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

III. Middle Latitude Stations: Puerto Rico and Falkland

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Received September 5, 1968

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

I. INTRODUCTION

IN earlier papers Rastogi and Alurkar (1966) and Rastogi (1968 *a*, *b*) have presented analyses of lunar tidal oscillations in f_0F_2 at equatorial and tropical latitude stations in the American zone during the low sunspot years 1951–55. Significantly large lunar tides were noticed at the southern stations even during night hours, specially during December Solsticial months. The present article describes the lunar perturbations in f_0F_2 at the northern mid-latitude station Puerto Rico and the southern mid-latitude station Falkland Islands, and the results are compared with those discussed in the earlier papers. The co-ordinates of these stations are given in Table I and their positions are shown in Fig. 1 which also contains the lines of constant dip and of total magnetic field. It is of interest to note that Puerto Rico though at a low latitude of 19° N. has a dip of 51° whereas Falkland having a dip of 46° S. is situated at 52° S. latitude. Further, the total magnetic field at Falkland is only three-fourths of that at Puerto Rico. The data utilised in the present study cover the period January 1951 to December 1955 which were obtained through the courtesy of CRPL (now ITSA), Boulder, U.S.A. Both Puerto Rico and Falkland are situated outside the so-called equatorial belt of anomalous F_2 region. The method of analysis has been described in the earlier papers.

II. ANNUAL AVERAGE LUNAR DAILY VARIATION AT FIXED LUNAR AGE

In Fig. 2 are shown the lunar daily variations of f_0F_2 at Puerto Rico (solid lines) and at Falkland (dashed lines) at different lunar ages as well as averaged over a whole lunar month. It is seen that the curves at both the stations are remarkably similar even at individual lunar ages. Noting that the geographic latitudes of these stations are very different while the dip angles are nearly the same, it may be concluded that the luni-solar tidal oscillation in the ionosphere is tied to the magnetic field of the earth rather to the geographic co-ordinates. However, there are likely to be differences in the pattern depending on the abnormalities in the earth's magnetic field itself.

TABLE I

Co-ordinates of ionospheric stations studied

Station		Geographical lat.	Geographical long.	Magn. Dip.	Total Magn. Field Oersted
Puerto Rico	..	18·5° N	67·2° W	57° N	0·43
Panama	..	9·6° N	79·9° W	37° N	0·37
Huancayo	..	12·3° S	75·3° W	2° N	0·29
Buenos Aires	..	34·6° S	58·5° W	31° S	0·26
Falkland	..	51·7° S	57·9° W	46° S	0·33

The lunar variations on individual days indicate comparable diurnal as well as semi-diurnal components, whereas the whole-month-average of lunar daily variation is purely semi-diurnal in character.

The coefficients of lunar daily variations of f_0F_2 averaged over the whole lunation at these and other stations in the American zone are given in Table II. For any of the stations, the most significant component is the lunar semi-diurnal one. The phase angle of L_2 oscillations at Puerto Rico and Falkland is 184° and 158° respectively. In other words, the maximum positive deviation of f_0F_2 at Puerto Rico and Falkland occurs at lunar times 8·9 and 9·7 lunar hours respectively. The corresponding values for other tropical stations Panama and Buenos Aires are 10·8 and 10·5 l.hr. respectively.

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

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

where c_n and a_n are independent of lunar age. To test Chapman's phase law, the lunar daily variations at individual lunar ages are harmonically analysed according to the equation

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

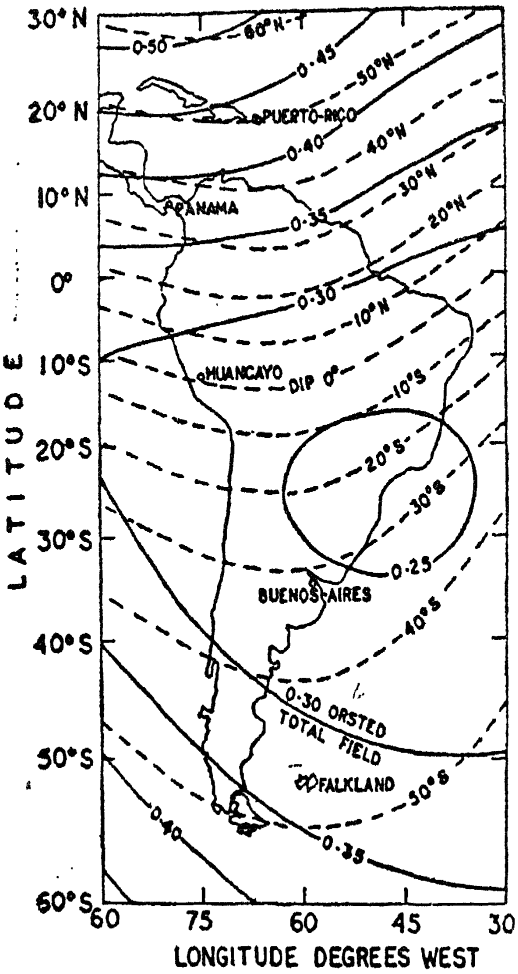

FIG. 1

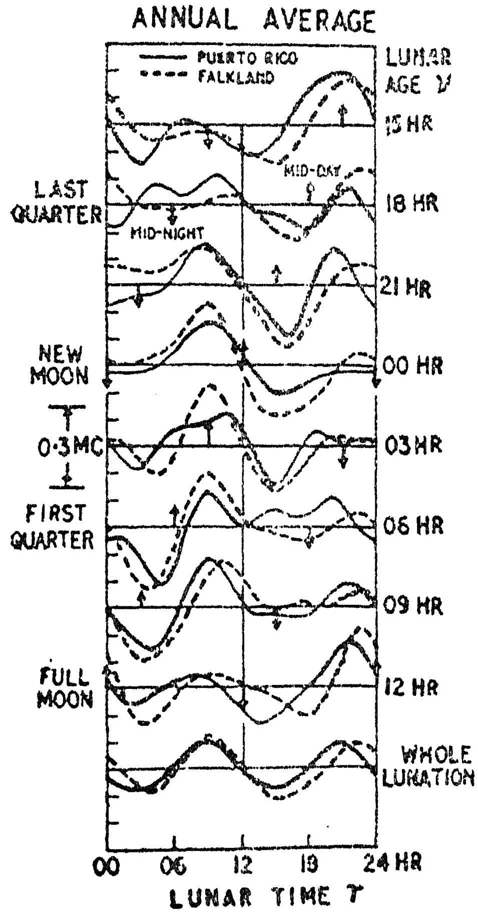

FIG. 2

FIG. 1. Map showing the positions of stations studied in the present and earlier papers together with contour lines of earth's total magnetic field and magnetic dip angles.

FIG. 2. The lunar daily variations of f_0F_2 at Puerto Rico (full lines) and Falkland (dashed lines) for eight ages of the moon and when averaged over the whole lunation.

The variations of phase angles (ϕ_n) with the lunar age for the annual average L variations at Puerto Rico and Falkland are shown in Fig. 3. It is seen, that at both the stations, the phase angle of the second harmonic, *i.e.*, ϕ_2 is fairly constant of the lunar age. The phase of L_1 oscillation, *i.e.*, ϕ_1 decreases through 2π during the course of one lunation. Similarly ϕ_3 and ϕ_4 at either of the stations increase by 2π and 4π respectively during one complete lunation. These results are in conformity with the Chapman's Phase Law derived from the dynamo theory of the atmosphere. This again confirms that the lunar tidal oscillations in the F_2 layer ionisations are in a great extent associated with the movements expected from the dynamo theory.

TABLE II

Coefficients of annual average lunar daily variation of f_0F_2 for the whole lunation according to the equation $L = \sum_{n=1}^{4} A_n \sin (n\tau + \beta_n)$.

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 °	Reference
Puerto Rico	0·007	286	0·086	184	0·004	352	0·007	274	Present article
Panama	0·016	110	0·084	127	0·014	319	0·007	10	Rastogi, 1967 *b*
Huancayo	0·006	13	0·095	331	0·004	286	0·002	226	Rastogi, 1967 *a*
Buenos Aires	0·016	343	0·144	135	0·005	339	0·011	166	Rastogi, 1967 *b*
Falkland	0·031	23	0·100	158	0·016	84	0·002	217	Present article

Referring to Fig. 3, it is seen that the amplitude of oscillation in f_0F_2 at either of the stations is slightly greater for the second than for the first harmonic; while the third and fourth harmonics have greatly reduced amplitudes. Further the amplitude of any particular harmonic is greater at Falkland than at Puerto Rico.

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 monthly and semi-monthly variations at fixed solar hours. In Fig. 4 are shown the average deviations of f_0F_2 from the corresponding monthly mean value as a function of lunar age (at Greenwich noon) separately for each of the solar hours 00, 03, 06, 09, 12, 15, 18 and 21. The smooth curves drawn through the points, built up of first and second harmonic coefficients, are also shown.

There is a distinct maximum in the amplitude of lunar tides at each of the stations during the midday hours, but there is another secondary maximum at about 18 hour solar time. The tides around midnight hours are insignificantly small at Puerto Rico but quite large at Falkland. As described earlier, the M_2 ($f_0 F_2$) amplitude at Huancayo is very small during nights, starts rapidly increasing about two hours after sunrise, reaches a broad maximum between 11–15 hours and slowly decreases afterwards towards a minimum around sunrise hours.

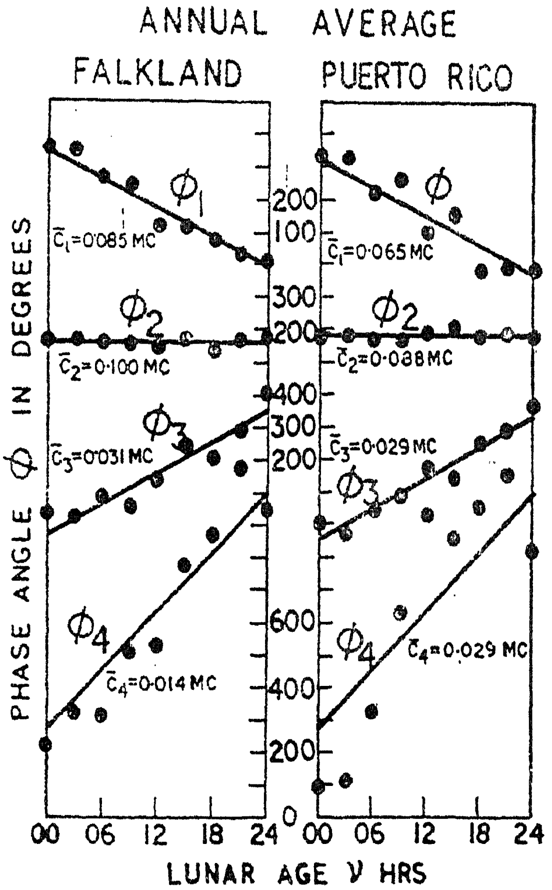

FIG. 3

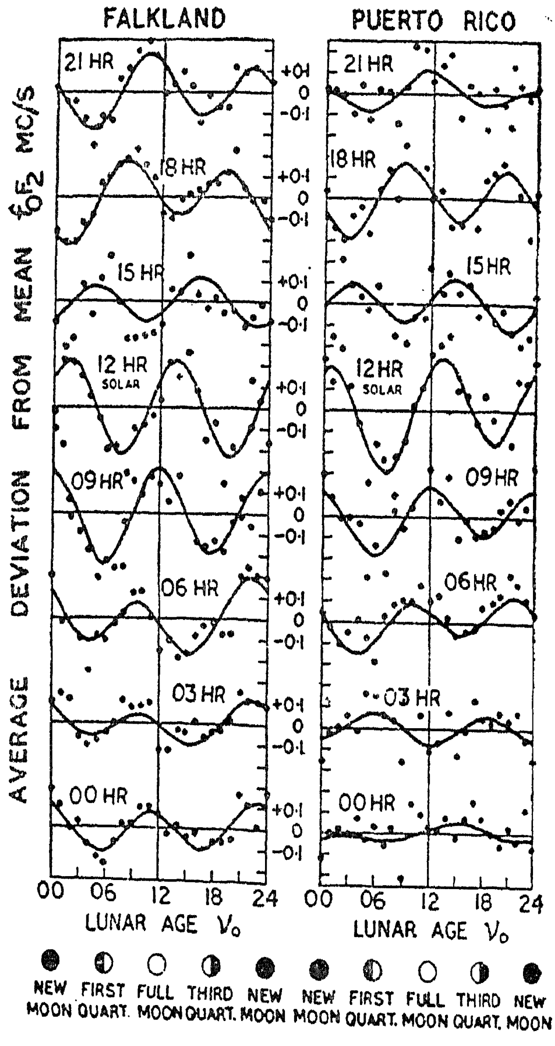

FIG. 4

FIG. 3. The variation with the lunar ages of the phases of the different harmonics of the lunar daily variations of f_0F_2 at Falkland and Puerto Rico for eight ages of the moon.

FIG. 4. The annual average variation of f_0F_2 at Falkland and Puerto Rico against lunar age (at Greenwich noon) for different solar hours.

The coefficients of annual average lunar monthly and semi-monthly waves in f_0F_2 with their probable errors at different solar hours are given in Table III for Falkland and Puerto Rico. The phases θ_1 and θ_2 are given in terms of local lunar time when the corresponding wave reaches the maximum positive deviation. The amplitudes whose values are less than three times the corresponding probable error are shown within brackets.

TABLE III

Coefficients of lunar monthly and semi-monthly oscillations in f_0F_2 at Puerto Rico and Falkland for the whole year. Phases θ_1 and θ_2 indicate lunar time of maximum positive deviation of the corresponding wave.

	Falkland						Puerto Rico					
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_4 l.hr.
00	4·3	0·017	(0·024)	2·3	0·105	1·3	4·2	0·024	(0·033)	8·6	(0·023)	8·8
03	4·0	0·017	(0·046)	3·1	0·078	5·2	4·0	0·022	(0·017)	0·9	0·067	8·7
06	4·3	0·022	0·072	6·8	0·136	8·4	3·2	0·018	(0·049)	12·5	0·107	7·8
09	6·1	0·029	(0·024)	16·2	0·212	9·3	6·1	0·024	(0·050)	15·6	0·138	8·7
12	7·1	0·035	(0·008)	5·8	0·229	10·3	7·6	0·033	(0·070)	17·9	0·232	10·4
15	6·2	0·026	(0·025)	0·6	0·104	10·4	8·3	0·034	(0·027)	3·9	0·113	11·5
18	5·1	0·025	(0·073)	5·5	0·152	10·2	7·3	0·037	(0·044)	4·0	0·152	8·5
21	4·6	0·020	(0·047)	7·7	0·143	10·6	4·4	0·027	(0·051)	7·7	(0·076)	8·8
All hour			0·029	4·9	0·108	10·1			0·004	10·3	0·092	9·43

It is seen that the amplitudes (r_1) of M_1 oscillations are not statistically significant for most of the hours at either of the stations and hence are not discussed further in the paper. The amplitude of M_2 oscillation at Falkland is statistically significant for all the hours both during day and night. The M_2 oscillations at Puerto Rico are significant for most of the daytime hours while during the night time hours they are not significant. The vectorial mean, *i.e.*, the lunar time variation of f_0F_2 averaged for all solar hours is 0·108 Mc/s at 10·1 lunar hour at Falkland and 0·092 Mc/s at 9·43 lunar hour at Puerto Rico. These values are in reasonable agreement with the coefficients of whole-lunation-L_2 variation deseribed earlier, indicating the consistency between the two methods of analyses.

IV. LUNAR DAILY VARIATION AT FIXED LUNAR AGES DURING DIFFERENT SEASONS

The lunar daily variations were computed separately for different seasons of the year, *viz.*, D-months consisting of November, December, January and February; E-months consisting of March, April, September and October; and J-months consisting of May, June, July and August.

The lunar daily variation curves for individual lunar ages were quite similar for Puerto Rico and Falkland during D- and E-months; while during the J-months insufficient correspondence between the lunar oscillations at the two places was noticed.

In Table IV are collected the first three coefficients of whole lunation average lunar daily oscillations in f_0F_2 at either of the stations during each of the seasons. It is seen that the amplitude of second harmonic is generally the most prominent mode of oscillation. At Puerto Rico the L_2 (f_0F_2) amplitude is 0·14 Mc/s during D-months, 0·13 Mc/s during E-months and only 0·04 Mc/s during J-months. Similarly, the L_2 (f_0F_2) amplitude at Falkland is 0·18, 0·09 and 0·03 Mc/s during D-, E- and J-months respectively. Thus it is seen that the lunar tides is about 4 to 6 times stronger in D- than during J-months at either of the stations even though these are situated in opposite hemisphere and have opposite local season during same months. Such an annual rather than the seasonal effect in the lunar tide has been already demonstrated by Rastogi (1964) for the midday values of f_0F_2.

The maximum positive deviation of f_0F_2 at Puerto Rico occurs at 8.3 l.hr. during D-months, at 9·1 l.hr. during E-months and at 11·3 l.hr. during J-months. Correspondingly at Falkland the maximum occurs at

9·5, 10·0 and 10·8 l.hr. during D-, E- and J-months respectively. The maximum of L_2 tide at Panama occurs at 9·7, 11·3 and 1·3 l.hr. during D-, E- and J-months; while at Buenos Aires corresponding times are 10·4, 10·8 and 12·1 l.hr. respectively (Rastogi, 1968 *b*). The L_2 tide in horizontal field H at Huancayo is shown to be maximum at 7·4, 8·3 and 8·7 l.hr. during D-, E- and J-months respectively (Rastogi, 1968 *a*). The seasonal variation of lunar tides in f_0F_2 and H at Huancayo have been shown to be extremely similar in character although remaining opposite in phase (Rastogi, 1963 *b*, 1965). The lunar daily as well as monthly tides in f_0F_2 at Huancayo are shown to be influenced by the lunar tides in the equatorial electrojet current (Rastogi, 1968 *a*). The seasonal shift in the lunar tides in f_0F_2 at Huancayo, and tropical and middle latitudes are remarkably similar. This indicates that the seasonal shifts in the phase of L_2 tide at most of the latitudes are due to corresponding shift in L_2 (H) and finally L_2 (f_0F_2) tide at the equator.

TABLE IV

The coefficients of whole lunation average lunar oscillation in f_0F_2 *at Puerto Rico and Falkland according to the equation* $L = A_n \sin(n\tau + \beta_n)$ *for different seasons of the year*

	A_1	β_1	A_2	β_2	A_3	β_3
	Mc/s	°	Mc/s	°	Mc/s	°
D-Months						
Puerto Rico ..	0·032	119	0·139	200	0·016	166
Falkland ..	0·007	319	0·178	165	0·001	132
E-Months						
Puerto Rico ..	0·026	111	0·126	173	0·008	169
Falkland ..	0·036	55	0·087	150	0·025	54
J-Months						
Puerto Rico ..	0·063	287	0·042	112	0·117	233
Falkland ..	0·003	79	0·034	127	0·010	25

V. Lunar Monthly Oscillation at Fixed Solar Hours During Different Seasons

The lunar monthly and semi-monthly oscillations in f_0F_2 at each hour of the day for the three seasons were computed for the stations Puerto

Rico and Falkland. For brevity only the coefficients of M_2 oscillations at 00, 03, 06······21 solar hours during different seasons are given in Tables V (*a*) and V (*b*) for Puerto Rico and Falkland respectively. The determinations which are not statistically significant are within brackets. The solar daily variations of the amplitude of lunar semi-monthly oscillation in f_0F_2 during each of the seasons have been shown in Fig. 5 separately for the northern and the southern American stations. The coefficients (both r_2 and θ_2) for each hour of each season for Puerto Rico and

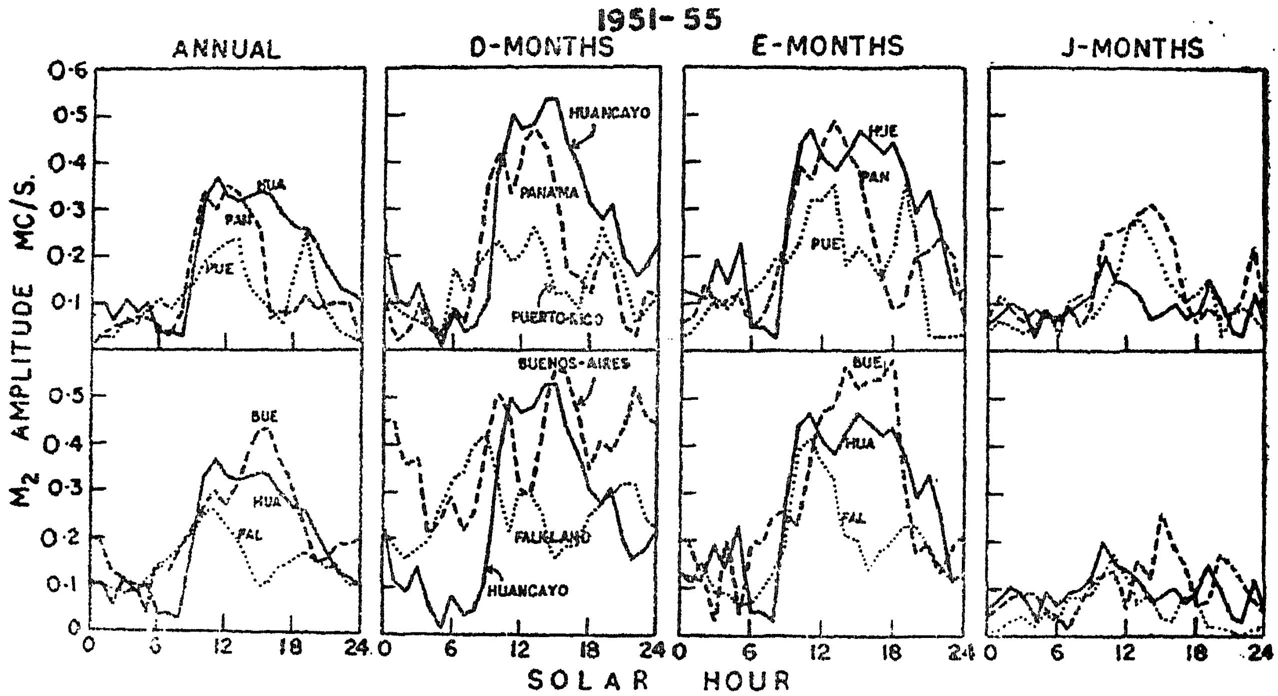

FIG. 5. The variations of lunar semi-monthly tidal amplitude in f_0F_2 at Falkland, Puerto Rico and Huancayo and at Puerto Rico, Panama and Huancayo, with the time of the day, for each of the seasons.

Falkland are plotted in harmonic dials of lunar age in Fig. 6, and those of lunar time in Fig. 7. The all-hour vector mean coefficients are also given in each harmonic dial. Seeing the diagrams in Fig. 5 it is distinct that the lunar semi-monthly oscillations are much stronger during the D- than during the J-months irrespective of the station.

At Puerto Rico the coefficients for D- and E- months are statistically significant for most of the solar hours except few hours around midnight, while during J-months, the amplitudes are significant only for 12–14 solar hours. The amplitude during D-months is 0·26 Mc/s at noon, slightly smaller during 14–16 hours and again another maximum of 0·26 Mc/s occurs around 18 hour. Similarly, during E-months largest amplitudes of about 0·35 Mc/s are found at 13 and at 19 solar hours with low amplitudes around 16–17 solar hours. During J-months the midday maximum of 0·28

TABLE V (*a*)

The amplitudes and the phases (in lunar time τ of maximum positive deviation) of lunar semi-monthly oscillation in f_0F_2 *at Puerto Rico during different seasons*

	D-Months			E-Months			J-Months		
Time	Ampl. Mc/s	Probable error Mc/s	Phase in l.hr.	Ampl. Mc/s	Probable error Mc/s	Phase in l.hr.	Ampl. Mc/s	Probable error Mc/s	Phase in l.hr.
00	0·115	0·032	9·3	(0·027)	0·037	5·9	(0·043)	0·052	2·7
03	(0·053)	0·039	8·7	0·107	0·032	8·7	(0·039)	0·042	8·8
06	0·124	0·027	7·4	0·128	0·032	8·1	(0·030)	0·032	8·6
09	0·232	0·043	7·6	0·194	0·040	9·3	(0·071)	0·041	9·9
12	0·255	0·052	9·2	0·323	0·057	10·3	0·259	0·062	11·6
15	(0·121)	0·050	10·1	0·224	0·061	10·7	(0·183)	0·066	2·0
18	0·259	0·052	8·8	0·212	0·066	9·0	(0·121)	0·071	6·8
21	0·146	0·033	8·1	(0·026)	0·046	10·6	(0·078)	0·056	9·3
All hour average.	0·136		8·70	0·140		9·40	0·044		11·7

TABLE V (*b*)

The amplitudes and phases (in lunar time τ of maximum positive deviation) of lunar semi-monthly oscillation in f_0F_2 at Falkland during different seasons

Time	D-Months			E-Months			J-Months		
	Ampl. Mc/s	Probable error Mc/s	Phase in l.hr.	Ampl. Mc/s	Probable error Mc/s	Phase in l.hr.	Ampl. Mc/s	Probable error Mc/s	Phase in l.hr.
00	0·217	0·036	0·6	0·132	0·032	2·6	(0·014)	0·014	0.3
03	0·176	0·041	5·2	0·087	0·029	4·8	(0·039)	0·013	9·9
06	0·326	0·049	8·5	(0·073)	0·039	8·4	(0·034)	0·023	9·6
09	0·421	0·060	9·5	0·204	0·054	9·1	(0·090)	0·36	10·2
12	0·299	0·063	9·7	0·365	0·067	10·1	(0·129)	0·049	0·7
15	0·160	0·048	10·7	0·201	0·049	10·4	(0·042)	0·038	6·8
18	0·245	0·048	9·5	0·201	0·047	10·3	(0·076)	0·033	12·4
21	0·316	0·041	9·9	0·193	0·042	12·0	(0·010)	0·018	6·0
All hour	0·184		9·8	0·112		10·5	0·030		11·5

Mc/s is seen and the evening peak is not distinct. The two maxima at about 13 and 19 hours are clearly seen in the annual average curve. Comparing the results at Panama one finds that the annual average curve indicates only the prominent midday peak and the evening peak is very feeble. During D-months the evening peak is quite distinct though lower than the midday peak. During E-months too there is a major midday peak and a smaller peak around 21 hour. Thus it is concluded that at northern tropical and mid-latitude stations the lunar semi-monthly tide has two maxima one for the midday and another for the evening hours.

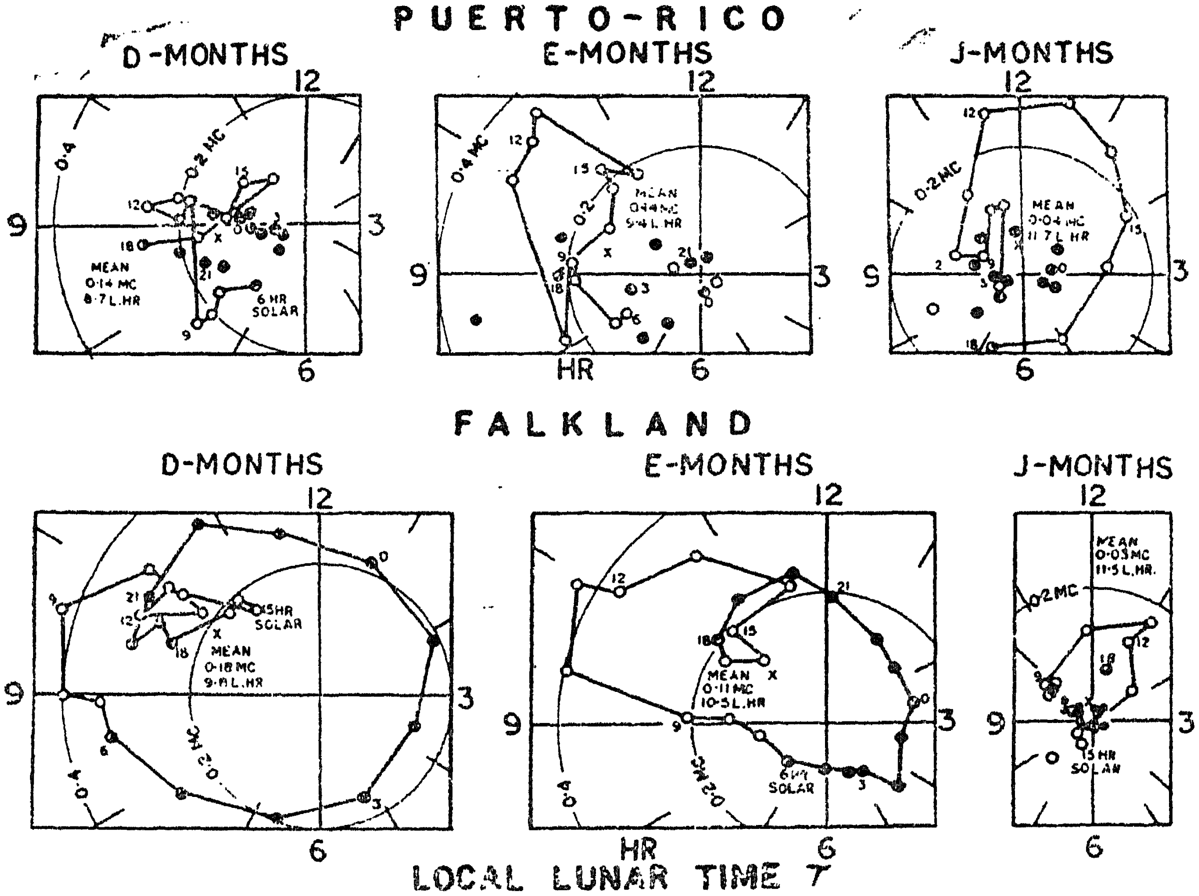

FIG. 6. Coefficients of lunar semi-monthly oscillation in f_0F_2 at Puerto Rico and Falkland at fixed hours for different seasons of the year plotted on harmonic dials of lunar age.

At Falkland the annual average curve shows two maxima similar to that at Puerto Rico except that the evening maximum is rather flat, and the coefficients during D-months are significant for any hour of the day or night. During E-months the amplitudes are significant for all solar hours except around early morning hours between 04 and 08 solar hours. During J-months the amplitude is statistically significant for 11 solar hours only. During D-months M_2 amplitude shows two maxima of 0·42 Mc/s at 09 solar hour and of 0·32 Mc/s at 21–22 solar hours. During E-months the first maximum of M_2 amplitude of 0·42 Mc/s occurs at 11 solar hours and another of 0·23 Mc/s at 19–20 solar hour. Similarly during J-months there are two maxima at 11 and 18 hours.

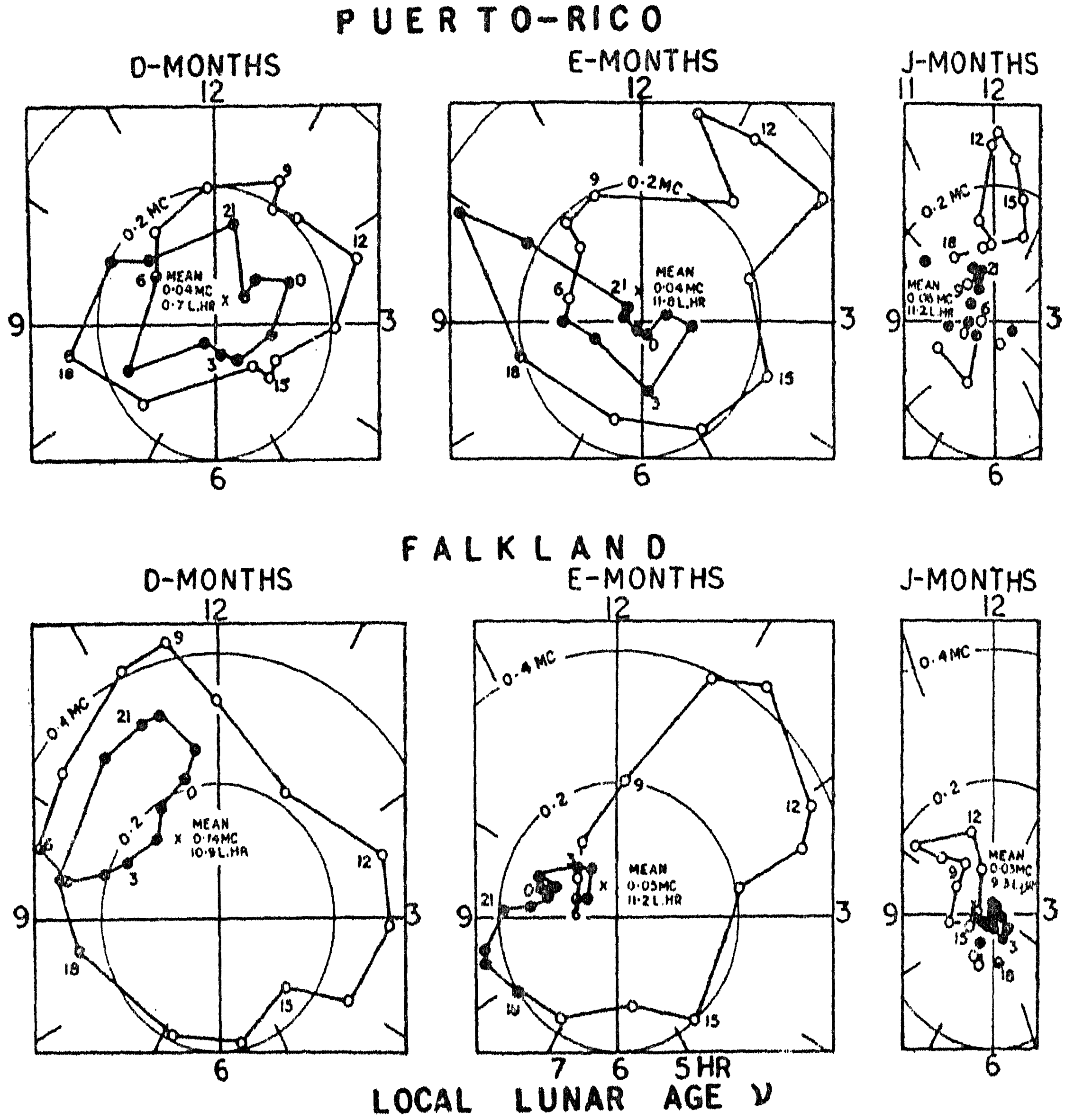

FIG. 7. Coefficients of lunar semi-monthly oscillation in f_0F_2 at Puerto Rico and Falkland at fixed hours for different seasons of the year plotted on harmonic dials of lunar time.

The M_2 amplitude at tropical latitude station is shown to be maximum in the afternoon around 15 solar hour. At higher latitude there are two maxima of M_2 tide one around noon and another around evening hours.

Referring to the lunar age (ν) harmonic dials for D-months at Puerto Rico, it is seen that the points form two loops around the origin giving a very low mean value of 0·04 Mc/s while the same coefficients plotted on lunar time dial group within the sector between 07–10 l.hr. giving the mean value of 0·14 Mc/s. Similarly during E-months the all-hour mean is 0·14 Mc/s on lunar time dial and only 0·04 Mc/s on lunar age dial. During J-months however the points form a loop around the origin on the lunar time dial giving a low mean value of 0·04 Mc/s while on lunar age dial most of the points lie between the 11–01 l.hr. sector giving a mean value of 0·08 Mc/s. This suggests that during D-months the M_2 tide is controlled by lunar time while during J-months it has greater control of lunar age.

Referring to the harmonic dials for Falkland for D-months, it is seen that on the lunar age dial the points for the night hours group within 10–11 l.hr. sector while on the lunar time dial points for the daytime hours group around 10 l.hr. The all hour mean is slightly larger on lunar time than on lunar age dial. During E-months also, grouping of daytime coefficients on lunar time dial and of the night time coefficients on lunar age dial is seen. During J-months no significant differences in the lunar age and lunar time dials is clearly seen due to small amplitudes of the M_2 tides. Thus it is found that during D- and E-months the M_2 tide during the day time is controlled by the lunar time and during the night time by the lunar age.

Summary

Lunar semi-diurnal (L_2) or lunar semi-monthly (M_2) tides in f_0F_2 at Puerto Rico and Falkland are shown to the maximum during D-months (November to February) and least during J-months (May to August). The lunar daily variations of f_0F_2 at different lunar ages conform to the Chapman's Phase law derived from the atmospheric dynamo theory for geomagnetism. The M_2 tide at different solar hours indicate two maxima around 12 and 21 solar hours. At Puerto Rico the M_2 tide is controlled by lunar time during D- and E-months and by lunar age during J-months. At Falkland, during D- and E-months, the M_2 tide for daytime hours is controlled by lunar time while that for the night time hours is controlled by the lunar age. Thus the tidal movements in the F_2 layer have control depending on the absolute position of the moon as well as on the relative positions of the sun and moon, the relative importance of the two changes with the season or between day and night hours.

Acknowledgements

The author is thankful to Professor K. R. Ramanathan and Professor S. Chapman for encouragements and suggestions during the course of work. Thanks are due to the Prediction Services of CRPL (now ITSA), Boulder, U.S.A., for providing the data to the author and to Mrs. Nila Deshpande for computational assistance.

REFERENCES

Chapman, S. .. *Phil. Trans. Roy. Soc.*, 1919, **218 A**, 1.

Rastogi, R. G. .. *Proc. Ind. Acad. Sci.*, 1963 *a*, **58**, 38.

——— .. *Nature*, 1963 *b*, **200**, 1083.

——— .. *J. Inst. Tele. Engrs.*, 1964, **10**, 394.

——— .. *Z. Geophysik.*, 1965, **31**, 27.

——— and Alurkar, S. K. .. *Proc. Ind. Acad. Sci.*, 1966, **63**, 75.

Rastogi, R. G. .. *J. Atmosph. Terres. Phys.*, 1968 *a*, **30**, 453.

——— .. *Proc. Ind. Acad. Sci.*, 1968 *b*, **68**, 23.