SEASONAL VARIATION OF THE LUNAR TIDAL EFFECTS IN THE F_2 LAYER OF THE IONOSPHERE OVER INDIAN STATIONS

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Abstract

The lunar semi-diurnal oscillations in the midday values of the critical frequency (f_0F_2) and the height of maximum electron density (h_pF_2) of the F_2 layer are computed for all Indian ionospheric stations separately for each season of the year. The amplitude of oscillation in f_0F_2 is found to be larger in winter than in summer at each of the stations. There is a reversal in the phase of the oscillation in f_0F_2 between the equatorial and tropical latitudes and this is most evident in the winter months and is almost absent in summer. The annual average oscillation in f_0F_2 is in agreement with that found in a previous paper (Rastogi, 1961). The phase has a large seasonal variation of about 180° at an equatorial or a tropical latitude station. The phase and amplitude of the lunar tide in h_pF_2 do not vary significantly with latitude or with season.

Introduction

The existence of large lunar tidal effects in the F_2 layer of the ionosphere was established by the analyses of data at Huancayo (Martyn, 1947; McNish and Gautier, 1949 *a*), Canberra (Martyn, 1948), Slough (Appleton and Beynon, 1948), and at a few other places (Martyn, 1949 *b*).

Geomagnetic control of the phase of the lunar semidiurnal oscillation L_2, in the noon critical frequency f_0F_2, was first demonstrated by McNish and Gautier (1949 *b*). At stations close to the geomagnetic equator, the noon f_0F_2 was shown to be maximum about two days after the first and last quarters of the moon, *i.e.*, at 04 and 16 lunar hours, while at about 20° geomagnetic latitude, the maxima were shifted about 180° in phase. These conclusions have been confirmed by later analyses (Osborne, 1952; Brown, 1956; Kotadia and Ramanathan, 1956).

Rastogi (1961 *a, b*) showed by an analysis of the lunar tide in f_0F_2 at a large number of stations that the phase of the tide in f_0F_2 at any station is determined by its magnetic rather than by its geomagnetic or geographic latitude. The reversal of phase from the equatorial type of variation with a maximum near 04 lunar hour to the higher latitude type with a maximum near 10 lunar hour occurs at about $\pm 11°$ magnetic latitude. The latitudinal variation of the amplitude shows a sharp maximum on the magnetic equator and two broad maxima at about $\pm 20°$ magnetic latitude.

The lunar perturbations in f_0F_2 at low latitudes are closely associated with the development of the anomalous equatorial belt of the F_2 layer (Rastogi, 1963). As there has been a chain of ionospheric stations in the Indian zone covering magnetic latitudes 02° to 25°, it seemed useful to study the lunar tide in F_2 at these stations in greater detail. In this article, the seasonal variation of the lunar tide in the midday values of the F_2 parameters are studied as a first step in this direction.

Material for Analysis

The data utilised in this paper are mainly the midday (11–13 hour mean) values of the critical frequency, f_0F_2, and the height of maximum electron density h_pF_2 as determined by the virtual height at a frequency equal to 0·834 times f_0F_2, for all Indian ionospheric stations during the period of low solar activity. The data used here cover the period January 1951 to December 1955 for all the stations other than Ahmedabad for which the data from March 1953 to February 1956 were used. The method of computation of the amplitude, phase and their probable errors are described in earlier papers (Rastogi, 1961 *b*, 1962).

Seasonal Variation of Lunar Tide in Midday Value of f_0F_2

The variation with lunar phase of the deviation of midday value of f_0F_2 from its monthly mean value averaged for winter (Nov., Dec., Jan. and Feb.), equinoxes (March, April, Sept. and Oct.), summer (May, June, July and Aug.) and the whole year are shown in Fig. 1 for each of the stations. The thick continuous line shows the 12 lunar-hourly wave derived from the Fourier analysis of the average deviation of f_0F_2 against lunar phase. The average values of f_0F_2 as well as the amplitudes (with probable errors) and phases of lunar semidiurnal variation in f_0F_2 for different seasons are given for each station in Table I. The coefficients of lunar semidiurnal variation at different stations are plotted in harmonic dial in Fig. 2 separately for each season,

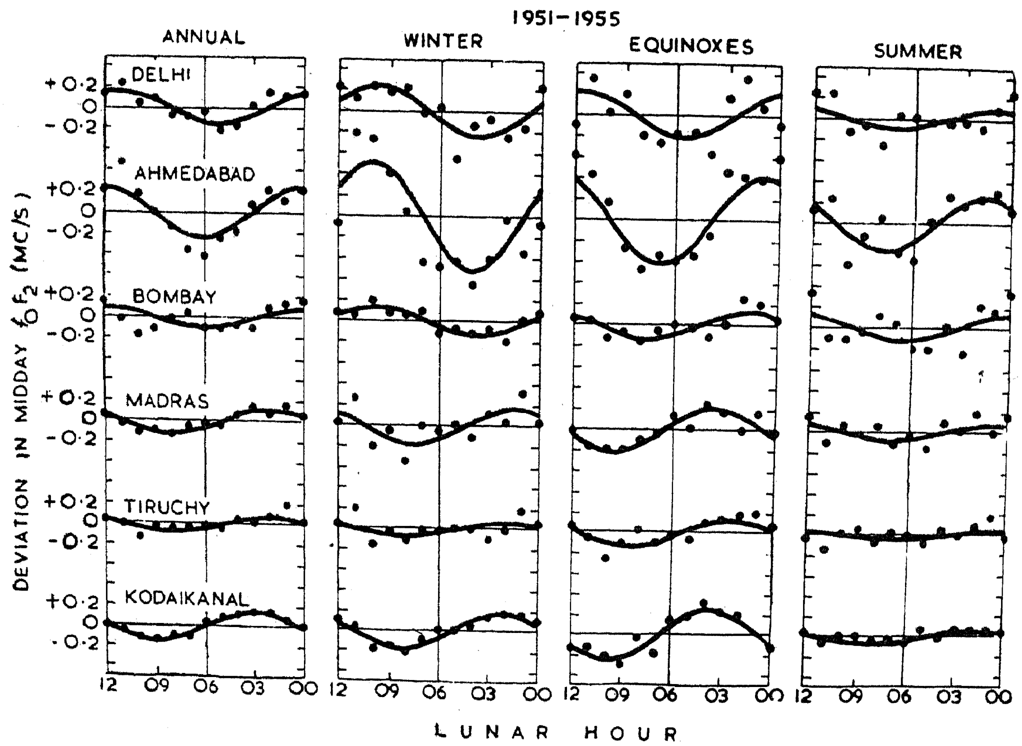

FIG. 1. Lunar tidal variations in the midday value of f_0F_2 at Indian stations during different seasons and average for the whole year.

Referring to the annual curves in Fig. 1, the shift of phase of lunar variation between the equatorial stations Kodaikanal, Tiruchy and Madras and the higher latitude stations Bombay, Ahmedabad and Delhi is clearly seen. Within the equatorial group of stations, the largest amplitude occurs at Kodaikanal which is nearest the magnetic equator. Similarly among the higher latitude stations, the largest amplitude occurs at Ahmedabad which is the station closest to the region of maximum afternoon f_0F_2. This confirms earlier conclusions (Rastogi, 1961).

The features described above are most clearly seen in the winter months. In the equinoctial months, however, the phase change takes place gradually between the equator and higher latitudes, the time of maximum being 3·7 lunar hour at Kodaikanal and 0·0 lunar hour at Delhi.

Rather unexpectedly, it is found that during the summer months there is an absence of phase reversal between the equatorial and temperate latitudes. Referring to Fig. 2, the points referring to different stations all lie in the first quadrant of the harmonic dial, the phases varying only with in

TABLE I

Lunar semi-diurnal oscillation in midday (11–13 *hr. mean*) *value of* f_0F_2 *at Indian Stations during* 1951–1955

Station	Annual average			Equinoxes		
	Average f_0F_2	Amplitude of L_2	Phase of max. L_2	Average f_0F_2	Amplitude of L_2	Phase of max. L_2
	Mc./s.	Mc./s.	Lunar Hr.	Mc./s.	Mc./s.	Lunar Hr.
hi ..	9·03	0·15±0·022	11·1	10·00	0·22±0·039	0·0
medabad	9·91	0·34±0·070	0·2	11·23	0·50±0·070	0·9
mbay ..	10·52	0·09±0·019	11·8	11·20	0·13±0·031	1·6
dras ..	8·45	0·01±0·018	2·0	8·91	0·21±0·033	3·6
ichy ..	8·13	0·07±0·016	2·0	8·45	0·13±0·028	2·5
laikanal ..	8·13	0·14±0·017	3·0	8·63	0·25±0·032	3·7

Winter			Summer		
Average f_0F_2	Amplitude of L_2	Phase of max. L_2	Average f_0F_2	Amplitude of L_2	Phase of max. L_2
Mc./s.	Mc./s.	Lunar Hr.	Mc./s.	Mc./s.	Lunar Hr.
8·50	0·24±0·039	9·7	8·60	(0·09±0·035)	1·0
10·00	0·51±0·080	10·0	8·50	0·26±0·060	1·7
10·70	0·13±0·035	9·7	9·67	0·12±0·032	0·4
8·60	0·17±0·032	1·4	7·84	(0·07±0·028)	0·9
8·31	(0·06±0·027)	2·0	7·61	(0·04±0·027)	0·1
8·24	0·17±0·031	2·2	7·51	(0·03±0·027)	2·3

N.B.—The bracketed figures indicate amplitudes which are not statistically significant according to man, 1951.

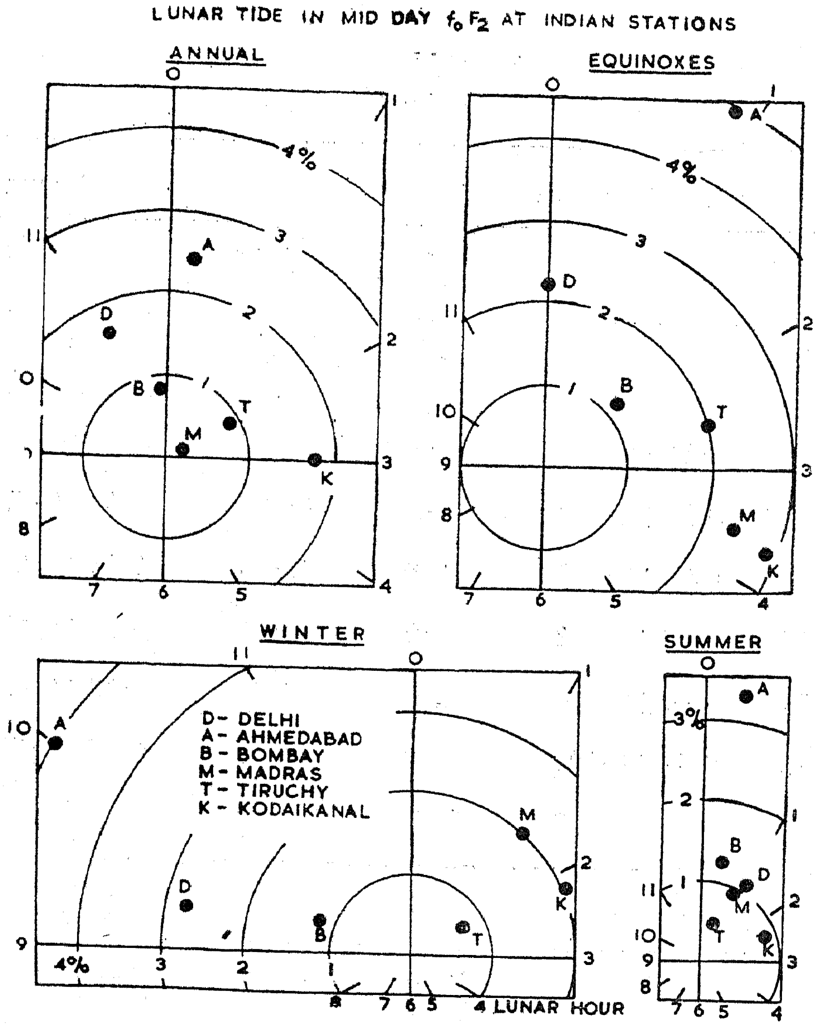

FIG. 2. Harmonic dials showing the coefficients of lunar tidal variation in midday value of f_0F_2 at Indian stations during different seasons of the year.

00 and 02 lunar hour. Except at Ahmedabad, the amplitudes at other stations are small and not significantly different from each other.

Chapman (1951) has expressed the view that any determination of amplitude should be considered as statistically significant only if it is at least three times its probable error. Values of amplitude in Table I which do not fulfil this condition are shown bracketed. It is seen from Table I that most of the amplitudes are statistically significant except those for equatorial stations in summer, when the amplitude itself is very small.

The phase at temperate latitudes is about 10 lunar hour during winter and about 01 lunar hour during equinoxes and summer. At equatorial stations, the phase is about 02 lunar hour during the winter or the summer and about 03 lunar hour during equinoxes. Thus the phase difference between the lunar variation of f_0F_2 at the two groups of stations is largest (about 120°) during the winter and the least (about 30°) during the summer months.

To check whether the non-reversal of the phase of lunar tide between equatorial and higher latitudes summer was peculiar to Indian stations an analysis was made of f_0F_2 data at the equatorial station Nhatrang and the temperate latitude station Okinawa which lie in the same zone but further east.

The lunar variations in midday value f_0F_2 at Okinawa and Nhatrang in winter and summer are shown in Fig. 3. The variations are seen to be almost opposite in phase in the winter months and about 3 hours out of phase in the summer months.

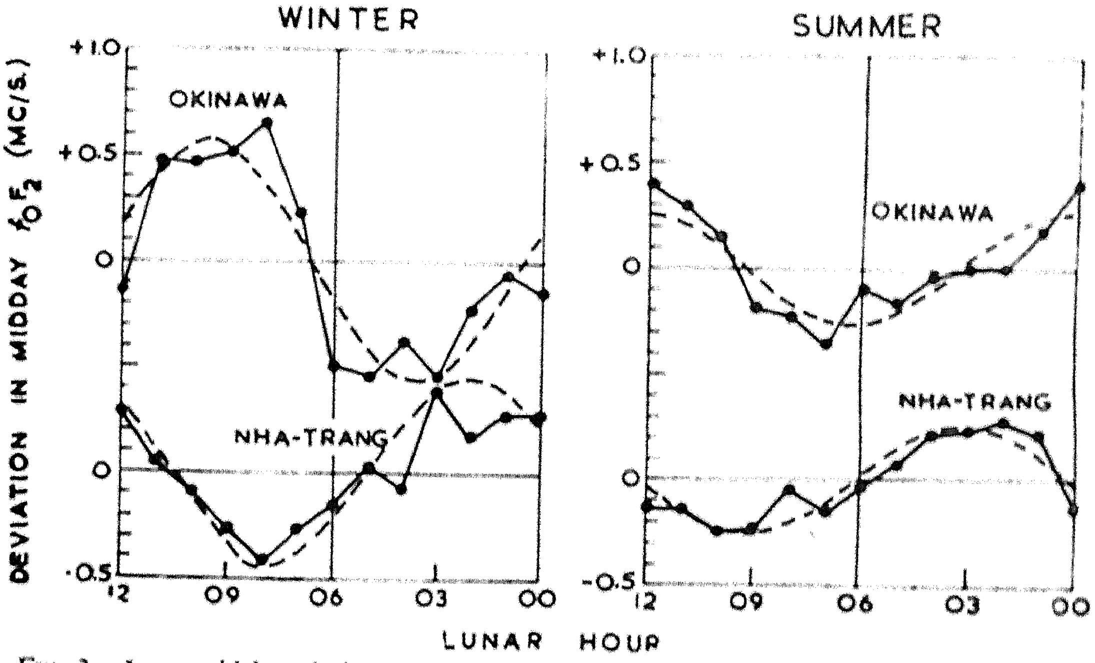

FIG. 3. Lunar tidal variations in midday value of f_0F_2 at Okinawa and Nhatrang during winter and summer months.

LUNAR TIDE IN f_0F_2 AT EQUATORIAL AND TEMPERATE LATITUDE STATIONS DURING INDIVIDUAL MONTHS

To elucidate further the seasonal variation of the lunar tide in f_0F_2, an analysis was made of f_0F_2 data at Ahmedabad and Kodaikanal separately for individual months. To keep up the volume of data analysed, all available data from July 1952 to December 1959 for Kodaikanal and from March 1953 to December 1962 for Ahmedabad were utilised. The results of the analysis are plotted as harmonic dials in Figs. 4 and 5 for Ahmedabad and Kodaikanal respectively.

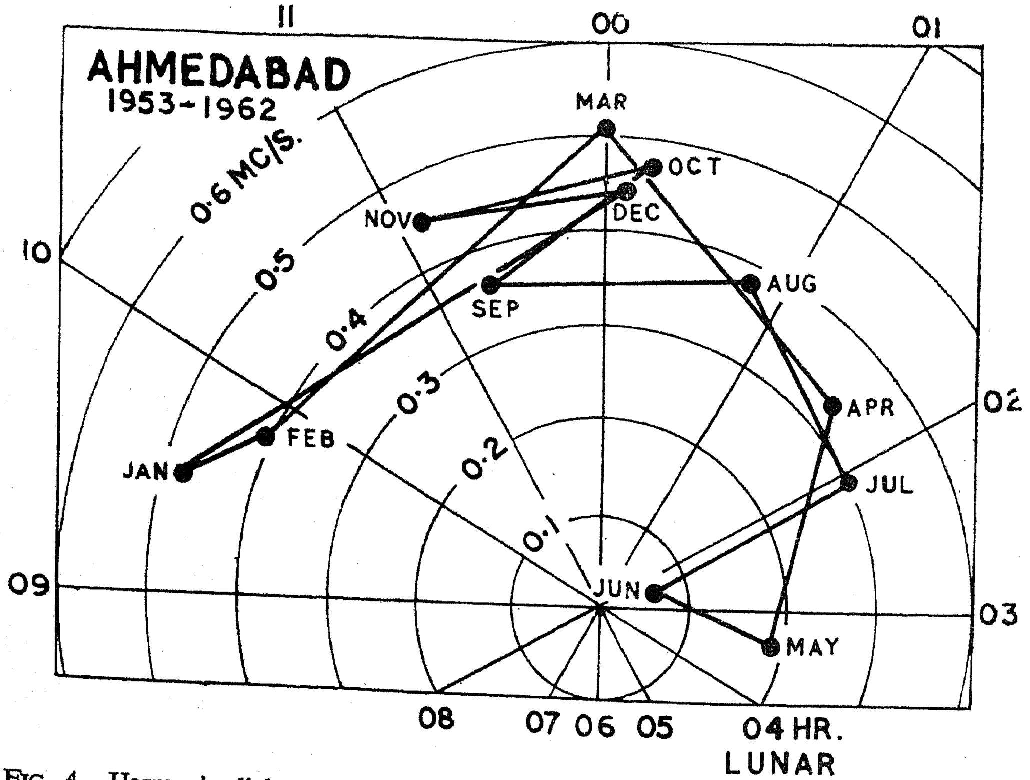

Fig. 4. Harmonic dials showing the coefficients of lunar tidal variations in midday value of f_0F_2 at Ahmedabad during each month of the year.

Referring to Fig. 4 one finds that the phase of the L_2 vector moves systematically through almost 180° during the year; being at about 9·5 lunar hour in January-February and at about 03 lunar hour in May–June. The length of the vector is greater in January than in June. The maximum amplitude occurs during equinoxes when the average value of f_0F_2 itself is also the maximum.

At Kodaikanal also the phase changes almost through 180° varying from 0·5 and 6·5 lunar hour. The amplitude is extremely small during August and its phase is apparently at 9·0 lunar hour. These are not at all significant.

Lunar Tide in Height of Maximum Electron Density in F_2 Layer

The published data of all the Indian stations except Kodaikanal include the virtual height of reflection at a frequency equal to 0·834 times f_0F_2

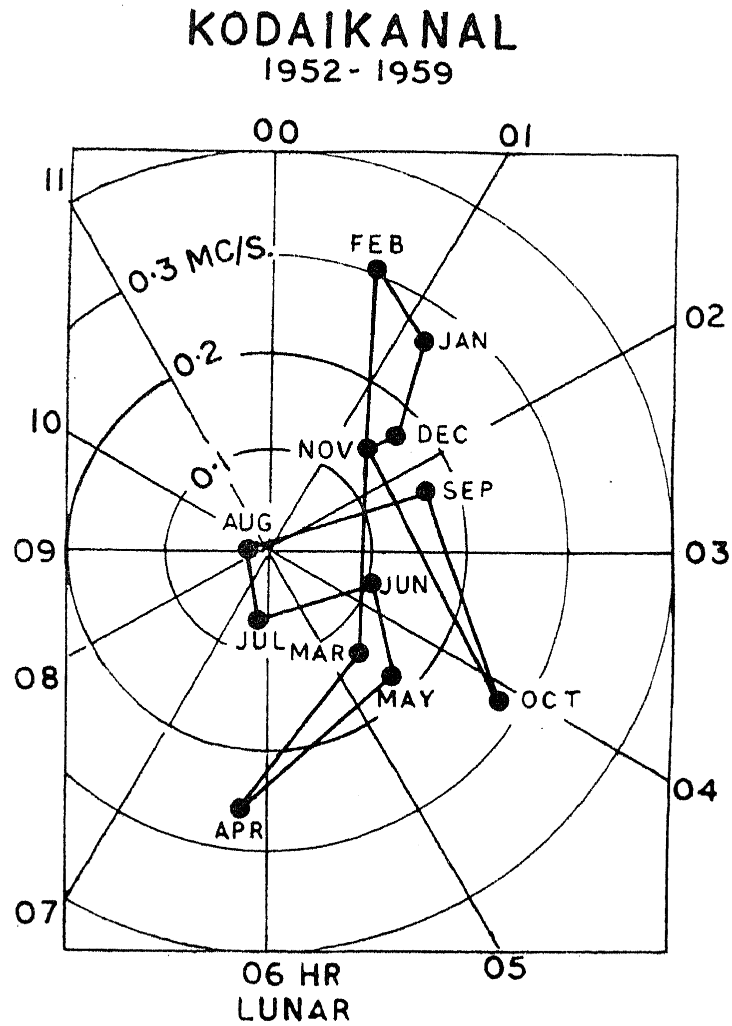

FIG. 5. Harmonic dials showing the coefficients of lunar tidal variations in midday value of f_0F_2 at Kodaikanal during each month of the year.

denoted as h_pF_2. This represents the height of the maximum electron density if the shape of the layer is assumed to be parabolic. An analysis was made of the midday values of h_pF_2 at each station separately for different seasons. The amplitudes and phases are given in Table II. Here again the statistically non-significant values are enclosed within brackets. The annual average deviations of h_pF_2 with the lunar phase for each station are shown in Fig. 6.

Referring to Table II, one finds that the determination of amplitude at Bombay for any of the seasons or for the whole year is not statistically significant. The annual average value of the amplitude at all other stations, except Bombay, are seen to fulfil the criterion of statistical significance. The large random errors in the points for Bombay are clearly seen in Fig. 6. The

TABLE II

Lunar semi-diurnal oscillation in midday (11–13 hr. mean) value of h_pF_2 *... Indian Stations during* 1951–55

Station	Annual average			Equinoxes		
	Average h_pF_2	Amplitude of L_2	Phase of max. L_2	Average h_pF_2	Amplitude of L_2	Phase of max. L_2
	Km.	Km.	Lunar Hr.	Km.	Km.	Lunar Hr.
Delhi ..	290	2·6±0·45	6·6	289	2·5±0·8	5·9
Ahmedabad	339	4·3±0·71	8·3	335	4·3±1·2	8·2
Bombay ..	405	(0·6±0·46)	2·5	409	(1·5±0·8)	5·2
Madras ..	441	2·8±0·54	5·9	444	(2·1±0·9)	8·3
Tiruchy ..	512	2·7±0·49	4·5	509	(0·8±0·8)	4·4

Winter			Summer		
Average h_pF_2	Amplitude of L_2	Phase of max. L_2	Average h_pF_2	Amplitude of L_2	Phase of max. L_2
Km.	Km.	Lunar Hr.	Km.	Km.	Lunar Hr.
260	2·4±0·6	6·5	322	(2·6±0·9)	6·8
300	4·1±0·9	7·2	382	5·4±1·5	9·1
379	(1·8±0·7)	10·7	428	(1·9±0·9)	3·6
425	3·7±1·0	5·5	454	4·1±0·9	5·4
508	4·2±0·8	5·3	518	3·8±0·9	3·6

N.B.—The bracketed figures indicate amplitudes which are not statistically significant according to Chapman, 1951.

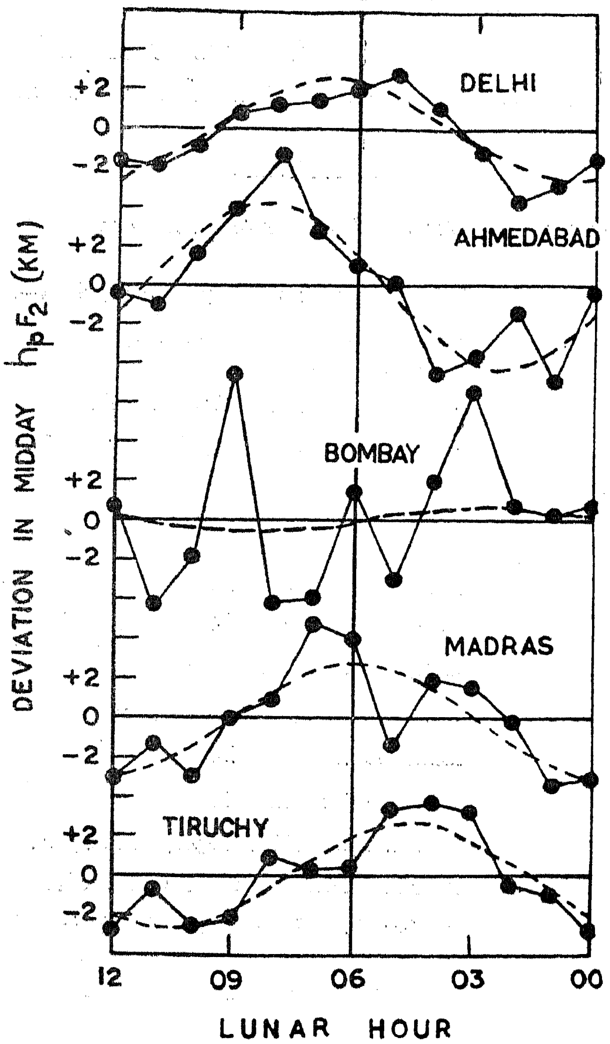

FIG. 6. Annual average lunar tidal variations in the midday value of h_pF_2 at Indian stations.

lack of significance at other stations for some reasons is not unexpected because the individual data of h_pF_2 are greatly affected by the retardations in the propagation of radio waves in the lower layers. The relative closeness of f_0F_1 to f_0F_2 would produce large errors in the determination of h_pF_2.

The amplitude of lunar tide in midday value of h_pF_2 is about 4 Km. at Ahmedabad and about 3 Km. at other stations. The phases are not significantly different at these places being within about 05 and 08 lunar hours. This confirms the conclusions by earlier authors (Duncan, 1956) that the lunar tide in the virtual height of the F_2 layer ($h'F_2$) does not show any significant variation with latitude.

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