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Annual variation of L(H) and S(H) at Alibag

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RESUME – *On calcule pour chaque mois de l'année les variations journalières solaires et lunaires de la composante horizontale du champ magnetique terrestre à Alibag, et l'on discute les changements des amplitudes et des phases en cours de l'année. De brusques variations des phases des deux premiers harmoniques de la variation solaire sont observées de septembre à novembre, même lorsque le niveau de perturbation croît ; ceci confirme leur relation soit aux forces atmosphériques de marée soit au système de vent des courants. La variation saisonnière de l'amplitude de la marée lunaire est opposée à celle de la marée solaire, la première étant la plus grande pendant les mois d'hiver. Le sens de rotation du vecteur des deux premiers harmoniques de la marée lunaire au cours de l'année est le même que celui observé en X à Sodankylä, une station de haute latitude, bien que la variation saisonnière de l'amplitude soit de sens opposé aux deux stations. La marée lunaire partielle présente une amplitude plus grande à Alibag au mois de juin.*

ABSTRACT. – *Solar and lunar (phase law and partial) diurnal variations in the horizontal component of the earth's magnetic field at Alibag have been computed for each of the calendar months of the year. Annual progression of these along with ranges, total daily movements and wave parameters are discussed. Sharp changes in the phase angles of the first two harmonics of solar diurnal variation from September to November are noticed even with increased disturbance, confirming their association with changes either in the atmospheric tidal forces or in the wind system of the current. Seasonal variation of the lunar phase law tide appears to be opposite to that of the solar tide, amplitudes of the lunar tide being higher in the four winter months than in the other months. The sense of rotation of the dial vectors of the first two harmonics of the lunar tide in the course of the year is the same as that noticed in 'X' at Sodankyla, a high latitude station, even though the seasonal variation of the tide is opposite at the two stations. Amplitudes of larger magnitude are observed in the lunar partial tide at Alibag in the month of June.*

Introduction

Seasonal change of the lunar daily variation, $L(H)$, in the geomagnetic horizontal intensity, H, at Alibag (Geographic Lat. N 18°38′, Long. E 72°52′), a low latitude station outside the influence of equatorial electrojet was found to be opposite to that of the solar daily variation $S(H)$, when the sub-division of the data was made by grouping the calendar months into the three Lloyd's seasons. $L(H)$ at this station was observed to attain maximum and minimum magnitudes in the northern winter and summer seasons respectively (Raja Rao, 1962b ; Rao, 1972a) which was rather unexpected for any of the stations in the northern hemisphere. For precise understanding of the annual progression, a computation of $L(H)$ for each of the calendar months has been carried out. The results of such an analysis along with the partial tide and $S(H)$ are presented and discussed in this communication.

Data and analysis

In the statistical theory for the estimation of lunar daily variations, the multiplication of the time dependent factors representing lunar semidiurnal tidal movements with factors representing the time variation of the electrical conductivity of the ionosphere, restricted to the first two harmonics, were considered by Chapman and Miller (1940). The important terms whose phase angle in the course of synodic month decreases by 4π relative to solar time are well-known terms of Chapman phase-law of geomagnetic lunar variations. Schneider (1963) showed that inclusion of the third and fourth harmonics to the expression for ionospheric electrical conductivity and its multiplication with tidal movement give extra terms whose phase angle relative to solar time increases by 4π per synodic month. These additional terms are designated by him as partial tides. Winch (1970) detailed a numerical procedure for their estimation. Using long series of hourly H for Alibag for the period 1932 to 1970 grouped into twelve calendar months of the year, amplitudes and phases of the first four harmonics of $S(H)$ and lunar phase law terms, $L(H)$, along with their probable errors, p.e., have been computed as outlined by Rao (1972a), which closely follows the statistical procedure of Chapman and Miller (1940). Lunar partial tide terms are calculated following the numerical procedure of Winch (1970). The lunar phase law and partial tides along with the number of days in each of the monthly groups are given in Table 1. Similar results for $S(H)$ are given in Table 2. First two harmonics of lunar phase law tides for the twelve months, plotted in a harmonic dial, are presented in Figure 1. Probable error circles are not drawn at the end of each dial vector to avoid cluttering.

Annual progressions of lunar and solar ranges are derived from the computed harmonic components. The range of solar daily variation can be estimated from a 24-hr series of hourly values or from synthesized harmonic components. Similar estimation of lunar range is more difficult to define, since the pattern of lunar variation does not repeat from day to day. For uniformity, lunar range $R(L)$ and solar range $R(S)$ are computed from the equations,

$$R(L) = 2 \sum_{n=1}^{4} L_n ,$$

and

$$R(S) = 2 \sum_{n=1}^{4} S_n ,$$

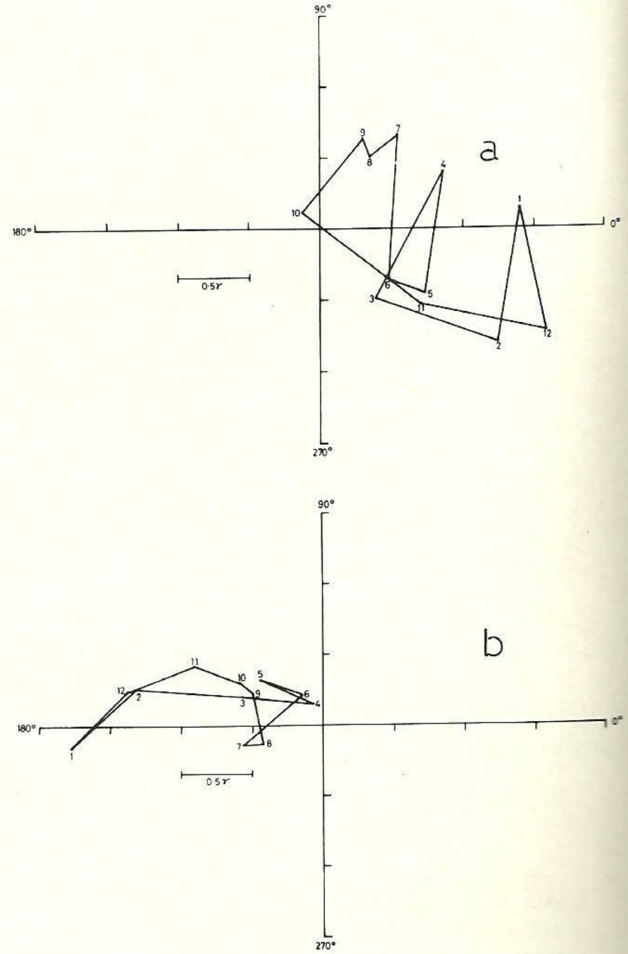

Fig. 1

Diagrams showing monthly points numbered 1 (January) to 12 (December) (a) for the first harmonic and (b) for the second harmonic of $L(H)$.

where L_n and S_n are respectively the lunar phase law and solar amplitudes of nth harmonic (Rao, 1972b). The solar and lunar 24-hourly values for each month are derived by synthesizing the respective amplitudes and phases. Using these hourly values, the total daily movements, $TDM(L)$ in case of $L(H)$ and $TDM(S)$ in case of $S(H)$, which are the sums of the hour to hour differences between successive values in the 24-hourly sequences taken without regard to sign, are obtained. The wave-parameter or waviness, W, is defined as the ratio of total daily movement to twice the range (Gupta, 1972), the range, r, here being the differences between the maximum and minimum hourly values. Accordingly, the ranges $r(L)$ and $r(S)$ are determined from the

Table 1

Lunar phase law and partial tides in H at Alibag

(Amplitude (A) and probable error (E) in units of 0.01γ and phase (P) in degrees)

Month	No. days	1st harmonic						2nd harmonic						3rd harmonic						4th harmonic					
		Phase law			partial			phase law			partial			phase law			partial			phase law			partial		
		A	E	P	A	E	P	A	E	P	A	E	P	A	E	P	A	E	P	A	E	P	A	E	P
January	1203	139	32	6	61	26	248	179	21	184	26	22	192	76	8	9	8	8	257	25	6	178	15	7	327
February	1100	148	43	327	33	41	247	133	17	169	7	17	97	53	11	1	12	12	94	9	6	191	6	5	135
March	1204	63	39	310	89	38	228	60	21	160	35	22	72	37	15	15	22	17	224	15	10	312	10	13	233
April	1167	96	32	24	36	41	137	16	18	114	13	20	41	18	12	11	2	13	280	3	8	211	2	9	229
May	1203	86	25	329	40	29	116	53	19	143	25	21	313	27	11	355	6	11	62	7	5	160	8	6	127
June	1168	60	42	323	93	46	113	25	32	125	83	36	253	29	23	138	53	30	52	45	22	277	33	34	142
July	1200	86	24	50	52	26	117	58	16	195	14	16	7	26	11	358	5	12	319	20	7	14	25	6	115
August	1202	61	21	55	51	24	171	44	14	197	28	13	320	27	7	358	16	7	65	7	5	279	6	6	332
September	1170	70	46	64	89	40	92	53	21	156	8	20	266	29	12	347	33	12	274	14	7	142	12	8	12
October	1205	17	28	136	9	30	236	66	20	151	37	23	226	31	14	6	20	17	45	23	11	158	5	13	52
November	1167	89	39	322	50	35	270	99	19	155	11	17	170	40	8	3	16	9	171	9	6	83	7	7	271
December	1206	174	35	335	82	28	355	139	16	170	68	15	233	64	9	353	24	8	33	20	6	187	19	7	257

Table 2

Solar tides in H at Alibag

(Amplitude (A) and probable error (E) in units of $1\ \gamma$ and phase (P) in degrees)

Month	No. days	1st harmonic			2nd harmonic			3rd harmonic			4th harmonic		
		A	E	P	A	E	P	A	E	P	A	E	P
January	1203	16.8	0.30	284	06.3	0.20	099	02.5	0.07	305	01.1	0.06	115
February	1100	19.4	0.39	284	08.1	0.16	100	03.4	0.10	302	01.2	0.05	110
March	1204	22.6	0.35	285	10.9	0.20	101	05.0	0.15	308	01.5	0.11	138
April	1167	23.0	0.29	281	11.6	0.18	101	04.8	0.12	313	02.0	0.08	174
May	1203	21.6	0.23	284	10.6	0.18	105	03.2	0.10	309	00.9	0.05	176
June	1168	21.5	0.38	283	10.8	0.30	103	02.5	0.22	301	00.6	0.21	215
July	1200	21.2	0.22	283	10.8	0.15	100	02.8	0.10	288	00.3	0.07	200
August	1202	18.9	0.19	281	09.8	0.13	092	03.2	0.06	291	00.8	0.05	156
September	1170	16.8	0.42	283	09.1	0.20	085	04.7	0.12	295	02.0	0.07	147
October	1205	20.7	0.25	289	10.0	0.19	100	05.1	0.13	309	02.0	0.11	141
November	1167	20.3	0.36	293	08.8	0.18	114	03.5	0.08	334	01.0	0.06	155
December	1206	17.7	0.32	290	06.4	0.15	108	02.5	0.09	325	00.8	0.07	140

synthesized values and $W(L)$ and $W(S)$, the wave parameters of $L(H)$ and $S(H)$ respectively are computed. These quantities, derived for each of the calendar months, are listed in Table 3.

Results and discussion

(i) *Solar diurnal variation* $S(H)$: All the amplitudes of $S(H)$ are well determined according to the criterion for statistical significance (Rao, 1972a). The amplitudes of the first and second harmonic components show, in general, equinoctial maxima and winter minima. Amplitudes during the four summer months are consistent and are higher than the amplitudes of winter months. The annual variation of $Sq(H)$ at Alibag, particularly changes of the phases of the first two harmonics during the later half of the year, has been discussed in detail by Yacob and Rao (1966). Variations in the phase angles of the first and second harmonics of $S(H)$ given in Table 2 are very similar to those of $Sq(H)$, even though the analysis here is based on the observations of all days. This result further confirms the earlier finding of Yacob and Rao (1966) that changes in the phase angles of the first two harmonics of solar diurnal variation are not associated with the ionization of the layer in which the currents flow but arise from changes in the atmospheric tidal forces or in the wind system of the current.

The solar range and the total daily movement, as expected, are found to be maximum and minimum during equinoctial and winter months respectively (Table 3). However, the wave parameter shows little variation from month to month, with the value around unity, in the course of the year.

(ii) *Lunar (phase-law) diurnal variation* $L(H)$: Compared to the solar terms, amplitudes of $L(H)$ are not so well determined in many cases by the criterion for significance (Table 1). Amplitude of the first harmonic shows winter maximum and equinoctial minimum which is contrary to that observed in the annual variation of the same harmonic of $S(H)$. Amplitude of this harmonic has its highest magnitude in December and lowest in October. No significance can be attached to the amplitude and phase of the harmonic in October month as the magnitude of p.e. is very large. The progression of the phase angle in the course of the year is rather random and does not show any systematic variation. There are, however, two sharp changes in the phase angles, one from June to July and the other from September to November. Amplitudes of the second harmonic are also higher in winter months and comparatively lower but significant in summer months with the exception of June. During the equinoctial months, the amplitudes are comparable with those of summer months. The phase angle of the second harmonic does not undergo variability in its annual progression like the phase angle

Table 3

Annual Variation of Ranges, Total Daily Movement and Wave Parameter

Month	SOLAR				LUNAR			
	$R(S)$ γ	$r(S)$ γ	$TDM(S)$ γ	$W(S)$	$R(L)$ γ	$r(L)$ γ	$TDM(L)$ γ	$W(L)$
January	53.4	40.0	78.97	0.99	8.38	6.67	14.46	1.08
February	64.2	46.9	92.13	0.98	6.86	5.14	10.52	1.02
March	80.0	57.3	112.79	0.98	3.50	2.28	6.15	1.35
April	82.8	57.8	118.25	1.02	2.66	2.01	3.76	0.94
May	72.6	51.9	103.28	0.99	3.46	2.51	4.91	0.98
June	70.8	50.7	97.89	0.96	3.18	2.52	7.40	1.47
July	70.2	49.9	99.31	0.99	3.80	2.40	6.44	1.34
August	65.4	46.4	90.96	0.98	2.78	1.83	4.68	1.28
September	65.2	45.2	94.37	1.04	3.32	2.35	5.79	1.23
October	75.6	54.7	107.45	0.98	2.74	1.88	6.37	1.69
November	67.2	50.0	97.07	0.97	4.74	3.52	8.25	1.17
December	54.8	42.2	82.76	0.98	7.94	5.99	12.10	1.01

of the first harmonic. However, there is a suggestion that the times of maxima shift by about an *hour in* late summer months of July and August compared to the equinoctial months, September and October. Leaton et al. (1962) have also obtained random variations of large magnitude from month to month of the phase angle of the first harmonic of $L(H)$ as compared with the smooth variation of the phase angle of the second harmonic at Abinger, a high latitude station in the northern hemisphere. Gupta (1972) has computed the solar and lunar daily geomagnetic variations for Sodankylä, another high latitude station in the northern hemisphere, for the period 1914-66 and discussed their annual progression. The diagrams, of the first two harmonics of $'X'$ given in his Figure 4*L*, are compared with those of $L(H)$ in Figure 1. Upto the 7th month the rotation is clockwise at both the stations and anticlockwise from then onwards. However, the vector of the second harmonic of $L(H)$ for May does not fit in the general rotational trend. It is surprising to note that the sense of rotation of the dial points are almost same at the two stations which are widely separated in latitude, even though the seasonal variation of the tide is opposite at the two stations.

While the seasonal variations in lunar components at Honolulu and San Juan are of the type expected for northern hemispheric stations (Raja Rao, 1962a ; Sharma and Rastogi, 1970), the seasonal variation observed here in amplitude of first two harmonics of $L(H)$ are opposite to that normally expected for a station located in the northern hemisphere. Onwumechilli and Alexander (1959) noticed seasonal variation in $L(H)$ at Ibadan

$$\left(\text{Geograph.} \begin{matrix}\text{Lat.} & N\ 07°26'\\ \text{Long.} & E\ 03°53'\end{matrix} \quad \text{Geomag.} \begin{matrix}\text{Lat.} & 10°.6\\ \text{Long.} & 74°.6\end{matrix}\right)$$

similar to that of Alibag. Showing closer association of lunar components with geomagnetic or magnetic latitude, than geographic latitude, Raja Rao (1961, 1962a, b) explained the similarity of seasonal variations at Kodaikanal and Alibag with those of Huancayo and Ibadan by envisaging asymmetry of ionospheric currents responsible for lunar geomagnetic tides with respect to the geomagnetic equator. The direction of equivalent current responsible for lunar variation *can be obtained* by studying the vectograms in horizontal plane using hourly *inequalities of* $L(H)$ and $L(D)$. An analysis using Alibag data of Declination is in progress which will throw more light about the extension of southern hemispheric current system towards north of the geomagnetic equator.

The lunar range is systematically higher in the four winter months with the largest magnitude registered in January. In the twelve months, the ratio of maximum to minimum solar range is 1.6 and in the case of lunar range it is 3.1 indicating a strong annual variation of range in respect of lunar terms. Annual variation of total daily movement, $TDM(L)$, is the same as that of lunar range. The wave parameter is found to have larger variations from 0.94 in March to 1.69 in October compared to the very smooth variation of the solar wave parameter. At Sodankylä, Gupta (1972) obtained for $'X'$ higher lunar wave parameters over the solar wave parameters in all seasons. His lunar wave parameters, however, were almost equal in all seasons.

(iii) *Lunar partial tides* : Many of the harmonics of lunar partial tides are statistically insignificant. The amplitudes in the month of June are the highest and are larger than even those of the lunar phase law tides in that month which may be ascribed to enhanced and complex nature of the ionospheric conductivity at this time of the year, as the solar zenith angle is minimum at local noon in the vicinity of the latitude of Alibag. This enhanced conductivity may justify, to some extent, the inclusion of additional terms in the representation of ionospheric conductivity whose time variations coupled with the atmospheric tide are responsible for the lunar partial tides.

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