LUNAR TIDAL VARIATIONS IN f_0F_2 IN THE AMERICAN ZONE DURING PERIOD OF LOW SOLAR ACTIVITY

I. Equatorial Station, Huancayo

By R. G. Rastogi and S. K. Alurkar

(Physical Research Laboratory, Navrangpura, Ahmedabad-9, India)

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1. Introduction

Bartels, in 1936, demonstrated the existence of abnormally large lunar tidal oscillations in the earth's horizontal magnetic field at Huancayo. Lunar tides in the ionosphere were found by Appleton and Weekes (1939) who showed that the minimum virtual height of the E region at Cambridge had a semi-diurnal lunar oscillation of about 1 km. amplitude. Later, Martyn (1947) showed that the amplitude of the lunar tide in the height of the peak ionisation in the F_2 layer at Huancayo was at certain solar epochs as much as 30 km. and the amplitude of the critical frequency of the layer went up to 14%.

Geomagnetic control of the lunar tide was found by McNish and Gautier (1949) in the noon value of the critical frequency of the F_2 layer, f_0F_2. At stations close to the geomagnetic equator, the amplitude of the tide was found to be a maximum about two days after the first and third quarters of the moon, while at about 20° geomagnetic latitude the phase was reversed by about 180°. The reversal of phase of lunar tide in noon f_0F_2 between the equatorial and tropical latitude stations in India was confirmed by Kotadia and Ramanathan (1956). By an analysis of noon f_0F_2 data at a large number of low latitude stations, Rastogi (1961) showed that the reversal of phase of lunar tidal oscillation in midday f_0F_2 from the equatorial type with a maximum at 04 lunar hour to the higher latitude type with a maximum at about 10 lunar hour occurred near ± 11° magnetic latitude. The latitudinal variation of the amplitude showed a sharp maximum on the magnetic equator and two broad maxima at about ± 20° magnetic latitudes.

Burkard (1951) found that the lunar tide calculated from daytime f_0F_2 at Huancayo was about four times larger than the amplitude calculated from all-day f_0F_2 and that the night time f_0F_2 at Huancayo did not show any significant lunar tidal variation. Similar analyses have been made with f_0F_2 and h_pF_2 data of Ibadan by Brown (1956) and with Ahmedabad data by Rastogi and Alurkar (1964). The latter found that during the course of one solar day, the amplitude phase vector of L_2 rotated through 360° in the clockwise direction on the lunar hour harmonic dial. A systematic change was found in the amplitude and phase of L_2 oscillation in the course of a year.

Comparing the solar daily variation of f_0F_2 at a number of stations averaged over days of selected lunar age, Rastogi (1963) showed that the effects in f_0F_2 were maximum at 11–12 hr. L.S.T. at equatorial stations and at 13–14 hr. L.S.T. at sub-tropical latitude stations and that the lunar perturbations in f_0F_2 at low latitudes were closely associated with the diurnal development of the anomalous equatorial belt of the F_2 region.

To understand the luni-solar variation in f_0F_2 in relation to the development of the anomalous equatorial belt of the F_2 region, it was felt necessary to compute the lunar tidal coefficients of f_0F_2 at each solar hour at a few stations at different latitudes near about the same meridian. With this in view, analysis has been made of f_0F_2 at equatorial, sub-tropical and high latitude stations in the American zone during the period of low solar activity. The present paper discusses the data of f_0F_2 analysed for lunar tides at the equatorial station, Huancayo, for the period January 1951 to December 1955.

2. TREATMENT OF DATA

In analogy to mean solar local time t, a mean lunar local time τ, can be defined such that $\tau = 0$ hr. for the lower transit and $\tau = 12$ hr. for the upper transit of the moon. If both t and τ are measured from the epoch of new (mean) moon, when the mean sun and mean moon are on the same meridian, after some period the lunar meridian would lag behind that of the solar one; the difference between t and τ would indicate the moon's phase. Bartels and Fanselau (1937) have published tables of moon's phase $\mu = \tau - t$ at Greenwich mean noon of each day of the years 1850 to 1975. The value of μ decreases from 360° to 0° or from 24 hr. to 0 hr. (of 15° each) between successive new moons in a synodic month of 29·5306 solar days. A related index called LUNAR AGE, ν, given by the expression $\nu = (24 - \mu)$hr. has been recommended and is often preferred. $\nu = 0$ hr. on New Moon;

$\nu = 6$ hr. on First Quarter Moon, $\nu = 12$ hr. on Full Moon and $\nu = 18$ on Third Quarter Moon. The local mean lunar time τ, at any longitude λ (reckoned in hours, and positive east of Greenwich) is given by the expression

$$\tau = t - \nu - (t - 12 - \lambda)/29{\cdot}5306 \text{ hour.}$$

For Huancayo $\tau = (0{\cdot}9661\ t - \nu - 0{\cdot}2373)$ hour. (1)

The data used consist of the hourly values of f_0F_2 at Huancayo for the period January 1951 to December 1955, kindly supplied by Mr. Alberto A. Giesecke, Jr. Missing and doubtful data are interpolated graphically to provide a reasonably complete series. The data for each solar hour are treated separately. From the individual hourly values of f_0F_2, their monthly mean values are subtracted to get the hourly values of the deviation Δf_0F_2. The data of days obviously affected by magnetic disturbances are discarded. Further values of Δf_0F_2 exceeding 30% of their corresponding monthly mean values are also excluded.

The remaining data are grouped according to the lunar age, ν, at the Greenwich noon of the day. The average curves of f_0F_2 *versus* lunar age $\nu = 0$ to $\nu = 23$ give the lunar variation (L) of f_0F_2 at the fixed solar hour and can be analysed into lunar monthly (L_1) and lunar semi-monthly (L_2) oscillations. Thus

$$\begin{aligned} L(f_0F_2) &= L_1(f_0F_2) + L_2(f_0F_2) \\ &= p_1 \cos(\nu - \phi_1) + p_2 \cos 2(\nu - \phi_2). \end{aligned} \qquad (2)$$

The amplitudes of L_1 and L_2 are given by p_1 and p_2 respectively. The phases ϕ_1 and ϕ_2 of L_1 and L_2 oscillation respectively are expressed throughout this article as the lunar age ν (or lunar time τ) when the corresponding wave attains its maximum positive deviation.

3. ANALYSIS OF THE DATA

The average annual variations of f_0F_2 against lunar age for each solar hour are shown in Fig. 1 and the coefficients of L_1 and L_2 oscillations derived from these curves are given in Table I. The smooth curves drawn over the histograms are obtained by combining the 12-hourly and 24-hourly component curves derived from harmonic analysis. A glance at these curves shows large lunar semi-monthly oscillations in f_0F_2 between 0900 and 2000 hour. In some cases, the two maxima are of unequal amplitude suggesting a small lunar diurnal component in the oscillation. During the night hours, the oscillations are much weaker and there is comparatively large scatter of points.

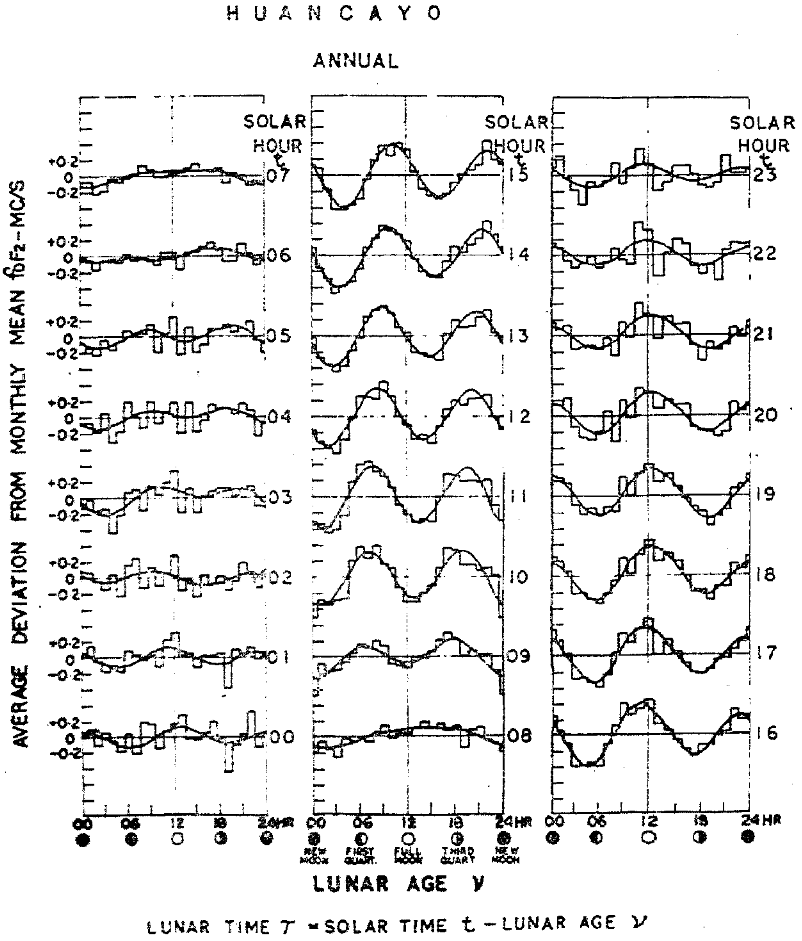

FIG. 1. Histograms showing the annual average variation of f_0F_2 at Huancayo for different solar hours against lunar age at Greenwich noon.

Another way of evaluating the lunar tidal effect in geophysical data is to subtract the mean solar variation from the data of individual hours, and find for each lunar age the variation of the deviations against local lunar time. These various curves can then be averaged to get the final lunar variation (Chapman and Bartels, 1940). Such a presentation of the annual average variation of f_0F_2 at Huancayo with local lunar time for the 12 lunar ages is shown on the left-hand side of Fig. 2. For comparison, similar curves are given of lunar variation of the horizontal magnetic intensity at Huancayo for the December solstices as given by Chapman and Bartels (1940) for zero sunspot number. The curves corresponding to the daylight hours are shown by full lines whereas those corresponding to the night hours by dashed lines.

TABLE I

Coefficients of lunar monthly L_1, and semi-monthly L_2 oscillations in f_0F_2 at Huancayo averaged for the whole year

Solar hour 75° EMT	Average f_0F_2 Mc./s.	L_1 oscillations		L_2 oscillations	
		Amplitude Mc./s.	Lunar hour τ of maximum amplitude	Amplitude Mc./s.	Lunar hour τ of maximum amplitude
0	5·9	0·05	9·5	0·10	11·6
1	5·4	0·03	12·9	0·10	2·0
2	4·7	0·03	19·8	0·06	4·6
3	3·9	0·11	12·3	0·11	5·8
4	3·4	0·07	12·9	0·08	8·0
5	2·9	0·05	13·4	0·10	9·1
6	4·2	0·06	13·3	0·04	0·0
7	6·6	0·10	17·7	0·04	0·3
8	7·9	0·12	17·9	0·03	1·1
9	8·4	0·10	19·2	0·17	2·7
10	8·2	0·06	20·3	0·33	2·9
11	8·0	0·05	23·2	0·37	3·5
12	7·9	0·05	23·0	0·33	3·7
13	8·0	0·06	23·5	0·32	4·0
14	8·2	0·07	23·1	0·33	4·3
15	8·5	0·06	0·8	0·34	4·5
16	8·6	0·11	2·4	0·33	4·9
17	8·6	0·09	3·4	0·29	5·2
18	8·5	0·11	4·4	0·26	5·6
19	8·1	0·08	7·3	0·26	6·3
20	7·7	0·08	6·9	0·21	7·3
21	7·5	0·08	8·4	0·17	8·0
22	7·2	0·04	10·1	0·13	9·7
23	6·6	0·05	7·0	0·12	11·6
Average of all hours		0·004 Mc.	2·0	0·106 Mc.	4·5
Ibadan (Brown, 1956)				0·119 Mc.	3·8
Huancayo (Martyn, 1947)				0·10 Mc.	4·32

It is clearly seen that the oscillations in f_0F_2 and H are larger during the day hours. The mean curves for f_0F_2 and H are predominantly semi-diurnal. The curves of f_0F_2 and H for the same lunar age and the average curves for the whole lunar month are almost opposite in phase, indicating anticorrelation between ΔH and Δf_0F_2 at the magnetic equator.

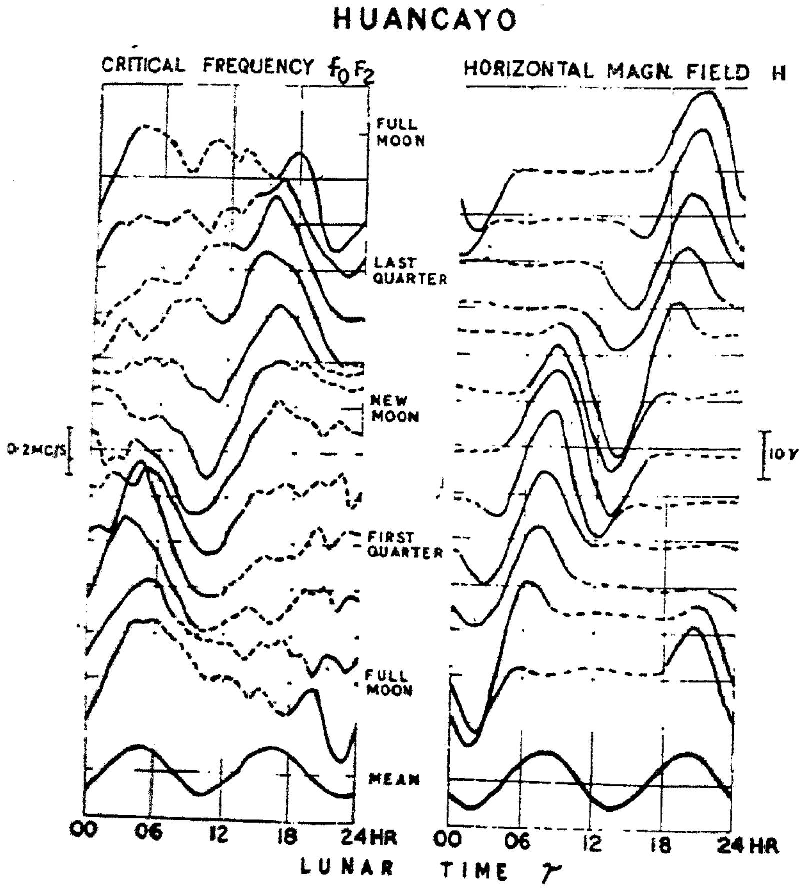

FIG. 2. Annual average local lunar time variation of f_0F_2 at Huancayo for different ages of the moon compared with similar variations of horizontal magnetic force H at Huancayo for the December solstical months corresponding to zero sunspot number as derived by Chapman and Bartels (1940).

The average annual L_1 variation has an amplitude of 0·03 to 0·12 Mc./s. with arithmetic mean values of 0·075 Mc./s., the phase expressed in lunar time τ varies through 360° for different solar hours, thus the L_1 oscillation is almost cancelled when averaged over all solar hours.

Average annual L_2 (f_0F_2) variation has an amplitude ranging between 0·03–0·37 Mc./s. with the average value of 0·193 Mc./s.; the amplitude for any solar hour between 10 to 15 hr. is more than 0·3 Mc./s. Lunar time variation of f_0F_2 averaged over all solar hours has the L_2 amplitude of 0·106 Mc./s. with the phase at $\tau = 4{\cdot}5$ lunar hour.

Seasonal Variation in the Lunar Oscillations of f_0F_2

The coefficients of lunar monthly (L_1) and semi-monthly (L_2) variations for individual solar hours averaged over the three seasons, *viz.*, Equinoxes (Mar., Apr., Sept. and Oct.), December solstice (Nov., Dec., Jan. and Feb.) and June solstice (May, June, July and Aug.) are given respectively in Tables II, III and IV. The coefficients of L_1 and L_2 oscillation are plotted on the harmonic dials of local lunar time, in Figs. 3 and 4 respectively.

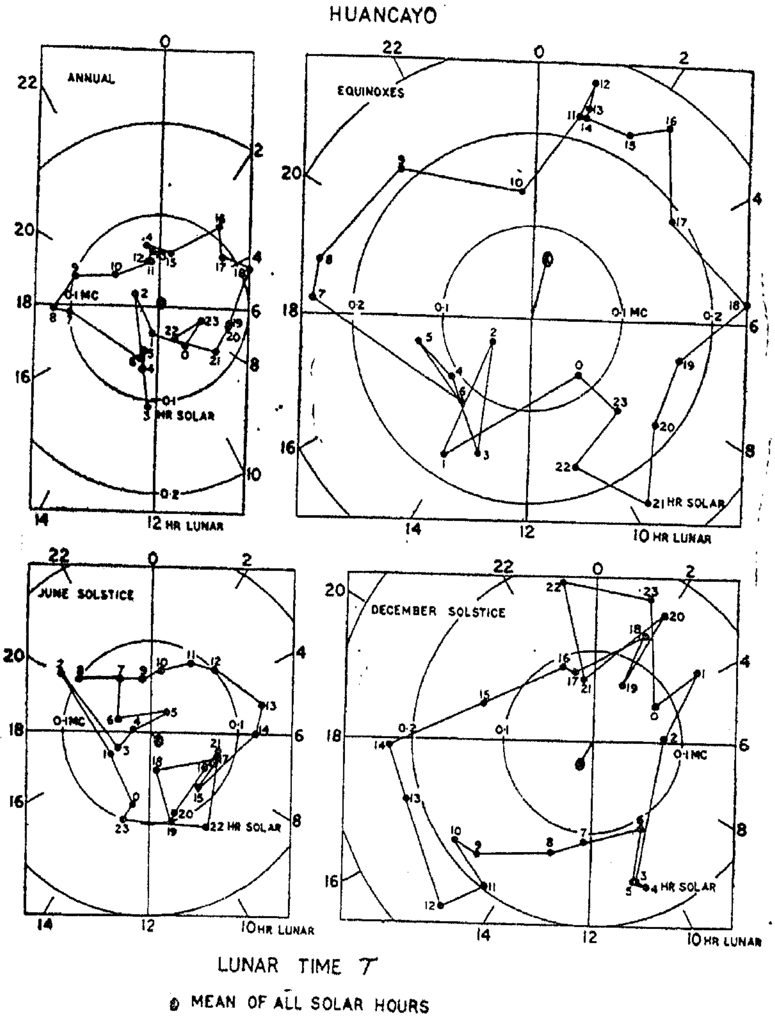

FIG. 3. The coefficients of lunar monthly oscillation in f_0F_2 at Huancayo at each solar hour represented on local lunar time (τ) dial, separately for each season of the year.

Referring to Fig. 3 one finds that for any of the seasons the coefficients of L_1 oscillations for different solar hours move around the origin during the course of a solar day keeping fairly the same distance from the origin. The vector averaged over all the solar hours has therefore insignificantly small amplitude. Thus the lunar oscillation in f_0F_2 has a component of one month periodicity when only the data of a fixed solar hour is considered, but when the oscillation is averaged over solar hours the lunar monthly component cancels out and one gets primarily lunar semi-diurnal oscillation.

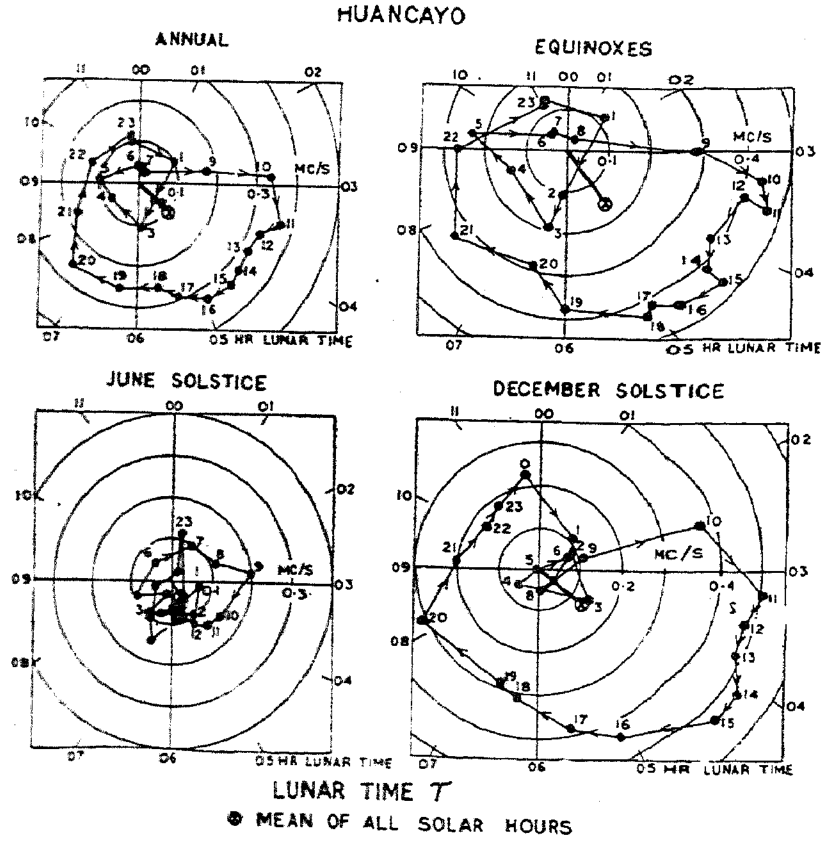

FIG. 4. The coefficients of lunar semi-monthly oscillation in f_0F_2 at Huancayo at each solar hour represented on local lunar time (τ) dial, separately for each season of the year.

Referring to Fig. 4, one finds that the coefficients of L_2 oscillations on a lunar time τ dial indicate a regular clockwise movement with increasing solar hour, there being two loops one for the daytime hours and the other for the night time hours. For the June solstices the amplitudes are small and the movements of points are comparatively irregular. The vectors for different solar hours when averaged do not cancel out, unlike in the case of L_1 oscillation, indicating that the lunar semi-monthly variation is a dominant component in the lunar time oscillation of f_0F_2 at Huancayo. The coefficients of L_2 oscillation averaged over all solar hours are given in the tables and are marked in the figures.

TABLE II

Coefficients of lunar L_1 and semi-monthly L_2 oscillations in f$_0F_2$ *at Huancayo averaged for the equinoxes*

Solar hour 75° EMT	Average f_0F_2 Mc./s.	L_1 oscillations		L_2 oscillations	
		Amplitude Mc./s.	Lunar hour τ of maximum amplitude	Amplitude Mc./s.	Lunar hour τ of maximum amplitude
0	7·3	0·08	9·9	0·13	11·2
1	6·6	0·18	14·2	0·12	1·6
2	5·5	0·05	15·9	0·11	6·1
3	4·5	0·16	13·4	0·19	6·4
4	3·8	0·11	15·6	0·14	8·3
5	3·3	0·13	17·2	0·23	9·3
6	4·6	0·12	14·7	0·05	10·6
7	7·3	0·25	18·3	0·05	10·8
8	8·6	0·25	18·9	0·03	2·3
9	9·0	0·22	21·1	0·29	3·0
10	8·7	0·14	23·6	0·44	3·3
11	8·3	0·23	0·8	0·47	3·6
12	8·2	0·27	0·9	0·41	3·5
13	8·4	0·24	0·9	0·38	4·1
14	8·6	0·23	0·9	0·42	4·4
15	8·9	0·23	1·8	0·47	4·4
16	9·0	0·26	2·3	0·45	4·8
17	9·0	0·19	3·6	0·42	5·0
18	8·9	0·24	5·0	0·44	5·1
19	8·5	0·17	6·9	0·38	6·0
20	8·2	0·18	8·6	0·29	6·5
21	8·2	0·24	9·7	0·34	7·7
22	8·1	0·17	10·8	0·26	9·0
23	7·8	0·14	9·0	0·12	11·1
Average of all hours		0·068 Mc.	0·8	0·162 Mc.	4·8
Ibadan (Brown, 1956)				5·32%	4·97
Huancayo (Martyn, 1947)				0·129 Mc.	3·8

TABLE III

Coefficients of lunar L_1 and semi-monthly L_2 oscillation in f_0F_2 *at Huancayo averaged for the December solstices*

Solar hour 75° EMT	Average f_0F_2 Mc./s.	L_1 oscillations		L_2 oscillations	
		Amplitude Mc./s.	Lunar hour τ of maximum amplitude	Amplitude Mc/s.	Lunar hour τ of maximum amplitude
0	5·7	0·08	4·0	0·23	11·7
1	5·1	0·14	3·7	0·11	1·6
2	4·3	0·08	5·7	0·09	2·0
3	3·4	0·16	10·7	0·14	4·0
	3·1	0·17	10·5	0·06	7·7
5	2·7	0·16	10·8	0·01	11·2
6	4·9	0·11	9·9	0·08	2·4
7	7·2	0·11	12·3	0·04	4·3
8	8·4	0·13	13·3	0·05	5·7
9	8·9	0·18	15·0	0·11	2·4
10	8·9	0·19	15·6	0·37	2·4
11	8·7	0·20	14·4	0·50	3·2
12	8·8	0·25	14·8	0·47	3·5
13	8·9	0·22	16·8	0·48	3·8
14	9·2	0·23	17·8	0·53	4·1
15	9·5	0·13	19·2	0·53	4·4
16	9·6	0·09	22·5	0·44	5·5
17	9·5	0·08	22·9	0·39	5·6
18	9·5	0·13	1·7	0·31	6·3
19	9·1	0·07	1·8	0·28	6·6
20	8·5	0·16	1·9	0·31	8·2
21	7·9	0·07	23·3	0·20	9·2
22	7·4	0·18	22·5	0·16	10·3
23	6·8	0·17	1·4	0·18	10·9
Average of all hours		0·029 Mc.	15·7	0·132 Mc.	4·2
Ibadan (Brown, 1956)				0·095 Mc.	2·6
Huancayo (Martyn, 1947)				5·14%	3·67

TABLE IV

Coefficients of lunar L_1 *and semi-monthly* L_2 *oscillation in* f_0F_2 *at Huancayo averaged for June solstices*

Solar hour 75° EMT	Average f_0F_2 Mc./s.	L_1 oscillations		L_2 oscillations	
		Amplitude Mc./s.	Lunar hour τ of maximum amplitude	Amplitude Mc./s.	Lunar hour τ of maximum amplitude
0	4·9	0·08	13·1	0·05	4·9
1	4·6	0·05	16·1	0·07	3·3
2	4·3	0·12	20·1	0·10	4·8
3	3·8	0·04	15·1	0·09	7·1
4	3·2	0·02	18·8	0·03	6·8
5	2·8	0·03	2·4	0·09	8·2
6	3·0	0·04	18·9	0·06	10·6
7	5·4	0·07	22·0	0·09	0·3
8	6·8	0·10	20·3	0·10	1·0
9	7·2	0·06	23·4	0·12	2·3
10	7·1	0·07	0·6	0·20	2·7
11	6·9	0·09	1·9	0·15	4·1
12	6·8	0·10	2·9	0·14	4·6
13	6·8	0·13	5·0	0·12	5·0
14	6·9	0·12	5·9	0·07	5·9
15	7·1	0·08	9·0	0·08	6·7
16	7·3	0·08	7·6	0·10	5·5
17	7·3	0·08	7·3	0·07	5·2
18	7·2	0·04	11·3	0·08	5·6
19	6·7	0·10	11·0	0·15	6·6
20	6·4	0·09	10·7	0·10	7·0
21	6·4	0·08	6·8	0·04	8·5
22	6·0	0·12	9·8	0·03	0·5
23	5·1	0·10	13·1	0·12	1·4
Average of all hours		0·014 Mc.	8·3	0·047 Mc.	4·9
Ibadan (Brown, 1956)				0·169 Mc.	4·5
Huancayo (Martyn, 1947)				2·48 %	4·4

The annual average L_2 oscillation for all hours has an amplitude of 0·106 Mc./s. with a maximum occurring at lunar time 4·5 lunar hour. This value compares fairly well with the value calculated by Martyn (1947) for Huancayo f_0F_2 during low sunspot years 1942–44, his value being 0·10 Mc./s. at 4·32 lunar hour. The corresponding value for another equatorial station, Ibadan, according to Brown (1956) is 0·119 Mc./s. at 3·8 lunar hour. Thus there is a fair agreement between the coefficients of annual average lunar oscillation of f_0F_2 at Huancayo and Ibadan. When seasonal variations of the coefficients are compared, one finds that the amplitudes are larger during December than June solstice at Huancayo but at Ibadan amplitudes are largest at June and least at December solstices. The phases for Ibadan and Huancayo also do not tally during individual seasons.

To compare the daily variations of the amplitudes of L_1 and L_2 in relation to the critical frequency f_0F_2 itself, these are plotted in Fig. 6 separately for each season. The amplitude p_1 does not show any significant diurnal variation during any of the seasons. The amplitude p_2 shows very significant daily variation during December solstices and the Equinoxes, whereas during the June solstices the p_2 values are almost the same for daylight as for night time periods. Further during June solstices the p_1 and p_2 values are almost of the same order whereas during other seasons the p_2 values are more than twice the corresponding p_1 values durnig the daytime. The daily variation of p_2 is very similar to that of f_0F_2 itself during December solstice and Equinoxes. It is of interest to note that f_0F_2 starts increasing in the morning almost at sunrise, *i.e.*, at about 0500 hour and reaches a peak at about 0900 hour, followed by a minimum at about noon, but the increase of p_2 amplitude after sunrise starts only at 08–09 hours reaching a maximum between 11 and 15 hours.

3. DISCUSSION

Duncan (1964) has expressed that the "semi-diurnal" lunar coefficient determined from observations at a fixed solar hour each day does not necessarily reflect semi-diurnal behaviour but may be caused by any variation of the form cos 2 $(\tau - nt)$ where n is an integer. If the phase of lunar coefficients for different solar hours is plotted against solar hours, the integer n would be given by the slope of the phase plot. According to him the variation is semi-diurnal in the true sense of the word if the phase plot is substantially horizontal during that interval. Using this criterion he concluded that in the analyses of f_0F_2 data by Martyn (1947) the simple semi-diurnal tide was present only between 08 and 17 solar hours. Using his criterion we have plotted in Fig. 6 the phases of lunar oscillations for each season, The phase plot is hardly horizontal for any period of the day. Of course the slope is small for period 09 to 18 hours and very large for the early morning hours during the December solstice and the equinoxes. During June solstice the slope is large even for the daylight hours.

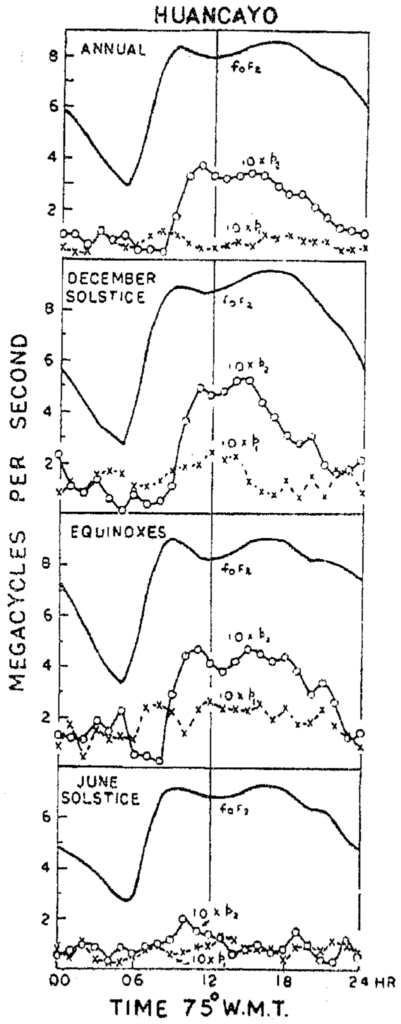

Fig. 5

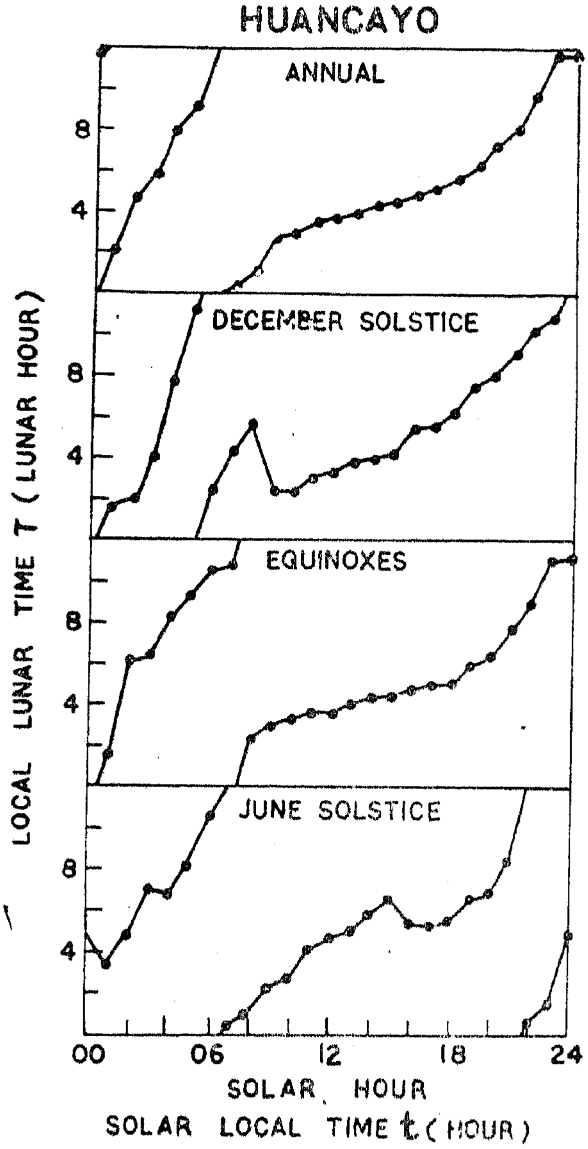

Fig. 6

Fig. 5. Solar daily variations of f_0F_2, the amplitudes p_1 and p_2 of lunar monthly and of semi-monthly oscillations in f_0F_2 at Huancayo during each season of the year.

Fig. 6. The phase of lunar semi-monthly oscillation in f_0F_2 at Huancayo for different solar hours in relation to the solar time separately for different seasons of the year.

It should be noted that the value of f_0F_2 at any time refers to the height of maximum ionisation (h_mF_2) which has a very large diurnal variation. Thus the lunar tide in f_0F_2 at different sloar hours refers to the tide in electron concentration at different heights of the ionosphere and so the phase angle need no be constant but may show slow and smooth variation with the solar time corresponding to the variation of $h_m F_2$. Haurwitz (1964) has expressed the lunar tidal variation at different heights according to the relation,

$$N(h) = N_0(h) + N_1(h) \sin\ [2wt + a_2(h)]$$

Burkard (1965) has found that L_2 shows considerable changes with height from the lunar tidal analyses of N (h) profile data of Puerto Rico. Thus the variability of lunar phases with the solar hour used is due to the fact that f_0F_2 values are situated at different heights during the course of the day and not due to the fact that it does not express genuine lunar tides.

Burkard (1951) had found that between the period 2100 and 0800 hours, only at 0500 hours was the lunar tide in f_0F_2 at Huancayo significant. Lange Hesse and Schott (1962) found that L_2 variation in the lowest value of f_0F_2 before sunrise at Lindau was 1·8% whereas the same for midday hours was only 0·6%. Rastogi (1963 *b*) had shown that the lunar tide in f_0F_2 at Huancayo and Canberra derived from Martyn's analysis and at Nhatrang by his own analysis showed very large amplitude at 05 or 06 hours near sunrise. This effect is not clearly indicated from the present analysis except probably during Equinoxes. The reason for it may be that during the period under study, *i.e.*, during the low sunspot period, the data for the early morning hours on many days were not available, because the value of f_0F_2 during that time was less than the minimum frequency recorded by the equipment. The coefficients of lunar tides during the early morning hours are therefore not significant.

Recently, Rastogi (1965) has shown that close similarities exist in the lunar tides in f_0F_2 and in the *Sq* range of H at equatorial stations and also in the latitudinal, seasonal, and sunspot cycle variations. The diurnal variation of amplitude of L_2 (f_0F_2) oscillation is significantly large only during the daylight hours when the equatorial electrojet is present. During the June solsticial months the lunar tide in *Sq* range at Huncayo is very small (Rastogi, 1964); and correspondingly it is found that the lunar tide in f_0F_2 is almost absent. It would be of interest to compare luni-solar tides in f_0F_2 and H at an equatorial station at identical periods to study the close relationships between the tides in geomagnetism and the ionosphere.

4. SUMMARY

The coefficients of lunar monthly (L_1) and semi-monthly (L_2) oscillations in f_0F_2 values at Huancayo for each solar hour are calculated for different seasons of a year of low solar activity. The amplitude of L_1 does not have a distinct variation with the time of the solar day and is about 0·1–0·2 Mc./s. for any particular solar hour; when the variation of f_0F_2 with local lunar time is averaged for all solar hours the amplitude of L_1 oscillation becomes negligibly small. The amplitude of L_2 oscillation is significantly larger for the daytime than for the night time hours. The L_2 amplitude for midday hours is largest during December solstice and least during June solstice. The solar daily variation of the L_2 amplitude is shown to be closely connected with the development of the abnormal belt of the F_2 region over the magnetic equator during the daytime. A close relationship is found to exist between the lunar tides in f_0F_2 and the horizontal magnetic intensity H at the magnetic equator.

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