LUNAR TIDAL VARIATIONS IN f_0F_2 IN THE AMERICAN ZONE DURING THE YEARS OF LOW SOLAR ACTIVITY AT HUANCAYO, PANAMA AND BUENOS AIRES—A GEOMAGNETIC ANOMALY EFFECT

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Received February 20, 1968

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

Abstract

Chapman's Phase Rule $L = \sum_{n=1}^{4} c_n \sin\{n\tau + (n-2)\nu + \alpha_n\}$ shown by him to be true for geomagnetic data is shown to be valid for the lunar oscillations in f_0F_2 also at the tropical latitude stations Panama and Buenos Aires. Lunar semi-monthly (M_2) oscillations in f_0F_2 at Panama are significantly larger during the day hours with a maximum amplitude near noon, while at Buenos Aires the tidal amplitudes are significant for all hours of the day and night and the maximum amplitude occurs in the afternoon around 15 hours. Regarding seasonal variation, the amplitude of lunar semi-diurnal or semi-monthly tides is largest during December solstices and least during June solstices.

I. Introduction

In an earlier paper, Rastogi and Alurkar (1966) have presented the analysis of f_0F_2 data at Huancayo during the period 1951–55, and later, Rastogi (1968) has compared lunar tides in f_0F_2 and in $\bar{H}$ at Huancayo using both the fixed lunar age method and the fixed solar time method. To understand the lunar tides in the F_2 region within the equatorial anomalous belt, it was felt necessary to compute the lunar perturbations of f_0F_2 at a few stations at different latitudes along the same longitude zone. The present article describes the lunar perturbations in f_0F_2 at the northern sub-tropical station Panama (Geog. lat. 9·6° N, Geog. long. 79·9° W and magnetic dip 37° N) and at the southern sub-tropical station Buenos Aires (Geog. lat. 34·6° S, Geog. long. 58·5° W, magnetic dip 31° S). The positions of these stations are shown on a map in Fig. 1; the lines of constant magnetic dip and of total magnetic field intensity are also shown in the diagram. Although

Buenos Aires is at a higher geographic latitude than Panama, the dip angle at Buenos Aires is smaller than that of Panama. Further Buenos Aires is located close to the region of minimum magnetic field such that the total field at Buenos Aires is only $\frac{2}{3}$ of that at Panama. The data utilised in the present study cover the period January 1952 to December 1955 for Panama and January 1951 to December 1955 for Buenos Aires. These data were collected by the author during his stay in C.R.P.L., Boulder, U.S.A. These stations are situated very close to the latitudes of sub-tropical peaks of f_0F_2 where large amplitudes of the lunar tides in f_0F_2 are found to occur.

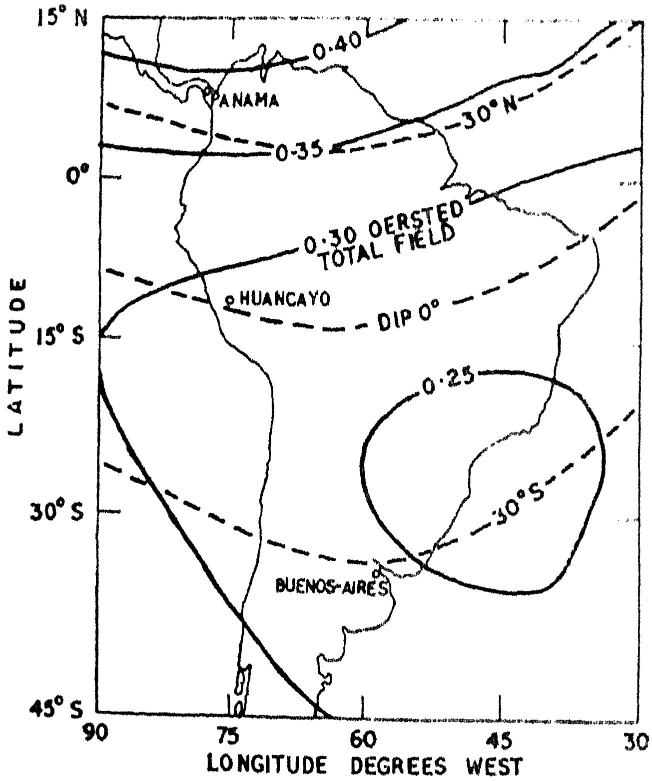

FIG. 1. Map showing the positions of Panama, Huancayo and Buenos Aires together with contour lines of the earth's total magnetic field and the magnetic dip angle.

II. ANNUAL AVERAGE LUNAR DAILY VARIATION AT FIXED LUNAR AGE

The mean solar daily variation was subtracted from the individual hourly values of f_0F_2 to get the residual deviation, *i.e.*, Δf_0F_2. Days of magnetic storms and large disturbances were excluded. The mean lunar daily variations of Δf_0F_2 are then derived separately for days with lunar age 00, 03, 06, 12, 15, 18 and 21, 1. hr. The lunar age 00 hr. corresponds to New Moon and lunar age 12 hr. to Full Moon. In the present article, data of 3 days centered on each of the above lunar ages are grouped together for analysis. The lunar variations in f_0F_2 at Huancayo, Panama and Buenos Aires averaged over the whole year for each of the eight lunar ages are shown in Fig. 2 (*a*), while Fig. 2 (*b*) shows the lunar daily variation averaged over the whole lunation obtained by averaging the variation for all the eight lunar ages. It may be noted that the scale in Fig. 2 (*b*) is enlarged five times as compared to that in Fig. 2 (*a*). The curves shown by solid lines

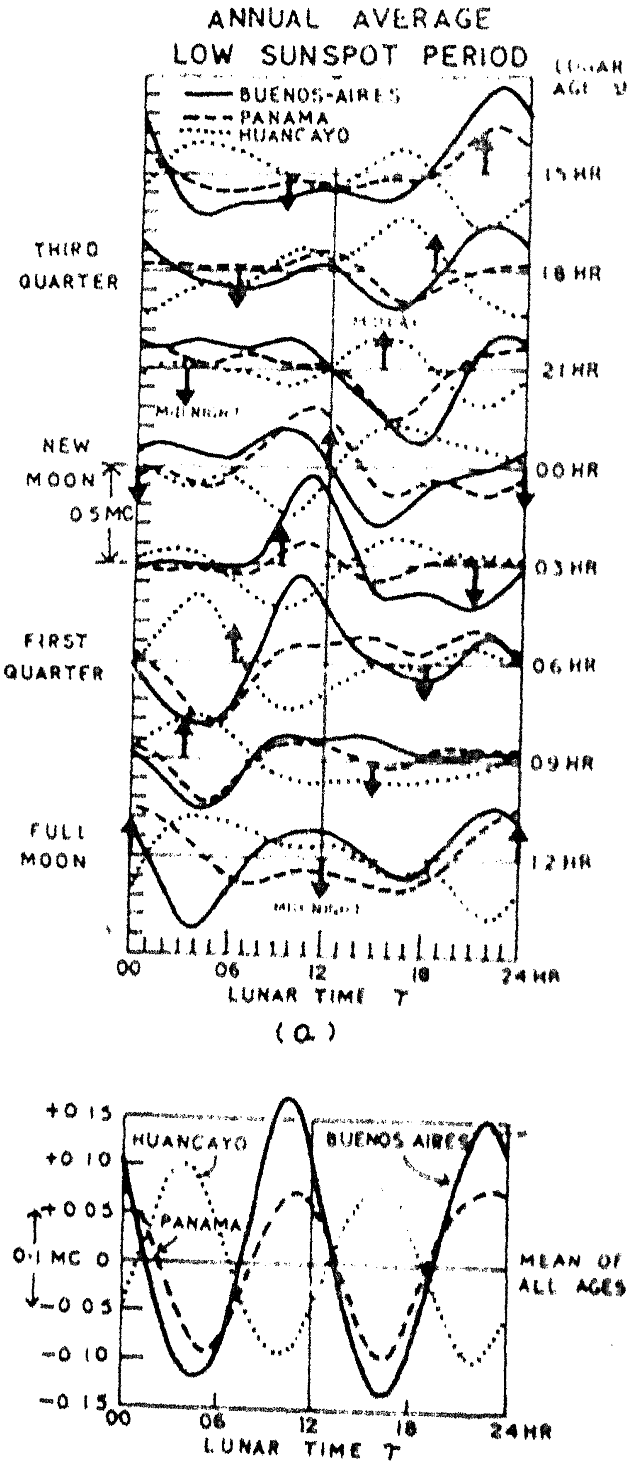

FIG. 2 (*a*). The lunar daily variations of f_0F_2 at Buenos Aires (full lines), Panama (dashed line) and Huancayo (dotted line) for eight ages of the moon.

FIG. 2 (*b*). The lunar daily variations of f_0F_2 at Buenos Aires, Panama and Huancayo averaged over the whole lunation.

relate to Buenos Aires, by dashed lines to Panama, and by dotted lines to Huancayo. The lunar hours at solar midday and midnight are marked by arrows pointing upward and downward respectively. Lunar time $\tau = 12$ hr. corresponds to zenith position of the moon and $\tau = 00$ hr. to its nadir position.

It is seen from Fig. 2 *a* that the greatest variation in f_0F_2 at each of the stations occurs during the daytime and there is a much smaller variation during the night hours. The curves for Panama and Buenos Aires at any particular lunar age are similar to each other and almost opposite in phase to the curve for Huancayo, *i.e.*, a positive peak in Huancayo is associated with a negative peak in Panama and Buenos Aires. The lunar variations at any particular age consist of two maxima of unequal amplitude within one lunar day indicating the presence of lunar diurnal and lunar semi-diurnal waves of comparable magnitudes. The lunar daily variation averaged over the whole lunation is almost a pure sinusoidal wave having two peaks within one lunar day. Thus the lunar diurnal component is largely cancelled out in averaging the curves over the whole lunation. Although the variation at Buenos Aires is very similar to that at Panama for each of the lunar ages as well as for the whole lunation, the deviations at Buenos Aires are much larger than those at Panama. The variation at Buenos Aires averaged over the whole lunation has an amplitude even larger than at Huancayo.

The coefficients of lunar daily variation of f_0F_2 averaged over a whole lunation are given in Table I. It is seen that the amplitudes of L_2 at different stations range between 0·084 and 0·144 Mc./s. whereas the L_1 amplitudes range between 0·006 and 0·016 Mc./s.; the higher harmonics have still smaller amplitudes. Thus the most significant component in the lunar daily variation is the semi-diurnal one. The L_2 amplitude at Buenos Aires is about $1\frac{1}{2}$ times that at Huancayo. The phase angles of L_2 oscillation at Panama and Buenos Aires are 127° and 135° respectively, and there is no significant difference between them. They are comparable to the phase angle at Ahmedabad (Rastogi *et al.*, 1964). The phase angle of L_2 at Huancayo is 331° and thus there is a phase difference of about 160° between L_2 oscillations at Huancayo and those at Panama or Buenos Aires.

Chapman (1919) has shown that the coefficients of different harmonics in the lunar daily variation of a magnetic element are given by the expression

$$L = \sum_{n=1}^{4} c_n \sin \{n\tau + (n-2)\nu + \alpha_n\} \quad (1)$$

indicating that c_n and α_n are independent of the lunar age.

In order to test whether Chapman's Phase Law holds good for f_0F_2 variations also, the lunar daily inequalities at each lunar age ν = 00, 03 ...21, l. hr. were harmonically analysed according to the equation

$$L = \sum_{n=1}^{4} c_n \sin(n\tau + \phi_n) \tag{2}$$

where $\phi_n = (n-2)\nu + a_n$. Thus in one complete lunation, the phase angle (ϕ_1) of the first harmonic decreases by 2π, the second harmonic has a constant phase while the third and fourth harmonics increase by 2π and 4π respectively. The amplitudes of c_n and phase constants a_n together with their mean values $\bar{c}_n$ and $\bar{a}_n$ over eight individual values of ν are given

TABLE I

Coefficients of annual average lunar daily variation of f_0F_2 for the whole lunation according to the equation $L = \Sigma A_n \sin(n\tau + \beta_n)$

Station	A_1 Mc./s.	β_1	A_2 Mc./s.	β_2	A_3 Mc./s.	β_3	A_4 Mc./s.	β_4
Panama ..	0·016	110°	0·084	127°	0·014	319°	0·007	10°
Buenos Aires ..	0·016	343°	0·144	135°	0·005	339°	0·011	166°
Huancayo (Rastogi, 1968)	0·006	13°	0·095	331°	0·004	286°	0·002	226°
Ahmedabad (Rastogi *et al.*, 1964)	0·010	234°	0·080	106°	..	..	..	..

in Tables II (*a*) and II (*b*) for Panama and Buenos Aires respectively. The relationship between the phase angle of a particular harmonic with the lunar age is shown in Fig. 3.

It is seen from Fig. 3 that for both Buenos Aires and Panama, the phase angle of the second harmonic, *i.e.*, of L_2 in f_0F_2 is fairly constant at different lunar ages, the values being 135° for Buenos Aires and 129° for Panama. The mean values of phase constant, *i.e.*, $\bar{a}_2$ are identical with the corresponding phase angle of the second harmonic of average lunar oscillation for the whole lunation, *i.e.*, β_2. The largest positive deviation of L_2 occurs at 10·5 l. hr. for Panama and 10·7 l. hr. at Buenos Aires which is similar to that observed at other tropical stations.

TABLE II (*a*)

Coefficients of annual average lunar daily variation of f_0F_2 at Panama at different lunar ages according to the equation

$$L = \Sigma c_n \sin \{n\tau + (n-2)\nu + \alpha_n\}$$

Lunar age	c_1 Mc./s.	α_1	c_2 Mc./s.	α_2	c_3 Mc./s.	α_3	c_4 Mc./s.	α_4
L. hr.—								
00	0·152	300°	0·104	127°	0·065	337°	0·034	64°
03	0·015	299°	0·056	153°	0·038	260°	0·021	67°
06	0·164	284°	0·121	125°	0·027	339°	0·036	111°
09	0·067	334°	0·096	135°	0·034	248°	0·026	16°
12	0·163	264°	0·100	91°	0·008	441°	0·006	217°
15	0·116	349°	0·076	145°	0·027	331°	0·022	139°
18	0·059	269°	0·061	119°	0·034	347°	0·018	230°
21	0·116	366°	0·090	139°	0·027	297°	0·035	119°
Mean ..	0·107	308°	0·088	129°	0·032	321°	0·025	116°

TABLE II (*b*)

Coefficients of annual average lunar time variation of f_0F_2 at Buenos Aires at different lunar ages according to the equation

$$L = \Sigma c_n \sin \{n\tau + (n-2)\nu + \alpha_n\}$$

Lunar age	c_1 Mc./s.	α_1	c_2 Mc./s.	α_2	c_3 Mc./s.	α_3	c_4 Mc./s.	α_4
L. hr.—								
00	0·160	377°	0·106	159°	0·066	353°	0·010	89°
03	0·212	354°	0·138	106°	0·093	276°	0·052	28°
06	0·179	339°	0·229	135°	0·032	284°	0·055	22°
09	0·123	357°	0·089	125°	0·051	298°	0·023	44°
12	0·103	374°	0·210	138°	0·058	311°	0·023	34°
15	0·230	355°	0·168	149°	0·053	304°	0·026	31°
18	0·101	373°	0·123	138°	0·044	338°	0·006	−56°
21	0·212	338°	0·130	131°	0·044	251°	0·043	−33°
Mean ..	0·165	358°	0·149	135°	0·055	302°	0·030	20°

The phase angle of L_1 at Buenos Aires or Panama decreases fairly iformly with increasing lunar age such that it varies through 2π during course of one lunation. Similarly ϕ_3 and ϕ_4 at either of the sations crease by 2π and 4π respectively during one complete lunation. There is, wever, some scatter in the case of ϕ_3 and ϕ_4 about the straight line. The lues of $\bar{a}_1$ are 308° at Panama, 358° at Buenos Aires and 177° at Huancayo. us the lunar daily oscillation is almost in opposite phase at Panama and enos Aires to that at Huancayo.

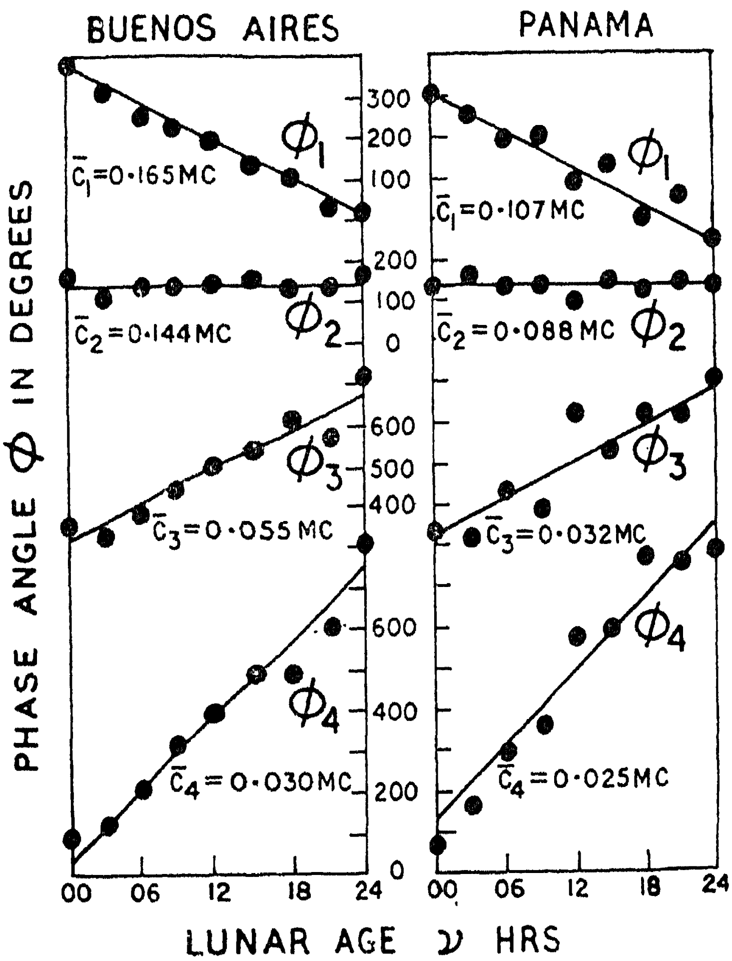

FIG. 3. The variation with the lunar age of the phases of the different harmonics of the ar daily variations of f_0F_2 at Buenos Aires and Panama for eight ages of the moon.

The amplitude of the lunar diurnal wave at any age of the moon is mparable to the lunar monthly semi-diurnal wave. When averaged over whole lunar month, the lunar semi-diurnal amplitude remains while the nplitude of the lunar diurnal component is reduced to insignificant magtude. The amplitudes of higher harmonics are also cancelled on averagg. One can conclude that Chapman's phase law derived for the omagnetic tide in H holds good also for the lunar daily variations in e critical frequency of the F_2 layer.

III. ANNUAL AVERAGE LUNAR MONTHLY VARIATION OF f_0F_2 AT FIXED SOLAR HOURS

Lunar tides in f_0F_2 can also be computed by analysing the lunar mo and semi-monthly variations at fixed solar hours. In Fig. 4 are shown average deviations of f_0F_2 from the corresponding monthly mean v plotted against lunar age ν_0 (at Greenwich noon) separately for the hours 00, 03, 06, 09, 12, 15, 18 and 21 for the stations Panama, Huan and Buenos Aires. The curves obtained by combining the first and se harmonic waves derived by Fourier analysis are drawn through the p

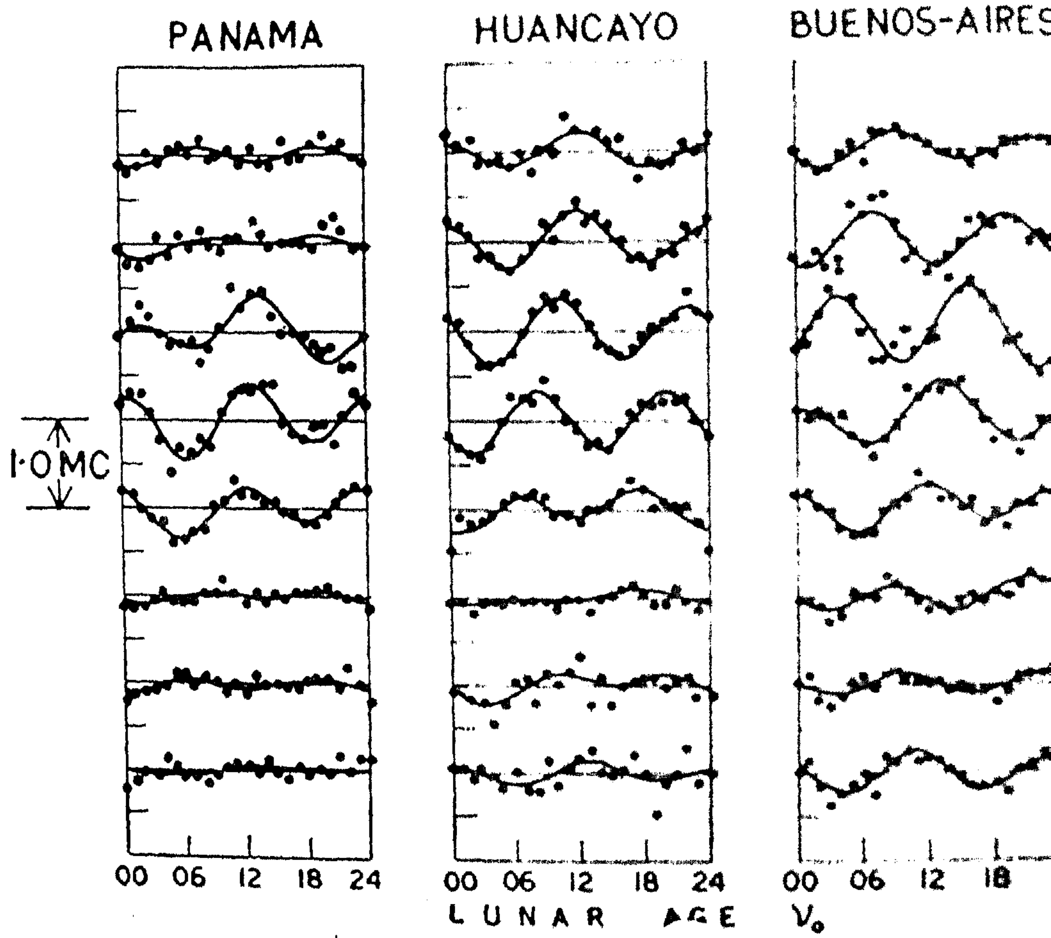

FIG. 4. The annual average variation of f_0F_2 at Panama, Huancayo and Bueno against lunar age (at Greenwich noon) for different solar hours.

It is seen that the lunar oscillations of f_0F_2 at Panama are large between 09 and 15 hr. and are insignificantly small from 03 to 06 hr Huancayo the oscillations are large between 09 and 21 hr. and are sm at 06 hr. At Buenos Aires the amplitude of the oscillations is l between 15 and 18 hr. but and is of significant magnitude even durin night hours. Thus there is a very distinct difference in the lunar ti

Panama and Buenos Aires. At Panama, there are no significant lunar oscillations in f_0F_2 during night hours while at Buenos Aires the oscillations are significant throughout the night hours.

The lunar variations at fixed solar hour, t, were analysed into lunar monthly and semi-monthly waves having amplitudes r_1 and r_2 respectively. The phases θ_1 and θ_2 are given in terms of the local lunar age ν, when the maximum positive deviation occurs for the respective wave. Proper longitude and so lar time corrections have been applied to these phases (Table III).

Probable errors involved in the derivations of these harmonic coefficients for any particular season are calculated according to the method described in Rastogi (1962) being equal to $0\cdot275\,(\sigma^2)^{\frac{1}{2}}$ where (σ^2) is the weighted mean variance of the mean deviation of f_0F_2 over all lunar hours. The probable

TABLE III

Coefficients of lunar monthly (r_1, θ_1) *and lunar semi-monthly* (r_2, θ_2) *oscillations in* f_0F_2 *at Panama and Buenos Aires for the whole year* (1951–55). *Phases* θ_1 *and* θ_2 *indicate lunar age* ν *of maximum positive deviation of the corresponding wave*

	Panama						Buenos Aires					
Solar time	Mean f_0F_2 Mc./s.	Probable error Mc./s.	Ampl. r_1 Mc./s.	Phase θ_1 l. hr.	Ampl. r_2 Mc./s.	Phase θ_2 l. hr.	Mean f_0F_2 Mc./s.	Probable error Mc./s.	Ampl. r_1 Mc./s.	Phase θ_1 l. hr.	Ampl. r_2 Mc./s.	Phase θ_2 l. hr.
00	4·4	0·030	(0·03)	15·2	(0·01)	8·4	4·5	0·026	(0·06)	12·5	0·20	10·8
01	4·1	0·027	(0·04)	17·3	(0·04)	9·1	4·4	0·026	(0·04)	14·6	0·19	10·6
02	3·7	0·024	(0·02)	0·0	(0·05)	6·5	4·4	0·026	(0·04)	15·7	0·13	10·6
03	3·3	0·023	(0·02)	12·1	(0·06)	6·7	4·3	0·025	(0·02)	7·8	0·11	10·0
04	3·1	0·021	(0·02)	20·2	0·07	7·4	3·9	0·025	(0·05)	8·7	0·10	8·3
05	2·9	0·021	(0·03)	17·5	0·07	8·7	3·7	0·025	(0·03)	4·6	(0·04)	8·1
06	3·2	0·017	(0·04)	18·1	(0·05)	8·8	4·3	0·024	(0·04)	21·5	0·15	8·8
07	5·1	0·018	0·09	14·7	(0·03)	7·8	5·4	0·021	(0·03)	19·2	0·13	9·8
08	6·1	0·023	(0·03)	15·8	0·08	8·6	6·0	0·027	(0·04	15·6	0·18	10·8
09	6·9	0·029	0·09	16·6	0·24	11·3	6·6	0·030	(0·07)	15·2	0·22	11·6
10	7·7	0·034	(0·10)	15·0	0·34	11·9	7·3	0·034	(0·09)	14·5	0·27	0·2
11	8·4	0·036	(0·10)	14·6	0·30	0·1	8·1	0·037	0·17	16·0	0·30	0·3
12	9·0	0·036	0·12	16·5	0·35	0·8	8·8	0·041	0·17	12·9	0·27	1·0
13	9·6	0·038	0·15	16·2	0·34	1·4	9·2	0·045	0·16	13·0	0·31	1·7
14	10·1	0·040	0·13	14·8	0·30	1·0	9·4	0·048	(0·10)	13·5	0·39	3·1
15	10·4	0·041	0·18	12·4	0·25	2·0	9·3	0·048	(0·08)	12·7	0·43	3·4
16	10·4	0·042	(0·10)	12·9	(0·07)	3·3	8·7	0·049	0·15	7·8	0·43	4·4
17	9·9	0·044	(0·07)	14·4	(0·08)	5·5	7·9	0·047	(0·12)	7·4	0·36	5·2
18	9·1	0·047	(0·09)	15·4	(0·08)	8·8	7·0	0·045	(0·03)	7·5	0·30	6·4
19	7·1	0·045	(0·04)	19·0	(0·12)	10·0	6·1	0·040	(0·04)	3·0	0·26	7·7
20	5·9	0·040	(0·04)	19·9	(0·09)	8·7	5·5	0·035	(0·06)	10·0	0·15	7·8
21	5·0	0·034	(0·02)	15·3	(0·10)	8·0	5·1	0·033	(0·05)	10·1	0·16	8·5
22	4·6	0·032	(0·02)	14·2	0·10	8·2	4·8	0·030	(0·08)	12·1	0·19	8·0
23	4·4	0·026	(0·05)	14·0	0·10	9·4	4·6	0·027	0·08	12·2	0·19	9·0

error (q) for the annual mean coefficients are taken to be $q^2 = \frac{1}{3}(q_1^2 + q_2^2 + q_3^2)$ where q_1, q_2 and q_3 are the probable errors for a particular hour during the individual season. The determination of a particular coefficient may be considered significant after Chapman (1951), only if its value exceeds three times its probable error. The doubtful amplitudes are noted in the tables within brackets.

In Table III are given the coefficients of M_1 and M_2 oscillations in f_0F_2 at Panama and Buenos Aires at each solar hour averaged over the whole year. The variation of the lunar semi-monthly amplitude with the time of the day is shown in Fig. 5 for Panama, Huancayo and Buenos Aires.

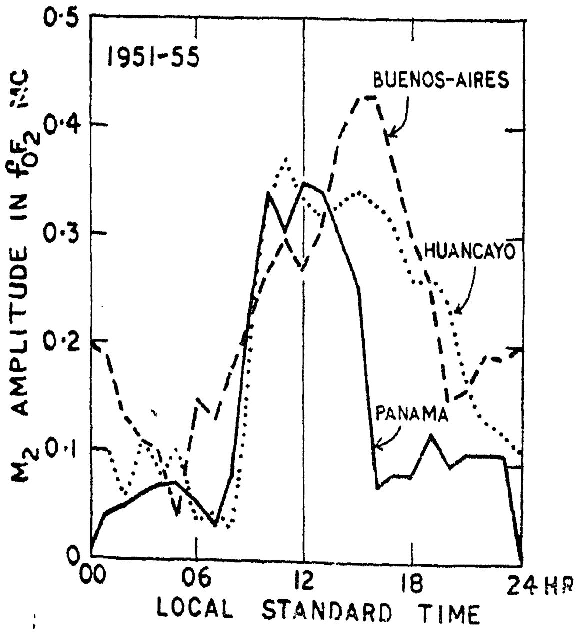

FIG. 5. The solar daily variation of the amplitude of annual average lunar semi-monthly oscillation in f_0F_2 at Buenos Aires, Panama and Huancayo.

The amplitude of lunar semi-monthly (M_2) oscillation in f_0F_2 at Panama is very small in the night hours, starts increasing after 07 hr., reaches a maximum of about 0·3 Mc./s around noon and reduces to low value by 16 hr.; the daily variation of M_2 amplitude is symmetrical about noon.

The amplitude of M_2 tide at Huancayo is almost the same as that at Panama for the forenoon hours but its decrease in the afternoon hours is slower at Huancayo than at Panama. The amplitude exceeds 0·29 Mc./s. for all hours between 10 and 16 s. hr.

The amplitude of M_2 (f_0F_2) oscillation at Buenos Aires is maximum around 15–16 hr. and is significantly large even during night hours. The amplitude of M_2 tide for any hour of the day except 05 hr. satisfies the statistical significance test.

The (r_2, θ_2) points for different lunar ages at Panama and Buenos Aires are plotted on harmonic dials in Fig. 6.

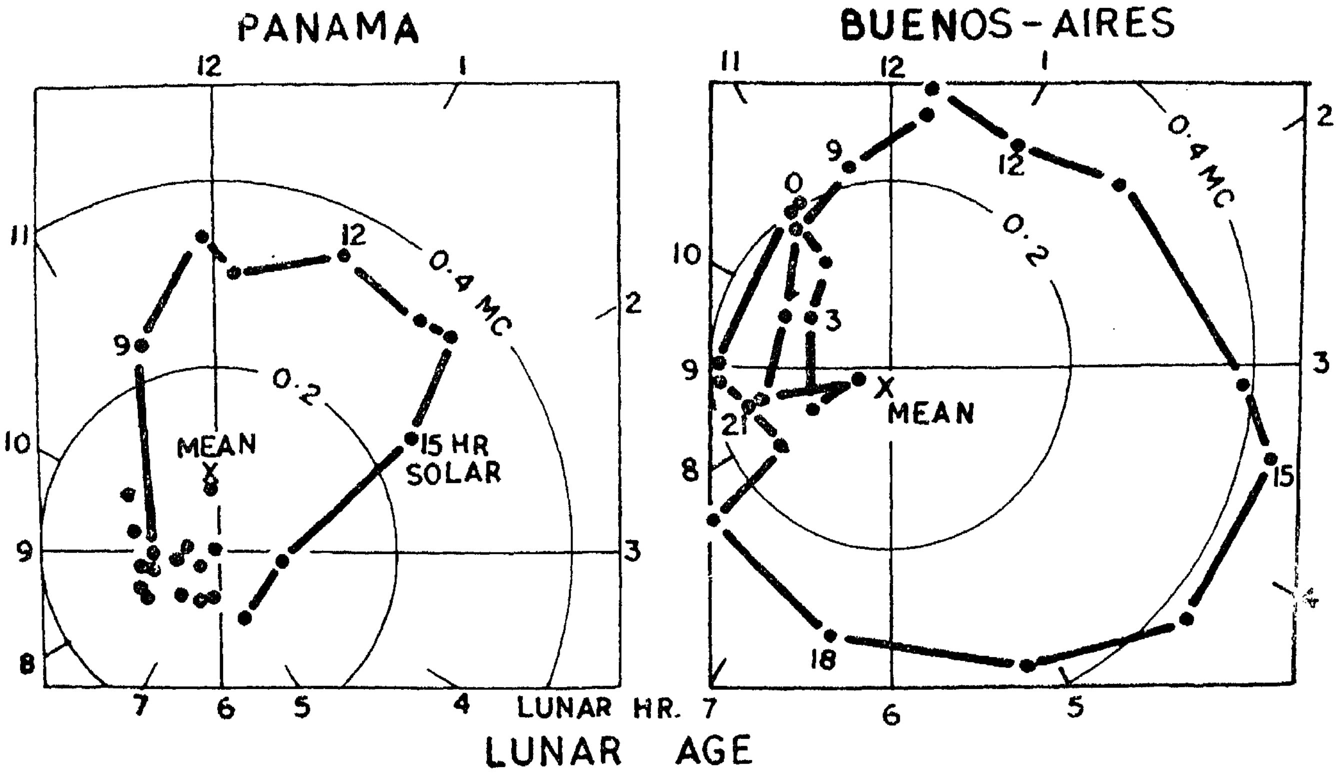

FIG. 6. The coefficients of yearly average lunar semi-monthly oscillation in f_0F_2 for each solar hour at Buenos Aires and Panama expressed on the harmonic dials of lunar age ν. The solar hour is marked at the end of each vector.

It is seen that on the lunar age ν dial, the coefficients for M_2 (f_0F_2) at Buenos Aires move around the origin systematically with increasing solar time; the movement of points for the night time hours are rather random. The vectorial average of these points is only 0·019 Mc./s. at 11·6 l. hr. although the individual amplitude value ranges from 0·04 to 0·43 Mc./s. Somewhat similar features are observed in the movements of M_2 coefficients of f_0F_2 oscillations at Panama. The vectorial average of all points on the lunar age dial is 0·07 Mc./s. at 11·9 l. hr.

Although the loops in the harmonic dials are roughly similar for Panama and Buenos Aires, the dial on lunar age appears to be expanded and rotated with respect to that at Panama. To show the differences between the tides at Panama and Buenos Aires, the vector which has to be added to that at Panama to obtain the vector at Buenos Aires were computed for each solar hour both from lunar age and is shown in Fig. 7. These difference vectors on the lunar age have a preferred direction around

12 to 19 lunar hour. The amplitudes of difference vector are very large between 14 and 19 solar hours. Thus there is a very large addition in the lunar tidal effects at Buenos Aires when the moon is near its lower or upper transit and the sun is around 15 hours position.

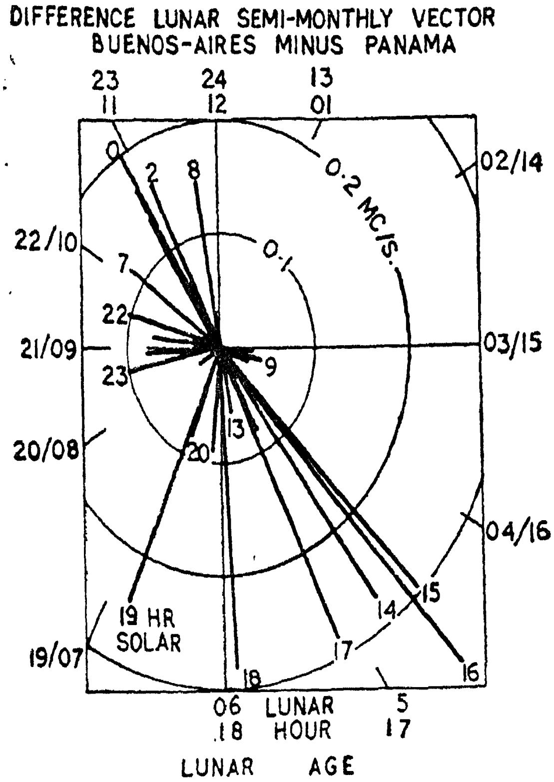

FIG. 7. The difference vector Buenos Aires *minus* Panama derived from the lunar age ν, harmonic dials of lunar semi-monthly tides for fixed solar hours.

The diurnal (r_1, θ_1) points, plotted on the lunar age dial, group in a narrow sector indicating that the maximum positive deviation of f_0F_2 for different solar hours occurs on the same lunar day. The vectorial average for all solar hours is therefore significant.

IV. LUNAR DAILY VARIATION AT FIXED AGE IN DIFFERENT SEASONS

The lunar daily variations of f_0F_2 at Panama and Buenos Aires for D-months (*viz.*, November, December, January and February), E-months (March, April, September and October) and J-months (May, June, July and August) were computed separately for each of the eight lunar ages and for the whole lunation. The latter was obtained by averaging the eight curves.

It was found that the curves for the two stations were similar in D- and E-months but during J-months the two curves showed small amplitude and no similarity could be distinguished.

The features of lunar daily variation on individual lunar ages during different seasons are similar to those for the whole year and are not discussed in detail here. The lunar daily variation of f_0F_2 at Panama and Buenos Aires averaged over the whole lunar month were also computed for each season and the coefficients of different harmonics are given in Table IV. The amplitudes of L_1 are much smaller than those of L_2. The L_2 amplitude is strongest in the D-months, and weakest in the J-months. The phase of L_2 at either station during December Solstice and Equinoxes ranges between 112° and 161° indicating that the maximum positive deviation occurs between 9·6 and 11·3 l. hr. which is almost in phase opposition to the variation at Huancayo when the phase angle ranges between 315° and 340°, *i.e.*, maximum positive deviation occurs between 3·6 and 4·5 lunar hours. During J-months the phase angle β_2 is 52° for Panama, 88° for Buenos Aires and 359° for Huancayo and thus the phase difference is only 1·8 to 3·0 l. hr.

TABLE IV

The coefficients of whole lunation average lunar oscillations in f_0F_2 *at Panama and Buenos Aires according to the equation* $L = \Sigma A_n \sin (n\tau + \beta_n)$ *for different seasons of the year*

	A_1 Mc./s.	β_1	A_2 Mc./s.	β_2	A_3 Mc./s.	β_3	A_4 Mc./s.	β_4
D-months—								
Panama ..	0·020	116°	0·171	161°	0·033	289°	0·018	292°
Buenos Aires ..	0·027	284°	0·219	138°	0·015	302°	0·025	204°
E-months—								
Panama ..	0·041	65°	0·097	112°	0·033	358°	0·023	42°
Buenos Aires ..	0·009	315°	0·192	133°	0·011	30°	0·007	247°
J-months—								
Panama .	0·034	209°	0·066	52°	0·008	244°	0·009	163°
Buenos Aires ..	0·041	74°	0·033	88°	0·004	96°	0·014	146°

V. LUNAR MONTHLY OSCILLATIONS AT FIXED SOLAR HOURS DURING DIFFERENT SEASONS

The variation of f_0F_2 with the lunar age ν at different solar hours have been computed for each season and the coefficients of lunar monthly and semi-monthly oscillations calculated. The amplitude of lunar semi-monthly oscillation and the lunar age at which maximum positive Δf_0F_2 occurs are collected in Tables V (a) and V(b), respectively for Panama and Buenos Aires; only coefficients for 00, 03, ... 21 solar hours are given. Probable errors of r_2 are given and the amplitudes which do not satisfy Chapman's criterion are shown within brackets. These coefficients for each solar hour are plotted in harmonic dials of lunar time in Fig. 8 for Panama and Buenos Aires. Smaller circles centred round the coefficients for particular solar hours denote the probable error.

In each of the seasons, the amplitudes at Panama are significant during the daytime and only between about 08 and 16 solar hours. The maximum amplitude of lunar oscillations is found to occur at 13 solar hours when the lunar age is about 15 hr. At Buenos Aires, most of the coefficients, both during day and night, are statistically significant in the D- and E-months. In the D-months, the maximum amplitude is about 0·5 Mc./s. and the largest amplitudes occur at 15 to 16 hr.

TABLE V (a)

The amplitudes and phases (lunar age v at which maximum positive deviation occurs) of semi-monthly oscillations in f_0F_2 *at Panama during different seasons*

75° WMT	D–months			E–months			J–months		
	Ampl.	Probable error	Phase	Ampl.	Probable error	Phase	Ampl.	Probable error	P
	Mc./s.	Mc./s.	l. hr.	Mc./s.	Mc./s.	l. hr.	Mc./s.	Mc./s.	l.
00	(0·11)	0·043	1·8	(0·06)	0·052	7·3	(0·06)	0·058	[illegible]
03	(0·10)	0·033	4·8	(0·09)	0·041	7·5	(0·06)	0·046	[illegible]
06	(0·09)	0·024	8·8	(0·05)	0·033	8·2	(0·07)	0·032	[illegible]
09	0·36	0·062	1·0	0·24	0·047	11·7	(0·09)	0·041	[illegible]
12	0·43	0·073	1·6	0·45	0·058	0·9	0·26	0·053	[illegible]
15	0·33	0·074	3·6	0·39	0·083	2·0	0·28	0·054	[illegible]
18	(0·12)	0·074	7·6	(0·09)	0·091	9·4	(0·06)	0·077	[illegible]
21	(0·05)	0·041	10·8	(0·21)	0·067	7·5	(0·08)	0·066	[illegible]

TABLE V (*b*)

amplitudes and phases (lunar age ν at which maximum positive deviation occurs) of lunar semi-monthly oscillation in f_0F_2 at Beunos Aires during different seasons

0° WMT	D-months			E-months			J-months		
	Ampl. Mc./s.	Probable error Mc./s.	Phase l. hr.	Ampl. Mc./s.	Probable error Mc./s.	Phase l. hr.	Ampl. Mc./s.	Probable error Mc./s.	Phase l. hr.
00	0·45	0·056	11·3	0·21	0·048	10·1	(0·04)	0·029	5·9
03	0·37	0·051	10·4	(0·03)	0·048	9·5	0·09	0·030	5·1
06	0·29	0·046	9·6	0·20	0·041	7·9	(0·04)	0·036	6·8
09	0·41	0·056	0·1	0·26	0·056	10·4	(0·06)	0·042	0·6
12	0·31	0·066	1·0	0·47	0·084	1·1	(0·05)	0·061	0·0
15	0·56	0·085	4·0	0·52	0·092	3·3	0·26	0·068	2·3
18	0·35	0·084	6·6	0·58	0·092	6·5	(0·06)	0·049	2·7
21	0·43	0·059	9·2	(0·19)	0·067	7·9	0·15	0·043	3·9

It is seen from Fig. 8 and Tables V (*a*) and V (*b*) that for either Panama or Buenos Aires the tides are much larger during D-months than during J-months, even though the two stations are situated in opposite hemispheres and the local seasons are different at the two places during a particular month.

During the D-months the coefficients for the daytime hours 08 to 18 hr. move around the origin almost through 180° indicating that the lunar age on which the tidal effects are maximum is different for different solar hour. The phase angle for a particular solar hour is not significantly different for Panama and Buenos Aires. The amplitudes at the two places are similar upto noon hour but during the evening hours the amplitudes are much larger at Buenos Aires than at Panama.

During E-months the points for the daytime hours for any of the stations seem to shift uniformly on the harmonic dial with the solar hour. The phases for any particular hour are not different at the two places but the amplitudes for the evening hours are much larger at Buenos Aires than at Panama.

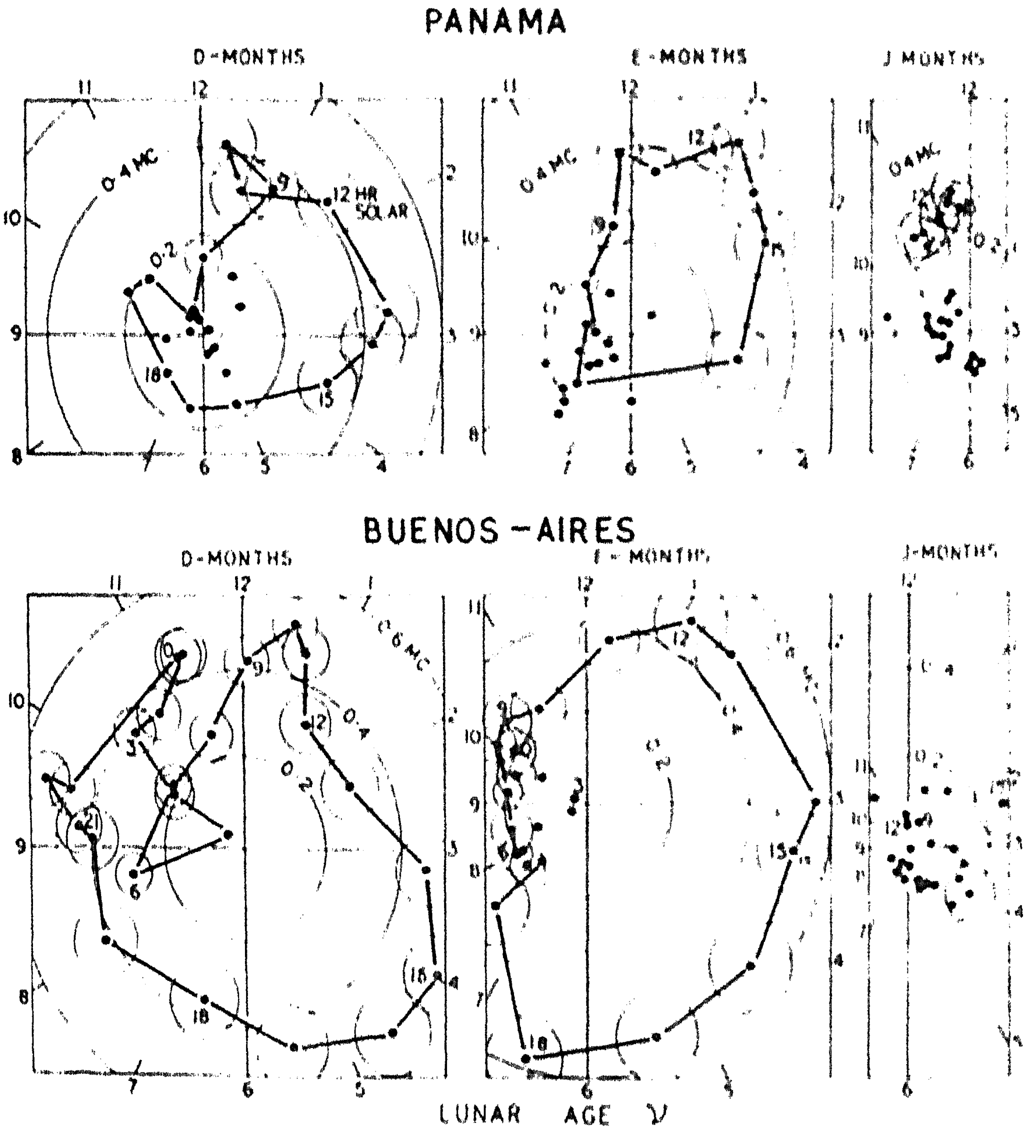

FIG. 8. Coefficients of lunar semi-monthly oscillations in f_0F_2 at Panama and Buenos Aires at fixed solar hours for different seasons of the year plotted on the harmonic dials of the lunar age ν.

During J-months the amplitudes are very small at either station. The coefficients at Buenos Aires are scattered around the origin. Regarding the harmonic dial for Panama, the points for the daytime hours 10 to 16 hr. which are all statistically significant do not move on the dial around the origin but cluster around a point roughly 0·25 Mc./s. at 11·0 l. hr. Thus there is a significant difference in the harmonic dials of M_2 oscillation at the two places in the two solstices.

ACKNOWLEDGEMENTS

Sincere thanks are due to the Ionospheric Prediction Services, Institute of Telecommunication Sciences and Aeronomy (formerly Central Radio

Propagation Laboratory), Boulder, U.S.A., for supplying the data used in the present analysis and to Prof. K. R. Ramanathan for the valuable discussions and suggestions during the course of work. Thanks are also due to Miss N. J. Modi for computational assistance.

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APPENDIX

t	.. local solar mean time.
τ	.. local lunar mean time.
ν_0	.. lunar age at Greenwich noon.
ν	.. local lunar age.
l. hr.	.. lunar hour = 1/24th mean lunar day.
s. hr.	.. solar hour = 1/24th of mean solar day.
$L_1(f_0F_2)_\nu$	.. lunar diurnal oscillation in f_0F_2 at fixed lunar age ν.
$L_2(f_0F_2)_\nu$	.. lunar semi-diurnal oscillation in f_0F_2 at fixed lunar age ν.
c_n, ϕ_n, a_n	.. amplitude, phase angle and phase constant of the n-th harmonics of lunar daily variation according to the

$$L = \sum_{n=1}^{4} c_n \sin\{n\tau + (n-2)\nu + a_n\}$$

$$= \sum_{n=1}^{4} c_n \sin(n\tau + \phi_n).$$

$M_1(f_0F_2)_t$	.. lunar monthly oscillation in f_0F_2 at fixed solar time t.
$M_2(f_0F_2)_t$	.. lunar semi-monthly oscillation in f_0F_2 at fixed solar time t.
A_n, β_n	.. amplitude and phase angle of the harmonic of lunar daily oscillation averaged over whole lunation.
$(r_1, \theta_1), (r_2, \theta_2)$	.. amplitude and time of maximum positive deviation of M_1 and M_2 oscillations respectively.