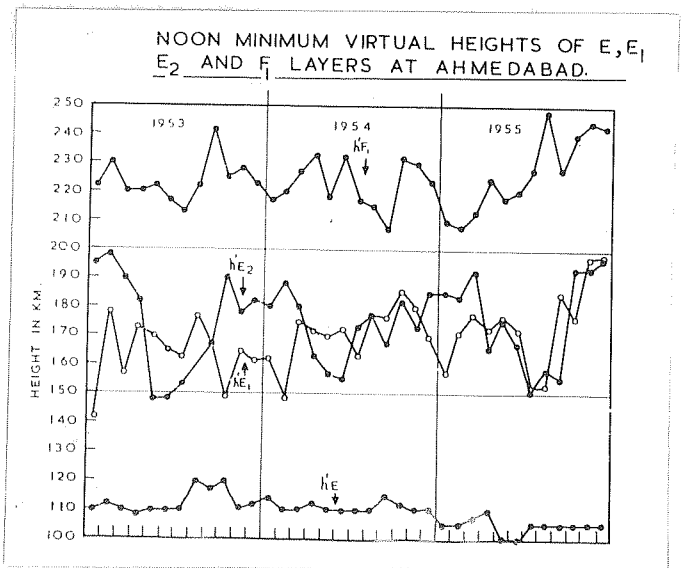


Fig. 29.

seasonal variation except that its height had gone up in 1955. It is of interest to note here that h'F1 at 1000 hr (Fig. 17) shows a seasonal variation with a maximum in winter and a minimum in summer. Seasonal variation of h'E2 is clear in both Figs. 17 and 29. h'E2 shows maxima in winter and minima in summer and this is consistent with Chapman's theory, that at greater altitudes of the sun, the ionisation is produced at lower levels. h'E1 does not indicate any regular variation, probably because it is very different from the actual height.

In Fig. 30 the monthly mean critical frequencies of E and E2 layers at Slough for the years 1940 to 1946 have been plotted. Both E and E2 layers follow the solar zenith angle, the critical frequencies showing minima during winter (December) and maxima during summer.

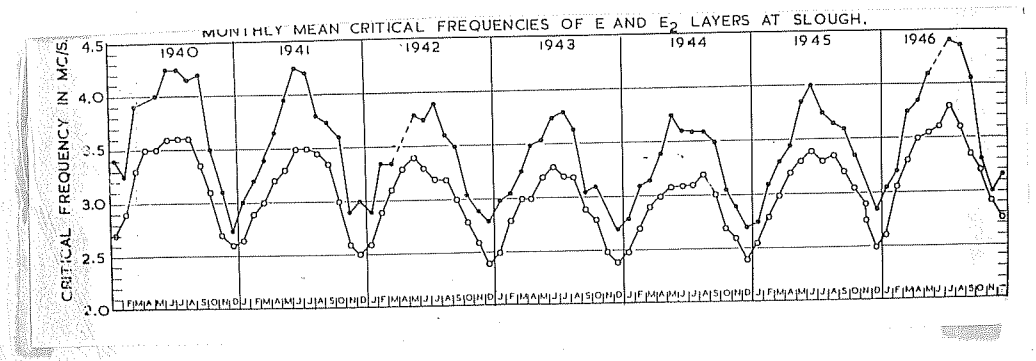


Fig. 30.

(4) Critical frequencies and sunspot activity :-

Figs. 24 and 28 indicate that the critical frequencies of

E and E2 layers were lowest during years of least solar activity and progressively increased with increasing sunspot number. To show the sunspot variation of the critical frequencies in a better way, the twelve months running average of noon critical frequencies were plotted against the twelve months' running average Zurich sunspot number. Such a diagram for E, F1, E2 and F1 layers at Ahmedabad is shown in Fig. 31 and for E, E2 and F1 layers at Slough in Fig. 32. The points lie almost

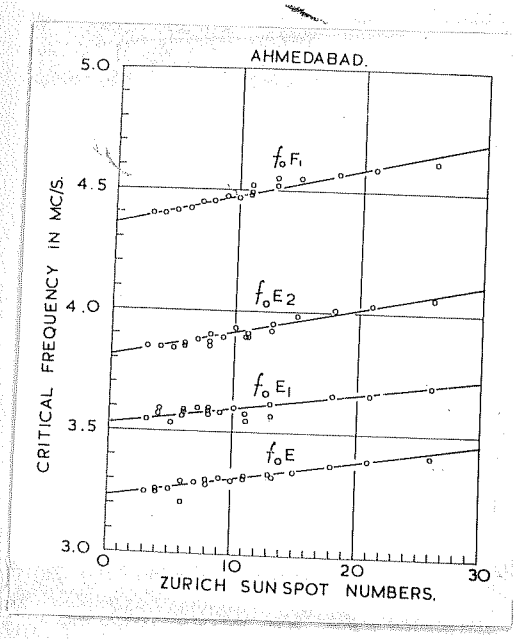


Fig. 31.

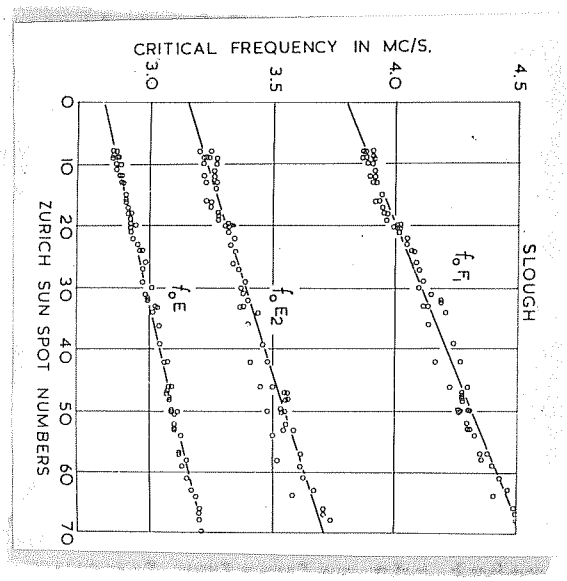


Fig. 32.

in a straight line indicating a linear relationship between f_0 and k_2

$$\overline{f_0} = a\,(1 + b\overline{k_2}).$$

The values of coefficients a and b for the different layers are given in Table 2.

Table 2.

Layer	Ahmedabad a Mc/s	Ahmedabad b x 10^3	Slough a Mc/s	Slough b x 10^3
E	3.23	3.30	2.80	1.58
E1	3.53	1.79	-	-
E2	3.81	3.62	3.15	2.58
F1	4.35	2.68	2.80	1.99

(5) Solar control of E1 and E2 layers :- Fig. 28 shows that the critical frequencies of E, E1, E2 and F1 layers are maximum at noon as expected of layers produced by photon radiations from the sun and following Chapman's relation

$$f_0 = k \cos^n \chi$$

If the process of decay of the ionisation is recombination of electrons with positive ions, the index n would be equal to 1/4. In the other extreme case of attachment of electrons with neutral molecules the index would be equal to 1/2. In general the index differed from either of these theoretical values. The equation can be written as

$$\log f_0 = \log k + n \log \cos \chi$$

The equation shows that $\log f_0$ is linearly related to $\log \cos \chi$ the slope of the straight line giving the value

of index n. The critical frequencies can be plotted against corresponding $\cos\chi$ values on a double logarithmic paper. The points are joined by a straight line. The intercept of the line on $\cos\chi = 1$ line gives k and the slope gives n. The monthly mean values of the critical frequencies were so treated and the curves for E, E2 and F1 in each of the months are shown in Fig. 33. The points fall in a straight line indicating that the critical frequencies obeyed the $\cos^n\chi$ law. Further the slope of the

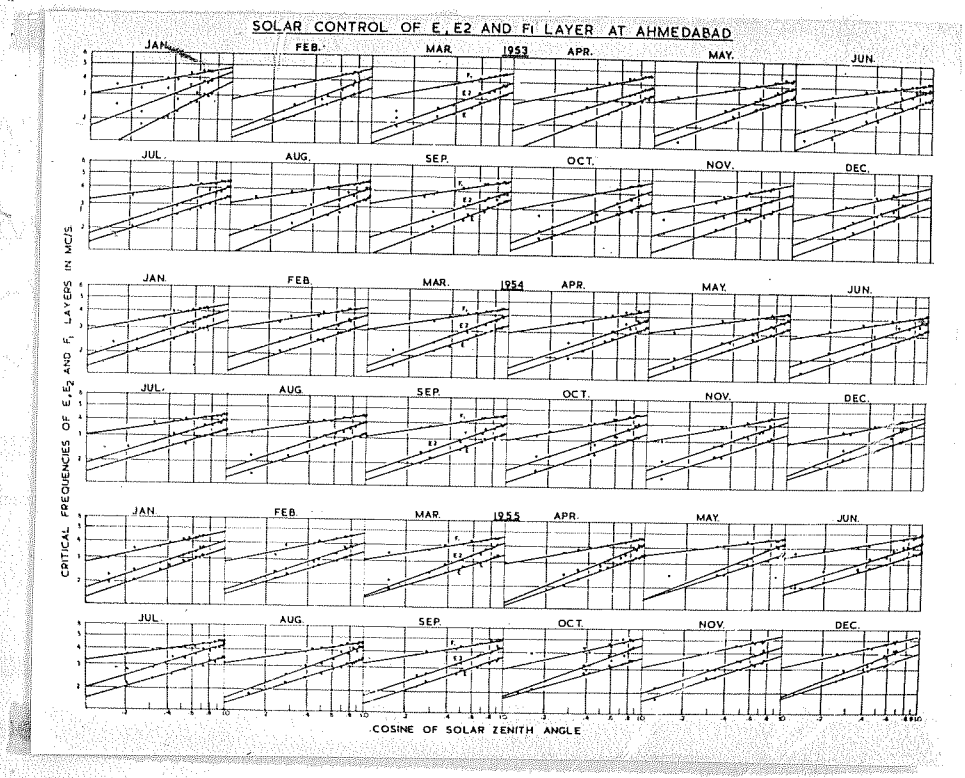


Fig. 33

straight line is much smaller for F1 than for E layer in any month. The straight line for E2 layer has almost the same slope as that for E layer. The values of the sub-solar frequency (k) and the sensitivity (n) for these layers in each month are given in Table 3. The sub-solar frequencies are plotted in Fig. 34 and the sensitivities in Fig. 35.

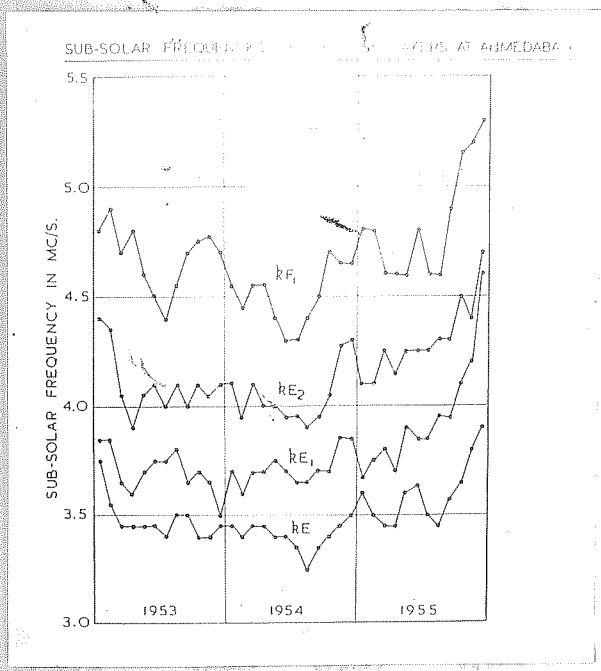


Fig. 34.

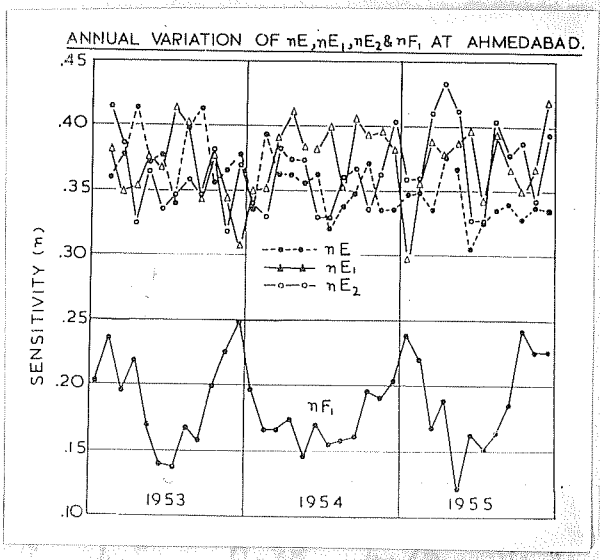


Fig. 35.

These figures show a seasonal variation in nF1 and kF1, these being minimum in summer and maximum in winter. The sensitivity of F1 varied from 0.15 in summer to about 0.24 in winter. Any seasonal variation of sub-solar frequency or sensitivity of E, E1 and E2 layers cannot be clearly detected. The sub-solar frequencies are, however, lowest in the period of least solar activity. The sensitivities of E, E1 and E2 layers do not show any difference from each

Table 3

Subsolar frequency (k) and sensitivity (n) of E, E1, E2 and F1 layers at Ahmedabad.

Year and month	kE Mc/s	nE	kE1 Mc/s	nE1	kE2 Mc/s	nE2	kF1 Mc/s	nF1
1953								
Jan.	3.75	-	3.85	0.33	4.4	0.29	4.8	0.20
Feb.	3.55	0.36	3.85	0.38	4.35	0.42	4.9	0.24
Mar.	3.45	0.38	3.65	0.35	4.05	0.39	4.7	0.20
Apr.	3.45	0.41	3.6	0.35	3.9	0.32	4.8	0.22
May	3.45	0.37	3.7	0.38	4.05	0.36	4.6	0.17
Jun.	3.45	0.38	3.75	0.37	4.1	0.34	4.5	0.14
Jul.	3.40	0.34	3.75	0.41	4.0	0.35	4.4	0.14
Aug.	3.50	0.40	3.8	0.40	4.1	0.36	4.55	0.17
Sept.	3.50	0.41	3.65	0.34	4.0	0.35	4.7	0.16
Oct.	3.40	0.36	3.7	0.38	4.1	0.38	4.75	0.20
Nov.	3.40	0.37	3.65	0.34	4.05	0.32	4.77	0.22
Dec.	3.45	0.38	3.5	0.31	4.1	0.37	4.7	0.25
1954								
Jan.	3.45	0.34	3.7	0.35	4.1	0.34	4.55	0.20
Feb.	3.40	0.39	3.6	0.35	3.95	0.33	4.45	0.16
Mar.	3.45	0.36	3.7	0.39	4.1	0.38	4.55	0.16
Apr.	3.45	0.36	3.7	0.41	4.0	0.37	4.55	0.17
May	3.40	0.36	3.75	0.38	4.0	0.37	4.4	0.15
Jun.	3.40	0.36	3.7	0.38	3.95	0.33	4.3	0.17

Cont...

Table 3 cont.....

Year and month	kE Mc/s	nE	kE1 Mc/s	nE1	kE2 Mc/s	nE2	kF1 Mc/s	nF1
1954								
Jul.	3.35	0.32	3.65	0.40	3.95	0.33	4.3	0.16
Aug.	3.25	0.34	3.65	0.35	3.90	0.36	4.4	0.16
Sept.	3.35	0.35	3.7	0.41	3.95	0.37	4.5	0.16
Oct.	3.40	0.37	3.7	0.39	4.05	0.34	4.7	0.20
Nov.	3.45	0.34	3.85	0.40	4.27	0.36	4.65	0.19
Dec.	3.50	0.34	3.85	0.38	4.3	0.40	4.65	0.20
1955								
Jan.	3.60	0.35	3.67	0.30	4.1	0.36	4.8	0.24
Feb.	3.50	0.35	3.75	0.36	4.1	0.36	4.8	0.22
Mar.	3.45	0.34	3.8	0.39	4.25	0.41	4.6	0.17
Apr.	3.45	0.38	3.7	0.38	4.15	0.43	4.6	0.19
May	3.60	0.37	3.9	0.39	4.25	0.41	4.6	0.12
Jun.	3.63	0.31	3.85	0.40	4.25	0.32	4.8	0.16
Jul.	3.50	0.32	3.85	0.34	4.25	0.33	4.6	0.15
Aug.	3.45	0.34	3.95	0.39	4.3	0.40	4.6	0.16
Sept.	3.57	0.34	3.95	0.37	4.3	0.38	4.9	0.19
Oct.	3.65	0.33	4.1	0.35	4.5	0.39	5.15	0.24
Nov.	3.80	0.34	4.2	0.37	4.4	0.34	5.2	0.23
Dec.	3.90	0.34	4.6	0.42	4.7	0.39	5.3	0.23

other. The values lie mostly between 0.33 and 0.40. Twelve-month running average values of nE, nE1 and nE2 are plotted in Fig. 36. nE1 remained almost constant throughout

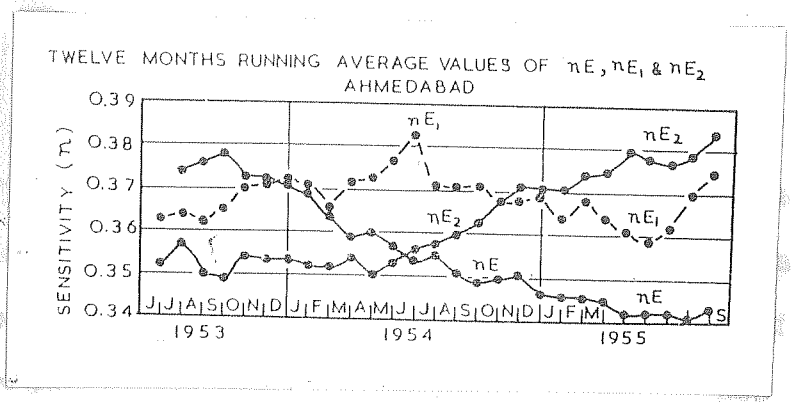


Fig. 36

the period having an average value of 0.37. nE continually decrease from a value of 0.375 in 1953 to 0.34 in 1955, whereas nE2 increased continually from 0.35 in 1953 to 0.38 in 1955. For comparison, the sub-solar frequencies and sensitivities of E, E2 and F1 layers at Slough are plotted in Figs. 37 and 38 for the years 1944 to 1946. nE2 had

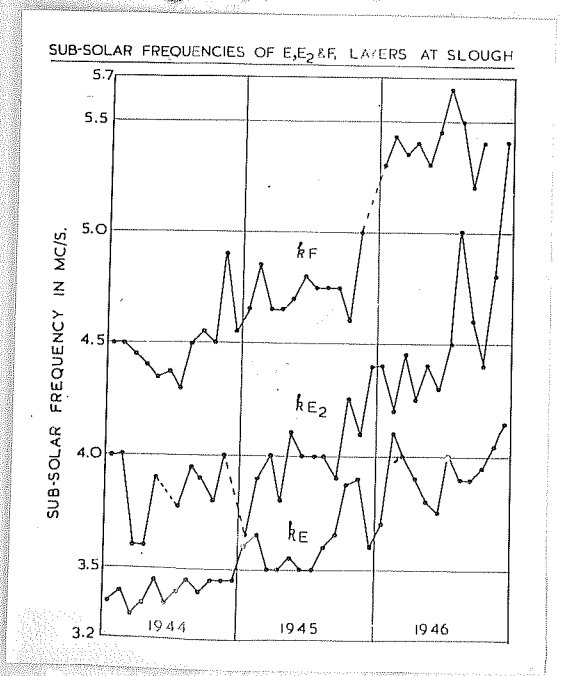


Fig. 37.

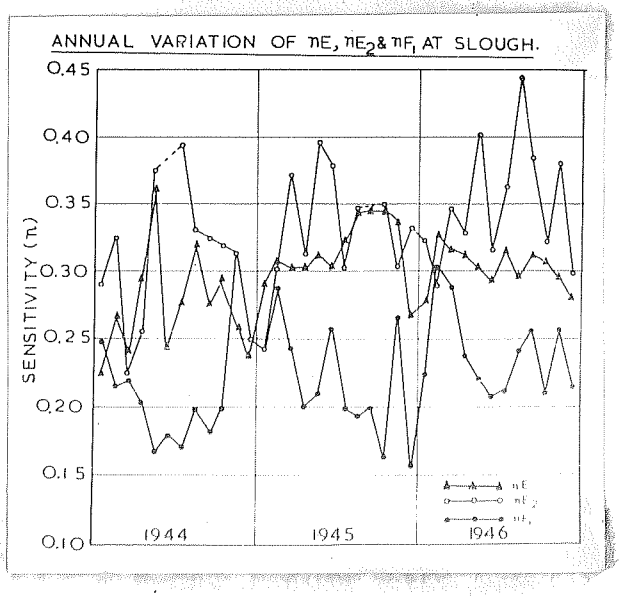


Fig. 38.

values very near those of nE but values of nF1 were lower than those of either nE or nE2. Values of nE2 were on the average slightly greater than those of nE.

IV. Intense E2 Layer

The study of the diurnal variation of the critical frequencies of E, E1 and E2 layers showed that at times, the curve of critical frequency departed from a smooth curve. Those departures from smoothness were more often in E2. On some occasions when the critical frequencies of E2 exceeded the normal day values they blanketed F1 reflections partially or completely and in some extreme cases F2 reflections also were obscured. The phenomenon may be temporary or may continue for hours. There have been some references of intense E, but knowing the evolution of this layer from E2 and its degeneration into E2, we have called it intense E2. E and E1 are, however, unaffected during the periods of intense E2 occurrences.

Fig. 39 shows an example of intense E2 occurrence on August 8, 1953. At 1300 hr all the different layers E, E1, E2 and F1 were clearly recorded. At 1400 and 1500 f_0E2 increased to 4.7 Mc/s, completely blanketing F1 reflections. Note that both ordinary and extraordinary components of the intense E2 are clearly seen, and F2 reflections start only after these critical frequencies. This indicates that intense E2 is a thin homogeneous layer and is not patchy like the

sporadic E layer.

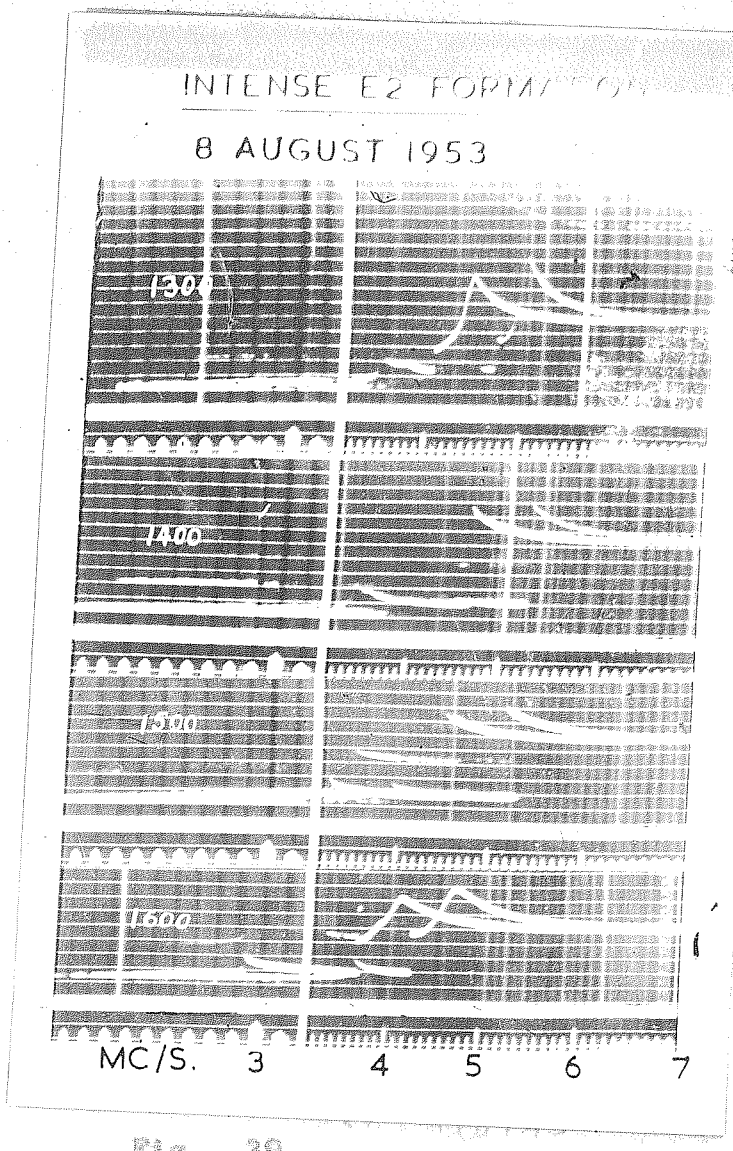


Fig. 39.

Fig. 40 shows another example of intense E2

Fig. 40.

occurrence on April 8, 1954. At 1415, 1430 and 1445 hr E2 partially blanketed F1 reflections. At 1500 all the layers were clearly seen. At 1515 E2 critical frequencies exceeded 8 Mc/s, blanketing F1 and most of F2 reflections. The variationsof E2 critical frequencies were erratic during the period. It may be noted that at all times there existed two magneto-ionic components of the intense E2 layer and corresponding two different minimum frequencies of reflection from higher layers.

Fig. 41 shows a few P'-f records of intense E2. Note that the critical frequencies of E and E1 did not show any abnormal behaviour and only E2 critical frequencies were at times abnormally high, blanketing F1 or even F2 reflections.

30 July 1954

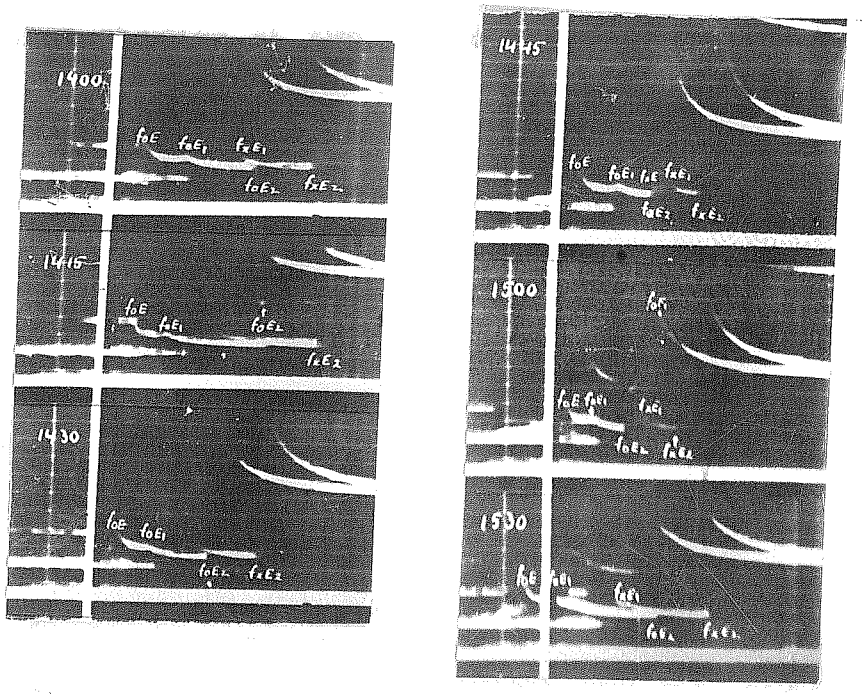


Fig. 41.

Fig. 42 shows another example of intense E2. Note that this layer is different from normal or sporadic E.

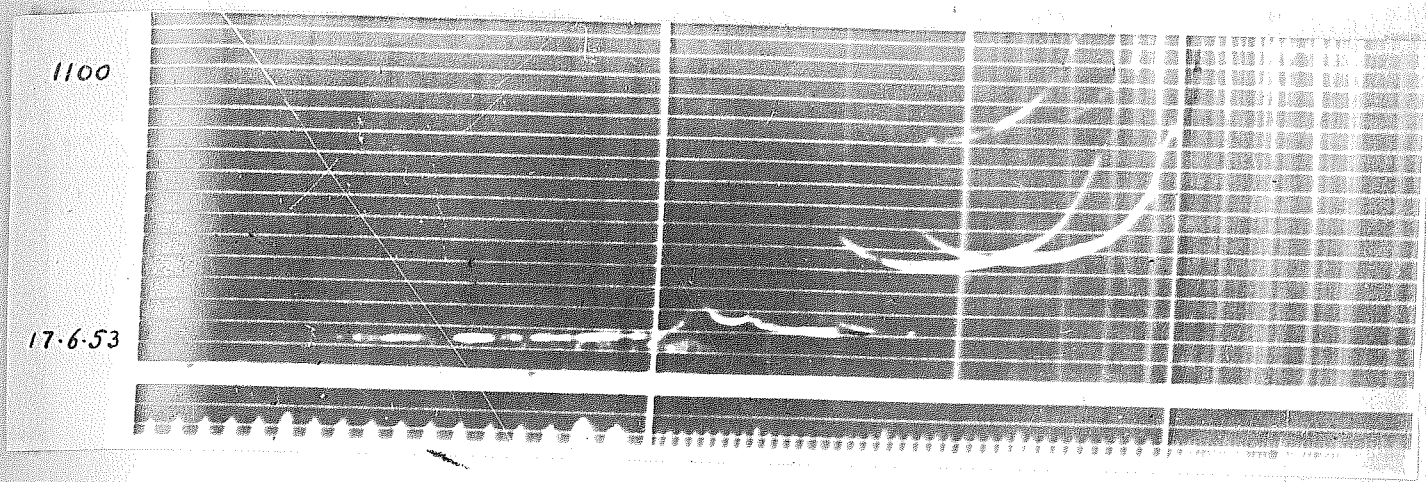
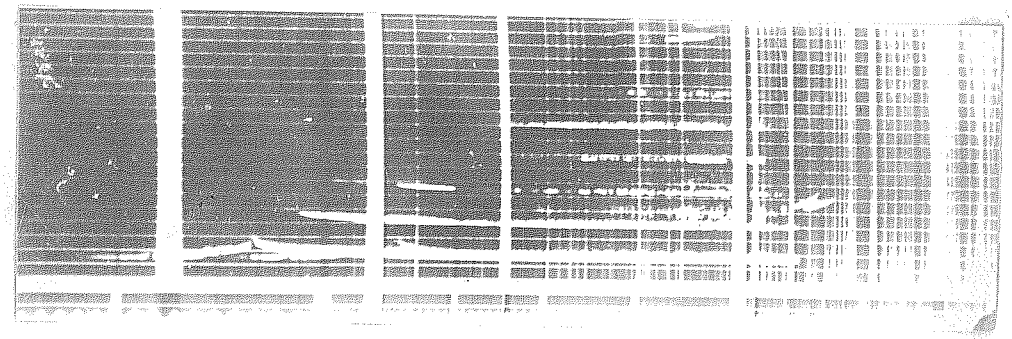


Fig. 42.

Fig. 43 shows intense E2 at 1630 hr on May 25, 1954. Intense E2 critical frequency exceeded 8 Mc/s. It is interesting to note that ordinary and extraordinary E2 reflections started at two frequencies corresponding to the o and x component critical frequencies of intense E2. These critical frequencies are however not seen in the E2 trace itself.



1630 25 May 1954
Fig. 43.

Fig. 44 shows the total number of intense E2's observed at different hours in the equinox, summer and winter seasons of the years 1953, 1954, 1955 and 1953-1955 (combined). Intense E2 occurred mostly in the afternoon hours. In equinoxes and winter these occurred most at about 1500, whereas in summer the peak time of occurrence was between 12-15 hr. Intense E2's are most frequent in the summer months. The seasonal variation of intense E2 is clearly seen in Fig. 45.

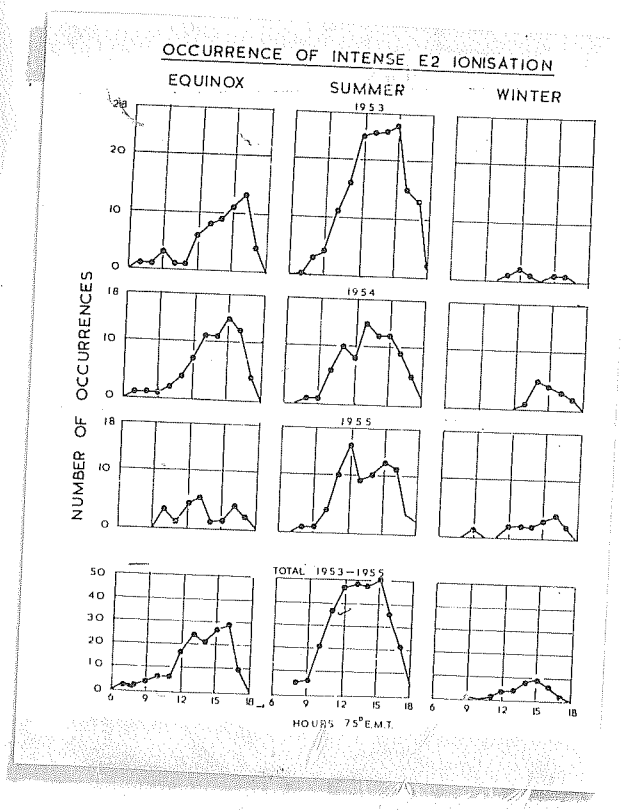


Fig. 44.

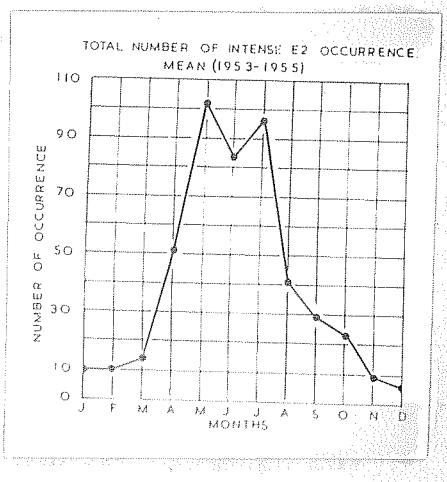


Fig. 45.

V. Night E2 Layer.

Another interesting phenomenon observed in the region intermediate between E and F1 is the occurrence of an ionised region at a virtual height of about 150 km during night hours.

In Fig. 46 (on page 44) is shown such an occurrence on February 26 1953. At 0415 only the F2 trace was seen. At 0430 a layer appeared below F2 at about 180 km with critical frequencies 1.0 and 1.7 Mc/s for the two magneto-ionic components. The height of this layer later decreased to 150 km. The ionisation in this region was maintained in later records.

Fig. 47 shows a formation of night E2 on December 3, 1954. At 0423 only the F2 reflections were recorded.

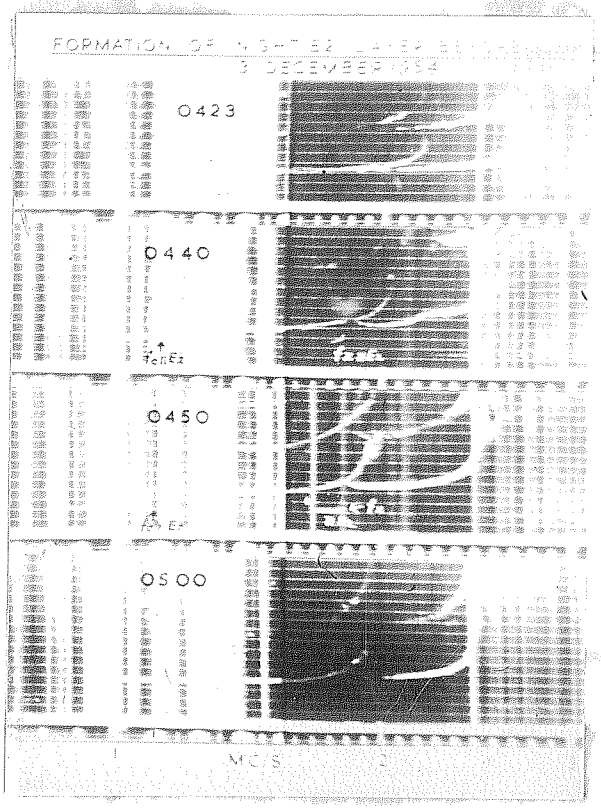


Fig. 47.

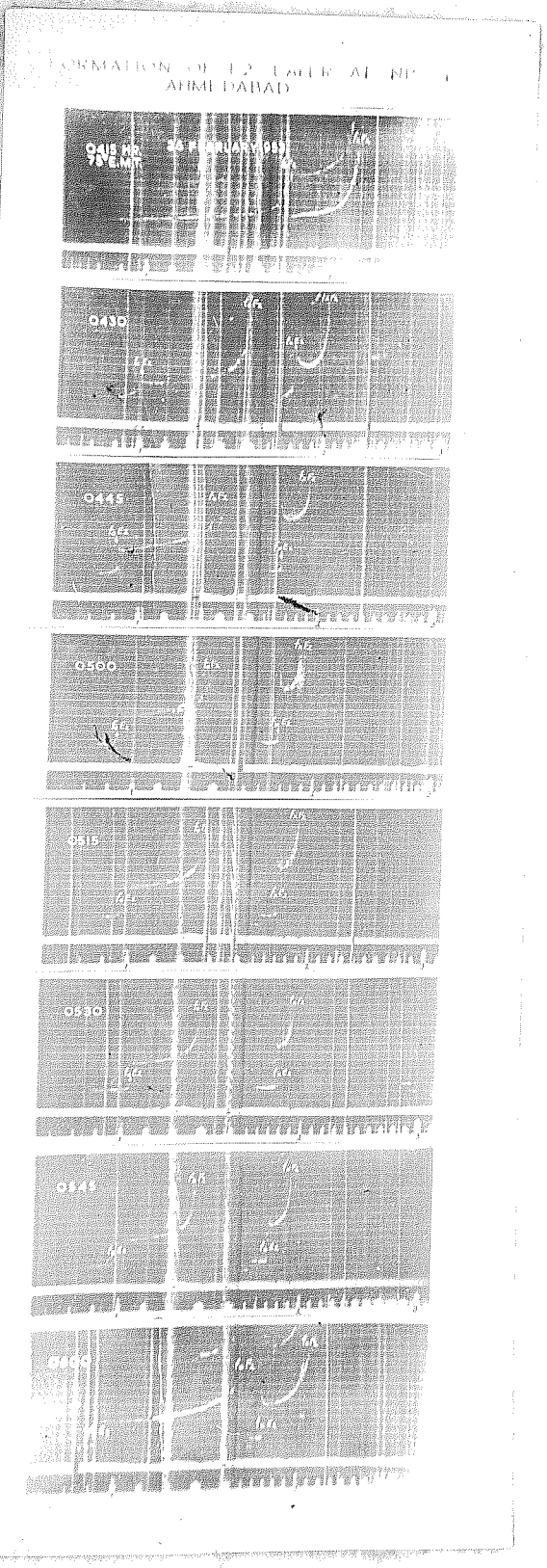

FORMATION OF LOW LEVEL JET AT NPL
AHMEDABAD
0430
0445
0500
0515
0530
0545
0600

Fig. 46

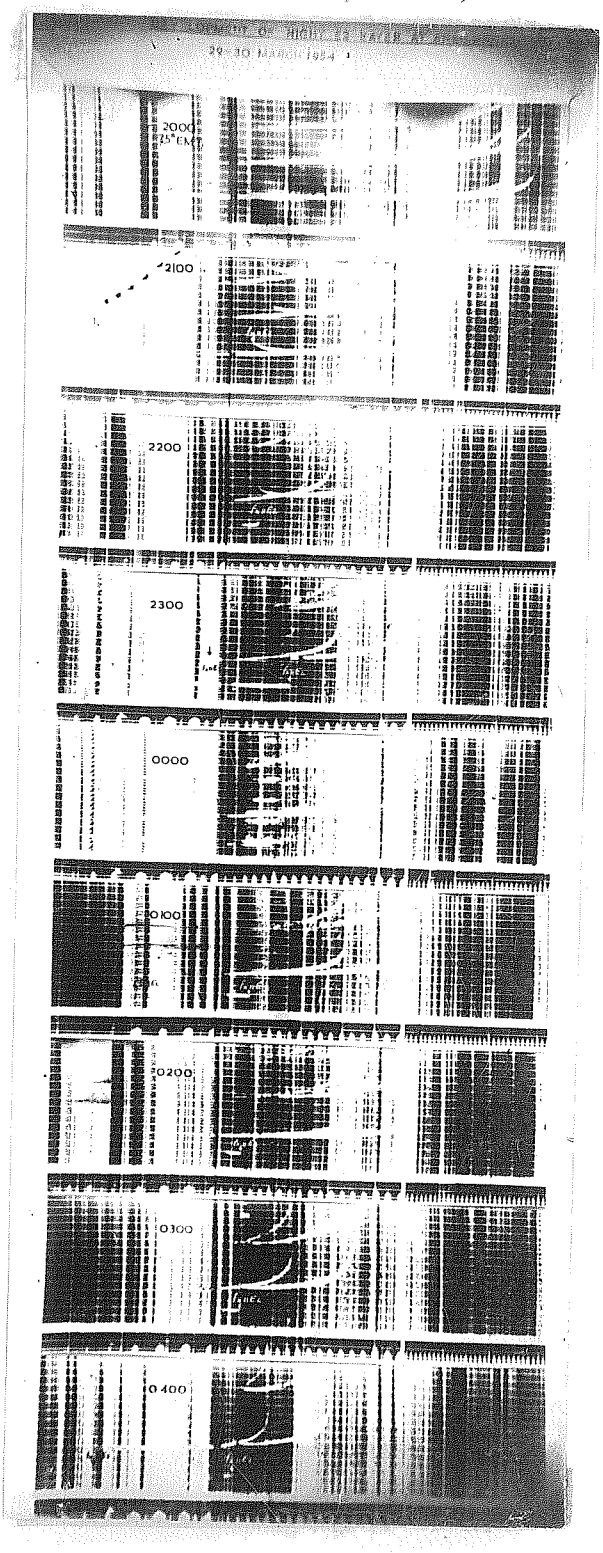

2000
2100
2200
2300
0000
0100
0200
0300
0400

Fig. 46

At 0440, the F2 layer was stratified and a night E2 layer was formed at about 160 km with f_o (nE2) = 1.1 Mc/s. At 0450, it became very thin and was not recorded at 0500. It may be noted that both o and x component traces were seen at 0440 and 0450.

Besides the early morning formation, night E2 has been seen developped in post-evening hours.

Fig. 48 (on page 44) shows an interesting case when night E2 was observed for the whole of the night of 29-30 November 1954. At 2000 only, F2 traces were recorded. At 2100, the x component of F2 showed large group retardation at its start at 1.6 Mc/s. At 2200, a layer clearly developed at 155 km with f_x (nE2) = 1.7 Mc/s. At 2300, it became very thin and f_x (nE2) increased to 2.1 Mc/s. Later records show that the critical frequency slowly decreased till 0400.

The occurrence of night E2 in the forms shown above were very few, but in many cases its existence could be inferred from the presence of group retardations in the F2 traces, more often in the extraordinary component. The extraordinary critical frequency of the layer generally was about 1.6-1.7 Mc/s. It was mostly formed between 20-21 hr. in the early part of the night or between 04-05 hr in the early morning.

An ionised layer below the F2 region in the night has been observed by other workers. There have been some

references to a nocturnal E layer. The phenomenon occurs frequently in the auroral zone. The records taken at Washinton[12] during the period 0000 to 0130 75° M.M.T. on May 21, 1946 showed echoes returning from heights between E and F regions. The traces were different from Es, in that there was group retardation and definite indication of a critical frequency at about 1.2 Mc/s.

Maubert[13] has described the formation of nocturnal E2 at Casablanca from a portion of F, before the rising of the sun and particularly in winter months. He held that an ionised region exists in the night between 100 and 200 km but escapes registration because the critical frequency is much lower than the limit of recording of the ionospheric sounder.

Bonnet[14] has described that at Lwiro, following a rise of h_pF2 in the night, an ionised region called by him "nocturnal E layer" detached itself from F2, and generally transformed itself into an E2s layer. This layer stayed for hours decreasing in height and increasing in critical frequency. He supposed that the layer was formed every night though it was not always visible because of blanketing by Es or E2s or by weakness of recordings at frequencies lower than 2 Mc/s.

Watts and Brown[15] have reported the occurrence of a night time layer between E and F1, in the P'-f records in the low frequency band. This layer exhibits magneto-ionic splitting and on some occasions descends to form sporadic E layer.

An interesting development of night E2 is shown in Fig. 49. At 0430 hr only F2 reflections were recorded, h'F2 being about 190 km. At 0440 f_0F2 decreased to 2.5 Mc/s.

Fig. 49.

At 0450, the height of the maximum ionization was generally increased due to sunrise effect in the F2 layer. At 0500,

the F2 was highly distorted due to sunrise. At 0510, F2 assumed its normal shape but an E2 detached itself from the F2 layer; and by 0520 separated itself from F2 and descended to 160 km. At 0530, the E2 trace was quite clear. At 0540 and 0550, the E2 traces could not be seen, but their existence could be inferred from the group retardations in F2. At 0600, reflections reappeared at about 160 km and the normal day-time E2 developed with the rise of the sun.

The F2 layer at 04-05 hr descends to a minimum height of about 200 km and afterwards rises quickly. The F2 traces are highly distorted, the height of F is considerably increased leaving a region of maximum ionisation at a level previously occupied. This residue of a layer when it descends to a level of 150 km, forms "night E2". The morning E2 is reformed at the same level and on some occasions gradually transforms itself into morning type E2.

VI. E2 and Sporadic E.

It has been stated by various authors that the afternoon E2 often breaks out from F1 descends to E region and forms sporadic E. This type of Es has been designated as Ees or E2s. At Ahmedabad, fEs shows a maximum near sunset and a great number of multiple Es reflections are recorded. The normal E as well as E1 and E2 are often merged in or blanketed by Es reflections. The hourly records may give an impression that the high Es values near sunset are formed out

of the E2, being degenerated after having descended to E region. On certain favourable occasions, when Es reflections were not broad (range spread), the E2 layer critical frequency could be followed till it went below the lower limit of the recording of the instrument.

Fig. 50 shows such a record obtained on May 5, 1954.

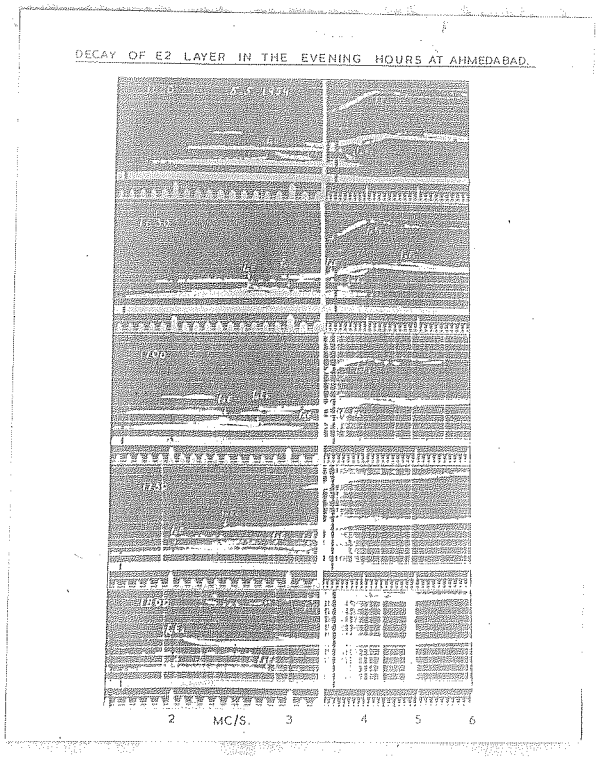


Fig. 50.

At 1800, the E2 trace was hardly distinguishable from the Es reflection trace, but its presence was evident by the group retardation in F1 trace and f_0E2 had decreased to 2.0 Mc/s.

Any sequence of Es development out of E2 cannot be easily ascertained from the ionospheric records taken at hourly intervals. To study the decay of E2 in the evening hours, special records at short intervals were taken from 16 hr till about an hour after ground sunset. A few such observations are described below.

Observations on August 25, 1956 (Fig. 51) :- At 1800 hr both o and x components of E, E1 and E2 were clearly

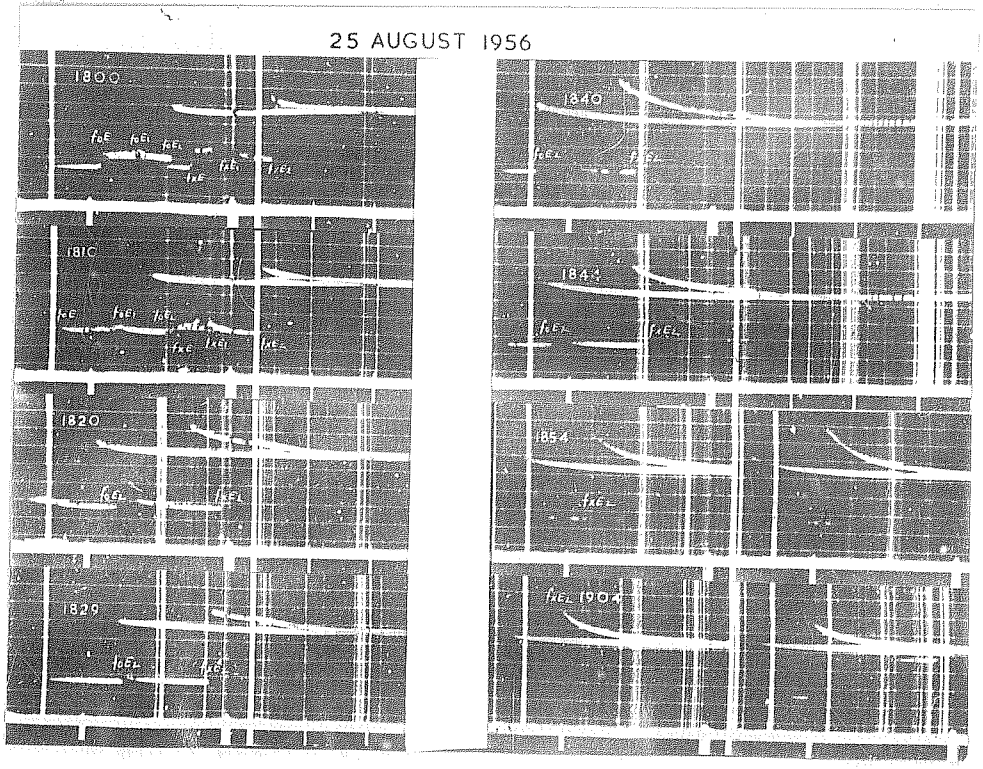


Fig. 51.

recorded. At 1810, the E traces were weak but f_0E and $f_{\frac{1}{2}}E$ could be determined from the E1 traces. At 1820, E and E1 traces were not recorded but the critical frequencies of E1 could be determined from the E2 traces. At 1904, no E2 trace was seen, but the beginning of F showed a large group retardation indicating the existence of E2. These group retardations decreased and E2 died out with the setting of the sun.

Observations on August 19, 1956 (Fig. 52) :- At 1400, the traces of E, E2 and F1 were very clear. At 1615 the traces became faint but E2 was clear. At 1830, E and E2 were too weak to be recorded but the existence of E2 could be

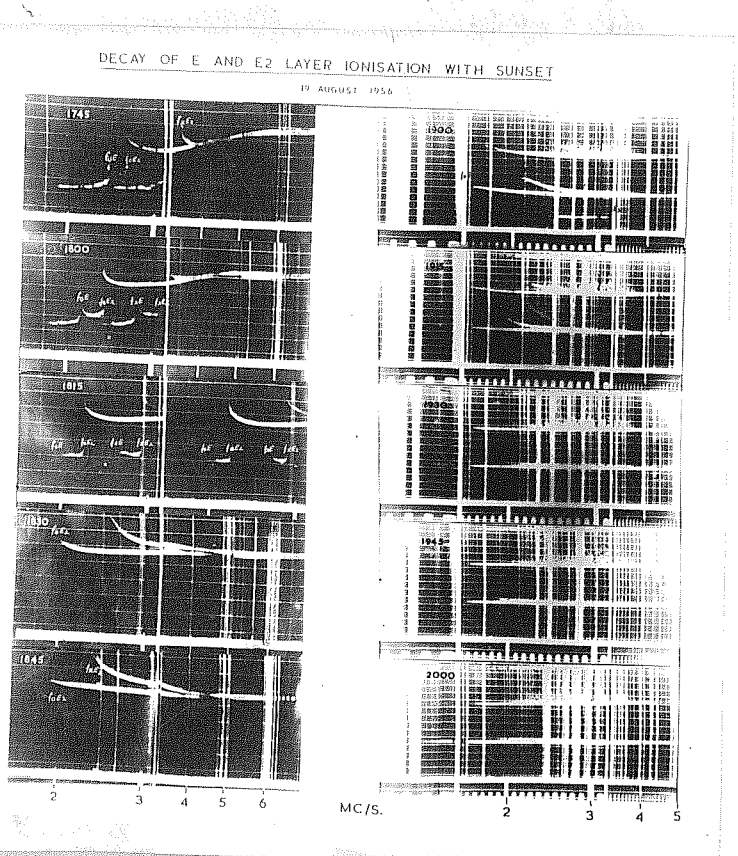


Fig. 52.

inferred and its critical frequency determined from the group retardation in F traces. At 2000, Fz vanished completely and F reflections started from the lowest frequency of the equipment. This example also shows a case when E2, like E1 disappeared with the setting of the sun without any formation of Es.

Observations on August 26, 1956 (Fig. 53) :- At

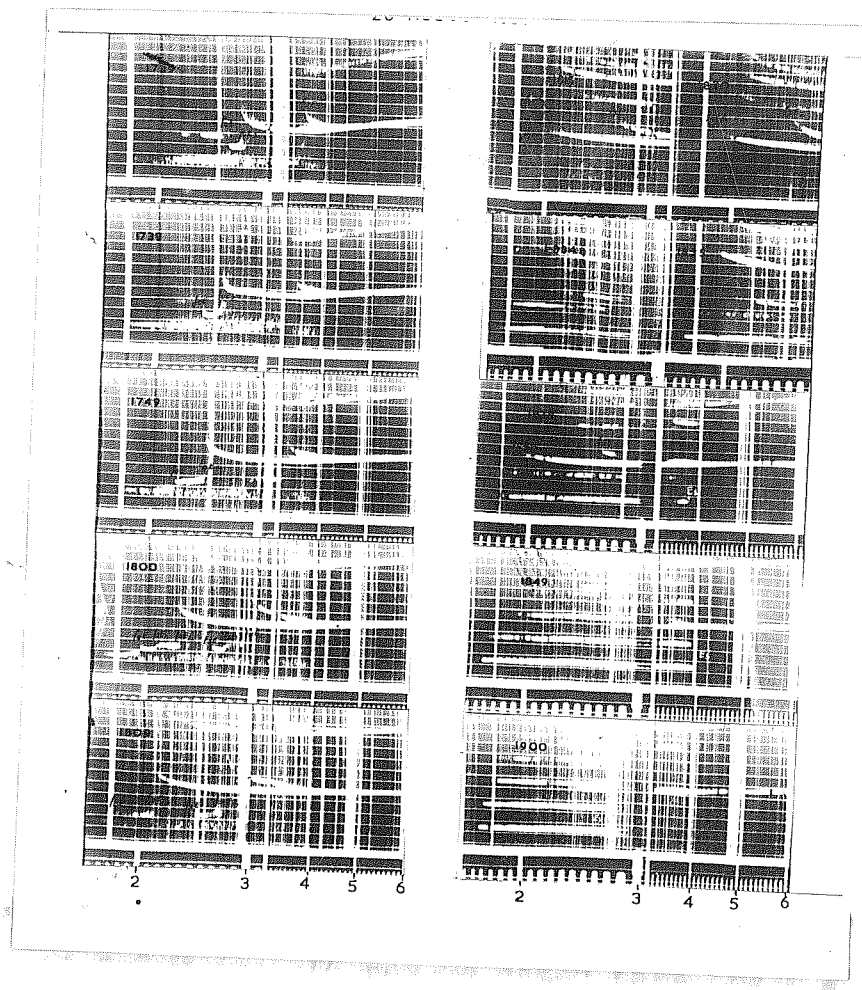


Fig. 53.

1729, 1739 and 1749 both E and E2 traces were clear. The critical frequencies of both E and E2 layers had steadily decreased between 1729 and 1809 hr E2 was all the time at 150 km. At 1809 E2 traces were too weak to be recorded still E layer critical frequencies could be ascertained from E2 traces. At 1815 and 1820 E2 was too weak to be recorded, but its existence may be concluded by the group retardations in the F traces. Note that there was no Es reflections recorded at 1815 and 1820 hr. At 1834 and 1835 strong Es had developed. At 1838, fEs increased to 3.9 Mc/s and at 1849, large number of multiple reflections were recorded. This case shows an example when E2 did not come down to the E region; still there was high fEs near about sunset.

Observations on August 18, 1956 (Fig. 54) :- The decay of E2 on this day could be interpreted as leading to the formation of sporadic E. At 1700 and 1715 hr both E and E2 layers clearly showed o and x components. At 1730 and 1745, the o and x components of E2 had merged in the first order traces but the second order traces showed the critical frequencies without any doubt. At 1800, o and x components of E2 traces were not distinguishable. At 1825 and 1830 the first order E2 echoes were hardly different from reflections from Es but the F1 traces did show two critical frequencies at 3.2 and 3.9 Mc/s. It may be noted that these special observations were taken with radio pulses of width much smaller than is usually used for routine soundings. Another

fact which may be noted is that f_0E decreased progressively from 3.0 Mc/s at 1700 to 2.0 Mc/s at 1815 and then disappeared but that f_0E2 decreased slowly from 4.0 Mc/s at 1700 to 3.3 Mc/s at 1800 and later remained steady almost at that value. Records taken later showed that E2 could be distinguished from its f_0E2 and $f_{min}F$.

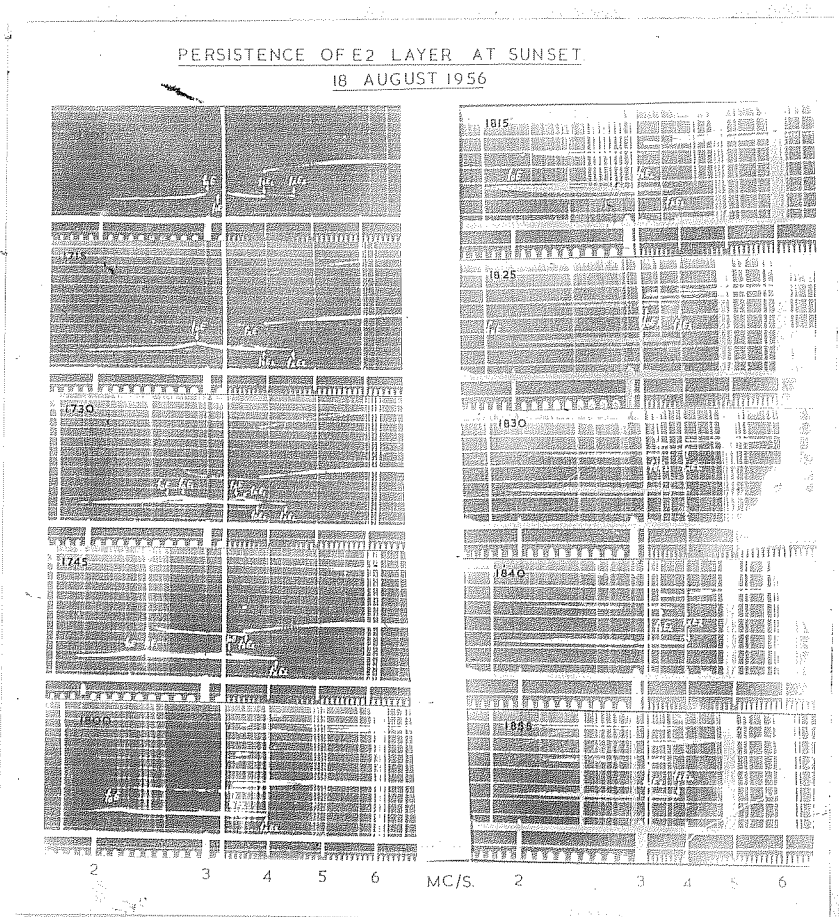


Fig. 54.

VII. Origin of E1 and E2 Layers.

Regarding the origin of the intermediate layers, there is little doubt that they are due to solar radiations either in the ultra violet or soft X-ray region. Observations made with photon counters in a rocket[16] show that there are at least three regions of spectrum at which the atmosphere begins to absorp, between 140-155 km viz. 1425-1650 Å, 1100-1350 Å and 5-10 Å. As the appearance of E2 is a daily phenomenon, and the layer makes its appearance in the morning even before E it is very likely that E2 is caused by the absoption of solar radiation by oxygen molecules; its absorption maximum is at about 1450 Å and according to rocket results, practically the whole of the solar radiation between 1350 and 1650 is absorbed between 175 and 125 km.

If E2 were due to absorption in 1100-1300 Å, the occasional bursts of solar flare should affect its intensity greatly and if due to absorption of short X-rays, its intensity should increase with increase of intensity of coronal radiation.

REFERENCES

1.	Rastogi R.G.	1954	Proc.Ind.Acad.Sci., 40, 158.
2.	Rastogi R.G.	1956	Jour.Atmos.Terr.Phys., 9.
3.	McNicol R.W.E. and Gipps G.De	1951	Jour.Geophys.Res., 56, 17.
4.	Rivault, R.	1952	Note preliminaire du L.N.R., No. 157.
5.	Naubert, A.	1954	Comptes Rendus, Soc.des Sci. Naturelles et Physique du Maroc. No. 1, 205.
6.	Skinner, N.J., Brown, R.A. and Wright, R.W.	1954	Jour.Atmos.Terr.Phys., 5, 92.
7.	Saha, A.K. and Ray, S.	1955	Jour.Atmos.Terr.Phys., 7, 107.
8.	Appleton, E.V.	1937	Proc.Roy.Soc.,London, 162 A,451.
9.	Appleton, E.V. and Boynon, W.J.G.	1940	Proc.Phys.Soc., 52, 518.
10.	Booker H.G. and Seaton S.L.	1940	Phys.Rev., 57, 87.
11.	Ratcliffe J.A.	1951	Jour.Geophys.Res., 56, 463.
12.		1946	C.R.P.L.Bulletin F23, 12.
13.	Naubert A.	1953	Note Preliminaires de L.N.R., No. 168.
14.	Bonnet G.	1954	Annales de Geophysique, 10, 348.
15.	Watts J.M. and Brown J.N.	1954	Jour.Geophys.Res., 59, 71.
16.	Friedman et al	1951	Phys. Rev., 83, 1025.

Monthly median ordinary ray critical frequency (in Mc/s) of E layer

1953

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	1.25	1.5	1.7	-	1.35	1.3	-	-	-
07	1.4	1.55	1.9	2.0	2.25	2.4	2.25	2.25	1.95	1.85	1.6	1.3
08	1.85	2.2	2.4	2.5	2.8	2.8	2.7	2.6	2.45	2.5	2.3	2.05
09	2.3	2.7	2.9	3.0	3.05	3.05	3.0	3.0	2.8	2.8	2.6	2.5
10	2.7	3.0	3.1	3.1	3.3	3.3	3.25	3.25	3.2	2.95	2.8	2.75
11	3.0	3.2	3.3	3.2	3.4	3.4	3.4	3.35	3.4	3.2	3.0	2.95
12	3.1	3.3	3.35	3.4	3.5	3.5	3.4	3.55	3.4	3.3	3.1	3.0
13	3.15	3.3	3.3	3.4	3.4	3.4	3.4	3.45	3.35	3.25	3.0	2.95
14	3.1	3.2	3.2	3.3	3.35	3.4	3.3	3.35	3.25	3.0	2.9	2.85
15	3.0	2.95	3.0	3.0	3.15	3.1	3.0	3.05	3.05	2.85	2.7	2.65
16	2.7	2.65	2.65	2.65	2.85	3.0	2.80	2.7	2.7	2.45	2.25	2.25
17	2.1	2.1	2.3	2.2	2.5	2.4	2.5	2.4	2.2	1.95	1.65	1.5
18	-	1.25	1.6	1.7	1.6	1.75	2.05	1.55	-	-	-	-

Monthly median ordinary ray critical frequency (in Mc/s) of E1 layer

1953

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	1.5	1.3	1.8	1.85	1.8	1.55	-	1.15	-	-
07	1.1	1.65	1.95	2.3	2.4	2.6	2.35	2.4	2.35	2.0	1.8	1.4
08	2.0	2.35	2.55	2.75	2.95	3.0	2.9	2.8	2.8	2.65	2.5	2.25
09	2.6	2.9	3.0	3.25	3.25	3.4	3.35	3.3	3.15	3.0	2.8	2.6
10	3.0	3.15	3.2	3.25	3.45	3.6	3.6	3.45	3.35	3.2	3.15	2.9
11	3.25	3.4	3.4	3.5	3.6	3.75	3.65	3.7	3.5	3.3	3.25	3.05
12	3.3	3.6	3.5	3.6	3.8	3.75	3.8	3.9	3.65	3.5	3.35	3.15
13	3.35	3.6	3.5	3.55	3.7	3.7	3.65	3.8	3.75	3.6	3.2	3.05
14	3.4	3.4	3.45	3.5	3.45	3.5	3.6	3.5	3.4	3.3	3.05	3.0
15	3.3	3.15	3.4	3.2	3.2	3.3	3.3	3.25	3.2	2.95	2.8	2.9
16	2.95	2.85	2.85	2.9	2.95	3.0	2.9	2.95	2.85	2.6	2.4	2.4
17	2.3	2.25	2.55	2.4	2.55	2.6	2.5	2.5	2.3	1.8	1.65	1.6
18	-	-	1.6	1.9	2.0	2.0	-	1.8	-	-	-	-

Monthly median ordinary ray critical frequency (in Mc/s) of F2 layer

1953

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	1.05	1.15	1.1	1.6	2.1	2.0	2.0	1.8	1.45	1.2	1.1	1.25
07	1.75	1.8	2.2	2.5	2.75	2.8	2.7	2.6	2.45	2.25	2.1	1.8
08	2.25	2.65	2.75	3.05	3.35	3.35	3.15	3.15	3.1	2.8	2.75	2.45
09	2.85	3.1	3.4	3.45	3.75	3.6	3.8	3.8	3.4	3.15	3.2	2.95
10	3.15	3.6	3.5	3.7	3.9	3.9	3.7	3.85	3.5	3.6	3.6	3.2
11	3.75	3.9	3.9	3.8	3.9	4.0	4.0	4.1	3.8	3.6	3.7	3.6
12	3.95	4.0	3.9	3.9	4.3	4.0	4.0	4.0	3.8	4.0	3.9	3.6
13	3.85	3.9	3.8	3.85	4.5	4.05	4.0	4.1	3.9	3.9	3.65	3.55
14	3.8	3.7	3.7	3.8	4.4	3.8	3.85	3.9	3.65	3.65	3.4	3.35
15	3.6	3.4	3.4	3.5	4.1	3.9	3.6	3.55	3.6	3.4	3.2	3.05
16	3.4	2.95	3.1	3.15	3.4	3.6	3.7	3.3	3.15	2.9	2.75	2.65
17	2.55	2.4	2.6	2.8	3.1	3.1	2.9	3.05	2.8	2.1	2.15	1.85
18	-	1.55	1.8	2.0	2.0	2.45	2.7	2.1	2.2	-	-	-

Monthly median ordinary ray critical frequency (in Mc/s) of F1 layer

1953

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	-	2.6	3.0	3.3	-	2.7	-	-	-
07	1.9	1.9	2.45	3.5	3.8	3.9	3.8	3.8	3.6	3.2	2.6	1.95
08	3.35	3.6	3.9	4.2	4.2	4.2	4.1	4.1	4.2	4.0	3.9	3.43
09	3.9	4.2	4.3	4.5	4.4	4.3	4.2	4.3	4.5	5.3	4.2	4.0
10	4.3	4.5	4.5	4.6	4.6	4.4	4.4	4.4	4.6	4.5	4.4	4.2
11	4.55	4.6	4.6	4.7	4.5	4.5	4.4	4.5	4.7	4.6	4.5	4.3
12	4.5	4.7	4.6	4.7	4.6	4.5	4.4	4.6	4.6	4.6	4.5	4.3
13	4.5	4.6	4.6	4.7	4.5	4.5	4.4	4.5	4.6	4.6	4.4	4.3
14	4.55	4.5	4.6	4.7	4.5	4.4	4.4	4.5	4.5	4.5	4.3	4.1
15	4.4	4.4	4.4	4.5	4.4	4.3	4.2	4.3	4.5	4.3	4.0	3.9
16	4.0	4.1	4.1	4.2	4.3	4.2	4.2	4.2	4.2	3.9	3.5	3.4
17	3.6	3.5	3.7	3.8	3.9	4.0	3.9	3.9	3.7	2.7	-	-
18	-	1.6	2.5	2.7	3.4	3.5	3.4	3.5	2.7	-	-	-

Monthly median ordinary ray critical frequency (in Mc/s) of E layer

1934

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	1.1	1.0	1.4	1.65	1.75	1.65	1.15	-	-	-
07	1.35	1.4	1.7	2.0	2.3	2.3	2.3	2.2	2.0	1.9	1.6	1.4
08	2.1	2.15	2.35	2.7	2.85	2.8	2.6	2.6	2.5	2.35	2.3	2.27
09	2.5	2.5	2.85	3.0	3.1	3.0	3.0	2.9	2.85	2.8	2.73	2.6
10	2.8	2.9	3.1	3.2	3.25	3.25	3.15	3.05	3.0	3.05	3.0	2.9
11	3.0	3.05	3.25	3.3	3.4	3.35	3.3	3.15	3.2	3.2	3.1	3.05
12	3.1	3.15	3.3	3.4	3.4	3.4	3.35	3.2	3.3	3.2	3.2	3.1
13	3.05	3.1	3.25	3.4	3.4	3.4	3.3	3.2	3.3	3.17	3.1	3.05
14	3.0	3.0	3.2	3.2	3.3	3.2	3.2	3.05	3.15	3.05	2.95	2.9
15	2.8	2.9	3.0	3.05	3.05	3.1	3.05	2.95	3.0	2.8	2.7	2.7
16	2.4	2.6	2.7	2.8	2.8	2.85	2.9	2.65	2.65	2.4	2.35	2.3
17	1.8	2.1	2.2	2.25	2.4	2.5	2.55	2.3	2.2	1.6	1.67	1.8
18	1.4	-	1.5	1.55	1.8	-	2.0	1.6	-	-	-	-

Monthly median ordinary ray critical frequency (in Mc/s) of E1 layer

1954

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	1.3	1.7	1.8	1.6	1.5	-	-	-	-
07	1.5	1.4	1.95	2.3	2.5	2.4	2.5	2.3	2.2	2.1	1.8	1.45
08	2.2	2.3	2.6	2.8	2.95	3.1	2.85	2.8	2.65	2.55	2.5	2.35
09	2.7	2.75	3.0	3.15	3.45	3.1	3.2	3.0	3.0	2.9	3.0	2.75
10	2.9	3.05	3.2	3.45	3.55	3.35	3.4	3.5	3.3	3.2	3.25	3.0
11	3.1	3.2	3.5	3.7	3.7	3.7	3.7	3.5	3.4	3.4	3.45	3.33
12	3.3	3.45	3.7	3.7	3.7	3.7	3.7	3.55	3.65	3.5	3.6	3.4
13	3.2	3.3	3.6	3.6	3.65	3.6	3.6	3.6	3.6	3.55	3.3	3.3
14	3.15	3.2	3.4	3.2	3.6	3.65	3.3	3.4	3.4	3.25	3.1	3.1
15	3.05	3.0	3.0	3.1	3.25	3.2	3.2	3.2	3.1	2.87	2.8	2.85
16	2.55	2.85	2.75	2.8	2.9	3.0	3.0	2.95	2.75	2.57	2.53	2.37
17	1.95	2.1	2.3	2.35	2.45	2.6	2.6	2.5	2.25	1.9	1.8	1.7
18	-	-	1.5	1.6	1.6	2.3	-	1.85	-	-	-	-

Monthly median ordinary ray critical frequency (in Mc/s) of E2 layer

1934

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	1.0	1.15	1.4	1.5	2.1	2.0	2.05	1.7	1.5	1.23	1.2	–
07	1.65	1.8	2.2	2.6	2.7	2.7	2.65	2.45	2.4	2.27	2.15	1.9
08	2.45	2.6	2.8	3.0	3.2	3.2	3.15	3.1	2.85	2.8	2.8	2.65
09	2.95	3.1	3.3	3.6	3.6	3.5	3.6	3.3	3.3	3.2	3.2	3.05
10	3.25	3.4	3.6	3.8	3.8	3.6	3.75	3.6	3.6	3.57	3.55	3.3
11	3.6	3.5	3.6	3.8	4.0	3.6	3.9	3.85	3.8	3.8	4.0	3.8
12	3.7	3.7	3.9	3.9	3.9	4.0	3.95	3.9	3.9	4.0	3.9	3.8
13	3.6	3.7	3.9	3.9	3.95	3.8	3.9	3.9	3.8	3.9	3.8	3.65
14	3.5	3.65	3.63	3.7	3.8	3.9	3.7	3.8	3.7	3.65	3.5	3.45
15	3.3	3.25	3.45	3.3	3.5	3.65	3.6	3.5	3.55	3.2	3.3	3.15
16	2.85	3.0	3.0	3.2	3.15	3.55	3.4	3.2	3.35	2.9	2.8	2.6
17	2.35	2.45	2.5	2.6	2.7	3.1	3.1	2.8	2.95	2.3	1.65	2.05
18	1.55	1.5	1.75	1.8	2.05	2.3	2.45	2.2	1.75	1.7	–	1.65

Monthly median ordinary ray critical frequency (in Mc/s) of F1 layer

1954

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	-	3.1	3.0	3.0	2.8	-	-	-	-
07	-	-	-	3.6	3.9	3.7	3.7	3.6	3.6	3.5	3.0	-
08	3.4	3.8	3.9	4.1	4.1	4.0	4.0	4.0	4.0	4.0	3.9	3.6
09	4.0	4.1	4.2	4.4	4.3	4.1	4.1	4.2	4.3	4.3	4.2	4.0
10	4.15	4.2	4.3	4.5	4.3	4.2	4.2	4.3	4.4	4.5	4.3	4.2
11	4.2	4.3	4.4	4.5	4.4	4.3	4.3	4.4	4.4	4.6	4.4	4.3
12	4.2	4.3	4.5	4.5	4.4	4.3	4.3	4.4	4.5	4.6	4.5	4.3
13	4.3	4.3	4.5	4.5	4.3	4.3	4.3	4.3	4.4	4.5	4.4	4.3
14	4.2	4.3	4.4	4.4	4.3	4.2	4.2	4.3	4.4	4.4	4.3	4.2
15	4.0	4.1	4.3	4.3	4.3	4.1	4.1	4.2	4.3	4.3	4.0	4.0
16	3.6	3.8	4.1	4.2	4.1	4.0	4.0	4.1	4.0	3.9	3.7	3.5
17	-	3.4	3.6	3.7	3.8	3.7	3.8	3.8	3.7	3.2	-	-
18	-	-	-	-	3.2	3.3	3.3	3.2	-	-	-	-

Monthly median ordinary ray critical frequency (in Mc/s) of E layer

1955

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	1.6	1.9	2.0	1.9	1.6	-	-	-	-
07	1.6	1.6	1.9	2.1	2.5	2.7	2.4	2.3	2.2	2.2	1.8	1.7
08	2.1	2.4	2.5	2.7	3.0	3.0	2.8	2.7	2.7	2.8	2.6	2.5
09	2.7	2.8	2.9	3.0	3.2	3.3	3.0	3.0	3.1	3.1	3.0	3.0
10	2.9	3.0	3.1	3.2	3.4	3.5	3.2	3.2	3.3	3.3	3.2	3.2
11	3.1	3.2	3.3	3.3	3.6	3.6	3.4	3.4	3.4	3.4	3.4	3.4
12	3.2	3.3	3.4	3.4	3.6	3.7	3.5	3.5	3.55	3.5	3.5	3.3
13	3.2	3.3	3.3	3.4	3.5	3.6	3.5	3.4	3.5	3.5	3.4	3.5
14	3.1	3.2	3.2	3.3	3.4	3.5	3.4	3.3	3.4	3.3	3.3	3.3
15	2.9	3.0	3.0	3.1	3.2	3.4	3.3	3.2	3.2	3.2	4.0	3.1
16	2.5	2.7	2.8	2.8	3.0	3.1	3.0	2.9	2.9	2.8	2.6	2.6
17	2.0	2.2	2.3	2.3	2.5	2.8	2.6	2.6	2.4	2.1	1.9	1.8
18	-	1.6	-	1.7	1.9	2.2	2.2	1.9	-	-	-	-

Monthly median ordinary ray critical frequency (in Mc/s) of E1 layer

1955

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	-	1.9	1.8	1.85	-	1.5	-	-	-
07	1.45	1.6	2.1	2.3	2.5	2.57	2.8	2.45	2.45	2.3	2.15	2.05
08	2.15	2.45	2.65	2.8	2.97	3.0	3.0	2.95	2.95	2.9	2.7	2.6
09	2.8	2.9	2.93	3.1	3.7	3.55	3.4	3.45	3.2	3.3	3.2	3.05
10	3.1	3.15	3.35	3.4	3.7	3.7	3.7	3.65	3.6	3.7	3.5	3.75
11	3.2	3.3	3.6	3.85	4.0	3.85	3.85	3.75	3.65	3.75	3.7	3.9
12	3.3	3.5	3.7	3.65	3.85	3.85	3.7	4.05	3.9	4.0	3.8	4.0
13	3.3	3.5	3.7	3.65	3.85	3.8	3.8	3.85	3.87	3.9	3.8	3.8
14	3.2	3.5	3.5	3.5	3.6	3.7	3.7	3.8	3.8	3.6	3.55	3.6
15	2.95	3.2	3.2	3.2	3.35	3.55	3.6	3.45	3.4	3.2	3.1	3.2
16	2.7	2.7	2.8	2.87	3.0	2.97	3.2	3.15	3.1	2.85	2.8	2.8
17	2.1	2.3	2.4	2.5	2.6	2.4	2.7	2.7	2.5	2.75	2.1	2.0
18	-	-	1.6	1.8	-	-	2.3	-	1.75	-	-	-

Monthly median ordinary ray critical frequency (in Mc/s) of E2 layer

1955

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	1.2	1.7	2.05	2.1	2.1	1.75	T.5	1.4	-	-
07	1.65	1.9	2.2	2.5	2.7	2.75	2.9	2.65	2.65	2.4	2.2	2.05
08	2.5	2.6	2.9	2.9	3.3	3.35	3.4	3.2	3.2	3.2	2.95	2.75
09	2.95	3.05	3.35	3.3	3.77	4.0	4.0	3.95	3.7	3.5	3.45	3.2
10	3.3	3.4	3.75	3.0	4.1	4.0	4.1	4.2	3.9	3.8	3.8	3.9
11	3.7	3.65	3.9	4.1	4.17	4.2	4.2	4.25	4.4	4.25	4.0	4.2
12	3.7	3.8	4.05	4.1	4.2	4.25	4.3	4.3	4.2	4.35	4.2	4.2
13	3.6	3.85	4.0	4.0	4.2	4.15	4.25	4.25	4.2	4.2	4.0	4.0
14	3.4	3.8	3.8	3.8	3.95	4.1	4.07	3.95	4.0	3.95	3.8	3.7
15	3.2	3.4	3.4	3.5	3.9	4.0	3.85	3.8	3.8	3.8	3.5	3.4
16	2.8	2.95	3.1	3.2	3.35	3.7	3.7	3.45	3.25	3.2	3.0	3.0
17	2.3	2.5	2.5	2.7	2.8	3.3	3.5	3.1	2.75	2.9	2.25	2.3
18	1.9	1.7	1.8	1.9	2.5	2.65	2.8	2.3	1.8	-	-	1.75

Monthly median ordinary ray critical frequency (in Mc/s) of F1 layer

1955

Hour 75° E. M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	-	-	3.6	3.2	-	-	-	-	-
07	-	-	3.5	3.6	4.1	4.0	3.9	3.8	3.8	-	-	-
08	3.6	3.9	4.0	4.0	4.4	4.4	4.2	4.2	4.2	4.0	4.1	4.0
09	4.0	4.2	4.3	4.3	4.5	4.5	4.4	4.4	4.5	4.4	4.5	4.4
10	4.3	4.4	4.4	4.5	4.5	4.6	4.5	4.5	4.7	4.7	4.7	4.7
11	4.4	4.5	4.5	4.6	4.6	4.8	4.6	4.6	4.8	4.9	4.8	4.9
12	4.5	4.6	4.5	4.6	4.6	4.9	4.6	4.6	4.8	4.9	4.9	5.0
13	4.4	4.6	4.5	4.6	4.6	4.9	4.6	4.6	4.8	5.0	4.9	4.8
14	4.3	4.5	4.5	4.5	4.5	4.7	4.6	4.5	4.8	5.0	4.8	4.7
15	4.2	4.3	4.3	4.3	4.5	4.6	4.4	4.3	4.6	4.6	4.5	4.4
16	3.7	4.0	4.1	4.1	4.3	4.5	4.2	4.2	4.4	4.3	4.0	4.0
17	3.0	3.3	3.7	3.8	4.1	4.1	4.0	3.9	4.0	3.4	-	-
18	-	-	-	2.9	-	3.8	3.6	3.4	-	-	-	-

Monthly median minimum virtual height (in km) of E layer

1953

Hour 75° M.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	105	115	115	-	120	115	-	-	-
07	105	110	115	105	115	110	115	110	110	125	115	110
08	115	110	110	105	110	110	115	110	110	110	110	115
09	110	110	110	105	110	110	110	110	110	110	110	110
10	110	110	110	105	110	110	105	118	115	115	110	110
11	110	110	110	105	110	110	105	120	120	120	110	110
12	110	115	110	110	110	110	110	120	115	120	110	110
13	110	110	110	110	110	110	115	120	115	120	110	115
14	110	110	110	110	115	110	110	120	115	115	113	115
15	110	110	110	110	115	110	110	115	115	115	115	120
16	110	115	110	110	115	110	110	115	115	120	120	120
17	110	115	115	110	115	110	120	115	120	115	125	125
18	-	115	120	100	120	110	110	-	-	-	-	-

Monthly median minimum virtual height (in km) of E1 layer

1953

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	150	150	135	150	130	135	-	-	-	-
07	125	130	140	150	150	160	135	175	130	140	-	130
08	140	130	140	138	160	155	150	160	135	130	140	145
09	135	150	150	175	150	165	160	170	135	143	140	145
10	145	165	150	180	155	170	155	150	135	140	160	150
11	125	175	150	160	170	170	150	175	140	130	160	160
12	140	180	165	180	170	160	160	180	130	148	175	175
13	160	180	155	180	170	165	180	175	180	170	160	150
14	135	170	140	160	150	165	170	175	165	135	150	150
15	125	145	140	135	150	160	150	140	180	135	150	165
16	130	135	135	130	135	135	140	135	160	145	145	150
17	130	130	125	130	140	125	145	140	145	135	150	140
18	-	140	150	130	150	130	-	135	-	-	-	-

Monthly Mediterranean Variable Heights (in km) of 52 Lanes

1933

Lane	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1	145	165	140	145	155	160	165	150	145	135	165	145
2	165	140	150	135	145	150	155	145	135	130	150	165
3	150	150	145	130	135	140	145	135	130	125	145	150
4	135	130	135	125	130	135	140	130	125	120	135	140
5	125	120	125	120	125	130	135	125	120	115	125	130
6	115	110	115	110	115	120	125	115	110	105	115	120
7	105	100	105	100	105	110	115	105	100	95	105	110
8	-	90	95	90	95	100	105	95	90	85	95	100
9	95	80	85	80	85	90	95	85	80	75	85	90
10	85	70	75	70	75	80	85	75	70	65	75	80
11	75	60	65	60	65	70	75	65	60	55	65	70
12	65	50	55	50	55	60	65	55	50	45	55	60
13	55	40	45	40	45	50	55	45	40	35	45	50
14	45	30	35	30	35	40	45	35	30	25	35	40
15	35	20	25	20	25	30	35	25	20	15	25	30
16	25	10	15	10	15	20	25	15	10	5	15	20
17	15	-	5	-	5	10	15	5	-	-	5	10
18	-	-	-	-	-	-	5	-	-	-	-	-

Monthly median minimum virtual height (in kms) of F1 layer

1953

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	-	230	230	250	250	250	-	-	-
07	-	190	220	230	225	230	235	230	240	235	230	230
08	250	210	220	230	220	230	225	225	215	225	230	230
09	230	230	215	220	225	215	225	200	225	215	235	225
10	215	225	210	220	220	215	210	210	205	217	225	220
11	210	220	210	215	210	220	200	210	245	210	220	225
12	230	235	220	220	215	220	210	225	240	235	235	225
13	225	235	230	225	240	210	230	230	240	230	230	220
14	235	230	233	230	230	225	225	230	235	250	230	225
15	215	225	230	235	250	240	240	230	235	240	240	230
16	240	230	225	235	245	230	215	230	245	235	240	235
17	245	230	235	230	240	230	230	240	245	245	-	-
18	-	220	240	235	245	250	250	240	250	-	-	-

Monthly median minimum virtual height (in km) of E layer

1954

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	-	110	-	110	110	-	-	-	-
07	120	110	115	110	110	110	110	110	115	120	125	115
08	120	115	110	110	110	110	110	110	115	110	110	110
09	115	110	110	115	110	110	110	110	115	110	110	110
10	110	110	110	115	110	110	115	110	115	110	110	110
11	113	110	110	110	110	110	110	110	115	115	110	110
12	113	110	110	115	110	110	110	110	115	110	110	110
13	115	110	110	110	110	110	110	110	115	110	110	110
14	115	110	110	110	110	110	110	110	110	110	110	110
15	115	110	115	110	110	110	115	110	115	115	110	110
16	115	110	110	115	110	110	110	110	110	115	115	110
17	120	115	115	115	115	115	115	110	120	115	125	117
18	130	-	-	125	115	120	115	120	-	-	-	-

Monthly median minimum virtual height (in km) of E1 layer

1954

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	135	140	120	140	130	145	-	-	-	-
07	150	135	135	145	135	125	155	145	150	130	145	135
08	130	130	135	150	160	165	165	150	130	135	150	130
09	138	145	145	180	170	150	160	160	150	150	170	157
10	150	150	160	150	165	135	160	150	130	180	175	160
11	148	150	170	180	170	170	180	180	175	185	180	170
12	178	150	175	170	170	170	160	170	175	193	180	170
13	160	145	180	165	170	175	150	180	180	180	180	170
14	180	150	170	170	170	160	150	170	150	150	170	170
15	175	135	140	150	170	160	150	135	150	150	170	165
16	160	160	130	130	150	155	150	170	155	130	138	145
17	143	140	140	135	140	170	130	135	135	128	135	145
18	-	175	140	145	120	160	130	125	-	-	-	-

Monthly median minimum virtual height (in km) of E2 layer

1954

Hour 75° E.M.T.	Jan	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	150	180	150	150	150	150	155	160	150	180	-	-
07	160	160	170	150	145	130	170	140	130	140	180	160
08	163	185	180	150	170	180	170	155	130	125	177	170
09	160	195	190	200	165	150	155	170	140	130	180	177
10	175	195	180	185	170	145	180	160	160	180	187	185
11	180	200	180	170	160	150	180	180	175	185	190	190
12	180	185	180	170	160	160	160	180	155	190	180	190
13	180	180	180	150	150	155	180	160	170	170	150	175
14	180	180	160	150	150	150	160	155	150	150	150	165
15	188	180	155	140	150	140	160	150	145	145	145	150
16	166	180	155	150	140	130	145	150	130	130	135	157
17	160	160	150	160	135	125	125	130	130	125	150	145
18	165	150	150	150	135	135	140	130	125	125	130	130

Monthly median minimum virtual height (in km) of F2 layer

1954

Hour 75° E.M.T.	Jan	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	150	180	150	150	150	150	155	160	150	180	-	-
07	160	160	170	150	145	150	170	140	130	140	180	160
08	163	185	180	150	170	180	170	155	130	125	177	170
09	160	195	190	200	165	150	155	170	140	130	180	177
10	175	195	180	185	170	145	180	160	160	180	187	185
11	180	200	180	170	160	150	180	180	175	185	190	190
12	180	185	180	170	160	160	160	180	155	190	180	190
13	180	180	180	150	150	155	180	160	170	170	150	175
14	180	180	160	150	150	150	160	155	150	150	150	165
15	168	180	155	140	150	140	160	150	145	145	145	150
16	166	180	155	150	140	130	145	150	130	130	135	157
17	160	160	150	160	135	125	125	130	130	125	150	145
18	165	150	150	150	135	135	140	130	125	125	130	130

Monthly median minimum virtual height (in km) of F1 layer

1954

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	-	235	235	225	225	-	-	-	-
07	-	-	-	230	225	225	227	230	235	235	235	-
08	235	230	225	220	215	215	225	220	225	220	227	230
09	225	225	220	215	225	213	215	210	210	212	225	220
10	215	225	220	210	230	205	212	200	203	220	225	215
11	210	220	230	225	205	230	210	220	200	210	227	225
12	210	215	225	250	220	235	220	207	210	240	233	223
13	220	225	225	235	230	230	220	217	212	245	230	225
14	220	215	220	225	240	250	225	225	227	235	220	220
15	220	230	230	230	235	240	230	220	233	235	230	230
16	225	230	230	230	230	240	225	225	233	235	230	230
17	-	230	230	235	225	230	225	227	235	237	-	-
18	-	-	-	-	235	235	235	235	-	-	-	-

Monthly median minimum virtual height (in km) of E layer

1955

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	130	110	110	125	-	-	-	-	-
07	125	125	120	115	105	100	113	110	110	113	120	125
08	112	110	110	110	100	100	110	110	107	107	110	110
09	110	107	110	110	100	100	107	105	105	105	107	110
10	105	105	110	110	100	100	100	105	105	105	105	107
11	105	105	107	110	100	100	107	105	105	105	105	105
12	105	105	107	110	100	100	107	105	105	105	105	105
13	105	105	107	110	100	100	107	105	105	105	105	105
14	107	105	107	110	100	100	109	105	105	105	105	110
15	107	107	110	110	100	100	107	105	105	107	110	110
16	110	110	110	110	100	100	107	107	110	110	115	112
17	115	112	115	115	100	100	112	115	112	115	123	135
18	-	125	-	125	105	105	120	120	-	-	-	-

Monthly median minimum virtual height (in km) of E1 layer

1955

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	-	140	150	130	175	145	-	-	-
07	140	140	155	150	135	155	170	140	160	150	175	155
08	145	135	150	170	210	160	165	140	125	160	190	150
09	150	140	150	160	185	157	150	130	125	190	175	160
10	160	155	160	175	185	175	150	150	135	180	180	200
11	150	150	180	180	180	175	155	160	180	165	190	200
12	170	187	180	175	160	165	140	150	195	180	200	200
13	150	175	175	160	170	160	160	150	180	183	200	190
14	160	185	175	177	170	160	150	155	175	190	185	200
15	160	175	170	160	150	145	170	150	150	160	170	170
16	165	183	140	150	150	145	145	145	150	150	170	160
17	135	155	175	130	150	140	130	145	130	175	150	145
18	130	-	150	140	-	130	125	-	125	-	-	-

Monthly median minimum virtual height (in km) of E2 layer

1955

Hour 75° E.M.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	150	160	150	145	140	145	150	-	-
07	150	165	200	165	160	170	165	150	140	170	175	170
08	150	180	185	180	150	170	170	180	125	150	200	200
09	185	185	200	200	200	200	150	150	165	190	200	200
10	180	180	200	195	180	160	175	150	145	165	200	200
11	200	180	200	185	177	175	150	160	155	200	200	200
12	185	185	190	160	167	170	150	160	140	200	200	200
13	170	185	190	150	160	170	150	155	170	180	180	190
14	150	165	180	150	160	150	145	150	150	150	160	190
15	155	150	175	150	150	135	125	145	155	135	135	170
16	190	150	150	140	140	140	125	135	170	130	145	155
17	160	120	145	125	130	130	120	125	150	125	135	135
18	128	125	125	135	125	125	120	125	135	135	125	125

Monthly median minimum virtual height (in km) of F1 layer

1955

Hour 75° E.S.T.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
06	-	-	-	-	-	220	235	-	-	-	-	-
07	-	-	230	230	220	210	220	220	230	-	-	-
08	225	225	225	215	220	200	215	210	215	225	230	230
09	220	215	215	210	200	200	230	210	210	210	225	225
10	215	210	210	215	190	200	210	210	205	215	220	220
11	210	210	205	225	190	200	205	215	200	210	220	220
12	210	205	210	210	200	200	205	230	205	220	230	225
13	210	210	225	240	200	200	210	240	220	230	225	225
14	215	215	225	225	200	210	220	225	220	230	225	225
15	220	225	230	225	210	210	215	215	225	240	235	235
16	220	220	230	225	200	210	220	230	225	240	240	235
17	230	230	-	225	220	220	225	230	235	-	-	-
18	-	-	-	235	-	220	240	245	-	-	-	-

CHAPTER II

ON HIGH MULTIPLE REFLECTIONS AND OTHER ABNORMALITIES OBSERVED IN THE P'-f RECORDS

CONTENTS

		Page
	Reprints of the paper : The occurrence of high multiple reflections from the F2 region of the ionosphere based on a study of the Ahmedabad records.	
I.	High multiple reflections.	1
II.	Anamalous intensity distribution of the multiple reflections.	2
III.	Anamalous height distribution of multiple reflection.	3
IV.	Echoes with split-height.	4

Reprinted from the "Proceedings of the Indian Academy of Sciences," Vol. XLI, 1955

THE OCCURRENCE OF HIGH MULTIPLE REFLECTIONS FROM THE F2 REGION OF THE IONOSPHERE BASED ON A STUDY OF THE AHMEDABAD RECORDS

By

R. G. Rastogi, M.Sc.

Reprinted from "The Proceedings of the Indian Academy of Sciences", Vol. XLI, No. 6, Sec. A, 1955

THE OCCURRENCE OF HIGH MULTIPLE REFLECTIONS FROM THE F2 REGION OF THE IONOSPHERE BASED ON A STUDY OF THE AHMEDABAD RECORDS

BY R. G. RASTOGI, M.SC.

(Physical Research Laboratory, Ahmedabad)

(Communicated by Dr. K. R. Ramanathan, F.A.SC.)

INTRODUCTION

SHORTLY after the installation of the automatic ionospheric recorder at Ahmedabad in January 1953, it was observed that on certain nights groups of pulses other than the regular ones moved swiftly across the time base on the monitor oscilloscope. On the P'-*f* records, they produced traces which started from below the ground pulse and crossed the various P'-*f* traces. Examples of such records are shown in Fig. 1. After the first three months of regular P'-*f* recording, the phenomenon was not observed for some months, but reappeared clearly in December 1953 and January 1954. A study of the phenomenon was then undertaken.

GENERAL FEATURES OF THE PHENOMENON

The following features were noticed about these abnormal traces: (1) They occurred only during night. (2) At any frequency the separation in height between two adjacent abnormal traces appeared to be the same as the virtual height of the first reflection trace at that frequency. (3) They ended at the ordinary critical frequency f_0F_2 of the F_2 layer, and on some occasions, there was another group of pulses ending at the extraordinary critical frequency f_xF_2 of the F_2 layer. (4) The ratio of the slope of an abnormal trace to that of the first reflection trace was found to be the same at any frequency and increased in steps of one from one trace to the next. It was therefore concluded that these abnormal traces represented high order reflections from the ionosphere.

The equipment at Ahmedabad is a British N.P.L. type automatic ionospheric recorder and the pulse repetition frequency is 50 per second. If the delay time of a high order multiple reflection is more than 1/50 second, it will be recorded in the second sweep of the time base, and the equivalent height of the multiply reflected trace will exceed 3000 km. (= 1/50 second). The order of reflection can be determined by dividing the slope or the equivalent height of the trace at any frequency by the corresponding slope or height of the first reflection trace at that frequency.

During regular recording, the duration of the time base is usually adjusted to record echoes of equivalent height upto 1000 km. only. However, the time base duration can be extended to record echoes of equivalent height upto about 2000 km. With such an extended time base, multiples upto the 17th order have been recorded. It was considered that it would be worthwhile to increase the height range still further and arrangements were made on a few occasions to record the echoes in two steps, first showing the reflections upto 1500 km., and then delaying the start of the time base so as to record heights between 1500 and 3000 km. Such a double record is shown in Fig. 2 where all multiple echoes from the first to the ninth can be seen.

An examination of the literature showed that high multiple reflections have been noticed by some previous workers on P′-t records (Pierce and Mimno,[1] Baird[2]). They attributed these to the curved shape of the ionosphere or humped ionisation contours in the ionosphere. These humps produce a mirror-like converging action on the reflected radio beam. Gipps, Gipps and Venton[3] also explained some abnormal traces in P′-f records in terms of humps and concavities in the ionosphere. Munro[4] described certain complexities observed on ionospheric records as the effects of the curvature of the ionospheric surface. Uyeda and Nakata[5] have recently described similar abnormalities observed on h'-t and fct records and explained them on an assumed inclination of the ionosphere and its movement.

ANALYSIS OF AHMEDABAD RECORDS SHOWING HIGH ORDER MULTIPLE REFLECTIONS

A detailed analysis was made of the records showing such abnormal traces and the present note contains a summary of the findings.

The parameters of the F_2 layers were determined by the method of Appleton and Beynon.[6] The virtual heights of the layer at various frequencies were plotted against the corresponding values of Booker and Seaton's function[7]

$$\phi\left(\frac{f}{f_c}\right) = \frac{1}{2}\frac{f}{f_c}\log_e\left|\frac{f_c+f}{f_c-f}\right| - 1$$

where f_c is the critical frequency of the layer and f any frequency less than the critical frequency. It was found that a neat straight line could be drawn through the points showing that the distribution of electrons in the F_2 layer during the night time was approximately parabolic. The values of the virtual heights at $\phi = -1$ and $\phi = 0$ gave respectively the true height of the base h_0F_2 and the height of the level of maximum ion density h_pF_2, the semi-thickness being given by $h_p - h_0$.

f Mc/s	ϕ	h_2 km.	$h_2/2=h_1$ km.	$h\,(n_1)$ km.	$hn_1/11$ km.	$h\,(n_2)$ km.	$hn_2/12$ km.	$h\,(n_3)$ km.	$hn_3/13$ km.	$h\,(n_4)$ km.	$h\,(n_4)/14$ km.	Mean h_1 km.
1·9	−0·52	445	223	..	..	..	..	..	..	..	..	223
2·0	−0·47	452	226	..	..	..	..	..	..	..	..	226
2·1	−0·37	460	230	..	..	..	..	..	..	..	..	230
2·2	−0·32	470	235	..	..	..	..	3000	231	..	..	233
2·3	−0·21	480	240	..	..	..	..	3090	238	..	..	239
2·4	−0·12	490	245	..	..	2900	242	3160	243	..	..	243
2·5	0·00	500	250	..	..	2970	248	3250	250	3500	250	250
2·6	+0·14	520	260	..	..	3080	257	3350	258	3640	260	259
2·7	+0·33	540	270	2900	264	3200	267	3450	265	3750	268	267
2·8	+0·54	560	280	3080	280	3360	280	3575	275	..	..	280
2·9	+0·95	615	308	..	..	..	..	..	..	..	..	308

The analysis of a typical record (Fig. 1 *b*) is given in the following table. The value of f_0F_2 was 3·0 Mc/s. $h(n_1)$, $h(n_2)$, $h(n_3)$ and $h(n_4)$ are the virtual heights of observed multiples and are found to be nearly equal to 11, 12, 13 and 14 times h_1. h_pF_2 was found to be 250 km., h_0F_2 to be equal to 198 km. and the semi-thickness of the layer was 52 km.

With a view to find out what ionospheric features were associated with high multiples, the parameters h_0, h_p and T obtained from the hourly ionospheric records during the occurrence of the phenomenon were examined.

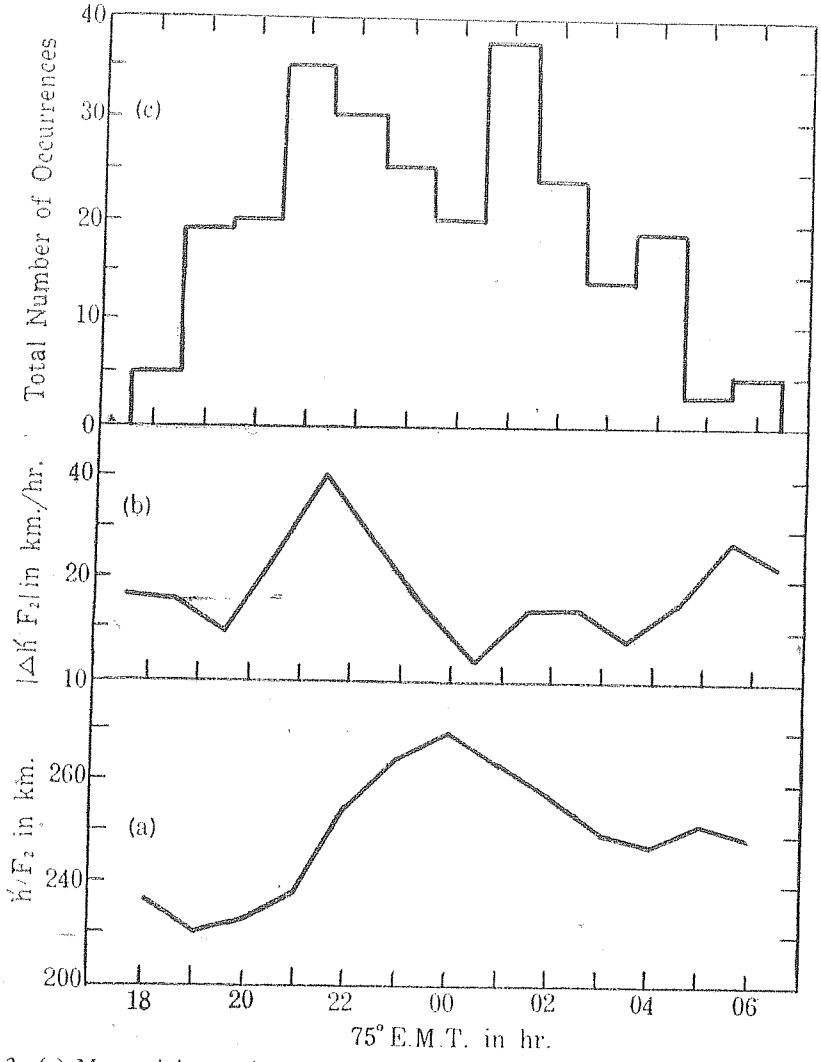


FIG. 3. (*a*) Mean minimum virtual height of the F_2-layer (January 1953 to December 1954). (*b*) Average hour to hour change in $h'F_2$ (January 1953 to December 1954). (*c*) Total number of occurrences of high multiples (January 1953 to December 1954).

In the records of the period January 1953 to December 1954 there were 256 such occurrences. It was found that in general high multiple reflections were associated with a hump in the ionospheric surface over the place of observation. High multiples occurred more or less continuously for many hours in certain periods of the night in some months. Near the critical frequency the multiples are generally weaker, due no doubt to increased absorption as well as to increased slope of the P′-*f* traces.

The distribution of the occurrence of high multiples with the hour of the night is shown in Fig. 3 (*c*). In Fig. 3 (*a*) and 3 (*b*) are shown the mean

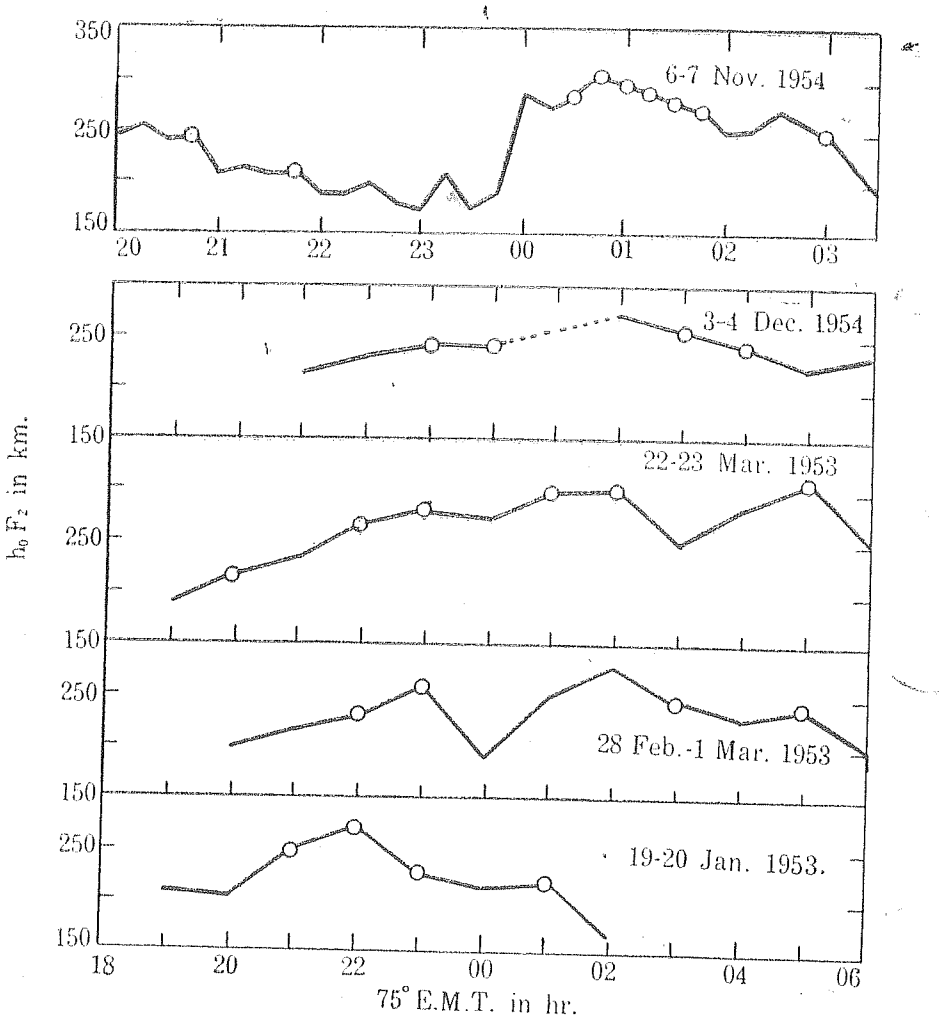


FIG. 4. Variation of h_0F_2 and the occurrence of high multiples on a few nights.

favouring stations one to observe all the multiples.

virtual height ($h'F_2$) and the average hour-to-hour change in virtual height ($h'F_2$) during the period January 1953 to December 1954.

It will be seen that the hour of maximum occurrence of high multiples are round about 21 hours, 01 hour and 04 hour. The times of maximum frequency of occurrence of high multiples nearly coincide with or precede the times of maximum rate of change of $h'F_2$. The strength of the peak at 01 hour in Fig. 3 (*c*) is abnormal due to the large number of occurrences of high multiples at that hour in one month only, namely in November 1954.

Figure 4 gives the analysis of the heights of the F_2 layer on a number of individual nights at times when high multiples were observed. The circles represent the times at which high multiples were observed.

Observations at short period intervals taken on a few nights showed fair correlation between the highest order multiple and the curvature of the

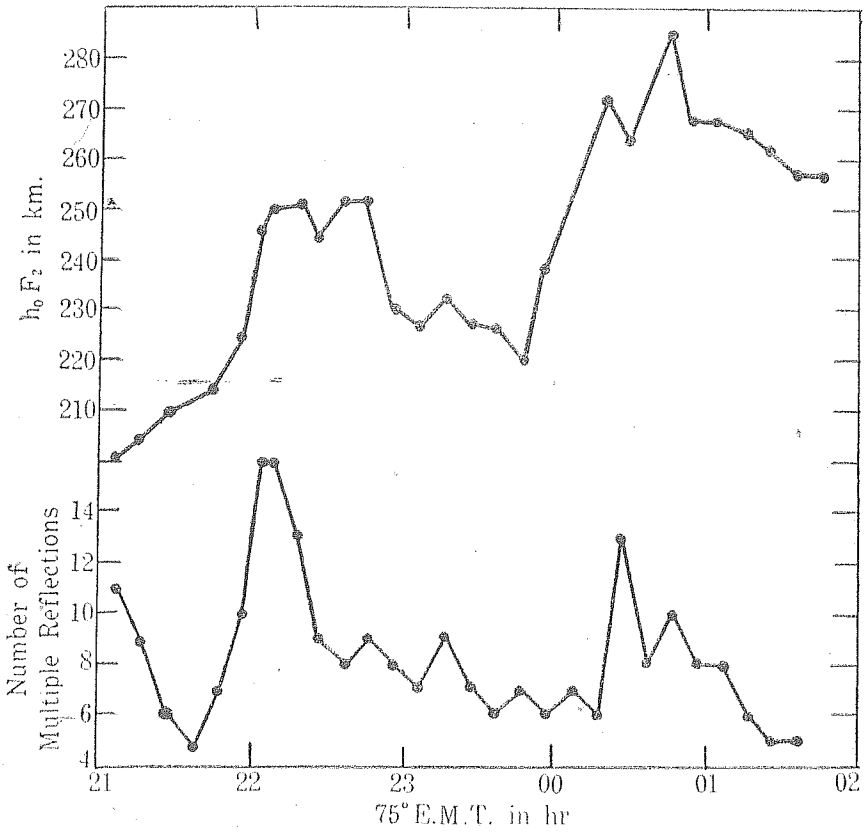


FIG. 5. The variation of the total number of multiple reflections and the height of base of the F_2 layer on the night of 10 to 11 March 1955.

ionospheric surface. Figure 5 shows the results of observations taken on the night of 10–11 March 1955.

It was found that sporadic E does not affect the high multiples except when it blankets the normal reflections. Sometimes high multiples of F_2 and sporadic E can be seen simultaneously recorded over the same frequency range (Fig. 1*b*).

1 F scatter usually reduces the number of multiple reflections but there are some exceptions to this also (Fig. 1 *c*).

Seasonal Variation of Multiple Reflections

It appears from Fig. 6 that high multiples are least frequent in the summer months May to July and most frequent in November to March or

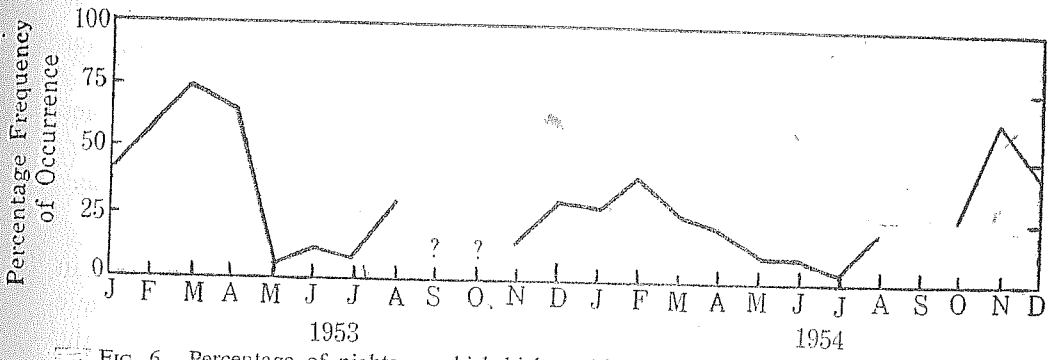


Fig. 6. Percentage of nights on which high multiple reflections were recorded in various months January 1953 to December 1954.

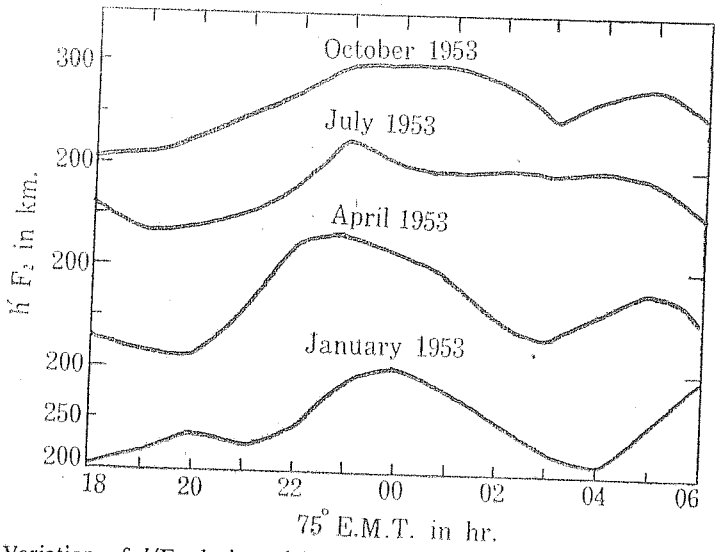


Fig. 7. Variation of $h'F_2$ during night time in different months of the year.

April. This accords with the fact that the daily variations of $h'F_2$ are least pronounced in the summer months and most pronounced in autumn and spring. During summer, E_s and 1 F—scatter are rather more frequent and these no doubt contribute partly to the rarity of high multiples in that season.

IRREGULARITIES IN THE INTENSITIES OF THE MULTIPLE REFLECTIONS

A phenomenon related to the above is the anomalous and varying distribution of intensity of multiple echoes. This phenomenon can be seen clearly on many occasions on the monitor oscilloscope and generally occurs on multiples higher than the third. It is difficult to determine quantitatively intensity ratios of the various multiples from the P'-*f* records but approximate estimates of their intensity can be obtained in some cases.

At times, depending upon the position of the hump with respect to the place of observation, a higher multiple may be formed by combination of waves leaving the transmitter at different angles and arriving at the receiver after being reflected from off-vertical points in the ionosphere. The intensity of some particular multiple may then be greater than that of the lower ones depending upon the curvature, height, and reflection coefficient of the F_2 layer, as well as on the radiation patterns of the transmitting and receiving antennæ.

CONCLUSION

These observations show clearly that even at night, the F_2 layer can by no means be considered as a simple plane reflecting surface and that there are dynamic changes going on in it most of the time. Determination of the reflection coefficient of the layer and of the absorption of the atmosphere below it is rendered particularly difficult because of these changes.

ACKNOWLEDGEMENT

The author is indebted to Prof. K. R. Ramanathan for his keen interest and guidance in the work. The Council of Scientific and Industrial Research (India) is supporting the ionospheric station with financial assistance.

REFERENCES

1. Pierce, J. A. and Mimno, H. R. — *Phys. Rev.*, 1940, **57**, 98.
2. Baird, K. .. — *Austr. Jour. Phys.*, 1954, **7**, 165.
3. Gipps, G. De, V., Gipps, D. I. and Venton, H. R. — *Jour. Coun. Sci. Industr. Res., Australia*, 1948, **21**, 215.
4. Munro, G. H. .. — *Proc. Roy. Soc.*, 1953, **219 A**, 447.
5. Uyeda, H. and Nakata, Y. — *Jour. Radio Res. Lab., Japan*, 1954, **1**, 17.
6. Appleton, E. V. and Beynon, W. S. G. — *Proc. Phys. Soc.*, 1940, **52**, 518.
7. Booker, H. G. and Seaton, S. L. — *Phys. Rev.*, 1940, **57**, 87.

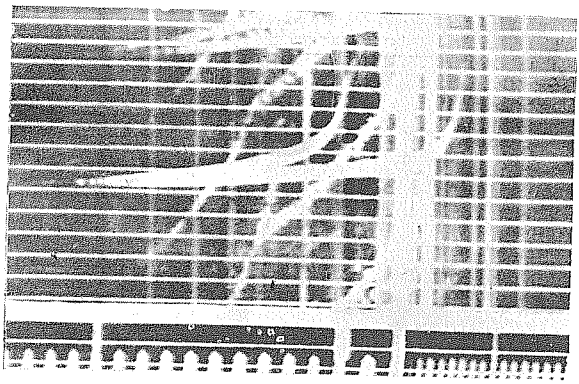


FIG. 1(*a*). P′-*f* record at 01 hr. on 28–10–1954.

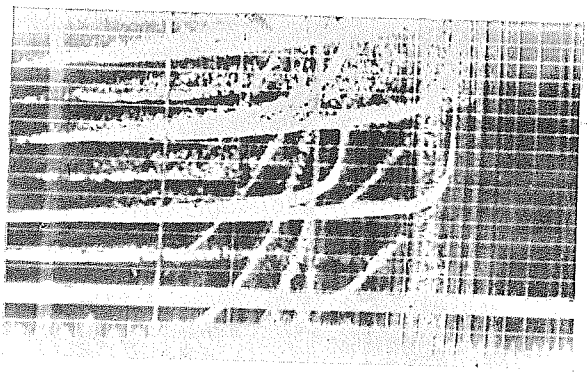


FIG. 1(*b*). P′-*f* record at 02 hr. on 31–1–1953.

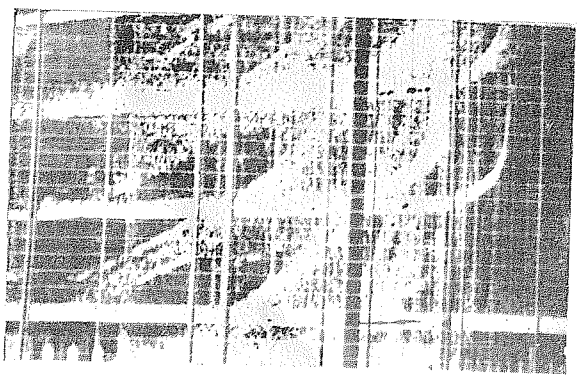


FIG. 1(*c*). P′-*f* record at 00 hr. on 17–3–1953.

FIG. 1. P′-*f* records showing abnormal traces crossing the lower order reflection traces.

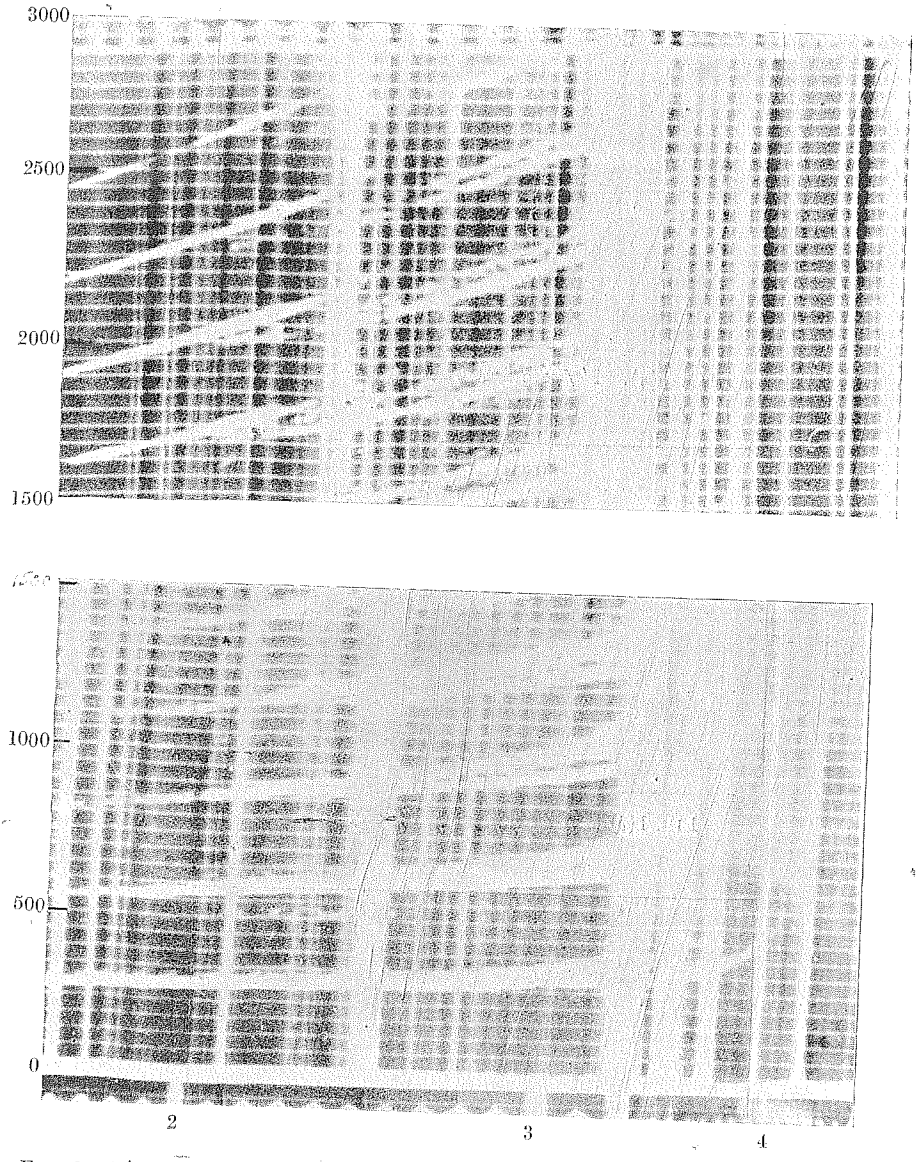


FIG. 2. P′-*f* record at 22 hr. on 10–3–1955 recorded in two steps, one recording echoes upto 1500 km, and the second immediately after, from 1500 km. to 3000 km.

(a)

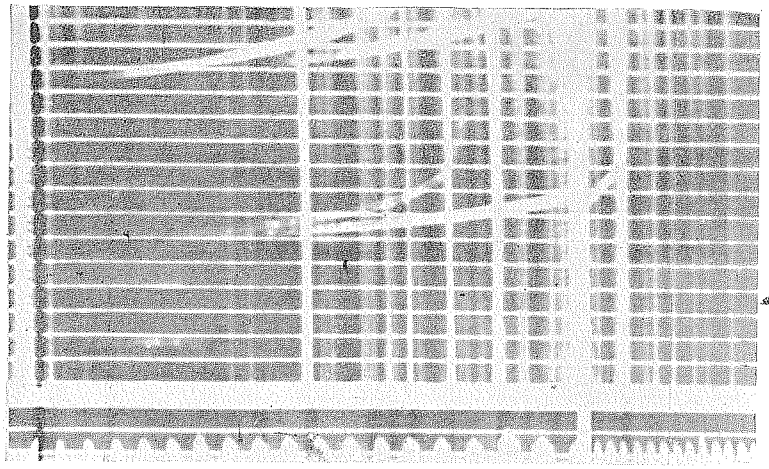


FIG. (a) P′-f record at 00 hr. on 18-3-1954.

(b)

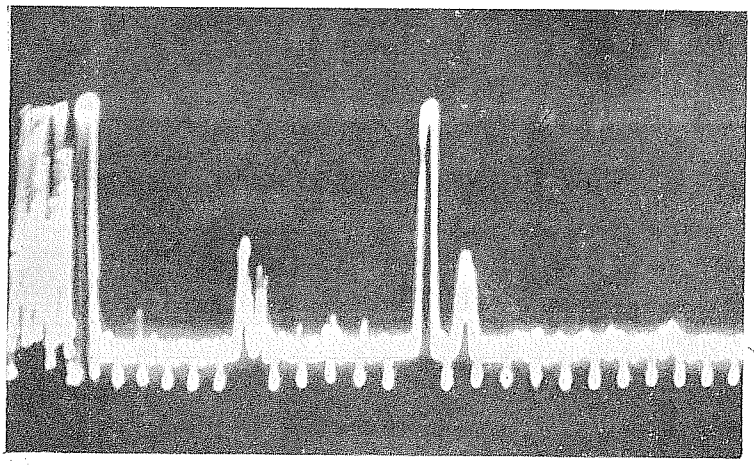
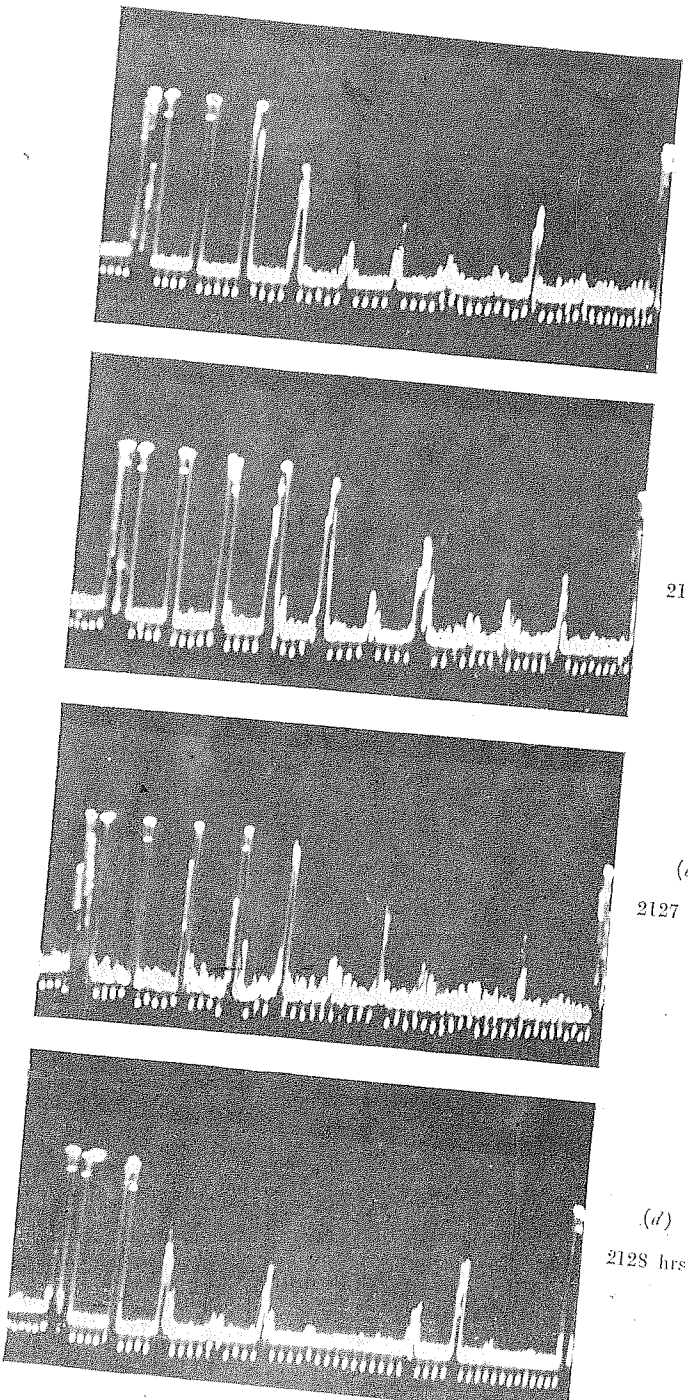


FIG. (b) Photo at 2230 hr. on 28-3-1955.

FIG. 8. Records showing second order reflection stronger than the first order reflection



(*a*) 2125 hrs.

(*b*) 2126 hrs.

(*c*) 2127 hrs.

(*d*) 2128 hrs.

FIG. 9. Multiple echoes at intervals of one minute on 24–3–1955.

Some effects of ionospheric irregularities on P'-f records observed in night hours at Ahmedabad.

(Supplement to the paper attached herewith)

1. High multiple reflections.

Further example of high multiple reflections similar to those shown in Fig. 1 are shown in Fig. 10. Fig. 11 shows some records taken at intervals of ten minutes each during the occurrence of high multiples. The variation of h_pF2 and h_pF2 during the period are shown in Fig. 12. High multiples were observed at 0520, 0530 and 0540 hr. when there was a hump in the ionospheric surface over the station.

Fig. 13 shows some records taken at intervals of 15 minutes on 7 November 1954. These records were taken with extended duration of time base, thereby the recording reflections from heights upto 2000 km. One can see that at 0000 hr there were only three weak x - components reflections from F2, but at 0015 their number had increased and they were also stronger. High multiples were recorded between 0030 and 0300 hr. These records will be discussed at a later stage.

Figs. 14 and 15 show two more examples of records taken in two steps similar to that shown in Fig.2. Such recording enables one to observe all the multiples.

Figs. 16 and 17 (see also Fig.5) show the variation of the highest order of multiple reflections and of h_0F2. These figures show that there is an increased number of multiples when the ionospheric surface presents a concave surface towards the station.

Kahizenya [6] et al have described the occurrence of high multiples from F2 layer at Akita.

2. Anomalous intensity distribution of the multiple reflections.

It was mentioned in the previous paper that the intensities of the multiple reflections did not on some occasions decrease with increasing order. Fig. 18 shows a few examples of such a phenomena.

The focussing effect of particular orders of reflection can be referred from the minimum frequencies of reflection of different order multiples. The minimum frequency of reflection is indicative of the reflection coefficient and normally $f_{min}F2$ increases with increasing order of multiple. An anomalous distribution of $f_{min}F2$ with increasing order of multiple can be seen in the records at 0200 and 0300 hr on 7 November 1954. (Fig.13). At 0200 hr $f_{min}F2$ for the 5th order was less than that for the 3rd or 4th order reflections. At 0300 hr $f_{min}F2$ for the 4th and 5th order reflections were smaller than that

for the 3rd order.

3. Anomalous height distribution of multiple reflection

Another phenomenon connected with the irregularities in the ionosphere is that sometimes the virtual heights of multiple reflections are not integral multiples of the heights of the first order echo. A few examples of the phenomenon are shown in Fig. 19 (a) and (b). In Fig. 19 (a) both o and x component traces for second order reflection have virtual height less than twice those of first order. In Fig. 19(b) the virtual height of x component F2 reflection at 5 Mc/s, is 430 km for the first order, 710 for second order and only 910 km for thethird order reflection. Two more examples of such a phenomenon are shown in Fig.20 and 21. The phenomenon can be explained in terms of reflection from an inclined ionosphere, the different order multiple reflections are received from directions off the vertical. The first order reflection would be more inclined to the vertical and so will have a greater virtual height. Successive reflections will approach the vertical and the separation between successive traces will get smaller with increasing order of reflection.

Uyoda and Nakata[9] have discussed similar phenomenon observed on sweep frequency records.

Records of this type are observed at Ahmedabad in the early and late portions of the night when the height of

F2 changes rapidly.

4. Echoes with split-height.

Referring to Fig. 13 we see that at 0245 hr the x component reflections are split and two simultaneous parallel traces are recorded in the second, third and fourth order reflections. Similar splitting in the heights of the multiple reflections can be seen in the records between 0130 to 0230 hr. Note that at 0245 hr the separation between the split-height echoes increased with increasing order of the multiple, whereas in Fig. 2 the separation decreased with increasing order. A good example of height splitting in higher multiple reflections is shown in Fig.22. At 0300 high multiples were recorded but without any height splitting. Split-height multiples were recorded at 0400 hr when there was a sudden change in the heights of the F2 layer and so the ionospheric surface was inclined. At 0500 hr, the lower order multiples were not equally spaced. When the surface is inclined or there is a bulge in the ionospheric surface, the higher reflections may arise from two or more directions and give rise to parallel traces slightly displaced in height.

On some occasions split-height echoes may be seen in low order multiples as shown in Fig.23. Note that the first order F2 trace is single, whereas second and higher order traces are duplicated.

On some occasions, even the first order reflections may be duplicated; two examples of the phenomenon are shown in Fig. 24. Note that all the reflection traces have duplication.

On some occasions the duplicate traces may merge giving a broad diffuse trace resembling scattered or spread F traces as shown in Fig. 25.

The duplicate traces may have same critical frequencies or their apparent critical frequencies may be different as shown in Figs. 26 and 27.

References

8. Kelivsanya Y., Katano S., and Ogata Y. — Jour. Rad. Res. Lab. (Japan), 1955, 2, 137.

9. Uyoda, H., and Nakata Y. — Jour. Rad. Res. Lab. (Japan), 1954, 1, 17.

****

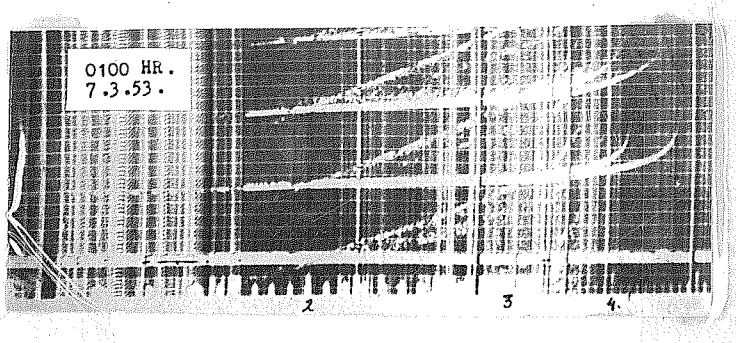


Fig.10.
Examples of high multiples reflections crossing the lower order reflections.

Fig. 11.

Fig. 12.

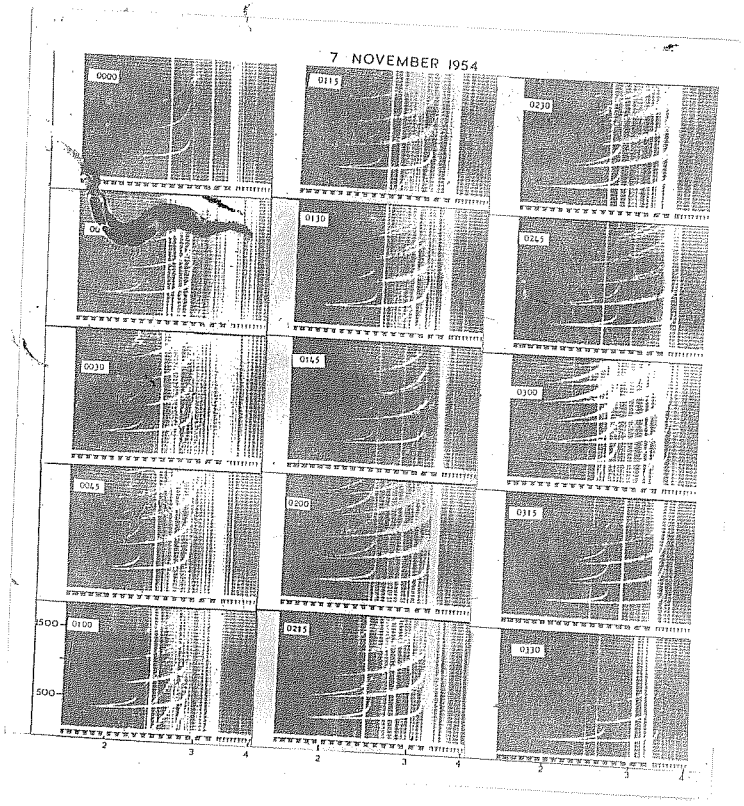


Fig.1
Fig.13.

P'-f records on 7 November 1954 showing the effects of the curvature of the ionospheric surface e.g. (1) high multiples at 0030 to 0145 , (2) anomalous intensity distribution of multiple reflections at 0200 0300 and (3) height split echoes at 0230 and 0245.

Fig. 14 Fig. 15

P'-f records taken in two steps to record all the echoes from the ionosphere.

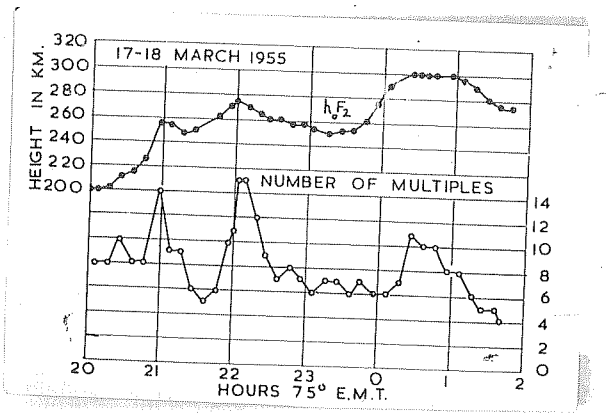


Fig. 16

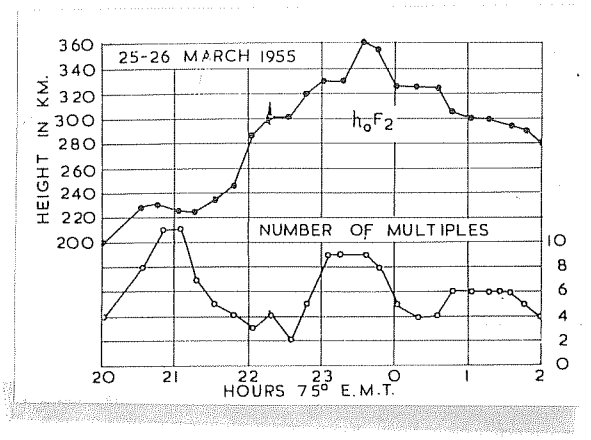


Fig. 17

Variation of the number of multiples reflections with the curvature of the ionospheric surface.

Fig. 18 (b)

P'-f records, showing 4th otder trace stronger than 2nd or 3rd order one,

Fig. 18 (a)

P'-f record showing 3rd order trace stronger than 2nd order one.

Fig. 18 (c)

P'-f record showing 5, 6 and 7th order reflections stronger than the lower ones.

Fig. 19 (b)

Fig. 19 (a)

P'-f records showing 2nd order F2 trace at heights less than twice the 1st order heights.

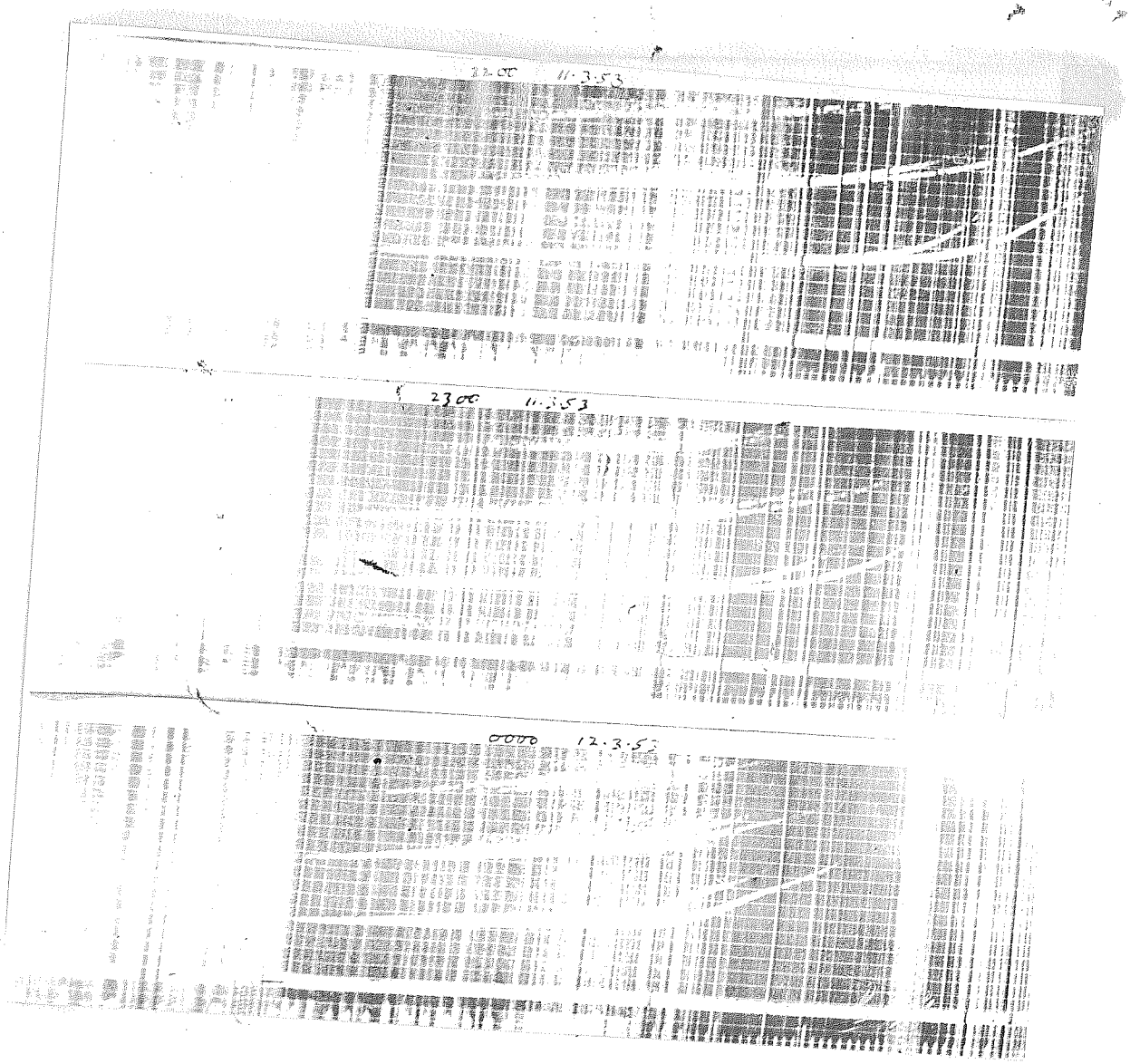


Fig. 20

P'-f records showing anomolous height distribution of the different order traces.

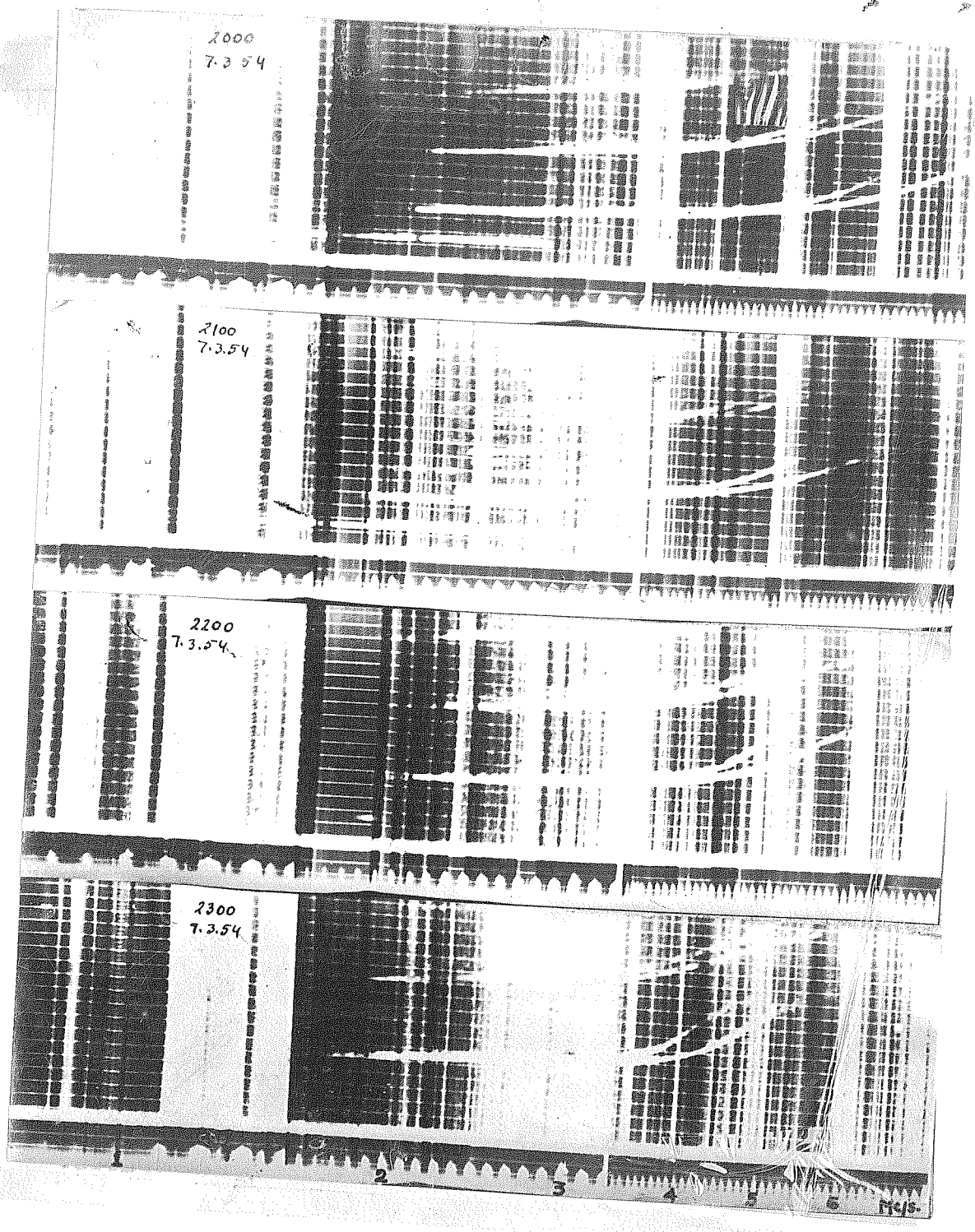


Fig. 21

Fig. 21.

P'-f records showing the anomalous distribution of virtual heights of multiple reflections.

Fig. 22

P'-f record showing the height split echoes on the high multiple reflections.

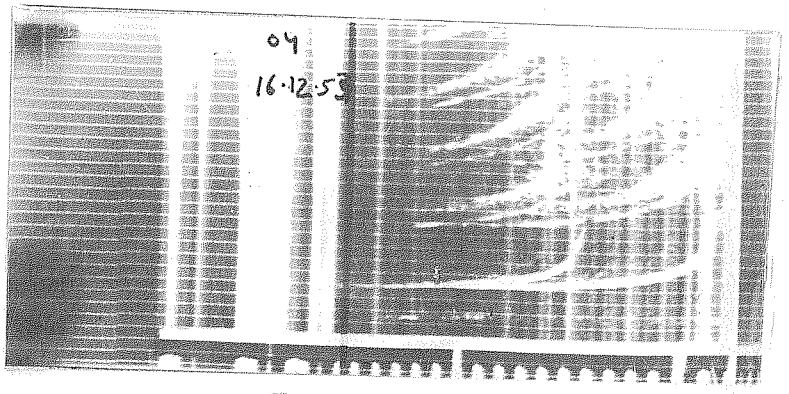


Fig. 23

P'-f records showing single first order traces whereas higher order ones are duplicated.

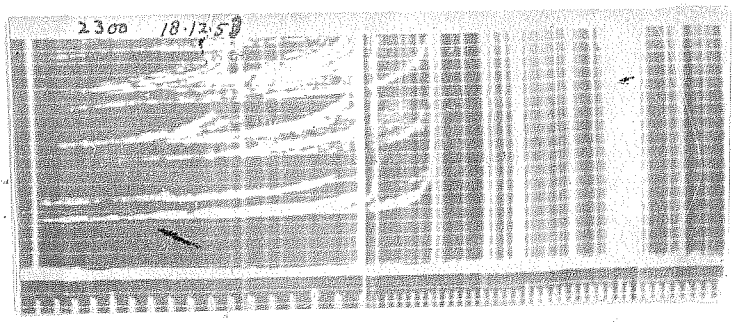


Fig. 24.

P'-f records showing duplicate traces on first as well as on higher order traces.

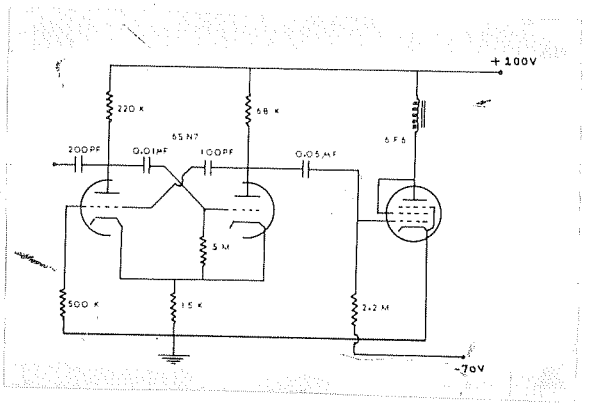


Fig. 25

P'-f records showing broad traces due to the duplicate traces having merged.

Fig. 26

P'-f records showing different critical frequencies for the duplicate traces.

Fig. 27.

h'-f record showing multiple critical frequencies of the F2 layer.

CHAPTER III

ON THE SOLAR CONTROL OF THE E AND F1 LAYERS OF THE IONOSPHERE - VARIATIONS OF k AND n WITH LATITUDE AND WITH SUNSPOT NUMBER.

CONTENTS

		Page
	Introduction	
I.	Latitudinal distribution of E and F1 ionisation at noon.	5
II.	Variation of k and n with latitude.	7
III.	Solar cycle variation of subsolar frequencies of E and F1 layers.	10
	References.	
	Tables.	

On the Solar Control of the E and F1 Layers of the Ionosphere. Variations of k and n with latitude and with sunspot number.

The E and F1 layers of the ionosphere vary with the time of the day and with season in a fairly regular manner. The well known theory of ionised layer formation by solar ultra violet radiation due to Chapman makes the following assumption : (1) the atmosphere is isothermal and (2) the electrons disappear by recombination with positively charged particles, the coefficient of recombination being invariant of height. It follows that when $dn/dt = 0$, the maximum electron density will be proportional to $\cos^{\frac{1}{2}} \chi$ and the critical frequency to $\cos^{\frac{1}{4}} \chi$. Further, stable conditions are assumed with no movement of the ionised particles. The investigations of Appleton (1937), of Best, Farmer and Ratcliffe (1938) and of Naismith (1942) showed that the variation of the ionisations of E and F1 agreed approximately with $\cos^{\frac{1}{4}} \chi$ law both in respect of diurnal as well as of seasonal variation. h_χ was also found to vary linearly with log sec χ in accordance with the theory.

Appleton and Naismith (1939) introduced a quantity called "Region character Figure" Q for the E and F1 layers. This is given by the equation

$$Q = \frac{f_0^4}{\cos \chi}$$

where f_0 is the noon ordinary ray critical frequency and χ is the zenith distance of the sun at noon. The region character figure seems to be independent of season, the seasonal variation being taken care of by $\cos \chi$. Later, Appleton and Naismith (1940) showed that E character figure at Slough had a good correspondence with sunspot number.

Waldemeir (1944) found that for the diurnal variation of the E layer at Kochel the factor $f_0^3/\cos \chi$ was more nearly constant in most of the months than $f_0^4/\cos \chi$. He concluded that the exponent of $\cos \chi$ lay between 3 and 4, being only just greater than 3.

Harnischmacher (1944) studied the variations of the E layer at Huancayo, Washington, Watheroo and Kochel. He obtained the value for the index to be respectively 0.34 0.30, 0.29 and 0.315 and showed that $f_0/\cos^n \chi$ had close agreement with the sunspot number.

Tremmellen and Cox (1947) found for the index of $\cos \chi$ for E and F1, the values 0.31 and 0.22 respectively.

Menzel and Wolbach (1950) studied the variations of f_0E and f_0F1 at various stations of the world and obtained the values of the indices as 0.28 for E and 0.22 for F1.

Scott (1952) in Canada and Saha (1953) in Calcutta

have also made studies of the diurnal variations of E and F1. Rastogi (1954) found that the indices for the E and F1 layers at Ahmedabad were about 0.38 for E and 0.21 for F1.

The seasonal variations of E and F1 layers in relation to cos χ are discussed by the author in a separate paper.

Regarding the latitudinal variation of the ionisation, according to Chapman's theory, the value of the maximum ion-density at noon should be greater at the latitude at which the sun becomes overhead. This is confirmed by observation, for both E and F1 layers. It is also found that the lowest virtual heights appear near the subsolar point and this is in agreement with the theoretical conclusion that for a greater zenith angle of the sun, the level of maximum ion density should descend to lower levels.

A study of the solar control of E and F1 layers has been undertaken in this paper both in years of high as well as low sunspot activity.

It is assumed that the critical frequencies of E and F1 layers follow the relation

$$f_0 = k \cos^n \chi \qquad (1)$$

k can be interpreted as the extrapolated critical frequency of the layer for zenith sun and appropriately called the

subsolar frequency of the layer. The index n which indicates the rate of increase of f_o with $\cos\chi$ may be called the sensitivity of the layer.

The zenith distance of the sun can be calculated as usual from the expression

$$\cos\chi = \cos\phi\cos\delta\cos t + \sin\phi\sin\delta \qquad (2)$$

where δ is the declination of the sun, ϕ is the geographical latitude of the place and t is the hour angle of the sun. Proper corrections have been made to the hour angle for the equation of time, the sweep time of the recorder and the difference between the local time of the place and the meridian time used.

Equation (1) can be written as

$$\log f_o = \log k + n \log\cos\chi \qquad (3)$$

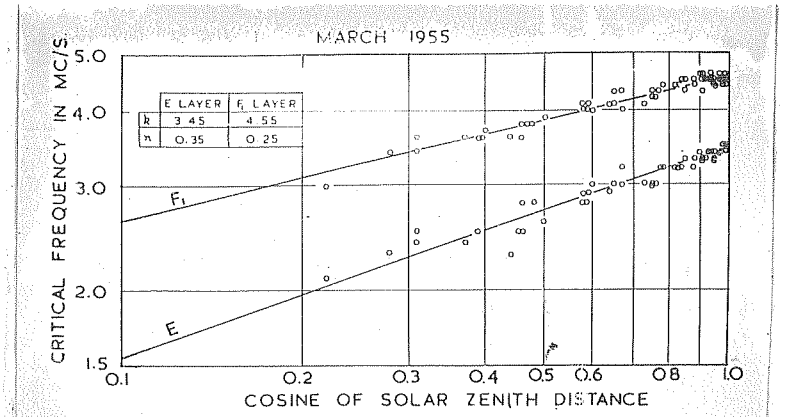
When the hourly mean (or median) critical frequencies of a station for a month are plotted against the corresponding mean $\cos\chi$ values on double logarithmic paper, a straight line could be drawn to pass through the points. The intercept of the line on $\cos\chi = 1$ would give the value of k whereas n would be given by the slope of the straight line or according to equation

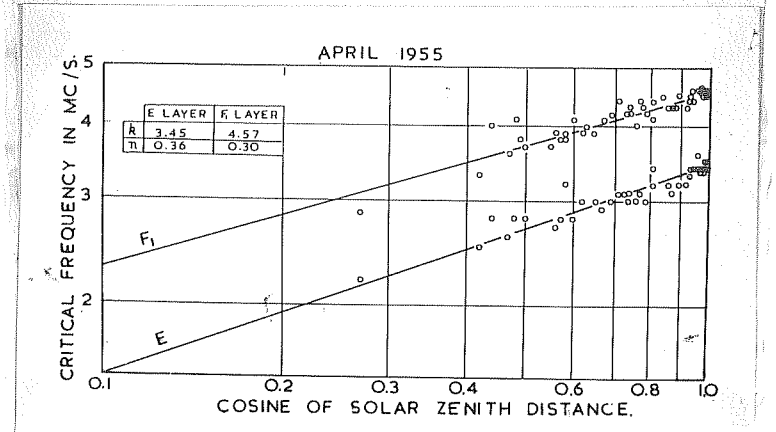
$$n = \frac{\log f_{o_1} - \log f_{o_2}}{\log\cos\chi_1 - \log\cos\chi_2}$$

where f_{o_1} and f_{o_2} are the critical frequencies corresponding to the sun's zenith distances χ_1 and χ_2 respectively. In actual practice cos χ_1 and cos χ_2 were taken as 1.0 and 0.1 so that n was equal to the difference of the logarithms of the intercepts of the straight line at cos χ = 1.0 and cos χ = 0.1 line. Such calculations of k and n were made from the available data of E and F1 for stations in different latitudes. The list of the ionospheric stations studied are given in Tables1 and 2. Tables 1 and 2 give the values of k and n for the two equinoctial months for a year of low sunspot activity (March, April 1955).and for a period of high sunspot activity (September, October 1947). During these equinoctial months the subsolar point is near the equator, and the seasonal difference between the northern and southern hemisphere is not present.

Latitudinal Distribution of E and F1 ionisation at noon.

Figs.1(a) and 1(b) show the latitudinal variation of noon critical frequencies of E and F1 in terms of the noon values of cos χ at the different places for the months of March and April 1955 respectively. The points f_0 and cos χ when plotted on logarithmic paper lie close on a straight line indicating that the latitudinal variation of noon critical frequencies of E and F1 obey $\cos^n\chi$ law. The index





n was 0.32 for the E layer and 0.22 for the F1 layer.

Fig. 2 shows the latitudinal distribution of noon f_0E and f_0F1 for the months of September and October 1947 respectively. The points corresponding to the E layer lie fairly close on a straight line and the value of n is 0.34.

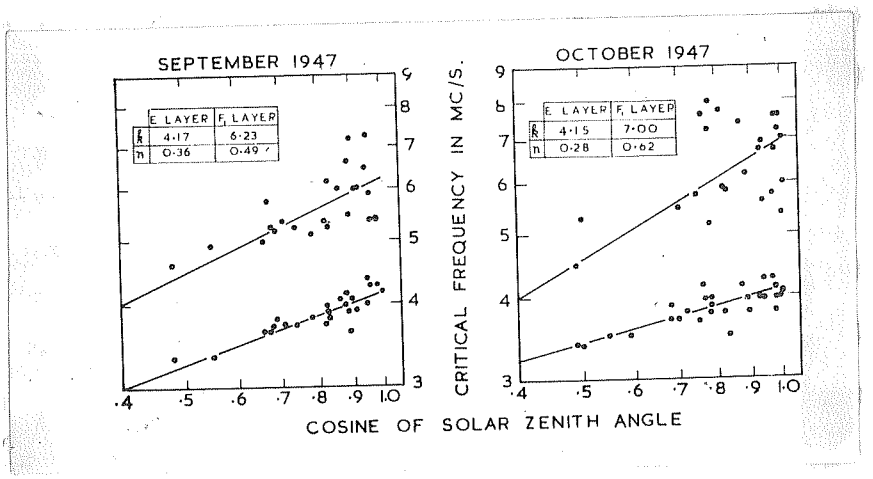


Fig. 2.

But the points corresponding to the F1 layer are scattered

and the value of the index n is very high.

Table 3.

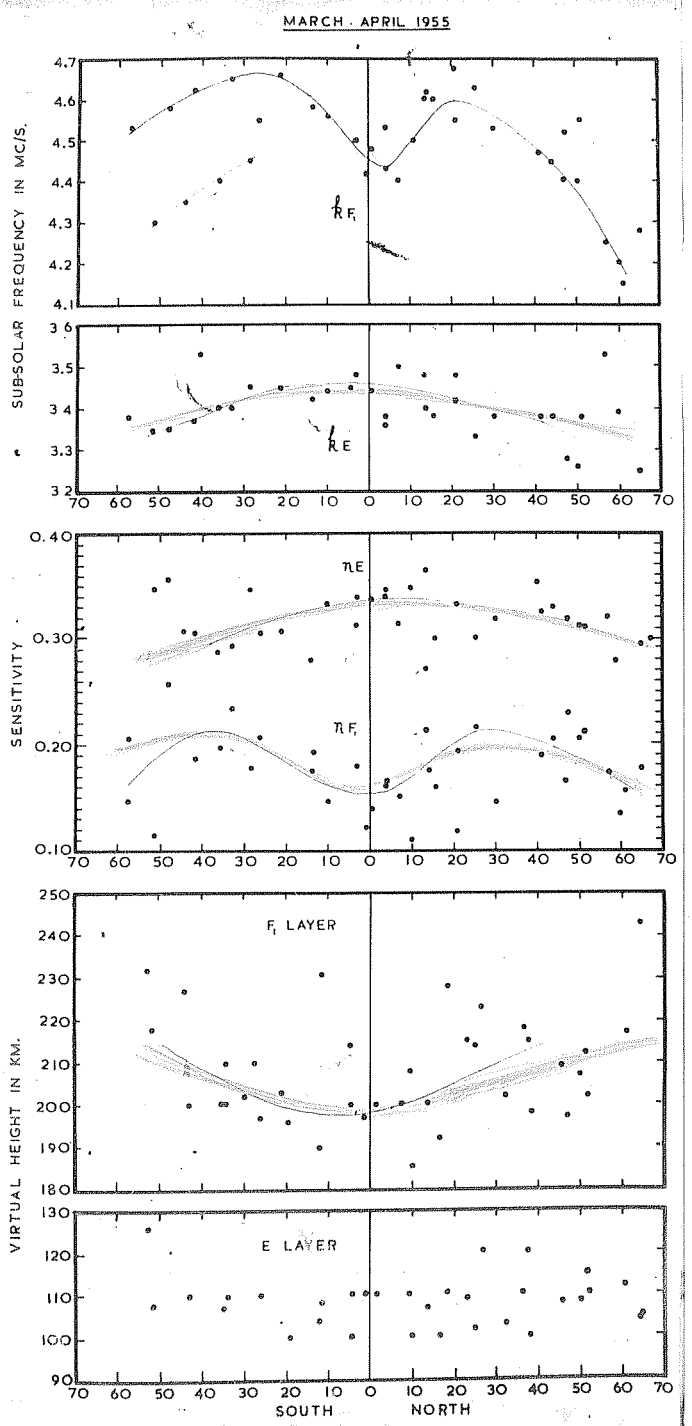
Month	Zurich sunspot no.	kE Mc/s	nE	kF1 Mc/s	nF1
March 1955	4.7	3.47	0.35	4.57	0.25
April 1955	11.3	3.50	0.38	4.60	0.29
Sept. 1947	169.4	4.17	0.36	6.23	0.49
Oct. 1947	163.6	4.15	0.28	7.00	0.62

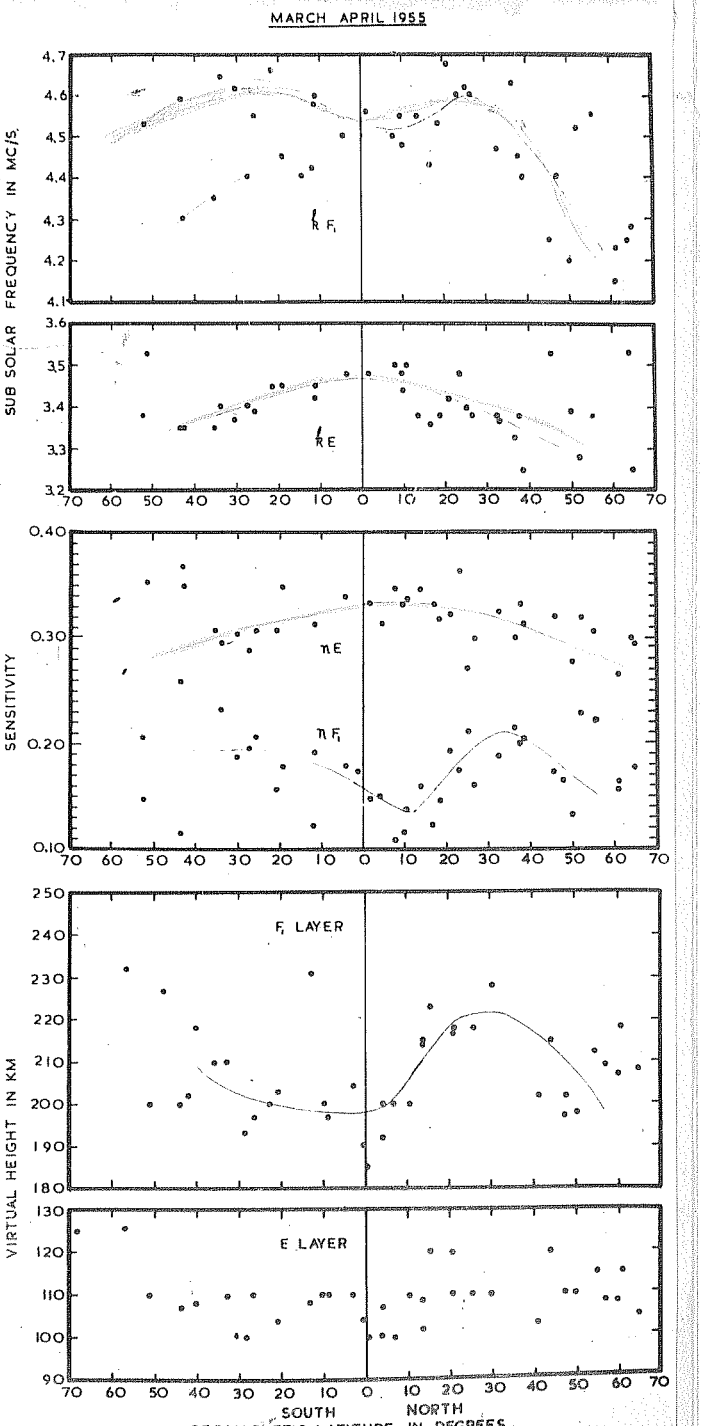
The index nE nearly the same in low and high sunspot periods, although the critical frequencies of the E layer are about 28% greater in high sunspot period than in low. The index nF1, however, has a much higher value in high sunspot period. The percentage increase of F1 layer frequencies from low to high sunspot period is about 50% in middle latitudes and only 15% at higher latitudes.

Variation of k and n with latitude.

The values of k and n of the E and F1 layers for each place from the diurnal variation of the critical frequencies with cosχ determined for the equinoctial months of March-April 1955 are shown in Fig. 3. The variation of heights of the layers are also included in the diagram. This figure shows that in March-April both k and n of E are maximum at the equator. From the scatter of the points,

it is very difficult to say whether geographic or geomagnetic latitude represents the latitudinal variation better. There does not seem to be any significant variation of the minimum virtual height of the E layer with latitude, and most of the points lie between the heights of 100 and 110 km.





As regards F1, there is a definite trough in kF_1, nF_1 and $h'F_1$ near the equator. There are two maxima in kF_1, and nF_1 in middle latitudes (20-40°). $h'F_1$ is low in equatorial latitudes and a maximum in the middle latitudes of the northern hemisphere, but a corresponding maximum is not seen in the middle latitudes of the southern hemisphere. The minima of kF_1 and nF_1 are slightly north of the equator and when plotted on geomagnetic coordinates, they are found at about 10°N.

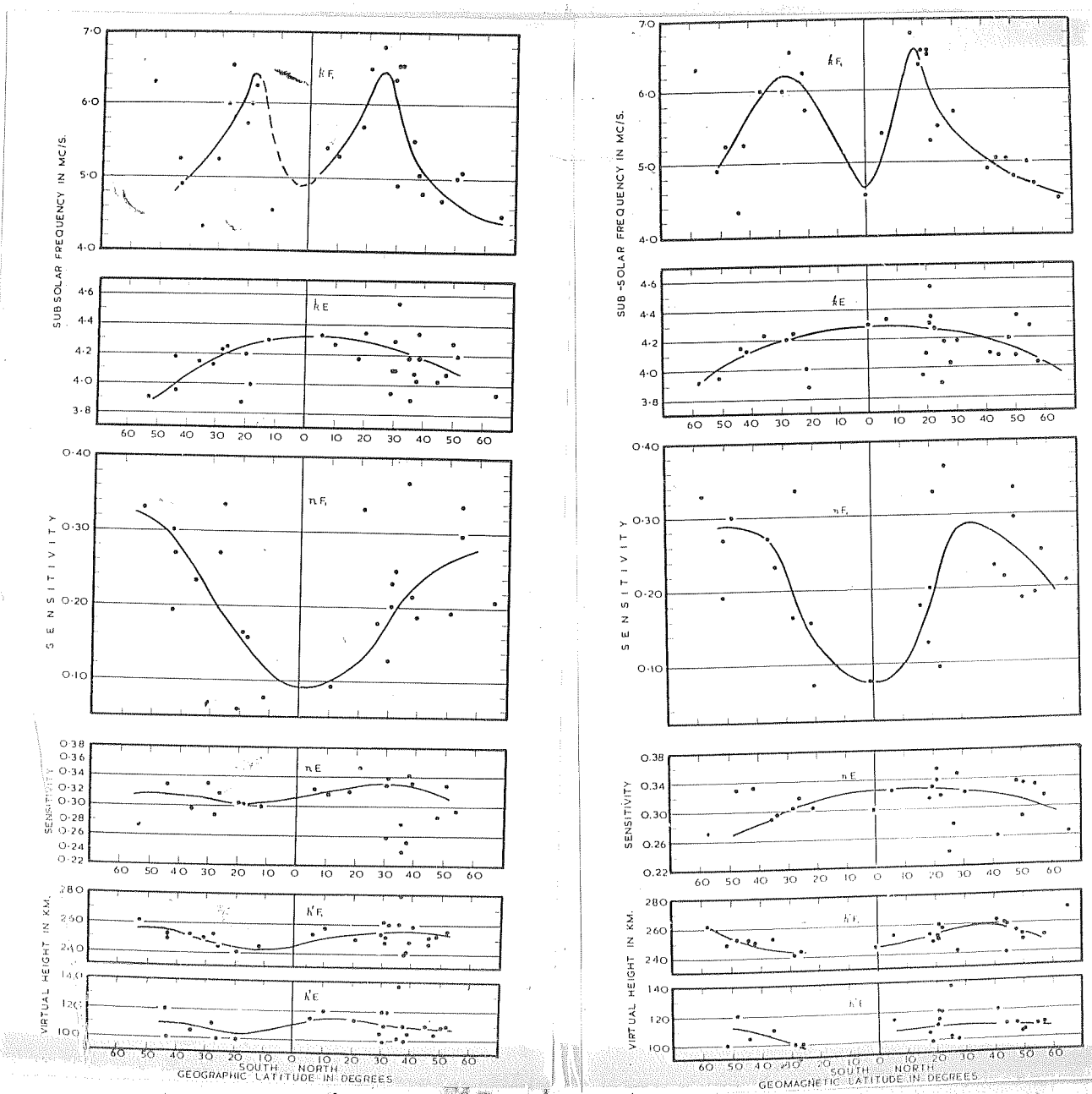


Fig. 4

and sensitivities of E and F1 with geographic and geomagnetic latitudes respectively for the high sunspot period September-October 1947. In this high sunspot period the two maxima in kF1 in middle latitudes are much more pronounced than in 1955. kE however continues to show a maximum at the equator. nF1 is a minimum at the equator. The middle latitude maximum is more clearly seen in the plot against geomagnetic latitudes than in the one against geographic latitude.

Solar Cycle Variation of Subsolar Frequencies of E and F1 Layers.

The relation of the critical frequencies of the ionospheric layers to solar activity has been studied by Allen (1946), Phillips (1947) and Bennington (1953). The critical frequencies for each of these ionospheric layers have been found to be closely related to the sunspot number. The subsolar frequencies of the E and F1 layers may be expected to have even a better correlation with sunspot than the critical frequencies. With this view, the subsolar frequencies of E and F1 at several ionospheric stations were studied. Figs. 5 and 6 show the variation of subsolar frequencies of E and F1 layers with sunspot number over a period of 15 years. The quantities plotted are the twelve-month running means of $\frac{k_E}{f_0 E}$ and $\frac{k_{F_1}}{f_0 F_1}$. The peaks in sunspot number are faithfully reproduced in the subsolar frequency curve.

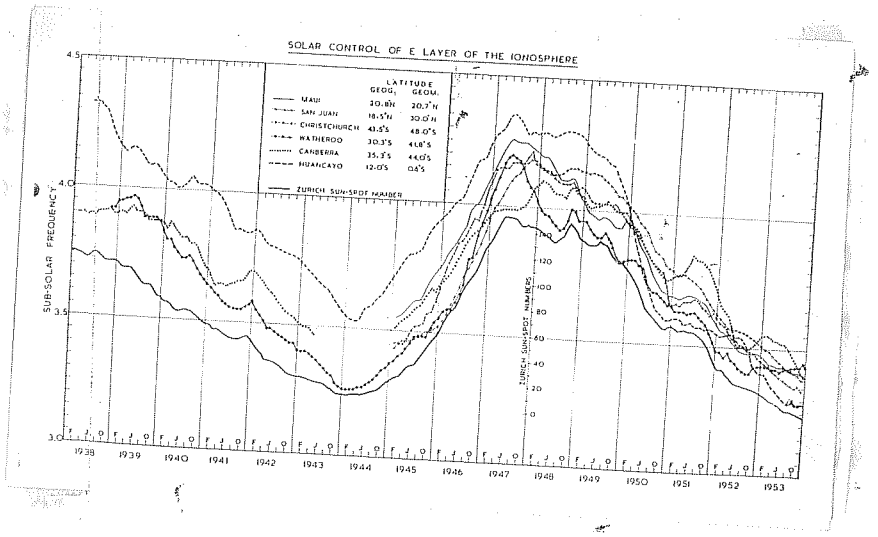


Fig. 5

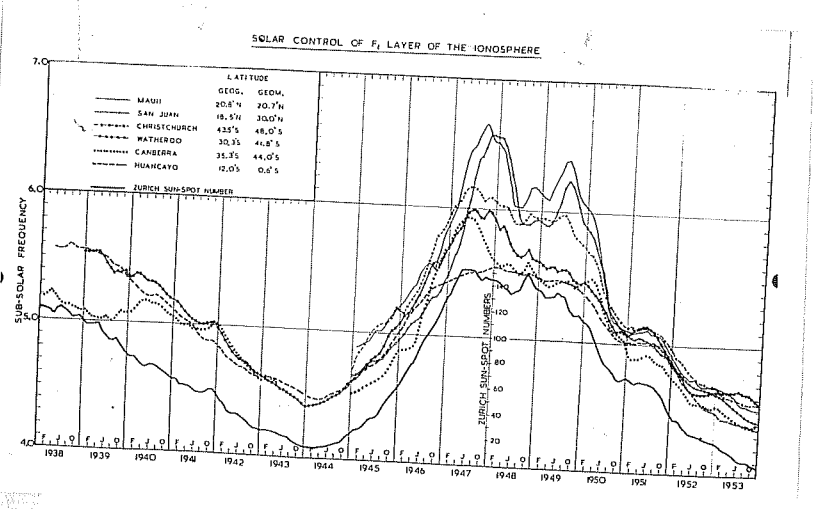


Fig. 6.

The dispersion of the subsolar frequencies of the E layer for different places is almost the same throughout the period indicating that the increase of E layer subsolar frequency which occurs from low to high sunspot period is almost the same at different places in low and middle latitudes.

On the other hand, in the case of the F1 layer, there is very little dispersion in the low sunspot years (see 1951 to 1953) and large dispersion in the high sunspot years. This indicates that the changes of kF1 with sunspot are different at different places on the earth. At a low latitude like Huancayo, the subsolar frequencies of F1 show very little increase for an increase of sunspot number beyond 100 i.e. there seems to be a saturation effect which is perhaps due to an expansion of the high atmosphere near the geomagnetic equator. On the other hand, the subsolar frequencies of F1 at stations at higher latitudes like Watheroo and Christchurch increase with increase in sunspot number and have a high correlation coefficient with it. The stations Maui and San Juan in middle latitude gave very high value of kF1 in 1947 and 1949.

REFERENCES

Allen C.W.	1946	Terr.Mag.Atmos.Elect., 51, 1.
Allen C.W.	1947	ibid 52, 433.
Appleton E.V.	1937	Proc.Roy.Soc., A 162, 451.
Appleton E.V. and Naismith R.	1939	Phil. Mag., 27, 144.
Appleton E.V. and Naismith R.	1940	Proc. Phys. Soc., (London) 52, 402.
Benington T.W.	1953	Wireless Engineer, 30, 175.
Best J.E., Farmer F.T. and Ratcliffe J.A.	1938	Proc. Roy. Soc.,A 164, 96.
Harnischmacher E.	1944	Dtsch.Luftfahrtforschg. Forschungsber, No. 827.
Menzel D.H. and Wolbach J.H.	1950	Proc. General Assembly, U.R.S.I., 8, Part III, 201.
Naismith R.	1942	Paper No. RRB/C.75 Dept. Sci. Ind.Res., England.
Phillips L.M.	1947	Terr.Mag.Atmos.Elect., 52, 321.
Rastogi R.G.	1954	Proc. Ind. Acad. Sci., 40, 158.
Saha A.K.	1953	Ind. Jour. Phys., 36, 1.
Scott J.C.W.	1944	Jour. Geophys. Res., 57, 369.
Waldemeir M.	1944	Helvetica Physica Acta, 17, 168.

Table 1.

List of stations studied for solar control of E and F1 layers during low sunspot period March-April 1955.

Station	Latitude		Mean values for March-April 1955.					
	Geog.	Geom.	kF1	nF1	kE	nE	h'F1	h'E
Fairbanks	64.9	65.1	4.28	0.18	3.25	0.30	208	105
Bakerlake	64.3	73.8	4.25	0.17	3.63	0.30	243	104
Anchorage	61.2	60.9	4.15	0.16	3.10	0.26	218	115
Narsarssuak	61.2	71.6	4.23	0.17	-	-	217	112
Adak	51.9	47.5	4.52	0.23	3.28	0.32	202	110
Winnipeg	49.9	59.7	4.20	0.13	3.39	0.28	207	108
Slough	50.5	54.3	4.55	0.22	3.38	0.31	212	115
Graz	47.1	47	4.40	0.17	-	-	197	-
Ottawa	45.4	56.8	4.25	0.20	3.38	0.33	209	108
Washington	38.7	50	4.4	0.21	3.26	0.31	198	100
Sanfransisco	37.4	44	4.45	0.20	3.38	0.33	215	-
Kokubunji	36.4	25.5	4.63	0.22	3.33	0.30	218	110
Whitesands	32.3	41.1	4.47	0.19	3.38	0.33	202	103
Okinawa	26.3	15.3	4.60	0.16	3.38	0.30	223	120
Formosa	25.0	13.7	4.62	0.21	3.40	0.27	214	102
Ahmedabad	23.0	13.6	4.60	0.18	3.48	0.30	215	109
Mauii	20.8	20.7	4.68	0.19	3.42	0.32	217	120
Puertorico	18.5	30.0	4.53	0.15	3.38	0.32	228	110

Cont.....

Cont... Table 1.

Station	Latitude Geog.	Latitude Geom	Mean values for March-April 1955. kF1	nF1	kE	nE	h'F1	h'E
Baguio	16.4	4.0	4.43	0.16	3.36	0.34	192	100
Guam	13.6	4.0	4.53	0.16	3.38	0.35	200	107
Kodaikanal	10.2	0.6	4.48	0.14	3.44	0.34	185	100
Panama	9.4	20.7	4.50	0.12	3.48	0.33	208	110
Ibadan	7 .4	10.4	4.50	0.10	3.43	0.33	-	-
Singapore	1.3	-10.1	4.56	0.15	3.48	0.33	200	110
Nairobi	- 1.3	- 4.2	4.60	0.18	3.45	0.28	197	110
Leopoldville	- 4.3	- 3.0	4.50	0.18	3.48	0.34	214	110
Tdlara	- 4.6	7.0	4.40	0.16	3.50	0.31	-	-
Elisabethville	-11.6	-13.5	4.58	0.20	3.42	0.31	231	108
Huancayo	-12.0	- 0.6	4.42	0.12	3.25	0.27	190	104
Townsville	-19.3	-28.4	4.47	0.16	3.45	0.33	-	-
Rarotonga	-21.3	-21.0	4.66	0.16	3.45	0.31	203	104
Johanesburg	-26.2	-26.7	4.55	0.21	3.39	0.31	197	110
Brisbane	-27.5	-35.9	4.40	0.11	3.40	0.29	-	-
Watheroo	-30.3	-41.8	4.62	0.19	3.37	0.30	202	-
Captown	-34.2	-33.0	4.65	0.24	3.40	0.29	210	110
Canberra	-35.3	-44.0	4.42	0.19	3.38	0.29	-	-
Hobart	-42.9	-51.4	4.30	0.12	3.33	0.33	-	-
Christchurch	-43.5	-48.0	4.58	0.26	3.35	0.36	227	-
Falkland	-51.7	-40.4	-	-	3.53	0.35	218	108
Campbell	-52.5	-57.2	4.53	0.15	3.38	0.20	232	126

Table 2.

List of stations studied for solar control of E and F1 layers during high sunspot period September-October 1947.

Station	Latitude Geog.	Latitude Geom.	Mean values for Sept.-Oct. 1947 kF1	nF1	kE	nE	h'F1	h'E
Fairbanks	64.9	65.1	5.50	0.21	3.93	0.26	259	-
Adak	51.9	47.5	6.08	0.34	4.2	0.30	230	110
Slough	50.5	54.3	6.00	0.19	4.28	0.33	238	109
Fribourg	48.1	49.4	-	-	4.08	0.29	223	104
Ottawa	45.5	56.8	5.70	0.25	4.03	0.32	222	100
Washington	39.0	50.0	5.80	0.19	4.35	0.33	216	110
Shibata	37.9	29.6	-	-	4.03	0.35	204	110
Sanfrancisco	37.4	44	6.05	0.21	4.08	0.25	220	110
Lanchow	36.1	24.7	6.50	0.37	3.90	0.24	280	137
Tokyo	35.7	25.5	-	-	4.18	0.28	240	102
Nanking	32.1	20.7	7.55	0.25	4.55	0.42	240	120
Yamagawa	31.2	20.3	-	-	4.30	0.34	224	110
Wuchang	30.6	19-2	7.55	0.20	4.10	0.33	216	98
Batonrouge	30.5	41.2	5.90	0.23	4.10	0.26	244	120

Cont....

Table 2 cont....

Station	Latitude Geog.	Latitude Geom.	Mean values for Sept.-Oct 1947 foF1	foF2	foE	MUF(3000)F2	h'F1	h'E
Chunking	29.4	17.9	7.35	0.13	3.95	0.21	227	105
Okinawa	26.3	15.3	7.80	0.18	-	-	-	-
Mauii	20.8	20.7	7.50	0.33	4.35	0.35	220	114
Puertorico	18.4	30.0	6.70	0.45	4.18	0.32	-	-
Trinidad	10.6	22.0	6.30	0.10	4.27	0.32	235	120
Palmyra	5.9	5.3	6.40	-	4.33	0.33	227	115
Huancayo	-12.0	-0 .6	5.55	0.08	4.30	0.30	210	-
Fiji	-18.0	-22.1	7.25	0.16	4.00	0.30	-	-
Townsville	-19.4	-28.4	7.0	0.16	4.20	0.30	201	100
Rarotonga	-21.0	-21	6.75	0.07	3.88	0.29	-	-
Johannesburg	-26.2	-26.7	7.55	0.34	4.25	0.32	208	100
Brisbane	-27.5	-35.9	7.00	0.27	4.23	0.29	225	110
Watheroo	-30-3	-41.8	6.25	0.43	4.13	0.33	220	-
Canberra	-35.3	-44	5.33	0.23	4.15	0.30	225	105
Hobart	-42.8	-51.4	5.90	0.19	3.95	0.27	219	98
Christchurch	-43.5	-48	6.25	0.30	4.18	0.33	243	-

CHAPTER IV

A STUDY OF THE NOON CRITICAL FREQUENCIES OF THE E AND F1 LAYERS OF THE IONOSPHERE

A Study of the Noon Critical Frequencies of the E and F1 Layers of the Ionosphere.

The E and F1 layers of the ionosphere experience regular changes during the day, with season and with solar activity. The average daily and seasonal changes in the ionisation of these layers are in approximate accord with the simple relation of Chapman's theory of ionized layer formation (Kirby and Judson 1935; Gilliland 1935; Appleton 1937; Best, Farmer and Ratcliffe 1938; Hulburt 1939). Noon ionisation of these layers is found to rise and fall with sunspot number and the ionisation can be expressed by a simple linear relation (Hulburt 1940; Phillips 1947; National Bureau of Standards 1948). Examining the E and F1 layer data more critically, the E layer was found to be more regular than F1. The seasonal variation of F1 noon critical frequencies at many places did not follow the cos$^{\frac{1}{4}}$ law strictly. Lejay and Ardillon (1950) pointed that the seasonal variation of F1 was very different from that of E. Further, the influence of the solar cycle on f_0F1 was found to be greater at higher latitudes.

Regular ionospheric soundings were started at Ahmedabad in January 1953. The coordinates of the station are

Geog. Lat.	23°02'N
Geog. Long.	72°38'E
Geomag.Lat.	13.6°N
Mag. Dip.	34°N.

The station is situated near the northern peak of F2 layer ionisation and hence the ionosphere at Ahmedabad has presentpd some interesting features. It was found that the F1 layer critical frequencies in the summer of 1953 had decreased below those in March-April 1953, and that another maximum of f_0F1 appeared in the months of September and October. The E layer critical frequencies,on the other hand, showed a single maximum in local summer and a minimum in local winter. The variation of f_0E and f_0F1 at Ahmedabad during the last three years is shown in Fig.1. The two maxima of f_0F1 in March-April and in September-October are most conspicuous in 1954, the year of least solar activity. This behaviour of f_0F1 is analogous to that of f_0F2 at Ahmedabad and at stations in middle latitudes.

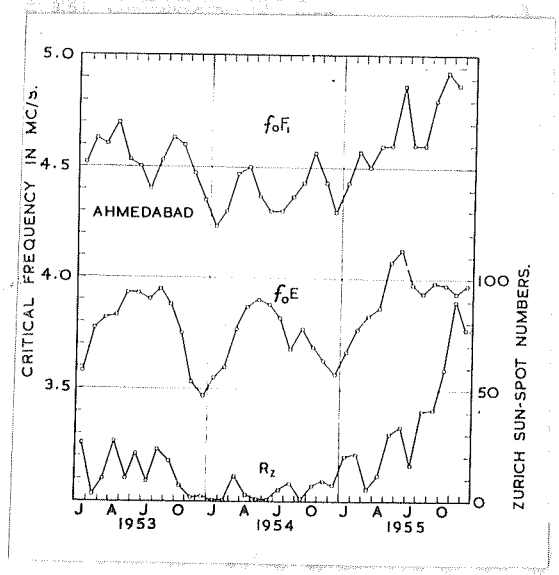


Fig. 1.

The seasonal variation of noon f_0E and f_0F1 at other stations at about the same latitudes as Ahmedabad viz. Maui (20.8°N), Rarotonga (21.3°S) Yamagawa (31.2°N) and Puertorico (18.5°N) during the years 1952-1954 are shown in Fig.2. At all the places f_0E shows a single maximum in local summer and a minimum in local winter. The inverse relationship between the North and the South hemisphere is seen in the curves for the E layer. On the other hand f_0F1 shows minima in solstices and maxima in equinoctial months. There is no inverse correlation between the stations of the Northern and Southern hemispheres.

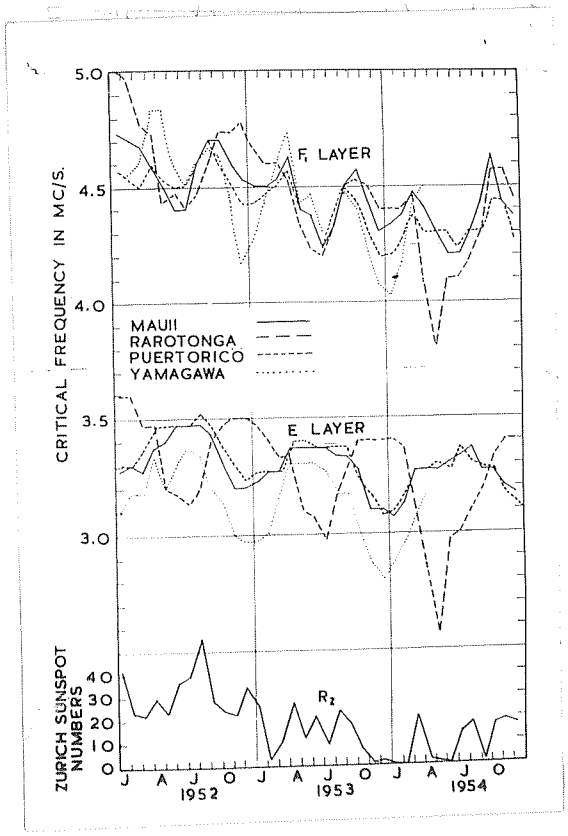


Fig.2.

With a view to examine whether the summer minimum in f_0F1 could be attributed to thermal expansion of the F1 layer, the actual heights and semi-thicknesses of the layer were calculated from the P'-f records at Ahmedabad by Ratcliffe's method (1956). These are shown in Fig.3. It is seen that the semi-thickness of the layer is maximum at noon

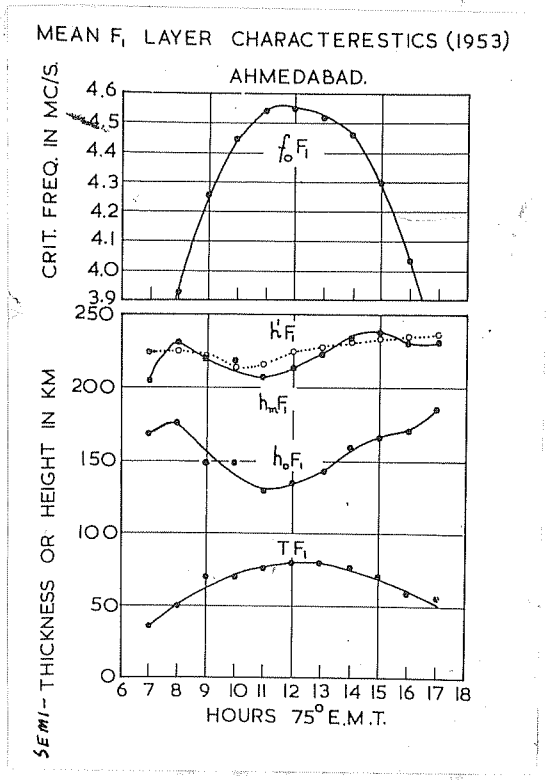


Fig. 3.

the variation being nearly symmetrical at about noon. The heights of these base (h_0F1) and of maximum electron density (h_mF1) are lowest at about 11 hr. In Fig. 4 are shown the seasonal variations of the semi-thickness and of the total electron content in a vertical column upto the level of

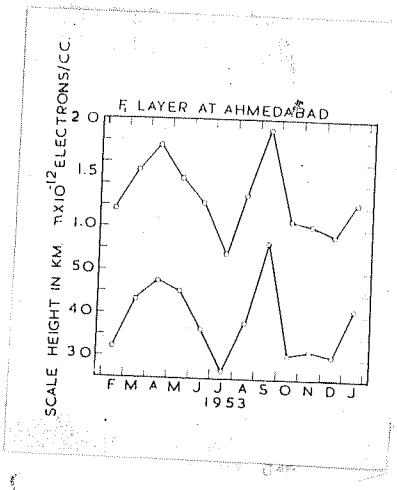


Fig. 4.

maximum electron density of the F1 layer (nF1). Both the electron content and the thickness varied in a similar way to f_0F1. The behaviour of the ionisation of the E and F1 layers at various other ionospheric stations are given below. Only the noon critical frequency of E and F1 layers were studied.

First the variations of f_0E and of f_0F1 with solar activity were examined. The noon critical frequencies of E and F1 can be expressed by a relation of the form

$$f_0 = a(1 + bR_z)$$

where a and b are constants depending on the layer, the position of the station, season and hour of the day and R_z is the Zurich sunspot number. Figs. 5,6,7 and 8 show mass plots of monthly mean noon critical frequencies of E and F1 against the corresponding ~~the~~ sunspot number ~~of~~ for the stations, Slough, Canberra, Huancayo and Rarotonga respectively. It will be

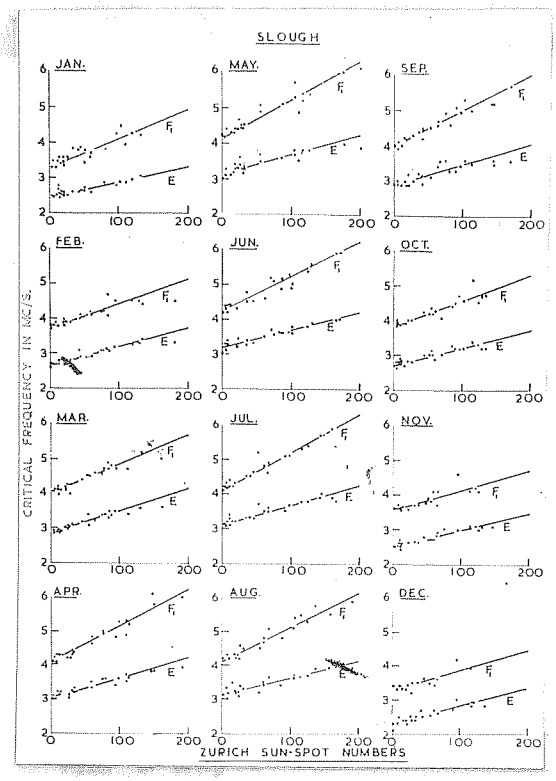


Fig. 5

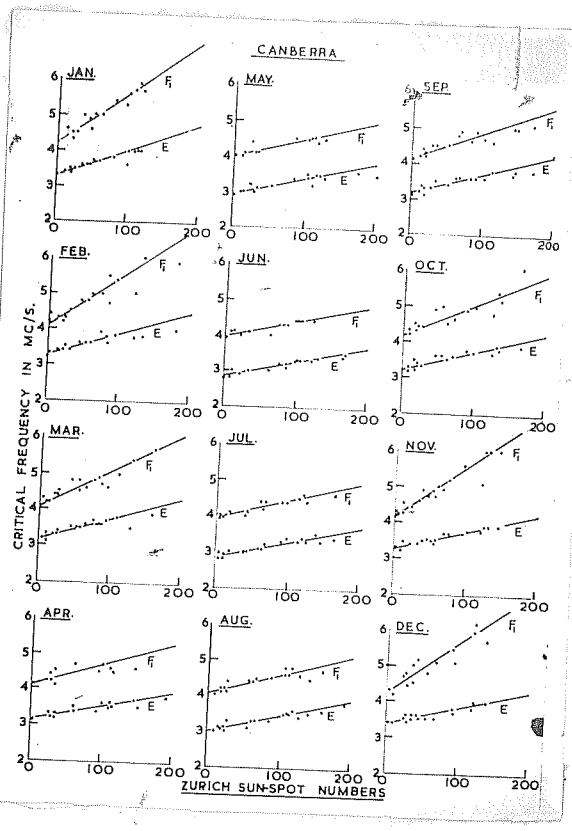


Fig. 6

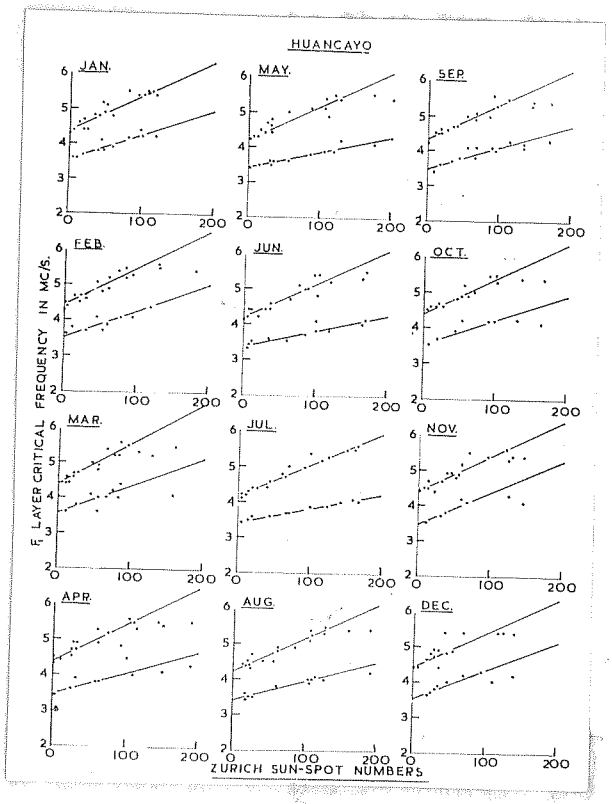


Fig. 7

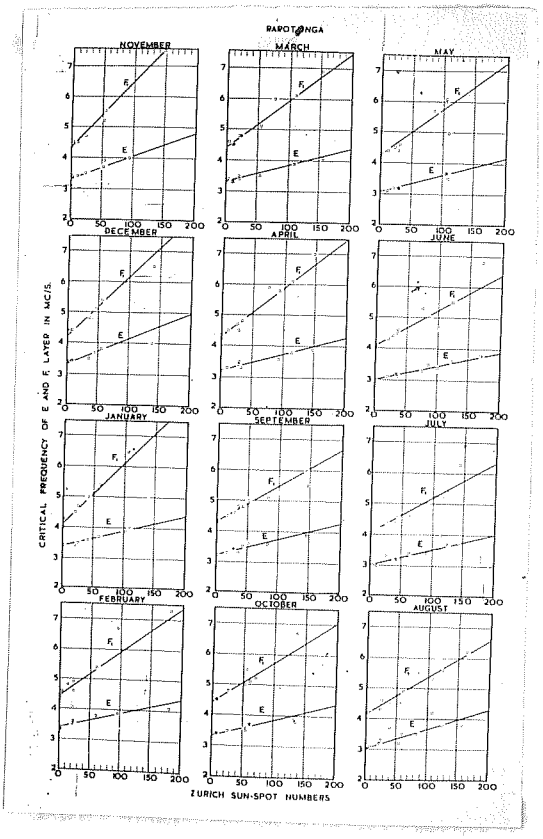


Fig. 8

seen that f_0E and f_0F1 vary with R_Z approximately linearly. From Fig. 5 it is clear that the slope of the straight line for F1 at Slough is a minimum in the winter months of November, December, January and February and a maximum in the summer months of May, June, July and August. The slope of E layer critical frequency does not show any such seasonal variation. In the case of Canberra, (Fig. 6) the slope of the line is maximum in November, December, January and February (Southern Summer), and the minimum in May, June, July and August (Southern winter). At Huancayo, the slope of line for F1 remains practically constant, whereas that of the E layer seems to be a maximum in local summer and a minimum in local winter. An interesting fact observed about Rarotonga is that the slope of the straight line for f_0F1 in any month is greater than that for any other stations studied.

In Fig. 9 are plotted the seasonal variations of b(E) and b(F1) for a few typical stations. b(E) at any place seems to be practically constant throughout the year except at Huancayo and Trinidad. b(F1) on other hand has a systematic seasonal variation. There does not seem any correspondence between the seasonal variation of b(F1) and the cosine of the solar zenith distance ($\cos \chi$), but b(F1) is maximum during local summer and minimum during local winter at ally station. b(F1) at Huancayo is practically constant throughout the year. It may be remembered that the sunspot cycle variation of f_0F2 is different in summer and

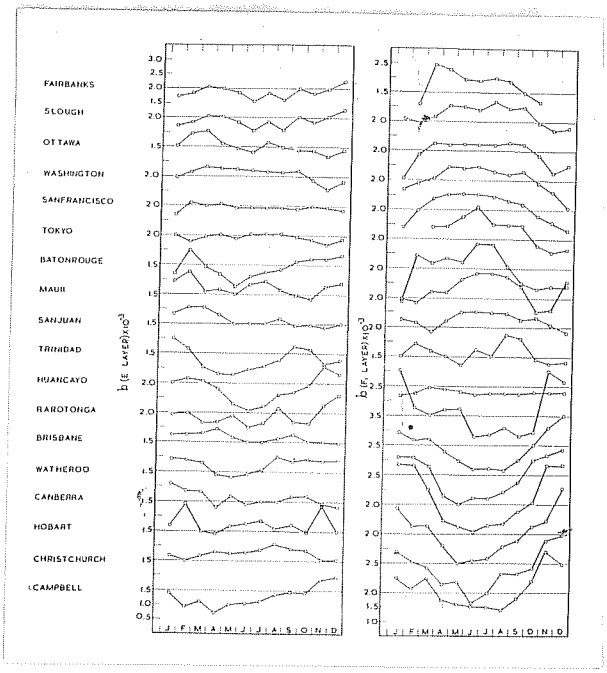


Fig. 9.

winter (Characteristics of the Ionosphere in England), being less in summer than in winter which is just opposite to the effect on f_0F1. A similar effect on f_0F2 at Washington has been found by Bennington (1953). He pointed out that the sunspot cycle effect was less in the months of minimum f_0F2 than in the months of maximum f_0F2 and called this a s saturation effect in f_0F2 during period of minimum f_0F2.

In Fig.10 are plotted the annual mean values of b(E) and b(F1) against geographical latitude. b(E) is practically constant or decreases slightly at high latitudes. b(F1) varies appreciably with latitude with two sharp maxima at 20-30° latitudes and a minimum at the equator. This means

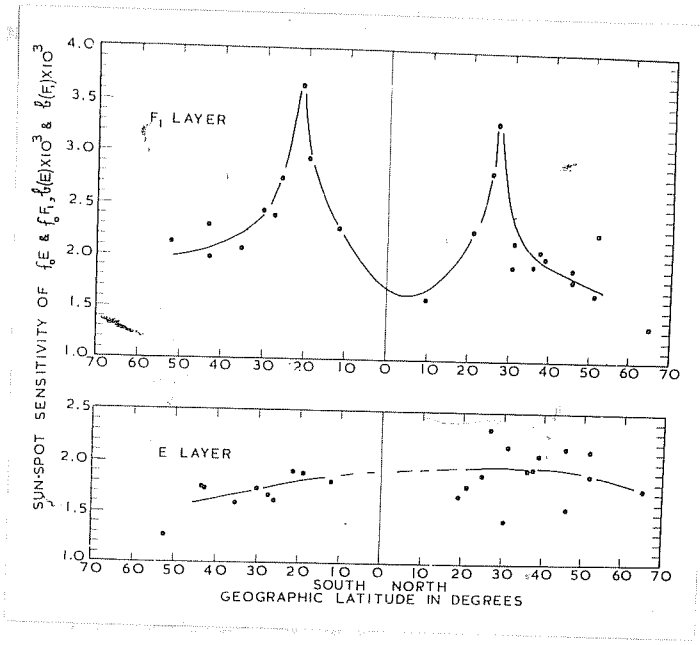


Fig.10

that the effect of sunspot activity on f_0F1 is maximum at middle latitudes. The two peaks in Fig.10 occur at Rarotonga (21°S) in the South and at Okinawa (26°N) in the North.

Referring again to Figs. 5 to 8, the intercepts of the lines on $R_z = 0$ i.e. the value of the constant a, gives

the critical frequencies of the E layer for zero sunspot number. It was found that the values of a(E) and a(F1) were nearly the same as the monthly mean noon values of f_0E and f_0F1 (11-13 hours L.M.T.) during the sunspot minimum year 1954. In Fig.11 are shown the seasonal variations of a(E) and a(F1) for a few stations.

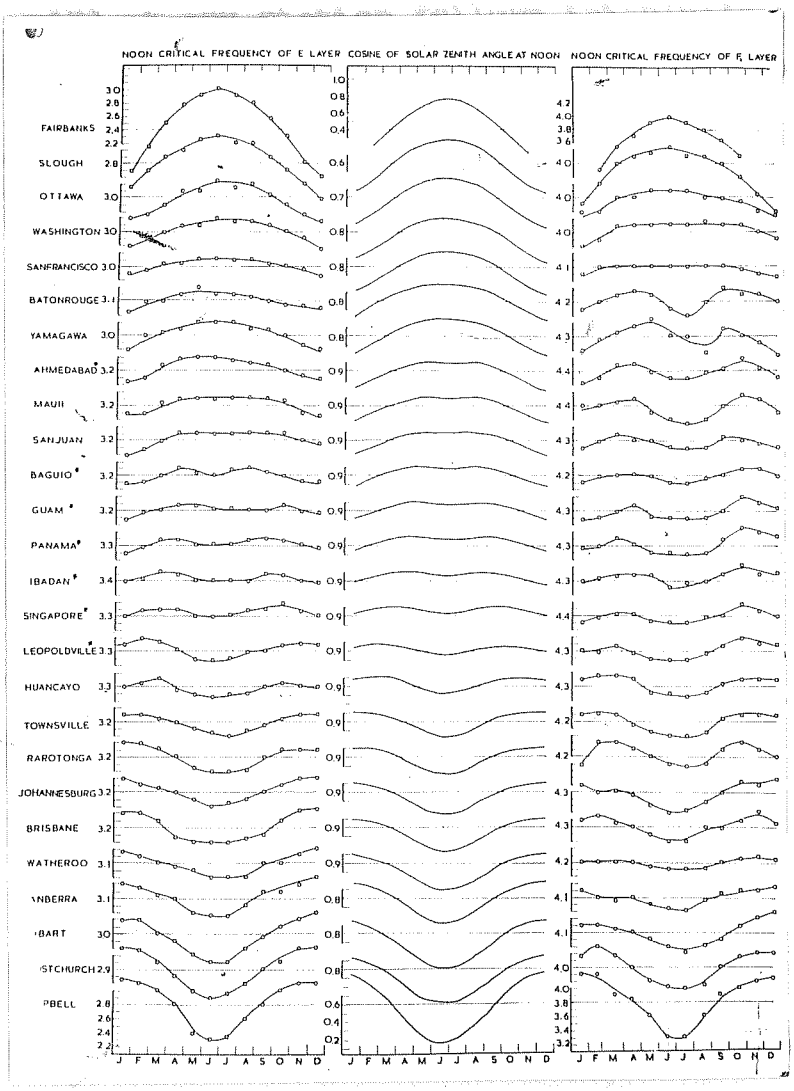


Fig. 11.

To give an idea of the latitudinal variation of these factors near the equatorial zone the noon critical frequencies of some additional equatorial stations have been included though these do not have long period observations. These stations are marked with asterisks. For comparison, the seasonal variation of $\cos\chi$ is also shown in the figure. It will be seen that a(E) at any station follows faithfully the corresponding cos χ curve, but that a(F1) behaves differently. At high latitudes a(F1) follows the $\cos\chi$ variation, but at the middle latitudes a(F1) has two pronounced maxima during the year, whereas $\cos\chi$ shows only one flat hump. At equatorial stations where $\cos\chi$ shows the maximum twice in a year, the maxima of a(F1) do not correspond to those of $\cos\chi$. The maxima in a(F1) appear in the equinoctial months irrespective of the geographic position of the station. This shows that besides the usual $\cos\chi$ effect on the ionisation of F1, there exists another perturbing influence causing maxima in the equinoctial months.

In Fig. 12 the annual mean values of a(E) and a(F1) are plotted against latitude. Both show maxima at the equator and decrease with increasing latitudes.

In order to ascertain whether a(F1) shows a maximum at the equator in all the months of the year, the mean values of a(F1) for March, April, September and October are plotted in Fig. 13.

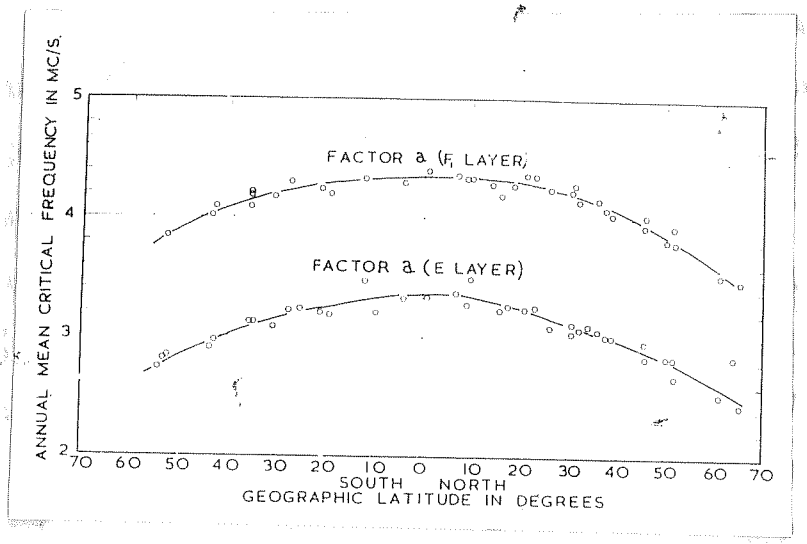


Fig. 12

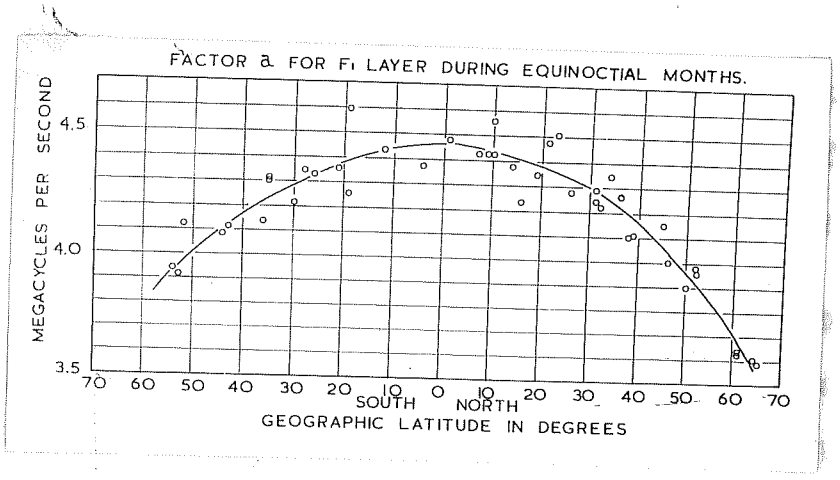


Fig. 13

It is seen that a(F1) shows a single maximum at the equator even in the equinoxes, when seasonal maxima of a(F1) are observed at stations in low and middle latitudes. It is concluded therefore, that a(F1), i.e. F1 layer critical

frequency for zero sunspot period, is maximum at the equator in all the months of the year. This does not agree with the conclusions of Miss Ghosh (1955) that F1 experiences a geomagnetic control analogous to that of the F2 layer both in high sunspot and low sunspot years. It may be noted that she had taken 1951 as a representative of the low sunspot year. Sato (1955) did not find any trough in the latitudinal distribution of noon critical frequencies of F1 layer during 1953, a period of less solar activity than 1951. The appearance of pronounced maxima of b(F1) at middle latitudes and single maximum of a(F1) at the equator suggests that as the sunspot activity increases, there is proportionately a greater increase of f_0F1 in middle latitudes. It must be remembered that f_0F2 showed maxima at middle latitudes during the low sunspot year of 1954. So F1 differs from F2 in its latitudinal distribution in minimum sunspot years.

According to Chapman's simple theory of layer formation the seasonalvariation of noon critical frequencies of a layer should follow the $\cos^{\frac{1}{2}}$ law. However, the exponent of cos has been found to be variable both in E and F1 The constant K of the equation ~~f_0 is equal to K $\cos^N$~~ $f_0 = K\cos^N\chi$ can be obtained by plotting the monthly mean noon critical frequencies (more exactly a(E) of a(F1)) against the corresponding cos χ on double logarithmic graph paper. Such an evaluation of N(E) and N(F1) was made either from the values of a, or of noon critical frequencies where athe former was

not available. Fig. 14 shows the variation of N with latitude for the E layer. It is seen that there are minima of N(E) at

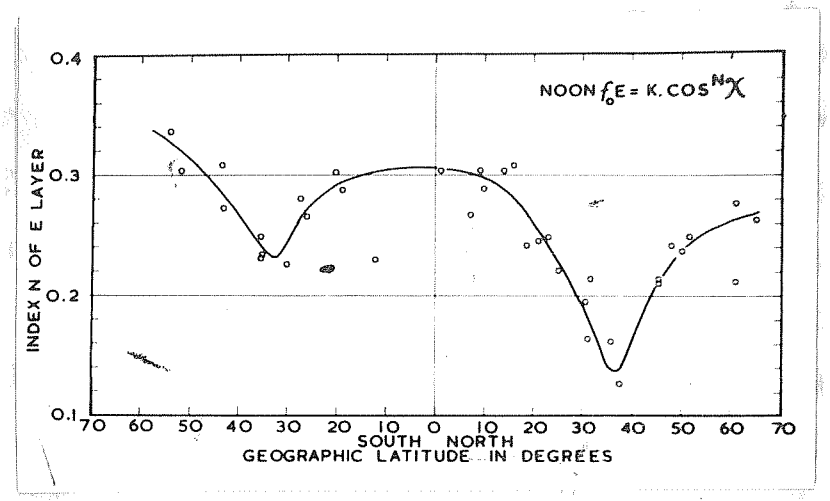


Fig. 14.

latitudes of about 35°. There appear to be similar minima in N(F1) also, though the scatter is much greater in this case. (Fig.15). N(F1) for equatorial stations could not be evaluated as the maximum value of f_0F1 does not occur ~~at noon~~ in summer when $\cos\chi$ is a maximum.

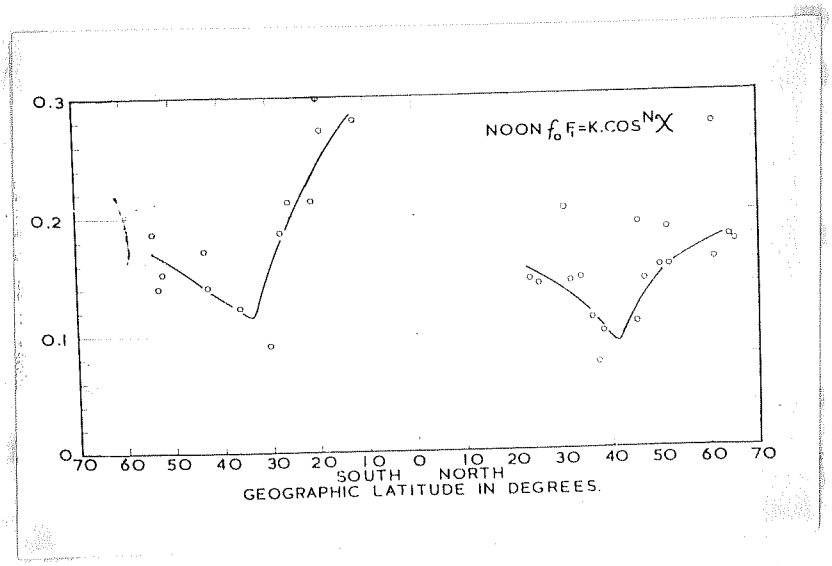


Fig. 15

Recently, Beynon and Brown (1956) have reported two maxima in the exponent n $\left[(fE)^n = k \cos^n \chi \right]$ of the seasonal variation of E layer noon critical frequencies. These correspond to the two minima of the exponent N in our analysis. Beynon explained these maxima in terms of vertical drifts in the E layer due to the S_q current system flowing in the ionosphere. Curiously, however, in the case F1 layer, the minima of the exponent N derived from the seasonal variation and the maxima of the factor b derived from solar cycle variation do not occur at the same latitude; the latter appears about ten degree nearer to the equator. The peaks of b(F1) at about twenty five degrees and the minima of N(F1) at about thirty five degrees may be due to the shift of the S_q current focus by ten degrees towards the equator in high sunspot years.

Summary

1. Solar cycle variation :

(i) The noon critical frequencies of E and F1 layers vary with Zurich sunspot numbers approximately according to the law $f_o = a(1 + bR_z)$.

(ii) The factor b for the E layer of a station is the same for the different months of the year.

(iii) The factor b for the F1 layer of a station is maximum in local summer and minimum in local winter.

(iv) The factor b(E) is almost same for any latitude.

(v) The factor b(F1) is maximum in middle la latitudes (20-30°) with a depression at equator.

(vi) The factor a(E) follows the solar zenith distance at the place, for any latitude.

(vii)The factor a(F1) follows the solar $\cos\chi$ variation only at high latitudes. It has two maxima in the equinoctial months for stations in middle and equatorial latitudes.

(viii)The annual mean values of the factors a(E) or a(F1) show maxima at the equator.

2. Seasonal Variation

The seasonal variation of a a(E) and a(F1) can be put in the form

$$f_o = K \cos^M \chi$$

and the exponents M for the E and F1 layers show minima in middle latitudes(30-40°).

References

Appleton E.V.	1937	Proc.Roy.Soc., A162, 451.
Best J.E. and Farmer F.T. and Ratcliffe J.A.	1938	Proc.Roy.Soc., A164, 96.
Beynon W.J.G., and Brown G.M.	1936	Nature, 177, 583.

Dept. Scientific & Industrial Research, London.	1953	Characteristics of the Ionosphere observed in Great Britain 1930-1945.
Ghosh M.(Miss)	1955	Jour.Geophys.Res., 60, 115.
Gilliland T.R.	1935	Proc.I.R.E., 23, 1078.
Hulburt E.O.	1939	Phys.Rev., 55, 639.
Kirby S.S. and Judson E.B.	1935	Proc.I.R.E., 23, 733.
Lejay P. and Ardillon M.J.	1950	Proc.General Assembly URSI, 8, 259.
Phillips M.L.	1947	Terr.Mag.Atmos.Elect., 52, 321.
Ratcliffe J.A.	1951	Jour.Geophys.Res., 56, 463.
Sato T.	1955	Rep.Ionospheric Research, Japan, 9, 205.
National Bureau Standard, Washington.	1948	Ionospheric Radio Propagation N.B.S., Circular 462.

* * * * * * *

CHAPTER V

SOLAR ECLIPSES AND THE IONOSPHERE

CONTENTS

Page

I. A. Vertical soundings at Ahmedabad during total solar eclipse on 30 June 1954.

B. Vertical soundings at Ahmedabad during partial solar eclipse on 14 December 1955.

II. Some measurements of the signal strength of radio waves reflected from the ionosphere during the solar eclipse of June 30, 1954 and June 20, 1955 (To be published in ~~Jour. Atmos. Terr. Phys.~~ Solar Eclipses and the Ionosphere.)

III. Reprints of the papers :-

(1) A note on Radio Field Strength....during the total eclipse on 30 June 1954.

(2) Field strength....during the partial solar eclipse of 14 December 1955.

III. Introduction. 1

(I) (1) Vertical incidence ionospheric absorption 3

(2) Oblique incidence propagation and absorption. 6

(3) Absorption of radio waves during a solar eclipse. 9

(II) A. Vertical incidence ionospheric absorption measurements. 12

page

B. Review of some oblique transmission measurements during eclipses. 16

C. Long distance short wave propagation during solar eclipses. 34

References.

PART I

A. Vertical soundings at Ahmedabad during total solar eclipse on 30 June 1954.

On June 30, 1954 there occurred a solar eclipse at Ahmedabad (23°02'N, 72°36'E). Ahmedabad lay to the south of the shadow track. As the eclipse occurred late in the evening it was considered that the characteristics of the eclipse would not be the same at different levels above the ground and the times and phases of the eclipse at heights of 0, 100, 200 and 300 km above Ahmedabad were therefore calculated. The results are given in Table 1.

Table 1.

Characteristics of the eclipse of 30 June 1954 at Ahmedabad.

Height above the ground	0 km	100 km	200 km	300 km
Time of the beginning of the eclipse.	1807.4	1808.4	1809.5	1810.7
Time of maximum phase of the eclipse.	1859.3	1858.3	1857.2	1856.2
Magnitude of the eclipse	93 %	94 %	97 %	99.6%
Time of Sunset.	1859	1944	2004	2021

The times are given as 75°E.M.T.

It is seen that though there was not much difference in the times of the various phases of the eclipse at different heights, the eclipse at 300 km was almost total whereas at ground level it was only 93%. The times of sunset at different heights were, of course, different. At ground level the sun had set at the time of maximum obscuration, but at greater heights, the sun had begun to be uncovered before it went below the horizon.

The British N.P.L. type automatic ionospheric height recorder installed in the laboratory was used for all the measurements. P'-f records were taken every fifteen minutes from 18 hours to 21 hours 75^{0}E.M.T. On the eclipse day, once every fifteen minutes observations were started at 1030 hours; the recordings were more frequent afterwards and during the eclipse, records were taken once every five minutes.

The lower layers :- As during the eclipse the solar altitude was very low, the ionisation of the lower layers was decreasing rapidly with decreasing $\cos\chi$ of the sun. The eclipse therefore could not be of much use to study the lower layers of the ionosphere. The critical frequencies of E, E2 and F1 layers, and the minimum vertical heights of the F1 layer on the eclipse day and on the control days are shown in Fig.1. The E layer reflection traces of the eclipse day were often merged with those of Es and so h'E is not shown on

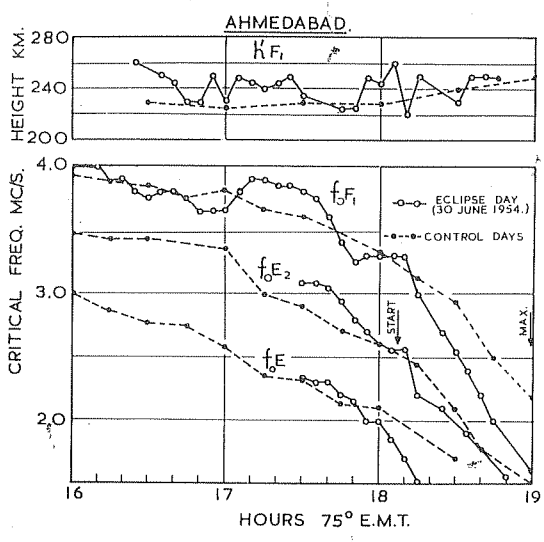


Fig. 1

the diagram. As expected, the critical frequencies of E and F1 decreased at a faster rate after the start of the eclipse. The E2 layer showed changes similar to F1, but the effect of the eclipse is not very clear.

An interesting feature was noted in the F1 layer at about 1745 hours. The relevant P'-f records are redrawn in Figure 2. On normal days the lowering of the sun, the cusp corresponding to F1 critical frequency gets flatter as the critical frequencies decreases, and the identity of the F1 layer gets lost with vanishing inflection on the F1-F2 layer trace. On the 30th June 1954, on the other hand, the F1 layer trace continued to get flatter with the time as

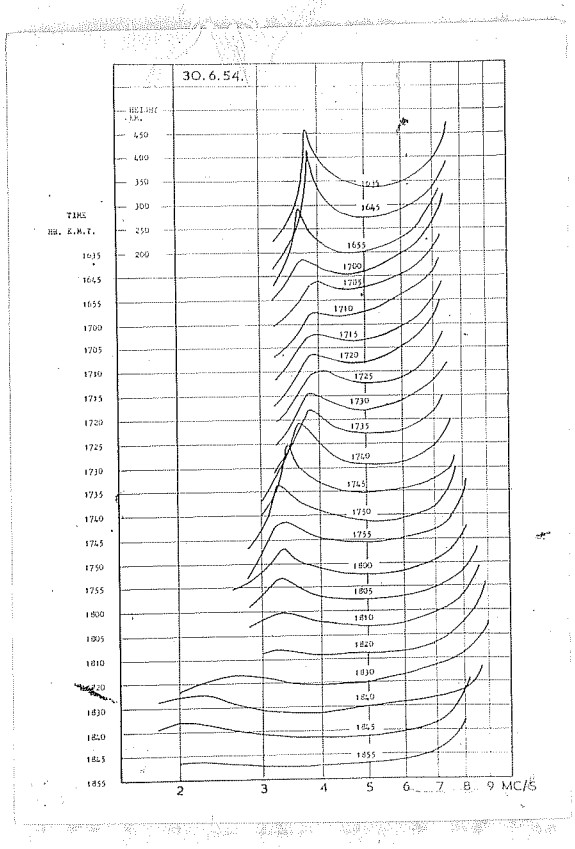


Fig. 2

on normal days upto about 1720 hr after which it increased in sharpness. At 1745 hr it had a very sharp cusp, and later the cusp died out slowly. During this period, the F1 reflections were very strong and many M reflections were recorded. Curiously however, the phenomenon occurred about half an hour before the beginning of the eclipse at Ahmedabad.

F2 layer :- The variations of the critical frequency (f_0F2) and the height of maximum ionisation (h_pF2) of the F2 layer on the eclipse day and on the control days are shown in Fig.3. f_0F2 values were higher on the eclipse day than on the controlled days. Curiously again the increase

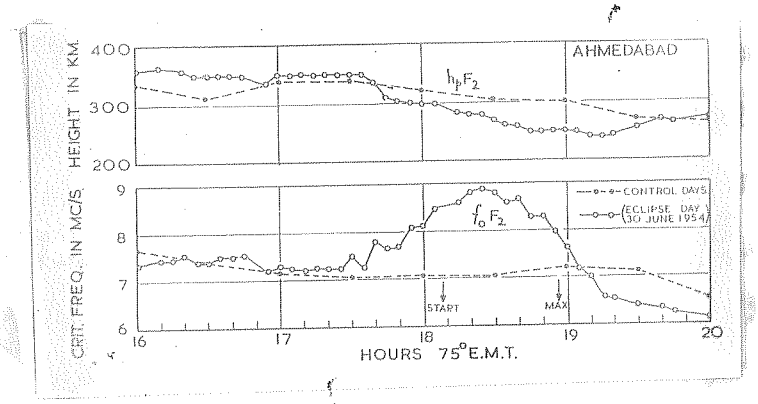


Fig. 3

in f_0F2 above the normal day values started about half an hour before the beginning of the eclipse. Similar sharp increases of f_0F2 before the start of the eclipse were also noted at some other ionospheric stations, e.g. Delhi[1], Tromsya, Kjeller and Tromso[2]. The variations of f_0F2 on a few individual days round the day of the eclipse are shown in Fig.4. The behaviour on the eclipse day was significantly

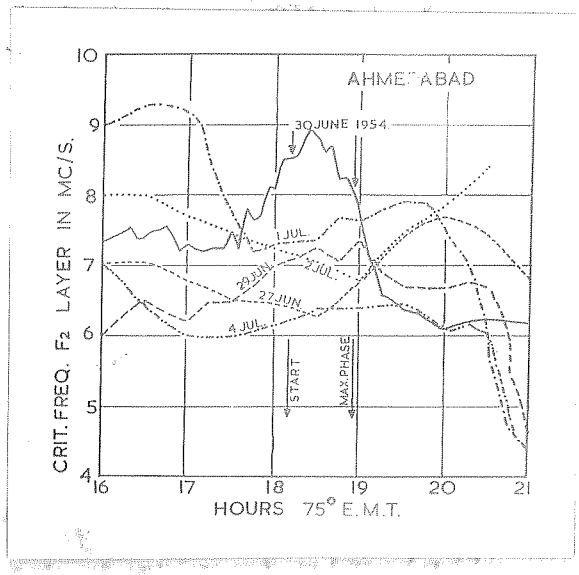


Fig. 4.

different from that on normal days.

In order to find how the changes in the critical frequency of the F2 layer were associated with changes in the electron density distribution, the heights of h_0F2 h_mF2 and semi-thickness (TF2) were calculated by Booker and Seaton's method[3]. These are plotted in Fig.5. The values of the maximum electron density (N_mF2) and total electron

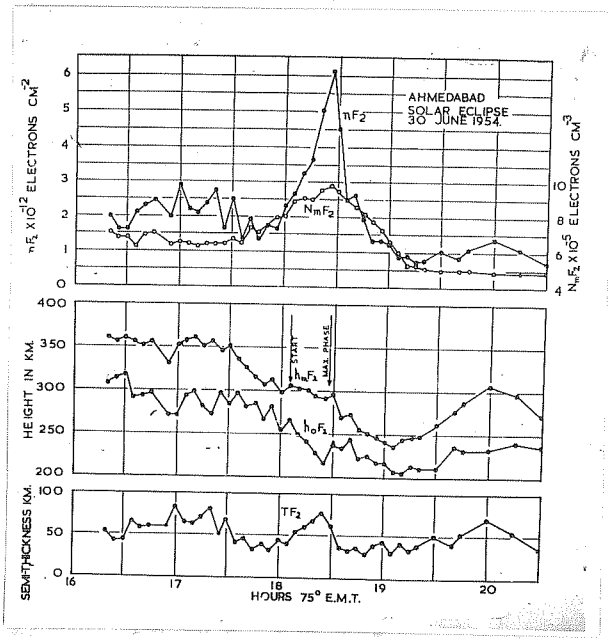


Fig. 5

content in a vertical column of the F2 layer upto the height of maximum ionisation density (nF2) are also plotted in the same diagram. It is seen that the semi-thickness of the F2

layer increased with the early part of the eclipse period. This increase was mainly due to a lowering of h_0F2. The total electron content therefore showed an increase during the eclipse period.

Another noteworthy change in the F2 reflection traces during the eclipse was the appearance of multiple splitting of the critical frequency and the appearance of range duplication on the first ordr reflection trace. At 1840 hr, 1 x F2 trace became very broad near the end showing a number of critical frequencies, whereas 2 x F2 and 3 x F2 traces showed clear f_0F2 and f_xF2. A few P'-f records during the period are shown in Fig. 6. At 1845 hr, the broadning of the F2 trace extended to lower frequencies and at 1855 hr, two parallel F2 traces very close to each other were recorded. The range duplication was observed till 1920 hr. At 1930, 1 x F2 trace was weak and defused, while t2 x F2 was strong and clear. After 1940 hr the reflections were again normal. Such records are not uncommon at Ahmedabad, and these are generally observed later in the night. Mitra[4] reported a similar effect in the F2 layer at Delhi anddescribed it as triple splitting. The phenomena can, however, be explained on the basis of a travelling discontinuity or hump on the surface of the F2 layer. Depending on the position and shape of the discontinuity a particular order of reflections may arrive from different directions and so with slightly differing time delays, and this would give rise to multiple splitting of the critical frequencies and parrallel F2 traces.

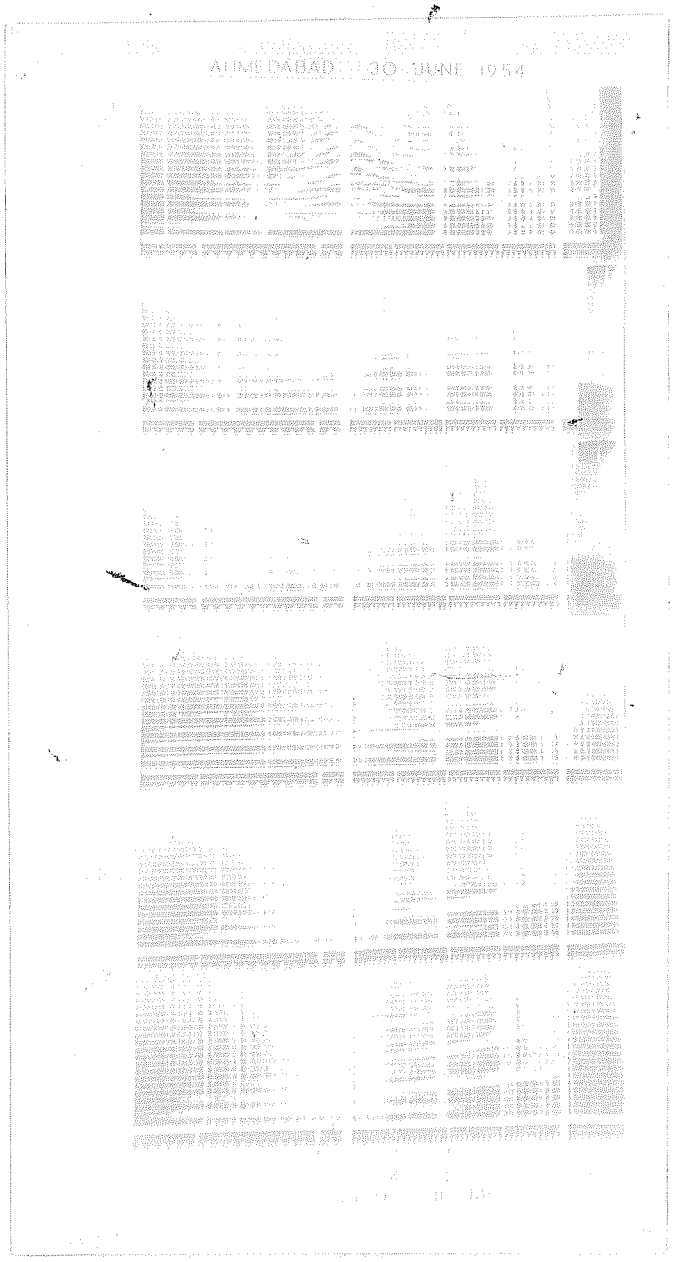


Fig. 6.

Further, the reflections of a particular order may be selectively focussed by the curved surface of the ionosphere

giving rise to anomalous intensity distribution of echoes of different orders.

Sporadic E layer :- Sporadic ionisations in the E region are more frequent and stronger during summer months at Ahmedabad. During the days of these observations Es was abnormally high and often blanketted all the higher reflections extending even above 15 Mc/s. The variations of maximum frequency of Es reflections (fEs) on the eclipse day and on the controlled days are shown in Fig. 7. fEs increased soon after the start of the eclipse and remained higher than the normal values upto 1900 hr.

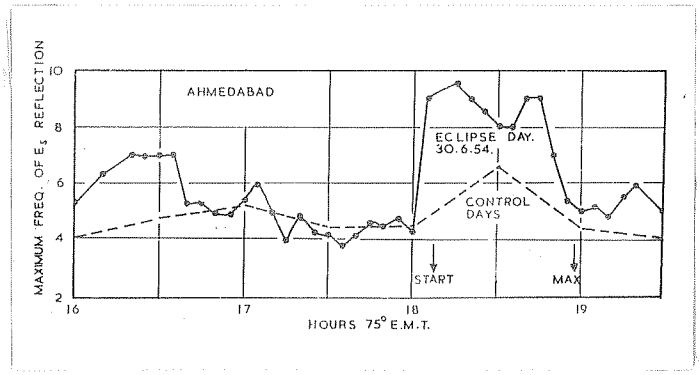


Fig. 7

Conclusion : The vertical ionospheric soundings at Ahmedabad during the solar eclipse on 30 June 1954 presented some interesting results. The ionisations of the lower layer E and F1 decreased during the eclipse. Half an hour before, the F1 layer showed a sharp cusp with a number of multiple and M reflections. It is difficult to say that this was due

due to the eclipse. The F2 critical frequencies, as well as the total ion content of the F2 layer during the eclipse were above normal. The semi-thickness of the F2 layer increased during the eclipse. This was due to a lowering of the base of the F2 layer. Range duplication and other effects of the curvature of the ionospheric surface were observed during the eclipse. It seems that the lower portion of the F2 layer was more affected by the withdrawal of solar radiation than the level of maximum ionization. Maximum Es frequencies were higher during the eclipse period.

References

1. Ionospheric data in connection with the eclipse of June 30, 1954 at Dehlit.
2. Geofysiske Publikasjoner Vol.XIX No.8.
3. Booker, H.G. and Seaton S.L., Physical Review, 57,87(1940)
4. Mitra, S.N., Proceedings of the Institute of Telecommunication Engineers(India).

****

PART I

5. Vertical soundings at Ahmedabad during Partial Solar eclipse on 14 December 1955.

The present article describes the results of vertical ionospheric soundings made at Ahmedabad during the partial solar eclipse of 14 December 1955.

The times of the various phases of the ground eclipse are given Table 1.

Table 1.

	Time 75°E.M.T.	Solar altitude
Commencement of the eclipse	1014 hour	37°
Maximum phase of the eclipse	1210 "	44°
End of the eclipse	1400 "	37°
Magnitude of the eclipse	47%	

As the eclipse occurred almost at noon, there was very little difference in the time of the phases of the eclipse at ground and at ionospheric levels, and so no detailed calculations of these latter times were made. The portion (p) of the solar disc unobscured by the moon, the cosine of solar zenith angle ($\cos \chi$), and the product $p.\cos \chi$ during the eclipse are shown in Figs.1(a) and 1(b)

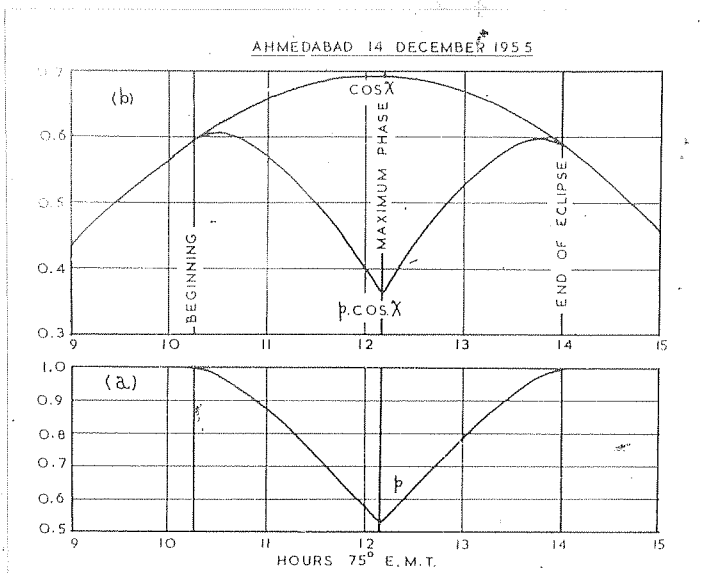


Fig. 1(a) and (b)

p.cos χ varied from 0.6 at the beginning and end of the eclipse to 0.37 at the maximum phase of the eclipse.

The N.P.L. ionospheric recorder of the Physical Research Laboratory was used for all the measurements. The equipment covered 0.65 to 15.4 Mc/s in four minutes; the frequency range 15.4 to 25 Mc/s. was not used. On the control days, P'-f records were taken at intervals of every fifteen minutes each day from 09 hr to 15 hr. On the eclipse day, records were taken every five minutes from 10 hr to 14 hr. The variation of critical frequencies and the minimum virtual heights of E, E1, E2 and F1 layers on control days and on the eclipse day are shown in Fig. 2. Fig. 3 shows the

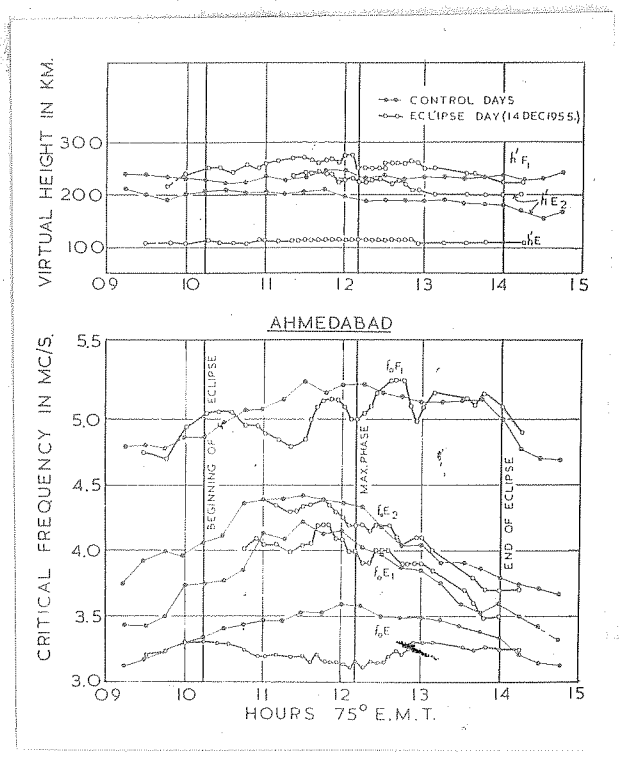


Fig. 2

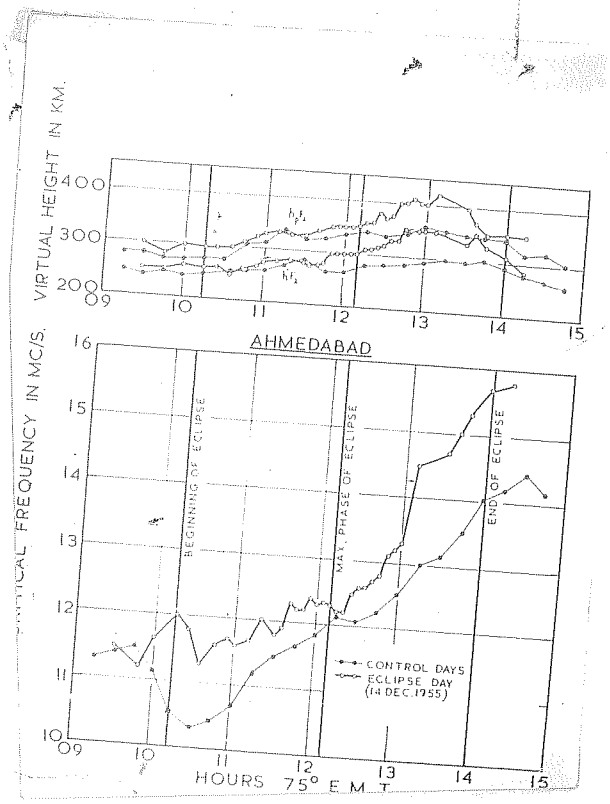


Fig. 3

critical frequencies (f_0F2), the minimum virtual heights (h'F2) and the virtual heights at 0.83 x f_0F2 (hpF2) on the eclipse day and on the control days.

E layer : As expected, the E layer critical frequencies decreased from the start of the eclipse and remained lower than the normal-day values during the entire period of the eclipse. The dip in f_0E during the eclipse was flat, as the eclipse occurred at noon and was only partial. The minimum virtual height of E did not show any change during the eclipse. The critical frequencies of the E layer on different control days are plotted against by corresponding values of $\cos\chi$ on double logarithmic paper in Fig. 4.

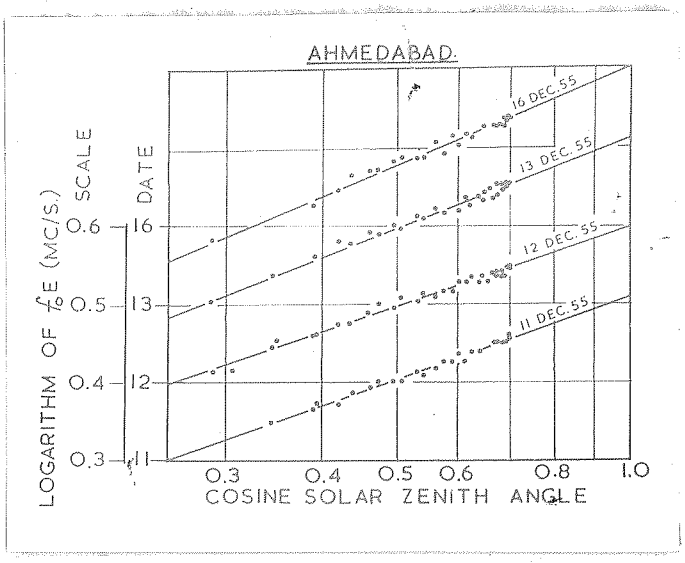


Fig. 4

The straight line nature of the curve joining the points indicated that f_0E varied with solar zenith distance according to the relation $f_0E = k \cos^n \chi$. The values of k and n on the control days are given in Table 2.

Table 2

December 1955	kf_0E	nf_0E
11	4.10	0.42
12	4.00	0.38
13	4.10	0.33
16	4.05	0.35
Mean	4.06	0.37

Ratcliffe has shown that during a solar eclipse

$$\frac{N_1^2}{N_0^2} = \frac{S_1 \cos \chi_1}{S_0 \cos \chi_0}$$

where N is the maximum electron density, S is the flux of ionising radiation, χ is the solar zenith angle and the subscripts 1 and 0 refer to the times when the ionisation is not changing with time. He find that for the E layer, N_1^2/N_0^2 was equal to 1.27 whereas $\frac{S_1 \cos \chi_1}{S_0 \cos \chi_0}$ equalled 1.67.

Appleton has shown that the recombination coefficient in the E region can be determined from the time delay γ of the maximum of f_0E behind noon according to the equation

$$\gamma = \frac{1}{2\alpha N}$$

Using the above equation the value of α E, was found to be 0.78×10^{-8} cm^3 sec^{-1}. In Fig. 5 the variation of maximum

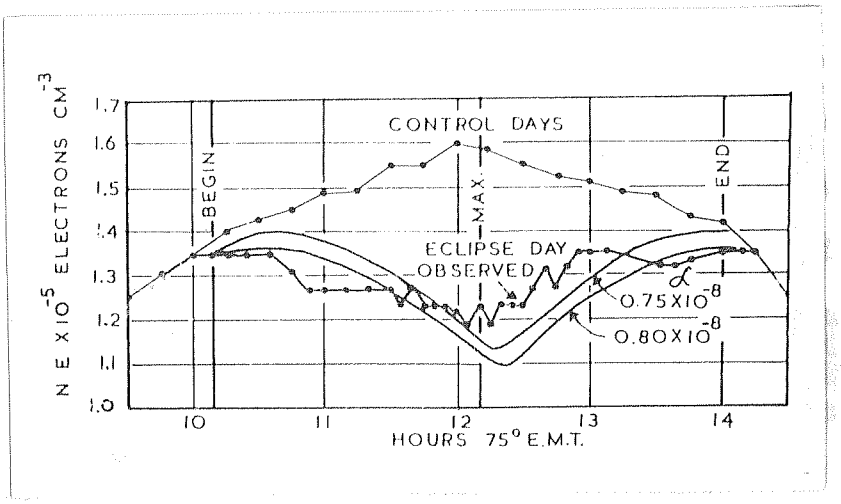


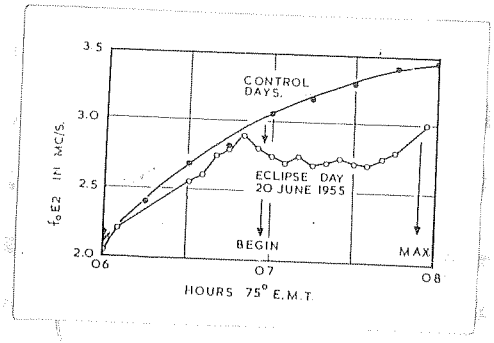
Fig. 5

electron density in E layer observed on control days and on the eclipse day are compared with the theoretical variations calculated for assumed values of $\alpha = 0.75 \times 10^{-8}$ and 0.8×10^{-8} cm^3 sec^{-1}. Neither of the theoretical curves satisfied the observed points. The observed values were lower than the theoretical values during the first half of the eclipse while they were higher during the latter half of the eclipse. Similar early falls of f_0E have been observed by other workers (Pierce 1940, Minnis 1955, Ssendrei and McElhinny 1956). This asymmetry has been attributed to the non-uniform distribution of the sources of ionizing radiation of the solar disc.

E1 and E2 layers : Besides the normal E layer two more intermediate layers, called E1 and E2 are regularly observed at Ahmedabad (Rastogi 1954). The eclipse occurred at the time when E1 and E2 layers were being formed out of the ledge in F1 layer. The effect of the eclipse was not so clear on E1 and E2 as on E.*

---

* A decrease of E2 layer ionisation during a solar eclipse was more clearly seen during another eclipse observed at Ahmedabad, viz., on 20 June, 1955, as shown in figure. Decreases of E2 ionisation during solar eclipses have been observed by other workers Schafer and Goodall (1935), Estrabaud (1953), Ssedenrei and McElhinny (1956), Bibl and Delobeau (1956).



F1 layer : It is known that at most places, the F1 layer is not quite clear during winter months and during times of high solar activity. At high latitudes it is observed only in the summer months in the middle of the day. At Ahmedabad the F1 layer is most defined during summer and in the period of low sunspot activity. In December 1955, solar activity had increased considerably and the F1 layer was not very clear. On the control days, the F1 layer never gave a sharp cusp on P'-f records and its presence could be detected on the P'-f traces only by a flat cusp. The f_0F1 values given are the frequencies at the point of inflexion in the P'-f trace and do not represent the maximum electron density in the F1 layer.

The f_0F1 values during the eclipse showed a decrease but the data cannot be considered to be on par with those of the E layer.

F2 layer : On the eclipse day, f_0F2 values were higher than on the control days, during the entire period of the eclipse. The deviation of f_0F2 on the eclipse day above the control-day values was minimum at the middle of the eclipse as shown in Fig. 6. On control days f_0F2 increased steadily from 10 hour to 14 hour with the same rate. On the eclipse day, the rate of increase of f_0F2 during the first half of the eclipse was smaller than that on normal days, while after the maximum of the eclipse, f_0F2 increased more rapidly than on normal days.

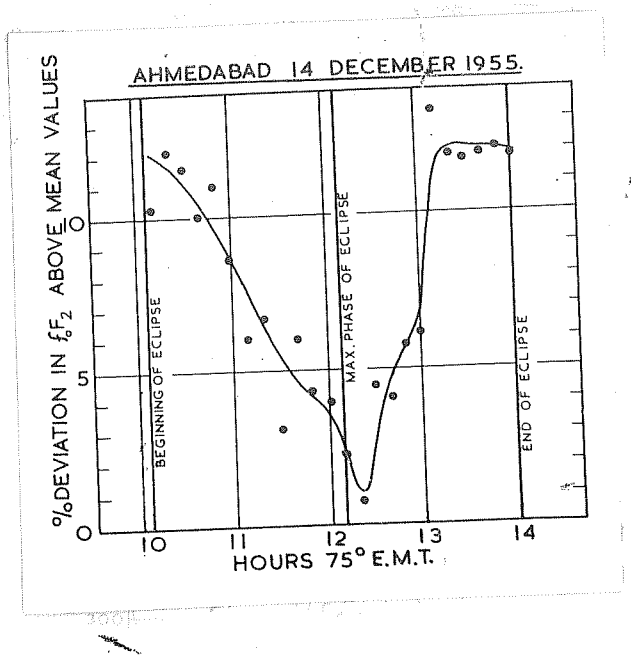


Fig. 6

The minimum virtual height (h'F2) and the virtual height at 0.834 x f_0F2 (h_pF2) on the eclipse day were not very different from those on control days till about 1130 hr. After 1130 hr both h'F2 and h_pF2 increased above the control day values and reached the maximum at about 13 hour, after which they returned to normal at about 14 hour. The values of the semi-thickness (YF2), the height of base (h_0F2) and the height of maximum electron density of the F2 layer were determined by Booker and Seaton's method (1940). The variations of these quantities during the eclipse period are shown in Fig. 7. The changes in the maximum electron density (N_mF2) and the total electron content in a unit vertical column upto h_pF2 ($nF2 = 2/3\ Y\ N_m^2$) are shown in Fig. 8. h_mF2 increased shortly after the beginning of the eclipse, reached a maximum about an hour after the maximum phase of the eclipse and dropped to its normal value after the end

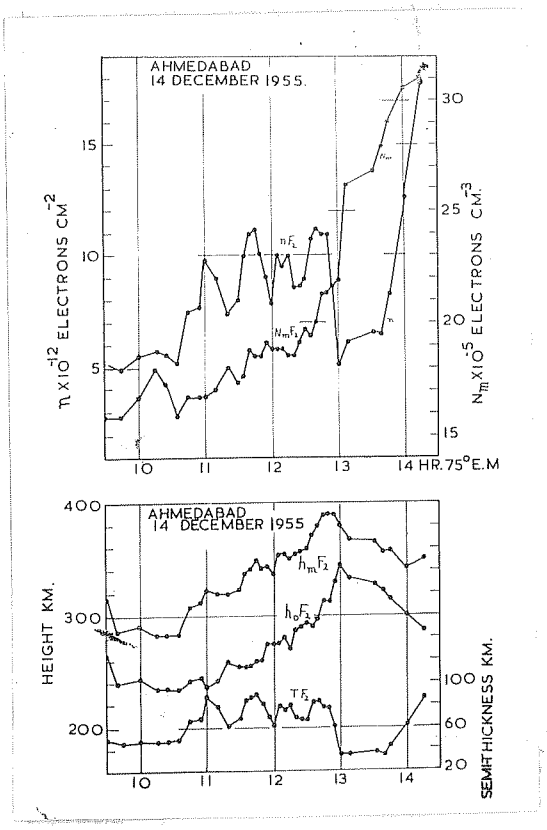


Fig. 7 and 8

of the eclipse. h_oF2 also increased similarly and reached a value as high as 340 km at 13 hour. A few P'-f traces during the eclipse are redrawn in Fig. 9. It is easily seen that though the structure of the F2 layer near the region of maximum electron density did not change much, the P'-f traces at the junction of F1 and F2 showed remarkable changes during the eclipse. The variation of virtual heights of reflection o of a few fixed frequencies are shown in Fig. 10. Virtual heights of reflections of 5 Mc/s and of 11 Mc/s waves did not vary much during the eclipse while those of intermediate frequencies showed a maximum at about 13 hour. The height of reflection of the 6 Mc/s wave showed the maximum change,

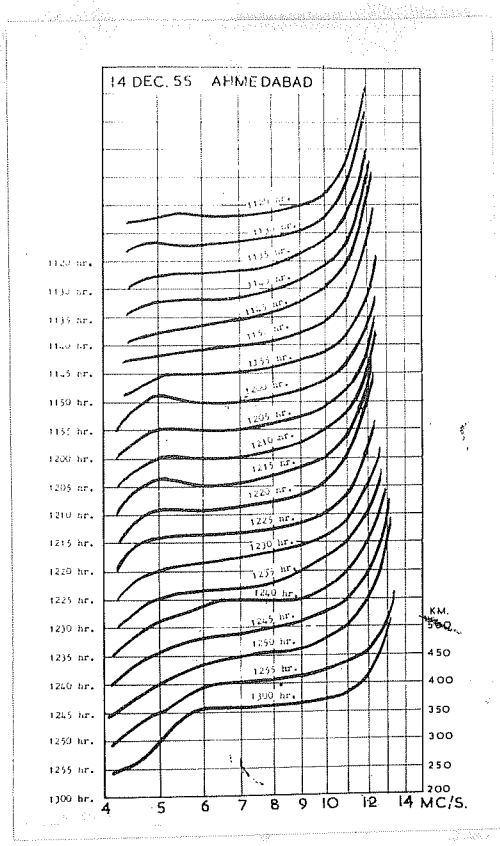


Fig. 9

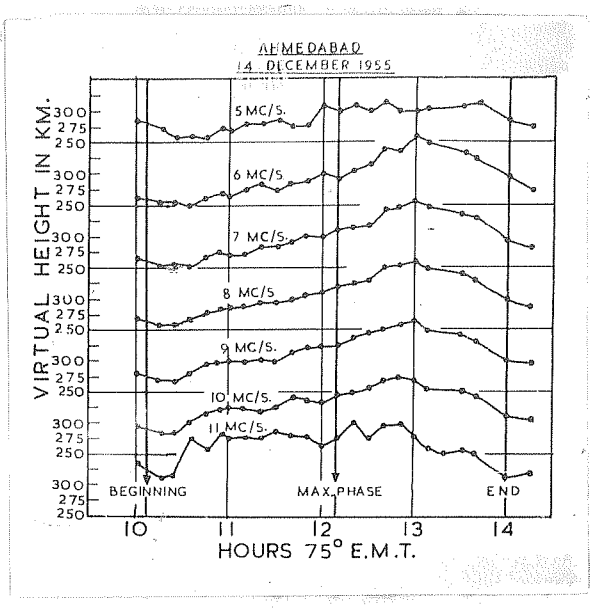


Fig. 10

which was probably at or about the junction of F1 and F2 layers.

Es layer : There was no change in the sporadic E layer which could be attributed to the eclipse.

Conclusion : The behaviour of E layer during the eclipse was roughly consistent with that of Chapman layer with a recombination coefficient of about 0.8×10^{-8} cm^3/sec.

There was no clear effect of the eclipse on the F1 and F2 layers; the critical frequencies were lower on the eclipse day.

F1 layer ionization decreased during the eclipse but the variation was irregular.

The eclipse caused a fall in the rate of increase of f_0F2. There was indication of the formation of F1½ during the latter part of the eclipse.

Es was not affected by the eclipse.

References

Appleton E.V.	1953	Jour. Atmos. Terr. Phys. 1, 282.
Bibl K. and Dalbeau, F.	1955	Zeit. fur Geophysik, 21, 215.
Estrabaud S.	1953	C.R. Acad. Paris, 236, 893.
Minnis C.M.	1955	Jour. Atmos. Terr. Phys., 6, 91.
Pierce J.A.	1948	Proc. Inst. Rad. Eng., 36, 8.
Rastogi R.G.	1954	Proc. Ind. Acad. Sci., 40, 158.
Rastogi R.G.	1956	Jour. Atmos. Terr. Phys., 2, 71.
Ratcliffe J.A.		Proc. symposium on "Solar eclipses and the Ionosphere" held in London 22-24 August 1955.
Schafer J.P. and Goodall W.M.	1935	Proc. Inst. Rad. Eng., 23, 1356.
Sraderdrei M.M. and Mokhimy M.M.	1956	Jour. Atmos. Terr. Phys., 8, 108.

Ionospheric Research Committee, Japan, 38th Cooperative Observations solar eclipse, Feb. 14th 1953.

.....

Some Measurements of the Signal Strength of Radio Waves reflected from the Ionosphere during the Solar Eclipse of June 30 1954 and June 20 1955.

Abstract : The signal strength of radio waves from B.B.C. transmissions on 15.07 Mc/s were measured at Ahmedabad during 1954 eclipse, with control observations on a few preceding and succeeding days. The signals, which could have been either by two-hop or three-hop reflections, showed well marked increases in intensity during the eclipse. The increase of the signal strength is considered to be due to a decrease of attenuation in the F1 layer.

Similar measurements were carried out for the 1955 eclipse at Trivandrum, on the radio transmission from Colombo on 4.87 Mc/s directed skyward, and at Ahmedabad on 7.19 Mc/s. Here again the signals showed well-marked increases during the eclipse. In both cases the signal intensity returned to its normal value well before the end of the eclipse. The reflections observed at Trivandrum could have been from F1, if there was an F1 layer. Near the geomagnetic equator, however, F1 is not usually observable at this hour of the day. Probably the reflections took place from F2, with decrease in attenuation mainly in F1. The reflections observed at Ahmedabad should have been from E, and the decrease of attenuation during the eclipse should have taken place below E.

Measurements made at Ahmedabad (23°02'N, 72°38'E) during the two solar eclipses on 30 June 1954 and 20 June 1955, and at Trivandrum in the 1955 eclipse, showed the significant increase of signal strength during the period of the eclipse. The present note gives a summary of the observations.

In the eclipse of 30 June 1954 the track of totality lay between London and Ahmedabad (Fig.1). Mastogi and Sherif (1955) measured the strength of B.B.C. transmission

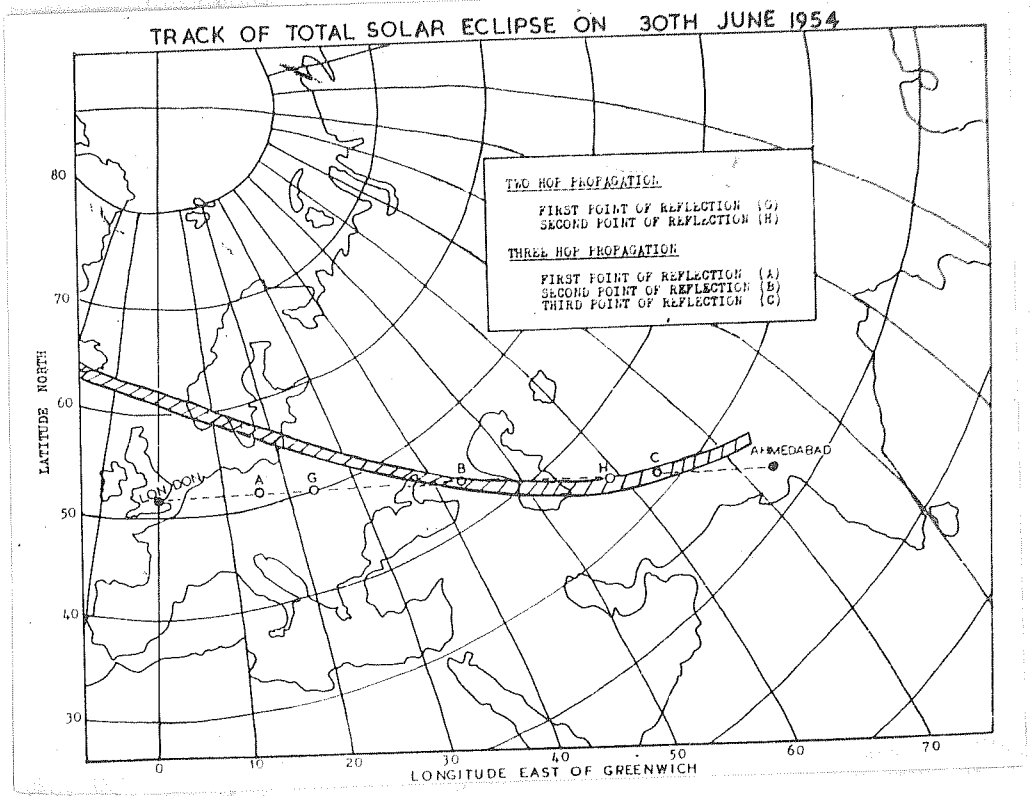


Fig. 1

on 15.07 Mc/s at Ahmedabad with a calibrated communication receiver between 26 June and 4 July from 1530 to 2130 I.S.T. (1000 to 1600 G.M.T.) on each day. The average signal strength on control days and the signal strength on the

eclipse day are plotted in Fig. 2. The increase in signal strength between 1820 and 1930 I.S.T. on the eclipse day is very pronounced.

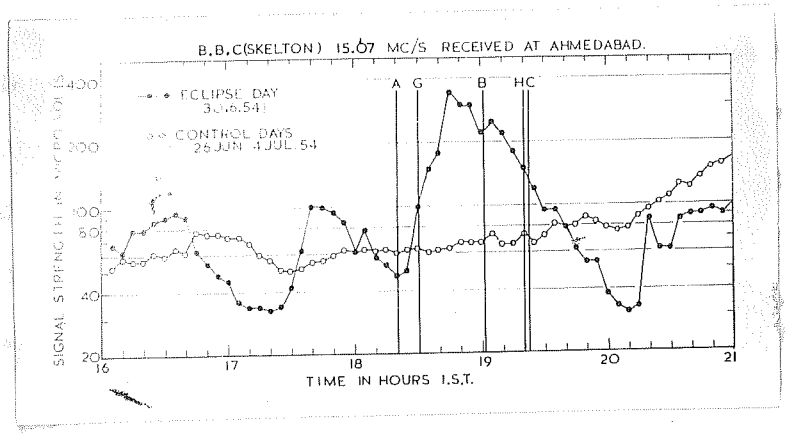


Fig. 2.

The distance between London and Ahmedabad is 6800 km. Considering the time of the day and the normal critical frequencies of the ionospheric layers at the place of reflection the principal mode of propagation between London and Ahmedabad should have been by two-hop reflection from F2, although the possibility of a three-hop reflection is not altogether excluded. The two-hop reflection points are G and H and the three-hop reflection points A,B,C in Fig.1. The times at which the maximum phase of the eclipse was reached at these different points are indicated in Fig. 2. The maximum signal strength was recorded at 1845 I.S.T.(1315 G.M.T.), with a value nearly five times the control day average at that time.

A probable explanation for this increase of signal strength is that, while the critical frequencies of the F2 layer remain comparatively unaffected during the eclipse,

there is a decrease of electron density and attenuation in the lower layers during the eclipse. The maximum useable frequency via F1 on normal days would be close to 15 Mc/s; there would thus be a large attenuation of waves reflected from F2 on normal days. The decrease in electron density in F1 which is known to occur during the eclipses would mean a less attenuation of the signals reflected from F2. This is considered to be the main reason for the increase in signal strength during the eclipse, though the changes in E would also produce a similar but less-marked effect.

The track of the total eclipse on 20 June 1955 passed over Ceylon, and the magnitude of the eclipse at Trivandrum was 0.97. Fig. 3. The signal strength of Colombo transmissions on 4.67 Mc/s were measured at Trivandrum (8.5°N, 77.0°E) between 0600 and 1030 I.S.T. (0030 to 1500 G.M.T.) on each day from 17 to 24 June. A modified

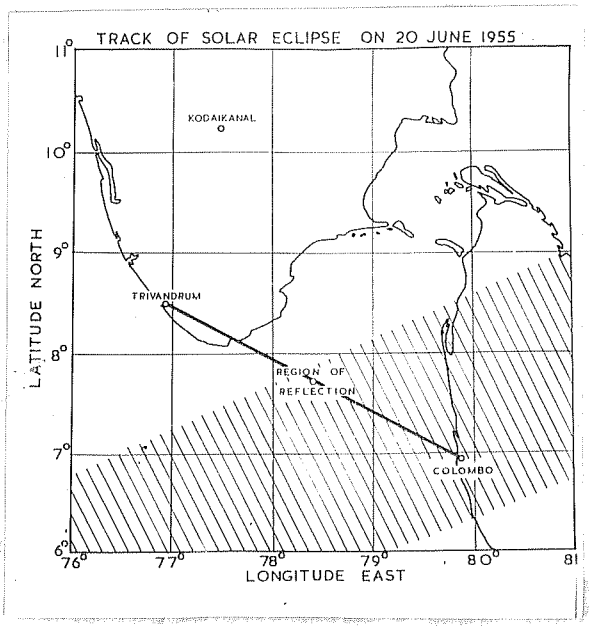


Fig. 3

communication receiver was used to receive the signals. The automatic control was removed from the R.F. and I.F. stages, and the voltages at the second detector was measured with a bridge type d.c. amplifier. The meter readings of the d.c.amplifier were calibrated daily against signal voltages fed to the receiver from the signal generator. The average of the meter readings were recorded every 30 sec on all control days and every 15 sec on the eclipse day. The readings were converted into signal input voltages, and these were averaged successive five-minute periods. Fig. 4 shows the signal strengths on the eclipse day and the

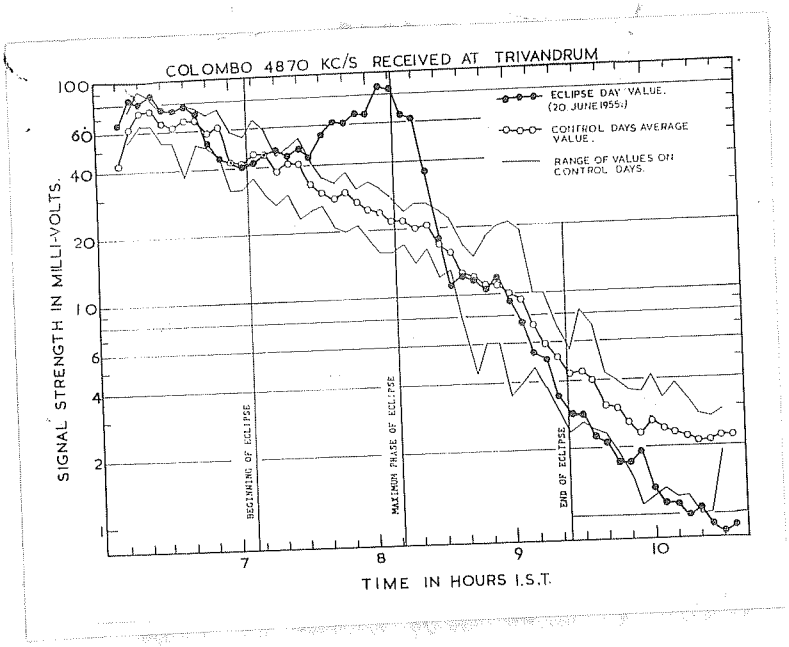


Fig. 4

averages of the strengths on the control days. The ranges of the values observed on control days are also shown by thin lines. The perturbations during the eclipse is seen even better in Fig. 5, in which the percentage differences

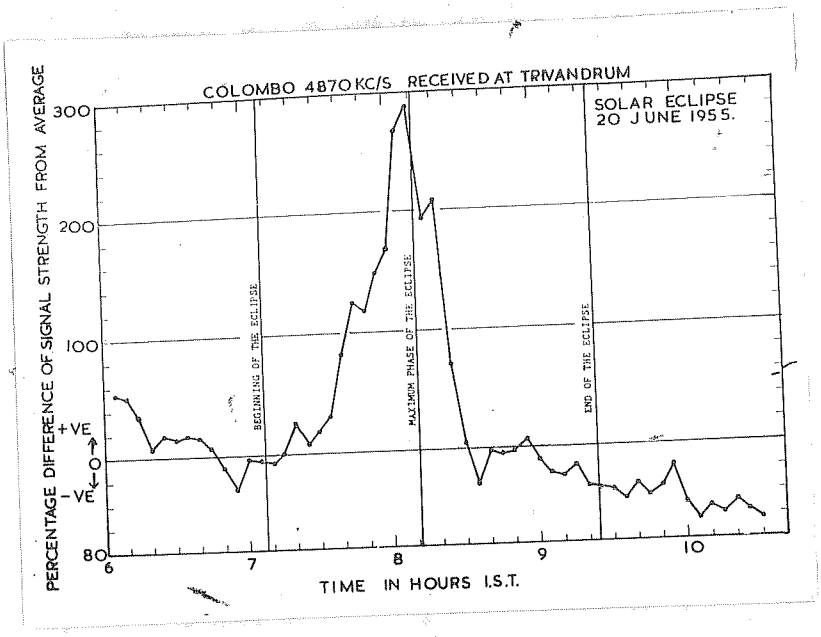


Fig. 5

of signal strength on the eclipse day from the average value at the same time on control days are plotted.

The distance between Colombo and Trivandrum is 420 km. Since the transmission from Colombo were directed upwards, the signal strength measured at Trivandrum may be assumed to mainly due to singly-reflected sky-waves reflected from F2.

It will be noted from Figs. 4 and 5 that the signal strength began to increase shortly after the beginning of the eclipse and that it reached its maximum at about the maximum phase of the eclipse. It then dropped fairly rapidly and attained the normal days' value well before the end of

the eclipse. The peak signal strength reached to about four times the strength on control days. This pronounced increase can be attributed to a decrease of electron density and of attenuation in F1 and to a lesser extent, in E.

Similar measurements were taken at Ahmedabad on 7.19 Mc/s transmissions. The magnitude of the eclipse at Ahmedabad and at the mid-point of the transmission path were 0.47 and 0.77 respectively. The distance between Colombo and Ahmedabad is 1950 km. Considering that the vertical equivalent frequencies for one-hop transmission by reflection from a height of 110 km. would be 1.33 Mc/s, and for two-hop transmission 1.84 Mc/s, it may be taken that the reflection was from the E layer by either of the modes. Fig. 6 and 7 show the comparative signal strengths on the eclipse day and on the normal days.

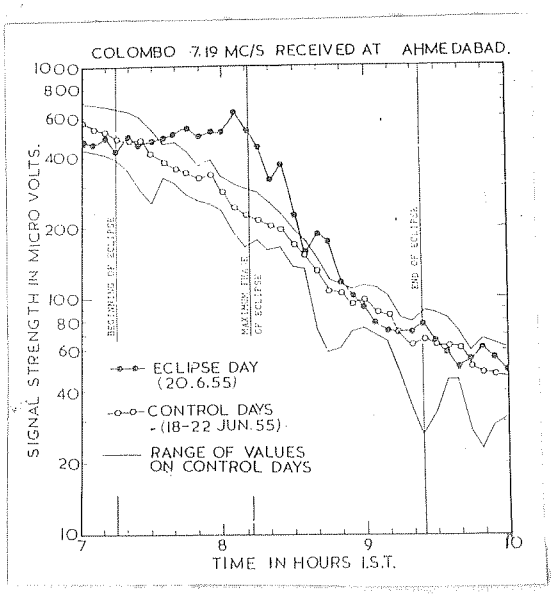


Fig. 6

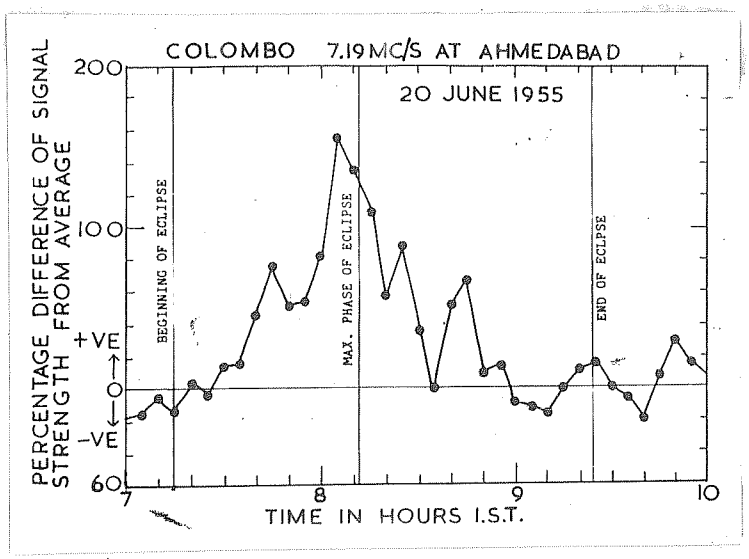


Fig. 7

In this case also, the signal strength began to increase shortly after the beginning of the eclipse and the maximum strength of a signal was observed at about the time of maximum phase. Curiously enough, here too the signal strength returned to a its normal value well before the end of the eclipse.

It is not possible to attach any significance to the small difference between the times of the maximum signal strength and of the maximum phase of the eclipse.

Acknowledgements : The authors are grateful to Professor K.R.Ramanathan for directing the work and provided all the necessary facilities. The Director of Radio Ceylon kindly arranged an earlier start of the morning transmissions

on 4.67 Mc/s for a few days before and after the eclipse. Thanks are also due to Dr.C.S.Venkateswaran, Principal of Trivandrum College, for providing the facilities for observation at the Trivandrum observatory, and to Mrs.Malati Rastogi for help in taking the observations at Trivandrum.

References

Rastogi, R.G., and Sheriff K.M. 1955 J.Sci.Indust. Res.(India), 14A, 159.

* * * * * * * * *

[Reprinted from the *Journal of Scientific & Industrial Research*, 1955, Vol. 14A, No. 4, pp. 159-161]

A Note on Radio Field Strength Observations made at Ahmedabad during the Total Solar Eclipse on 30 June 1954

R. G. RASTOGI & R. M. SHERIFF
Physical Research Laboratory, Ahmedabad

IN order to study the effects of the solar eclipse on 30 June 1954 on the propagation of radio waves, the field strengths of the transmissions from the British Broadcasting Corporation (London) on 15·07 Mc/s. and from Moscow on 15·36 Mc/s. were recorded at Ahmedabad (23°02'N, 72°38'E) during the eclipse day and a few days before and after it.

Due to certain instrumental troubles, complete observations of the Moscow transmissions could not be taken and the results have, therefore, not been discussed. The present note describes the results of the field strength measurements on the B.B.C. transmissions from London only.

The signal strengths of the transmissions from B.B.C. on 15·07 Mc/s. were measured from 15.30 to 21.30 hr. I.S.T. on each day from 26 June to 4 July 1954. A Hammerlund Super-Pro communication receiver was used to receive the signal. A constant voltage transformer was used to supply a.c. power to the receiver. The receiver was switched on 2 hr. before the commencement of the observations in order to avoid variations due to the heating of the various components. The 'S' meter of the receiver was replaced by a sensitive micro-ammeter and the a.v.c. was on during the observation period. For calibration, the meter readings were compared against the signal voltage at the receiver input when the feeding was done from a General Radio standard signal generator. Calibration was made both before and after each day's observations.

The readings were taken every half a minute. During rapid fadings, the average meter readings were noted. The meter readings were converted into signal input voltage, and they were averaged for every 5 min. period. Signal strength (5 min. average) was plotted against time on all control days and on the eclipse day. The curves for all the control days were similar except that for 3 July 1954. The field strengths on that day were markedly higher than those on the other control days and were, therefore, not included for averaging.

The curves in Fig. 1 give the average field strength on four control days before and on three control days after the eclipse. The curves in Fig. 2 give the average signal strength on all the seven control days and on the eclipse day. On the control days, the signal strength on the average remained steady up to nearly 20.00 hr. I.S.T. after which there was an increase reaching a maxi-

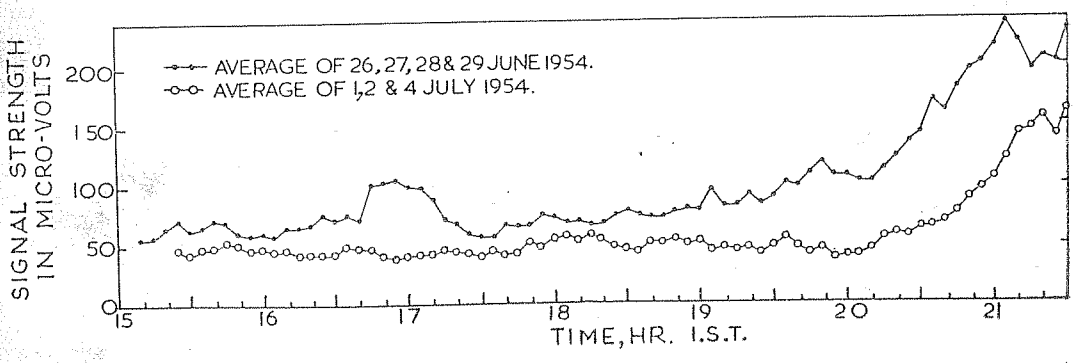


FIG. 1 — AVERAGE FIELD STRENGTH ON CONTROL DAYS BEFORE AND AFTER THE ECLIPSE

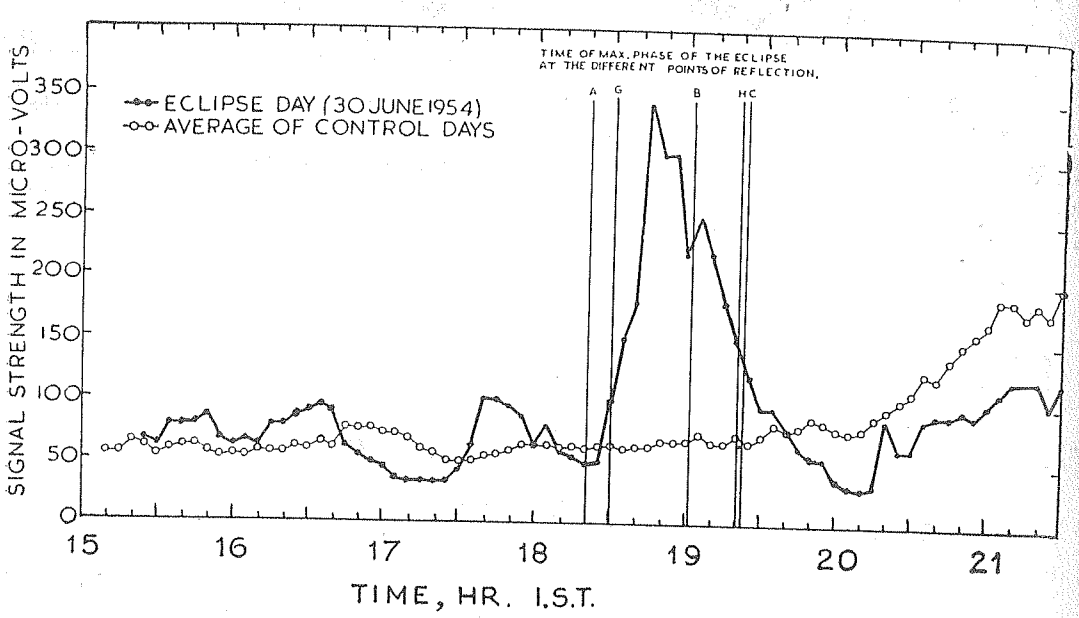


FIG. 2 — AVERAGE SIGNAL STRENGTH ON CONTROL DAYS BEFORE AND AFTER THE ECLIPSE DAY AND ON THE ECLIPSE DAY

mum at about 21.20 hr. I.S.T. The average time of sunset at the last point of reflection on these days was nearly 21.00 hr. I.S.T. It was found that the signal strength did not show any further increase after 21.30 hr. I.S.T.; on the other hand there was a slight decrease after which it remained steady.

The distance between London and Ahmedabad is 6,800 km. The points of reflections for two-hop and three-hop propagation between London and Ahmedabad were determined. These are shown in Fig. 3. The two-hop reflection points are G and H and the three-hop reflection points are A, B and C. The path of totality of the eclipse is also shown in the same figure. The approximate critical frequencies of F_1 and F_2 layers at the points of reflection and at the appropriate local times were estimated from the ionospheric data published in C.R.P.L. bulletins. Assuming the heights of the F_1 and F_2 layers to be respectively 200 and 300 km., the maximum usable frequencies for two-hop and three-hop propagations via F_1 and F_2 layers were calculated. Table 1 gives the approximate maximum usable frequencies corresponding to the different points of reflection at appropriate times for normal days.

The times of the maximum phase of the eclipse at these points are indicated in Fig. 2.

From the values of the normal maximum usable frequencies given in Table 1 it can be inferred that the most probable mode of propagation was two-hop one via F_2 layer; however, three-hop propagation via F_2 and two-hop propagation via F_1 layer are also possible.

The signal strengths on the eclipse day were steady up to 18.30 hr. I.S.T., the time corresponding approximately to the time of the maximum phase of the eclipse at the first points of reflection. Then there was a sudden increase reaching a value nearly five times the average field strength for those hours. The peak value occurred before the

TABLE 1

	Maximum usable frequency via F_1 and F_2 layers	
	F_1 Mc/s.	F_2 Mc/s.
Two-hop propagation		
First point of reflection (G)	16·4	16·0
Second point of reflection (H)	15·2	21·0
Three-hop propagation		
First point of reflection (A)	15·6	14·1
Second point of reflection (B)	15·2	15·6
Third point of reflection (C)	14·2	19·5

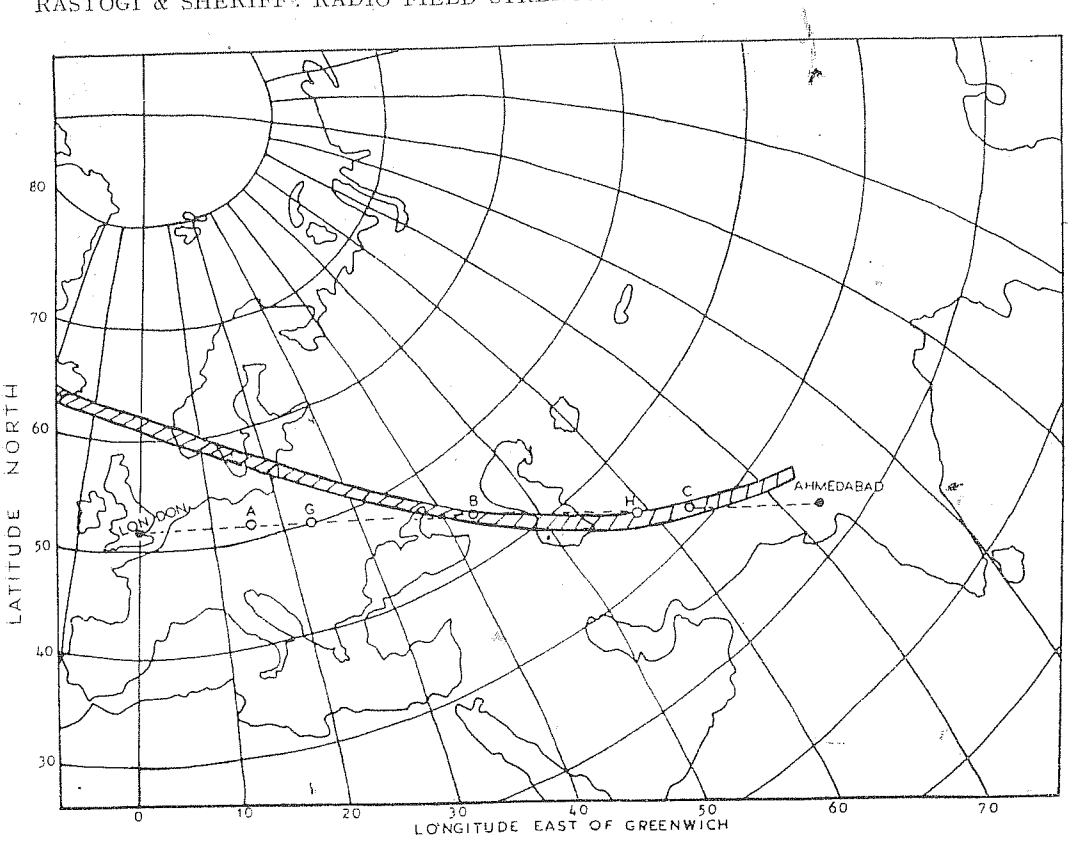


FIG. 3 — POINTS OF REFLECTION FOR TWO-HOP AND THREE-HOP PROPAGATION BETWEEN LONDON AND AHMEDABAD

time corresponding to that of the maximum phase of the eclipse at the midpoint of the transmission path. The signal strength again dropped to its normal value after the maximum phase of the eclipse at the last point of reflection. The average maximum signal strength during the night was less than half the maximum during the eclipse.

The increase in the signal strength during the period of the eclipse is very probably due to a decrease in the absorption of the lower layers of the ionosphere when the solar radiations are cut off by the moon. It is well known that the critical frequency of the F_1 layer decreases significantly during the eclipse. With the decrease in electron density of F_1, the maximum usable frequency via F_1 layer will also decrease. We have seen that the maximum usable frequencies via F_1 on normal days are very close to 15 Mc/s.; this would involve considerable attenuation in the F_1 layer. With a decrease in the maximum usable frequency during the eclipse, the attenuation caused by the F_1 layer will decrease and thereby the signal strength will increase. The similar decrease in the maximum usable frequency of the E layer will alter the absorption of such a high frequency as 15 Mc/s. to a much smaller extent. The decrease in the ionization of the D layer would affect mainly the propagation of long waves. Therefore, it seems that the increase in the signal strength observed during the eclipse period was due to the decrease of the absorption mainly in the F_1 layer.

Acknowledgement

We are thankful to Prof. K. R. Ramanathan for his keen interest and guidance in the work. We are also indebted to our colleagues Mr. K. M. Kotadia, Dr. Bh. V. Ramanamurthy and Mr. V. B. Nyayadish for assistance in taking the observations.

(Supplement to the paper " A note on radio ------- 30 June 1954)

Observations on the signal strengths of Moscow 15.36 Mc/s transmissions were also made during the eclipse. The observations could not be continued on the control days. The signal strengths on the eclipse day are shown in Fig.1 They rose continuously from 13 hr I.S.T. to 16 hr I.S.T.,

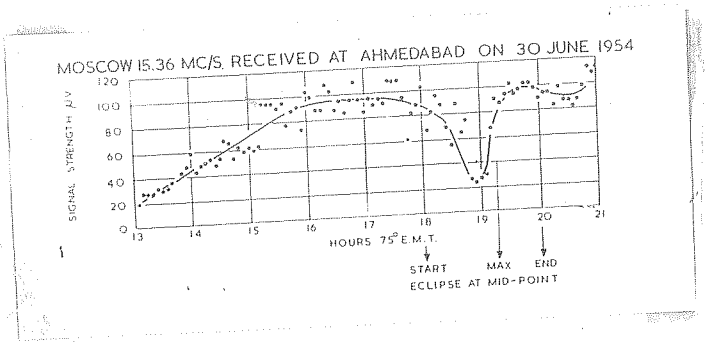


Fig. 1

remained steady upto about 18 hr, after which there was a rapid decrease reaching a minimum at about 19 hr. The times of the start, maximum phase and of the end of the eclipse at the mid-point of the path are shown in the diagram. The signal strengths started decreasing soon after the eclipse commenced at the mid-point of the path. It reached a minimum before the maximum phase of the eclipse at that point and recovered to its pre-eclipse value in a very short time.

[Reprinted from the *Journal of Scientific & Industrial Research*, 1956, Vol. 15A, No. 7, pp. 303-305]

Field Strength Measurements of Radio Waves during the Partial Solar Eclipse of 14 December 1955 at Ahmedabad

R. G. RASTOGI & R. SETHURAMAN
Physical Research Laboratory, Ahmedabad

THE study of ionospheric reflections during a solar eclipse has been of great help in ascertaining the causes of formation and maintenance of ionization in the ionized layers of the atmosphere. Field strength measurements during a solar eclipse also give an indication of the changes in the absorption of radio waves. When the waves are incident obliquely, the intensity of the reflected waves is sensitive to smaller changes in ionization than when they are incident vertically. Measurements of field strengths of obliquely reflected radio waves were taken during the last two solar eclipses at Ahmedabad. During the total solar eclipse on 30 June 1954, Rastogi and Sheriff[1] observed at Ahmedabad an increase in the signal strength of the B.B.C. signal on 15·07 Mc/s. The propagation in that case was presumably by two-hop reflection from the F_2 layer and the increase in the signal strength was due to a decrease in the absorption in the F_1 layer. A more convincing result was obtained from the field strength measurements of the Colombo transmission on 4·87 Mc/s. received by Rastogi[2] at Trivandrum during the total solar eclipse on 20 June 1955. The propagation in this case was single-hop reflection from the E layer and the increase in field strength observed during the eclipse could be attributed to a decrease of absorption in the D layer.

The study of the results obtained by a number of other workers indicated that the observed changes in field strength during a solar eclipse could be better understood by comparing the equivalent vertical incidence frequency of the signal with the critical frequencies of the reflecting layer and the layer through which the waves passed. There would be a decrease or an increase in the intensity of the reflected waves as the critical frequency of the reflecting layer approached or receded from the equivalent vertical incidence frequency. In order to verify the above conclusion, the field strength measurements of two different frequencies on the same path, one of which would be reflected from the layer and the other penetrated it, were taken during the partial solar eclipse of 14 December 1955. The transmissions from the Bombay station of All India Radio on 7·24 and 9·55 Mc/s. were chosen since it was found that 7·24 Mc/s. would be reflected from the E layer and 9·55 Mc/s. was expected to penetrate it on normal days.

The details of the eclipse at Ahmedabad and Bombay are given in Table 1.

The distance between Bombay and Ahmedabad is about 470 km.

In Table 2 are given the equivalent vertical incidence frequencies for 7·24 and 9·55 Mc/s.

TABLE 1 — DETAILS OF ECLIPSE

	Ahmedabad	Bombay
Commencement of the eclipse	10.44 I.S.T.	10.36 I.S.T.
Maximum phase of the eclipse	12.40 I.S.T.	12.39 I.S.T.
End of the eclipse	14.30 I.S.T.	14.38 I.S.T.
Magnitude of the eclipse	47%	55%

TABLE 2 — EQUIVALENT VERTICAL INCIDENCE FREQUENCIES OF TRANSMISSION FROM BOMBAY AT AHMEDABAD

Signal Frequency Mc/s.	Equivalent vertical incidence frequency for reflection from	
	E layer Mc/s.	F_1 layer Mc/s.
7·24	3·1	5·1
9·55	4·2	6·7

from Bombay to Ahmedabad for a single-hop transmission through the E and F_1 layers.

The sky waves were received on two modified BC-342 communication receivers from which the A.V.C. had been removed and the voltages across the second detector were measured by a bridge type d.c. amplifier V.T.V.M. These were calibrated with a standard G.R. signal generator. In order to eliminate the errors due to fluctuations in the mains voltage, a constant voltage transformer was used. The readings were taken daily from 12 to 16 December 1955. On the eclipse day, a recording milliammeter was also connected to the receivers to study the fading patterns during the eclipse. Half-minute readings were taken daily from 10.00 to 14.30 I.S.T. except on the eclipse day when, due to some unavoidable causes, the transmissions started only from about 11.00 I.S.T. The readings were later averaged over successive ten-minute intervals and the averaged readings were plotted against time on each day. It was found that the field strength curves on the control days were all similar and a single mean curve was plotted to represent the variations on the control days. Figs. 1 and 2 show the signal strength variations on the control days and on the eclipse day on the 7·24 and 9·55 Mc/s. transmissions respectively from Bombay.

These curves show that on normal days the field strengths on both the transmissions were minimum at about noon, indicating that the non-deviative D layer absorption was effective in both the transmissions. The minimum in the field strength was attained earlier on the 9·55 Mc/s. transmission than on the 7·24 Mc/s.

Shortly after the commencement of the eclipse, the field strength of the 7·24 Mc/s. transmission decreased below the normal control-day values, while the 9·55 Mc/s. transmission showed an increase. Neither the maximum of the 9·55 Mc/s. transmission nor the minimum of the 7·24 Mc/s. transmission coincided with the maximum phase of the eclipse. The minimum occurred after the maximum phase in 7·24 Mc/s. transmission while the maximum of the 9·55 Mc/s. transmission occurred before it. The critical frequencies of the E and F_1 layers at Ahmedabad on the control and eclipse days are given in Table 3.

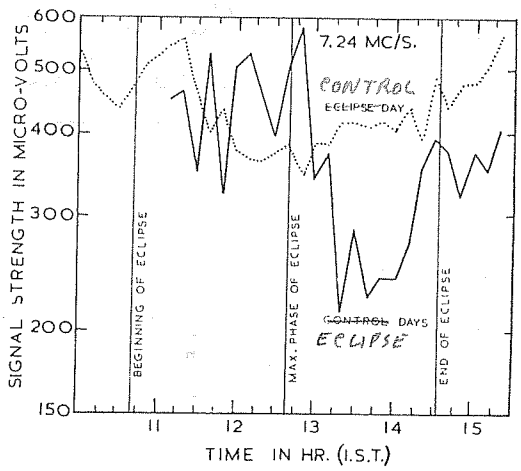


FIG. 1 — AVERAGE SIGNAL STRENGTH OF THE TRANSMISSION FROM BOMBAY (7·24 Mc/s.) AT AHMEDABAD ON CONTROL DAYS AND ON THE ECLIPSE DAY

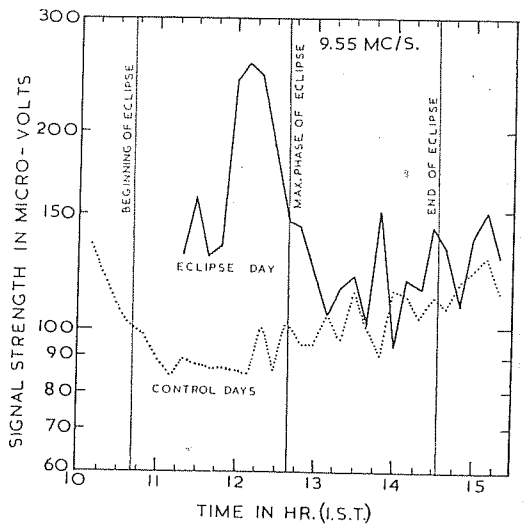


FIG. 2 — AVERAGE SIGNAL STRENGTH OF THE TRANSMISSION FROM BOMBAY (9·55 Mc/s.) AT AHMEDABAD ON CONTROL DAYS AND ON THE ECLIPSE DAY

TABLE 3 — CRITICAL FREQUENCIES OF E AND F_1 LAYERS AT AHMEDABAD

Time I.S.T.	Control days		Eclipse day	
	f_0E (*Mc/s.*)	f_0F_1 (*Mc/s.*)	f_0E (*Mc/s.*)	f_0F_1 (*Mc/s.*)
10.00	3·4	5·0	3·25	5·00
11.00	3·5	5·2	3·15	4·80
12.00	3·5	5·2	3·25	5·20
13.00	3·4	5·1	3·30	5·15

Comparing these with the figures given in Table 2, it will be seen that on normal days, the 7·24 Mc/s. transmission could be reflected from the E layer, while the 9·55 Mc/s. transmission would have penetrated the E and F_1 layers and got reflected from F_2. On the eclipse day, the critical frequencies of the E layer were lower than those on normal days and were very near the vertical incidence frequency for 7·24 Mc/s. transmission. This increased the deviative absorption for 7·24 Mc/s. and, therefore, the field strength decreased on the eclipse day. There was, apparently, not much change in the F_2 layer during the eclipse as seen from the ionospheric records at Ahmedabad. However, as 9·55 Mc/s. transmission penetrated both the E and F_1 layers there was decreased absorption of this transmission in the lower layers during the eclipse resulting in increased field strength.

Conclusions

The above observations show that although there is a general decrease in the non-deviative absorption in the D layer during the solar eclipse, the field strength changes observed at any particular place depend not only upon this factor but also upon the deviative absorption in the layers penetrated by the wave.

Summary

The results of field strength measurements made at Ahmedabad during the partial solar eclipse of the 14 December 1955 on radio transmissions from Bombay on 7·24 and 9·55 Mc/s. are described. The 7·24 Mc/s. waves are reflected from the E layer, while the 9·55 Mc/s. waves penetrate E and are reflected from the F_2 layer on normal days. During the eclipse, the field strength of the 7·24 Mc/s. transmission decreased below the value for normal days, while the 9·55 Mc/s. waves showed increased field strength. The changes are explained in terms of the vertical incidence frequencies of the waves and the critical frequencies of the ionospheric layers at Ahmedabad.

Acknowledgement

The work was done under the kind guidance of Prof. K. R. Ramanathan to whom the authors are indebted. Thanks are also due to Shri K. M. Kotadia for assistance in taking the observations, and to the authorities of the All India Radio for arranging special transmissions from their Bombay station. The authors are in receipt of financial assistance from the Council of Scientific & Industrial Research, India.

References

1. Rastogi, R. G. & Sheriff, R. M., *J. sci. industr. Res.*, **14A** (1955), 159.
2. Rastogi, R. G., Sheriff, R. M. & Nanda, N. G., *Proc. Symposium: Solar Eclipse and the Ionosphere* held at London, 22-24 August 1955, in press.

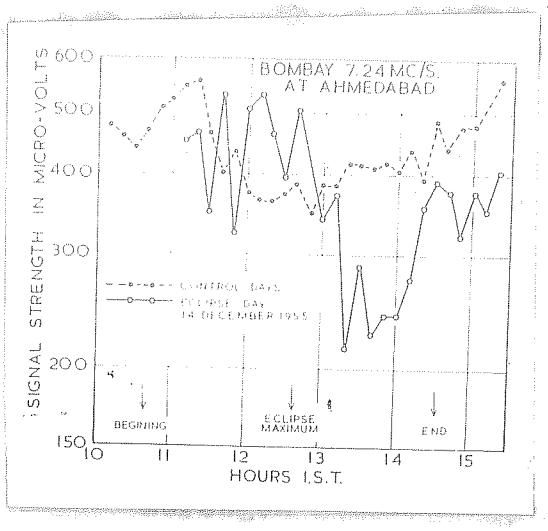


Fig. 1

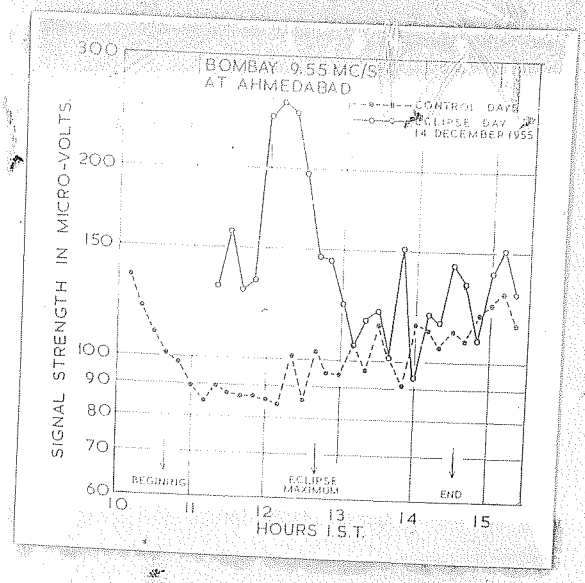


Fig. 2

Fig. 1. Variation of signal strength of Bombay 7.24 Mc/s transmissions received at Ahmedabad during the solar eclipse on December 14, 1955 and on control days. Note the decrease in the signal strength during the eclipse period.

Fig. 2. Variation of signal strength of Bombay 9.55 Mc/s transmissions received at Ahmedabad during the solar eclipse on December 14, 1955 and on control days. Note the increased signal strength during the eclipse period.

Oblique Reflections of Radio Waves from the Ionosphere during Solar Eclipse

The Physical Research Laboratory has in its programme of research the study of the ionosphere both by vertical pulse soundings and by oblique incidence field strength measurements. Observations taken at Ahmedabad during the last three solar eclipses are discussed below.

Observations during the total solar eclipse on June 30, 1954 :- During this eclipse, field strength measurements were made at Ahmedabad on B.B.C. 15.07 and Moscow 15.36 Mc/s. transmissions. Further special vertical ionospheric soundings at short intervals were also made to study the ionospheric changes at Ahmedabad. Results of field strength measurements of B.B.C. 15.07 have been published (Rastogi and Sheriff[1]) and vertical soundings are described in a separate note (Rastogi[2]).

Observations on the solar eclipse on June 20, 1955 :- The next solar eclipse was observed at Ahmedabad on June 20, 1955. The following observations were taken during the eclipse.

(1) Field strength observations of Colombo 4.87 Mc/s transmissions received at Trivandrum by Rastogi.

(2) Field strength observations of Colombo 7.19 Mc/s

transmissions received at Ahmedabad by Sheriff and Nanda.

A summary of the results of these observations was presented at the symposium on "Solar eclipses and the Ionosphere" held in London 22-24 August 1955[3].

Observations on the solar eclipse on December 14, 1955 :- Another solar eclipse occurred at Ahmedabad on December 14, 1955. Both vertical ionospheric soundings as well as oblique incidence field strength measurements were taken during the eclipse.

The results of the ionospheric soundings are described in a separate note (Rastogi[4])

The results of the field strength observations have been published by Rastogi and Seturaman[5]. Observations taken during the same solar eclipses by other workers have given results which are different from those obtained at Ahmedabad during the eclipse of June 30, 1954, Karnov[6] observed the signal strength of Moscow 25 metre signals at Stalingrad and obtained a decrease of 46 db. below normal during this eclipse. Ghosh et al[7] observed the field strength of Moscow 15.17 Mc/s transmission at Jabalpur and got a decrease in signal strength during the eclipse. The Canadian Broadcasting Corporation[8] observed a reduction in signal strength of the 12 Mc/s and 15 Mc/s band transmissions on the circuits to East Europe during the same eclipse. The B.B.C.[9] issued a report on the effect of the solar eclipse on the reception of B.B.C.

transmissions in Europe, America, Africa, Australia and the Far East. The effect of the eclipse was different at different places and different at different frequencies. A bulletin prepared by the Netherland Post and Telegraph Department[10] on the effect of the solar eclipse on radio communication circuits to the Scandinavian countries, Japan and Indonesia showed that there was decrease in field strength during eclipse.

During the eclipse of June 20, 1955, Gopal Rao and Ramachandra Rao[11] observed the field strength of Colombo 9.52 Mc/s signals at Waltair. The results were different from those obtained by us on Colombo transmission on different frequencies received at Trivandrum and Ahmedabad.

Thus, field strength observations by workers in different parts of the world during eclipse present non-uniform results. An attempt has been made in this paper to examine the results of field strength observations made during solar eclipses and interpret them in a consistent manner.

I. A brief resume of the basic theory of the reflection of radio waves from the ionosphere is given first.

(1) Vertical incidence ionospheric absorption.

The attenuation of radio waves in their passage through the atmosphere can be expressed in terms of an absorption coefficient (k). The amplitude of a plane wave after passing through a distance s is given by

$$I = I_0 e^{-\int k ds} \qquad (1)$$

where I_0 is the intensity of the wave before entering the absorbing medium and the integral $\int k ds$ is taken over the whole path traversed by the wave.

According to magneto-ionic theory, the absorption coefficient (k) of a wave of angular frequency (ω), per unit path length in a medium of electron density N is given by

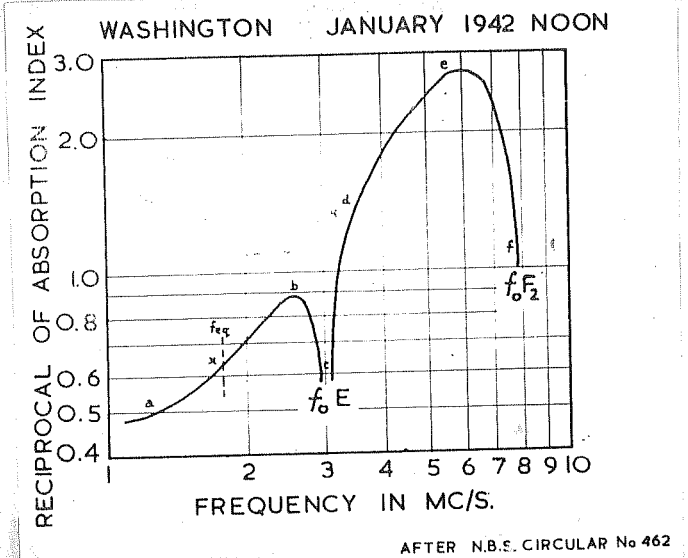
$$k = \frac{2\pi e^2}{mc} \frac{1}{\mu} \frac{N\nu}{\nu^2 + (\omega \pm \omega_L)^2}$$

where μ is the refractive index; e and m are the charge and mass of the electron; ν is the electron collision frequency and ω_L is the component of the angular gyro-frequency in the direction of propagation. The positive and negative signs refer to the ordinary and extraordinary waves respectively.

The absorption is large when (i) μ is small (then called deviative absorption) and (ii) $N\nu$ is large (then called non-deviative absorption due to the collisions).

The variation of absorption of the ordinary wave with frequency is shown in Fig. 1 for noon in January 1942 at Washington[12] and in Fig. 2 for noon on July 11, 1950 at Slough (Appleton and Piggot[13]). It may be noted that the inverse of the index of absorption is plotted in the figure, therefore the higher the ordinate, the higher is the value of the signal strength. One sees from these figures that there are large

dips in the curves. These correspond to increased deviative absorptions near the critical frequencies of the ionospheric layers due to a very small μ.



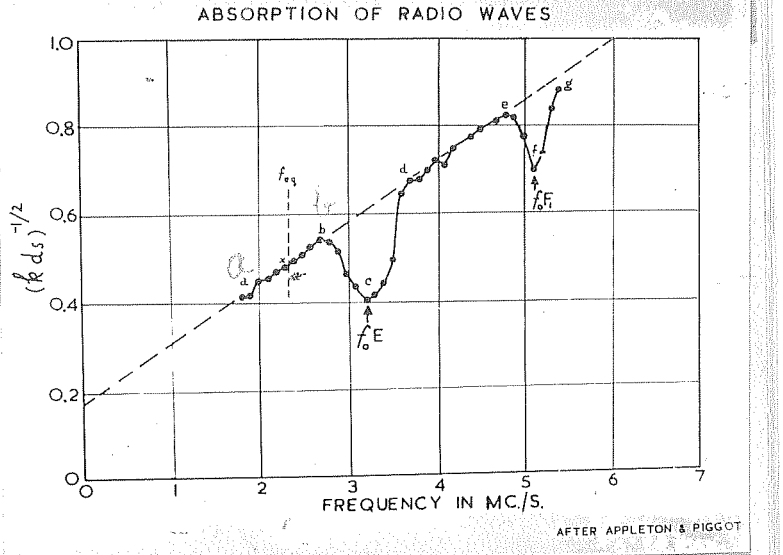


Fig. 1. and 2.

When μ is approximately equal to unity i.e. the absorption is non-deviative, it varies with frequency according to expression

$$k = \frac{2\pi e^2}{mc} \cdot \frac{N\nu}{\nu^2 + (w \pm w_L)^2}$$

i.e. $k \propto (w \pm w_L)^{-2}$

or $k^{-1/2} \propto (w \pm w_L)$

In Fig. 2 $\frac{1}{\sqrt{k.ds}}$ is plotted as a function of frequency. The absorption at all frequencies except close to the critical frequencies obey the linear law given by the equation. The above relation has been varified by many

workers e.g. Appleton[14], Davies and Nagg[15] have shown that the dependence of non-deviative absorption on solar zenith distance for a Chapman region would be given by the expression

$k \, ds \, \cos^{n}\chi$

Actually in temperate latitudes the power of $\cos\chi$ is found to be in the neighbourhood of 0.75.

(2) Oblique incidence propagation and absorption :- According to Martin the equivalent height of reflection of a wave of frequency f incident obliquely on the ionosphere at an angle of incidence i is the same as that of a wave of frequency f cos i incident vertically, provided the two waves are reflected from the same region. f cos i is called equivalent vertical incidence frequency or briefly equivalent frequency and is designated by f_{eq}

$$f_{eq} = f. \cos i$$

The angle of incidence i of the wave reflected from a height h in the ionosphere can be calculated by the equations given by Appleton and Beynon[16].

$$D = 2R\theta$$

$$\cos^2 i = \frac{(h + R - R\cos\theta)^2}{(h + R - R\cos\theta)^2 + R^2 \sin^2\theta}$$

$$\text{or}^{\prime} \cos^2 i = \frac{h + \frac{1}{2} R\theta^2}{(h + \frac{1}{2} R\theta^2) + R^2\theta^2}$$

where D is the distance between the transmitting and receiving sites and R is the radius of the earth. For propagation involving n hops

$$D = 2 n R\theta$$

Martyn[17] introduced another theorem relating coefficient of oblique incidence absorption to vertical incidence absorption namely

$$\left[\log \rho\right]_{i_o}^{f} = \cos i_o \left[\log \rho\right]_{o}^{f \cos i_o}$$

The experimental results fitted better the relation

$$\left[\log \rho\right]_{i_o}^{f} = \left[\log \rho\right]_{o}^{f \cos i_o}$$

Appleton[18].

Beynon and Davies[19] have shown that the absorption of obliquely incident C.W. signals is well correlated with the vertical incidence pulse absorption of waves of the corresponding equivalent frequency. Thus the field strength of an obliquely incident C.W. signal can be interpreted in terms of its equivalent frequency. The changes in the signal strength of continuous wave signals during an eclipse can therefore be interpreted in terms of the changes of the critical frequency and the height of the reflecting region.

From Fig. 2 showing the absorption curve at noon, we derive another Fig. 3 showing the absorption curve for

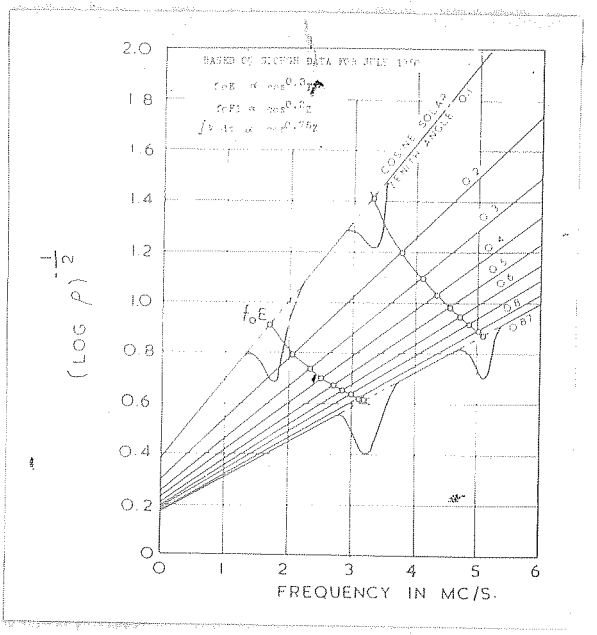


Fig. 3.

different solar zenith distances. Assuming the relation, $\int k ds \propto \cos^{0.75}\chi$ for the diurnal variation of non-deviative absorption, a series of straight lines are drawn indicating the variation of non-deviative absorption with frequency at different times ($\equiv \cos\chi$). As $\cos\chi$ decreases, the critical frequencies of E and F1 also decrease and so the cusps in the figures due to deviative absorption would also move towards lower frequencies. The variation of f_0E or f_0F1 with $\cos\chi$ can be expressed by the expression $f_0 = \cos^n\chi$. The values of n can be determined from the critical frequencies at different hours of the day. The index n at Slough in July 1950 was 0.3 for E layer and 0.2 for F1 layer. The position of f_0E and f_0F1 at different values of $\cos\chi$ are shown by small circles.

(3) Absorption of radio waves during a solar eclipse :- A solar eclipse produces a decrease in values of the critical frequencies of E and F1 layers. The amount of decrease depends on the magnitude of the eclipse, the time of the day, the season and the place of observation. During the eclipse the D layer ionisation and consequently non-deviative absorption also decreases. The effect of the solar eclipse on the absorption frequency curve is, therefore, analogous to the changes of absorption curve due to decreasing solar zenith distance.

If we are studying the signal strength of a fixed frequency transmitter from a distant station, f_{eq} will remain constant during the eclipse (provided signals are reflected from the same region), but the absorption curve will move across f_{eq} during the course of the eclipse.

The changes in field strength of a fixed frequency radio waves during an eclipse can be estimated as follows. Let f_{eq} be the equivalent frequency of the wave corresponding to the position of reflection. Let x be the point on the absorption curve corresponding to f_{eq}. With the start of the eclipse the point x will shift to the curves corresponding to small $\cos\chi$, and the recovery of the eclipse would correspond to the movement of the reference point in the other direction. The changes in the field strength of any fixed frequency can be estimated from the position of the

reference point on the absorption curve at different times of the eclipse.

Let the reference point before the start of the eclipse be between points a and b in Fig. 2. With the commencement of the eclipse the reference point would move to a higher point on the curve and the signal strength would increase. If the changes in f_0F during the eclipse are small, so that the deviative region of E layer does not approach f_{eq}, the eclipse would produce a single maximum of field strength at the time of maximum phase of eclipse as shown in Fig. 4(a).

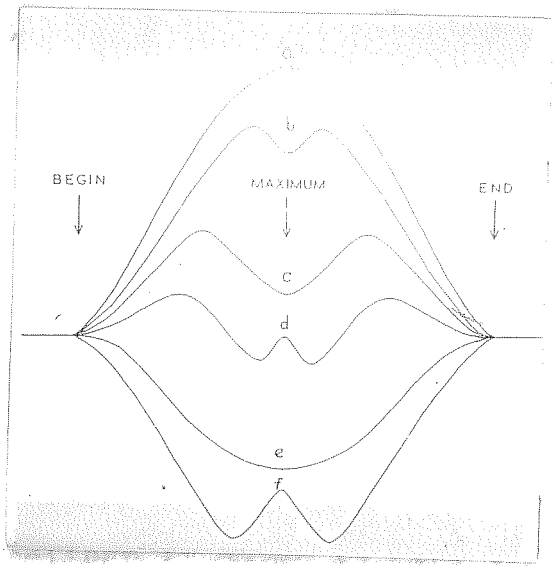


Fig. 4.

If the decrease in f_0F during the eclipse is large, or if the reference point x was nearer to b, there would again

be a decrease in signal strength due to E layer deviative absorption, and the field strength time curve would have two maxima before and after the middle of the eclipse with a drop at the period of maximum eclipse as shown in Fig. 4(b).

If the decrease in f_0E during eclipse is still larger so that f_0E decreases below f_{eq} before the maximum eclipse, the expected field strength curve would produce two maxima shortly after the start and before the end of the eclipse and another maximum at the middle of the eclipse as shown in the Fig. 4(d).

Let f_{eq} before the start of the eclipse be very near to f_0E, so that the reference point lies on the cusp (i.e. between points b and c). With the start of the eclipse f_0E would come nearer to f_{eq}, deviative absorption would increase thereby decreasing the signal strength of the waves. If the decrease in f_0E during the eclipse is small, the field strength curve would show a single minimum at the middle of the eclipse. The decrease in f_0E during the eclipse is large so that f_0E decreases below f_{eq}, the field strength curve during the eclipse would be broad dip with a maximum at the middle of the eclipse is shown in Fig. 4(f).

Similarly, field strength variations can be estimated corresponding to any frequency of the wave, provided we know the critical frequencies of the ionospheric layers at the point of reflection on the normal day and on the eclipse day. It may be noted that if the eclipse at the point of

reflection occurs at a time different from noon, changes in f_oE or f_oF1 would not be symmetrical and would correspondingly alter the field strength variation curves. Actual quantitative changes of field strength of C.W. signals are, however, very difficult to be estimated. The observed field strength is the resultant of both ordinary and extraordinary components of the wave, the exact contribution of each of which is unknown. The field strength may further be due to more than one mode of propagation, and the changes of these during an eclipse cannot be determined from C.W. signals. Study of the absorption of pulsed signals are not so complicated and provide more information about the ionosphere. But the present study helps to understand some of the apparently contradictory results of oblique incidence C.W. field strength measurements made by several workers during solar eclipses.

II. A. Vertical Incidence Ionospheric Absorption Measurements

A few observations of field strength measurements during solar eclipses are described and the observed changes are explained in the following chapter. The observations discussed here are given in Table 1 for easy reference.

(1) Jen et al[20] measured the intensity of 3 Mc/s radio pulses incident almost vertically at Kunming during the eclipse on June 20, 1944 (magnitude 76%). The reflections on

Date of eclipse	Transmitting station	Receiving station	Signal frequency Mc/s	Distance km	Mode of propagation	Equivalent frequency	Time of Eclipse: Maximum	Time of Eclipse: At mid-point	Results	Reference
20-6-1944	Kunming	Kunming	4.0	-	E layer	4.0	1252 L.M.T		General increase and a sharp dip at the middle of the eclipse.	Jen et al
20-5-1947	Bebedouro	Bebedouro	4.0	-	E1 layer	4.0	0924 Hours.		Dips at times when f_0F1 equalled 4 Mc/s.	Bosson et al
30-6-1954	Freiburg	Freiburg	1.95	-	E layer				No clear change.	Busch et al
			2.9		F1 layer				Increase.	-do-
30-6-1954	Varnamo	Varnamo	1.5	-	E layer		1247 G.M.T.		Increase at the middle of eclipse.	
			2.0	-	E layer			-do-	A dip followed by a peak at the middle of the eclipse.	
			2.5	-	E,F1 layers			-do-	An increase and later a dip after the middle of the eclipse.	
20-6-1955	Colombo	Trivandrum	4.87	420	Single hop E	2.3	0811 I.S.T.		Increase at the middle of the eclipse	Rastogi et al
	Colombo	Ahmedabad	7.19	1950	One or two hop E layer.	1.3 or 2.1	0812 I.S.T.		Increase at the middle of the eclipse	-do-
	Colombo	Waltair	9.52	1300	One hop E	2.05	0816 I.S.T.		One peak shortly after the start and another at the middle of the eclipse.	Gopal Rao and Ramchandra Rao
14-12-1955	Bombay	Ahmedabad	7.24	470	One hop E	3.1	1240 I.S.T.		Decrease during the latter half of eclipse.	Rastogi and Sethuraman
	Bombay	Ahmedabad	9.55	470	One hop F2			-do-	Increase during the first half of the eclipse.	
30-6-1954	Moscow	Stalingrad	12	920	One hop E	3.1			Decrease 48 db.	Karnov
	Kootwijk	Enkoping	9.24	1100	-do-	2.03	1245 G.M.T.		Decrease 30 db. at 1246 hr.	Fokker et al
	Karlsbourg	Nederhorst den Berg	9.397	920	-do-	2.31	1245 "		Decrease 27 db. at 1246 hr.	-do-
	Kootwijk	Ski	9.24	900	-do-	2.32	1241 "		Decrease 25 db. at 1242 hr.	-do-
	Jeloy	N.den Berg	9.311	875	-do-	2.34	1241 "		Decrease 25 db. at 1248 hr.	-do-
	Kootwijk	Keimola	9.24	1500	-do-	1.75	1248 "		No clear decrease.	-do-
	Helsinki	N.den Berg	10.807	1500	-do-	2.04	1248 "		Decrease not pronounced and irregular	-do-

the normal days as well as on the eclipse day were from the E layer h' = 120 km. The intensity of the reflected waves on the eclipse and control days are shown in Fig. 5. On the

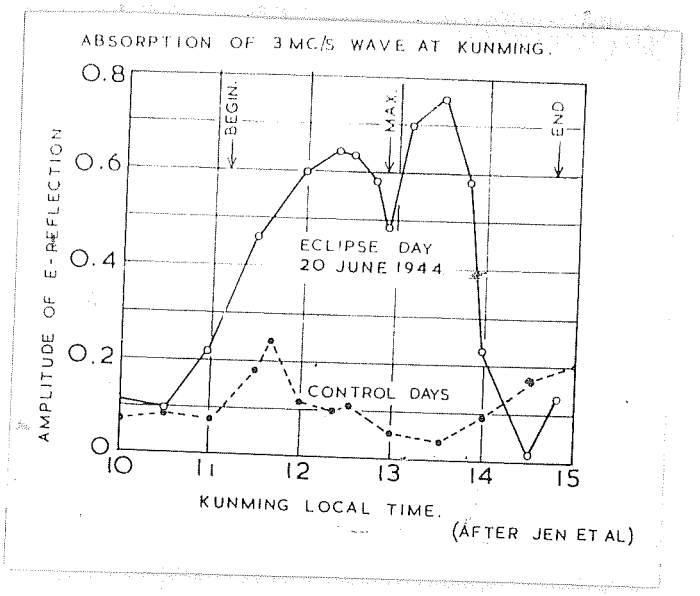


Fig. 5.

eclipse day, there was a general elevation of the reflected amplitude but at the maximum phase of the eclipse, there was a sharp fall of intensity. The general rise of amplitude during the eclipse was due to a decrease of non-deviative D layer absorption, and the sharp dip in amplitude at the maximum phase of the eclipse was due to increased E layer deviative absorption. The changes correspond to those shown in Fig. 4(b).

(2) Bosson et al[21] observed the vertical absorption of radio pulses of 4 Mc/s at Bebedouro (48.5°E, 20.9°S) during the solar eclipse of May 20, 1947. The amplitudes of the

first order echoes and the values of f_0F1 on the eclipse day are shown in Fig. 6.

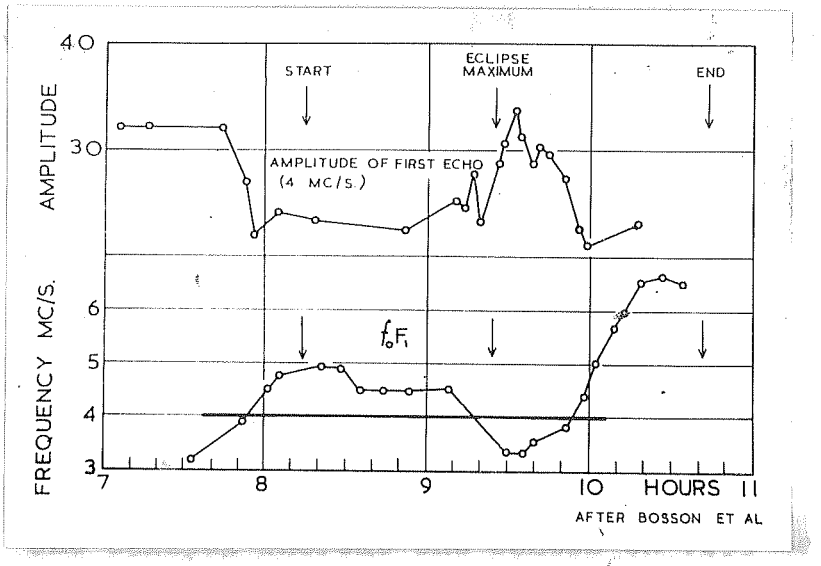


Fig. 6

At the beginning of the observations, the reflections were from F2. As f_0F1 increased with increasing zenith distance of the sun, there was observed a small dip in the intensity of reflection at the time when f_0F1 equalled 4 Mc/s (0755 hr). After the eclipse started, f_0F1 again decreased and there was another dip in the amplitude of the pulse when f_0F1 equalled 4 Mc/s (at 0910 hr). In the later half of the eclipse, f_0F1 had decreased well below 4 Mc/s and there was a broad maximum of amplitude during this period due to a decrease in D layer non-deviative absorption. There was yet another minimum of amplitude at 0955 when f_0F1 was 4 Mc/s. The three dips correspond almost precisely to the times

when f_0F1 was equal to the frequency of the signal. The observations show that there was general decrease of non-deviative absorption when the exploring frequency was less than the critical frequency and significant deviative absorptions at time when the signal frequency approached the critical frequency of the layer that was penetrated.

(3) : Busch, Harnischmacher and Rawer[22] described vertical incidence absorption measurements at Fribourg during the solar eclipse on June 30, 1954 on 1.95 Mc/s and 2.9 Mc/s. The field intensity of echoes on 2.9 Mc/s attended a maximum during the eclipse whereas the echoes on 1.95 Mc/s do not show any visible effect. They explained the results of 1.95 Mc/s waves in terms of the compensation of two opposing effects, the selective absorption increasing with the occultation of the sun and non-selective absorption showing the normal diminishing effects. They further showed that the values of non-selective absorption were proportional to the effective intensity of the solar radiation i.e.

$$B \doteqdot (1 - p) \cos \chi \quad 1.1$$

B. Review of some Oblique Transmission Measurements during Eclipses.

(1) Colombo 4.87 Mc/s received at Trivandrum during the solar eclipse on June 20, 1955. :- A summary of these observations was presented at the symposium on Solar Eclipses

and the Ionosphere. Further explanations are given below. The distance between Colombo and Trivandrum is 420 km. The transmissions from Colombo were directed skyward and so the signal strength measured at Trivandrum were taken to be mainly due to singly reflected skywaves. The equivalent frequencies corresponding to reflections from the E layer (110 km.), the F1 layer (230 km) and the F2 layer (350 km) were calculated and are given in Table 2.

Table 2.

Equivalent vertical incidence frequency for Colombo 4.87 Mc/s transmissions received at Trivandrum.

Reflecting layer.	Equivalent frequency.
E	2.29 Mc/s
F1	3.61 Mc/s
F2	4.18 Mc/s

In Table 3 are given the critical frequencies and heights of the ionospheric layers at Kodaikanal (10.2°N, 77.5°E) for the month of June, 1955. The bracketed values of f_0E and f_0F1 were calculated according to the $\cos^n$ law with n = 0.4.

On examining the critical frequencies of E and F1 layers at Kodaikanal and other equatorial stations, it is seen that the F1 layer was generally not formed during the first part of the period of these observations and that f_0E

Table 3

Ionospheric characteristics at Kodaikanal in June, 1955.

Time I.S.T.	f_0E Mc/s	f_0F1 Mc/s	f_0F2 Mc/s
0630	(1.7)	(3.1)	-
0700	(2.2)	(3.5)	-
0730	2.5	3.75	7.0
0800	2.75	(3.95)	-
0830	3.0	(4.1)	7.7
0930	3.3	4.3	8.0
1030	3.4	4.4	8.0

was lower than f_{eq}. The signal thus penetrated E and F1 and got reflected from F2 on normal days. With the increase of solar altitude, reflections were from E when its critical frequency exceeded 2.3 Mc/s. This transition would have occurred between 0700 and 0730 (as inferred from f_0E values in table 3). There is a dip in the field strength on normal days as well as on the eclipse day just before 0700 hr which is probably due to the increased E layer deviative absorption. Later on, the reflections may be taken to have continued from the E layer on the control days.

The variation of signal strength with the cosine of solar zenith distance is shown in Fig. 7. The point

corresponding to the observations between the period 0845 to 0845 lie in a straight line indicating that the absorption during the period varied according to $\cos^n \chi$ law with n being equal to 0.3. At about 0845, there is a sudden change and the later points lie in a straight line with a greater slope, the index n being 4.2.

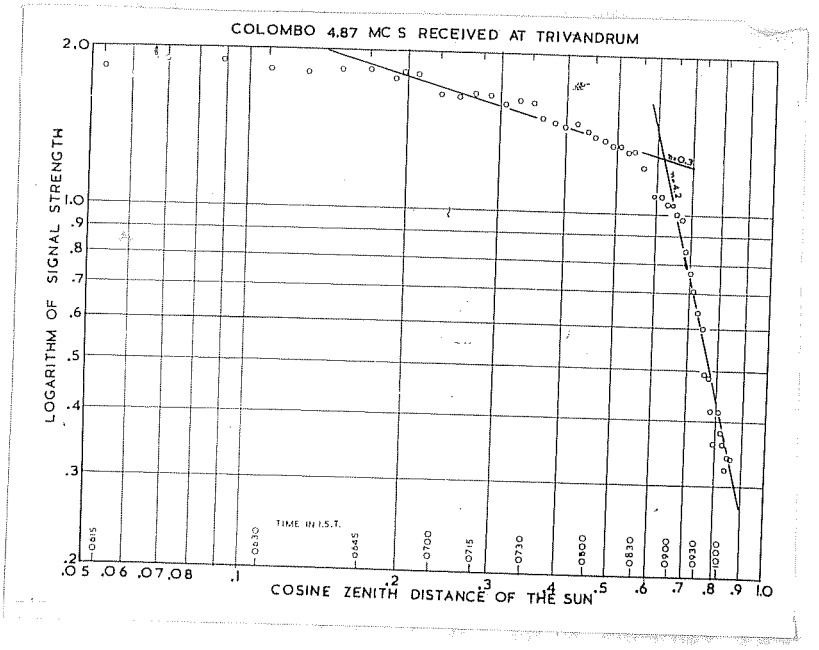


Fig. 7.

Minute to minute averages of signal strength on the eclipse day are plotted in Fig. 8.

On the eclipse day, the waves penetrated the E layer and reflections took place from the F2 layer during the earliest part of the observations, as on normal days. The reflections continued to be from F2 till about 0700 when the E layer started reflecting causing a dip in signal strength. The eclipse started at 0707 decreasing the D layer absorption.

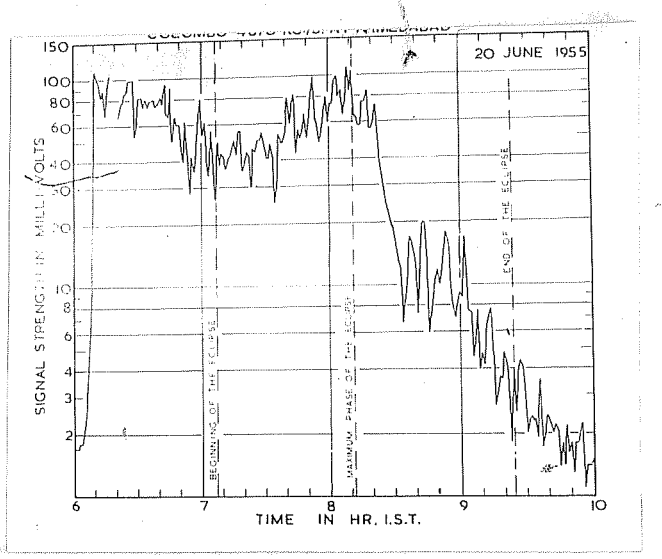


Fig. 8.

The F layer critical frequency also decreased giving rise to increased deviative absorption. The signal strengths remained almost steady due to the two opposing effects till about 0730 (see fig. 8). Later, both D layer and E layer absorptions continued to decrease resulting in a steady rise of signal strength till the middle of the eclipse. After the totality of the eclipse, both $\cos\chi$ and the unobscured portion of the solar disc increased progressively resulting in a rapid rise in the ionospheric ionisations. Consequently, the signal strength decreased rapidly after the totality of the eclipse and reached the normal value well before the end of the eclipse.

(2) <u>Colombo 7.19 Mc/s received at Ahmedabad during the solar eclipse on June 20, 1955</u> :- The distance between Colombo and Ahmedabad is about 1950 km. The

equivalent frequencies for the reflections from E and F1 layers calculated for one and two-hop propagation are given in Table 4.

Table 4.

Equivalent vertical incidence frequencies for Colombo 7.19 Mc/s at Ahmedabad.

Reflecting layer.	Equivalent frequency propagation	
	One-hop	Two-hop
E	1.33 Mc/s	1.84 Mc/s
F1	2.14 Mc/s	3.27 Mc/s

The signals are received by one-hop or two-hop reflections from the E layer on normal days frequency was only 50 to 60% of the normal E layer critical frequencies. The logarithms of signal strength are plotted against log $\cos\chi$ in Fig. 9 and show that the points lie approximately on a straight line. If the absorption on normal days be represented by $\cos^n\chi$, the value of n is roughly equal to 0.49. This further shows that on normal days the absorption was mainly D non-deviative one.

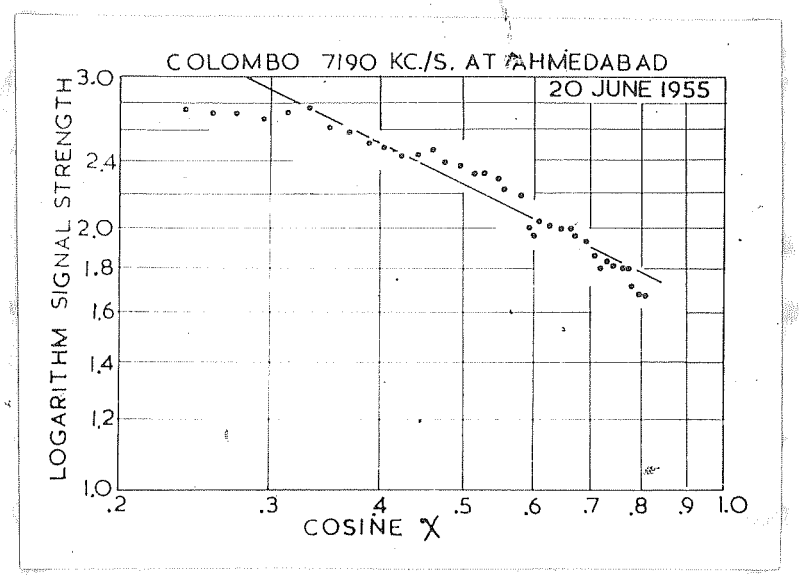


Fig. 9.

(3) Colombo 9.52 Mc/s transmission received at Waltair during the solar eclipse of June 20, 1955 :- Gopal Rao and Ramchandra Rao[11] reported the results of their observations on Colombo 9.52 Mc/s at Waltair (17.6°N, 83.2°E) during the eclipse on June 20, 1955 (Fig. 10). Their results were quite different from those observed at Trivandrum and Ahmedabad.

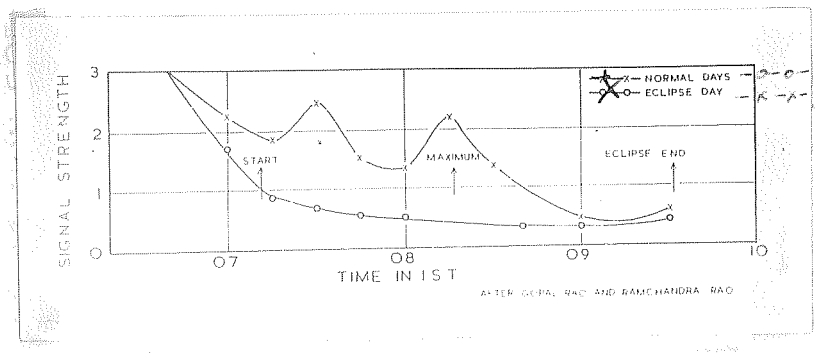


Fig. 10

½ The distance between Colombo and Waltair is 1300 km. The magnitude of the eclipse at the mid-point of the path was

86% and the maximum occurred at 0816 I.S.T. The equivalent frequencies for single hop reflection E and F1 layers were about 2.05 and 3.57 Mc/s respectively.

On examining the critical frequencies of E and F1 layers at the ionospheric stations of the same latitudes as the mid-point of the path (e.g.Kodaikanal Guam etc.), it is inferred that the reflections on the normal days were one-hop E layer during the entire period of the observations. f_oE at 0700 was about 2.2 Mc/s (f_{eq} = 2.05 Mc/s). The absorption on normal days was therefore non-deviative D layer absorption. Absorption coefficients on the normal days when plotted against corresponding $\cos\chi$ values on a double logarithmic paper lay in a straight line (Fig. 11). This indicated that

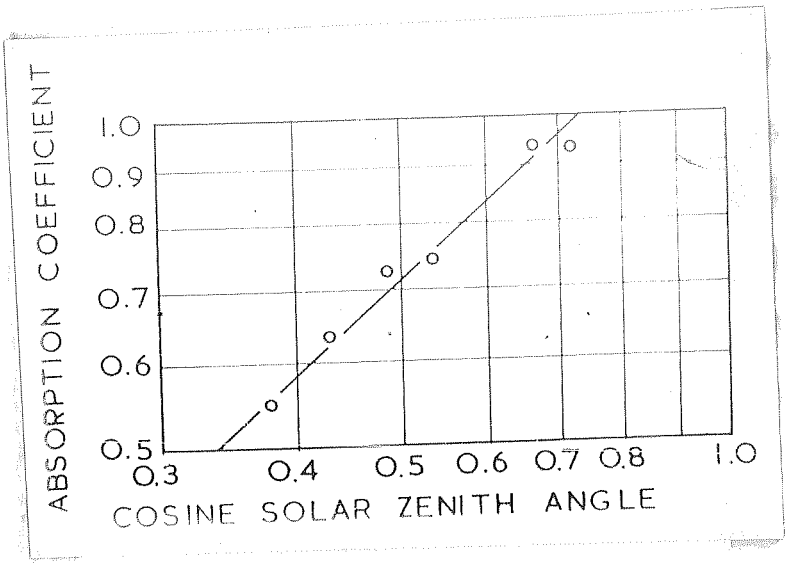


Fig. 11

the absorption coefficients varied with solar zenith distance according to the $\cos^n\chi$ law, and being equal to 0.87, and

therefore non-deviative D layer absorption was operative during the period of observation on the control days.

Making a rough estimate of the expected minimum value of f_0E during the eclipse according to the formula given by Ratcliffe[23],

$$\frac{N_1^2}{N_0^2} = \frac{S_1 \cos \chi_1}{S_0 \cos \chi_2}$$

It was found that it should be 1.5 Mc/s. Recently[24] it has been reported that at Kodaikanal the lowest value of f_0E during the eclipse was 1.85 Mc/s at 0809.

The field strength on the eclipse day first increased with the start of the eclipse, reached the maximum at 0715, and another peak was observed at the time of the middle of the eclipse. These changes can be explained if we assume that on eclipse day f_0E had dropped below f_{eq} before the maximum phase of the eclipse and the reflections then were from the F region. With the start of the eclipse, D region absorption decreased increasing the signal strength for some time (0715-0730 hr). At the same time f_0E also decreased as it approached f_{eq}, the E layer deviative absorption increased stopping the increase in field strength and later decreasing it. The E layer absorption would be maximum when f_0E equalled f_{eq}, and the dip between 0745 and 0800 hr corresponds to period when f_{eq} was very near f_0E. Later f_0E still decreased below f_{eq},

now reducing the deviative absorption which together with continued decrease of D layer absorption gave rise to the peak at the maximum phase of the eclipse. The results correspond to that shown in Fig. 4(d).

In the observations of Karnov[6] of Moscow 25 metre transmission received at Stanlingrad during the solar eclipse of June 30, 1934, the equivalent frequency for E layer reflection was 3.1 Mc/s (distance 920 km). The signals were received by E layer reflections on normal days and the decrease in the signal strength on the eclipse day observed by Karnov was due to increased E layer deviative absorption during the period.

(4) Field strength measurements during the total solar eclipse on June 30, 1954 at Netherland, Sweden, Norway and Finland :- The solar eclipse on June 30, 1954 crossed the southern part of Norway and Sweden, a series of field strength observations were undertaken during the eclipse to study the changes in radio telegraphic communication circuit from Netherland to Norway, Sweden and Finland. Signals from radio Kootwijk, Netherlands (52.2°N, 5.8°E) on 9.24 Mc/s were received at Enkoping, Sweden (59.6°N, 17.1°E), at Ski, Norway (59.7°N, 10.8°E) and at Keimola, Finland (60.3°N, 24.8°E). Similarly, signal strengths were recorded at Nederhorst den Berg, Netherlands (52.3°N, 5.1°E) of the transmissions from Karlsbourg, Sweden (58.4°N, 14.5°E) on 9.397 Mc/s, Jeloy, Norway (59.4°N, 10.6°E) on 9.311 Mc/s and from Helsinki,

Finland (60.3°N, 24.3°E) on 10.007 Mc/s. These transmitting and receiving stations are shown in Fig. 12. The track of

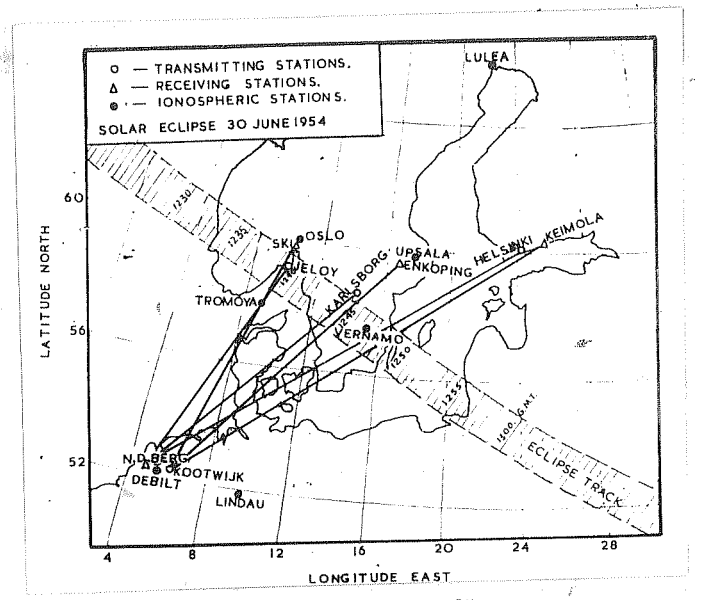


Fig. 12.

the shadow is also shown in the figure. The regular ionospheric sounding stations in the region were Oslo (60.0°N, 11.1°E), Upsala (59.8°N, 17.6°E), Lindau (51.6°N, 10.1°E) and DeBilt (52.1°N, 5.2°E). Norwegian Defence Research Establishment made ionospheric soundings at three places viz. Tromoya (58.0°N, 9.0°E), Kjeller (60.0°N, 11.0°E) and Tromso (59.8°N, 19.0°E). Temporary ionospheric sounding station was established at Varnamo (57.2°N, 14.1°E) observations concentrated on 1.5, 2.0 and 2.5 Mc/s only.

The distances and the equivalent vertical frequencies for single hop reflection via E, F1 and F2 layers were calculated for all the transmissions and are

given in Table 5.

Table 5.

Radio Circuit	Signal frequency	Distance	f_{eq} from layer		
			E	F1	F2
	Mc/s	km	Mc/s	Mc/s	Mc/s
Kootwijk to Ski	9.24	900	2.32	4.01	6.02
Kootwijk to Enkoping	9.24	1100	2.03	3.48	5.47
Kootwijk to Keimola	9.24	1500	1.75	2.86	4.46
Jeloy to Nederhorst den Berg	9.31	875	2.38	4.12	6.26
Karlsberg to "	9.40	920	2.31	4.00	6.14
Helsinki to "	10.81	1500	2.04	3.35	5.22

Equivalent frequencies of the transmission from Kootwijk to Ski, Enkoping and Keimola as well as from Jeloy, Karlsborg and Helsinki to Nederhorst den Berg for one hop reflection via E, F1 and F2 layers.

To determine the region of reflection of the radio waves on the transmission paths the normal critical frequencies of E, F1 and F2 layers at various European stations were studied. In Table 6 are given the critical frequencies of the E layer at different ionospheric stations in that region.

Table 6

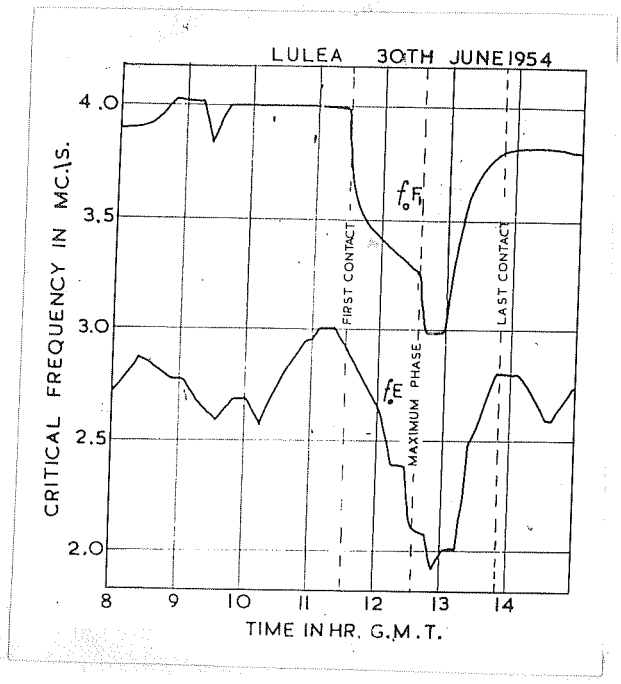
Critical frequencies of E layer at Ionospheric stations in Sweden, Norway, Finland, Netherland and Germany during June-July 1954.

Time	DeBilt	Lindau	Oslo	Upsala	Mean	Lulea 27 to 29 Jun. & 1 to 3 Sept.
G.M.T.	Mc/s	Mc/s	Mc/s	Mc/s	Mc/s	Mc/s
1000	3.05	3.00	2.80	2.90	2.94	2.87
1100	3.15	3.00	2.95	3.00	3.03	3.00
1200	3.25	3.05	2.95	2.95	3.04	2.94
1300	3.20	3.00	2.90	2.85	2.99	2.96
1400	3.15	3.00	2.85	2.85	2.95	2.84
1500	2.95	2.80	2.75	2.65	2.79	2.70

These ionospheric stations were at the two ends of the transmission path and hence the mean critical frequencies of all these stations can be taken as at the mid-point of the path. The E layer critical frequencies at 12-13 hours were about 3 Mc/s and f_{eq}s range from 1.8 Mc/s to 2.4 Mc/s on normal days, therefore the radio waves were reflected from E layer. The ratios of f_{eq} to f_0E range from 0.6 for Kootwijk-Kelmola to 0.75 for Kootwijk-Ski circuit. The absorption on normal days for all these circuits can be assumed to be mainly non-deviative D layer absorption.

On the eclipse day f_0E and f_0F1 would decrease

with the increasing occultation of the sun. We examine the variation of the critical frequencies of the ionospheric layer at a few places in that region. The decrease in f_oE and f_oF1 at Lulea is shown in Fig. 13, the magnitude of the eclipse at Lulea was 81%. The decrease in the critical



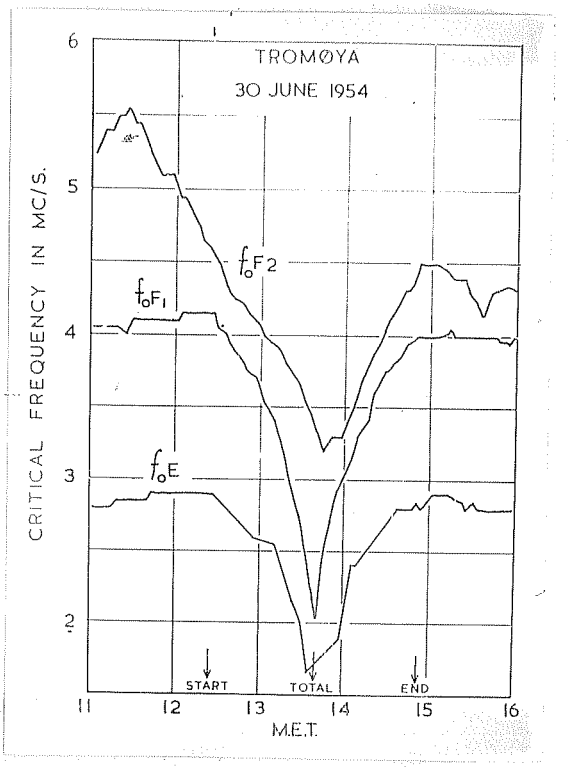


Fig. 13. and 14.

frequency from estimated undisturbed value was for the E layer 35% and for F1 layer 24%. The lowest value of f_oE was about 1.9 Mc/s near the maximum of the eclipse.

The variation of the critical frequencies of E, F1 and F2 layers at Tromoya during the eclipse is shown in Fig. 14. The minimum values of the critical frequencies recorded were 1.65 Mc/s for E layer. At Kjeller, the

variations were similar, the minimum values of f_0E, f_0F1 and f_0F2 were 1.75, 2.36 and 3.28 Mc/s respectively.

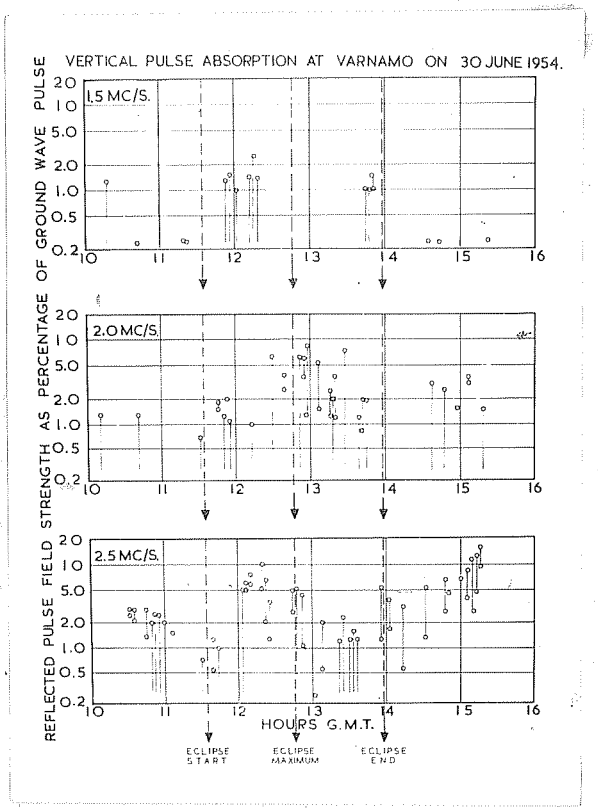


Fig. 15.

The intensities of the vertically propagated radio waves of 1.5, 2.0 and 2.5 Mc/s during the eclipse at Varnamo are shown in Fig. 15. Varnamo was in the track of total eclipse. From the figure it appears that the echoes from 1.5 Mcs were stronger during the period of the eclipse. This increase may be due to a decrease of D layer absorption. Echoes on 2.0 Mc/s varied in quite a different way.

There seems to be a dip in the intensity at about 40 minutes after the start of the eclipse. This was followed

by an increase in intensity reaching a maximum at about the middle of the eclipse. The dip in intensity before the totality seems to be due to increased E layer deviatiye absorption when f_0E approached 2 Mc/s. The intensity of the echoes on 2.5 Mc/s was decreasing even before the eclipse, because f_0E was approaching 2.5 Mc/s with increasing solar zenith angles. With the start of the eclipse, f_0E started decreasing and the intensity of the echoes also started increasing. There was a dip before the end of the eclipse again due to E layer deviative absorption. After the eclipse the intensity increased steadily.

The field intensities of almost all the circuits had decreased at the time of maximum eclipse.

The recordings of the transmissions from radio, Kootwijk to Enkoping during June 29, June 30 and July 1, 1954 are shown in Fig. 16. We find that on normal days the signal strength was substantially constant during the period (11-14 G.M.T.). On the eclipse day, soon after the beginning of the eclipse, the field intensity started increasing and reached a maximum much before the middle of the eclipse. The early increase was due to the decrease of D layer absorption with the start of the eclipse, the maximum was due to the opposing E layer absorption as the decreasing f_0E approached f_{eq} (2.03 Mc/s). The continued decrease of f_0E after the waves have penetrated the E layer would decrease E layer deviative absorption and one would expect

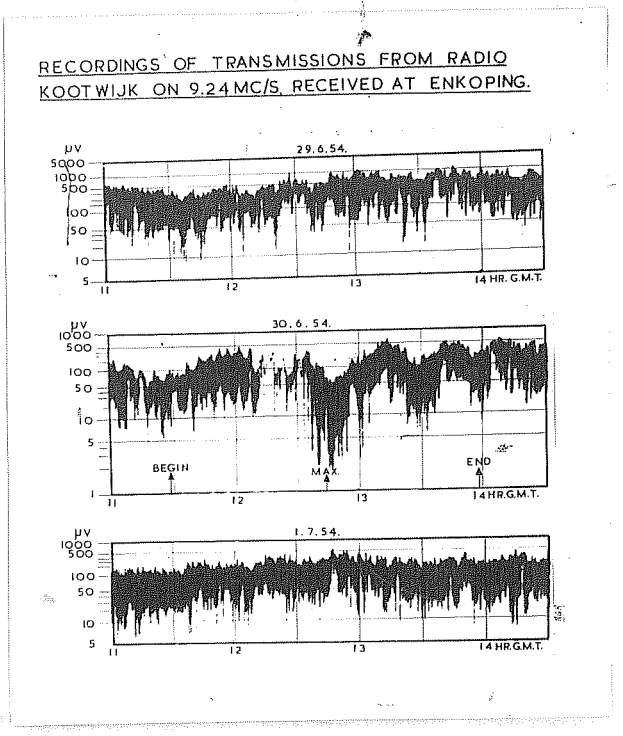


Fig. 16.

again an increase of signals strength. Referring to table 5 we find that f_{eq} for F1 reflection was about 3.5 Mc/s and from Fig. 14 we see that f_0F1 were much lower than f_{eq} at the time. Thus once the rays penetrated the E layer the higher F1 and F2 layers were not enough ionized to reflect the waves. The reception might be partly from the higher layers and partly by the extraordinary component of the waves reflected from the layer E. The received waves would be so highly attenuated and a well pronounced dip was recorded at the middle of the eclipse. With the recovery of the eclipse the signal strength again increased and there was a dip before the end of the eclipse (1330 hr) due to increased E layer deviative absorption. Karlsbourg transmission at N.D.Berg

also showed similar changes during the eclipse. The signal strength variations of Jeloy, Karlsberg and Helsinki transmissions received at N.D.Berg are shown in Fig. 17.

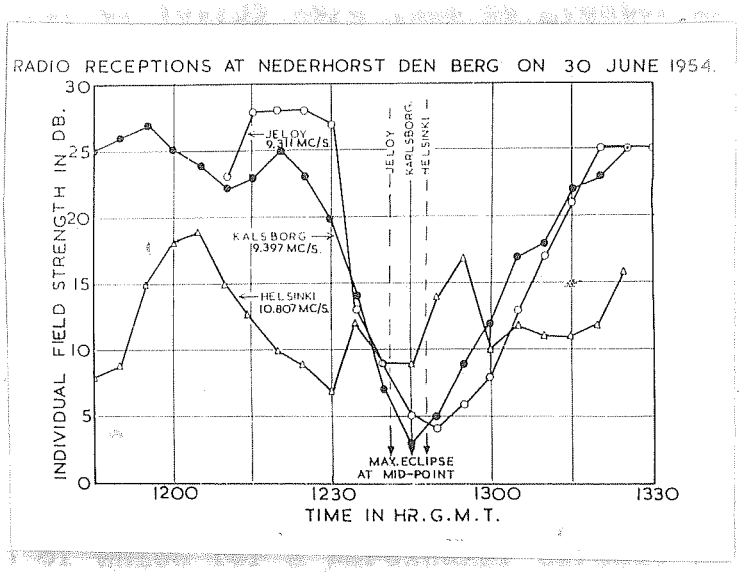


Fig. 17.

These changes can be explained similarly. The equivalent frequency of Kootwijk-Keimola transmission was as low as 1.75 Mc/s and no clear decrease was recorded on the received signal strength. f_0E would have just approached f_{eq} without crossing and thereby there would have been increased E layer absorption during the eclipse period. This effect was opposed by the decrease of D layer absorption and so no significant changes were recorded. The Finnish receiving station at Keimola, did observed, a decrease on other circuits. A decrease of 13 db between 1200 and 1345 hr was found on 9.057 Mc/s transmissions from Elmshorn (Germany). Dutch stations 10.735 Mc/s showed complete fading between 1210 and

1320. These observations are in contrast to previously described, transmissions between Finland and Netherlands. The difference can be attributed to equivalent frequency of the waves of 10.735 Mc/s (due to greater frequency) and of 9.057 Mc/s (due to shorter distance).

C. Long distance Short Wave Propagation during Solar Eclipses

The interpretation of field strength measurements on a long transmission path becomes more complicated because the transmission takes place in many hops, the exact knowledge of which for a particular circuit is very difficult. The effect of an eclipse on a long transmission path is further made uncertain because the difference regions of reflections would be far apart where the ionisation conditions would be very different, the magnitude of the eclipse, the altitude of the sun and the changes in ionisation would not be the same in these regions. During the eclipse there may also be changes in the mode of propagation (number of hops).

Due to the curvature of the earth the propagation by E layer is restricted to a certain distance. Even when the ray leaves the earth tangentially to the ground, the maximum span of the hop is only about 2400 km for an E layer at 110 km. For E layer transmission beyond 2400 km; it is essential that the radio part include more than one hop.

Usually the F layer transmission are more effective than multi-hop E layer transmissions for distances greater than about 2000 km. Further in the case of long distance propagation, quite a good fraction of the total path may be inside the reflecting region due to the finite thickness of the layer. The results have to be interpreted in terms of the maximum usable frequency for the mode of propagation concerned.

Therefore, to interpret the influence of eclipse on long distance propagation, it is necessary to determine first the most probable mode of propagation on normal days and then to calculate the effect of the eclipse on each of the reflecting regions.

REFERENCES

1. Rastogi R.G., and Sheriff R.M. 1955 Jour.C.S.I.R.(India),14A, 159.

2. Rastogi R.G. A study of the ionosphere over Ahmedabad during the total solar eclipse of 30 June 1954.

3. Rastogi R.G., Sheriff R.M., and Nanda M.G. Proc.Symposium "Solar eclipse and the Ionosphere".

4. Rastogi R.G. A study of the ionosphere over Ahmedabad during the partial solar eclipse on 14 December 1955.

5. Rastogi R.G., and Sethuraman K. 1956 Jour.G.S.I.R.(India), 15A, 302.

6. Karnov A.N. May 1955 Priroda (Moscow),p.113.

7. Ghosh A.K. et al 1955 Jour.Inst.Tell.Engrs., (India),1, 20.

8. Canadian Broadcasting Corp. 1954 Eclipses of the sun, June 30, 1954.

9. B.B.C. 1954 Solar eclipse of June 30, 1954, and the reception of short wave transmissions

10. Fokker A.D. ,et al 1955 I.G.A.Report No. 7 Netherlands,P.T.T.

11. Gopalrao M.S.V., and Ranchendrarao B. 1955 Current Science,24,408.

12. National Bureau of Standards, U.S.A. 1948 Ionospheric Radio Propagation, N.B.S.Circular No.462.

13. Appleton E.V.and Piggott W.R. 1954 Jour.Atmos.Terr.Phys.,5,151.

14. Appleton E.V. 1937 Proc.Roy.Soc.,A162, 451.

15. Davies K., and Baker D.M. 1955 Jour.Atmos.Terr.Phys.,6,20.

16. Appleton E.V. et al 1940 Proc.Phys.Soc.London, 52, 518.

17. Martyn D.F.	1935	Proc.Phys.Soc., London, 47, 323.
18. Appleton E.V., and Beynon W.J.G.	1955	Jour.Atmos.Terr.Phys., 6, 141.
19. Beynon W.J.G.	1954	Jour.Atmos.Terr.Phys., 5, 280.
20. Jen C.K., et al	1944	Phys.Rev., 66, 226.
21. Bosson F., et al	1947	Colloques Internationaux Lyon 2, 117.
22. Bush K., et al	1956	Annales de Geophysique, 12, 1.
23. Ratcliffe, J.	1955	Proc. of the symposium on solar eclipses and the ionosphere held in London.
24. Astrophysical Observatory, Kodaikanal	1956	Indian Jour.Met.Geophy., 7 October, 1956.

****

CHAPTER VI

THUNDERSTORMS AND SPORADIC E LAYER IONISATION

Thunderstorms and Sporadic E Layer Ionisation

ABSTRACT : The paper describes the results of vertical P'-f recordings of ionospheric reflections carried out during the passage of isolated thunderstorms over Ahmedabad. The thunderstorms were found to be accompanied by an increase in sporadic E ionisation as shown by a rise in the maximum frequency of the Es or an increase in the intensity of reflection from Es.

INTRODUCTION : Various agencies such as meteors, thunderstorms, and solar corpuscles have been suggested as possible causes of Es ionisation. Wilson (1925, 1926) was the first to suggest that thunderstorms might cause ionisation in the upper layers of the atmosphere. His idea was taken up by several workers and some observational evidence was produced to show that the ion content of Es was affected by thunderstorms. Ratcliffe and White (1933, 1934) found that the nocturnal E region ionisation was associated with thunderstorms. Other workers (Appleton and Naismith 1933, Watson Watt 1933, Bhar and Syam 1937) reported that abnormal day time E region ionisations were associated with thunderstorms. Later, however, Appleton, Naismith and Ingram (1936) obtained a low correlation coefficient between Es and thunderstorms and held that the effect of thunderstorms on Es has not been established. Bhar and Syam (1937) get a correlation coefficient of 0.50

between thunderstorm index and Es. In 1938, Best, Farmer and Ratcliffe stated that statistically there was not much evidence of thunderstorms affecting Es. In 1944, Stoffregen found close relationship between intense Es and thunderstorms and showed that the effect was more pronounded during magnetically quiet days. Mitra and Kundu (1954) reported an increase in fEs soon after the arrival of Nor'wester thunder squalls at Calcutta and subsequent decay of Es. But Rangarajan (1954) at Kodaikanal did not find any effect of thunderstorms on Es. Isted (1955) found that lightning discharges had strong correlation with abnormal bursts of h region ionisation in vertical p'-f records on 10.6 Mc/s and also observed that there were bursts of increased signal strength in oblique incidence transmissions at 53.25 Mc/s. Besides the direct measurements of Es ionisation, other effects of thunderstorms on Es have been reported. For example Himmo (1937) observed increased multiple reflections from Es during a thunderstorm and Chatterjee (1952) reported increased reflections from Es.

In view of this conflicting evidence, a study of ionospheric reflections during thunderstorms was undertaken at Ahmedabad. Isolated thunderstorms sometimes occur at this place on days which are otherwise free from Es and this makes it easy to see the effect of the thunderstorms.

There was a thunderstorm on the evening of 8 June

1954. The microbarograph record of the day between 17 and 22 hr is shown in Fig. 1. The P'-f records taken during the period are shown in Fig.2. During the thunderstorm, fEs values were much higher than the normal values. Moreover, the number of multiple reflections from the Es also increased considerably. There occurred another thunderstorm on the evening of the 10 June 1955. The Es critical frequencies were very high during the period and more than 12 multiple reflections from the Es region were recorded.

An examination of the P'-f records in some more instances showed that in general thunderstorms did affect Es at Ahmedabad. It was considered desirable therefore, to study with special vertical soundings at short intervals the changes during individual thunderstorms. When a thunderstorm was seen approaching the station more frequent P'-f recordings were started till the storm had passed over. This article describes the results of such a study.

There occurred an isolated thunderstorm on the afternoon of 1 October 1955. The monsoon had ended by then and the weather was calm. The disturbance started suddenly at about 1445 hr and lasted for about an hour. The anemometer and micrograph charts for the period are shown in Fig.3 and 4. The variations of fEs are shown in Fig.5. There was a sudden increase in fEs shortly after 1500 hr about 10 minutes from the onset of the surface storm. The increase continued till

1640 hr about half an hour after the storm had passed over. Fig. 6 shows the portion of the P'-f records taken during the period. At 1500 hr there was only very weak echoes from Es at 100 km below 3.5 Mc/s and normal E and F2 reflections were quite clear. At 1510 hr the reflections from Es Es at 100 km grew stronger and weak sporadic reflections appeared from a height of 140 km. At 1520 hr Es reflections from 100 km increased in strength and the maximum frequency went upto 3.6 Mc/s. The Es reflections from 130 km strengthened and merged with F2 reflections. At 1530 hr Es from 130 km grew still stronger, fEs increased to 5.0 Mc/s and the F1 reflections were completely blanketted. At 1600 hr six multiples of Es reflections were recorded. At 1640 hr fEs reached the maximum value of 6.2 Mc/s. It then decreased and came down to the normal value at about 1700 hr. Alibag observatory reported the magnetic character of the day as Ca (a quiet day) and International character figure was very low (0.7).

There occurred another isolated thunderstorm on the afternoon of 23 October 1955. The International magnetic character figure for the day was 0.3. Thunder on the day started at about 1445 hr and was overhead at 1500 hr and subsided by 1600 hr. Fig. 7 shows increased fEs during 14 hr to 16 hr corresponding to the period of the thunderstorm activity.

Another set of observations was taken in the early

morning hours of the 27 February 1956. The weather on the 26 was clear except for a few scattered clouds; the night was more disturbed and there started a succession of thunderstorms in the early morning hours followed by rain and hail. The anemometer and the microbarograph charts for the period are shown in Figs.8 and 9. The thunderstorm and disturbed conditions continued till about 0800 hr after the weather cleared up. This disturbance was of a frontal type and on the days before and after, the weather was calm. The International C figure was 1.1. Kodaikanal magnetogram did not show any magnetic disturbance on 27th. During these days fas were very low particularly during the early morning hours. On some days, there were no Es reflections at all during these hours. The variations in fEs on the 27 February 1956 are shown in Fig.10 and a few P'-f records in Fig.11. fEs suddenly increased soon after first impulse on the microbarograph at about 0340 hr. In this case there were large variations in fEs during the period because of successive storms. An interesting feature is evident from Fig.11. At 0450 hr there were only weak Es reflections. These later became stronger and at 0520 and 0540 hr there were six multiples of Es reflections. According to Kawer (1949) the reflection coefficient (number of multiple reflections) is a good index of Es ionisation. So, this corresponds to increased general ionisation of Es . There occurred an isolated thunderstorm on the 14 March 1956. This storm was weak and of short duration. Es reflections on these

days were weak and fEs values were low. There was no Es reflections on the days before and after 14 March 1956 during 17-19 hr. The magnetograms of Kodaikanal showed slight agitation only and there was no magnetic storm. P'-f records taken during the period are shown in Fig.13.

The most convincing instance of the thunderstorm affecting Es was observed on 28 May 1956. The microbarograph chart for the period is shown in Fig.14. On May 28, 1956 no magnetic disturbance was recorded by Kodaikanal. Lightning was first seen at about 1930 hr to the east of the station and the thunderstorm came overhead at about 2000hr. It continued upto about 2300 hr. The variation of fEs on 28 May and on the normal days (25-31 May 1956) are shown in Fig. 15. The values of h'Es and changes in surface pressure are also shown in the figure. A few P'-f records taken during the period are shown in Fig. 16. At 1930 hr there were Es reflections upto 4.5 Mc/s. At 1940 hr there appeared few diffused Es reflections from frequencies upto 14 Mc/s from a height of 150 km. fEs at 115 km increased to 8 Mc/s at 1945 hr and to about 15 Mc/s at 1950 hr. Es reflections grew stronger when the thunderstorm approached the station and at 1955 hr fEs went above 15 Mc/s. As Es reflections became stronger, F2 reflections get weaker and portions of F2 trace were blanketted by Es. F2 reflections were completely blanketted at 2010 and 2015. They started reappearing at 2020 when the thunderstorm activity began to decrease in intensity. The multiple reflections from Es were more in number during the

of the blanketing by Es. Another interesting feature was that there were indications of h'Es increasing with frequency during the high Es period. (See record at 2145 hr) This may be due to a tendency for the formation of a homogeneous thin layer in the Es region during the thunderstorm. Chatterjee (1952) found that during thunderstorms Es obliterates F echoes and the Es ionisation then is preponderately of the thin layer type. The magnetogram at Kodaikanal was practically calm on 28 May 1956.

One more instance of a large temporary increase of fEs during a thunderstorm is given below. A thunderstorm occurred in the evening of 1 September 1956. There was slight rain at 16 hr and thunder was heard almost overhead at the station, with maximum intensity at about 1615 hr. It decreased by 17 hr and ended 1730 hr.

A few P'-f records taken during a thunderstorm on 1 September 1956 are shown in Fig. 17. In Fig. 17, we see that at 1500 hr, fEs was low and Es reflections were weak. At 1600 (record not reproduced) fEs rose to 11 Mc/s and Es reflections continued weak. At 1613, Es reflections became stronger giving four multiples, and part of the F1 trace was blanketed by Es. At 1633, fEs exceeded 14 Mc/s and the F1 traces were completely blanketed. Thereafter, fEs showed a decrease and at 1800, normal conditions were restored.

The variations of fEs on 1 September and on four control days are shown in Fig. 18.

It may be interesting to note that on the 3rd September 1955 there was continuous lightning with rain and there was a lightning discharge over the antenna system of the ionospheric station at 1819 hr. Short period records taken during the period did not show any change in Es reflections. Further in June-July 1956 when the rainy season had well developed at Ahmedabad, thunder did not seem to influence Es. It appears that low thunderstorms during the monsoon and lightning discharges between the clouds and the earth do not affect Es ionisation.

Regarding the mechanism of production of ionisation by thunderclouds, two process have been suggested by Wilson (1925). According to the first electrons inside a thundercloud are accelerated by the electric field inside the cloud and a stream of electrons moving upward from the upper boundary of the clouds are created. These electrons moving with large velocity would reach the E region and increase ionisation there. Wilson pointed out that while the electric force due to the thunderclouds falls off as $1/r$, the electric field required to cause the sparking falls of approximately as $1/r^2$. This is due to the decrease of the intensity with height. Thus if the electric movement of the cloud is not too small, there will be a height above the cloud where the electric field due to the cloud would exceed the sparking limit. Appleton and Naismith (1933) showed from theoretical considerations that even when a field near the cloud was only 1/27 of the sparking value, the field at a

distance of only 7 km below the E layer could reach the sparking values. Thus because of large potential difference between the thundercloud and E layer, upward discharges are possible inspite of the great distance between them. Normell (1953) has stated that thunderclouds could drive a vertical current upward from the earth through the cloud and on to the highly conducting regions above. Gish and Wait (1950) have measured from aircraft upward currents from the top of a thundercloud towards the upper atmosphere. Thus there are probably continuous discharges from a thundercloud besides an impulse discharges, and these too may modify the E region ionisation.

CONCLUSION : Observations of Es made at Ahmedabad during some isolated thunderstorms indicate that they cause a temporary increase in the electron content of the ionosphere. The effect takes the form of an increase in fEs or merely increase in the intensity of the Es reflection. The effect of a thunderstorm is localised and temporary. The Es changes generally appear within half an hour of the change at ground level during the passage of an moving thunderstorm; Es gradually returns to the normal value after the storm passes over the station. The ionisation due to a thunderstorm may be produced below the normal the E layer at 100 km or above it, upto 150 km It is known that there is a stable region at 140 km, for ionisation as evidenced by the occurrence of E2 layer and occasional night ionisation. During thunderstorms the Es region tends to become a homogeneous layer and sometimes produces group

retardation effects. The number of multiple reflections increase during the thunderstorms.

ACKNOWLEDGEMENTS : The work described is a part of the programme of ionospheric research in this laboratory with financial assistance from the Council of Scientific and Industrial Research (India). The author is indebted to Prof.K.R.Ramanathan for his keen interest and guidance. Thanks are due to Astrophysical Observatory, Kodaikanal for supplying the magnetic characteristic of selected days prior to their regular publication.

REFERENCES

Appleton, E.V., and Naismith, R.	1933	Proc.Phys.Soc.London, 45, 389.
Appleton, E.V., Naismith, R. and Ingram, L.J.	1936	Phil.Trans.Roy.Soc. London, A 236, 191.
Best, J.E., Farmer, F.T. and Ratcliffe, J.A.	1938	Proc. Roy.Soc.London, A 164, 96.
Bhar, J.N. and Syam P.	1937	Phil.Mag.22, 513.
Chatterjee, B.	1953	Jour.Atmos.Terr.Phys. 3, 229.
Gish,O.H., and Wait,G.R.	1950	Jour.Geophys.Res.55, 473.
Istead, G.A.	1955	Physics of the ionosphere (Physical Society,London,P.152)
Mimno, H.R.	1937	Rev.Mod.Phys. 9,37.
Mitra S.K. and Kundu,M.K.	1954	Nature, 174, 798.
Nangarajan, B.	1954	Jour.Geophys.Res.59, 239.

Ratcliffe, J.A. and White E.L.C.	1933	Proc.Phys.Soc.London, 45,399.
Ratcliffe, J.A. and White E.L.C.	1934	Proc.Phys.Soc.London, 46, 107.
Rawer, K.	1949	Nature, 163, 528.
Stoffregen, W.	1944	Arkiv.fur.Mat.Astr.och Fysik, 30A, No.19.
Watson Watt, R.A.	1933	Nature, 132, 13.
Wilson, C.T.R.	1925	Proc.Phys.Soc.London, 37. 32D.
Wilson, C.T.R.	1926	Proc.Roy.Soc.London, A 111, 5.
Wormell, T.W.	1953	Quart.Jour.Roy.Met.Soc. London, 79, 3.

* * * * * * * * *

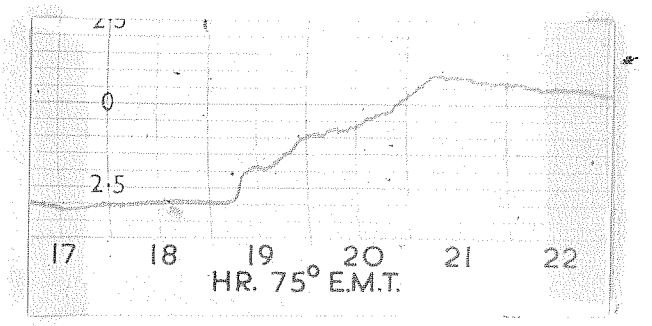


Fig:1. Microbarograph record on June 8, 1954 during a thundersstorm.

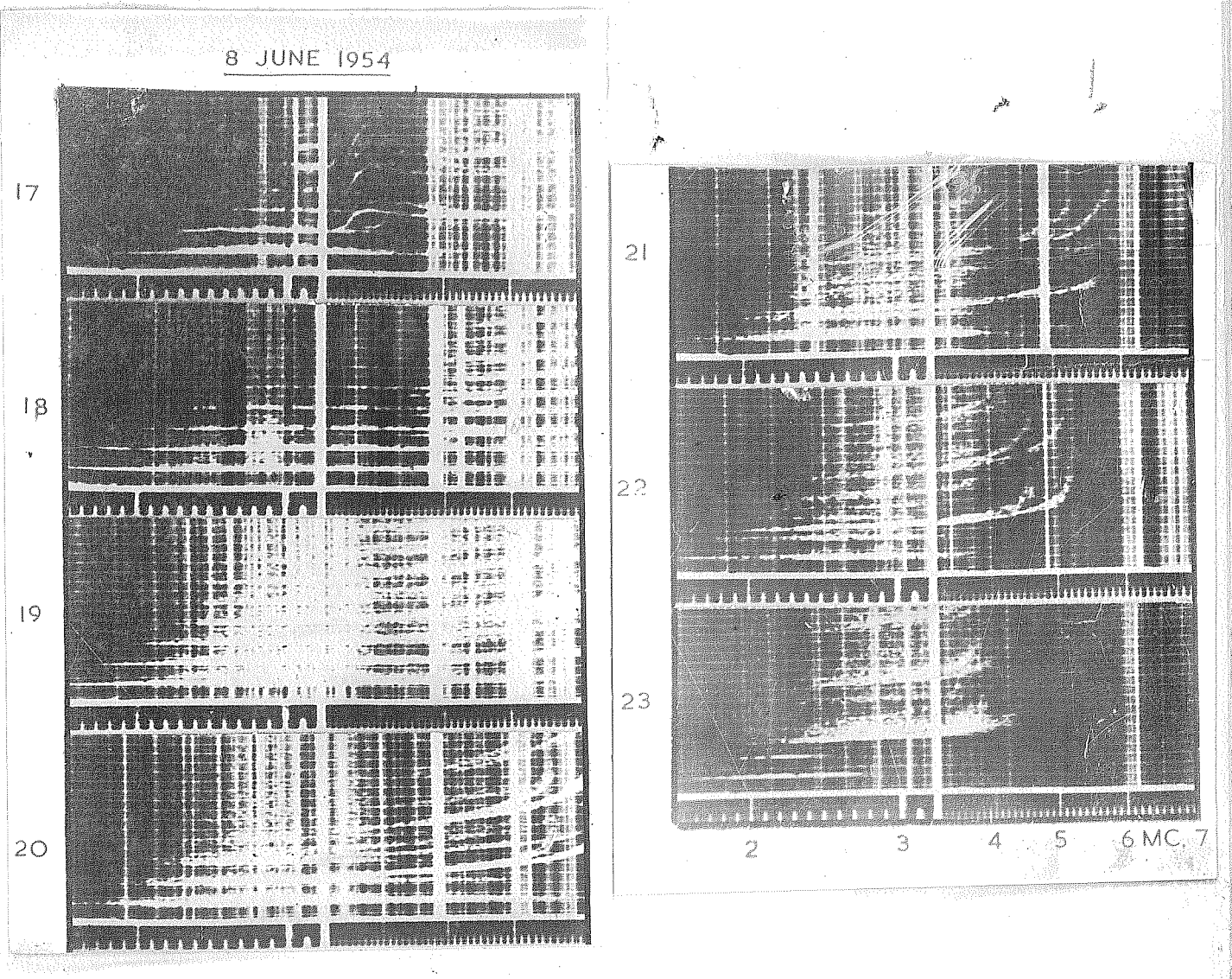


Fig. 2. P'-f records on June 8, 1954 during a thunderstorm.

Note high fEs and multiple reflections between 18 and 20 hr.

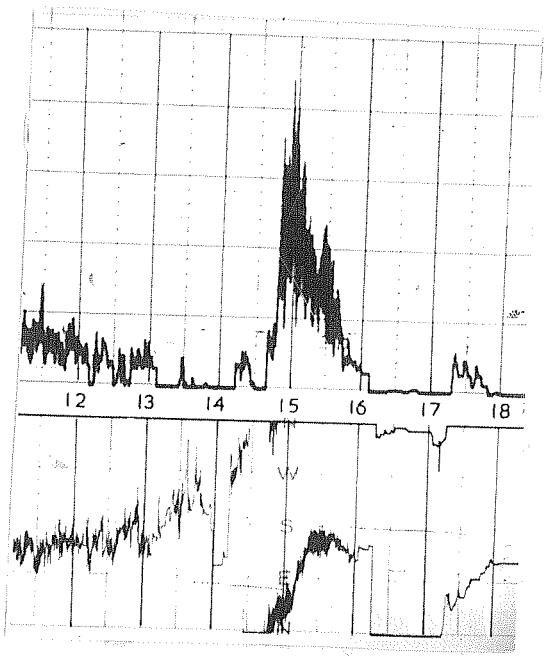


Fig.3. Anemometer chart on October 1, 1955 during the passage of a thunderstorm over the station.

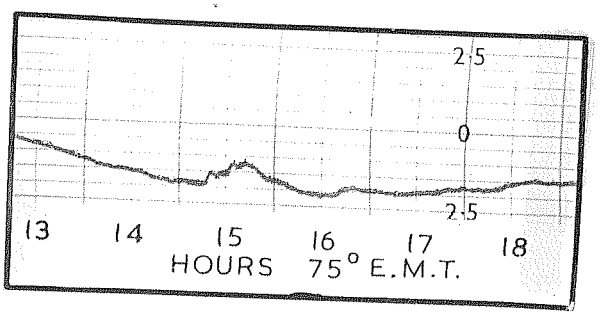


Fig.4. Microbarograph chart on October 1, 1955 during the passage of a thunderstorm over the station.

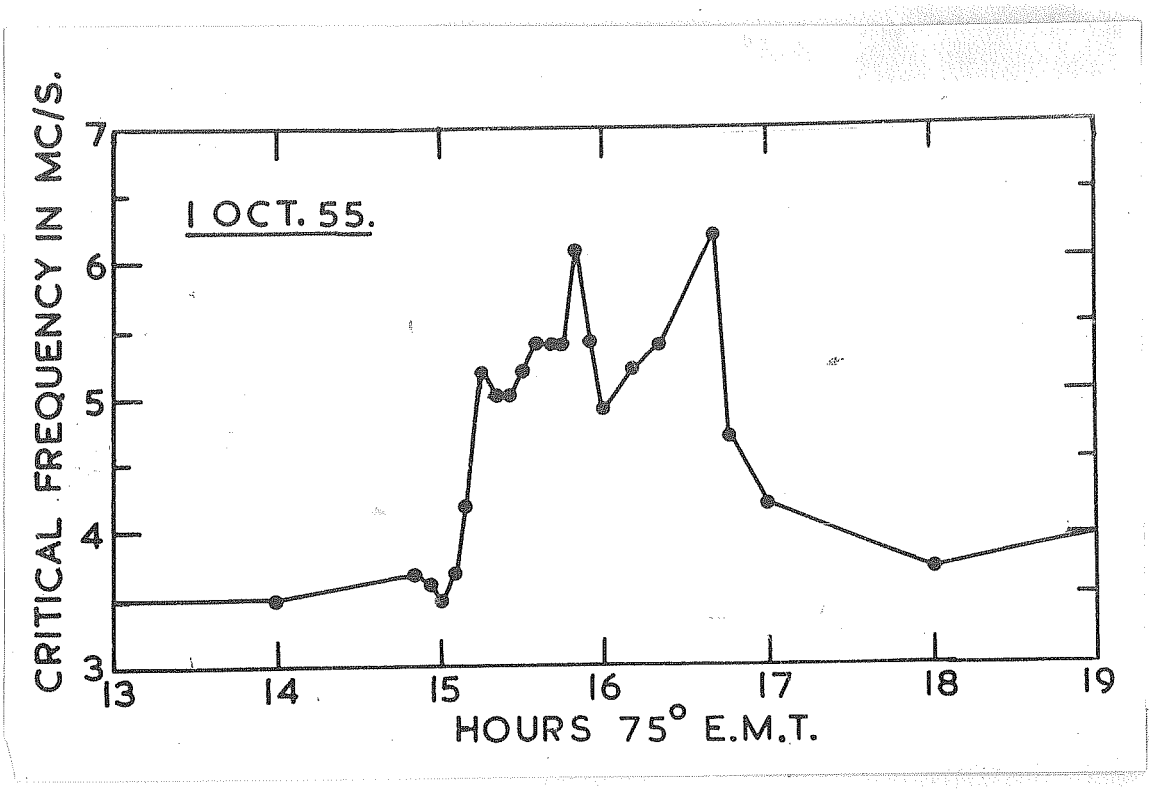


Fig.5. The variation of fEs during the thunderstorm on October 1,1955.

Fig 5.

The variation of fEs

Fig 6. P'-f records on October 1, 1955 showing the effect of thunderstorm on the E_s region of the ionosphere

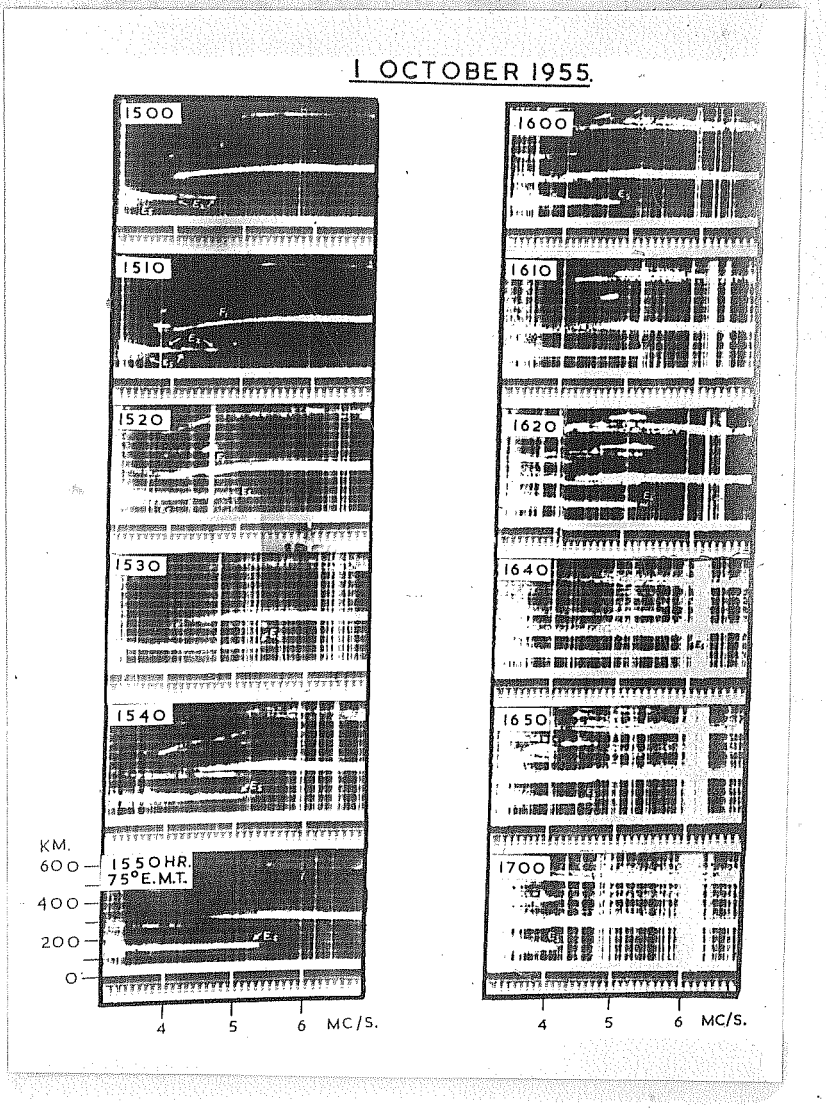


Fig. 7. The variation of $f E_s$ during the thunderstorm on October 23, 1955 and on control days. Note the high values of $f E_s$ during the thunderstorm period.

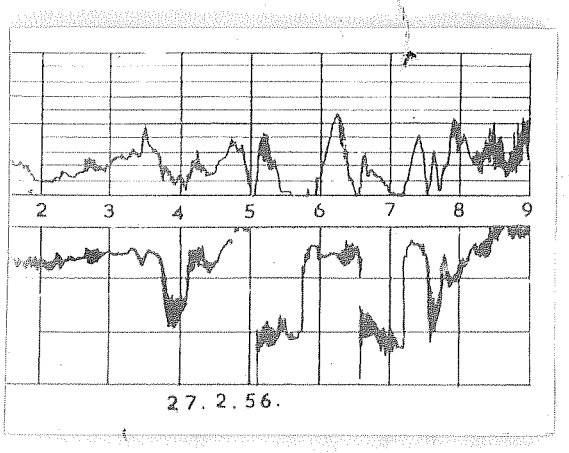


Fig 8. Anemometer chart on February 27, 1956. during the thunderstorm

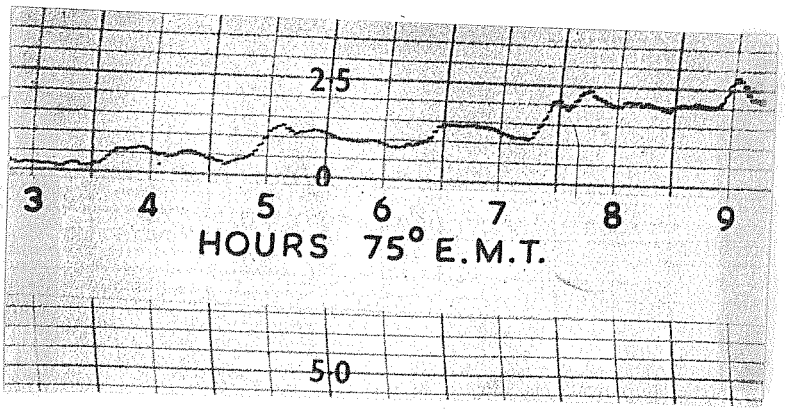


Fig. 9 Microbarograph chart on February 27, 1956 during the thunderstorm

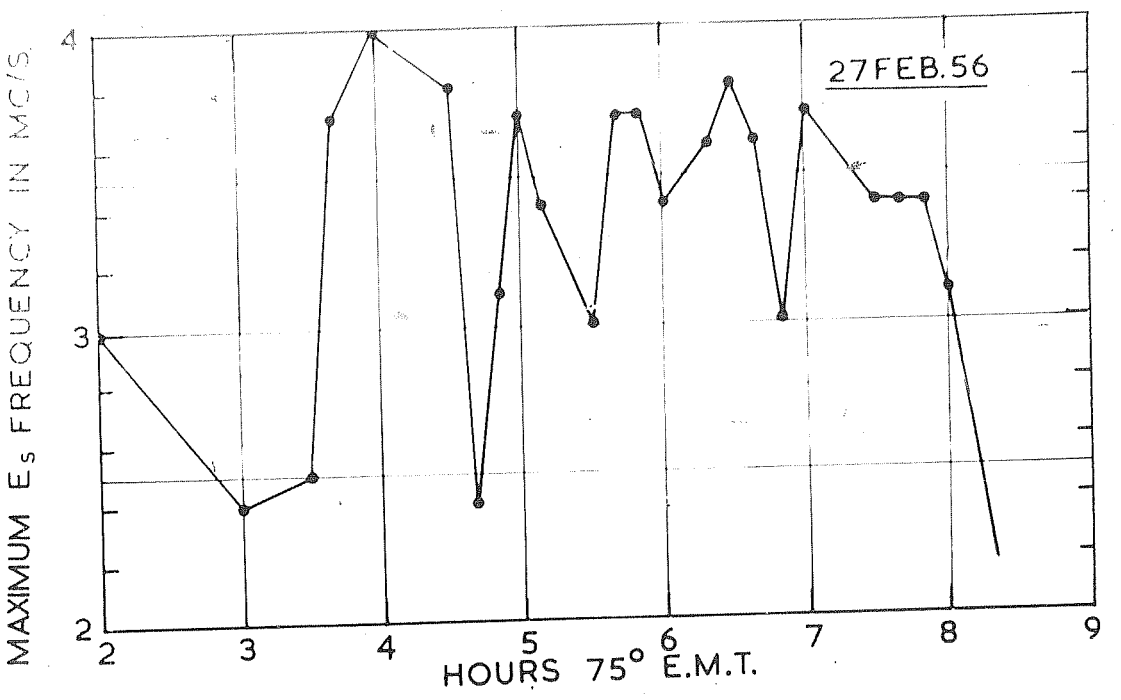


Fig 10. The variation of $f E_s$ during the thunderstorm on February 27, 1956.

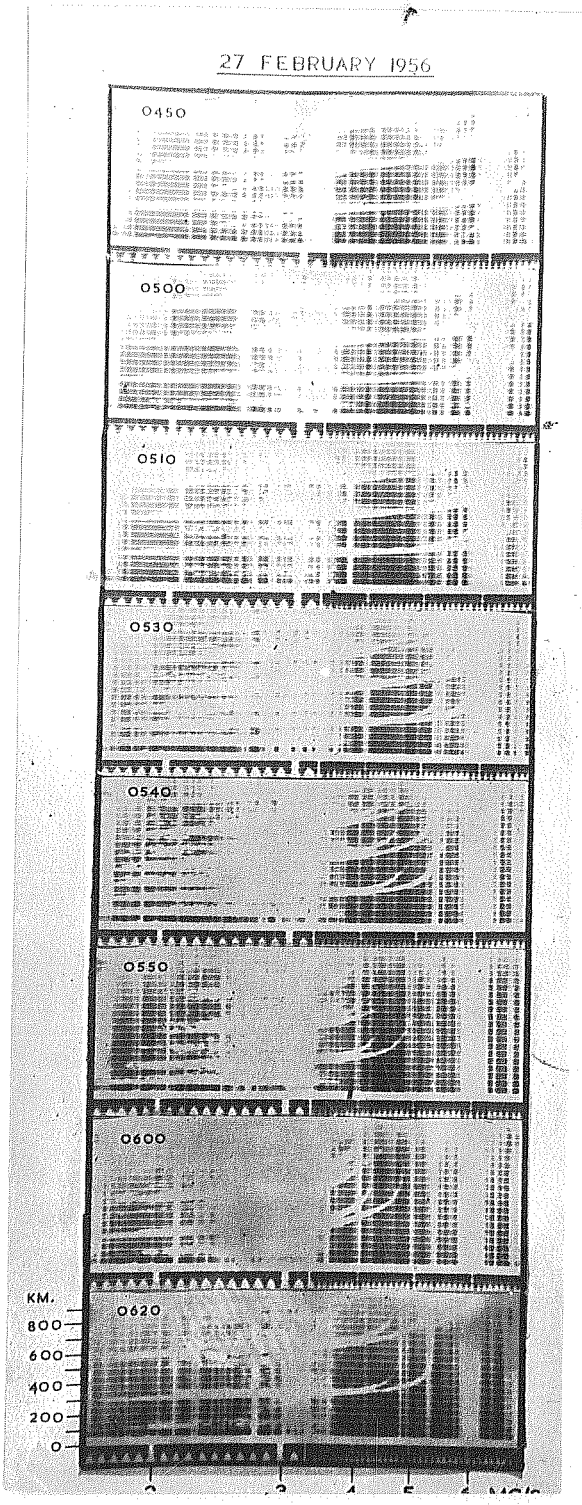


Fig 11. P'-f records on February 27, 1956. Note the large number of multiple reflections at 0530 and 0540 hr.

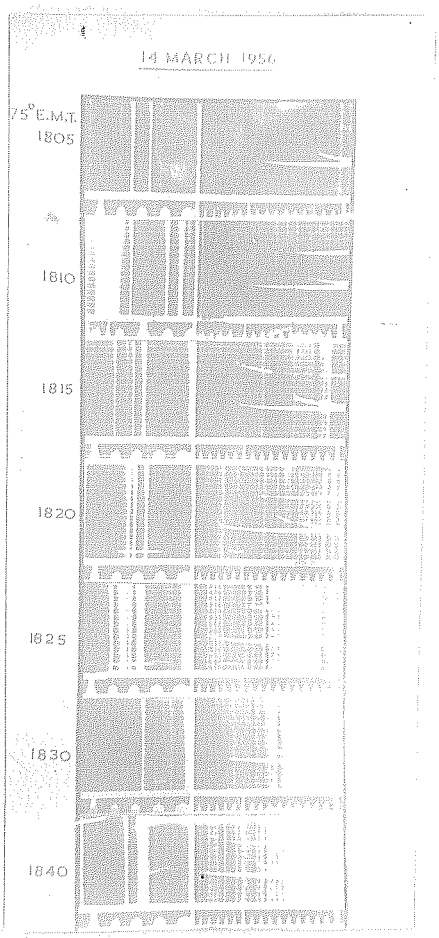


Fig 12. P'-f records on March 14, 1956. Note the formation of fE_s ionization during the thunderstorm

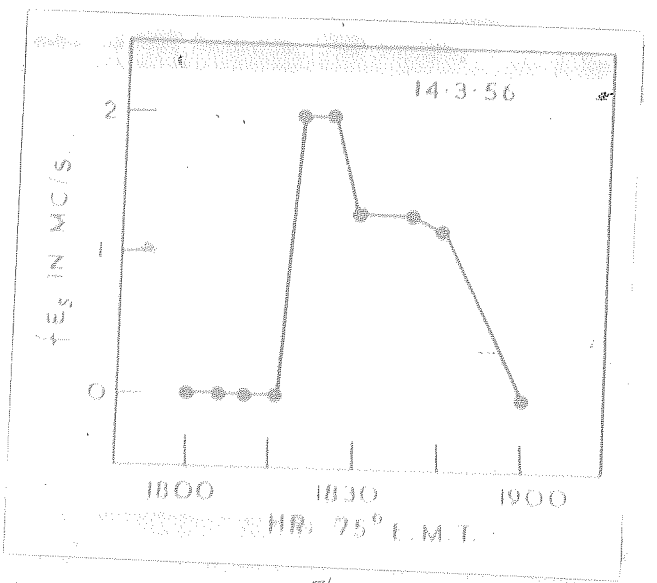


Fig 13. Formation of the E_s ionisation during the thunderstorm on March 14, 1956.

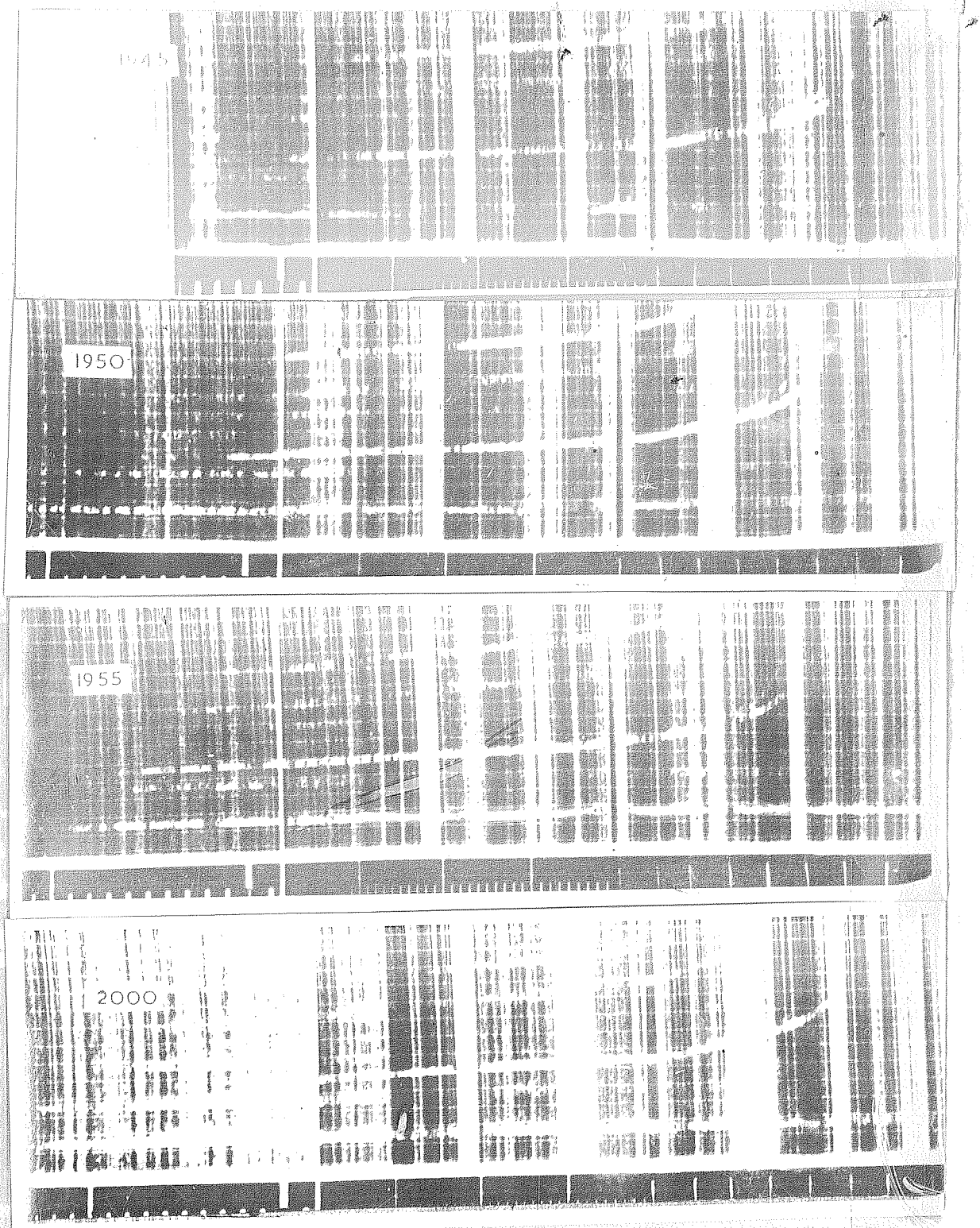
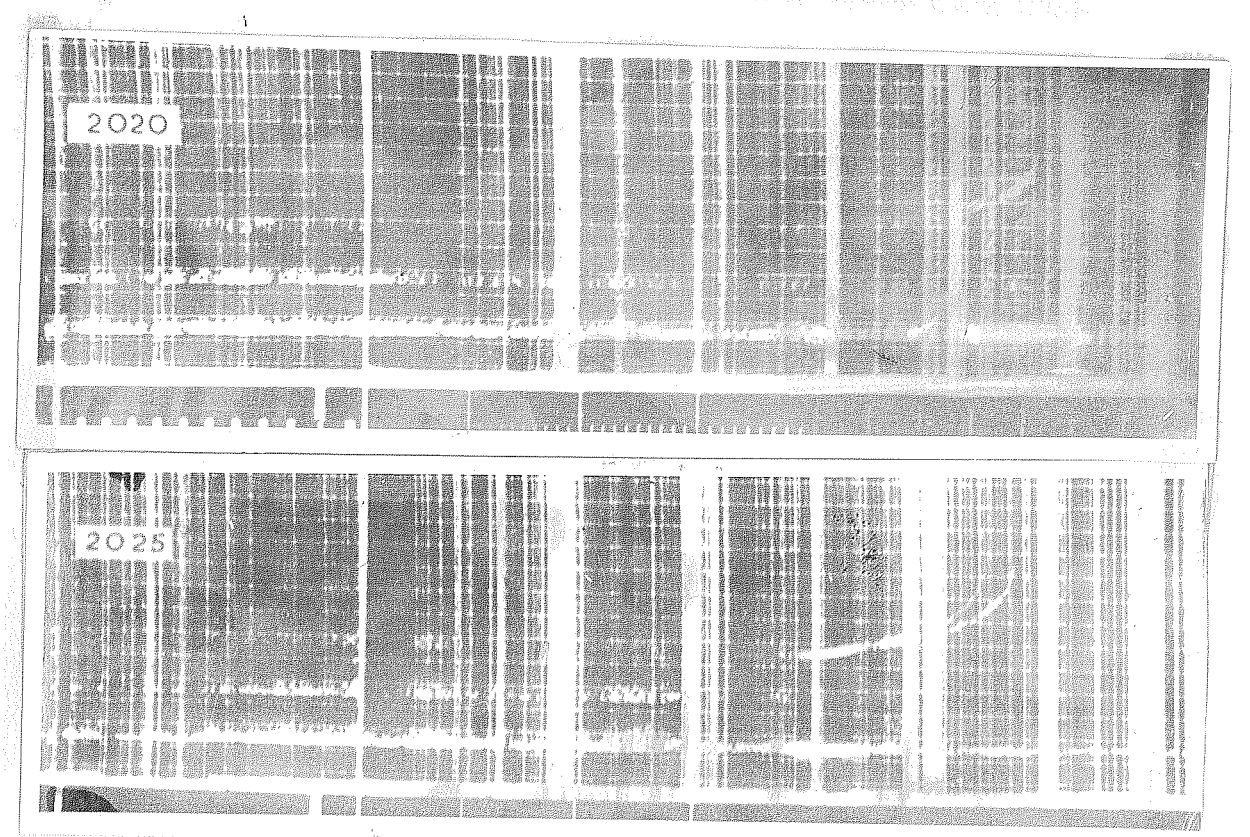
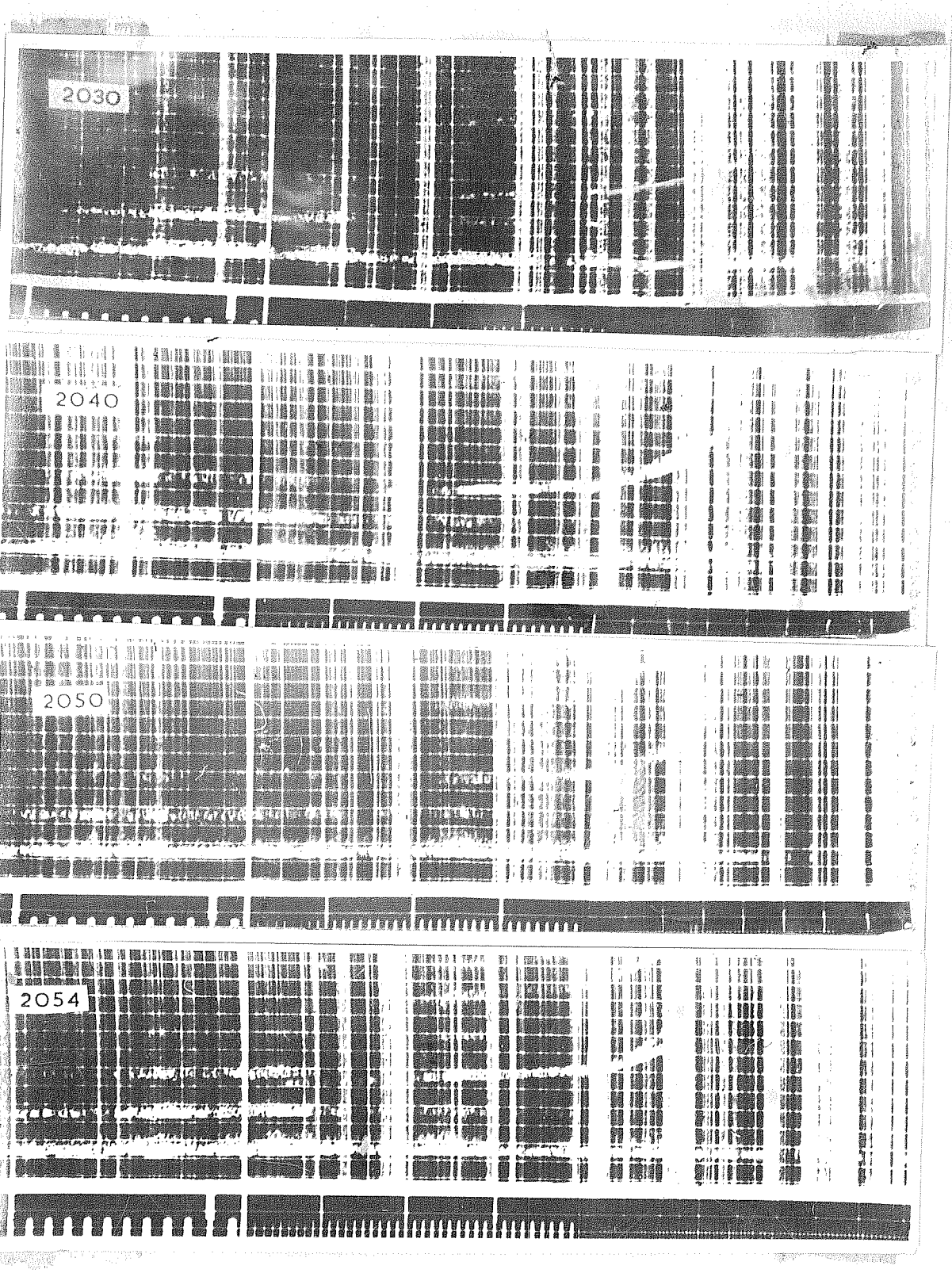
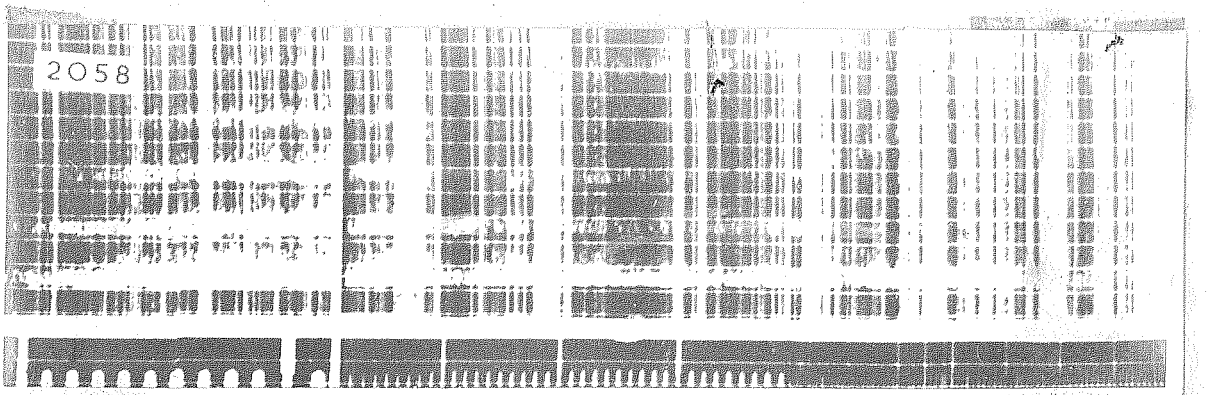
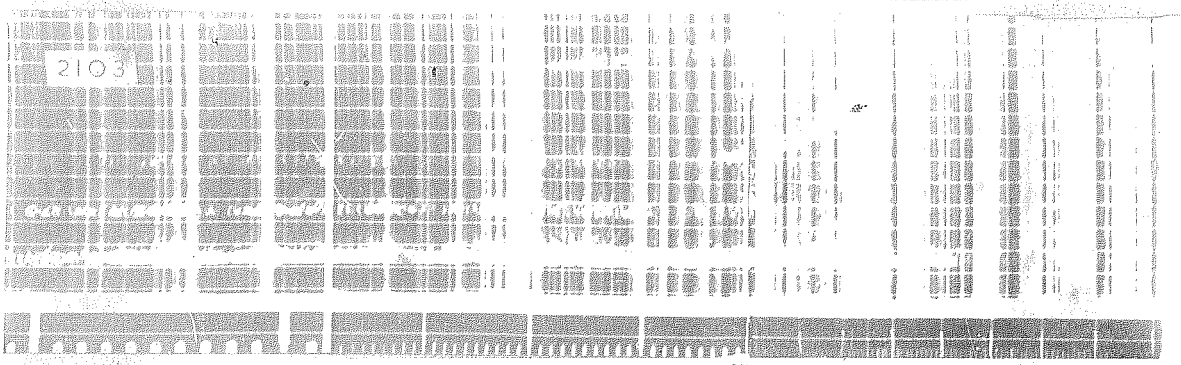


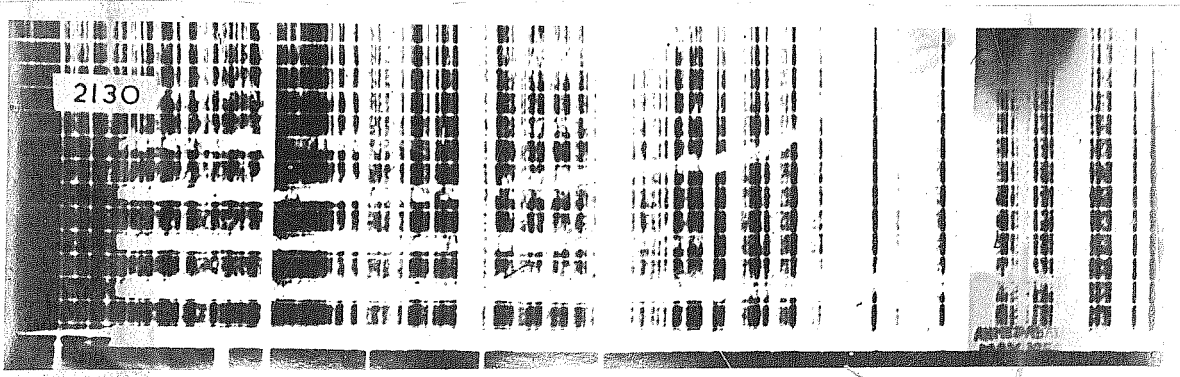
Fig 16. P'-f records during the thunderstorm on May 28, 1956. Note complete blanketing of F reflections at 2010 and 2058 hg and gradual increase of h'F at 1950, 1955 and 2145 hg

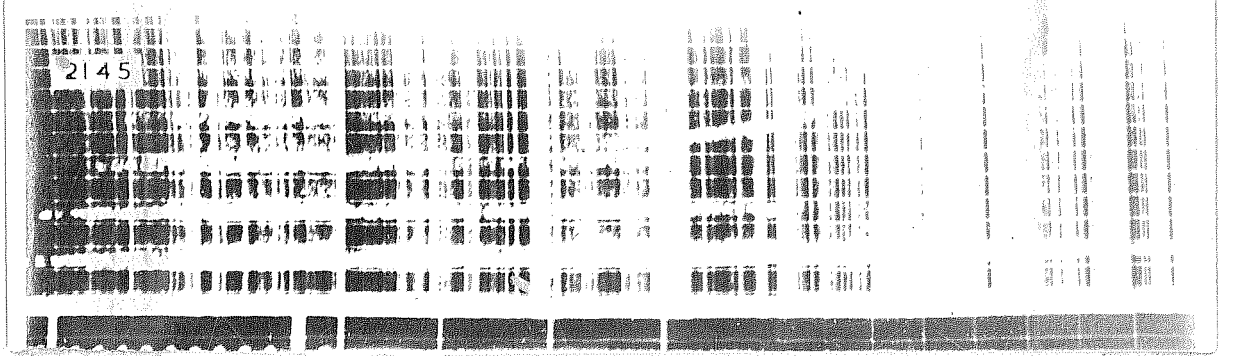

2020
2025


2030
2040
2050
2054


2058


2103


2130


2145

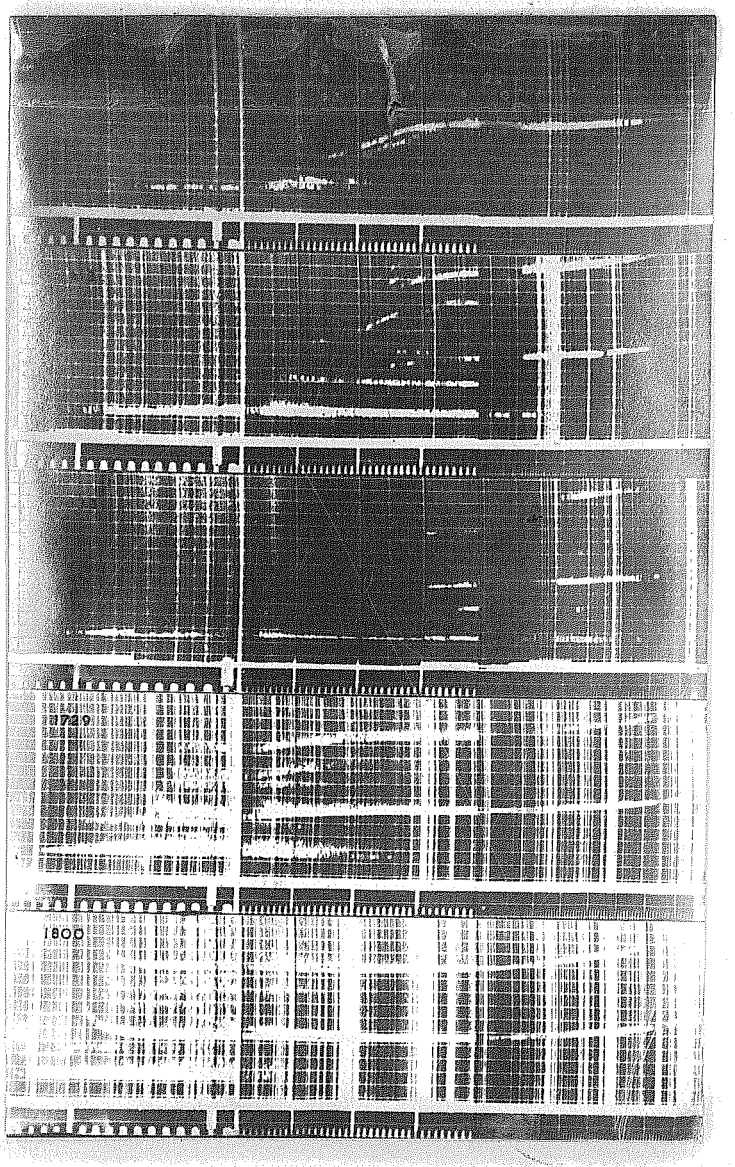


Fig. 17

Jerv. P'j records taken during the thunderstorm on September 1, 1956. Note high f.c.s at 1613 and 1633 hr.

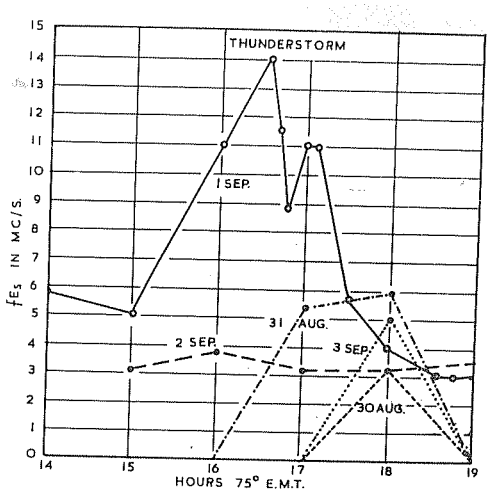


Fig 18.

Variations of f_{Es} on thunderstorm day September 1, 1958 and on control days