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

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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.

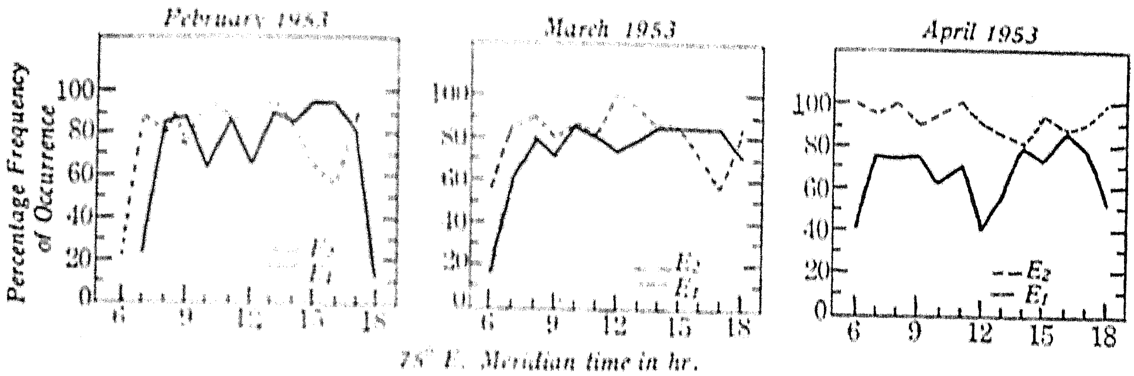

FIG. 2. Frequencies of occurrence of the E_1 and E_2 Layers during February, March and April 1953.

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 1 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.

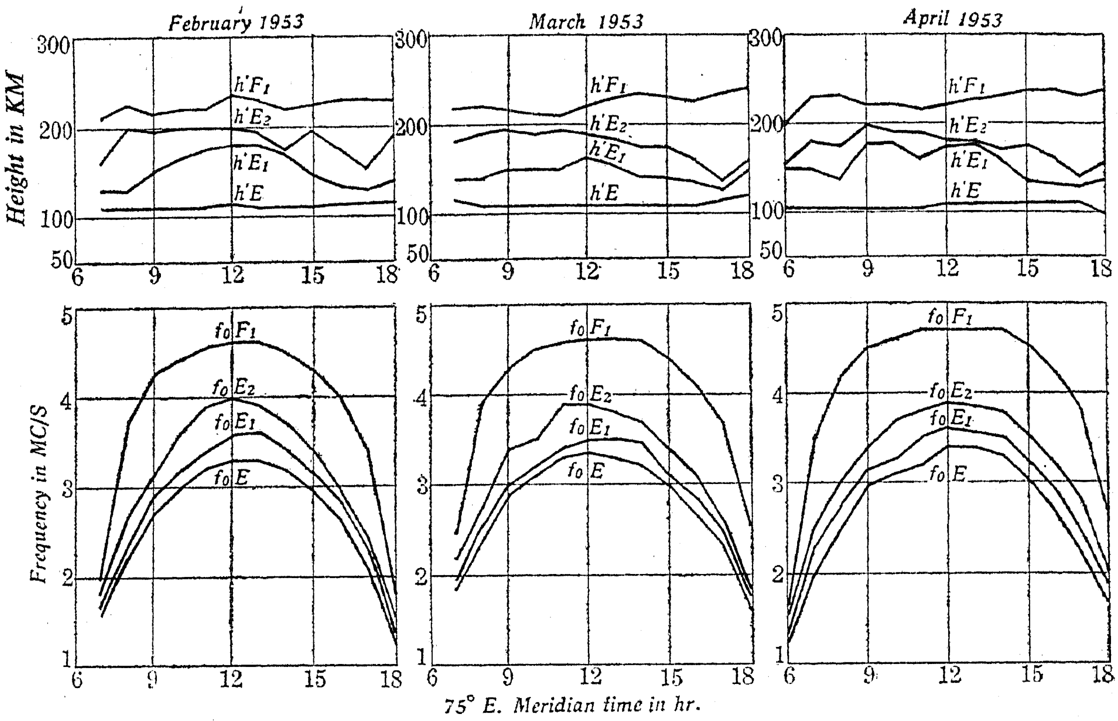

FIG. 4. Curves showing the median values of the critical frequencies and virtual heights of E, E_1, E_2 and F_1 layers during the months of February, March and April 1953.

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_9E	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.

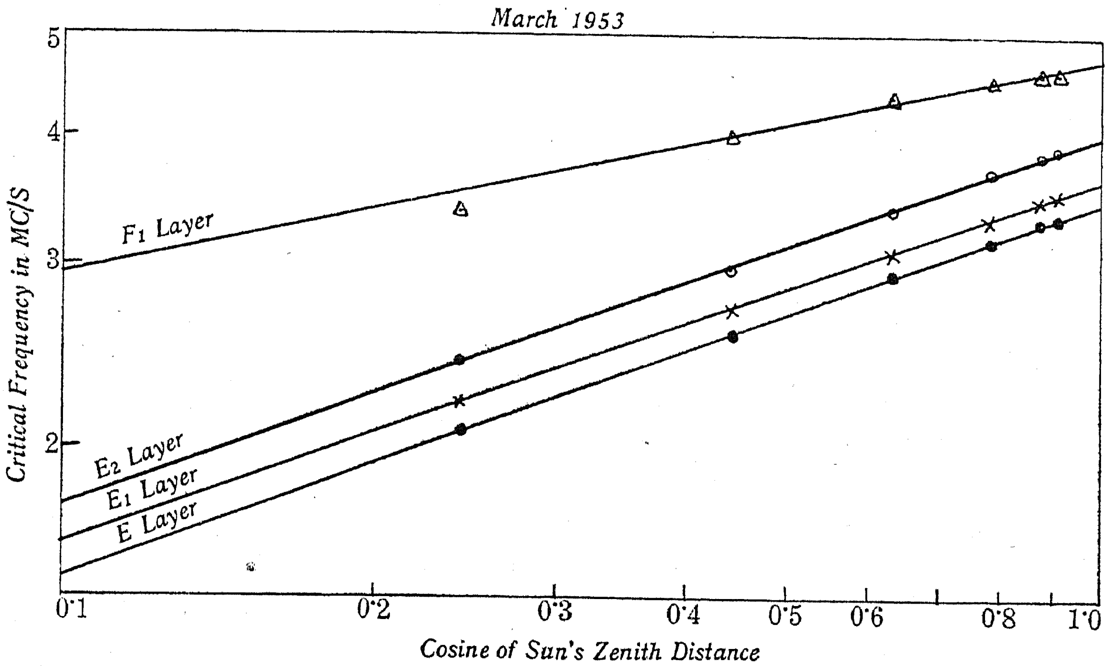

FIG. 5. Graph of critical frequency *versus* cos Z for the layers E, E_1, E_2 and F_1 during the month of March 1953.

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]

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

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

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

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]

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

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

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.

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