SOME PROBLEMS OF GEOMAGNETIC SOLAR AND LUNAR DAILY VARIATIONS IN LOW LATITUDES

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CONTENTS

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Synopsis

The subject of the present dissertation is the determination and discussion of the daily variations of the geomagnetic field at Alibag, near Bombay (geographic : latitude 18°38'N, longitude 72°52'E; geomagnetic : latitude 9°.5N, longitude 143°.6). The dominant variations which can be represented as harmonics of solar day are attributed to the magnetic effects of the electric currents induced in the upper atmosphere, made conductive by the Sun's ionising radiation (and hence called ionosphere), by the tidal movements of the ionised layers across the earth's magnetic field under the influence of the thermal and the gravitational actions of the Sun. The mechanism is analogous to a self-exciting dynamo and therefore this formulation is called the dynamo theory of diurnal variations. The Moon by its nature can exert only gravitational influence and, being nearest to the Earth, produces preceptible tides in the ocean waters and in the atmosphere. These lunar tidal movements in the ionosphere also constitute a dynamo, the effect of which on the geomagnetic field is obviously related to lunar time and is of relatively smaller magnitude compared to the solar influence. Lunar gravitational tides, mainly lunar semidiurnal in period (M_2), act in conjunction with the electrical state of the atmosphere which is a function of solar time. Solar and lunar days being incommensurable, the geomagnetic lunar variations are not purely lunar semidiurnal

COLABA BOMBAY

but contain other harmonics whose phases are, in general, dependent on both solar and lunar times and are therefore called luni-solar variations. The geomagnetic solar and lunar variations are conventionally represented by the letters S and L respectively. Studies of S and L in relation to different parameters viz., season, relative sunspot number and magnetic activity, that affect the ionospheric conductivity in preference to the air motions yield valuable information enabling one to have a precise understanding of the relative importance of the tidal oscillations and conductivity. Although studies of this nature appear simple, their execution has proved remarkably difficult. The results of such studies have so far been conflicting and inconclusive which implies that the simple dynamo theory may not be sufficient to explain all the variations adequately and sources other than the ionosphere have also to be considered for their contributions to the daily variation.

Recent advances in the knowledge of the properties of solar wind and magnetosphere have suggested that contributions to the daily variation from magnetospheric currents, field aligned currents, quiet-time and partial ring currents are also to be taken into account. Declinational (O_1) and elliptic (N_2) components of the Moon's orbital motion round the Earth are also found to make detectable contributions to the lunar gravitational tide. Determination of the variation associated with N_2, the lunar distance constituent, enables one to test whether L effects are in direct proportion to the gravitational pull of the Moon or not. O_1 component has the same frequency as the seasonal modulation of the first harmonic of L associated with M_2, $L(M_2)$, and thus it is likely that the estimation of the $L(M_2)$ may be contaminated by the O_1 associated effects which are to be removed for a proper estimation of $L(M_2)$. A contribution from the oceanic dynamo, resulting from the tidal movements of the conducting waters of the sea across the geomagnetic field, complicates the lunar variations. It is, therefore, necessary to take all these contributions into account while attempting a study of the morphology of the ionospheric dynamo variations. Further, L is determined statistically by removing the effect of S and since the magnitude of L is very much smaller than that of S and of the irregular effects of magnetic disturbance, any attempt to a reliable determination of L demands the analysis of a large amount of data. To fulfil this requirement, comparatively long and continuous series of homogeneous magnetic observations at Alibag has been taken advantage of in this study.

Pioneering studies of S and L with the data from the Colaba Magnetic Observatory, Bombay, predecessor to the Alibag Magnetic Observatory were made by Dr. Charles Chambers and Dr. N.A.F. Moos in the last part of the 19th and early years of this century, and were discussed in the light of the then very imperfect knowledge of the ionosphere and the tidal and thermal oscillations of the atmosphere. Later several workers analysed Alibag data, particularly of the horizontal component, for limited periods to serve special purposes. Their results will serve as a guide to and independent check on the results of the present study.

The data used in the analysis consist of mean hourly values of Horizontal intensity, H, Declination, D, and Vertical intensity, Z, of the Earth's magnetic field at Alibag for the period 1932 to 1972. The computations have been carried out on CDC-3600/160-A computer system of the Tata Institute of Fundamental Research, Bombay.

The study has been separated into eight Chapters. The Chapterwise description is as follows:

In the first Chapter the relative merits and demerits of various methods used for the estimation of solar and lunar daily variations, S and L respectively, are briefly reviewed. The Chapman-Miller method, generalised by Winch, has been chosen for the present analysis because of its many advantages over the other methods. The method permits the determination of longer period tide and partial tide in addition to the wellknown Chapman's phase law tide associated with the atmospheric lunar tides M_2 and O_1. Harmonics of the solar tide are also obtained as a by-product. While determining L, the effect of non-cyclic variation and of S are completely removed. In addition, the method allows greater freedom in the selection of data. A brief account of the lunar phase law and partial tides is given and the numerical procedure of the method is detailed. A listing of the Fortran IV program incorporating the various steps is appended.

In the second Chapter, the first four harmonics of solar tide and lunar phase law and partial tides in the three seasons and the year are computed and their variations with seasons are discussed in detail. Considering all the elements, seasonal changes of S at Alibag are of the type expected for any northern hemispheric station i.e. amplitudes are maximum during summer and minimum in winter. The solar daily variation in D and Z during winter are complex due to the northward incursion of southern current system in the early morning and late evening. Seasonal changes of L are radically different. Amplitudes at their maximum are largest in winter and least in equinox. The daily variation of L in D shows almost a complete reversal of phase between winter and summer. From the study of seasonal day-graph of H, D and Z coupled with vectograms of L(H) in horizontal plane, it is conclusively proved that lunar variations at Alibag during winter months are under the control of the southern current system. Seasonal changes of partial terms are not consistent in the three elements. The results further indicate that though the seasonal movement of the current vortices associated with S and L are in the same direction, the extent of seasonal movement for L is greater than that for S.

In the third Chapter, the solar cycle influence on S and L is studied by first examining the harmonics, day-graphs and vectograms for varied epochs of solar activity derived by analysing the data for four sunspot groups classified according to the annual sunspot numbers, R_z. Both S and L exhibit definite positive association with sunspot number but changes in L are not as systematic and sharp as those for S. Next, the association is numerically estimated by computing the Wolf ratio, M, derived from the coefficient of straight line fitting R_z and ranges of S and L in different elements for varying epochs of solar activity. The Wolf ratio shows considerable variation from element to element and from one season to another. The overall enhancement of S, as measured by the mean Wolf ratio for the three elements, is about 1.7 times the enhancement of L. The mean Wolf ratio for L at Alibag is close to the value of Wolf ratio for E-region conductivity, suggesting that solar cycle modulation of L at Alibag results primarily from the corresponding variation in the E-region conductivity. The source for the excess enhancement of S over the effects caused by the increase in ionospheric conductivity are discussed in terms of solar cycle modulation of the various other contributing sources, e.g. thermal tides, magnetospheric compression and partial ring current field etc. The amplitudes of the harmonics of S do not increase in the same proportion and the time of maximum of the first harmonic shifts to the later part of the day with increasing R_z. This could be the effect of increasing contamination of S by geomagnetic disturbances or is the result of skewing of the latitude axes of the Sq current system. The behaviour of lunar partial tide to sunspot is not significantly different from that of phase law tide. Results of the analysis are compared with those available for other stations.

In Chapter four, the association of solar and lunar daily variations, S and L respectively, with the degree of magnetic activity in each of the seasons and the year is investigated by direct comparison and by computing Wolf ratios using index Ap as a measure of magnetic activity. While the amplitude of solar harmonics are found to show an increasing trend with increasing magnetic activity, the lunar harmonics, in general, show a negative dependence on magnetic activity. The enhancement of S appears to arise from the superposition, on the dynamo field, of an additional field due to asymmetric ring current. Seasonal differences in the behaviour of S to magnetic activity are ascribed to the changing position of symmetric and partial ring current with respect to the latitude of Alibag. Comparison of the results of L reported earlier for some stations and those of Alibag suggests that there is a general decrease of amplitude with increase in magnetic activity at stations where the lunar time of maximum is around the time of magnetospheric expansion for the lunar tide and an increase in amplitude for stations where lunar time of maximum is around the magnetospheric contraction. No definite trend with increasing Ap is discernible in the amplitudes or phases of lunar partial terms.

In the fifth Chapter, long-term variability of S and L, and its association with solar and magnetic activity, in the three geomagnetic elements, H, D and Z, at Alibag is studied by an analysis of the data separately for each year during the period 1932-1972. For S, changes in amplitude are found to be more important than changes in phase, whereas, for lunar daily variation, phase changes are of significance. Prominent solar cycle influence is observed in solar as well as in lunar ranges; the observed influence of magnetic activity on these variations appears to be merely a reflection of the strong association between solar and magnetic activities. About 96 per cent of long-term variability of S is accounted for by solar and magnetic activities. The corresponding figure for L is only about 32 per cent. As indicated by the waviness parameters, the solar daily variation in H is dominantly diurnal in all phases of solar activity and, in D and Z, it tends to be prominently diurnal with increasing sunspot activity. A suggestion of a probable modulation of L by 22-year cycle in the polarity of sunspots is noticed in D.

In the sixth Chapter, the formulae due to Malin are applied to the lunar harmonics presented in chapters 2 and 3 to examine the manner in which oceanic and ionospheric dynamo modulate L and its variations with seasons and solar activity. The results indicate that oceanic dynamo is weaker in the vicinity of Alibag than that observed at median and high latitudinal stations. This is ascribed to the small vertical component of geomagnetic field in low-latitudes. Amplitudes of ionospheric part are greater than those of oceanic part in all seasons. Eventhough the oceanic effects are small and do not show any marked seasonal variation, they appear to play an important role in determining the seasonal changes of total lunar daily variation, particularly in D and Z. This is primarily due to the varying phase of ionospheric part with respect to the oceanic part. However, seasonal variation of the phases of ionospheric and lunar semidiurnal components are alike. It is clearly important to remove oceanic part prior to any study of seasonal change with respect to the overhead ionospheric current system responsible for L. Removal of the ocean dynamo part does not make any significant change in the bahaviour of L with respect to solar cycle.

In the seventh Chapter, a search for geomagnetic lunar daily variation, $L(O_1)$, associated with atmospheric tide O_1 is made. The results indicate the existence of clear and significant $L(O_1)$ tide in all the elements. Partial tides are small in comparison with phase law tides, suggesting that the variation resulting from the product of atmospheric tide O_1 and higher harmonics of ionospheric conductivity contribute little to the $L(O_1)$ at Alibag. O_1 tide being lunar diurnal in nature, the first harmonic of $L(O_1)$ is expected to be dominant; but the first harmonic observed here is smaller than the second. The possibility that it is due to the presence of oceanic dynamo contribution to $L(O_1)$ is examined by separating $L(O_1)$ into parts oc oceanic and ionospheric origin by suitably modifying the method of Malin. The separation showed that the primary source of $L(O_1)$ in Z is the oceanic dynamo. But even after the removal of oceanic part, first harmonic is smaller than the second harmonic. Discussing probable reasons, it is concluded that even yearly $L(O_1)$ contain some contribution from lunar variation, $L(M_2)$, associated with the atmospheric tide M_2. This also explains why the observed ratio of $L(M_2)$ to $L(O_1)$ is significantly less than that predicted by tidal theory. Next, by applying formulae due to Winch, the seasonal harmonics of $L(O_1)$ and $L(M_2)$ are corrected for the possible contamination of one by the other. It is found that seasonal progression of $L(O_1)$ and $L(M_2)$ prior to and after the removal of the effect of one from the other remain the same.

In the eighth Chapter, the dependence of L on lunar distance in different seasons and for varied epochs of solar activity is investigated using the horizontal intensity observations at Alibag. The observed ratio of L when the Moon is at perigee to that when it is at apogee, during different seasons and for the total period closely agrees with the expected from gravitational tide theory. This not only strengthens the belief that the direct effect of the Moon on the upper atmosphere is primarily gravitational, but also suggests that the observed amplitudes ratio $N_2 : M_2$ in all seasons departs insignificantly from that expected from tidal theory. A systematic increase of the ratio of L at lunar perigee to apogee with change in phase of solar cycle implies that $N_2 : M_2$ has a measure of dependence of solar activity. Ionospheric and oceanic parts of L are poorly determined at both apogee and perigee.

The results obtained and the main conclusions drawn from each of the above investigations are summarized at the end of the corresponding chapters.

Statement required under 0.770 Statement No. 1

I hereby declare that the work described in this thesis has not been submitted previously to this or any other University for Ph.D. degree or any other degree.

Statement required under 0.771 Statement No. 2

"Whether the work is based on the discovery of new facts by the candidate or of new relations of facts observed by others, and how the work tends to the general advancement of knowledge"

The dissertation describes new results about some of the salient features of geomagnetic variations in the three geomagnetic elements at a low-latitude station, Alibag. The magnitude of the investigation is indicated by the fact that the discussion of Solar and Lunar daily variations given here is based upon more than a million hourly values of the three magnetic elements.

The results obtained by original computations in this dissertation are of help, in addition to a deeper understanding of the morphology of average geomagnetic solar and lunar variations, towards the solution of a few of the problems designated by the joint International Association of Geomagnetism and Aeronomy/International Association of Meteorology and Atmospheric Physics (IAGA/IAMAP) Committee on Lunar effects as requiring special attention, e.g., i) lunar variations in the magnetosphere and ii) explanation of the anomalous dependence of lunar magnetic tides on solar activity. Solar cycle control of geomagnetic solar daily variation, S, is well known and is also observed in the present investigation. A marked 11-year variation in the lunar ranges observed here indicates a definite control of lunar daily variation, L, by solar cycle, which even after a century of argument has been a subject of controversy. Variations in L during a solar cycle can be accounted for by the corresponding changes in ionospheric E-layer conductivity. This coupled with the detection of currents responsible for S in E-layer by rocket-borne experiments lead to the conclusion that currents mainly responsible for S as well as L flow in the same region.

Variations in the form of S with magnetic activity indicate the presence of contributions from non-ionospheric sources, such as partial ring current. Differences in the behaviour of L, in relation to magnetic activity, at Alibag and amongst other stations are concluded to be associated with the magnetospheric expansion and contraction for the lunar tides.

The seasonal changes of S and L at Alibag not only support the hypothesis that the current systems oscillate northwards and southwards across the magnetic equator but also indicate that the oscillation for L is of a larger magnitude than that for S currents, suggesting differences in dynamics of upper atmosphere related to S and L. Results obtained here further strengthen the belief that direct effect of the Moon on the atmosphere is purely gravitational. In addition, it is shown that the ocean dynamo effects evaluated for different harmonic constituents of the lunar tides can lead to a better understanding of the pelagic tides.

Finally the significantly determined solar and lunar tides at Alibag for varied epochs of solar activity and for different seasons provide valuable basic data for constructing equivalent ionospheric current systems responsible for S and L over the globe.

Statement required under 0.771 Statement No. 3

"The sources from which his information has been derived and the extent to which he has based his work on the work of others, and shall indicate which portion or portions of his thesis he claims as original".

The following investigations from the sources from which the information has been derived.

1. General features and seasonal progression of solar and lunar daily variations.

2. Solar cycle influence on solar and lunar daily variations.
3. On the association of solar and lunar daily variations with the degree of magnetic activity.
4. Some features of the variability associated with solar and lunar daily variations - by B.R. Arora and N.S. Sastri (communicated to Geophys. J.R. astr. Soc).
5. Contribution of Oceanic and Ionospheric Dynamo to Lunar daily variation.
6. O_1 component of geomagnetic lunar daily variation.
7. Modulation of geomagnetic lunar daily variation in H at Alibag with lunar distance - by B.R. Arora and D.R.K. Rao, Geophys. J.R. astr. Soc. (1975), 43, 627-633.

The numerical procedure of the method used for the derivation of harmonics of geomagnetic solar and lunar daily variations all through the dissertation is due to Winch. The formulae for the separation of lunar variation into parts of oceanic and ionospheric origin in item 5 above are given by Malin. The method of estimation of the absolute variability by harmonic dials in item 4 is taken from Bartels. Full references have been given in the thesis for the above methods and any other material used from published papers or from published reports.

The scheme of analysis, developments of computer programmes for the computations referred to in the preceeding paragraph and for many more analyses have entirely been prepared by the candidate. The discussion and presentation of the results are to the candidate's credit. Modification of Malin's formulae for estimating the oceanic and ionospheric parts of lunar variations associated with atmospheric tide O_1 is also to the credit of the candidate.

The results and the calculations referred to above and in statement No.2 are original.

<u>Statement required under O.771</u> <u>Statement No.4</u>

"Where a candidate presents joint work, he shall clearly state the portion which is his own contribution as distinguished from the portion contributed by his collaborators".

In item No.4 of statement No.3, the preparation of computer programme, planning of the analysis, discussion and presentation of results of the study are entirely due to the candidate. The collaborator's contribution is mainly in some computations and in preparation of the material for publication.

In item No.7 of statement No.3, the computer programme, editing of results and preparation of the manuscript for publication are to the credit of the candidate. The collaborator's contribution is mainly in the discussion of results.

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The following published papers are submitted as additional support to the candidature :

1. 'On the universal time component in the daily variation of the geomagnetic disturbance field'
   B.R. Arora
   Pure and Appl. Geophys., (1974), 112, 456-463

2. 'On abnormal quiet-day variation in the low-latitudes'
   B.R. Arora
   Indian J. Met. Geophys., (1972), 23, 195-198.

3. 'On the local time dependence of annual and semiannual modulation of geomagnetic disturbance field'
   B.R. Arora and G.K. Rangarajan
   J. Geomag. Geoelectr., (1974), 26, 467-474.

4. 'Lunar modulation of the diurnal variation of H at Trivandrum'
   B.R. Arora and N.S. Sastri
   Proc. Sym. on 'Equatorial Geomagnetic Phenomena', May 15-16, 1975, Indian Institute of Geomagnetism.

5. 'Diurnal features of day-to-day variability in quiet-day geomagnetic horizontal intensity'
   A. Yacob and B.R. Arora
   Ann. Geophys., (1974), 30, 473-476.

6. 'Modulation of Geomagnetic Lunar Variations by the Sector Polarity of IMF'
   D.R.K. Rao and B.R. Arora (Communicated)

7. 'Longer period lunar magnetic tides in the Indian Equatorial region'
D.R.K. Rao, B.R. Arora and N.S. Sastri
Presented at the Interdisciplinary Symposium 24 on 'Tidal interactions, including Earth tides' during XVI IUGG General Assembly, Grenoble, France (1975).
Ann. Geophys. (1976) - in press.

8. 'High resolution geomagnetic spectra in Indian region: Lunar tides'
G.K. Rangarajan and B.R. Arora (under preparation)

9. 'The O_1 component of geomagnetic lunar daily variation in H at Alibag, 1927-1970'
N.S. Sastri, B.R. Arora and D.R.K. Rao
J. Geomag. Geoelectr., (1975), 27, 85-94.

10. 'Semiannual modulation of Earth's magnetic field in the equatorial electrojet region'
B.N. Bhargava, D.R.K. Rao and B.R. Arora
Planet. Space Sci., (1973), 21, 1251-1255.

CHAPTER 1

GEOMAGNETIC SOLAR AND LUNAR DAILY VARIATIONS AND THEIR DETERMINATION

Geomagnetic Solar and Lunar Daily Variations and their Determination

1.1 Solar and Lunar Daily Variations:

One of the most spectacular variations exhibited by all the geomagnetic elements is the daily variation having a period of one solar day and consequently denoted generally by S. This has been the subject of many elaborate and extensive studies since its discovery from observations of compass needle motions by Graham (1724). Besides the solar daily variation, there is also a systematic, though smaller, periodic variation discovered by Kreil (1850), called the lunar daily variation and is denoted by L. This variation is associated with the period of rotation of the Earth relative to the Moon, about 24.84 solar hours. The earlier studies of L dealt only with its monthly mean, and revealed mainly the semidiurnal component. Broun (1874) and later Chambers (1887) independently showed that L depends on the lunar phase and that at any epoch in the lunation its changes are greatest during sunlit hours, indicating that L is dependent on both solar and lunar time and therefore Chambers called it luni-solar daily variation. The phenomenon was further studied by Moos (1910) and extending his discussion of L, Chapman (1913) gave the formula

$$L = \sum L_n = \sum l_n \sin\left[n\tau + (n-2)\nu + \lambda_n\right]$$

Where τ denotes mean lunar time reckoned in angle from mean lower transit of the Moon, ν, a measure of the lunar phase, and is equal to $t - \tau$ where t is the mean solar time.

Stewart (1882) put forth a hypothesis that solar daily variation is due to the effect of electric currents induced in the conducting layers of the upper atmosphere on the sunlit side by a regular system of winds carrying the ionised gas across the lines of force of the Earth's main magnetic field. This has become known as dynamo theory, which has been quantitatively formulated by Schuster (1889, 1908). This theory could also explain the generating mechanism of L. However, the air motions in this case are probably entirely due to gravitational tide, since the Moon could hardly affect the atmosphere appreciably in any other way. Later, Chapman (1913, 1919) developed dynamo theory suitable for both S and L and mapped the distribution of equivalent overhead current systems which could reproduce the major features of S and L at all latitudes. Since then, it has been a popular and fascinating exercise to postulate these overhead current systems using ground-based data for different conditions of solar activity and for each season. However, for a precise understanding of the dynamo theory of either S or L, one needs to know details of the following(Malin, 1971):

(i) the source of energy that causes atmospheric movement

(ii) the response of the atmosphere to (i)

(iii) the distribution of the conductivity of the ionosphere both in space and in time

(iv) the distribution of the Earth's main magnetic field

(v) the effect of induction within the Earth.

Given these data, it should be possible to construct a model that would accurately reproduce the observed S and L variations. Since clear understanding of these factors is still lacking, a practical approach to this problem would be to make certain assumptions about the nature of (i) to (iv) and test the validity of these assumptions by comparing the predicted with the observed variations. A history of the various assumptions made and their modification with the gain of further knowledge about (i) to (iv) have been reviewed by Matsushita (1967), Maeda (1968) and Price (1969).

Earlier studies of the ionosphere by ground-based radio-wave soundings revealed that the assumption of the time-variation of conductivity being proportional to solar-zenith angle was satisfactory and from a consideration of the magnitude of the required conductivity in space, it was thought that the electrical currents responsible for S and L would flow in the E-region of the ionosphere. Rocket and satellite observations, made in the last few years, detected currents

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in the E-region. The intensity of these currents was in good agreement with that deduced from geomagnetic S variations on the ground. These studies not only provided confidence in the existence of actual dynamo region but also permitted the measurements of various geophysical parameters by which electric conductivity could be determined more accurately. From the study of Maeda and Fujiwara (1967), it has become certain that air motions associated with L arise from gravitational tide, but the sources of energy for the movement of atmosphere associated with S are less certain. The gravitational forces only do not seem to be the main cause; otherwise lunar effects should have been greater than the solar effects. This problem has received the attention of several workers and thermal excitation of solar tides was emphasized, i.e. the rotation of the Earth in the radiation field of the Sun and the absorption of radiation by different atmospheric constituents cause periodic heating of the atmosphere. The anomalously large amplitude of the solar tides in atmospheric pressure in comparison with lunar tide could be interpreted as an even stronger indication of thermal rather than gravitational origin of the winds for S. The solar oscillations due to Sun's heating of the atmosphere have periods identical with those of conductivity, so for S the effects of solar modulation of conductivity and the response of the atmosphere to thermal oscillation are inseparable.

In the past, S has been studied in more detail than L, mainly because the amplitude of S is, in general, about ten times that of L, and is, therefore, more readily determined from observational data. However, despite its small amplitude and the labour involved in reliably determining it for even a single station, it is likely that a study of L will reveal more information about the dynamo mechanism than will a study of S. There are two main reasons for this. Firstly, the source of energy for the oscillations of the atmosphere associated with L is purely gravitational and is known in greater detail (Doodson, 1921) whereas for S it is both gravitational and thermal. Secondly, the main harmonic term in the lunar tidal atmospheric oscillations has a period of half a lunar day (12.420 mean solar hours) and is quite distinct from the periods associated with the changes in the ionospheric conductivity, which have periods of a solar day and simple fractions of a solar day. Further, the comparison of the mechanisms of the solar and lunar dynamos would be greatly simplified if the electric currents associated with L and S were similarly distributed in the ionosphere. If this were so, the differences between S and L would be more directly related to the corresponding air motions than if the currents were differently distributed. Also, it would imply that the variations of L and S with parameters that affect the ionospheric conductivity in preference to the air motions should be essentially similar for L and S. Two such parameters are sunspot number and the season. Thus, the studies of S and L in relation to sunspot number and in different seasons could be of great significance. Unfortunately the results available regarding the general dependence of S and L on sunspot number, R_z, and the seasons are inconclusive. Chapman (1925) and Chapman et al. (1971) have arrived at the conclusion that the influence of R_z on L is only about one-third of that on S, whereas Matsushita and Maeda (1965b) have concluded that solar activity dependence of L does not differ particularly from that of S. Similarly for seasonal dependence, Matsushita and Maeda (1965b) state 'that seasonal variation of the L field is similar to that of the S field' which is in conflict with the view of Chapman and Bartels (1940) 'that the seasonal variation of L is much greater than that of S'. More contradictory are the results of Gupta and Malin (1972) who have reported the similarity of seasonal variations of L and S for one sample of data and L exceeding S for another sample. Can these conflicting results be reconciled?

It is less easy to resolve this question. However, the results point out to several possibilities, namely : (i) there are differences in the changes of S and L air tides with sunspot number, (ii) the electric currents associated with S and L are not similarly distributed in the ionosphere, (iii) the main part of S and L current systems are situated at different levels in the ionosphere, (iv) the differences are due to the small magnitude of L, compared to solar variation, which makes its determination liable to uncertainty, (v) the theories of S and L are over simplified.

Recent advances in the knowledge of the properties of solar wind and the magnetosphere suggest a number of interesting ideas and conjectures relating to the theory of daily variations. One of these concerns the possible contribution, to the S field, of the electric currents, produced on the magnetospheric boundary by solar wind (Mead, 1964). Another concerns the modification to dynamo theory which may be required by linkage of the ionosphere with the magnetosphere due to high effective conductivity along the lines of force of the Earth's main field. Some workers have also indicated the presence of contribution from quiet-time and partial ring currents (Olson 1970,a,b: Sarabhai & Nair, 1969, 1971).

One complication present in L, but negligible in S, is the presence of a contribution from an ocean dynamo, powered by the tidal movements of the sea across the Earth's main magnetic field. Recent attempts by Malin (1970) and a few other workers have revealed that the removal of the ocean dynamo effect leads to a more consistent pattern of ionospheric dynamo. Since the conductivity of ocean waters does not change with solar activity or season, it would be interesting to know how the presence of this constant tide would modulate the seasonal and solar activity variations of the part of L of ionospheric origin. However, there are other complications as well. The dominant term in the lunar tide-producing potential being the lunar semidiurnal tide, denoted M_2, the discussion of time dependent terms in L is facilitated by simply assuming that M_2 only gives the atmospheric tidal movement. But in fact there are other terms in time-producing potential, especially O_1 and N_2 connected with changing declination of the Moon and its changing distance respectively, whose amplitudes are not insignificant compared with that of M_2. More recently it has been found that these tides are able to produce detectable variations in the atmospheric pressure (Malin and Chapman 1970a) and in the geomagnetic field (Gupta and Chapman, 1969; Winch, 1970b). Because of the coincidence of the period of O_1 tide with that of the 1st harmonic of luni-solar variation associated with M_2 tide, it is likely that each such transient variation might contribute to the numerical estimate of the other. Using Toolangi data, Winch (1970b) showed that by making proper adjustments to the computed seasonal L variation associated with M_2 tide for the presence of O_1 associated variation, the seasonal variation of L reduced almost to equivalence with the seasonal variation of the solar terms. He suggested that if this result were found to hold at other observatories, the obstacle of unduly large seasonal variations in L will be removed, thereby permitting the assumption that the currents responsible for solar and lunar geomagnetic variations flow in the same ionospheric layers. Many others working with the problems of S and L variations have stressed that answers to some of the above mentioned ambiguities must await the results of lunar analysis of many more long series of observatory data. Extensive analysis of long series of data carried out in the past were mostly confined to the data from higher and middle latitude stations. Auroral electrojet in the high latitudes and the location of the Sq current foci in the middle latitudes further complicate the interpretation of the results of analysis in these latitudes. Analysis of data from a station free from these complications should provide a better insight into the understanding of solar and lunar daily variations. The magnetic observatory at Alibag in the Indian region by virtue of its location in the low-latitudes, away from Sq focus and outside the equatorial electrojet belt, provides such data. An attempt is made in this dissertation to study the various features of geomagnetic solar and lunar daily variations in all the three components using the long series of data from Alibag. The coordinates of the Alibag Observatory are: Geographic lat. 18°38'N and long. 72°51'E and Geomagnetic lat. 9°.5 N and long. 143°.6 .

Pioneering studies of S and L with the data of Colaba magnetic observatory, Bombay, predecessor to the Alibag magnetic observatory, were made by Chambers (1887) and Moos (1910), and were discussed in the light of the then very imperfect knowledge of the ionosphere and the tidal and thermal oscillations of the atmosphere. Later several workers analysed Alibag data, particularly of the horizontal intensity, for limited periods to serve special purposes. Their results will serve as a guide to and independent check on the results of the present study.

1.2 Methods of computing solar and lunar magnetic variations:

The determination of solar daily variation in geomagnetic field owing to its relatively large magnitude and simpler form is comparatively easy. In fact, the estimation of S can simply be accomplished by averaging hourly values, arranged in solar hours, over a good number of days so chosen that they are uniformly distributed with respect to the phase of the Moon and hence the contribution of L sums to zero in the average field. But because of the small amplitude of L and its changing pattern, it is very difficult to separate the lunar effects from the pronounced S effects. For this reason, several methods have been put forward to estimate effectively the lunar daily variation. The available methods can be broadly divided into two classes : (1) Harmonic analysis, (2) Spectral analysis.

The complete description of all the methods will be out of the scope of the present dissertation. Therefore, only the primary features and relative merits of some of the methods are briefly reviewed here. However, the method chosen for the extensive analysis done here will be discussed in detail.

1.2.1 Method 1:

Under this classical analysis procedure two distinct submethods of analysis have been developed:

(a) Fixed-hour method: in this, variation of L with lunar age is studied keeping solar time constant. Bossolasco and Egedal (1937) and Bartels and Johnston (1940 a,b) were among the earlier workers to use this method.

(b) Fixed-age method: this method permits the study of L with lunar as well as solar time at different epochs of lunation.

In this fixed-hour method it is not possible to eliminate a day in between the sequence of data set. The merits of fixed-age method are apparent in the Chapman-Miller (1940) method, hereafter referred to as C-M method, which is based on the principle of this method and has many advantages. The important ones are:

(i) method's ability to analyse broken data sequences (permitting grouping of days by season, sunspot number, magnetic character figure etc.)

(ii) method's ability to provide a probable error with the estimates of amplitude and phase of magnetic variation.

(iii) Variations having a period of solar day or simple fraction of solar day are determined as a by-product.

(iv) allowance is made for non-cyclic variation.

On the other hand, the disadvantage of the method is that it determines the parameters of only prespecified frequencies, i.e. it does not examine the spectrum. There is, thus, no check that periodicities under investigation are not contaminated by other periodic signals. With slight modification the method can be easily extended to deal with other periodic signals predicted by tidal theory (for example see - Tarpley (1971), Winch and Cunningham (1972))

Yet another method developed under this category is by Matsushita and Campbell (1972) and is called the Fourier analysis of residuals. This method is essentially similar to the fixed-hour method except that it has been suitably modified to utilize the fine-time digitized data (scaled at 2.5 min. interval). Although the amplitudes of fundamental lunar semidiurnal component only were found to be significant, Matsushita and Campbell felt the method to be useful for studies of short period data. However, the method is computationally costly and they have stated that the best way to obtain L with hourly data is the C-M method.

1.2.2 Method 2:

Using the Blackman & Tukey's (1958) approach of power spectral analysis, Gupta & Chapman (1969) initiated the frequency domain study of lines in the geomagnetic spectrum due to atmospheric tides in the ionosphere caused by lunar gravitational forces. In addition to the first four harmonics of L associated with atmospheric tide M_2, they also observed some minor terms, whose periods closely agreed with those of minor terms predicted by tidal theory.

Thus, this method is very suitable for detecting periodic signals predicted by lunar tidal theory which have remained unexplored till this day. But the spectral methods have several limitations:

(i) Since in the Blackman-Tukey's approach resolution is directly proportional to the lags (M) and the stability of each spectral estimate is inversely proportional to M, a trade off between resolution and stability of estimate is adopted. Therefore, the method is able to provide only a rough approximation to the true spectrum.

(ii) The spectrum does not provide information about the phase of the fluctuations contained in the original series.

(iii) If a series is dominated by a very strong periodic variation, the spectrum can be slightly influenced at other wave-lengths by leakage through the lobes of the spectral window. As the geomagnetic time series is known to contain strong solar harmonics, whose periods are quite close to the periods of lunar harmonics, there always remains the possibility of lunar harmonic amplitudes to be biased through leakage.

(iv) The method adopts equivocal attitude regarding the significance of the spectral estimates.

(v) Like the fixed-hour method, this method also cannot be applied to analysis of time series with breaks.

However, the limitations (i) and (ii) can be circumvented to a great extent by using the method of Fast Fourier Transform based on Cooley-Tukey (1965) algorithm. But any attempt to overcome limitation (iii) either by pre-whitening a series before processing the data or by averaging together spectral values in the hamming and hanning processes will result in loss of information and will also inhibit the application of any realistic statistical test of significance. Black (1970) has given a method of arriving at the 'best' estimates of amplitude of any periodic variation in a time series by combining the discrete Fourier transforms of the block of data, not necessarily consecutive, in such a way that the best estimate is not biased by noise at the same frequency. Thus, the method is advantageous because it is not only possible to estimate the probable error but also provides amplitudes of signals free from noise. However, in the processes of block averaging, generally done in the frequency domain, phase information is lost. This method is used by Raja Rao et al. (1973) and Raja Rao and Reddy (1973).

More recently, Burg (1968) has orginated a fundamentally new approach to power spectrum analysis based on the information or entropy content of time series which is termed as Maximum Entropy Method (MEM) and has been applied by Currie (1975) to Hermanus horizontal intensity data to detect major and minor lunar tidal terms. Among its various advantages, the important ones are : the ability of the method in detecting weak signals due to its high resolution capability; unbiased estimates of spectrum because no fixed smoothing windows are applied.

Beside the potential superiority of MEM over other spectral estimators, the usefulness of this approach is marred by:

(i) the lack of criterion for choosing the length of prediction error filter,

(ii) the spectrum peaks in Maximum Entropy spectrum are not directly proportional to the square of the amplitude as is the case with the techniques mentioned above; it is the area under the curve which is proportional to the output power,

(iii) no confidence limit is yet available for the spectral estimates,

(iv) phases of the waves are not obtained.

It is felt that this method in the present form is suitable if the interest is confined to detecting periodic signals. The possibility of detecting minor lunar tidal terms in the horizontal intensity at Alibag and Trivandrum has been investigated by Rangarajan and Arora (1976) applying this technique.

1.2.3 Choice of the method:

As stated by Chapman (1942) choice of the method is partly one of taste, and partly it depends on the results desired and the computational resources available.

To examine the relative dependence of S and L on various geophysical parameters, it would be required to group the days according to various indices. And also to avoid the complication of interpolation of the loss of record due to various reasons, few days have to be excluded. Hence, the method should be able to work with broken data sequences.

Significance of the results can only be judged by considering their uncertainty. Since lunar terms are usually of very small amplitude an estimate of the accuracy of the measure (e.g. probable error) is essential. The method should, therefore, permit the determination of probable errors.

The understanding of any vector quantity is not complete unless both the magnitude and direction are available. No study of S and L is, therefore, complete unless their amplitudes are supplemented by phase angles. The method should be able to provide these.

All these requirements are largely met with by the Chapman-Miller method. Therefore, in view of the above requirements and many other advantages of C-M method listed earlier, any method based on the principle of C-M method is suitable for the present work. More recently, Chapman-Miller method has been generalised by Winch (1970a) to enable determination of partial tides and long period tide (defined later) in addition to phase-law and solar tides. The method of Winch closely follows the statistical procedure of C-M method and retains most of the advantages of C-M method. Hence this method is used in the present dissertation. The numerical procedure of the method is given in the following sections.

1.3 Lunar phase-law and partial tides and their representation

As stated earlier, the dominant term in lunar tide producing potential is the lunar semidiurnal tide denoted by M_2. The time dependence of the atmospheric tidal movement associated with M_2 can be represented by:

$$M_2 = A \sin (2\tau + \delta_2) \qquad (1)$$

(denotes mean lunar time, increasing by 2π per solar day). Similarly the time variation of electrical conductivity of the ionosphere is represented by:

$$K = k_0 + k_1 \sin (t + \beta_1) + k_2 \sin (2t + \beta_2) \qquad (2)$$

The product of the expressions (1) and (2) indicates the time dependence of the lunar geomagnetic effect, and has the form:

$$k_0 A \sin (2\tau + \lambda_2) + (c_1 \sin (2\tau - t + \lambda_1) + (c_3 \sin (2\tau + t + \lambda_3) + (c_0 \sin (2\tau - 2t + \lambda_0) + (c_4 \sin (2\tau + 2t + \lambda_4) \qquad (3)$$

solar time t increases slightly faster than lunar time τ, i.e.

$$t = \tau + \nu \qquad (4)$$

where increase by 2π in a mean synodic month of M mean solar days (M = 29.5306)

If $t = \tau + \nu$ is substituted in equation (3), then the expression is analogous to the emperically derived Chapman's phase law given by:

$$L(M_2) = \Sigma_{n=0}^{4} L_n = \sum_{n=0}^{4} c_n \sin \left[n\tau + (n-2)\nu + \lambda_n\right] \qquad (5)$$

However, the phase law can be more simply represented by substituting $\tau = t - \nu$ in equations (1) and (3)

$$M_2 = A \sin (2t - 2\nu + \delta_2)$$

and $$L(M_2) = \sum_{n=0}^{4} C_n \sin (nt - 2\nu + \lambda_n) \quad (6)$$

Symbol $L(M_2)$ indicates the geomagnetic lunar effects associated with atmospheric tide M_2. For brevity of symbol, M_2 is often omitted. It is clear that the phase law terms have a phase angle which decreases by 4π during the synodic month relative to solar time t regardless of the order n of the harmonic.

If the third and fourth harmonics

$$k_3 \sin (3t + \beta_3) + k_4 \sin (4t + \beta_4)$$

are added to the expression for electrical conductivity K, then in the notation of Schneider (1963), the following extra terms:

$$\Xi_2 = C_{-2} \sin (2t + 2\nu + \lambda'_{-2})$$

$$\Xi_1 = C_{-1} \sin (t + 2\nu + \lambda'_{-1})$$

$$L_5 = C_5 \sin (5t - 2\nu + \lambda_5)$$

$$L_6 = C_6 \sin (6t - 2\nu + \lambda_6)$$

must be added to the expression for the geomagnetic transient lunar variation. Schinder (1963) suggests that those terms whose phase angle relative to solar time increases by 4π per synodic month be denoted as 'partial tides', whilst those terms whose phase angle decreases by 4π per synodic month relative to solar time be denoted as 'phase law tides'.

The term partial tide used here should not be confused with Chapman's (1942) use of the term to represent various minor harmonic constituents in lunar gravitational tide producing potential developed by Doodson (1921). Although it should be kept in mind that partial tide terms here do not stem from air oscillations of period $(\tau + 3\nu)$ and $(2\tau + 4\nu)$ superposed on expression (1); they originate in the conductivity factor in (2).

Chapman (1913) states that the amplitudes of partial tides, as predicted by dynamo theory, are much smaller than the amplitudes of the corresponding phase law tides, thereby justifying exclusion of partial tides in the expression for geomagnetic potential. It seems that there is a need to determine from observational data whether or not the theoretical prediction that partial tides are negligible is justified. The first results of such an analysis were presented by Schneider (1963), showing from observations of declination at Batavia, that the partial tides Ξ_1, and Ξ_2 were not negligible. Winch (1970a), using data from Toolangi magnetic observatory, showed good agreement with the corresponding results for Batavia. Rao and Sastri

(1972) studied the lunar partial tides using observations in the Indian region and showed that the second harmonic of partial tide, in both H and Z, is generally prominent. As the computation of lunar partial tides in addition to lunar phase law and solar tides require very little extra effort, it is considered worthwhile that further computation of partial tides with the long series data of Alibag may provide additional useful information over and above that provided by the phase law tide.

1.4 Numerical Procedure:

The Moon moves eastward relative to the Sun and the hour-angle between the Sun and the Moon (measured eastward from the Sun) is called the phase or age of the Moon and is denoted by ν . It increases from 0 at one new Moon to 24 at the next. An alternative measure of the Moon's age is μ number. The μ number , in contrast to ν number, is a decreasing measure of Moon's age, i.e., it is zero or 24 at the new Moon but decreases from 24 to 0 in the interval from one new Moon to the next. In the present analysis μ numbers (rounded off to integers) calculated by the procedure outlined by Bartels and Fanselau (1938) are used. Thus, μ is the hour-angle (counted positive towards west from the upper transit) of ~~the mean Moon at the time of~~ the mean Moon at the time of Greenwich mean noon.

To determine the geomagnetic effects of the atmospheric tide M_2, it is sufficient to consider half lunation, and to use the integer μ' which increases from 0 to 11 twice in each lunation; μ' is defined as the nearest integer to the Greenwich noon value of μ, but is diminished by 12 or 24 during the interval from near new Moon to full Moon, so that it is always between 0 and 11 but never exceeds 11.

The practical method of analysis proceeds by assigning a sequence of S+1 observations for the day J and including the first observation on day J+1 to one of the R (R=12) groups by means of characteristic number μ'. S is 24 as hourly data are used.

A group sum sequence g_{sr}

(s = 0,1,2 ......, S; r = 0,1, ..., R-1) is formed for each of the R groups:

$$g_{sr} = \sum_{J}^{N_r} f_{sJ}$$

summation being over the N_r days of the r th group.
Numerical analysis of geomagnetic group sum sequences can be divided into three distinct parts:

(a) determination of lunar terms,

(b) determination of solar terms,

(c) determination of probable errors.

Parts (b) and (c) were not discussed in the original paper of Chapman and Miller (1940), but are usually carried out by means of average group sum sequences $g_{s\pi}/N\pi$, rather than by use of the group sum sequences $g_{s\pi}$ directly. It seems to be a logical step to carry out (a) also by using average group sum sequences for the determination of lunar terms and this is Wilkes' (1962) modification. Its use implies that the intractable term is reduced to zero; it also simplifies the calculation, prevents contamination of terms by those predicted corresponding to higher harmonics of atmospheric oscillation, and prevents contamination of lunar terms by solar terms. On the other hand, the use of average group sum sequences does not give equal weight to the group sum sequences.

According to Winch (1970a) the advantages of Wilkes' modification outweigh the disadvantages and therefore this modification has been used. The calculations can be described briefly by the following steps:

(1) Normalize the group sum sequences by computing

$$g'_{s\pi} = \sum_J f_s J/N\pi$$

$$s = 0,1,\ldots,S-1; \quad \pi = 0,1,\ldots,R-1.$$

(2) 'Primary' harmonic analysis of the normalized group sum sequences, with correction for noncyclic variation.

$$A'_0 S\pi = \sum_s g'_{s\pi} - \frac{1}{2}(S-1)(g'_{s\pi} - g'_{0\pi}); \; B_0 S\pi = 0$$

$$A'_{pS\pi} = \Sigma_s\, g'_{s\pi}\cos(2\pi ps/S) + \frac{1}{2}\,(g'_{s\pi} - g'_{o\pi})$$

$$B'_{pS\pi} = \Sigma_s\, g'_{s\pi}\sin(2\pi ps/S) + \frac{1}{2}\,(g'_{s\pi} - g'_{o\pi})\cot(\pi p/S)$$

(3) A 'secondary' harmonic analysis of the coefficients $A'_{pS\pi}$ and $B'_{pS\pi}$ computed in the primary analysis gives:

$$A'_{pSA} = \sum_{\pi} A'_{pS\pi}\cos(2\pi\pi/R),$$

$$A'_{pSB} = -\sum_{\pi} A'_{pS\pi}\sin(2\pi\pi/R),$$

$$B'_{pSA} = \sum_{\pi} B'_{pS\pi}\cos(2\pi\pi/R),$$

$$B'_{pSB} = -\sum_{\pi} B'_{pS\pi}\sin(2\pi\pi/R).$$

As the days are grouped according to the value μ of day, at the secondary harmonic analysis stage the signs of A'_{pSB} and B'_{pSB} are changed (Lindzen and Chapman, 1969).

(4) To smoothen the amplitudes and phases, the iterative procedure is initiated with

$$(h_m)_o = 2\sum_p \Big[(R_eD_{mpS})(B'_{pSA} - A'_{pSB}) - (I_mD_{mpS})(A'_{pSA} + B'_{pSB})\Big] / RSe_R$$

$$(g_m)_o = 2\sum_p \Big[(R_eD_{mpS})(A'_{pSA} + B'_{pSB}) + (I_mD_{mpS})(B'_{pSA} - A'_{pSB})\Big] / RSe_R$$

$$(h_m')_o = 2\sum_p \Big[(ReDm'pS)(B'_{pSA} + A'_{pSB}) - (I_mDm'pS)(A'pSA - B'_{pSB})\Big] / RSe_R$$

$$(g_m')_o = 2\sum_p \Big[(ReD_{m'pS})(A'_{pSA} - B'_{pSB}) + (I_mD_{m'}pS)(B'_{pSA} + A'_{pSB})\Big] / RSe_R$$

where $e_R = \sin(\pi/R)/\pi/R$; when R=12, eR = 0.9886 and is a factor included to compensate for the effect of summing days according to integral values of μ number in group $\hbar$.
Numerical values of ReD_{mpS}, ImD_{mpS}, $ReD_{m'pS}$ and $ImD_{m'pS}$ are given in Table 1.1.

(5) Four times interation is carried out for final converged values:

$$(h_m)_{j+1} = (h_m)_o + \Sigma_n \left[(ReE_{mm'S})(h_{m'})_j + (ImE_{mm'S})(g_{m'})_j \right]$$

$$(g_m)_{j+1} = (g_m)_o - \Sigma_n \left[(ReE_{mm'S})(g_{m'})_j - (ImE_{mm'S})(h_{m'})_j \right]$$

$$(h_{m'})_{j+1} = (h_{m'})_o + \sum_k \left[(ReE_{m'mS})(h_m)_j + (ImE_{m'mS})(g_m)_j \right]$$

$$(g_{m'})_{j+1} = (g_{m'})_o - \sum_k \left[(ReE_{m'mS})(g_m)_j - (ImE_{m'mS})(h_m)_j \right]$$

m = k - 2/29.5306, m' = k + 229.5306,

K, n=0,1,2,3,4

(6) Lunar phase law and partial tides:

If g_m, h_m, g_m', h_m' denote final converged values, then amplitudes and phase angles of phase law tides and partial tides are given by

$$c'_m \cos\lambda_m = h_m ; \quad c'_m \sin\lambda_m = g_m$$

and $C'_{m'} \cos\lambda_{m'} = h_m'$; $C'_m{}' \sin\lambda_m{}' = g_m'$

respectively. (Notation m,m' designates phase law and

Table 1.1

(a) Numerical values of Re D_{mps}, Im D_{mps} for hourly data

k	Re D_{mps}; $m = k - \frac{2}{29.5306}$; $S = 24$				
	p = 0	1	2	3	4
0	0.963766	0.028165	-0.005849	-0.019575	-0.028993
1	0.004695	1.073680	0.147720	0.121519	0.118897
2	0.001052	-0.034696	1.031281	0.103655	0.077263
3	0.000445	-0.010553	-0.046977	1.018966	0.092771
4	0.000237	-0.004917	-0.015938	-0.051759	1.016856

k	Im D_{mps}; $m = k - \frac{2}{29.5306}$; $S = 24$				
	p = 0	1	2	3	4
0	-0.206516	-0.223860	-0.236325	-0.249643	-0.271779
1	-0.001006	-0.001091	-0.001151	-0.001216	-0.001324
2	-0.000225	-0.000244	-0.000258	-0.000272	-0.000297
3	-0.000095	-0.000103	-0.000109	-0.000115	-0.000125
4	-0.000051	-0.000055	-0.000058	-0.000062	-0.000067

contd.

Table 1.1 (contd.)

(b) Numerical values of Re $D_{m'ps}$ and Im $D_{m'ps}$ for hourly data

k	Re $D_{m'ps}$; $m' = k + \frac{2}{29.5306}$; $S = 24$				
	p = 0	1	2	3	4
0	0.963116	-0.101122	-0.062668	-0.049182	-0.040598
1	0.004228	0.937634	-0.123970	-0.083485	-0.066836
2	0.001212	0.033797	0.965150	-0.097339	-0.056738
3	0.000599	0.012856	0.044854	0.976239	-0.085195
4	0.000387	0.007411	0.019698	0.052364	0.986090

k	Im $D_{m'ps}$; $m' = k + \frac{2}{29.5306}$; $S = 24$				
	p = 0	1	2	3	4
0	0.206224	0.189428	0.179322	0.169864	0.156703
1	0.000905	0.000832	0.000787	0.000745	0.000688
2	0.000259	0.000238	0.000226	0.000214	0.000197
3	0.000128	0.000118	0.000112	0.000106	0.000097
4	0.000083	0.000076	0.000072	0.000068	0.000063

partial tides respectively). Numerical values of ReF_{mm}'s, ImR_{mm}'s, ReE_m'ms and ImF_m'ms are given in Table 1.2.

(7) Solar tides:

The amplitudes s_p and phase angle σ_p of the solar terms are calculated by

$$\frac{1}{2} S s_p \cos \sigma_p = B'_{pSN}/R$$

$$\frac{1}{2} S s_p \sin \sigma_p = A'_{pSN}/R$$

where A'_{pSN} and B'_{pSN} are the sums of the computed harmonic coefficients

$$A'_{pSN} = \sum_{n} A'_{pSn}; \quad B'_{pSN} = \sum_{n} B'_{pSn}.$$

(8) Corrections to phase angles:

The phase angles for solar terms in Winch's method refer to the local solar time whereas the data of the station under analysis viz. Alibag is tabulated in Universal Time (U.T.). The corrections for this effect have been discussed by Malin and Chapman (1970b) and are as follows:

The correction that is to be added to the determined values of phase angles, σ_p, for solar terms (σ_p in degrees) are:

$$p(L' - L) - 15\,pH' \quad \text{(degrees)}$$

where

L = East longitude, in degrees, of the station to which the data refer,

Table 1.2

(a) Numerical values of Re $E_{mm'ps}$, Im $E_{mm'ps}$ for hourly data S = 24

k	Re $E_{mm'ps}$; $m = k - \frac{2}{29.5306}$; $m' = n + \frac{2}{29.5306}$				
	n = 0	1	2	3	4
0	0.000000	0.103206	0.073363	0.062740	0.057161
1	0.000000	-0.040234	-0.053790	-0.061156	-0.065956
2	0.000000	-0.012125	-0.018328	-0.022354	-0.025266
3	0.000000	-0.005811	-0.009423	-0.012045	-0.014093
4	0.000000	-0.003330	-0.005660	-0.007490	-0.009007

k	Im $E_{mm's}$; $m = k - \frac{2}{29.5306}$; $m' = n + \frac{2}{29.5306}$				
	n = 0	1	2	3	4
0	0.000000	0.203983	0.215806	0.221440	0.225027
1	0.000000	0.000994	0.001051	0.001079	0.001096
2	0.000000	0.000223	0.000236	0.000242	0.000246
3	0.000000	0.000094	0.000100	0.000102	0.000104
4	0.000000	0.000050	0.000053	0.000055	0.000055

contd.

Table 1.2 (contd.)

(b) Numerical values of Re E_m'mps and Im E_m'mps for hourly data
S = 24

k	Re E_m'ms; $m = k - \frac{2}{29.5306}$; $m' = n + \frac{2}{29.5306}$				
	n = 0	1	2	3	4
0.	0.000000	-0.029980	0.004399	0.015110	0.020376
1	0.000000	0.028551	0.038923	0.043969	0.047006
2	0.000000	0.010986	0.016927	0.020511	0.022980
3	0.000000	0.006148	0.010161	0.012904	0.014966
4	0.000000	0.004259	0.007375	0.009696	0.011558

k	Im E_m'ms; $m = k - \frac{2}{29.5306}$; $m' = n + \frac{2}{29.5306}$				
	n = 0	1	2	3	4
0	0.000000	-0.208456	-0.196158	-0.190966	-0.187841
1	0.000000	-0.000915	-0.000861	-0.000838	-0.000825
2	0.000000	-0.000262	-0.000247	-0.000240	-0.000236
3	0.000000	-0.000130	-0.000122	-0.000119	-0.000117
4	0.000000	-0.000084	-0.000079	-0.000077	-0.000075

L' = East longitude, in degrees, of the meridian of time reckoning in which the initial data are tabulated,

H' = Solar time, in hours, according to the same time reckoning as L', of the first value of each daily sequence.

The first term of the correction compensates for the difference between local time and the meridian time used in the tabulation of the data, and the second term corrects for the difference between zero hour meridian time and the meridian time of the first value of the daily sequence.

The value of phase angle, λ_n, corresponding to lunar terms is based on local lunar time and local solar time. In the analysis μ number is used, which is defined in terms of the phase of the Moon at Greenwich noon instead of local noon. The corresponding correction to be added to the determined value of λ_n or $\lambda'n$ (expressed in degrees) is $p(L'-L) - 15 pH' + C (15 h'-L)$. The first two terms are the same as those used to correct σ_p and the last term compensates for the difference between the value of μ at Greenwich noon and the value of μ at the time of the first value of each daily sequence. C is a constant depending on the nature and period of the tide corresponding to n=0 in the expression (6) of section 1.3. For M_2-tide the factor is 2/29.5306. As the data of Alibag is in U.T., L=L' and nL'=15 nH', hence, one need to correct only for the longitudinal difference between Greenwich and the station. The same corrections are carried out in the analysis of phase angles.

(9) Corrections to amplitudes:

The amplitude of sine curve, deduced from discrete mean values rather than spot values, are less than the true amplitude. (Bath, 1974). Since the tabulated values used in this analysis are mean hourly values, the amplitudes of harmonic components of solar, lunar phase law and partial tides are multiplied by the correction factor obtained using the expression given by Winch (1970a, pp. 301 and 309). The relevant correction factors for the amplitudes of solar, lunar phase law and partial tides are given in the following Table 1.3.

(10) Vector probable errors:

The accuracy of each vector is measured by its vector probable error. The radii of the probable error circles for estimates of phase law, partial tide and fortnightly tide amplitudes are

$$1.6652\ \delta p/(S\ e_R \sqrt{R})$$

whilst for the solar terms, the radii of the probable

TABLE 1.3 Correction factors for amplitudes and probable errors

Harmonic / Term	1	2	3	4
Solar	1.00286	1.01152	1.02617	1.04720
Lunar Phase Law	1.00249	1.01074	1.02498	1.04556
Lunar Partial	1.00326	1.01232	1.02739	1.04886

error circles are:

$$1.6652\,\delta_p/(S\sqrt{R})$$

where δ_p is the square root of sum of squares of residuals. The value of δ_p^2 is derived from the following expression:

$$\delta_p^2 = \Big[\sum_{\pi}(B'_{pS\pi}{}^2 + A'_{pS\pi}{}^2) - (B'_{pS}N^2 + A'_{pS}N^2)/R$$
$$- \left\{(B'_{pS}A - A'_{pS}B)^2 + (B'_{pS}B + A'_{pS}A)^2\right\}/R$$
$$- \left\{(B'_{pS}A + A'_{pSB})^2 + (A'_{p3A} - B'_{pSB})^2\right\}/R\Big]$$

Probable errors are also corrected for the use of mean hourly values using the procedure detail in step (9) of this method. Though the correction factors for the probable error of lunar phase law and partial harmonics are different (Table 1.3), the probable errors after correction for both the tides are almost equal because the magnitude of the probable errors themselves and also the differences in the correction factors are very small. Therefore, the probable errors for phase law have been used for both the tides. A listing of the Fortran IV program incorporating the various steps is given in Appendix.

(11) Test of Significance:

Following Leaton et al. (1962) vector is to be considered significantly different from zero at five percent level only if its amplitude is not less than 2.08 times its vector probable error. This criterion of significance will be used all through the dissertation.

1.5 Treatment of Data:

The data used for major part of the analysis are the absolute hourly values of Horizontal intensity (H), Declination (D) and Vertical intensity (Z) of the Earth's magnetic field at Alibag during the period 1932-1972. While the data of H and Z are in units of nano Tesla (nT; 1 nT = 1 gamma = 10^{-5} Gauss) basic data for D are expressed in degrees and minutes west (negative). Declination at Alibag is westerly throughout the period and therefore is treated as a negative quantity in all the computations so that results of analysis directly refer to east declination. H data were available on magnetic tape while D and Z data were available only on punched cards. The data were checked for punching errors by comparing directly with the published data. A very few wild values may easily mask the true lunar effect. To avoid this possibility, the differences between successive hourly values were computed and a list giving date and hour of value exceeding by 20 nT, (or 2.5 min) on an average quiet day and 30 nT (4.0 min) on disturbed day, from its preceeding value was prepared and examined for the cause. If the cause was spurious such days were excluded from the analysis. Days on which even a single hourly value was missing, were excluded. Because of these reasons the number of days available for each element were slightly different.

Malin (1967) and Chapman et al. (1971) have shown that omission from the analysis of five International Disturbed days of each month reduces the probable error of L at all dip latitudes, varying from a slight reduction near magnetic equator to over 40% reduction at latitude 60°. Since such reduction in probable errors would be very small in low-latitudes, only very highly disturbed days (daily magnetic character $A_p > 1000$) are omitted.

Amplitude and probable error of S and L harmonics for D have been multiplied by 0.000291 H, to convert them to force units; here the numerical factor is the value of 1' of arc. When data for the period 1932-1972 are used as a whole, the mean value used for H was 38298 nT. But when analysis is done for each of the years separately or by grouping years according to annual sunspot number, the respective mean values of H are used. Symbols s_n and σ_n denote the amplitude and phase of the n^{th} harmonic of S. The corresponding symbols used for lunar phase law and partial tides are l_n, λ_n and l'_n, λ'_n respectively. In the tables the units of s_n is 0.1 nT and for l_n or l'_n it is 0.01 nT. Phase angles σ_n, λ_n and λ'_n are all in degrees.

```
           * BALDEV RAJ ARORA *
      PROGRAM LUNISOL
C    *  B.R. ARORA          *
      DIMENSION NLP(12),GS(12,25)
      COMMON/7/ DRE1(5,5),DIM1(5,5),DRE2(5,5),DIM2(5,5),ERE1(5,5),ERE2(5
     1,5), EIM1(5,5),EIM2(5,5)
C
C  PROGRAM TO COMPUTE THE HARMONIC COMPONENTS OF
C  SOLAR AND LUNAR DAILY VARIATIONS BY THE METHOD OF WINCH
C  THE GROUP SUMS FOR 12 SETS OF LUNAR  PHASES ARE FORMED SEPARATELY
C
C  READING OF MATRICES REQUIRED FOR ITIRATIVE PROCEDURE
C  MATRICES ARE CARRIED TO SUBROUTINE PARSHL THROUGH *COMMON *
C
      DO 60 I=1,5
      READ 20,(DRE1(I,J),J=1,5)
      READ 20,(DIM1(I,J),J=1,5)
      READ 20,(DRE2(I,J),J=1,5)
      READ 20,(DIM2(I,J),J=1,5)
   60 CONTINUE
   20 FORMAT(5F8.6)
      DO 21 I=1,5
      READ 20,(ERE1(I,J),J=1,5)
      READ 20,(EIM1(I,J),J=1,5)
      READ 20,(ERE2(I,J),J=1,5)
   21 READ 20,(EIM2(I,J),J=1,5)
      NSET=2
      DO 5 NRT=1,NSET
C
C  READING GROUP SUM SEQUENCES FOR 12 LUNAR PHASES
C
      DO 15 I=1,12
   15 READ 10,NLP(I),(GS(I,J),J=1,25)
   10 FORMAT(5X,I2,1X,9F8.0,/,(8X,9F8.0))
      CALL PARSHL(NLP,GS)
    5 CONTINUE
      END
C
C
      SUBROUTINE PARSHL(N,X)
C
C  SUBROUTINE TO COMPUTE COMPONENTS OF LUNAR PHASE LAW, PARTIAL AS WELL
C   AS SOLAR TIDES. HOURLY  SEQUENCES ARE USED ,  S724
C THIS SUBROUTINE CALLS ANOTHER SUBROUTINE FIX
C
      DIMENSION X(12,25),AP(12,5),BP(12,5),AS(5),BS(5),HM(5,5),GM(5,5),
     1HMM(5,5),GMM(5,5),N(12),DIF(12),AA(5),AB(5),BA(5),BB(5),
     2AL(12),XX(5),YY(5),XXX(5),YYY(5),PE1(5),PE2(5),
     3SP1(5),SP2(5)
      DIMENSION VP1(5),VP2(5)
```

```
      COMMON/7/ DRE1(5,5),DIM1(5,5),DRE2(5,5),DIM2(5,5),ERE1(5,5),ERE605
     1,5), EIM1(5,5),EIM2(5,5)
      PIE=3.141592
      S=24.0  $ ER=(SINF(PIE/12.0))/(PIE/12.0)
      EL =72.87
C     EL= EAST LONGITUDE OF THE STATION, ALIBAG
      PRINT 697,(N(I),I=1,12)
  697 FORMAT(/,6X,*NO OF DAYS IN DIFF.LUNAR PHASES*,12I6)
      DO 61 I=1,5
      DO 61 J=1,5
      HM(I,J)=0.0  $ GM(I,J)=0.0    $ HMM(I,J)=0.0
   61 GMM(I,J)=0.0
C
C   NORMALIZATION OF GROUP SUM SEQUENCES, STEP=1 OF METHOD
C
      DO 130 I=1,12  $ AL(I)=N(I)  $ DO 130 J=1,25
  130 X(I,J)=X(I,J)/AL(I)
      PRINT 603 , N(1),(X(1,J),J=1,25)
  603 FORMAT(/,20X,* LUNAR PHASE  0 NO, OF DAYS*,I5,* MEAN DIURNAL VARIA
     1TION*,/,(8X,9F12.1))
C
C   PRIMARY HARMONIC ANALYSIS OF NORMALIZED GROUP SUM SEQUENCES, STEP- 2
C
      ALL=0.0
      DO 5 I=1,12    $  DO 5 J=1,5    $ AP(I,J)=0.0
    5 BP(I,J)=0.0
      DO 6 I=1,12      $ DIF(I)=(X(I,25)-X(I,1))*0.5
      DO 8 K=1,24
    8 AP(I,1)=AP(I,1)+X(I,K)
      DO 7 J=2,5  $ AJ=J-1
      DO 9 K=1,24 $ AK=K-1
      AP(I,J)=AP(I,J)+X(I,K)*COSF(2.0*PIE*AK*AJ/24.0)
    9 BP(I,J)=BP(I,J)+X(I,K)*SINF(2.0*PIE*AK*AJ/24.0)
      AP(I,J)=AP(I,J)+DIF(I)
    7 BP(I,J)=BP(I,J)+(COSF(PIE*AJ/24.0)/SINF(PIE*AJ/24.0))*DIF(I)
      AP(I,1)=AP(I,1)-DIF(I)*23.0      $ BP(I,1)=0.0
    6 ALL=ALL+AL(I)
      DO 11 J=1,5  $ AS(J)=0.0  $ BS(J)=0.0  $ AA(J)=0.0  $ AB(J)=0.0
      BA(J)=0.0  $ BB(J)=0.0
      DO 11 I=1,12    $  AS(J)=AS(J)+AP(I,J)
   11 BS(J)=BS(J)+BP(I,J)
      PRINT 53,ALL,(AS(J),BS(J),J=1,5)
   53 FORMAT(40X,F10.0,/,(4X,2F15.2))
C
C   SECONDARY HARMONIC ANALYSIS STARTS, STEP- 3
C
      DO 13 J=1,5
      DO 14 I=1,12  $ AI=I-1  $ AN=AI*PIE/6.0
      AA(J)=AA(J)+AP(I,J)*COSF(AN)
      AB(J)=AB(J)+AP(I,J)*SINF(AN)
      BA(J)=BA(J)+BP(I,J)*COSF(AN)
   14 BB(J)=BB(J)+BP(I,J)*SINF(AN)
```

```
      AB(J)=-AB(J)
      BB(J)=-BB(J)
   13 CONTINUE
      R=12.0
      QUAN=R*S*BR
C
C     ITIRATIVE PROCEDURE STARTS, STEP - 4
C
      DO 63 I=1,5
      DO 64 J=1,5
      HM(I,1)=HM(I,1)+(DRE1(I,J)*(BA(J)-AB(J))-DIM1(I,J)*(AA(J)+BB(J)))
      GM(I,1)=GM(I,1)+(DRE1(I,J)*(AA(J)+BB(J))+DIM1(I,J)*(BA(J)-AB(J)))
      HMM(I,1)=HMM(I,1)+(DRE2(I,J)*(BA(J)+AB(J))-DIM2(I,J)*(AA(J)-BB(J))
     1)
      GMM(I,1)=GMM(I,1)+(DRE2(I,J)*(AA(J)-BB(J))+DIM2(I,J)*(BA(J)+AB(J))
     1)
   64 CONTINUE
      HM(I,1)=2.0*HM(I,1)/QUAN
      GM(I,1)=2.0*GM(I,1)/QUAN
      HMM(I,1)=2.0*HMM(I,1)/QUAN
      GMM(I,1)=2.0*GMM(I,1)/QUAN
   63 CONTINUE
      DO 71 I=2,5  $ II=I-1
      PE1(II)=GM(I,1)
   71 PE2(II)=HM(I,1)
C
C    FOUR TIMES ITIRATION FOR FINAL CONVERGED VALUES, STEP-5
C
      DO 67 K=2,5 $ KK=K-1
      DO 65 I=1,5
      DO 66 J=1,5
      HM(I,K)=HM(I,K)+(ERE1(I,J)*HMM(I,KK)+EIM1(I,J)*GMM(I,KK))
      GM(I,K)=GM(I,K)+(ERE1(I,J)*GMM(I,KK)-EIM1(I,J)*HMM(I,KK))
      HMM(I,K)=HMM(I,K)+(ERE2(I,J)*HM(I,KK)+EIM2(I,J)*GM(I,KK))
   66 GMM(I,K)=GMM(I,K)+(ERE2(I,J)*GM(I,KK)-EIM2(I,J)*HM(I,KK))
      HM(I,K)=HM(I,1)+HM(I,K)
      GM(I,K)=GM(I,1)-GM(I,K)
      HMM(I,K)=HMM(I,1)+HMM(I,K)
      GMM(I,K)=GMM(I,1)-GMM(I,K)
   65 CONTINUE
   67 CONTINUE
      DO 68 I=1,5
      XX(I)=GM(I,5)    $ YY(I)=HM(I,5)    $ XXX(I)=GMM(I,5)
   68 YYY(I)=HMM(I,5)
      DO 26 J=1,5
      SP1(J)=(2.0*AS(J))/(R*S)
   26 SP2(J)=(2.0*BS(J))/(R*S)
C
C     PROBABLE ERROR DETERMINATION, STEP-10
C
      DO 30 J=1,5  $ VP1(J)=0.0
      DO 31 I=1,12
```

```
   31 VP1(J)=VP1(J)+(AP(I,J)**2+BP(I,J)**2)
      AAA=(AS(J)*AS(J)+BS(J)*BS(J))/(R*R)
      BBB=((BA(J)-AB(J))**2+(BB(J)+AA(J))**2)/(R*R)
      CCC=((BA(J)+AB(J))**2+(AA(J)-BB(J))**2)/(R*R)
      VP1(J)=ABSF((VP1(J)-R*AAA-R*BBB-R*CCC)/(R-2.0))
      VP1(J)=SQRTF(VP1(J))
      VVP=VP1(J)
      VP1(J)=1.6652*VVP/(S*ER*SQRTF(R))
C
C     HARMONIC COEFF OF LUNAR PHASE LAW TIDE, STEP-6 A
C
   30 VP2(J)=1.6652*VVP/(S*SQRTF(R))
      PRINT 33
   33 FORMAT(/ ,37X,*AMPLITUDES AND PHASES OF LUNAR PHASE LAW TIDES*,/ ,
     14X,*HARMONIC NO*,18X,*AMPLITUDE*,10X,*PHASE ANGLE*,10X,*VECTOR PRO
     2BABLE ERROR*)
      DO 35 J=1,5  $  JJ=J-1
      CALL FIX(XX(J),YY(J),JJ,VP1(J),EL,1)
   35 CONTINUE
C
C     HARMONIC COEFF OF LUNAR PARTIAL TIDE, STEP - 6 B
C
      PRINT 36
   36 FORMAT(/ ,37X,*AMPLITUDES AND PHASES OF LUNAR PARTIAL   TIDES*,/ ,
     14X,*HARMONIC NO*,18X,*AMPLITUDE*,10X,*PHASE ANGLE*,10X,*VECTOR PRO
     2BABLE ERROR*)
      DO 40 J=2,5
      JJ=J-1
      CALL FIX(XXX(J),YYY(J),JJ,VP1(J),EL,2)
   40 CONTINUE
C
C     HARMONIC COEFF OF SOLAR TIDE, STEP - 7
C
      PRINT 41
   41 FORMAT(/ ,37X,*AMPLITUDES AND PHASES OF  SOLAR  TIDES *,/ ,
     14X,*HARMONIC NO*,18X,*AMPLITUDE *,10X,*PHASE ANGLE*,10X,*VECTOR PR
     2OBABLE ERROR*)
      DO 45 JJ=1,4  $ J=JJ+1
      CALL FIX(SP1(J),SP2(J),JJ,VP2(J),EL,3)
   45 CONTINUE
C
C     HARMONIC COEFF. OF LUNAR PHASE LAW TIDE CALCULATED WITH
C     THE INITIAL VALUES BEFORE ITERATION FOR FINAL CONVERGENCE
C
      PRINT 72
   72 FORMAT(20X,* AMPLITUDES AND PHASES OF LUNAR COMPONENTS BEFORE
     1ITERATION*, /)
      DO 73 IP=1,4
      CALL FIX(PE1(IP),PE2(IP),IP,0,0,EL,1)
   73 CONTINUE
  311 CONTINUE
  427 CONTINUE
      END
```

```
C
      SUBROUTINE FIX(A,B,IP,VPE,EL,JK)
C   THIS SUBROUTINE GETS AMPLITUDES (CORRECTED FOR USE OF
C   MEAN HOURLY VALUES,USING FACTORS FROM RL-ARRAY)AND PHASES IN DEGREES
C   RECKONED FROM LOCAL MIDNIGHT
C    JK=1 FOR PHASE LAW TIDE, JK=2 FOR PARTIAL TIDE, JK=3 FOR SOLAR TIDE
C
      DIMENSION  RL(3,4)
      RL(1,1)=1.00249  $ RL(1,2)=1.01074  $ RL(1,3)=1.02408
      RL(1,4)=1.04556  $ RL(2,1)=1.00326  $ RL(2,2)=1.01232
      RL(2,3)=1.02739  $ RL(2,4)=1.04886  $ RL(3,1)=1.00206
      RL(3,2)=1.01152  $ RL(3,3)=1.02617  $ RL(3,4)=1.04720
      PI=IP  $ PIE=3.141592   $ CORR=-PI*EL
C
C   CORR=CORRECTION TO PHASE ANGLE FOR THE DIFFERENCE
C   BETWEEN LOCAL TIME AND UNIVERSAL TIME - STEP 8 OF THE METHOD
C
      C=SQRTF(A*A+B*B)
      IF(B)110,115,110
  115 QQ=0.0  $ GO TO 75
  110 QQ=ATANF(ABSF(A)/ABSF(B))
      IF(A)74,105,85
   74 IF(B)90,75,500
   90 QQ=180.0+QQ*180.0/PIE
      GO TO 75
  500 QQ=360.0-QQ*180.0/PIE
      GO TO 75
   85 IF(B)120,115,125
  120 QQ=180.0-QQ*180.0/PIE
      GO TO 75
  125 QQ=QQ*180.0/PIE
      GO TO 75
  105 IF(B)130,115,135
  130 QQ=180.0
      GO TO 75
  135 QQ=0.0
   75 QQ=QQ+CORR
      IF(QQ)100,101,101
  100 QQ=360.0+QQ
  101 CONTINUE
C
C   CORRECTION TO AMPLITUDES AND PROBABLE ERROR FOR USE OF MEAN
C   HOURLY VALUES - STEP 9 OF NUMERICAL PROCEDURE
C
      IF(JK.EQ.1.AND.IP.EQ.0)20,25
   20 VPR=VPE  $ GO TO 30
   25 C=C*RL(JK,IP)  $ VPR=VPE *RL(JK,IP)
   30 CONTINUE
      PRINT 401,IP,C,QQ,VPR
  401 FORMAT(8X,I2,15X,F15.4,10X,F10.2,12X,F15.4)
      END
```

C H A P T E R 2

GENERAL FEATURES AND SEASONAL PROGRESSION OF SOLAR AND LUNAR DAILY VARIATIONS

General Features and Seasonal Progression of Solar and Lunar Daily Variations

2.1 Introduction :

Of the more systematic changes in the geomagnetic daily variations at a station the most obvious ones are associated with seasons. Ionospheric currents, mainly responsible for the daily variations, vary in intensity and form due to two factors, conductivity and winds in the ionosphere. Conductivity is, to a large extent, controlled by the solar zenith angle which is maximum in local summer and minimum in local winter. The winds, resulting from the ever changing atmospheric structure, modify the gravitational as well as solar-thermal atmospheric tides. Changes in the conductivity would cause variations primarily in the amplitude of solar and lunar variations, S and L respectively. But the large observed changes in phase and shape of S and L, practically at all stations, are suggestive of the variability in the atmospheric dynamics, which would cause the movement and deformation of current system to produce required changes in S and L with seasons. After normalising the monthly mean solar quiet-day ranges in H at Alibag for solar-zenith-angle modulation of conductivity and partly the solar thermal effects, Yacob (1970) derived the residual annual variation in solar ranges which showed a remarkable similarity with the annual variation of the east-west component of the prevailing wind reported by Greenhow and Neufeld (1961). This suggests that the winds have an important role in determining the seasonal variation of geomagnetic daily variation. Several other workers have also stated that the magnitude and nature of seasonal variation of S can not be explained by the seasonal modulation of conductivity or its differences in the two hemisphere alone (Pogrebnoy 1969; Stening 1969). However, it is not yet clearly understood as to what extent the seasonal variations in S and L are due to (i) solar modulation of ionospheric conductivity and (ii) changing movements of the atmosphere. Gupta (1967) and Brown and Williams (1969), in their studies of solar variations, have stressed on solar radiation as the primary agency contributing to the variation both in the electrical conductivity and the winds in the conducting layers of the upper atmosphere. The combination of changes in the two factors, conductivity and winds, produces a variety of seasonal changes, which are different at different stations. These changes in S and L at Alibag are examined in this Chapter.

2.2 Analysis :

As a first step to study the seasonal variation of S and L in the three elements H, D and Z at Alibag, the data for the period 1932-1972 have been divided into three Lloyd's seasons :

d - December solstice : November, December, January and February e - Equinoctial months : March, April, September and October

j - June solstice : May to August

Results for all seasons, added up, have been designated as the 'year' which is indicated by the letter 'y'. The first four harmonics of solar tide and lunar phase law and partial tides together with their probable errors are determined by the procedure given in Chapter 1. The first four harmonics of S for the three elements are listed in Table 2.1. Tables 2.2 and 2.3 give similar harmonics for lunar phase-law and partial tides respectively. The total number of days includes in the analysis for each group is also given in Table 2.1. When compared to the amplitudes, the probable errors in the case of S are very small, < 0.2 nT, and hence they are omitted in Table 2.1. Since lunar phase-law tide is the primary tide in lunar daily variation, the symbol 'L' will generally refer to the daily variations of phase-law tide only.

2.3 Seasonal variation in the harmonics of S and L :

2.3.1 Solar harmonics :

The prominent harmonic of S(H), i.e. S in H, is the diurnal component. The semidiurnal term is quite significant and its amplitude is about 40-50 per cent of that of the first. Though the amplitudes in summer months are the largest, they exhibit little seasonal variation. The phase angles also do not show any significant change with season,

TABLE 2.1 Yearly and seasonal harmonics of S in the three geomagnetic elements, H, Z and D at Alibag for the period 1932-1972. (Amplitudes, s_n, in unit of 0.1 nT and phases, σ_n, in degrees).

Element	Season	Harmonic / No. of days.	n = 1 s_1	n = 1 σ_1	n = 2 s_2	n = 2 σ_2	n = 3 s_3	n = 3 σ_3	n = 4 s_4	n = 4 σ_4
H	y	14125	199	285	94	102	36	308	11	151
	j	4725	208	283	105	101	30	299	6	183
	e	4716	206	284	104	99	49	308	18	152
	d	4684	183	288	73	106	29	318	10	129
D	y	14097	62	40	65	238	58	73	20	280
	j	4716	128	30	121	244	81	81	15	323
	e	4709	69	38	77	234	74	72	28	272
	d	4672	28	151	6	131	23	50	21	263
Z	y	14092	51	83	49	301	47	137	18	345
	j	4709	88	83	79	300	61	140	13	20
	e	4706	75	86	61	304	59	140	26	340
	d	4677	11	295	9	282	20	120	18	328

TABLE 2.2 Yearly and seasonal harmonics of lunar phase law tide, L, in the three geomagnetic elements, H, D and Z for the period 1932-1972. (Amplitudes, l_n, and probable errors, pe, in units of 0.01 nT and phases, λ_n, in degrees)

Element	Season	n = 1			n = 2			n = 3			n = 4		
		l_1	pe	λ_1	l_2	pe	λ_2	l_3	pe	λ_3	l_4	pe	λ_4
H	y	68	07	345	72	06	165	32	04	0	08	03	207
	j	48	15	351	36	12	174	14	11	13	14	10	286
	e	29	15	354	48	11	139	27	07	348	10	06	166
	d	129	14	340	139	09	171	57	05	2	15	04	177
D	y	23	04	146	44	03	343	38	02	125	09	01	322
	j	65	08	95	126	05	285	81	03	105	02	03	159
	e	24	06	83	40	06	288	58	04	88	21	03	272
	d	66	05	221	148	04	54	64	03	220	24	02	8
Z	y	36	03	174	30	02	33	55	02	205	13	01	45
	j	56	05	184	73	04	334	72	03	172	02	02	277
	e	43	05	128	38	03	322	63	02	174	17	02	358
	d	30	05	213	106	04	99	88	03	259	31	02	71

TABLE 2.3 Yearly and seasonal harmonics of lunar partial tide in the three geomagnetic elements H, D and Z at Alibag for the period 1932-1972. (Amplitudes, l_n, and pe in 0.01nT and phase, λ_n, in degrees)

Element.	Season	n = 0			n = -1			n = -2			n = -3			n = -4		
		l'_0	pe	λ'_0	l'_1	pe	λ'_1	l'_2	pe	λ'_2	l'_3	pe	λ'_3	l'_4	pe	λ'_4
H	y	90	83	85	27	07	196	15	06	173	03	04	270	03	03	15
	j	245	205	191	56	15	139	18	12	278	14	11	61	17	10	13
	e	86	305	100	19	15	200	05	11	118	13	07	276	04	06	32
	d	363	230	40	55	14	250	49	09	156	12	05	226	08	04	26
D	y	55	28	313	13	04	341	16	03	19	09	02	151	05	01	8
	j	161	68	11	34	08	349	42	05	59	21	03	160	05	03	5
	e	86	98	291	13	06	20	09	06	333	26	04	150	05	03	9
	d	97	93	226	12	05	244	21	04	306	20	03	349	06	02	7
Z	y	126	37	314	11	03	10	07	02	340	09	02	0	06	01	6
	j	238	56	337	33	05	2	18	04	51	06	03	358	09	02	9
	e	100	101	272	29	05	84	19	03	353	06	02	68	08	02	10
	d	79	82	302	22	05	268	23	04	241	20	03	349	09	02	35

indicating that the changes in the form of S(H) with season are negligible. Unlike S(H), the amplitudes of the first three harmonics of S(D) and S(Z) are of comparable magnitude and undergo strong seasonal variation with the largest values in summer and the least in winter. Thus, the seasonal variations of S at Alibag are of the type expected of a northern hemispheric station. The phase angles of $S_1(D)$, $S_2(D)$ and $S_1(Z)$, the subscript indicating the harmonic number, show a phase difference of about 120°, 110° and 210° respectively between summer and winter months.

It is interesting to note that i) the proportion in which different harmonics constitute solar daily variation in H and D (or Z) are significantly different and ii) the seasonal changes in D as well as in Z are greater then those in H. Variation in D is a consequence of the variation in the meridional, north-south (N-S) currents and variation in H is due to variation in the zonal, east-west (E-W), currents. The time dependence of H and D variations is determined by the product of a term representing the ionospheric movement and a sum of the terms representing the variations of ionospheric conductivity. Since all components of the conductivity tensor, i.e. either N-S or E-W, depend strongly on the electron density, it is unlikely that the relative sizes of all the components will change differently either with local time or with season. Hence differences in the characteristics of S(H) and S(D) apparently result from corresponding differences in the N-S and E-W components of ionospheric winds.

Radar observations of meteor tail by Greenhow and Neufeld (1961) have supplied some information about the winds in 80-100 km region. They indicated dominantly a semidiurnal pattern for the E-W component and a diurnal pattern for the N-S component. Thus, it seems that these differing wind patterns coupled with daily variation of conductivity would produce the observed seasonal variation in S(H) and S(D).

The larger seasonal variation in S(D) than in S(H) further requires the meridional currents to undergo stronger annual variation than the zonal currents. This is in accord with Johnson's (1964) idea that during solstices the asymmetry in the heating of the two hemispheres sets off convection currents at the ionospheric level with a meridional component. Kochanski (1963) also indicated that there is a nett flow directed from the summer to the winter hemisphere.

2.3.2 Lunar Harmonics :

2.3.2a Phase law tides :

With the exception of $L_1(H)$ during equinox and $L_3(H)$ in summer all the first three harmonics of L given in Table 2.2 are statistically well determined. L(H) is mainly composed of lunar diurnal and semidiurnal oscillations of comparable magnitude but in L(D) and L(Z), like in S(D) and S(Z), first three harmonics have larger amplitudes. The amplitudes of all the harmonics systematically have higher values in winter except for $l_1(Z)$ and $l_3(D)$. Amplitudes are in general minimum during equinox. It is interesting to note that phase angles of $L_2(D)$ during j and e seasons are nearly same, but differ by about 230° from that of d season. Significant phase differences between d and j seasons can also be seen in the phase angles of $L_2(Z)$ and $L_1(D)$. The magnitude of variation in the phase angles of $L_1(D)$ and $L_2(D)$ between the seasons is such that they produce equal but opposite changes in the time of maximum of the respective waves.

The seasonal variations in $L_2(H)$ observed here are in agreement with results obtained earlier for the same station using data for low solar activity years 1950-1954 (Raja Rao, 1962a), for high solar activity years 1958-1961 (Rao, 1972a) and for the period 1931-1966 (Raja Rao and Reddy, 1973). Onwumechilli and Alexander (1959) noticed seasonal variation in $L_2(H)$ at Ibadan similar to that of Alibag. At Kodaikanal also similar seasonal variations were observed (Raja Rao, 1961; Rao, 1972a). In general, the seasonal variation of the amplitudes at these stations, though in the northern hemisphere, appears to be similar to that of southern hemispheric stations, e.g. Huancayo, Apia (Raja Rao, 1962b).

On the other hand, the variations at Honolulu and San Juan are of the type expected for northern hemispheric stations (Raja Rao, 1962b; Sharma and Rastogi, 1970). Demonstrating a closer association of the amplitudes of lunar variations with the geomagnetic or magnetic latitude rather than with the geographic latitude, Raja Rao,(1962b) explained the similarity between seasonal variations at Kodaikanal, Alibag and Ibadan and those at Huancayo and Apia by envisaging that the southern hemispheric current system in the ionosphere would extend at least upto 10°N geomagnetic latitude in northern winter. He based his speculations on his study of $L_2(H)$ amplitudes. It may be recalled that L_2 is not purely of ionospheric origin but contains contribution from oceanic dynamo (Malin, 1970) which may be considerable at coastal stations like Alibag. The contributions of oceanic and ionospheric dynamos of L have been studied in Chapter 6 where it is found, among other features, that while the phase of L_2 and its seasonal progression is primarily determined by ionospheric part, there are marked differences in the seasonal behaviour of the amplitudes. For example, the amplitudes of the ionospheric part in D and Z are maximum in summer, whereas the corresponding amplitudes of L_2 have maximum values in winter. Thus the postulation of the penetration of southern hemispheric currents into the northern hemisphere, based solely on the fact that the amplitude of

L_2 is larger during winter than in summer, may not be tenable. More relevant would be an investigation of either the daily variations of D and Z in the seasons, which are expected to show phase reversal between winter and summer months if the above expected penetration takes place, or by determining the direction of equivalent current system responsible for L_2. This is studied in section 2.4.

2.3.2b Lunar Partial Tides :

An obvious feature of Table 2.3, where the lunar fortnightly tide together with partial tides corresponding to n=-1, -2, -3 and -4 in H,D and Z at Alibag are listed, is that when compared to the phase law tide, the magnitude of the partial tide terms, particularly n=-1 and -2, is not negligible and, thus, warrants their inclusion in the expression for geomagnetic potential.

No consistent seasonal variation is seen in the amplitude and phase of the various harmonics. However, there is a suggestion that the amplitude of the first harmonic of partial tide is larger during summer. This may be ascribed to the enhanced and complex nature of ionospheric conductivity at this time of the year, as the solar zenith angle is minimum at local noon in the region of the latitude of Alibag.

Fortnightly tide (n=0) in D during j season and in Z during y and j seasons are significantly determined but are considerably smaller than those obtained by Rao and Sastri

(1972) for high solar activity period, 1958-1961. They observed that prominent fortnightly tides in H during e and j seasons are associated, especially at the electrojet stations, with larger amplitudes of the second harmonic of partial tide and with weaker fortnightly tide in d-season the first and third harmonics become prominent. No such association is, however, seen in the present analysis of long series of Alibag data. The feature observed by them may, therefore, pertain to the lunar tide in the equatorial electrojet region only.

2.4 Daygraphs and Vectograms of S and L :

The magnitude of variation at any instant is governed by both the amplitude and the phase of the different harmonics into which the variation is approximately resolved. Two methods of representation of the simultaneous changes in amplitude and phase have been devised, viz., the daygraph and the vectogram. The daygraph is a representation of the variation in the 24-hourly values synthesized generally from the first four harmonics. A vectogram is a graph of the simultaneous variation in any two of the components of the field. Vectographic representation of the daily variation of geomagnetic field in the horizontal plane, i.e. graph between H and D hourly inequalities, has the added advantage of showing the pattern of change in the overhead ionospheric currents responsible for the variation, when the vectors are rotated through a right angle in the clockwise direction. The expected progression of vectograms is in clockwise sense to the north and counter-clockwise to the south of the focus in the northern hemisphere and vice versa in the southern hemisphere.

The first four harmonic coefficients have been used to compute for each element and season a sequence of 24 hourly values, h_i, (reckoned from local midnight) 0, 1, 2, ..., 23. The sequence represents S or L as departures of hourly values from the daily mean value of the element. The following formulae have been used in synthesizing the harmonic coefficients of S and L :

for S :

$h_i = \sum_{n=1}^{4} s_n \sin (ni +$ [illegible] ... (1)

for L :

$$h_i = \sum_{n=1}^{4} l_n \sin (ni - 2\nu + \lambda_n) \quad \ldots \quad (2)$$

As the sequence is calculated from only the first four harmonic coefficients, it represents a slightly smoothed version of S or L. Fig.2.1 illustrates the yearly and seasonal daygraphs for S and L in all the three elements. Figs. 2.2 and 2.3 give yearly and seasonal vectograms in the horizontal plane for S and L respectively. The numbers along the vectograms give the local time in hours. In vectograms, the part traversed during the hours of daylight is drawn thicker than the part described at night, night and day are

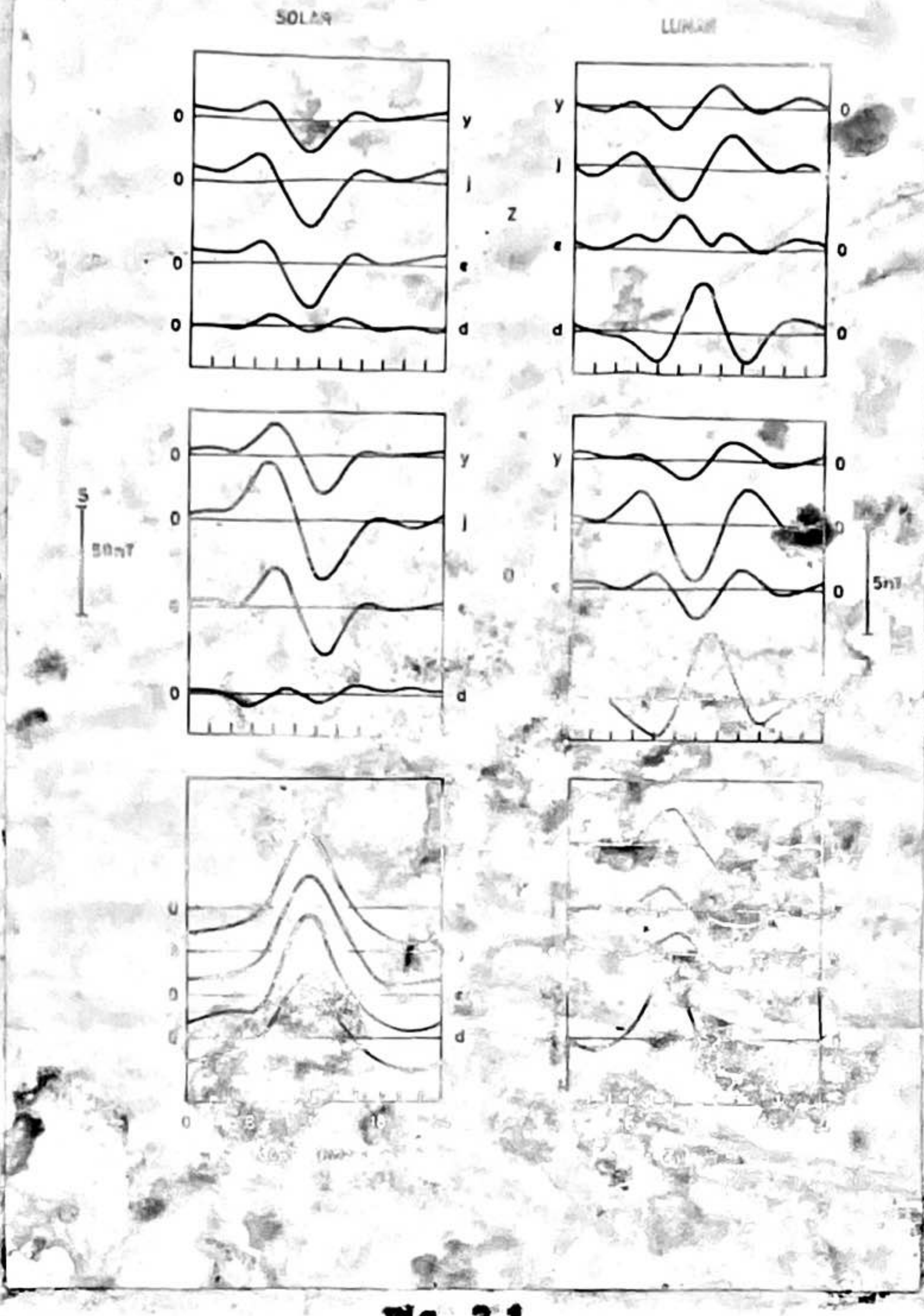

Fig. 2.1

Yearly (y) and seasonal (j,e,d) daygraphs of S and L in H, D and Z at Alibag. Lunar daygraphs refer to the epoch of new Moon. The scale of L curves is ten times the scale for S curves.

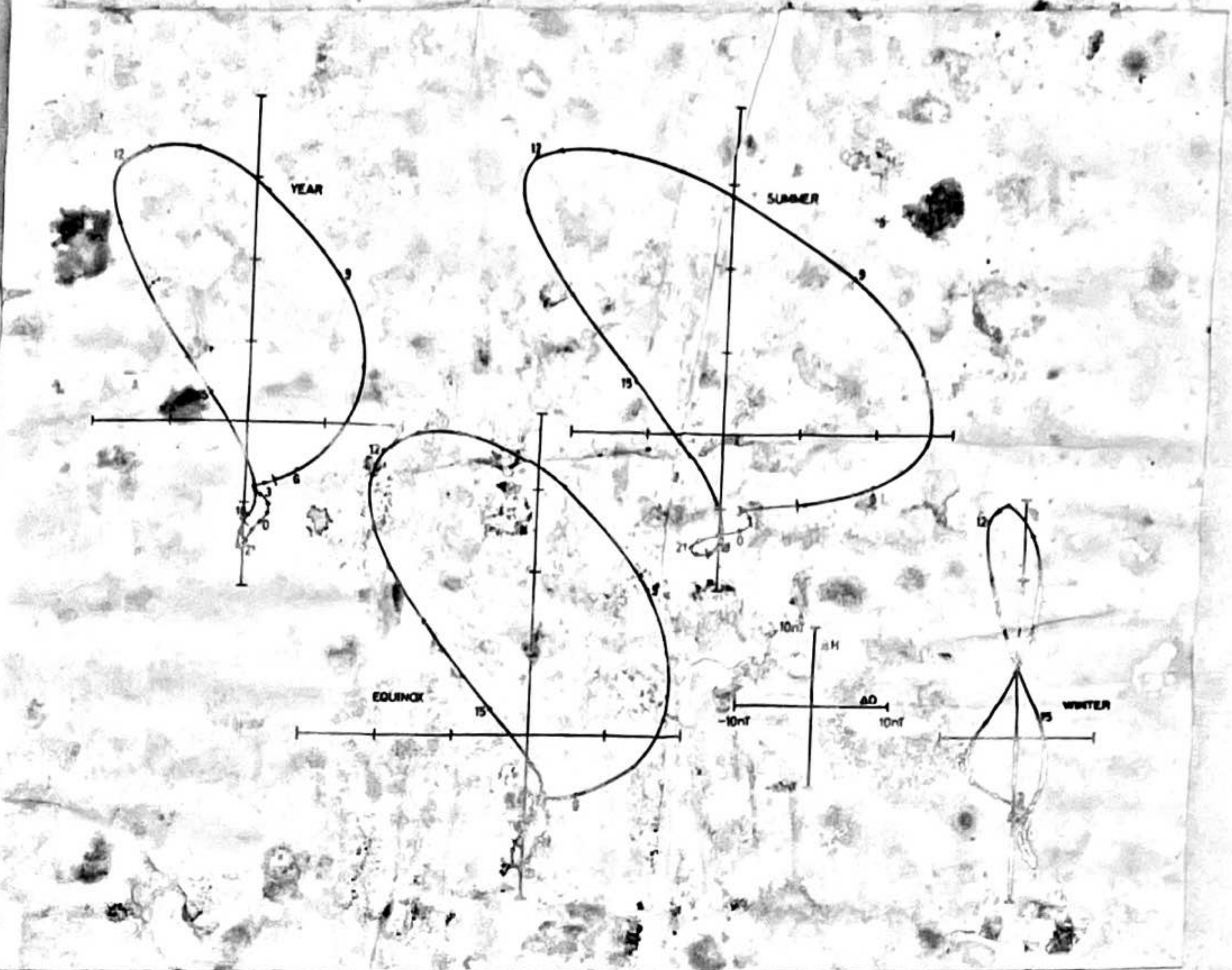

Fig. 2.2

Yearly and seasonal vectograms of S(H) at Alibag. Some solar hour points are numbered and others are marked. Day and night portions are separated by short lines across the curve.

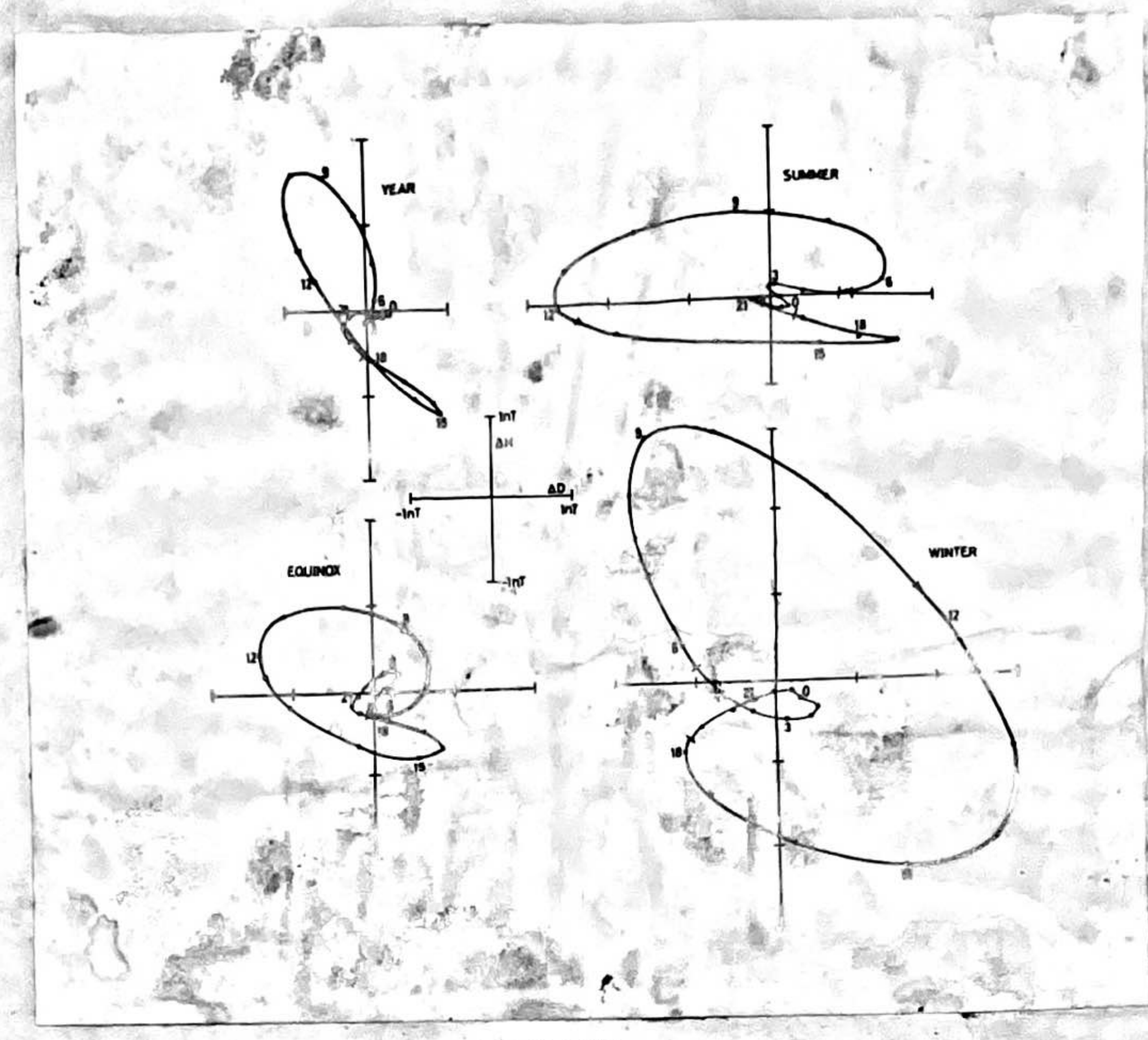

Fig. 2.3

Yearly and seasonal vectograms of L($\overline{H}$) at Alibag. The curves refer to the epoch of new Moon. The numbers along the curves give local solar hours. Day and night portions are separated by short lines across the curve.

also separated by vertical bars across the curve. The vertical bars, during any season, correspond to the average of the earliest and the latest time of sunrise or sunset at a height of 110 km, this being the probable height at which the electric currents responsible for S and L flow. The L daygraph and vectograms refer to the epoch of new Moon ($\nu = 0$). The largest range, i.e. algebraic difference between the maximum and minimum values of the daygraph or the dimension of vectograms, shows approximately the maximum change in the current intensity over the station during a day. Since the pattern of daygraph and vectogram changes with lunar age, the calculation of average lunar range or dimension is more difficult to define. Following Chapman, Gupta and Malin (1971), the lunar range, R(L), is calculated by the expression :

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

where l_n is the amplitude of the n^{th} harmonic of phase law tide. R(L) represents the difference between the greatest and the least values that L can attain over a long period. The probable error of R(L) is given by

$$\rho = 1.146 \left[\sum_{n=1}^{4} \rho_n^2\right]^{\frac{1}{2}}$$

where ρ_n is the probable error of the amplitude of n^{th} harmonic. However, solar range, R(S), is simply computed as the difference between the greatest and the least of the 24 values of S synthesized at hourly intervals. The probable error of R(S) is also computed from the above relation using probable errors of the solar harmonics. S and L ranges thus defined are used throughout the thesis unless otherwise stated.

2.4.1 Seasonal variations in Daygraphs and Vectograms :

2.4.1a Solar terms :

The general distribution of the Sq variation over the Earth has the expected pattern, namely that which would result from an ionospheric current system and its complementary induced earth current system. (For example see Matsushita, 1967). It is seen from Fig.2.2 that the form of the vectogram, i.e. the sense of progression of horizontal field vector, $S(\bar{H})$, during summer, equinox and for the average of all the seasons, viz. the year, is similar and is of the pattern that would result from the northern hemispheric current system. The range of daygraph and the dimension of vectogram are the largest during summer and smallest in winter. But both the daygraph (Fig.2.1a) and the vectogram (Fig.2.2) for winter are of complex nature.

From a study of the daygraph of Sq(Y), quiet-day variation of the easterly component, in the equatorial region, Price and Stone (1964) have shown that the boundary line between the northern and the southern current system crosses and recrosses the magnetic equator during all seasons. Mayaud (1967) has shown that the phenomenon of invasion of Sq current of one hemisphere into the other is extremely frequent, particularly at the winter solstice of either hemisphere. The daily variation of declination in the equatorial region of the northern hemisphere is characterized by a morning eastward maximum around 06-08 LT and a westward minimum around 13-14 LT. The effect of the incursion of the southern current system into the northern hemisphere is registered in declination as a westward depression in a mainly eastward field in the morning hours and it generally occurs before the morning maximum. Similarly an invasion in the evening produces an eastward maximum in a mainly westward field and generally occurs after the westward minimum (Mayaud, 1967). The daygraph of D for winter in Fig.2.1a shows these secondary effects clearly. These secondary effects may at times tend to dominate the normal maximum and minimum. The vectogram of D for winter in Fig.2.2 also shows that while the sense of rotation of the S(H) vector between 08 and 13 LT is anticlockwise and is the same in all the seasons, it becomes clockwise between 03-07 LT and again between 14-18 LT in the d-season, which leads to the conclusion that the ionospheric currents that control S(H) and S(D) during these hours have a clockwise flow and, clockwise flow characterizes the southern hemispheric current system north of its focus.

This suggests that the incursion of southern current system during winter is as far north as Alibag. Price and Stone (1964) estimated the geographic latitude of the boundary between the northern and southern current systems during winter at midday local time to be $11^{o}N \pm 2$ for western Asia. The present results, however, indicate that during morning and evening the boundary is at least as high as the latitude of Alibag.

2.4.1b Lunar terms :

As mentioned earlier, the lunar daily variation changes from day to day so that the pattern of L repeats itself after an interval of half a lunar month, approximately 14.7653 solar days. For a complete study of the changing pattern during half a lunation, lunar phase law and partial tides for different ages of the Moon are plotted against local solar time as abscissa and lunar age (ν) as ordinate (Winch 1970a). for H,D and Z and are shown in Fig.2.4 a,b and c respectively. Lunar phase law tides for different values of ν were obtained from equation (2) and partial tides were synthesized from the expression given below :

$$h_1 = \sum_{n=1}^{4} l'_n \sin (nt + 2\nu + \lambda'_n) \quad \ldots \quad (3)$$

The noteworthy features of Figs.2.1b, 2.3 and 2.4 a,b,c are the following:

(i) The contour lines for lunar phase law tides in Fig.2.4 a,b,c are concentrated mostly in the daylight portions and very few lines are seen during night portions of the diagrams.

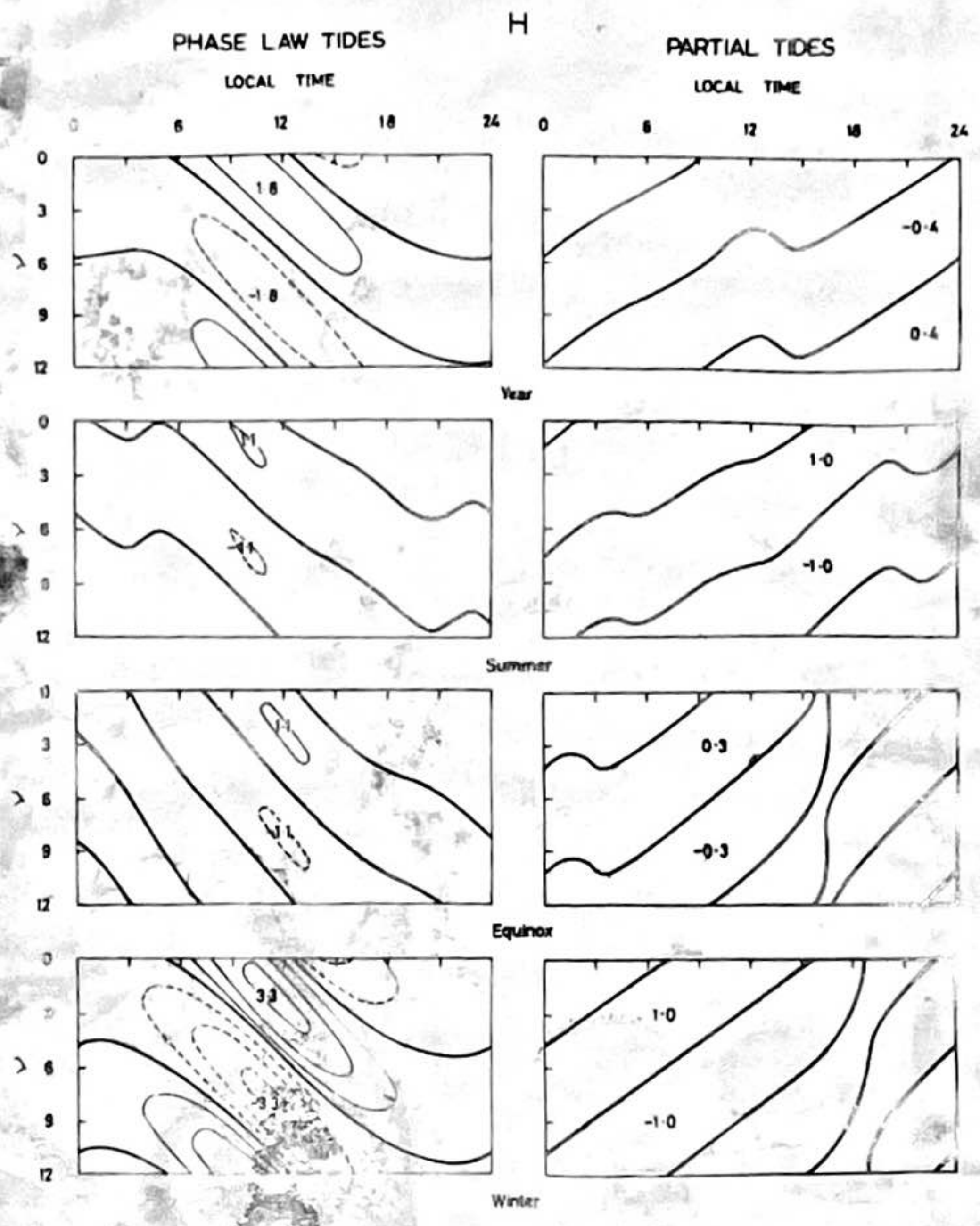

Fig. 2.4a

Contour diagrams of lunar phase law and partial tides in H at Alibag as function of lunar age (ν) and solar time in different seasons and the year.

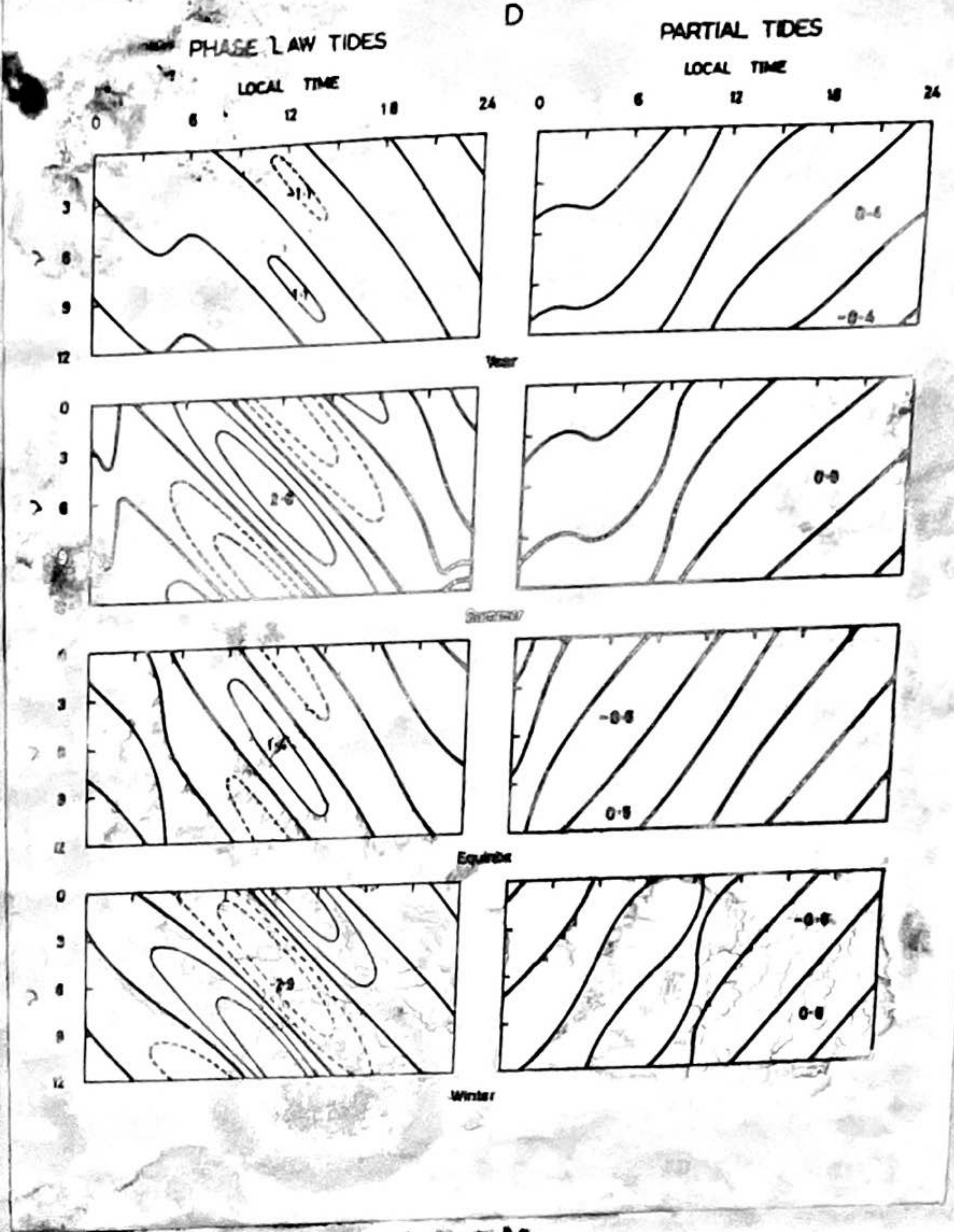

Fig. 2.14b

Contour diagrams of lunar phase law and partial tides in D at Alibag as function of lunar age (ν) and solar time in different seasons and the year.

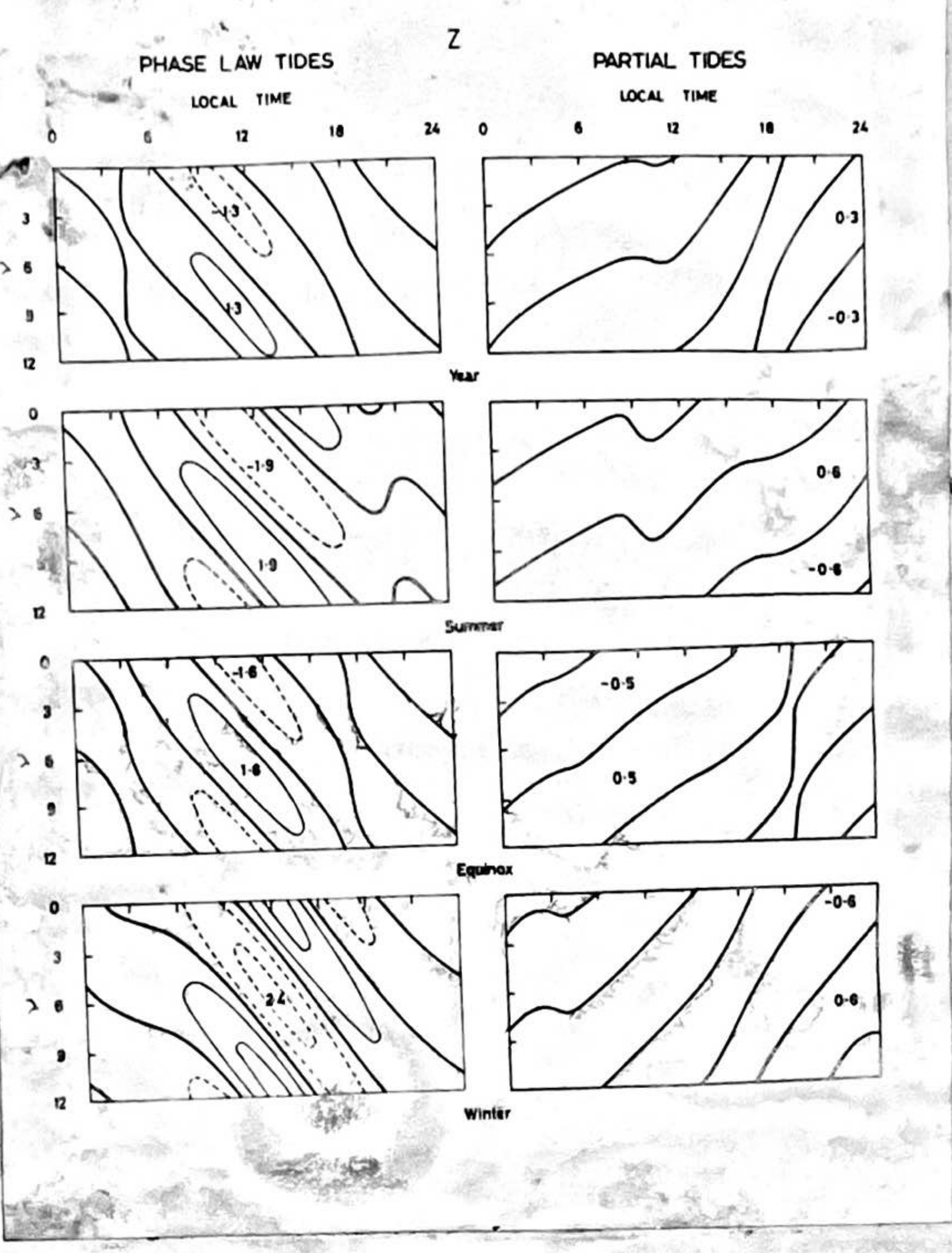

Fig. 2.4c

Contour diagrams of lunar phase law and partial tides in Z at Alibag as function of lunar age (ν) and solar time in different seasons and the year.

This clearly brings out the luni-solar nature of lunar phase law tides. However, the effect of lunar partial tide is the same during both the day and the night.

(ii) The variation of L with lunar age at any solar hour shows one high (positive) and one low (negative) value, indicating the dominance of lunar fortnightly harmonic in the lunar variation. The amplitude of the fortnightly tide is largest around local noon in all the elements and in all the seasons. This is in sharp contrast to the results for San Juan (Sharma and Rastogi; 1970), a mid-latitude station, where the lunar semimonthly oscillation in H is nearly the same at all solar hours. But the results are in agreement with the results of Rastogi and Trivedi (1970) and Sen and Rao (1973) who find that daily variation of the amplitude of lunar semimonthly tide in H at equatorial stations is in the same way as the intensity of Sq(H), viz. maximum around local noon.

(iii) The lunar phase law tides are the largest in winter and the least in equinox. The summer values are comparable to the winter values in D and Z, while in H they are closer to the equinoctial values. Another striking feature of Fig. 2.1b and 2.4b,c is that, in D, the daily variation of L during d season is nearly in phase opposition with that in both j- and e- seasons and resembles that of a typical southern hemispheric station. It is seen from Fig.2.3 that during most of the daylight hours the direction of traverse of the vectogram in d season is clockwise and is opposite to that in j season, indicating that the current system responsible for L variation at Alibag in the d season is clockwise in direction around morning hours which may be identified as the first day-time loop of southern hemispheric current system associated with L.

(iv) The amplitudes of partial tide in d and j seasons are comparable and are slightly larger than that in e season. In H, the amplitudes of phase law and partial tides are of comparable magnitude during summer.

2.5 The ratio of S to L :

For the purpose of estimating the relative strengths of S and L, the solar and lunar ranges, R(S) and R(L) respectively, as defined earlier are considered. The ratios of R(S) to R(L) in the three elements are given in Table 2.4 for different seasons and the year. The ratio R(S)/R(L) varies from element to element and from one season to another. Considering all the elements, S variations averaged over all the seasons, i.e. in year, are about 12 times larger than the corresponding average L variations at Alibag. Large variations in the seasonal ratios are probably due to the differing seasonal variations in S and L.

2.6 The relative changes of S and L with season :

The ratio of summer to winter seasonal range which is

TABLE 2.4 Ratio of solar range to lunar range, during different seasons and years, for the three geomagnetic elements and their mean.

Season	H	D	Z	Mean
y	13.6	14.1	8.9	12.3
j	22.1	9.8	8.9	13.6
e	23.4	13.7	9.6	15.6
d	6.5	1.7	1.6	3.3

often used as an index of seasonal change is not quite suitable for Alibag because the minimum range is not observed always in the same season uniformly in all the elements. Following Gupta and Malin (1972), the ratio of the range for a season to the annual mean range is used as a measure for comparison of seasonal variations of S and L. The ratios of seasonal to yearly ranges for both S and L are computed for each element.

The probable error of this ratio is given by the expression :

$$\rho' = \frac{\left[\rho^2(\text{season}) + \text{Ratio}^2 \times \rho^2(\text{year})\right]^{\frac{1}{2}}}{\text{Range(year)}}$$

The mean ratio of the three elements for each season is obtained by weighing the ratios for different elements for a particular season by the inverse square of the respective probable errors (ρ')

$$\bar{R} = \frac{\sum_{n=1}^{3} W_n R_n}{\sum_{n=1}^{3} W_n}, \text{ where } W_n = \frac{1}{(\rho'_n)^2}$$

The probable errors of $\bar{R}$ is given by the relation :

$$\rho = \left[\frac{1}{\sum_{n=1}^{3} W_n}\right]^{\frac{1}{2}}$$

Ratios and their weighted means are given in Table 2.5 both for S and L terms.

In the case of S, the ratios, in general, behave as expected, being greatest for the summer season and least for the winter season, except for H where the maximum ratio

TABLE 2.5 Ratio of seasonal range to yearly mean range for S and L in the three geomagnetic elements and their weighted mean.

Element	SOLAR TERMS			LUNAR TERMS		
	j/y	e/y	d/y	j/y	e/y	d/y
H	1.01	1.09	0.91	0.62±0.10	0.63±0.07	1.89±0.11
D	1.67	1.22	0.32	2.40±0.08	1.25±0.06	2.65±0.08
Z	1.51	1.29	0.34	1.51±0.08	1.20±0.04	1.90±0.05
Weighted mean: H+D+Z	1.40	1.17	0.52	1.57±0.03	1.11±0.03	2.08±0.04

Probable errors of ratios for solar terms are not given, since in all cases they are small, none exceeding 0.01nT.

is observed for equinox. Yacob (1966) also showed that monthly quiet-day ranges at Alibag exhibit equinoctial maximum. He infers that this phenomenon may arise, as suggested by Appleton (1964), from the two contributing factors, namely ionization of the conducting layer and atmospheric tidal oscillations becoming more in phase at the equinoxes than at the solstices. However, when all the elements are combined, the highest ratio is obtained for summer. The mean ratio of summer to winter range is about 2.7. This value is higher than the corresponding ratio given by: Matsushita and Maeda (1965a) for total Sq equivalent current system for IGY period; Gupta and Malin (1972) from the global data of IGY and also that obtained from seven stations with long series of data. However, the value obtained is in agreement with the theoretical value given by Zaytsev (1968), in his study of the longitudinal, i.e. effect of universal time, and seasonal variation of Sq based on the flux of ultraviolet radiation absorbed by each dynamo region. The study has shown among other features, that at 4 UT, when the focus of Sq current system is approximately above Asia, the summer to winter change of the absorbed flux of wave radiation will be 2.7 for northern hemisphere. The agreement between the theoretical and observed values suggests that the causative source of seasonal variation in Sq is essentially the wave radiation from the Sun.

The picture is very different when the ratios in Table 2.5 for R(L) are examined. For all the three elements the ratios are in general largest for the d-season and smallest for e-season. The overall seasonal variation averaged over all the elements given by the ratio of winter to equinox range is 1.78 ± 0.03. Since the nature of seasonal variation of L at Alibag due to the incursion of southern hemispheric current system is remarkably different from that observed for other northern middle-latitude stations, no direct comparison with other stations, of the extent of seasonal changes, is possible. However, it may be noted that at Alibag the percentage change of L from minimum to maximum is less than the corresponding change observed for S, during the course of a year.

2.7 Alibag in relation to the position of overhead current systems of S and L :

Since the various components of conductivity tensor are not expected to vary differently with season, one would expect, if the seasonal changes in S and L were only due to changes of conductivity, the nature and magnitude of seasonal changes of S in all the three elements to be the same eventhough they may differ from the corresponding variations in L which may be explained on the assumption that S and L currents flow at different heights in the ionosphere. But different elements show differing seasonal progression and daily variations in different seasons show significant departures from the respective expected patterns. This warrants an inference of the seasonal movement of the overhead current system of S and L. While the geographical distribution of Sq current system is known with fair accuracy, the distribution and pattern of current system for L is very much less well ascertained. This is primarily because most of the workers, in their attempts to determine the overhead currents, considered only the semidiurnal term and thus ignored the important difference between the day and night time variations. However, the more recent attempt by Malin (1973) to determine the overhead currents for different epochs of UT and for different ages of the Moon reveals that four of the vortices of L current system falling during the daylight hours are enhanced and the resulting pattern of daily variation in H and D, though primarily semidiurnal, will nearly have the same latituinal distribution as those of S(D) and S(H), viz. daily variation in H is maximum near the equator and minimum at the focus and for D, the amplitude decreases from the latitude of focus towards that of the boundary. Hence the ratio of daily range in H to that in D, hereafter referred to as ratio H/D, may roughly indicate the position of the observatory with respect to the overhead current system. The ratio would be zero at the latitude of focus and will increase as one moves towards the boundary of current system. In other words smaller the ratio closer is the focus to the station and higher the ratio nearer the boundary. However, it may be noted that this interpretation of the ratio H/D is possible only when the movement of the foci of current systems and displacement of the boundary between the northern and southern current systems are similar and this would be expected if the entire current pattern moves as a whole with the seasons. The results of Gupta (1973) and several other workers have revealed that both northern and southern current systems move in the same direction as a rigid system and the boundary crosses and recrosses the equator with season.

The ratio H/D for S during year and j,e and d seasons are 1.52, 0.93, 1.36 and 4.27 respectively. The corresponding ratios for L are 1.58, 0.41, 0.80 and 1.13.

The ratio H/D for S is least during the summer and its value, 0.93, suggests that D variation is slightly greater than the H variation, a characteristic feature of a mid-latitude station. In the other seasons the ratio is greater than one indicating that H variations are larger than the variations in D, a common feature of low-latitude or equatorial zone. These ratios imply that during summer focal latitude is closest to Alibag. During winter this value tends to be very large and as already seen, D variation exhibits, during the day, the characteristics of both the northern and southern hemispheric stations. It may be inferred that northern hemispheric current system is shifted northward so that Alibag is close to the boundary between northern and southern current systems and the focus of northern system is farthest north in winter. This is in sharp contrast to the earlier results of Matsushita (1960), Price and Stone (1964) and Gupta (1973). They have all shown that the focal latitude in summer is higher than that in winter for the IGY period. On the other hand, using data for the second polar year, Ota (1949) and Hasegawa (1960) showed that the position of the focus shifts towards the pole in winter and towards the equator in summer. The same conclusion is reached by Bartels (Chapman and Bartels, 1940) from the spherical harmonic analysis of geomagnetic data obtained in the sunspot minimum year of 1902. Shiraki(1973) in his study of the seasonal progression in the focal latitude of northern current cell for different phases of solar activity finds that during quiet solar activity the focus would be at a higher latitude in winter but during high solar activity the focus would be at a higher latitude in summer. Chapman and Fogle (1968), from the study of seasonal daygraph of S(X) at San Fernando, averaged over 1911-1960, find the focus to be at a slightly higher latitude in winter than in summer, as also indicated by the present analysis. Thus, it appears that seasonal progression in the focal latitude for average condition of solar activity is similar to that obtained for low solar activity years. For L also ratio H/D is found to be the least during j-season but is smaller than the corresponding ratio for S and indicates that, in summer, L focus is nearer to Alibag than S focus because the smaller this ratio, closer is the focus. This leads to the conclusion that L focus is at a lower latitude than S focus. This is in conformity with the results of Matsushita and Maeda (1965a,b) who have reported the average position of northern focus for S and L to be 34^{o} and 20^{o} dip latitude respectively.

The interpretation of winter ratio for L is more complex because during this season the sense of rotation of the field vector is opposite to that expected for a northern hemispheric station. If it is accepted that variation at Alibag during winter is associated with southern hemispheric current system, then the value of 1.13 of ratio H/D for winter would require the penetration of southern current system far beyond the latitude of Alibag so that it could produce daily variation in H and D of comparable magnitude but of the type expected for southern hemispheric station. But a question arises whether a deep penetration of this magnitude is feasible or whether this is the effect of ocean dynamo whose effects are not removed. When the ratios H/D are recomputed afresh using ranges corrected for the effect of oceanic dynamo (defined in Chapter 6), ratio H/D for summer and winter are 0.48 and 1.49. Winter value, though enhanced, is still less than the corresponding value for S and still requires the boundary of the southern current system to be north of the latitude of Alibag.

Rougerie (1967) showed that at Chambon la Foret (Geog. lat. 48°01'N, dip lat. 46°) lunar daily variation in H during summer and winter show reverse trends. His $L_2(H)$ variation for summer and winter when compared with L_2 pattern given by Matsushita and Maeda (1965b) warrants the conclusion that in winter the station is to the south of focal latitude indicating that focus of L is at a higher latitude than the latitude of Chambon la Foret. Further support that focus of L is at a higher latitude during winter than in summer comes from the examination of lunar harmonics of H at Trelew (Geograph. lat. 43°15'S, Geomag. lat. -32° dip lat. -22°) reported by Affolter and Schneider (1972). Examination of the results given in their Table 1 for whole period (1958-1966) shows that the first two harmonics of L(H) are nearly in phase opposition. Nature of $L_2(H)$ variation suggests that the focus of L is to the south of the station in j-season (winter at Trelew) and to the north of the station in d-season (summer). Hence from the features of L at Chambon la Foret, Trelew and those observed at Alibag, it appears that northern and southern foci of L current system move, as a rigid system, in the same direction so that during d-season, northern foci have shifted northward as high as the latitude of Chambon la Foret and in turn Alibag comes fully under the control of the southern hemispheric current system. During j-season, southern foci is to the south of Trelew and northern foci is closer but north of Alibag.

2.8 <u>Summary</u> :

The various harmonics of S and L contribute in different proportions to the daily variation of H,D and Z. The dominant harmonics in the case of H are the first two harmonics, while in D and Z, amplitudes of the first three harmonics are nearly equal and account for most of the daily variation. On an average, solar daily variation is approximately 12 times larger than the lunar daily variation but owing to their radically different seasonal progressions ratio of the range of S to that of L is highly variable. In general, seasonal progression of S in the three elements is of the type expected for a northern hemispheric station. The solar daily variations in D and Z during winter are complex due to the northward incursion of southern current system in the early morning and in the late evening hours.

In contrast to S, the seasonal progression of L is markedly different. Amplitudes at their maximum are largest in winter and least in equinoxes. The daily variation of L(D) shows almost a complete reversal of phase between winter and summer. The study of the daygraphs of L(H), L(D), L(Z) and the vectograms of $L(\bar{H})$ in the horizontal plane reveals that L at Alibag during winter months is under the control of the southern current system. When all the elements are considered the percentage change in S during the course of the year is greater than the corresponding change in L. Results, though based on a simple assumption that the value of the ratio of range in H to that in D is indicative of the position of the observatory in relation to the overhead current system, have suggested several interesting features : seasonal movements of the current vortices associated with S and L are in the same direction and the extent of seasonal movement of the foci associated with L is much more than that for S. During summer, L-foci are closer to Alibag than the S-focus. In winter because the L-foci shift northward to as high as the latitude of 40°N, Alibag comes fully under the control of the southern hemispheric current system.

The amplitudes of partial tide in d and j seasons are comparable and are slightly larger than those in e season.

CHAPTER 3

SOLAR CYCLE INFLUENCE ON SOLAR AND LUNAR DAILY VARIATIONS

Solar Cycle Influence on Solar and Lunar Daily Variations

3.1 Introduction:

The influence of solar cycle on the quiet-day solar daily geomagnetic variation (S_q) has been studied from very early days. Ellis (1880), Wolf (1892), Chree (1903) and Moos (1910) made significant contributions to this aspect of solar-terrestrial relationship. Studies of this subject upto about the year 1936 were summarized by Chapman and Bartels (1940). Immediately after the recognition of sunspot cycle control of the electron density in the ionosphere, attempts were made to associate it with the already well known sunspot cycle variation in the quiet geomagnetic field. From the similarity of solar activity dependence of quiet-day solar range of East component (Y) at Abinger and Hartland and the electron density of ionospheric E-region at Slough, Appleton (1964) concluded that overhead Sq currents flowed in the E-region. He thence deduced that the solar-cycle effect on the range of Sq could be entirely attributed to variation of E-layer conductivity. Matsushita (1968) observed that the dependence of first three harmonics of Sq was larger than that expected by the increase of E-region conductivity and attributed this to the enhancement of the amplitude of thermal tides as sunspot maximum. While the increase of S with sunspot number has never been in doubt, the mechanism responsible for this increase with solar activity is still not clearly understood. If the changes in S with sunspot cycle is only due to the changes in ionospheric conductivity, one would expect L and S to increase in the same proportion from sunspot minimum to sunspot maximum. Although this test sounds very simple, its application has proved remarkably difficult. Firstly, the assumption of the origin of S solely due to the dynamo action is over simplified, since there are other contributions to S (such as contributions from non-ionospheric sources) and L (such as an oceanic dynamo contribution), and neither the thermal tides nor the non-ionospheric contributions may be independent of sunspot number. Secondly, there has been considerable disagreement over the observational evidence regarding the dependence of L on solar activity. Views of research workers are conflicting on this subject. Chapman, Gupta and Malin (1971), have listed the investigators who supported the association of lunar variation with solar cycle and those who argued against the association. Sabine in 1857, Chambers in 1887 and Figee in 1905 said no association; Broun in 1874 and van der Stok in 1888 said there exists an association. Chapman in a series of papers based on studies of the few good determinations of L then available reached the conclusion that the influence of solar cycle on L is much less than on solar variations. Matsushita and Maeda (1965b) reached a contrary conclusion that the solar activity dependence of L does not differ particularly from that of the S_q field. Gupta (1972) using long series of Sodankylä data found that the influence of sunspot numbers, R_z, on L to be larger than that on S, especially at very high solar activity, and suggested that the effects of increasing sunspot numbers on S and L in low and middle latitude stations are different than those in auroral zone. Chapman et al. (1971) considered the changes in S and L during IGY/C and preceding sunspot minimum at a well distributed set of observatories and reached the conclusion that the influence of R_z on L is only one third that on S. Since the data used were from extremely high solar activity period, they raised the doubt whether the results obtained were valid for all sunspot cycles or for intermediate values of R_z between sunspot maximum and minimum. To overcome this, they also examined longer series of data of a few stations, mostly in high latitudes or near the focus of Sq current system. Shiraki (1973) found the focus of overhead Sq current system to shift systematically with solar activity, particularly in winter months. Thus, the estimation of solar dependence of S using data of stations close to Sq focus will include another component of variability associated with the changing position of the station with reference to the overhead current system. Hence a study of solar cycle responses of S and L from a station quite away from the focus and outside the influence of equatorial electrojet may give a better insight in understanding the mechanism of solar cycle variation of S and L and the differences in their dependence on R_z. Raja Rao et al. (1973) and Raja Rao and Reddy (1973) have analysed the Declination and Horizontal data of Alibag, but they divided the data according to daily sunspot number. Wilkes (1962) has pointed out that the daily sunspot numbers are not sufficient to characterize the level of general solar activity. For this reason along Chapman et al. (1971) excluded the results of Sitka Observatory (Cain 1957) while examining the dependence of solar activity at stations with long series of data. Rao (1972b) divided the Alibag horizontal intensity data for the period of 1925-1969 into ten groups so that the mean R_z for three consecutive three-year periods were in the range 0-50, 51-100 and > 100. He found that the sunspot cycle association in S was three times that of L. However, his results suffer from lack of the determination of probable error associated with Wolf ratio, used as a measure of solar activity dependence. As quoted by Chapman and Fogle (1968) comparisons of solar cycle influence on S and L should be made on the same basis and careful attention should be given to the probable errors. Therefore, in view of this, in this chapter the dependence on solar activity of S and L in the three elements H, D and Z of Alibag over the period of 1932-1972, is examined afresh by dividing the data into four sunspot groups according to the annual sunspot numbers.

3.2 Analysis and Results:

Absolute hourly mean values of the three geomagnetic elements H, D and Z at Alibag for the period 1932-1972 are used in the analysis. The data of each element are first classified into four groups of solar activity: quiet, low, medium and high solar activities with annual sunspot numbers, R_z, in the ranges 0-30. 31-60, 61-100 and > 100 respectively. The annual mean sunspot numbers for the years of data included in the above four solar activity groups are 12.3, 39.5, 79.1 and 134.5 respectively. Days in each of the above groups are further subdivided into three Lloyd's seasons, d, e and j.

Amplitudes and phases of the first four harmonics of solar daily variation, S, Chapman's phase law tides, L, and of partial tide of Schneider (1963) for the three seasons and for the whole period, denoted by y, of each group of solar activity are computed using the generalized method of Winch (1970a), as detailed in Chapter 1. The computed S and L harmonic constants for each element H, D and Z are listed in Tables, 3.1, 3.2, 3.3 and 3.4, 3.5, 3.6. Since most of the harmonics of lunar partial tide are small and poorly determined in e and j seasons, the results for y and d seasons only are presented in Table 3.7. The four groups of solar activity, quiet, low, medium and high are denoted by A,B,C and D respectively in the Tables. Any harmonic is considered to be statistically significant at five per cent level if its magnitude exceeds 2.08 times the corresponding probable error.

All the solar harmonic components (mainly the 1st and 2nd harmonics) are significantly determined and hence the probable errors of solar harmonics are not included in Tables 3.1, 3.2, 3.3. Out of the 192 lunar phase law harmonic components determined for the three seasons and the year of the four groups, only 41 are not significant at 5 per cent level when compared with their respective probable errors.

Table 3.1 Annual (y) and Seasonal (d,e,j) mean harmonic components and range of S in H at Alibag for group of years classified according to annual mean sunspot numbers. Amplitudes(s_n), Range R(S) and probable error (pe) in units of 0.1 nT. Phases (σ_n) are in degrees.

Season	Sunspot Group	Harmonic	n=1		n=2		n=3		n=4		Range	
		No. of days	s_1	σ_1	s_2	σ_2	s_3	σ_3	s_4	σ_4	R(S)	pe
y	A	3462	141	291	71	101	27	306	9	144	363	2
	B	2972	170	288	82	99	31	301	9	146	424	3
	C	3154	207	285	97	104	35	311	10	154	503	3
	D	4537	258	280	118	102	46	310	14	154	614	3
j	A	1098	145	288	79	101	22	299	4	166	365	4
	B	1041	174	284	91	97	26	290	5	166	423	4
	C	1055	220	284	111	104	29	300	5	193	522	3
	D	1531	269	279	130	102	38	303	10	191	621	6
e	A	1196	138	291	78	98	38	305	16	143	384	3
	B	969	175	289	90	97	43	302	15	152	460	5
	C	1045	218	283	107	100	50	310	18	153	556	6
	D	1506	273	279	132	99	63	310	23	156	684	5
d	A	1168	142	293	56	107	21	316	7	137	343	3
	B	962	161	292	64	104	24	313	9	124	393	4
	C	1054	185	290	75	110	28	323	9	136	447	5
	D	1500	231	283	90	104	39	318	13	124	555	4

Table 3.2 Annual (y) and Seasonal (d, e, j) mean harmonic components and range of S in D at Alibag for group of years classified according to annual mean sunspot numbers. Amplitudes (s_n), Range R(S), and probable error (pe) in units of 0.1 nT. Phases (σ_n) are in degrees.

Season	Sunspot Group	Harmonic No. of days	n=1 s_1	n=1 σ_1	n=2 s_2	n=2 σ_2	n=3 s_3	n=3 σ_3	n=4 s_4	n=4 σ_4	Range R(S)	Range pe
y	A	3450	46	49	51	243	50	72	17	273	253	1
	B	2965	56	43	58	239	54	70	19	272	291	1
	C	3149	65	40	67	241	59	77	20	287	323	2
	D	4533	77	34	80	235	67	73	22	285	389	2
j	A	1096	113	30	98	246	71	81	14	310	454	2
	B	1036	121	29	104	243	74	77	15	309	484	3
	C	1053	111	31	124	246	82	85	15	331	547	2
	D	1531	140	29	146	241	91	80	16	335	617	2
e	A	1192	52	45	61	240	62	72	24	268	311	2
	B	968	59	44	66	235	66	69	26	262	340	2
	C	1045	76	36	81	233	77	75	28	278	414	3
	D	1504	86	32	95	231	85	73	32	276	474	3
d	A	1162	41	164	4	95	21	45	17	253	128	2
	B	961	35	157	4	147	23	45	20	256	117	2
	C	1051	28	152	5	80	21	54	21	270	104	3
	D	1498	16	114	12	148	27	52	26	268	103	2

Table 3.3 Annual (y) and Seasonal (d,e,j) mean harmonic components and range of S in Z at Alibag for group of years classified according to annual mean sunspot numbers. Amplitudes (a_n), Range, R(S), and probable error (pe) in units of 0.1 nT. Phases (σ_n) are in degrees.

Season	Sunspot Group	Harmonic No. of days	n=1 a_1	n=1 σ_1	n=2 a_2	n=2 σ_2	n=3 a_3	n=3 σ_3	n=4 a_4	n=4 σ_4	Range R(S)	Range pe
y	A	3452	35	97	41	303	39	134	15	336	183	1
	B	2957	41	88	43	301	42	133	16	336	203	1
	C	3153	59	83	51	304	48	142	18	350	254	1
	D	4530	68	74	59	298	55	139	22	350	301	1
j	A	1097	74	90	67	302	53	140	12	10	300	2
	B	1030	76	83	67	299	53	137	12	10	306	2
	C	1053	91	85	81	304	62	144	13	28	366	2
	D	1529	104	77	96	298	72	139	15	26	437	2
e	A	1191	56	95	50	307	50	138	21	334	239	2
	B	967	59	88	52	304	53	136	23	330	258	3
	C	1044	83	86	65	305	62	143	26	344	331	2
	D	1504	95	80	72	301	70	142	31	344	383	2
d	A	1164	27	252	7	281	17	107	13	313	85	2
	B	960	16	264	9	291	20	114	16	316	74	2
	C	1056	7	10	8	302	21	130	19	335	89	2
	D	1497	16	358	11	267	24	125	23	336	114	2

Table 3.4 Yearly (y) and Seasonal (j,e,d) mean harmonic components and Range of lunar phase law term in H at Alibag for group of years classified according to annual mean sunspot numbers. Amplitudes (l_n) Range, R(L), and probable error (pe) in units of 0.01 nT and phases (λ_n) are in degrees.

Season	Harmonic / Sunspot Group	n=1			n=2			n=3			n=4			Range	
		l_1	pe	λ_1	l_2	pe	λ_2	l_3	pe	λ_3	l_4	pe	λ_4	R(L)	pe
y	A	69	11	15	58	08	172	36	04	13	12	04	217	350	17
	B	74	17	355	73	09	166	38	08	353	09	07	164	388	25
	C	86	20	338	76	11	171	30	04	346	06	05	144	396	27
	D	64	22	332	80	14	156	28	08	4	11	10	240	366	33
j	A	63	23	41	26	15	210	25	09	13	16	10	251	260	35
	B	47	28	350	42	18	178	24	10	9	12	06	280	250	40
	C	74	20	335	37	11	186	16	10	325	15	08	38	284	30
	D	54	33	325	48	28	151	10	26	97	33	25	281	290	65
e	A	79	24	13	56	16	156	16	09	359	11	06	239	324	35
	B	35	29	274	58	17	159	32	20	341	31	17	145	312	49
	C	25	45	13	37	20	145	24	11	331	11	08	180	194	59
	D	12	33	301	55	23	106	36	12	354	05	08	121	216	49
d	A	74	21	357	98	15	172	67	08	16	18	06	175	514	32
	B	165	31	341	125	16	164	62	10	353	03	06	121	710	42
	C	161	30	336	156	21	173	53	11	358	16	08	170	772	45
	D	132	29	335	167	13	172	50	09	359	20	08	186	738	39

Table 3.5 Yearly (y) and Seasonal (j, e, d) mean harmonic components and Range of lunar phase law terms in D at Alibag for group of years classified according to annual mean sunspot numbers. Amplitudes (l_n) Range, R(L), and probable error (pe) in units of 0.01 nT and phases (λ_n) are in degrees.

Season	Harmonic / Sunspot Group	n=1			n=2			n=3			n=4			Range	
		l_1	pe	λ_1	l_2	pe	λ_2	l_3	pe	λ_3	l_4	pe	λ_4	R(L)	pe
y	A	21	06	187	43	05	347	32	04	119	06	03	318	204	11
	B	21	08	145	37	07	345	36	06	127	06	03	308	200	14
	C	24	11	124	36	07	335	47	05	112	20	04	306	254	18
	D	29	08	137	56	08	345	41	05	137	09	03	356	270	15
j	A	48	13	114	103	07	287	67	06	97	02	04	156	440	19
	B	61	15	90	127	13	278	80	09	108	07	06	112	550	26
	C	72	14	96	128	10	280	88	08	103	07	05	300	590	22
	D	80	15	90	146	10	291	90	08	109	06	05	155	644	23
e	A	21	08	191	33	09	295	48	07	83	16	05	253	236	17
	B	18	14	54	11	12	273	52	09	77	30	05	262	222	24
	C	43	21	57	43	14	286	71	11	87	35	11	289	384	34
	D	43	16	84	61	13	287	63	09	97	13	04	272	360	26
d	A	47	09	244	122	09	48	54	07	210	21	05	8	468	18
	B	69	12	212	144	09	51	69	07	216	21	04	21	606	20
	C	78	17	222	140	13	64	42	07	222	20	05	334	560	26
	D	76	09	215	176	09	55	85	06	227	33	05	18	740	17

Table 3.6 Yearly (y) and Seasonal (j,e,d) mean harmonic components and Range of lunar phase law term in Z at Alibag for group of years classified according to annual mean sunspot numbers. Amplitudes (l_n) Range, R(L), and probable error (pe) in units of 0.01 nT and phases (λ n) are in degrees.

Season	Harmonic / Sunspot Group	n=1 l_1	n=1 pe	n=1 λ_1	n=2 l_2	n=2 pe	n=2 λ_2	n=3 l_3	n=3 pe	n=3 λ_3	n=4 l_4	n=4 pe	n=4 λ_4	Range R(L)	Range pe
y	A	26	07	182	19	05	45	43	05	199	11	03	62	198	12
	B	28	09	165	20	05	22	48	03	201	09	03	37	210	13
	C	38	08	148	32	04	7	60	04	199	16	03	27	292	12
	D	51	06	186	49	06	43	66	04	214	16	02	52	364	11
j	A	51	11	192	53	07	326	58	05	167	05	03	142	334	16
	B	23	13	149	66	09	312	65	06	166	01	05	259	310	20
	C	78	09	161	94	08	336	78	06	174	07	04	342	514	16
	D	77	10	199	87	08	348	85	06	179	04	05	254	506	17
e	A	22	11	119	20	07	293	45	07	164	11	05	339	196	18
	B	39	19	135	21	11	302	48	07	170	18	06	342	252	27
	C	59	16	105	52	09	316	77	07	176	22	05	8	420	23
	D	57	10	141	60	09	338	78	07	178	19	04	7	428	18
d	A	22	13	208	87	08	96	72	08	251	31	05	75	424	21
	B	38	16	206	92	09	92	83	05	253	25	02	77	476	22
	C	24	14	258	92	09	111	71	08	259	24	05	52	422	22
	D	43	12	203	142	07	98	118	07	267	40	05	76	686	19

TABLE 3.7 Annual (y) and December solstice (d) mean harmonic components and Range of lunar partial terms at Alibag for group of years classified according to annual sunspot number. Ampli tudes (l'_n) Range, r (L) and probable error (pe) in unit of 0.01 nT. Phases (λ'_n) are in degrees.

Season	Element	Harmonic / Sunspot Group	n=1 l'_n	n=1 pe	n=1 λ'_1	n=2 l'_2	n=2 pe	n=2 λ'_2	n=3 l'_3	n=3 pe	n=3 λ'_3	n=4 l'_4	n=4 pe	n=4 λ'_4	Range r (L)	Range pe
y	H	A	10	11	202	20	08	161	10	04	229	03	04	164	86	17
		B	26	17	207	03	09	110	12	08	67	04	07	13	90	25
		C	29	20	219	20	11	146	05	04	146	05	05	275	118	27
		D	45	22	182	22	14	202	14	08	293	11	10	150	184	33
	D	A	16	06	281	14	05	35	08	04	151	01	03	131	78	11
		B	10	08	24	13	07	20	07	06	158	08	03	86	76	14
		C	10	11	20	12	07	355	12	05	160	06	04	78	80	18
		D	25	08	344	23	08	20	10	05	137	07	03	75	130	15
	Z	A	21	07	4	03	05	304	07	05	343	03	03	77	68	12
		B	10	09	4	04	05	29	08	03	0	07	03	82	58	13
		C	07	08	81	14	04	13	07	04	12	08	03	52	72	12
		D	12	06	1	12	06	307	13	04	5	05	02	63	84	11
d	H	A	67	21	267	39	15	146	13	08	226	04	06	226	246	32
		B	74	31	231	26	16	148	11	10	250	14	06	342	250	42
		C	64	30	261	46	21	149	13	11	117	20	08	221	286	45
		D	32	29	234	78	13	165	25	09	238	10	08	292	290	39
	D	A	06	09	135	17	09	312	24	07	8	07	05	200	108	18
		B	10	12	53	31	09	300	13	07	6	12	04	84	132	20
		C	23	17	197	27	13	290	13	07	331	06	05	67	138	26
		D	38	09	271	14	09	323	29	06	338	10	05	48	182	17
	Z	A	31	13	358	28	08	246	19	08	12	07	05	302	170	21
		B	45	16	232	17	09	265	11	05	356	12	02	16	170	22
		C	48	14	210	12	09	290	13	08	327	10	05	22	166	22
		D	34	12	308	38	07	221	32	07	344	11	05	346	233	19

Further, the yearly (y) and seasonal (j,e,d) mean solar and lunar daily variations of H, D and Z, all in units of force, are obtained for four epochs of solar activity by synthesizing the harmonic coefficients of Tables 3.1 to 3.6 at hourly intervals and are shown as daygraphs in Figs. 3.1 and 3.2 for S and L respectively. The L daygraphs refer to the epoch of new Moon and are drawn on the assumption that Sun and Moon stayed at the same meridian during a period of lunar day. The solar daygraphs show considerable magnification in their size from Group A to D without seriously affecting the form of daily variation. The complete picture of solar cycle influence on L is graphically represented in Figures 3.3 a,b,c for H,D and Z respectively by plotting lunar phase law tides against local time (t) as abscissa and lunar age as ordinate (Winch 1970a). There is a tendency for the magnitude of L to increase from group A to D but more often the changes are not systematic. The local time of maximum and also the lunar age at which the L attains maximum does not show any systematic change with R_z. Solar cycle influence on L(H) during equinox appears to be of particular interest where L tends to decrease from group A to C. However, lunar variations during this season are very small and, therefore, do not claim full statistical significance.

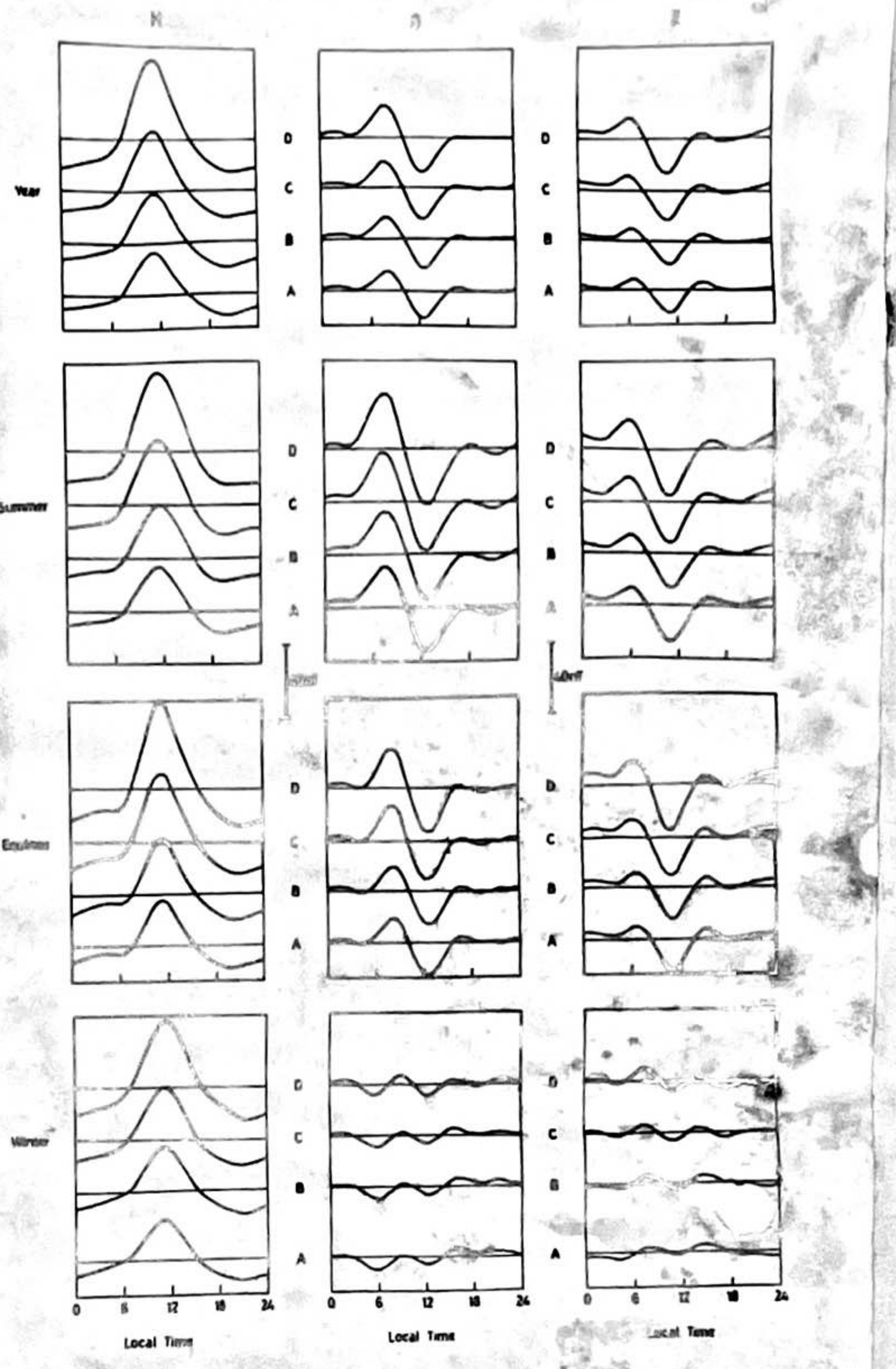

Fig. 3.1

Yearly and seasonal daygraphs of S in H, D and Z at Alibag for the four sunspot groups : quiet (A), low (B), medium (C) and high (D).

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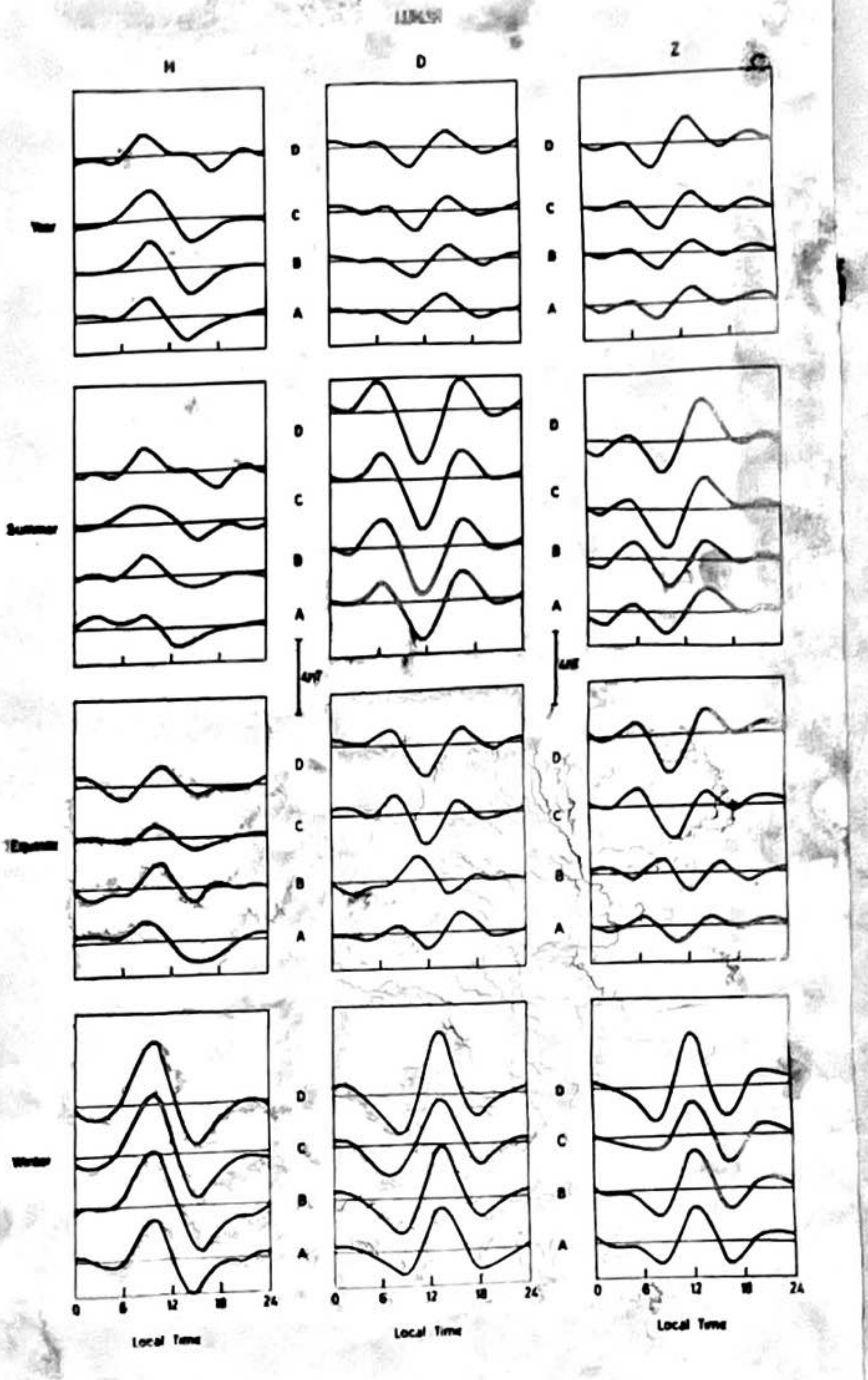

Fig. 3.2

Yearly and seasonal daygraphs of L in H, D and Z at Alibag for the four sunspot groups : quiet (A), low (B), medium (C), high (D). Daygraphs correspond to the epoch of new Moon.

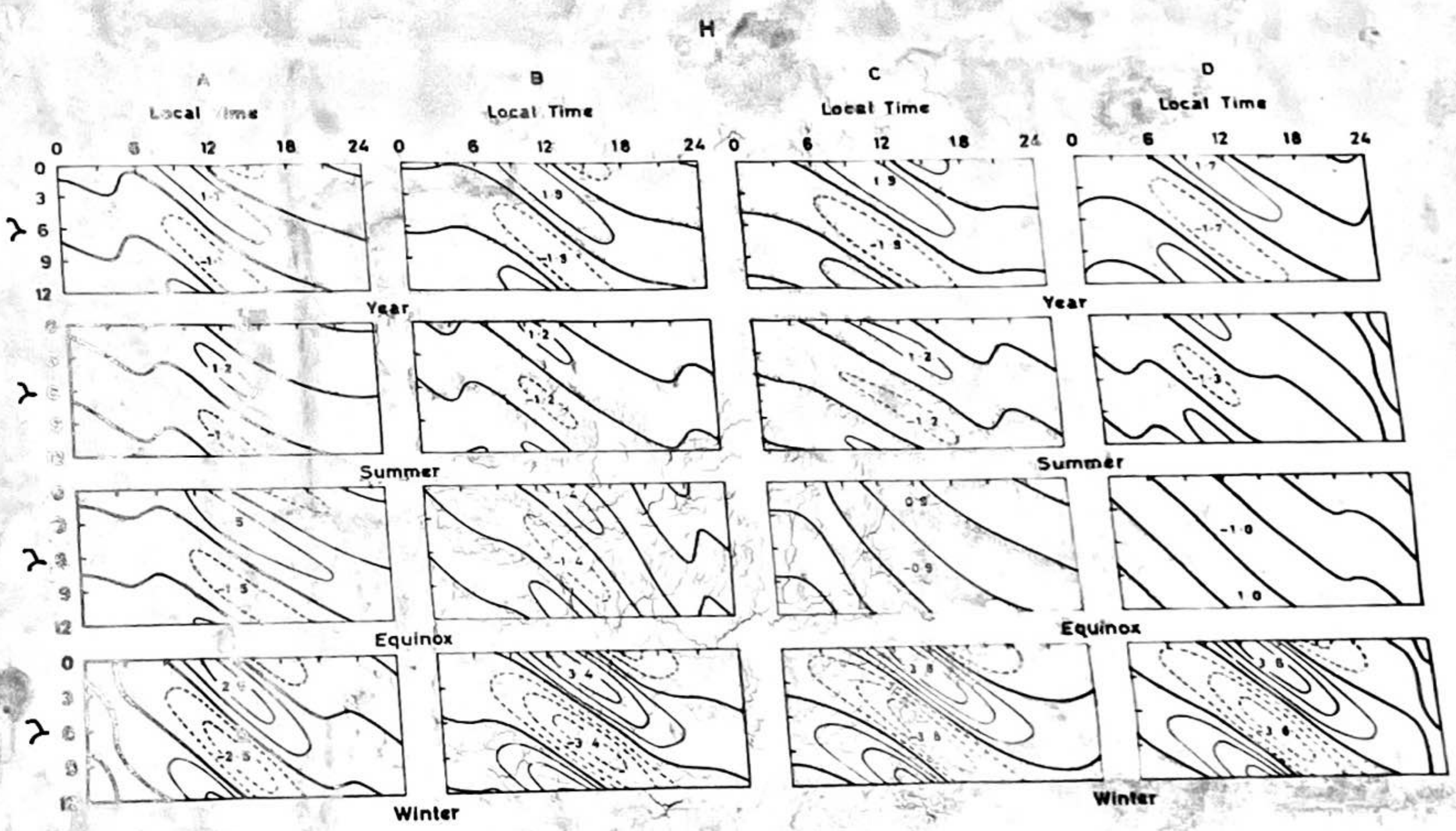

Fig. 3.3a

The changes in L(H) from quiet (A) through low (B) and medium (C) to high (D) solar activity shown by the contour diagrams of lunar phase law tide as a function of lunar age (ν) and local solar time in different seasons and the year.

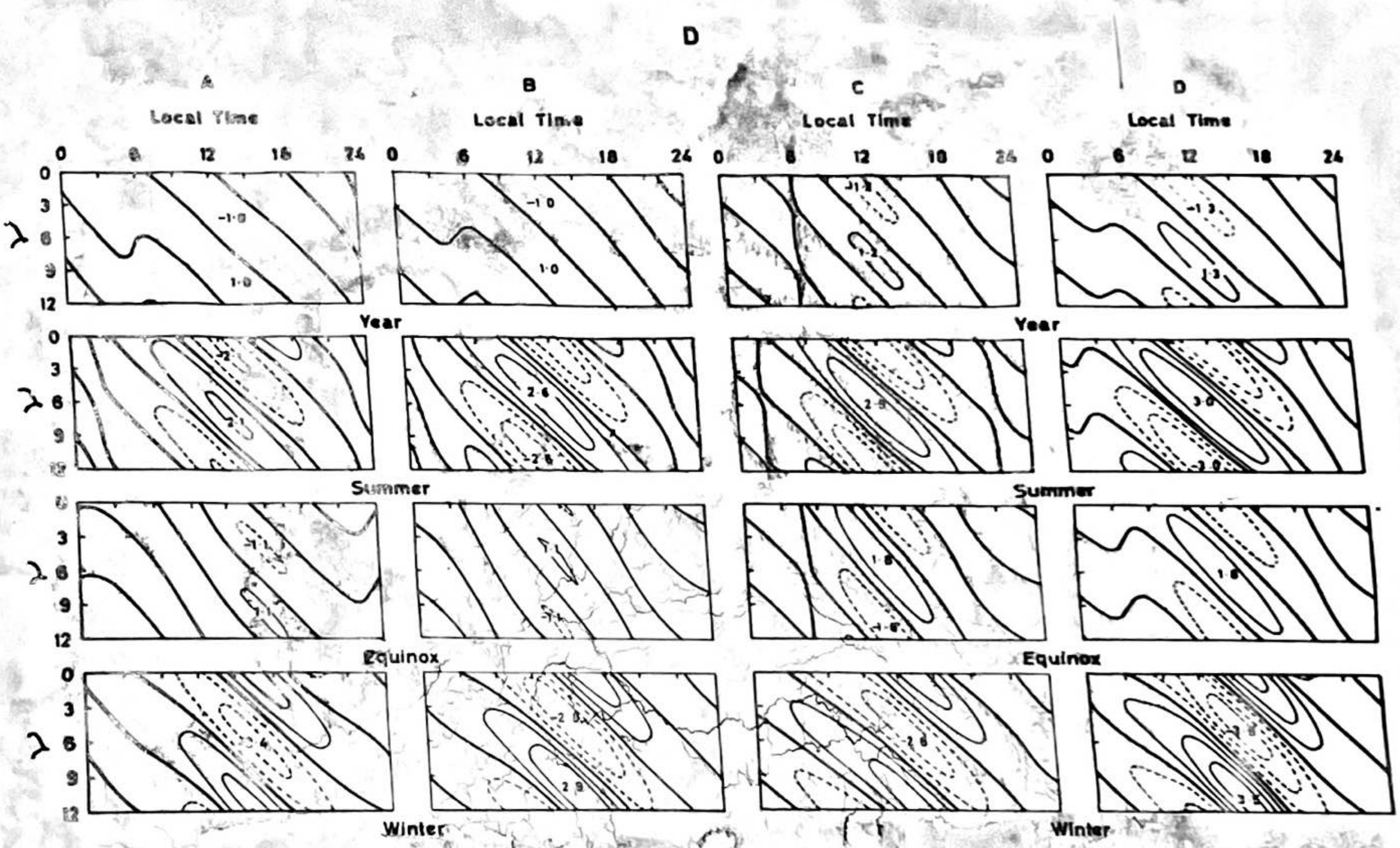

Fig. 3.3b

The changes in L(D) from quiet (A) through low (BO and medium (C) to high (D) solar activity shown by the contour diagrams of lunar phase law tide as a function of lunar age (ν) and local solar time in different seasons and the year.

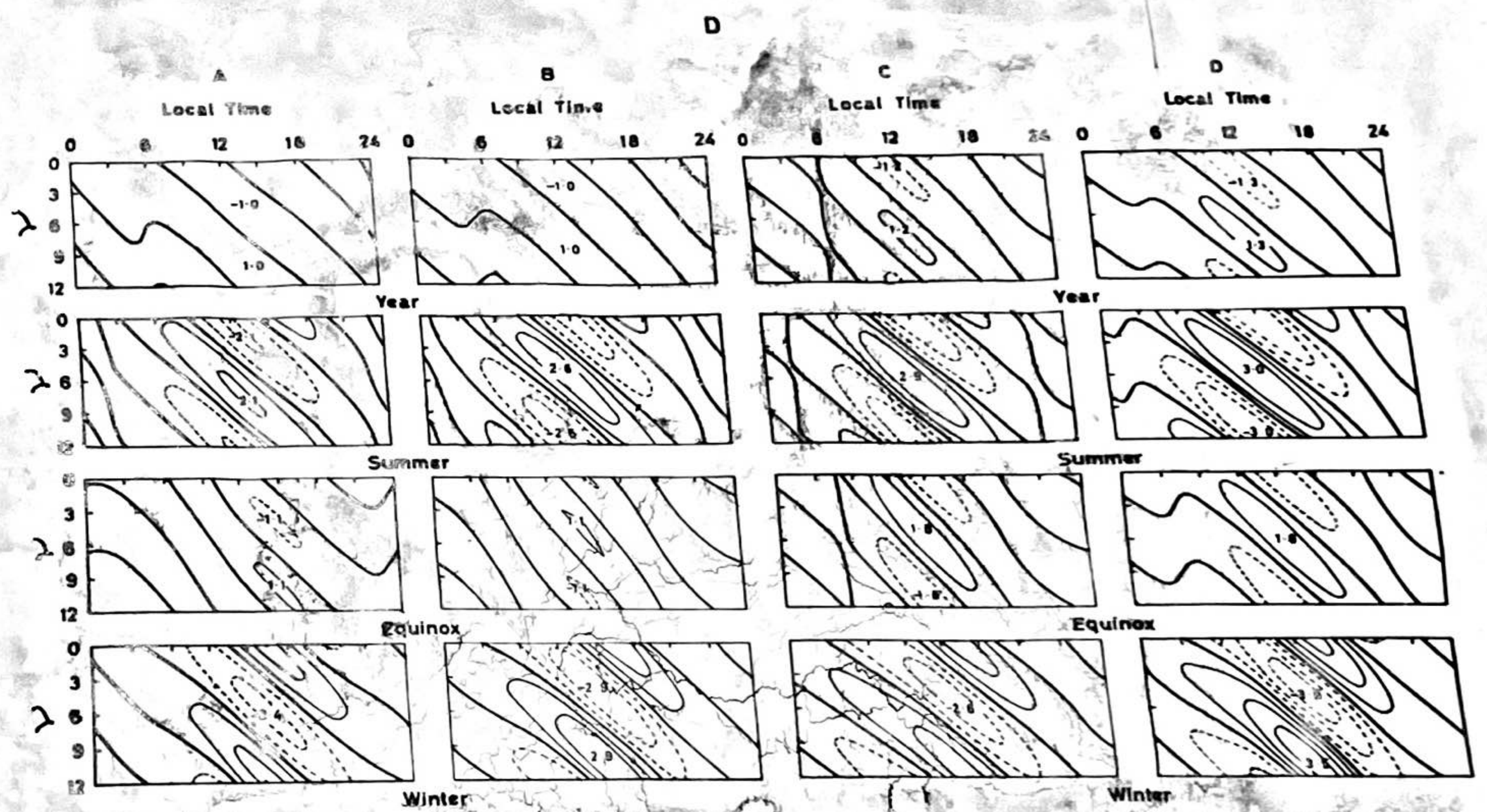

Fig. 3.3b

The changes in L(D) from quiet (A) through low (BO and medium (C) to high (D) solar activity shown by the contour diagrams of lunar phase law tide as a function of lunar age (ν) and local solar time in different seasons and the year.

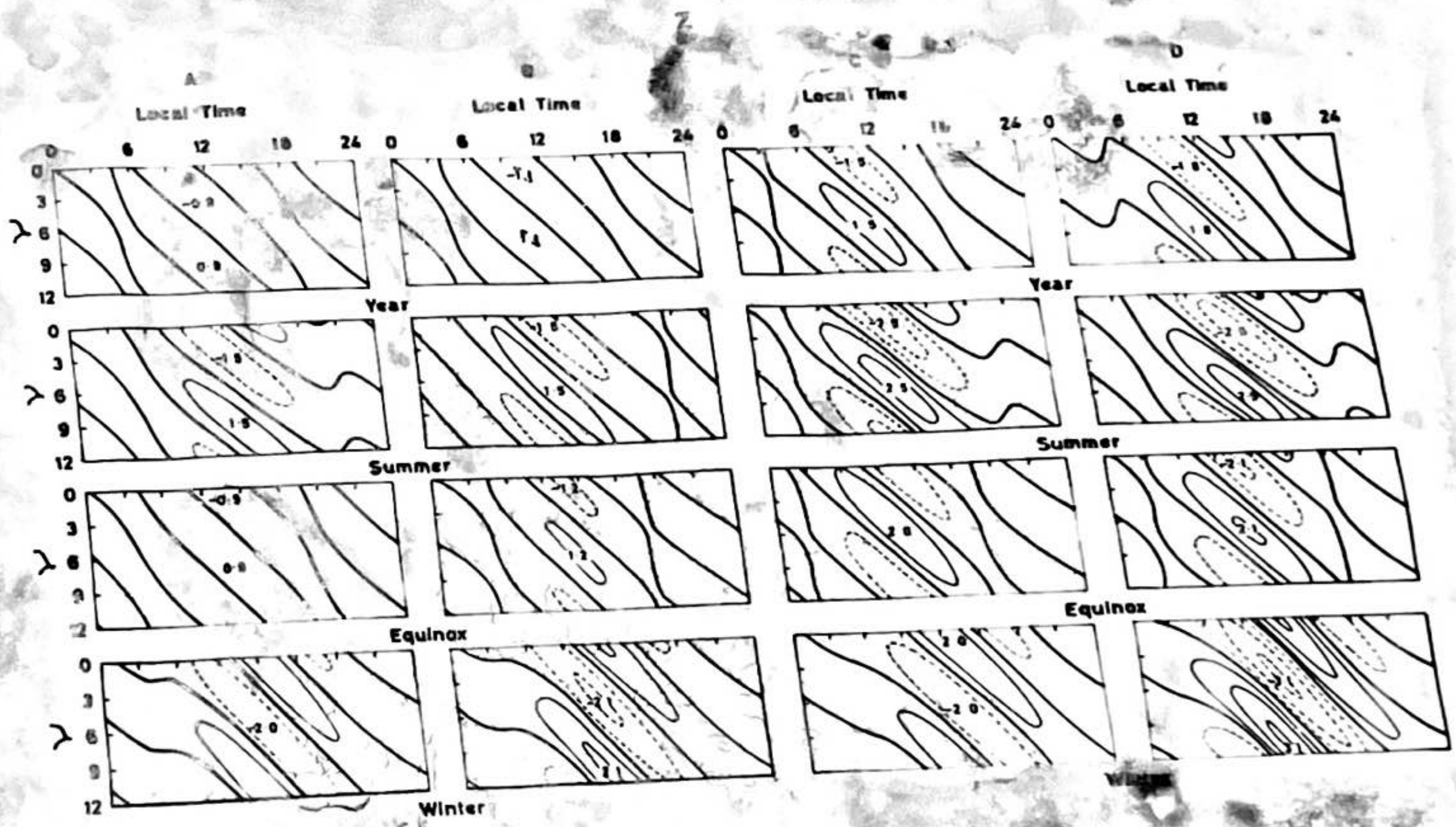

Fig. 3.3e

The changes in L(Z) from quiet (A) through low (B) and medium (C) to high (D) solar activity shown by the contour diagrams of lunar phase law tide as a function of lunar age (ν) and local solar time in different seasons and the year.

Figs. 3.4 and 3.5 show the vectograms of $S(\bar{H})$ and $L(\bar{H})$ respectively obtained by plotting simultaneously the H and D variations in different groups of years of sunspot number varying from quiet to high. Besides the seasonal changes in the shape of the vectograms of $S(\bar{H})$, discussed in Chapter 2, the curves clearly show a regular and considerable progression of size, with little change of shape from years of small sunspot numbers to years of large sunspot numbers. Changes in the size of $L(\bar{H})$ vectogram with increasing solar activity are not as sharp and systematic as in the case of S but apparently the $L(\bar{H})$ appears to increase with solar activity. The total variability in S and L, using annual solar and lunar ranges, has been studied in Chapter 5. There it is found, that while about 96 per cent of the variability in S can be accounted for by the changes in R_z and A_p, only about 32 per cent of the variability can be attributed to the variation of sources of such regular nature. It is likely that the effect of the variability from other sources on lunar variation in the four epochs of solar activity, classified by grouping years according to varying annual R_z, may not be fully averaged out and may mask the regularity in the variation of L with R_z.

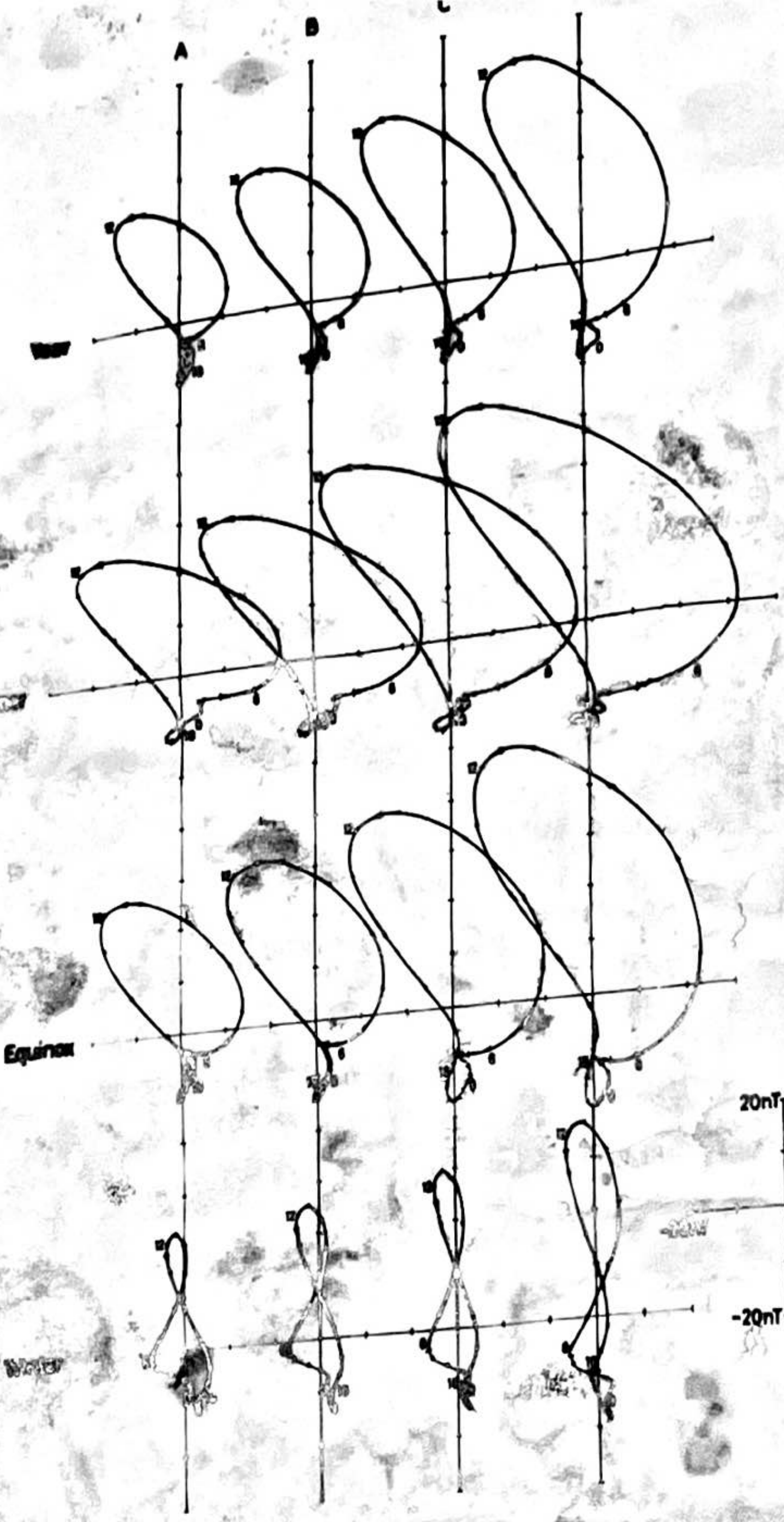

Fig. 3.4

S(H) vectograms (yearly and seasonal means) for four epochs of solar activity, from A to D in order of increasing sunspot numbers. The numbers along the curve give local time. Day and night portions are separated by short lines across the curve.

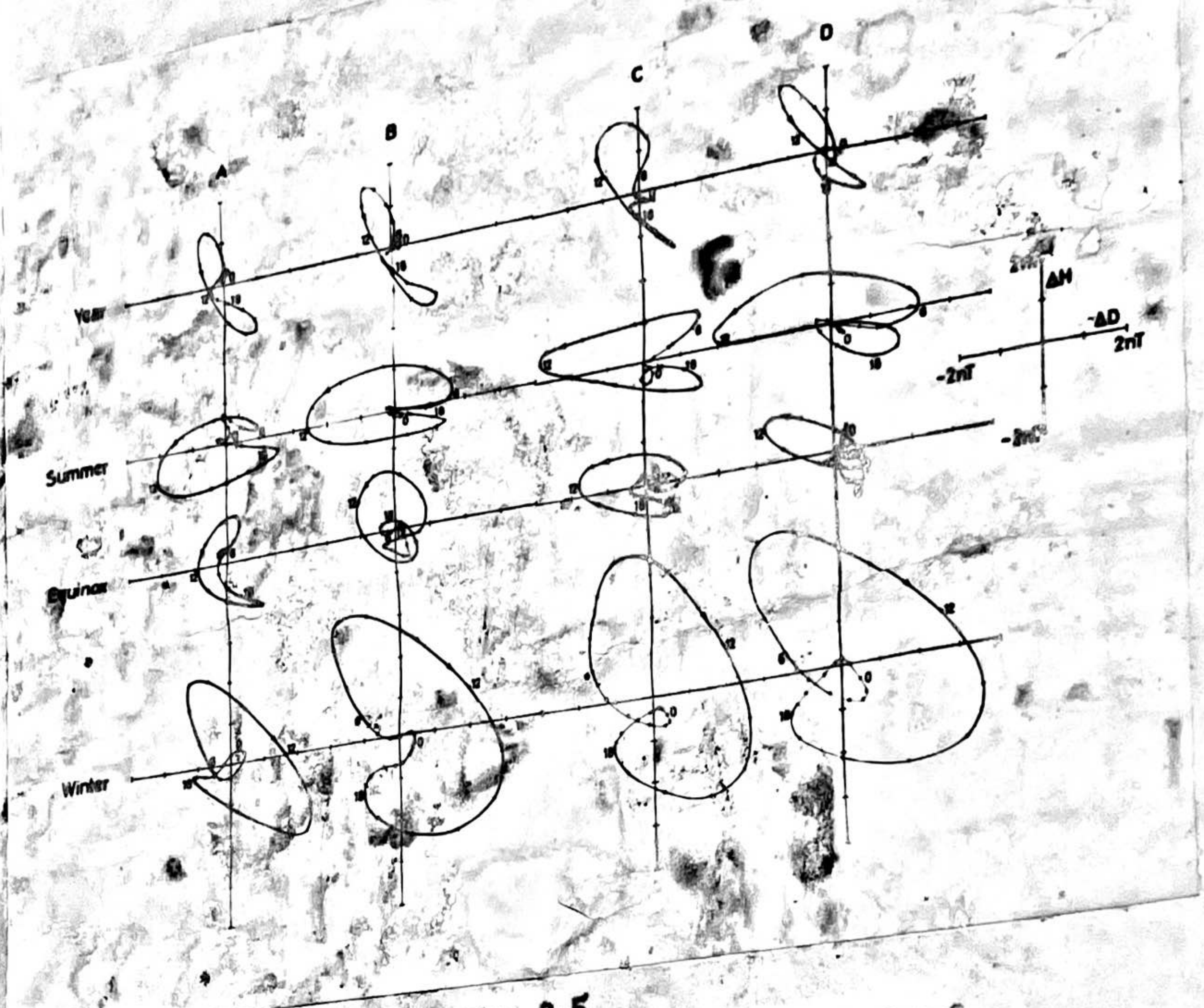

Fig. 3.5

L(H) vectograms (yearly and seasonal means) for four epochs of solar activity, from A to D in order of increasing sunspot numbers. The numbers along the curve give local time. The curves refer to the epoch of new Moon. Day and night portions are separated by short lines across the curve.

3.3 Numerical relationships between sunspot number (R_z) and solar and lunar ranges:

Long ago Wolf (1859) found a fairly good linear relationship of the form, $R(S) = A+BR_Z$

$$\text{or} \quad R(S) = A(1+MR_Z) \quad \ldots \quad (1)$$

where $M = B/A$, between the annual sunspot number (R_z) and the mean geomagnetic S_q ranges at Munich. Other workers have examined how far this relationship fits the data from different stations and have reached the conclusion that the formula fits the data well but the value of M, called Wolf ratio, varied from station to station, from element to element and from one period to another. The dependence of lunar ranges on R_z is also similarly investigated by several workers. Chapman et al. (1971) found that changes in L with R_z do not reveal any significant departures from linearity. In this section the influence of solar cycle on solar and lunar ranges, defined in Chapter 2, is investigated by determining the Wolf ratios.

The method of determining the Wolf numbers 'A' and 'M' in case of S and 'a' and 'm' in case of L is the same as that used by Chapman et al. (1971) for lunar terms for their long period data analysis, i.e., a straight line is fitted to the data by the method of least squares, weighting each range inversely as the square of its probable error (Brunt, 1923). The probable error of M or m is deduced from the probable errors of the ranges used in the determination of M or m. Though most of the solar ranges greatly exceed their probable errors, it would have been sufficient to fit a straight line giving unit weight to solar ranges but for closer compatibility with L results, solar ranges are also weighted inversely as the square of their probable errors, p.e. The Wolf numbers, so computed for yearly (y) and seasonal (j,e,d,) terms are given in Table 3.8 for both S and L.

3.3.1 Solar ranges:

As seen from Table 3.8 the values of Wolf ratio, M, varies from one element to the other but the value for D only differs significantly at five per cent from the corresponding values for H and Z. The values of $M \times 10^4$ observed here for the yearly solar ranges of H, D and Z and for the mean value for all elements are in good agreement with the respective mean values of 56, 49, 56 and 52 observed by Chapman et al. (1971) by combining the results of analysis of long term data from seven observatories. Using annual mean solar quiet-day ranges in H, D and Z at Alibag over the period 1905-1971, Murty and Yacob (1976) estimated the linear Wolf relation and found the values of $M \times 10^4$ to be 67 ± 3, 34 ± 3, 48 ± 5 and

TABLE 3.8 Wolf numbers A(or a) and M(or m) x 10^4 for solar and lunar ranges, R(S) and R(L).

Ranges	Season	H: A nT	H: $Mx10^4$	D: A nT	D: $Mx10^4$	Z: A nT	Z: $Mx10^4$	Weighted mean H+D+Z: $Mx10^4$
Solar	y	33.9	61±2	24.2	45±1	17.0	59±1	52±1
	j	34.0	65±4	43.6	31±1	27.6	42±2	37±1
	e	35.7	69±3	29.3	47±2	22.3	54±2	53±1
	d	32.2	53±3	12.7	-15±3	7.2	39±7	25±2
		a nT	$mx10^4$	a nT	$mx10^4$	a nT	$mx10^4$	$mx10^4$
Lunar	y	3.58	7±15	1.92	31±15	1.71	84±21	32±9
	j	2.51	14±8	4.43	37±12	3.11	54±15	42±9
	e	3.34	-30±28	2.15	55±22	1.87	105±32	41±15
	d	5.50	32±15	4.83	39±9	3.71	55±15	41±7

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10.5.95

50 ± 4 for H, D, Z and the weighted mean of all elements respectively. It is interesting to note that the values of M for H and Z differ insignificantly at five per cent level from those derived here from all days data. However, the value for D is at variance with the result obtained here, suggesting that the additional north-south current of disturbance origin, the effect of which will be present even in all days data, has stronger solar cycle modulation than the north-south current associated with Sq current system.

The value of M shows a marked seasonal progression. The maximum value is in equinox and the minimum in winter for all the elements.

It is surprising to note that solar ranges in D during winter show negative dependence on solar activity and hence need particular attention. As already seen in Chapter 2, solar daily variation in D for this distorted by the penetration of southern current system into the northern hemisphere. As the effect of invasion is more pronounced than the normal feature, the range in D, taken as the algebraic difference of maximum and minimum hourly values, is not the measure of normal north type of S(D) but is a measure of invasion. Critical inspection of daygraphs of D shows that these secondary effects tend to diminish in magnitude from group A to D and results in the decrease of D-range with increasing solar activity. Hence it may be concluded that the negative dependence of D-range on R_z during winter results from the decreasing invasion of southern current system into the northern hemisphere with increase in R_z.

3.3.2 Lunar ranges:

In comparison with solar terms, the Wolf ratio for lunar terms is poorly determined and shows considerable variation among the elements and from one season to another. The solar cycle enhancement is maximum in Z with the highest values of m in equinox. In the case of L(H), eventhough the values of m are far below the level of significance, the seasonal progression of m is in agreement with the earlier results of Rao (1972b). The weighted mean values of m observed here for the total period are at variance with the weighted mean values of seven observatories, obtained by Chapman et al. (1971) but show a fair agreement with the values for Toolangi (Green, 1972).

3.3.3 Comparison of solar cycle influence on S and L:

As seen in earlier sections, both solar and lunar daily variation show a definite positive association with the sunspot number. The overall enhancement of S, as measured by the mean Wolf ratio of the three elements, is about 1.7 times the L enhancement in contrast to the value of three obtained by Chapman et al. (1971), Green and Malin (1971) and Rao (1972b).

Wolf ratio in the linear relation in respect of sunspot number and E-region electron density has been investigated by several workers. Appleton and Beynon (1969) reported the value of 0.0033. The mean Wolf ratio of L at Alibag, considering all the elements in different seasons and year, are in fair agreement with the Wolf ratio of E-region conductivity. It is further shown in Chapter 6 that even the removal of oceanic dynamo part from the observed L does not make any significant difference in the behaviour of L with respect to sunspot number as the Wolf ratios derived prior to and after the removal of oceanic part remain the same. Thus, the solar cycle modulation of L at Alibag appears to result primarily from the corresponding variation in E-region conductivity.

The enhancement of S, however, is much larger than that caused by the increase in the E-region conductivity. The significant difference between the responses of S and E-region conductivity (or L) to sunspot number raises a doubt whether S currents flow mainly in the E-region as hitherto supposed. However, rocket observation of ionosphere by Burrows and Hall (1964, 1965) Davis et al

(1965, 1966), Fatkullin and Fel'dshteyn (1965) and several other workers have shown that the current flowing in the E-region is in good agreement with that deduced from the Sq variation on the ground, indicating the E-region as the seat of Sq currents. If it were so and if the solar cycle enhancement of S were only due to changes in the E-region conductivity, the expected change in solar range at Alibag as R_z varies from 0 to 100 would be of the order of 11nT, 8nT and 6nT for H, D and Z respectively, computed by substituting in relation (1) the range of S for ideal period of zero sunspot number (value of 'A' from Table 3.8) and Wolf ratio of E-region electron density (0.0033). But the observed changes in S are in excess of these values by about 5-6nT. The causes of this excess enhancement in S are then have to be sought in the variation of the following sources contributing to S, though their contributions are of smaller magnitude:

(1) Solar cycle enhancement of magnetospheric compression – The effect of magnetospheric compression due to solar wind on quiet day magnetic variations at the Earth's surface under conditions of quiet-sun have been computed by Beard and Jenkins (1962), Midgley and Davis (1963), Mead (1964) and Olson (1970a). They found that the daily variation produced by such effect is similar to the

average Sq pattern but their magnitude is only 3-4 nT. The magnitude of increment in S after giving allowance for the increase of E-region conductivity is nearly double that of the daily range produced by magnetospheric currents. To obtain the variations of about 10nT due to these magnetospheric currents, variations of 10-20% in the dimension of magnetosphere would be required (Mead 1964, Yukutake, 1965). But the studies of long term variation of solar wind velocity (Gosling et al., 1971) and density (Hundhausen et al. 1971) have shown little or no evidence for an increase of these parameters with increasing solar activity. Thus in the presence of little or no change of solar wind properties over a solar cycle, it is unlikely that the variation in the dimension of magnetosphere, if any, would produce a change in the daily variation by the required factor.

(ii) The effect of partial ring current system - Since all days data have been used for the present analysis the daily variation derived from these days will include a fraction due to disturbance in the form of a disturbance daily variation, SD. The SD field is generally attributed to either the return currents from the auroral electrojet or to a partial ring current superposed on the symmetric ring current. Recently, Fukushima and Kamide (1973a) have interpreted the origin of SD field in terms of the appearance or intensification of partial ring current system consisting of three segments: the Birkeland currents in the magnetosphere, partial ring current in equatorial plane and the electric currents in the ionos- phere. In low- and mid-latitudes, SD of horizontal inten- sity is diurnal in character with maximum southward directed field around sunset hours (Sugiura and Chapman, 1958). The effect of SD in the daily variation appears as an evening depression of field and thus is a source of significant contribution to the range of S(H) (Bhargava and Yacob, 1971). An examination of H daygraphs in Fig. 3.1 indicates the presence of evening depression, the magnitude of which increases from solar activity group A to D. If this decrease is accepted to be due to the partial ring current, the systematic increase in the magnitude of the depression seen in Fig. 3.1 is consis- tent with the assumption of enhancement of partial ring current with increasing solar activity. This additional component of disturbance with increasing amplitude with solar activity may account for the greater increase of solar ranges with solar activity than the effect caused by E-region conductivity. However, there remains some doubt as to whether the observed effects are apparently the disturbance effects, because the Wolf ratios observed by Murty and Yacob (1976), using quiet-day ranges, are similar to those observed here with all days data. If the evening depression of the field in all days data is only disturbance effect, this agreement would require that similar contamination of quiet-day range by disturbance takes place.

Solar cycle variation in horizontal field has been found to be in phase opposition to that in sunspot number and has been ascribed to greater magnetic activity during solar maximum (Vestine et al. 1947). However, from an examination of data of all days and quiet days of each month from Tucson, Yukutake (1965) observes that solar cycle effects are present without diminution of amplitude even during quiet period. He concludes that the decrease of H can not be ascribed to subnormal field associated with storm time ring current. Considering the relative magnitudes of several other contributing factors, he ascribes the reduced field to an increase in the current intensity or to a slightly closer approach of the quiet-time ring current or to a slightly closer approach of the quiet-time ring current (Akasofu, 1963) during periods of increased solar activity. The presence of partial ring current effects under quiescent conditions (Ap$\sim$5) has been already indicated by Bhargava and Yacob (1971). Therefore, if the solar activity enhances the intensity of the ring current system, including partial ring current, in the equatorial plane, which is supposed to flow even on apparently quiet days, or if the orbit of partial ring current in equatorial plane comes nearer to the earth, magnitude of the evening depression will increase sufficiently, so as to explain the observed 11-year variation in quiet as well as all days solar ranges.

(iii) Solar cycle enhancement of thermal tides - The solar air tide, which is mainly of thermal origin, may be enhanced in amplitude at solar maximum as envisaged by Matsushita (1968). Chapman et al. (1971) have shown that the enhancement of S is three times that of L and, therefore, felt that it is unlikely that the changes in the thermal tide along produce a change by the required factor of three. The factor obtained in the present analysis is only 1.7 and as such the solar cycle modulation of thermal tide may possibly be one of the sources to account for the difference between the Wolf ratios of S and L.

3.4 Solar cycle influence on the amplitudes and phases of S and L harmonics:

In order to investigate whether solar cycle enhances the amplitude of various harmonics of S and L in the same proportion and also to test whether solar cycle effect is simply a change of amplitude or the form of daily variation is also affected, the solar cycle dependence of amplitudes and phases of the first four harmonics of S and L daily variations is examined in this section. The harmonic dials showing the variations of prominent harmonics S_1 and S_2 of S and L_2 of L with solar activity in the three seasons and year are shown in Fig. 3.6a,b for H, D, Z components. The examination of Fig. 3.6a,b shows that while the amplitude of solar harmonic in general shows a systematic increase with increasing R_z, except S_1(D) and S_1(Z), the only significant phase changes accompanying increasing sunspot number appear to be the decrease of phase of first harmonic of H, D and Z. In the case of lunar harmonics, the amplitudes exhibit an increase from low solar activity to high solar activity group but the amplitudes are not always highest in group D. No systematic changes in the phase angles of L_n are discernible.

For the convenience of representing the changes in the form of daily variation with increasing R_z, the local time T_n (n=1 to 4), expressed in hours, when the harmonics attain their first maximum are computed using phase angles of respective terms. It is not usual to associate probable error with the phase angle but as many of the amplitudes of lunar harmonics are not significantly determined, phase angles also will be in error. So one requires some measure of significance that is associated with phase angles. Following Chapman (1957)

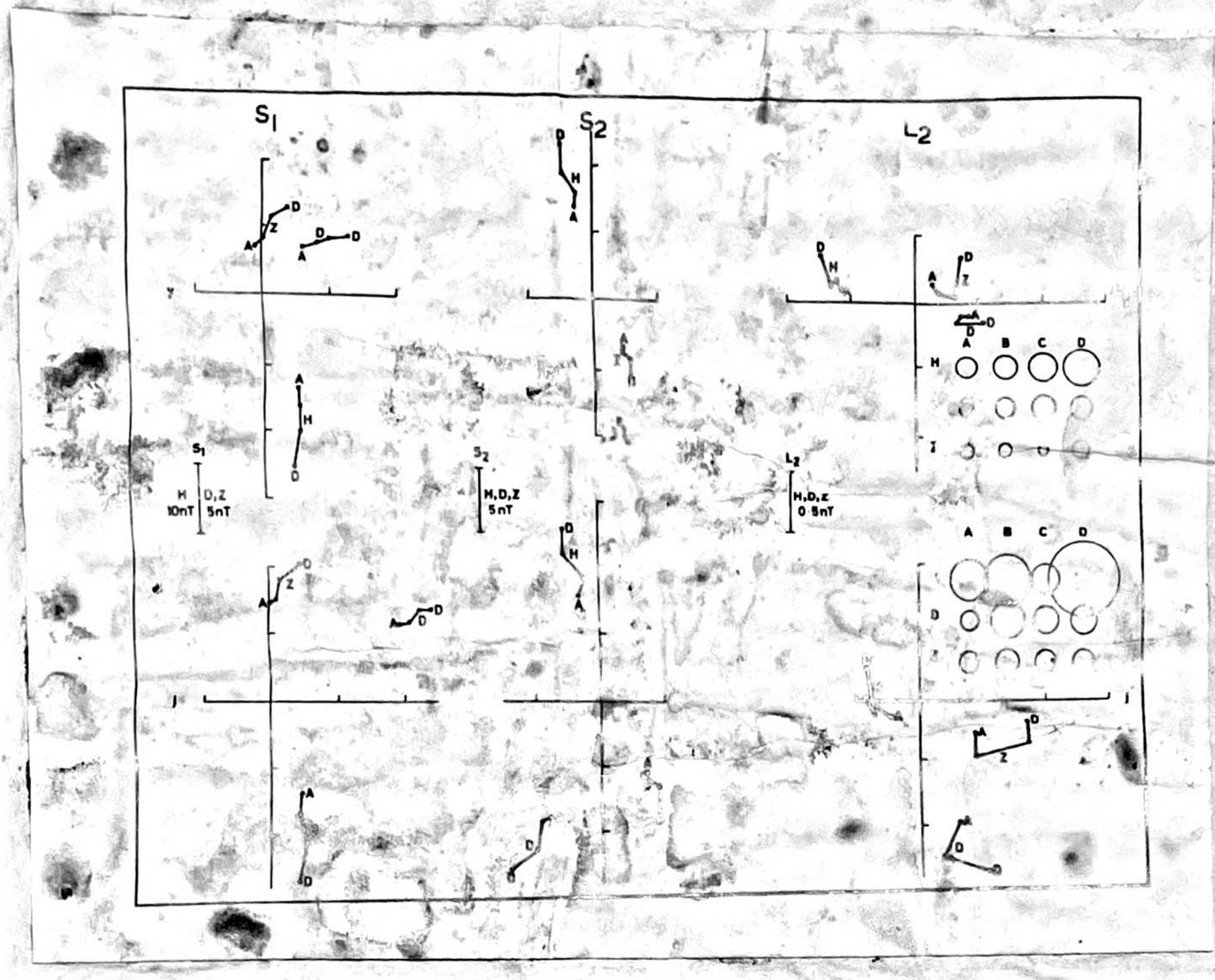


Fig. 3.6a

Harmonic dials showing the variation with solar activity, from quiet (A) to high (D), of harmonic components S_1, S_2 and L_2 in H, D and Z at Alibag separately during year (y) and summer (j). The probable error circles are shown separately to avoid cluttering.

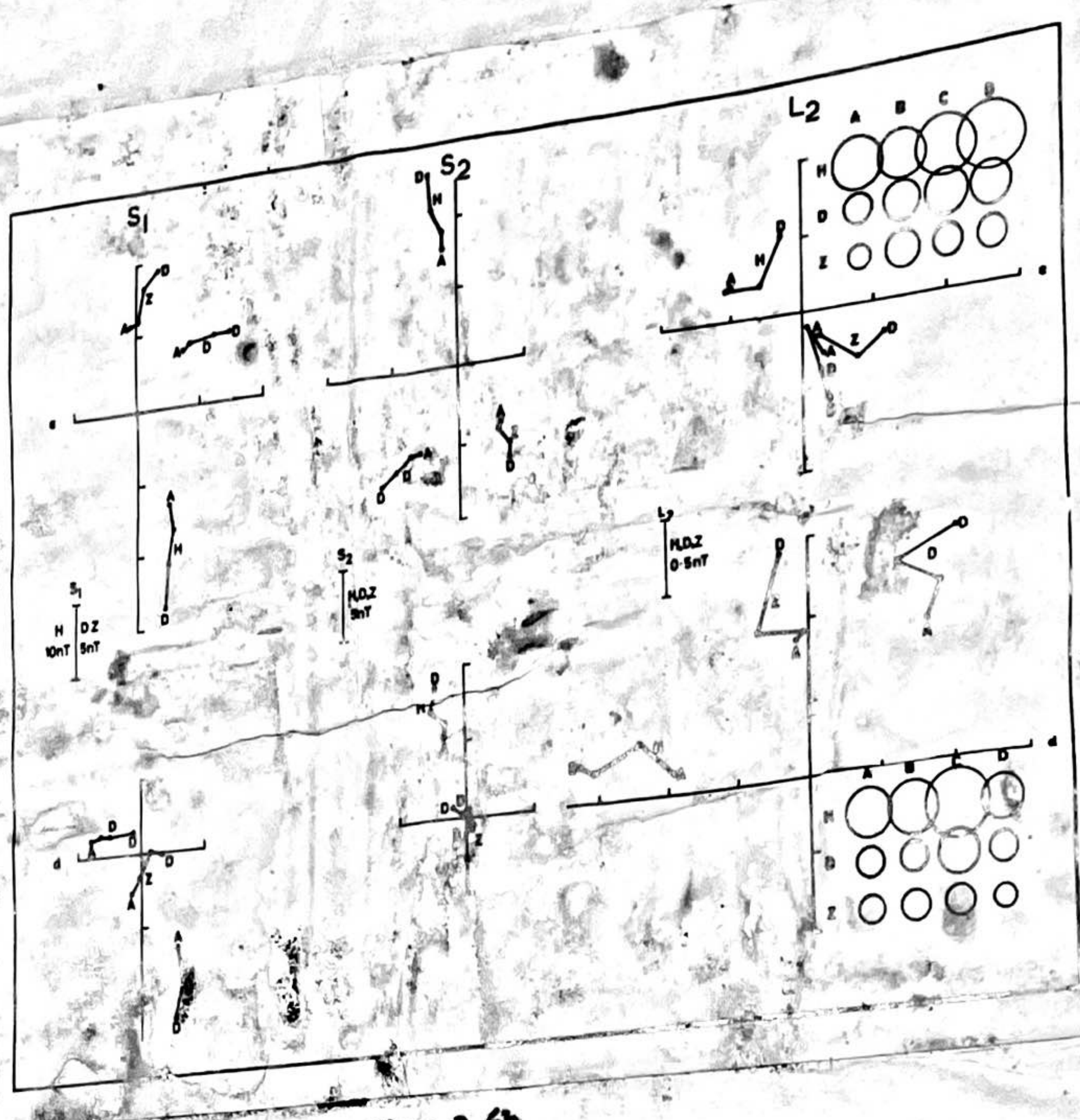


Fig. 3.6b

Harmonic dials showing the variation with solar activity, from quiet (A) to high (D), of harmonic components S_1, S_2 and L_2 in H, D and Z at Alibag separately during equinox (e) and winter (d). The probable error circles are shown separately to avoid cluttering.

the probable errors of phase angles, λ_n, are computed by:

$$\Delta\lambda_n = \sin^{-1} (\rho_n/A_n)$$

Where An is the amplitude of nth harmonic and ρ_n is the probable error associated with An. $\Delta\lambda_n$ is also converted into unit of hour by dividing $\Delta\lambda_n$ by 15 x n.

Next, the Wolf numbers in respect of R_z and amplitude and time of maximum of each harmonic of S and L are computed for different seasons and year. As many of seasonal lunar harmonics in different groups of solar activity are not of equal significance, the results of this analysis for the year only are given in Table 3.9 and are discussed.

3.4.1 Solar harmonic components:

Solar cycle variation of the first two harmonics of Sq(H) at Alibag has been extensively studied by Yacob and Prabhavalkar (1965) and Yacob and Rao (1966). The Wolf ratios for the amplitude of first two harmonics of S(H), observed here, are in good agreement with the corresponding values of 74 and 58 for annual mean Sq(H), obtained by Yacob and Prabhavalkar (1965). There is a suggestion for the Wolf ratio of the amplitudes of four harmonics to decrease with increasing harmonic number. From this it may be inferred that amplitudes of terms n = 1,2,3 and 4 do not preserve the same ratio to each other

TABLE 3.9 Wolf ratios for amplitudes and times of maximum of S and L harmonics.

		H	D	Z	Weighted Mean H+D+Z
	Parameter	$(\bar{M} \pm pe) \times 10^4$	$(\bar{M} \pm pe) \times 10^4$	$(\bar{M} \pm pe) \times 10^4$	$(\bar{M} \pm pe) \times 10^4$
S	s_1	73 ± 3	57 ± 4	85 ± 7	69 ± 2
	s_2	58 ± 4	49 ± 3	40 ± 4	49 ± 2
	s_3	57 ± 6	29 ± 2	37 ± 3	33 ± 2
	s_4	36 ± 17	24 ± 3	41 ± 4	32 ± 2
	T_1	6 ± 1	28 ± 4	5 ± 1	6 ± 1
	T_2	-1 ± 0	3 ± 1	2 ± 1	-1 ± 0
	T_3	-3 ± 2	-9 ± 6	-2 ± 0	-2 ± 0
	T_4	-3 ± 2	-6 ± 1	-10 ± 2	-7 ± 1
L	l_1	2 ± 47	34 ± 80	96 ± 101	23 ± 38
	l_2	31 ± 41	23 ± 36	195 ± 196	29 ± 27
	l_3	-21 ± 37	27 ± 33	48 ± 28	24 ± 18
	l_4	-38 ± 124	59 ± 118	53 ± 80	34 ± 58
	T_1	56 ± 44	13 ± 14	-5 ± 14	6 ± 10
	T_2	4 ± 8	2 ± 15	-22 ± 49	3 ± 7
	T_3	29 ± 30	-3 ± 6	-5 ± 5	-4 ± 4
	T_4	8 ± 32	-25 ± 56	-10 ± 84	-1 ± 27

throughout the solar cycle. It may also be noticed that the Wolf ratio for all harmonics of S, except for S_3(D) and S_4(D), are either in excess or comparable to the Wolf ratio of E-region electron density. Both these results corroborate the finding of Matsushita (1968), viz., the solar cycle influence on solar harmonics is frequency dependent and the relative increase in diurnal and semidiurnal term is larger than that expected from the solar cycle effect on ionospheric conductivity.

The time of the maximum of first harmonic of S only is found to show significant association with sunspot number which is to delay the time of maximum of the first harmonic with increasing R_z. From the results obtained here it is seen that as R_z changes from 0 to 100, T_1(H), T_1(D) and T_1(Z) shift to the later part of the day by 38 min., 48 min. and 1h.11 min. respectively. The shift of time of maximum to the later part of the day with increase of sunspot could be the effect of increasing contamination of Sq by geomagnetic disturbance as contemplated by Yacob and Rao (1966) or the result of skewing of the latitude axes of Sq current systems as explained by Brown (1975).

3.4.2 Lunar harmonic components:

Leaton et al. (1962) observed some tendency for the amplitude of individual harmonics of L at Abinger and Greenwich to increase with R_z but indicated that there is little evidence of any systematic variation of phase angle. Green and Malin (1971) have also stated that no systematic changes in the phase angles are discernible in the data of Watheroo. Large probable errors associated with the values of m in the linear relation of R_z and each of the amplitudes and times of maximum obtained here may be either due to poor determination of harmonics or would suggest that the variation of harmonics with R_z is affected by a high degree of random variability. No systematic changes in the values of m with increasing harmonic number are seen in Table 3.9. This is, however, contradictory to the result of Malin et al. (1975), who found that the value of m x 10^4 change linearly from 74 for the first harmonic to -20 for the fourth harmonic.

3.5 Solar cycle influence on lunar partial terms:

It can be seen from Table 3.7 that, even though many of the harmonics are not significantly determined, there is some suggestion for the amplitudes of lunar partial tide to increase with solar activity especially in l_1(H), l_4(H), during the year and l_2(H), l_1(D) and l_1(Z) during d season. The increase of partial tide with R_z can be more effectively seen by the inspection of lunar partial tide ranges given in the last column of Table 3.7. The values of $m \times 10^4$ in the linear relation of R_z and lunar partial ranges in H,D and Z are 104 ± 87, 60 ± 45 and 28 ± 50 respectively during the year. The corresponding values for d-season are 16 ± 34, 56 ± 44 and 33 ± 33. The resulting values of $m \times 10^4$ for the mean of three elements during y and d seasons are 53 ± 31 and 32 ± 21 and do not differ significantly from those for lunar phase law ranges.

3.6 Summary:

Results of work described in this chapter may be summarised as follows:

(i) Both S and L exhibit definite positive association with sunspot number but changes in L are not as systematic and sharp as those for S. This is probably because the amplitudes of L are affected by a high degree of random variability.

(ii) The overall enhancement of S, as measured by the mean Wolf ratio, is about 1.7 times the enhancement of L. The close agreement between the Wolf ratio for L and E-region conductivity suggests that solar cycle modulation of L at Alibag results primarily from the corresponding variation in the E-region conductivity. The enhancement of S, however, is much larger than that resulting from the increase of ionospheric conductivity; this excess enhancement seems to be caused by the solar cycle modulation of solar thermal time and/or the field of the partial ring current.

(iii) The value of Wolf ratio for S shows marked seasonal progression, so that solar cycle modulation is strongest in equinox and least in winter. Large probable errors, associated with seasonal Wolf ratios, make it difficult to ascertain the seasonal changes in the behaviour of L to solar cycle.

(iv) The negative dependence of solar ranges in D on sunspot number during winter results from the decreasing invasion of southern current system into the northern hemisphere with increase in sunspot number.

(v) Solar cycle influence on the amplitudes of solar harmonics is frequency dependent and the relative increase in the diurnal and semidiurnal terms are larger than the effects caused by the increase of conductivity.

(vi) The time of maximum of first harmonics of S in all elements shifts to the later part of the day with increasing sunspot number. This is ascribed to the effect of either the skewing of the latitude of S current system or the increasing contamination of Sq by disturbance.

(vii) Response of partial tide to solar cycle is similar to that of phase law tide during winter and the year.

CHAPTER 4

ON THE ASSOCIATION OF SOLAR AND LUNAR DAILY VARIATION WITH THE DEGREE OF MAGNETIC ACTIVITY

On the Association of Solar and Lunar Daily Variation With the Degree of Magnetic Activity

4.1 Introduction

While the dynamo theory of quiet-day variation of earth's magnetic field has received general recognition, it has become increasingly apparent in recent years that contributions to the daily variation may also arise from non-ionospheric current systems, e.g., magnetopause currents, quiet-time and partial ring currents (Mead, 1964; Poeverlien, 1965; Olson, 1970; Sarabhai and Nair, 1969; 1971 and Bhargava and Yacob, 1971). The energy for these currents is, however, derived directly or indirectly from the solar wind. Because of large scale fluctuation in the solar wind parameters, which determines the strength of non-ionospheric currents, it is suggested that these currents may make a significant contribution to the day-to-day variability in S. Sarabhai and Nair (1969, 1971) have suggested that the asymmetric ring current was the principal source of Sq. Their treatment is based on all days data, so that it my include appreciable disturbance effects (Hutton, 1970; Kane, 1970). Bhargava and Yacob (1971), using index Ap of magnetic activity as a measure of solar wind velocity and the ranges in S(H) at Alibag, indicated the presence of a secondary component in the daily variation of H in the form of an evening depression of the field. The results of these workers have, however, failed to show the precise contribution of non-ionospheric currents under extremely quiet conditions but have enumerated the existence of systematic increase in the contribution of non-ionospheric sources to S with increasing magnetic activity. These contributions tend to increase the total daily variation. Leaton, Malin and Finch (1962), and Gupta (1972) and many other workers by classifying the days in different groups of magnetic activity conclusively proved the positive association of S with magnetic activity. Similar analysis for the dependence of L on magnetic activity has been investigated for several stations but different workers have reached differing conclusions. In the present Chapter the dependence of S and L at Alibag on magnetic activity is investigated using index Ap as a measure of magnetic activity. The results of this analysis are discussed and compared with the results of other stations.

4.2 Treatment of Data :

As a first step to study the effect of magnetic activity on solar and lunar variations of the elements H, D and Z at Alibag, all days for the period 1932 to 1972 are classified by daily magnetic activity index Ap into seven groups M-1 to M-7. The seven groups consisted of days with Ap in the intervals 0-4, 5-7, 8-10, 11-14, 15-20, 21-40 and 41-100 respectively. Days in each of the magnetic groups are further subdivided into three Lloyd's seasons (j,e,d). Following the numerical procedure of Winch (1970a), as detailed in Chapter 1, amplitudes and phases of solar, lunar phase law and partial tides are obtained for each of the magnetic groups during the three seasons and the year. Solar harmonic components computed for all the above subgroups are listed in Tables 4.1, 4.2 and 4.3 for H,D and Z respectively. Also given are the number of days included in each group and their mean Ap. The number of days in seasonal magnetic groups M-5, M-6 and M-7 are relatively smaller to permit any significant determination of lunar terms. Hence lunar harmonics of the above seven groups only for the year are presented in Table 4.4.

The probable errors of the amplitude of solar harmonics are negligibly small and may be safely ignored in discussing the results. But in case of L many of the amplitudes when compared to their respective probable errors are found to be of doubtful significance and discussion of lunar harmonics will therefore necessitate consideration of the associated probable errors.

4.3 <u>Results and discussion</u> :

4.3.1 <u>Results for solar terms</u> :

A glance at the results of Tables 4.1, 4.2 and 4.3 reveals that, in general, amplitudes of only the first harmo-

TABLE No. 4.1 Yearly(y) and seasonal(j,e,d) harmonic components as well as range of S(H) at Alibag for seven groups of magnetic activity with Ap in the ranges 0-4, 5-7, 8-10, 11-14, 10-20, 21-40 and 41-100 respectively. (Amplitudes a_n, and ranges, R(S), in units of 0.1nT and phases, σ_n, in degrees).

Season	Mag. Group	Harmonic: No. of Days	Harmonic: Mean Ap	n = 1: a_1	n = 1: σ_1	n = 2: a_2	n = 2: σ_2	n = 3: a_3	n = 3: σ_3	n = 4: a_4	n = 4: σ_4	Range: R(S)	Range: pe
y	1	2773	3.2	184	276	88	104	34	308	10	148	434	2
	2	2943	5.9	195	277	92	103	36	308	10	150	460	2
	3	2318	8.9	201	279	94	102	36	309	10	152	479	2
	4	1904	12.4	204	284	97	103	37	310	10	153	497	2
	5	1668	17.3	207	287	94	98	33	313	13	165	514	6
	6	1858	28.0	221	298	103	97	38	303	12	144	567	5
	7	661	56.7	247	318	99	102	40	306	17	139	617	14
j	1	931	4.3	200	276	103	101	29	301	6	182	458	3
	2	1141	6.7	209	276	105	101	31	300	5	178	475	3
	3	818	10.0	212	280	106	102	30	301	6	183	494	4
	4	624	13.8	217	282	107	103	32	302	4	198	505	5
	5	522	19.4	213	285	100	98	22	304	13	205	512	19
	6	509	31.0	220	296	114	102	35	287	6	174	564	8
	7	180	63.7	238	322	100	102	25	293	14	127	593	28
e	1	768	3.2	204	272	100	102	49	308	19	146	496	2
	2	846	5.9	208	275	99	101	50	309	18	154	511	5
	3	746	9.0	209	277	103	100	48	309	18	152	520	4
	4	649	12.5	207	281	106	100	49	309	17	152	529	6
	5	589	17.4	215	285	106	97	48	311	18	161	555	6
	6	785	28.3	209	297	110	95	49	304	17	150	567	7
	7	333	58.0	236	316	107	99	52	305	22	151	626	20
d	1	1074	3.8	159	278	67	111	28	315	9	134	374	3
	2	956	7.6	168	281	70	109	29	315	10	126	400	3
	3	754	10.2	182	283	73	106	30	319	9	129	435	5
	4	631	14.0	189	288	76	108	30	320	9	133	455	5
	5	557	19.5	193	292	76	101	28	323	11	132	477	6
	6	564	32.0	239	301	84	97	29	317	13	121	581	8
	7	148	59.3	286	318	79	111	31	317	12	106	636	25

Table 4.2 Yearly (y) and seasonal (j, e, d) harmonic components as well as range of S(D) at Alibag for seven groups of magnetic activity with Ap in the ranges 0–4, 5–7, 8–10, 11–14, 15–20, 21–40 and 41–100 respectively. (Amplitudes, s_n, and ranges, R(S), in units of 0.1 nT and phases, σ_n, in degrees).

Season	Mag. Group	Harmonic No. of Days.	n=1 s_1	n=1 σ_1	n=2 s_2	n=2 σ_2	n=3 s_3	n=3 σ_3	n=4 s_4	n=4 σ_4	Range R(S)	Range pe
y	1	2766	54	36	62	237	56	71	19	276	303	1
	2	2936	66	36	68	239	60	74	19	283	331	7
	3	2313	66	37	68	240	60	74	20	282	334	2
	4	1898	65	39	66	239	59	74	20	280	325	3
	5	1667	62	43	64	240	58	73	20	279	315	3
	6	1855	59	49	62	236	57	73	19	280	306	3
	7	662	67	52	66	240	58	75	21	286	324	7
j	1	928	118	30	117	244	81	81	14	315	513	2
	2	1140	128	31	119	244	81	81	15	322	532	3
	3	818	128	29	120	245	80	81	15	322	531	3
	4	621	133	30	123	244	82	81	15	326	548	4
	5	520	128	29	120	245	80	82	16	328	532	4
	6	508	134	28	125	241	79	79	16	330	551	4
	7	181	136	28	127	240	73	78	20	327	549	9
e	1	766	64	31	74	233	73	70	28	269	381	3
	2	844	67	32	78	234	75	73	30	275	398	3
	3	745	72	35	80	234	75	72	28	272	404	3
	4	648	73	36	80	234	75	73	28	272	404	4
	5	589	74	40	78	235	74	72	28	271	398	4
	6	784	67	46	75	232	70	73	25	270	372	3
	7	333	75	52	74	240	71	76	26	276	377	7
d	1	1072	16	155	10	178	26	46	20	262	94	2
	2	952	20	150	7	150	24	47	20	263	92	2
	3	740	24	143	4	157	25	54	22	265	96	2
	4	629	27	150	5	107	22	51	21	263	103	3
	5	558	33	149	5	104	23	46	22	260	114	3
	6	563	50	154	11	78	20	55	20	265	140	4
	7	148	73	158	27	52	13	51	19	266	184	11

Table 4.3 Yearly (y) and seasonal (j,e,d) harmonic components as well as range of S(Z) at Alibag for seven groups of magnetic activity with Ap in the ranges 0-4, 5-7, 8-10, 11-14, 15-20, 21-40 and 41-100 respectively. (Amplitudes, s_n, and ranges, R(S), in units of 0.1 nT and phases, σ_n, in degrees).

Season	Mag. Group	Harmonic No. of Days	n=1 s_1	n=1 σ_1	n=2 s_2	n=2 σ_2	n=3 s_3	n=3 σ_3	n=4 s_4	n=4 σ_4	Range R(S)	Range pe
y	1	2766	45	83	48	298	44	133	17	340	226	1
	2	2934	51	82	52	300	47	137	17	347	244	2
	3	2310	54	82	52	301	49	138	18	346	250	2
	4	1900	53	82	49	302	47	139	18	345	243	3
	5	1666	52	82	48	302	47	138	18	343	237	3
	6	1855	52	82	46	301	46	139	18	344	234	3
	7	661	63	84	49	303	50	144	20	353	262	5
j	1	925	78	87	77	302	61	139	12	11	337	2
	2	1138	84	84	79	300	61	140	13	19	355	3
	3	814	87	83	79	301	61	141	13	21	359	2
	4	623	92	81	81	300	63	141	13	21	373	3
	5	521	91	81	79	301	62	141	14	23	367	3
	6	508	100	81	82	298	61	139	13	24	382	3
	7	180	110	84	86	296	62	141	18	27	409	6
e	1	767	67	85	60	303	59	137	26	338	297	3
	2	842	73	84	62	304	60	140	26	342	313	2
	3	745	76	85	63	303	61	140	26	339	317	3
	4	647	77	87	62	304	60	141	25	338	312	4
	5	588	78	87	61	305	60	141	26	338	311	3
	6	784	75	86	56	303	57	141	24	338	294	3
	7	333	84	88	59	306	59	145	26	344	314	6
d	1	1074	6	4	17	274	22	111	17	325	101	2
	2	954	10	301	11	277	20	116	18	328	85	3
	3	751	7	304	12	289	23	125	19	331	93	3
	4	630	10	291	6	293	20	124	18	329	78	4
	5	557	13	290	5	286	20	118	18	324	74	3
	6	563	24	278	2	44	18	132	18	331	82	4
	7	148	42	268	15	104	14	153	16	343	119	8

Table 4.4 Yearly harmonic components as well as range of L(H), L(D) and L(Z) at Alibag for seven groups of magnetic activity with Ap in the ranges 0–4, 5–7, 8–10, 11–14, 15–20, 21–40 and 41–100 respectively. (R(L), l_n, pe's in units of 0.01 nT and λ_n in degrees).

Element	Harmonic Mag. group	No. of days	n=1 l_1	pe	λ_1	n=2 l_2	pe	λ_2	n=3 l_3	pe	λ_3	n=4 l_4	pe	λ_4	Range R(L)	pe
H	1	2773	78	14	3	84	10	171	37	05	349	11	02	209	420	19
	2	2943	84	15	339	92	06	168	32	05	356	11	06	159	438	22
	3	2318	51	17	338	56	08	166	22	05	335	06	05	194	270	23
	4	1904	66	19	19	79	10	182	25	08	8	02	06	354	344	27
	5	1668	74	34	306	68	28	145	13	21	35	23	26	258	356	63
	6	1858	91	33	308	46	22	157	54	11	12	10	06	230	402	48
	7	661	205	107	309	58	49	116	62	33	10	17	27	144	684	143
D	1	2776	34	06	85	56	06	321	51	03	127	09	04	1	300	11
	2	2936	22	10	147	28	08	304	41	06	101	11	05	288	204	17
	3	2313	38	10	152	44	10	348	46	06	124	14	03	298	284	18
	4	1898	35	17	178	65	17	11	32	12	149	10	06	322	284	32
	5	1667	26	16	217	41	17	2	27	13	127	12	05	336	212	31
	6	1855	18	20	105	48	13	2	29	08	137	06	04	13	202	29
	7	662	30	47	121	87	35	335	58	21	132	18	11	324	386	72
Z	1	2766	49	08	157	36	06	6	63	04	206	16	03	76	328	13
	2	2934	29	11	154	22	07	352	52	06	192	09	04	31	224	17
	3	2310	36	09	172	31	07	35	55	06	200	12	04	27	268	15
	4	1900	47	19	202	35	14	70	49	10	216	11	05	17	284	30
	5	1666	24	22	207	33	14	48	53	10	207	17	05	34	254	33
	6	1855	36	18	197	41	13	60	51	08	217	15	04	67	286	27
	7	661	46	31	119	70	21	24	80	15	199	25	11	32	442	48

nic is significantly affected by magnetic activity. The effect of such association is an increase of amplitude with increasing magnetic activity. The changes in amplitude of this harmonic are most apparent in H and are accompanied by similar changes in the phase angle of this harmonic. The drifts in the phase angles are such that, with increasing magnetic activity, the time of maximum amplitude shifts systematically to the earlier part of the day. The other important changes in the phase angle of first harmonic are those of $S_1(D)$ during year and equinox and $S_1(Z)$ during summer and winter; the changes in phase angles of Z are of opposite sense to those observed for H and D. The relative changes in amplitude with increasing magnetic activity appear to be more pronounced in winter than during summer and equinox. Amplitudes of both $S_1(D)$ and $S_1(Z)$, obtained by combining the data of all seasons, fail to show any positive association with the degree of magnetic activity. Almost an opposition in phase between winter and summer is seen in the first harmonic of both S(D) and S(Z), with a phase difference of about 120° and 220° in D and Z respectively. Consequently, the effect of amplitude changes with magnetic activity, though similar in both the elements and in both the seasons, would be cancelled out to a great extent and the magnetic dependence of $S_1(D)$ and $S_1(Z)$ during the year would, thus, be primarily determined by the changes in equinox which, even in H, are small. There is little tendency for $S_2(H)$ during j season, $S_2(D)$ and $S_2(Z)$ during year to increase with increasing magnetic activity and these components are not accompanied by any systematic changes of phase angles.

4.3.2 Numerical estimate of the dependence:

Making the first order approximation that changes in S with magnetic activity are linear functions of Ap, the overall changes in the daily variation of all elements are studied by computing the Wolf's linear relationship between ranges, R(S), and Ap. The method of computing the Wolf numbers is the same as that used in the earlier Chapter for the estimation of solar cycle influence on solar and lunar ranges. The Wolf numbers so computed for yearly and seasonal terms are given in Table 4.5. Since the diurnal term generally dominates the other harmonics, range of daily variation is determined primarily by this component. The changes observed in the amplitude of first harmonic only are, therefore, reflected in the results of ranges. The values of Wolf ratio, M, suggest that it is only the horizontal component which undergoes significant changes with Ap. It is interesting to note that the changes in solar ranges of H during j and e seasons are only about one-third of the corresponding changes during d-season. It is also interesting to note that the Wolf ratio in the linear relation of yearly solar ranges of H and Ap is larger than the corresponding Wolf ratio in the linear relation between

TABLE 4.5 Wolf ratios in the linear relation of solar ranges and magnetic activity index, Ap.

Season	$\frac{H}{M \times 10^4}$	$\frac{D}{M \times 10^4}$	$\frac{Z}{M \times 10^4}$	Weighted Mean $\frac{H + D + Z}{M \times 10^4}$
y	114 ± 7	10 ± 5	18 ± 5	34 ± 3
j	80 ± 12	18 ± 4	37 ± 6	29 ± 3
e	61 ± 8	-10 ± 4	-2 ± 6	6 ± 3
d	193 ± 14	202 ± 31	-18 ± 22	143 ± 11

ranges and annual R_z, suggesting that in case of S(H) magnetic activity has a greater effect than sunspot activity. Gupta (1972) also observed similar differences in the behaviour of S to magnetic and solar activity in the data of Sodankylä. Another striking difference in the behaviour of S(H) to solar and magnetic activities is that while the magnetic dependence of H is found to be highest during winter, the changes with solar activity are found to be highest during equinoxes and least in winter. This suggests that the mechanism responsible for solar and magnetic modulation may be different.

Fig.4.1 shows the daily variation of S(H) computed from the results of the year for different groups of magnetic (M-1 to M-7) and solar (A to D) activities, obtained by synthesizing the harmonic coefficients of respective groups given in Tables 4.1 and 3.1. The examination of Fig. 4.1 a,b shows that while the changes in S(H) with increasing R_z are primarily due to the enhancement of midday field, the changes with increasing magnetic activity appear to arise from the decrease of field in the evening sector. Bhargava and Yacob (1971) attributed the changes in daily variation of S(H) on days of different Ap to the effect of asymmetric ring current belt consisting of a symmetric ring current and a superposed partial ring current system on the right side of the magnetosphere. The effect of symmetric ring

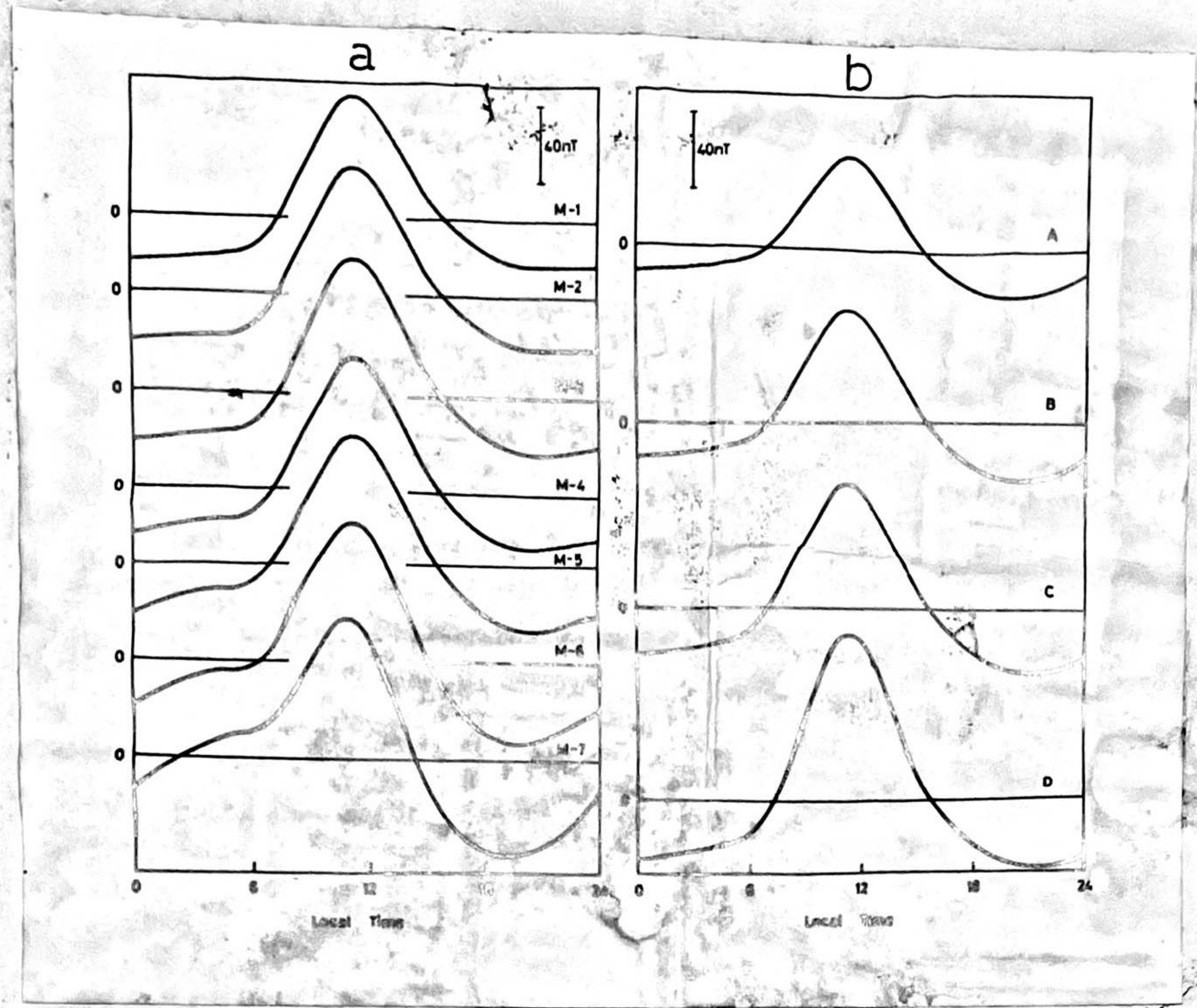


Fig. 4.1

A comparison of changes in the yearly mean solar daily variation of H at Alibag with increasing (a) magnetic activity (M-1 to M-7) and (b) solar activity (low (A) to high (D).

current on average solar daily variation is nearly same at all hours of the day and results only in diminishing the daily base-level on which Sq is superposed. However, the southward directed field of partial ring current, with a maximum observed between 19-21 LT, is the source of significant contribution to daily range.

To explain the latitudinal asymmetry in the field of symmetric ring current with respect to equator during solstices, Fukushima and Nagata (1968) studied the local time dependence of $\Delta Z/\Delta H$ values at Honolulu and from this they concluded that symmetric ring current on the night side of the magnetosphere might be deflected from the geomagnetic equator towards the winter hemisphere side. The daily variation at a station located in the winter hemisphere and rotating with the earth under such tilted ring current of uniform intensity will have, in addition to the field due to other sources, an additional diurnal component with maximum southward directed field in the night hours. Since the asymmetric ring current is considered to be superposed on the symmetric ring current it seems reasonable to assume that asymmetric ring current is also deflected towards the winter hemisphere. Thus, it is likely that changes in the intensity of symmetric and asymmetric ring currents due to varying magnetic activity will produce large change in S(H) at Alibag during winter than in summer and equinox owing to the closer approach of the current system to the latitude of Alibag in winter.

This probably may explain the differences in the value of M during winter and summer or equinox.

4.3.3 Results for Lunar terms:

No systematic changes either in amplitudes or in phases of lunar harmonics from magnetic group M-1 to M-7 are discernible in the results of Table 4.4. However, it should be noted that by virtue of large data in Groups M-1 to M-3, harmonics are better determined (the ratio of probable error to the amplitude is sufficiently low) than in groups M-4 to M-7. In fact the probable errors show a sharp increase in their magnitude from group M-3 (or M-4) to M-4 (or M-5). Malin and Leaton (1969) have shown that the amplitude of lunar harmonics derived from noisy data are likely to be over-estimated by an amount proportional to their respective probable errors and have given a method for their correction. When the amplitudes of different harmonics are corrected for the variation of probable error, the magnitudes of amplitude in higher groups have sufficiently reduced but still fail to show any systematic trend in the changes with magnetic activity. Hence, in order to have a better insight of the influence of magnetic activity on L, the data have been reanalysed by successively adding days of increasing Ap to days of Group M-1, i.e. the new magnetic group M-2 now contains days of earlier groups M-1 and M-2 and new group M-3 will have days of group M-1 to M-3, and so on. In other words, these new groups consist of days with Ap in the ranges 0-4, 0-7, 0-10, 0-14, 0-20, 0-40 and 0-100 respectively. For each of these seven groups, S and L harmonics are recomputed. Since the general features of S-harmonics are the same as obtained in earlier groups, the results of L harmonics only are presented in Tables 4.6, 4.7 and 4.8.

The most noticeable feature of the results presented in Tables 4.6, 4.7 and 4.8 is that with the successive addition of days with higher values of Ap to low Ap groups, the probable errors in seven groups of magnetic activity have sufficiently reduced compared to those given in Table 4.4. Also the probable errors associated with the individual harmonics do not show any appreciable change from magnetic groups M-1 to M-7, suggesting that the effects of transient variation on the significance of results is approximately equalised and hence changes observed in L are of high significance. The first three harmonics of all elements during year and in different seasons (with few exceptions in equinox) are found to be significant in all groups of magnetic activity. The amplitude of first three harmonics of all the elements derived from yearly data show a general decrease with increasing magnetic activity. But there are some marked seasonal differences in the behaviour

Table 4.6 Yearly (y) and seasonal (j,e,d) harmonic components as well range of L(H) at Alibag for seven revised groups of magnetic activity with Ap in the range 0–4, 0–7, 0–10, 10–14, 0–20, 0–40 and 0–100 respectively. (Amplitudes, l_n, Range, R(L), and probable errors, pe, are in units of 0.01 nT and phases, λ_n, in degrees).

Season	Mag. Group	No. of Days	Mean Ap	l_1	pe	λ_1	l_2	pe	λ_2	l_3	pe	λ_3	l_4	pe	λ_4	R(L)	pe
		Harmonic		n=1			n=2			n=3			n=4			Range	
y	1	2773	3.2	78	14	3	84	06	171	37	05	349	11	02	209	420	19
	2	5716	4.6	77	09	351	88	05	170	34	05	353	10	03	183	418	14
	3	8034	5.8	70	09	349	79	04	169	31	04	349	09	03	185	378	13
	4	9938	7.1	68	09	355	79	04	171	29	03	352	07	02	186	366	12
	5	11606	8.6	66	08	349	77	05	168	26	04	355	08	04	211	354	13
	6	13464	11.3	65	07	348	73	06	167	30	04	359	08	04	212	352	12
	7	14125	13.4	68	07	345	72	06	165	32	04	0	08	03	207	360	12
j	1	931	4.3	68	22	24	44	10	207	24	07	17	08	04	263	288	29
	2	2072	5.7	61	12	357	49	07	180	26	06	4	04	03	260	280	18
	3	2890	7.0	53	12	348	39	06	182	19	05	1	07	03	276	236	17
	4	3514	8.2	51	13	7	40	07	190	17	05	0	07	03	288	230	18
	5	4036	9.7	54	14	345	31	12	184	12	12	39	19	11	184	232	28
	6	4545	12.2	51	13	347	33	12	175	13	12	30	17	10	281	228	27
	7	4725	14.3	48	15	351	36	12	174	14	11	13	14	10	286	224	28
e	1	768	3.2	14	16	89	46	11	148	14	06	320	02	05	94	152	24
	2	1614	4.6	04	17	128	55	11	151	10	10	291	15	08	130	168	27
	3	2360	6.0	16	16	42	41	11	151	16	08	295	14	06	137	174	25
	4	3009	7.4	25	15	31	42	11	153	12	07	309	12	05	148	182	23
	5	3598	9.0	30	13	39	50	10	155	18	06	315	14	05	147	224	21
	6	4383	12.5	28	10	120	46	10	148	23	07	339	09	05	152	212	19
	7	4716	15.7	29	15	354	48	11	139	27	07	348	10	06	166	228	24
d	1	1074	3.8	139	18	0	137	11	172	67	05	349	27	06	195	740	26
	2	2030	5.4	154	13	350	151	08	173	68	05	357	22	05	198	790	19
	3	2784	6.8	138	13	348	154	06	172	61	04	357	17	04	191	740	18
	4	3415	8.2	130	12	345	156	07	171	61	04	358	14	04	187	722	17
	5	3972	9.7	121	10	341	151	07	169	57	04	356	13	04	176	684	15
	6	4536	12.7	120	13	341	144	08	170	59	04	359	15	03	177	676	18
	7	4684	14.2	129	14	340	139	09	171	57	05	2	15	04	177	680	20

Table 4.7 Yearly (y) and seasonal (j,e,d) harmonic components as well range of L(D) at Alibag for seven revised groups of magnetic activity with Ap in the ranges 0–4, 0–7, 0–10, 10–14, 0–20, 0–40 and 0–100 respectively. (Amplitudes, l_n, Range, R(L), and probable errors, pe, are in units of 0.01 nT and phases, λ_n, in degrees).

Season	Harmonic Mag. Group	No. of Days	n=1 l_1	pe	λ_1	n=2 l_2	pe	λ_2	n=3 l_3	pe	λ_3	n=4 l_4	pe	λ_4	Range R(L)	pe
y	1	2766	34	06	85	56	06	321	51	03	127	09	04	1	300	11
	2	5702	24	05	112	41	05	316	44	03	115	08	03	319	234	09
	3	8015	27	05	126	41	04	325	44	03	118	10	02	312	244	08
	4	9913	26	05	139	42	04	338	41	03	122	10	02	314	238	08
	5	11580	24	04	148	42	04	342	39	02	123	10	02	317	230	07
	6	13435	22	03	147	42	03	345	37	02	124	09	01	321	220	05
	7	14097	23	04	146	44	03	344	38	02	125	09	01	322	228	06
j	1	928	61	10	113	133	10	277	94	07	101	01	06	141	578	19
	2	2068	73	08	106	135	08	277	89	07	100	03	05	190	600	16
	3	2886	74	08	103	129	07	279	87	05	102	02	04	217	584	14
	4	3507	69	08	101	124	05	282	84	04	104	02	03	207	558	12
	5	4027	69	08	101	126	05	283	82	03	105	01	03	152	556	12
	6	4535	69	07	98	126	05	284	82	03	104	02	02	155	558	11
	7	4716	65	08	95	126	05	285	81	03	105	02	03	159	548	12
e	1	766	47	13	82	39	15	256	62	11	67	23	11	268	342	29
	2	1610	33	09	84	41	09	258	68	06	71	30	07	265	344	18
	3	2355	24	08	84	35	09	284	61	05	81	26	05	265	292	16
	4	3003	21	08	87	38	08	287	60	05	85	25	05	272	288	15
	5	3592	15	08	86	34	08	283	61	06	84	25	04	273	270	15
	6	4376	21	06	80	37	07	283	57	05	86	22	03	269	274	13
	7	4709	24	06	83	40	06	288	58	04	88	21	03	272	286	11
d	1	1072	62	11	237	119	11	53	67	08	213	28	04	25	552	21
	2	2024	63	07	228	124	07	59	59	05	217	23	03	15	538	13
	3	2774	63	05	223	129	05	57	58	04	217	22	03	4	544	10
	4	3403	61	05	220	136	05	55	59	03	218	21	02	3	554	09
	5	3961	63	05	219	142	04	54	62	03	220	20	02	5	574	08
	6	4524	64	05	222	147	03	55	64	03	221	23	02	10	596	08
	7	4672	66	05	221	148	04	54	64	03	220	24	02	8	604	08

Table 4.8 Yearly (y) and seasonal (j,e,d) harmonic components as well range of L(Z) at Alibag for seven revised groups of magnetic activity with Ap in the ranges 0-4, 0-7, 0-10, 10-14, 0-20, 0-40 and 0-100 respectively. (Amplitudes, l_n, range, R(L) and probable errors, pe, are in units of 0.01 nT and phases, λ_n, in degrees).

Season	Harmonic Mag. Group	No. of Days	n=1 l_1	pe	λ_1	n=2 l_2	pe	λ_2	n=3 l_3	pe	λ_3	n=4 l_4	pe	λ_4	Range R(L)	pe
y	1	2766	49	08	157	36	06	6	63	04	206	16	03	76	328	13
	2	5700	39	06	157	29	04	1	57	03	200	11	02	59	272	09
	3	8010	38	05	161	29	04	11	57	03	200	12	02	49	272	08
	4	9910	38	04	170	27	03	24	55	03	203	11	01	44	262	07
	5	11576	36	03	174	28	02	28	54	02	203	12	01	42	260	05
	6	13431	36	03	177	28	03	34	54	02	205	12	01	46	260	05
	7	14092	36	03	174	30	02	33	55	02	205	13	01	45	268	05
j	1	925	65	13	177	83	07	322	79	05	168	06	05	96	466	19
	2	2063	56	10	180	82	07	329	77	06	169	01	03	147	432	14
	3	2877	50	08	186	76	05	329	74	04	171	01	02	208	402	12
	4	3500	51	07	187	71	04	332	72	04	173	01	03	239	390	11
	5	4022	52	05	183	73	04	332	73	03	172	01	02	310	398	08
	6	4530	56	05	183	73	04	333	73	03	172	01	02	306	406	08
	7	4710	56	05	182	73	04	334	72	03	172	01	02	299	404	08
e	1	767	47	11	113	43	13	283	51	12	164	13	08	344	308	26
	2	1609	53	10	114	52	07	301	64	05	164	17	04	347	372	16
	3	2354	42	09	131	42	07	311	64	04	167	16	03	344	328	14
	4	3001	43	07	140	40	06	315	65	04	171	18	03	353	332	12
	5	3589	39	07	137	39	06	314	66	04	170	19	02	353	326	12
	6	4373	41	06	136	36	04	319	62	03	173	16	02	355	310	09
	7	4706	43	05	128	38	03	322	63	02	174	17	02	358	322	07
d	1	1074	35	14	204	86	11	93	91	08	255	37	04	80	498	23
	2	2028	23	12	197	88	07	104	82	05	258	30	03	77	446	17
	3	2779	28	08	176	92	05	102	83	04	257	30	02	73	466	12
	4	3409	29	07	181	94	03	101	83	03	258	27	02	70	466	10
	5	3966	28	06	195	100	03	100	85	03	259	28	02	71	482	09
	6	4529	28	05	211	105	03	100	88	03	260	30	02	72	502	08
	7	4677	30	05	213	106	04	99	88	03	259	31	02	71	510	08

of dependence of L on magnetic activity. For example the amplitude of the principal semidiurnal component of L in D and Z during winter shows an increasing trend with increasing magnetic activity. Certain trends in the changes of phase angles of various harmonics with magnetic activity can also be seen. It is interesting to note that while in H the trend in the change of the amplitude and phase angle of lunar semidiurnal component with magnetic activity are similar, in D and Z they show opposite trends, i.e. when amplitudes are decreasing the phase angles tend to increase.

The general decrease of amplitude with increase in magnetic activity observed here is in agreement with the earlier result of Rao and Arora (1975) for H at Alibag but is in sharp contrast to the results of Raja Rao and Reddy (1973) and Raja Rao et al. (1973); they found an increase in amplitudes with increasing magnetic activity. Chapman (1957) and Leaton et al. (1962) also reported such conflicting results for Greenwich. While grouping the days according to magnetic activity, Chapman (1957) had not removed the effect of solar activity or equalised the effect of noise on the probable error by using more data for disturbed days than for quiet days. For both these reasons, it is to be expected that the amplitude would show an increase with magnetic activity and for these reasons Green and Malin (1971) have concluded that Chapman's results do not necessarily conflict with those of Leaton et al. (1962). Examination of the distribution of days in the three epochs of solar activity for each of the three magnetic groups of Raja Rao and Reddy (1973), showed that their highest magnetic group was dominated by days from high solar activity indicating that the influence of solar activity on magnetic activity had not been eliminated. The importance of eliminating the influence of solar activity while attempting to determine the dependence of L on magnetic activity is more clearly demonstrated in Chapter 5, where it is found that the correlation between annual values of lunar ranges and magnetic activity index Ap is merely a reflection of the strong association between solar and magnetic activities. Thus it appears that the differences in the results obtained here and those of Raja Rao and Reddy are due to differences in the criterion for grouping of the days according to magnetic activity. It seems that the criterion chosen for grouping of the days play an important role in the determination of magnetic activity influence on L and hence while comparing the general dependence of L on magnetic activity at various stations, mention must be made of the criterion for grouping of the days. Rao and Arora (1975) have compared the behaviour of L with respect to magnetic activity at several stations. For precise understanding of the phenomena, their results are discussed below together with the recently available results of

Sodankylä and those presented here.

Leaton et al. (1962), in their analysis of data from Greenwich and Abinger, selected the international character figure C as a measure of magnetic activity and coded each day of any particular month into three categories - 0 for five international quiet days, 2 for fifteen most disturbed days and 1 for the remaining days of the month. They showed that there was a marked tendency for the lunar semidiurnal component in H and D to decrease with increasing magnetic activity. Winch (1970a) divided the geomagnetic data of Toolangi according to magnetic activity by calculating the daily range of each daily sequence of values about the corresponding monthly mean sequence. The daily ranges were then placed in order of magnitude and ranges were selected which divided the data into three equal parts after allowing for missing days. It can be seen from the results given in his Table 6 that there is a systematic increase of lunar semidiurnal component of H with the increase in magnetic activity. Green and Malin (1971), following the criterion for grouping the days according to magnetic activity used by Leaton et al. (1962), have also shown, for Watheroo, an increase in the magnitude of the lunar harmonics of all the elements with increase in magnetic activity. Gupta (1972) examined the dependence of L on magnetic activity by dividing the Sodankylä data by three different methods and showed an increasing trend in the magnitude of amplitudes of different harmonics. Thus, both the selection criteria for grouping the days and the principal results regarding the general dependence of lunar phase law variations on magnetic activity are differing. The association between amplitude and magnetic activity observed in the present analysis is in agreement with the results for Greenwich and Abinger, given by Leaton et al.

Maeda (1971) reported that the background plasma in the magnetosphere above about 150 km could oscillate by the electromagnetic forces where the electric field seems to be transferred from the dynamo region along the geomagnetic field lines. These oscillations, known as hydromagnetic tides in the magnetosphere, were obtained on the basis of the electrostatic fields in the dynamo region as deduced from solar and lunar magnetic variations. He found that apart from the expansion during the day and contraction during the night for the solar tides, the magnetosphere expands around 00 and 12 hours and contracts around 06 and 18 hours lunar time for the lunar tides. The times of first maxima of lunar semidiurnal component of H for the quiet magnetic group at Sodankylä, Greenwich, Abinger, Alibag, Toolangi and Watheroo are respectively 4.1, 2.0, 1.6, 9.3, 6.0 and 4.6 hours lunar time. Thus the times of maxima at Greenwich, Abinger and Alibag are near the times of expansion of the magnetosphere for the lunar tides, whereas the times of maxima at Sodankylä, Toolangi and Watheroo are close to the times of contraction of the magnetosphere. It, therefore, appears that for stations where the lunar time of maximum is around the time of magnetospheric expansion for lunar tides, there is a general decrease of amplitude with increase in magnetic activity. For those stations where the lunar time of maximum is around the time of magnetospheric contraction an increase of amplitude with increase in magnetic activity is observed.

4.3.4 Results for Lunar Partial terms:

The terms of lunar partial tide in H, D and Z for each of the seven revised magnetic groups during year are listed in Table 4.9. There is a suggestion for the amplitudes to decrease with magnetic activity but nowhere they are well marked. Some trends in the phase angles of various harmonics are also noted but they are inconsistent and one tends to feel that they may be purely accidental. For partial tides at Toolangi, Winch (1970a) found that only the phase angle showed a dependence on magnetic activity.

Table 4.9 Yearly harmonic components as well as range of lunar partial tides in H, D and Z at Alibag for seven revised groups of magnetic activity (l'_n, pe, r(L) in units of 0.01 nT and λ'_n in degrees).

Element	Mag. Group	No. of Days	n=1 l'_1	n=1 pe	n=1 λ'_1	n=2 l'_2	n=2 pe	n=2 λ'_2	n=3 l'_3	n=3 pe	n=3 λ'_3	n=4 l'_4	n=4 pe	n=4 λ'_4	Range r(L)	Range pe
H	1	2773	29	14	213	14	06	181	12	05	260	05	02	168	120	19
	2	5716	21	09	185	16	05	179	09	05	273	02	03	25	96	14
	3	8034	22	09	177	13	04	181	08	04	285	03	03	31	92	13
	4	9938	18	09	167	14	04	181	05	03	278	01	02	300	76	12
	5	11606	26	08	173	15	05	193	04	04	335	04	04	157	98	13
	6	13464	22	07	200	16	06	183	03	04	318	04	04	157	90	12
	7	14125	27	07	196	15	06	173	03	04	270	03	03	158	96	12
D	1	2766	35	06	341	25	06	162	19	03	56	04	04	350	166	11
	2	5702	18	05	347	08	05	77	14	03	137	06	03	33	92	09
	3	8015	17	05	333	12	04	55	12	03	146	06	02	67	94	08
	4	9913	10	05	322	16	04	27	11	03	155	06	02	68	86	08
	5	11580	12	04	334	16	04	21	11	02	155	06	02	83	90	07
	6	13435	11	03	345	17	03	15	11	02	155	05	01	85	88	05
	7	14097	13	04	341	16	03	19	09	02	151	05	01	81	86	06
Z	1	2766	28	08	24	19	06	288	14	04	54	10	03	34	142	13
	2	5700	22	06	18	07	04	332	05	03	24	11	02	53	90	09
	3	8010	22	05	14	05	04	351	08	03	1	09	02	64	88	08
	4	9910	12	04	6	07	03	3	08	03	353	08	01	67	70	07
	5	11576	10	03	14	06	02	357	09	02	357	06	01	70	62	05
	6	13431	09	03	11	07	03	353	08	02	353	05	01	68	58	05
	7	14092	11	03	10	07	02	340	09	02	0	06	01	67	66	05

4.4 Summary:

In general, the amplitudes of S, particularly of the first harmonic, are found to have positive association with the degree of magnetic activity. With increasing magnetic activity, the time of maximum amplitude of the first harmonic of S(H) shifts systematically to an earlier part of the day. Changes in solar ranges with increasing magnetic activity, as indicated by Wolf ratios, are more pronounced in H than in D and Z, and in winter than in summer and equinoxes. Examination of daily variation of yearly S(H) for seven groups of magnetic activity has revealed that enhancement of S(H) with increasing level of magnetic activity is not of the type expected from simple augementation of the overhead Sq current system but appears to arise from the superposition, on the normal field of dynamo currents, of additional diurnal component with maximum southward directed field in the evening sector. This additional component is considered to be of asymmetric ring current origin. Owing to the closeness of symmetric and asymmetric ring currents to the latitude of Alibag during night hours in winter than in equinox and summer, the day-to-day changes in the intensity of the ring current would produce large changes in the field at Alibag during winter than in other seasons and may, thus, explain the larger value of Wolf ratio during winter.

In contrast to S, L amplitudes show a decreasing trend with increasing magnetic activity. A clear association is seen between the time of maximum of $L_2(H)$ and the time of magnetospheric expansion or contraction, which indicates the presence of additional component of disturbance origin whose time variation is such that it either reinforces or diminishes the lunar variation at a particular station depending upon the phase of the daily variation at that station under quiet conditions. The source of this additional component is not clear. No systematic and consistent association of either the amplitudes or phase angles of lunar partial terms with magnetic activity is observed in the results of Alibag.

CHAPTER 5

SOME FEATURES OF THE VARIABILITY ASSOCIATED WITH SOLAR AND LUNAR DAILY VARIATIONS

Some Features of the Variability Associated With Solar and Lunar Daily Variations

5.1 Introduction :

A complete description of a geophysical phenomenon must give an account not only of its average value or appearance but also of its variability (Bartels, 1932). Variability in geomagnetic solar and lunar daily variations, S and L respectively, has been investigated by several workers by grouping the daily data in different ways, e.g., according to season, sunspot number or magnetic activity and the influence of these factors on S and L, which is of a regular nature, has been estimated. The variation that still remains, unaccounted by these factors, is called by Bartels (1932) as irregular or fortuitous variation. He describes a method of estimating the total variability of S by the use of harmonic dials. In the numerical procedure of this method, S is treated as a vector quantity which facilitates the study of total variability due to variation in both the amplitude and the phase together. The method also enables one to test the assumption of normality in the distribution of the vector S or L, which is often assumed in applying various statistical tests of significance. Bartels (1932) applied this method to the daily data of Huancayo and Watheroo and found surprisingly large variability in S and the assumption of normality in the distribution of the vector, S, to be valid. Gupta (1972) arrived at similar conclusions in his analysis of the geomagnetic data at Sodankyla by computing the mean annual harmonics in D,H and Z for a 52-year period.

In this Chapter Bartels' method is applied to the yearly mean harmonics of S and L in H,D and Z at Alibag to investigate the long-term variability in S and L. The relative contributions of the variations in solar activity and in magnetic activity to the variability of S and L are calculated to ascertain which of the two is the largest contributing factor.

5.2 Analysis and Results :

Yearly mean harmonics of geomagnetic solar and lunar tides in H,D and Z at Alibag for each of the years during the period 1932-1972 are computed by the generalized method of Winch (1970a) given in Chapter 1. Lunar partial tides are not considered in this investigation as many of the harmonics are not significantly determined. Consequently the term 'lunar tide' refers here to the lunar phase law tide. Harmonic dials and probable ellipses for each of the solar harmonics in each of the elements are drawn by the procedure given by Bartels (1932), as also detailed by Chapman and Bartels (1940), and are presented in Fig.5.1. In the case of L, the analysis is restricted to the fundamental harmonic, L_2, as only that harmonic is generally large and well determined, especially in H. Of the 41 yearly values of L_2 for each element, 30, 27 and 23 are significant in H, D and Z respectively. These only are used in drawing the harmonic dials and probable ellipses for L_2, which are also presented in Fig.5.1.

Ellipticity statistic, L_e, which is a measure of the ellipticity of a cloud of points is defined as (Mauchly, 1940) :

$$L_e = \frac{2R}{1 + R^2}$$

where R is the ratio of major axis, M_1, to the minor axis, M_2, of the probable ellipse and $P(L_e)$, the probability that a value as small as or smaller than L_e might be obtained from a random sample of N points drawn from a circular population, is given by

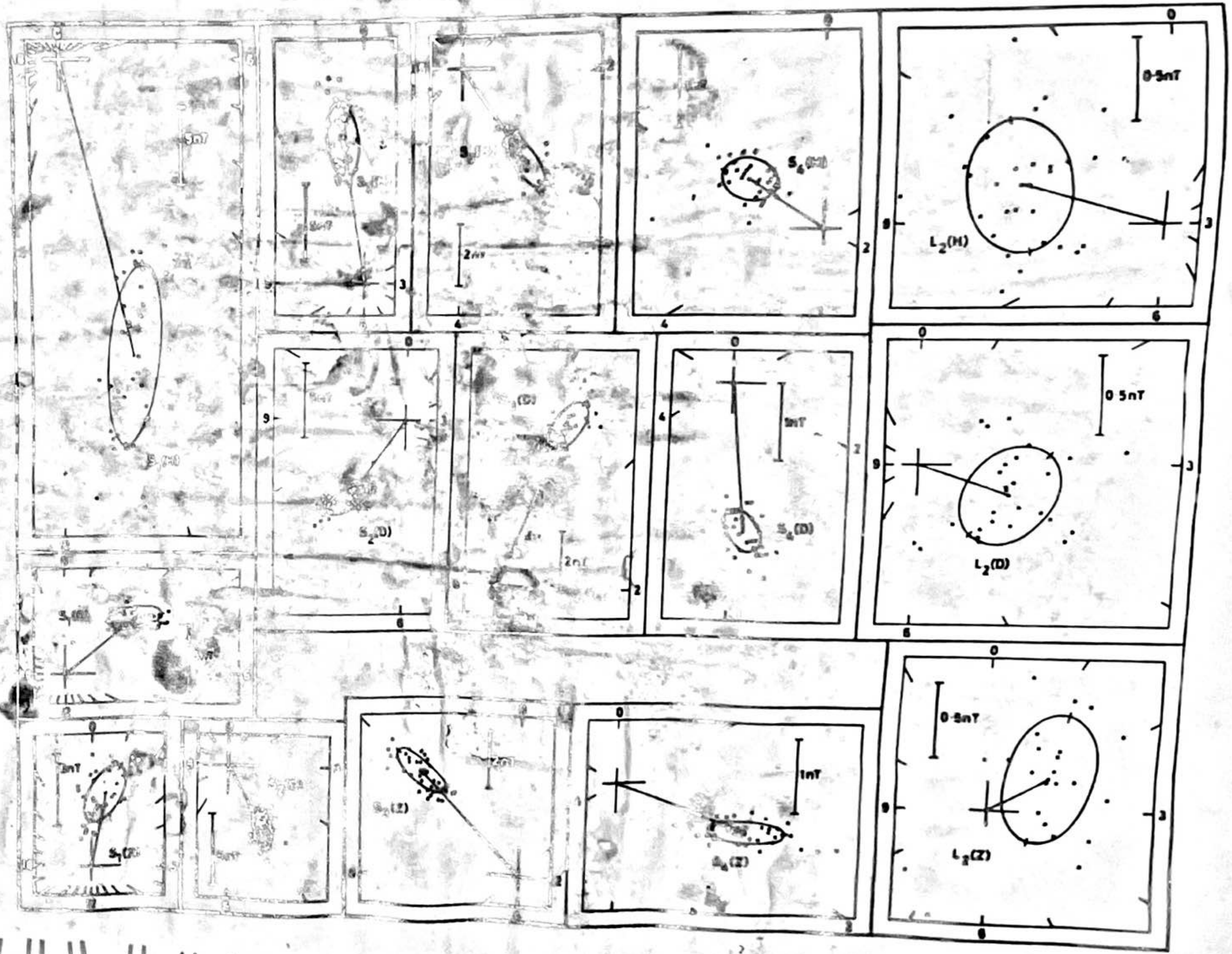
$$P(L_e) = (L_e)^{N-2}$$

A value of $P(L_e)$ close to unity indicates that L_e is computed from a circular population and a smaller value of $P(L_e)$ indicates that the population, from which L_e is obtained, is elliptical.

An easy method to test whether the distribution of points in the cloud is fairly Gaussian or not is that the number of points inside the probable ellipse should be equal to the number of points outside the ellipse. A count of the points inside and outside of each of the ellipses in Fig.5.1 shows that they are nearly equal. Thus

Fig. 5.1

Harmonic dials of the first four harmonics of annual mean solar daily variation and the second harmonic of lunar daily variation in H, D and Z at Alibag for the period 1932-1972.



the assumption of Gaussian distribution of the cloud of points appears to be valid.

It is interesting to note that the amplitudes and phases of average solar daily variation observed here (Table 5.1) are nearly the same as those obtained by analysing the data for the period 1932-1972 as a whole (Table 2.1 of Chapter 2), but the values of L_2 are larger than those given in Table 2.2 of Chapter 2 probably because values of all the years are not used here.

5.2.1 Variability characteristics of solar and lunar terms :

The values of L_e and P (L_e) for solar harmonics in Table 5.1 indicate that except for the fourth harmonic in H, S_4(H), the clouds of points are highly elliptical. With increasing harmonic number ellipticity diminishes in D and H, but increases in Z. Absolute scatter, M, is the largest for the first harmonic in all the elements and systematically decreases with increasing harmonic number. Ellipticity as well as absolute scatter is largest in H. Larger scatter in S(H) than in S(D) and S(Z) is also indicated by the ratio $\bar{C}$/M. The direction of the major axis does not differ appreciably from the direction of the average solar daily variation vector, suggesting that for solar variation the changes in the amplitude are more important compared to the changes in the phase.

Compared to the solar harmonic dials, the dials for L_2

Table 5.1 The average daily variations and the variability characteristics of the ellipses computed from 41-year period, 1932-1972, annual harmonic coefficients of the average Solar daily variations and L_2 of the elements, H, D and Z, at Alibag. The suffix on the component indicates the order of the harmonic.

Component	Period (Solar hours)	The Average Daily Variation: Amplitude $\bar{C}_n$ (nT)	Phase ϕ_n (degrees) (LMT)	Local Time of First Maximum (Solar hours)	The Variability: Major Axis M_1 (nT)	Minor Axis M_2 (nT)	Standard Deviation $M=(M_1^2 + M_2^2)^{1/2}/(1.1774)$	Direction of the Major Axis (Solar hours)	Ratio $\bar{C}_n/M$	Axis Ratio M_1/M_2	Ellipticity statistic L_e	Probability $P(L_e)$
H_1	24	19.88	283	11.12	6.26	1.24	5.42	12.40	3.67	5.03	0.382	5.08×10^{-17}
H_2	12	9.44	99	11.69	2.39	0.55	2.08	11.80	4.53	4.35	0.437	9.18×10^{-15}
H_3	8	3.61	304	3.24	1.02	0.33	0.91	3.24	3.96	3.06	0.591	1.24×10^{-9}
H_4	6	1.09	145	5.08	0.36	0.27	0.38	4.77	2.90	1.33	0.960	2.02×10^{-1}
D_1	24	6.09	39	3.41	1.80	0.67	1.63	5.33	3.73	2.69	0.653	9.12×10^{-8}
D_2	12	6.47	236	7.14	1.60	0.69	1.49	7.83	4.35	2.31	0.730	6.25×10^{-6}
D_3	8	5.82	69	0.46	0.90	0.43	0.85	0.69	6.84	2.08	0.781	8.15×10^{-5}
D_4	6	1.96	275	2.91	0.32	0.18	0.31	2.55	6.29	1.74	0.864	3.89×10^{-3}
Z_1	24	5.20	80	0.64	2.20	1.08	2.08	1.93	2.50	2.04	0.791	1.73×10^{-4}
Z_2	12	4.99	298	5.07	1.12	0.56	1.07	5.63	4.67	2.02	0.796	2.12×10^{-4}
Z_3	8	4.73	133	7.03	0.95	0.34	0.86	6.96	5.52	2.81	0.631	4.00×10^{-8}
Z_4	6	1.81	340	1.83	0.50	0.15	0.44	1.57	4.12	3.29	0.556	3.69×10^{-10}
L_2	12.42	D 0.60	341	3.63	0.35	0.27	0.37	1.37	1.62	1.30	0.97	4.14×10^{-1}
		H 0.89	165	9.50	0.41	0.30	0.43	11.77	2.07	1.37	0.95	2.50×10^{-1}
		Z 0.43	30	2.00	0.43	0.27	0.44	0.53	0.98	1.59	0.90	1.08×10^{-1}

show negligible ellipticity. The points in the harmonic dials of H and D tend to scatter nearly at right angles to the direction of the average variation vector indicating that, in lunar variation, phase changes are more important than changes in amplitude, in contrast to the solar variation. The absolute scatter, M, is apparently small, because of the smaller magnitude of the lunar amplitudes.

5.3 Relative influence of solar activity and magnetic activity on ranges :

As the harmonics are derived using the data of each year as a whole, the effect of, for example, seasonal variation, 27-day recurrence tendency of magnetic storms etc. are considerably averaged out, leaving the effect of changes in solar as well as magnetic activity to prevail. An estimate, however coarse, of the variability in solar and lunar harmonics arising from year-to-year fluctuations in solar and magnetic activities would be of interest. But the general level of magnetic activity is known to be highly correlated with solar activity which complicates estimating separately the effects due to these two factors. However, an estimate of their relative contributions can be had by recourse to the partial correlation technique. In calculating the correlation coefficients, the annual mean sunspot number R_z and the annual mean index A_p are used as measures of solar activity and magnetic activity respectively. Ranges, as defined in Chapter 2, instead of the individual harmonic amplitudes, are used as measures of solar and lunar variations.

Variations, over the years, of solar ranges in H,D and Z, annual mean R_Z and annual mean A_p, during the period 1932-1972, are shown in Fig.5.2. A close parallelism is seen between the variations of R_Z and the solar ranges in each of the elements. As lunar ranges, calculated from the expression given in Chapter 2, show considerable irregular variation, they are smoothed by taking 5-year running averages of the computed ranges. The smoothed ranges in H,D and Z and similarly smoothed annual mean R_Z and A_p are also presented graphically in Fig.5.2b. A marked 11-year variation in the lunar ranges, seen in the plots, indicates a definite control of L by the solar cycle, which even after a century of argument is still a subject of controversy.

To study the relative influence of R_Z and A_p on solar and lunar ranges, total and partial correlation coefficients between the solar and lunar ranges and yearly mean R_Z as well as yearly mean A_p are calculated by the standard methods (Fisher, 1930) and are given in Table 5.2. The correlations found directly between each pair of variates are distinguished as 'total' correlations. The subscripts 1,2 and 3 to the correlation coefficient, r, refer to solar or lunar range, RZ and A_p respectively. In all the computations in regard to L, only smoothed values of the parameters are used. Total

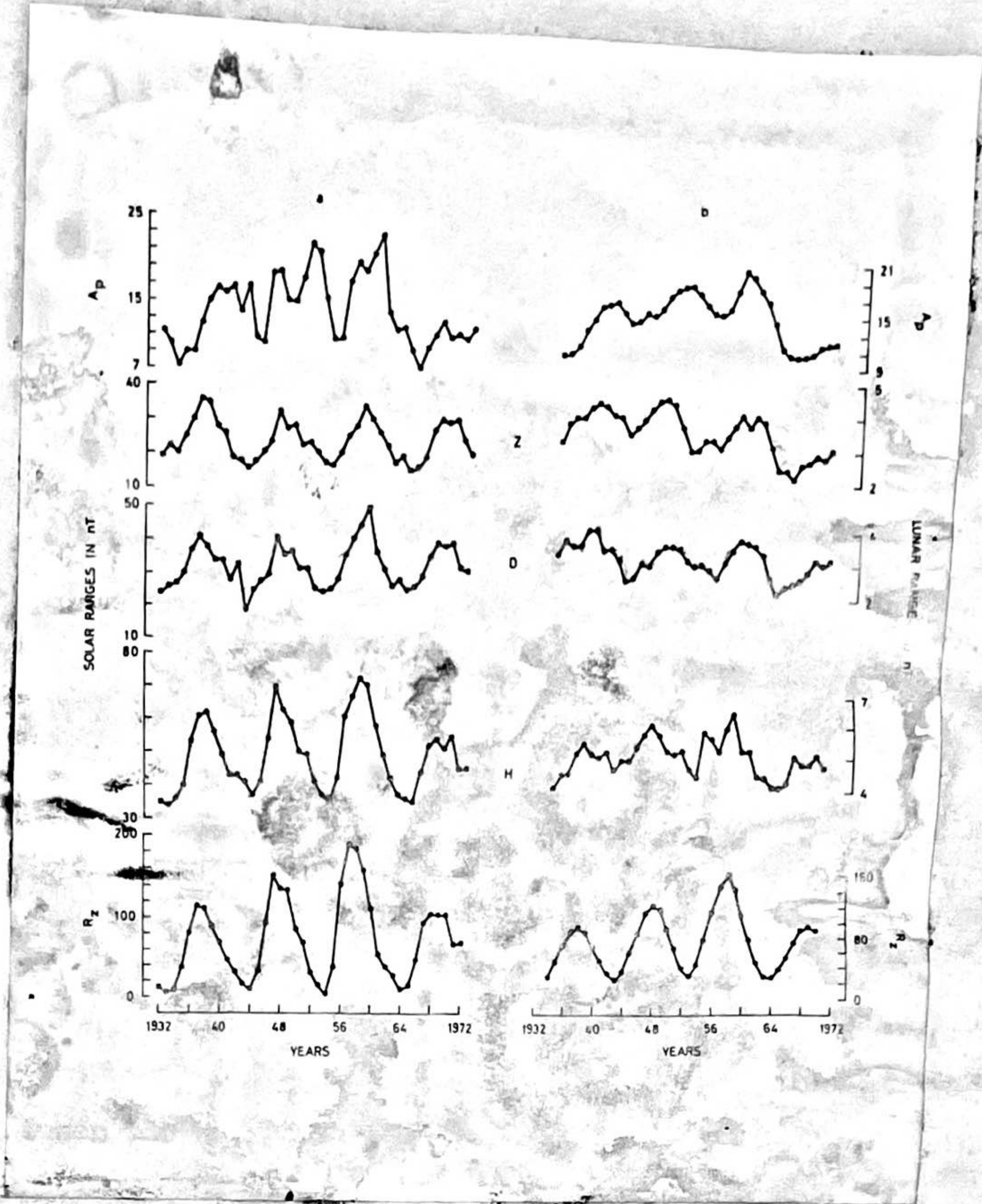


Fig. 5.2

Solar and lunar ranges in H, D and Z at Alibag for each of the years 1932 to 1972 and the annual mean R_z and A_p. For lunar variations five-year running averages of the mean annual lunar ranges and the corresponding averages of R_z and A_p are used. Fig. 2a is for solar ranges and Fig. 2b is for lunar ranges.

TABLE 5.2 Total and Partial Correlation Coefficients between Ranges and R_z & A_p, Wolf Ratios and Percentage Variability

1 = Range; 2 = R_z; 3 = A_p

	Correlation Coefficients					Wolf Ratio with R_z (x 10^4)		Percentage variability accounted for	
	Total Correlation Coefficient			Partial Correlation Coefficient					
	r_{12}	r_{13}	r_{23}	$r_{12.3}$	$r_{13.2}$	Ratio	Probable error	$r_{12.3}$	$r_{13.2}$
Solar Ranges:									
H	.974	.598	.564	.961	.261	60	3	93	7
D	.89[illegible]	.377	.564	.896	-.354	45	4	80	13
Z	.87[illegible]	.321	.564	.881	-.415	52	6	78	17
Mean						58	2	84	12
Lunar Ranges (5-year running averages)									
H	.710	.606	.561	.562	.357	30	5	32	13
D	.627	.405	.561	.528	.083	32	8	28	1
Z	.524	.540	.561	.317	.349	35	11	10	12
Mean						31	4	23	9

correlation coefficients are all positive, and significant at 99 per cent level of confidence except for that between A_p and solar range in the elements D and Z. The partial correlation coefficient $r_{12.3}$, between solar ranges and R_Z with the influence of A_p eliminated, is nearly the same as r_{12}, which indicates that the correlation between solar ranges and R_Z is stable. But $r_{13.2}$, the partial correlation coefficient between solar ranges and A_p with the effect of R_Z eliminated is much reduced from the value of the total correlation coefficient between these two parameters, which itself is comparatively small, and even turns significantly negative for solar ranges in Z. In regard to lunar ranges, the correlation coefficients are relatively small though significant, $r_{13.2}$ is much reduced compared to r_{13} and is not significant. The apparent significant correlation of lunar ranges with magnetic activity is, thus, merely the reflection of strong association between solar and magnetic activities. Isikara (1973) obtains similar results from the data of Istanbul (Geog.lat.41°N) and concludes that the results of analyses of sunspot cycle dependence which ignore magnetic activity are valid, but it is not valid to ignore the effect of sunspot number when attempting to determine the dependence of L on magnetic activity.

Using the partial correlation coefficients, the percentage variations in ranges accounted for by the changes in R_z and A_p are calculated by the expression, $r^2 \times 100$. These are given in Table 5.2. In the case of solar ranges, considering all the elements, an average of 84 per cent of the variability arises from the variation in R_z and the contribution of A_p to the variability is very small, about 12 per cent. In regard to lunar ranges, these contributions are about 23 and 9 per cent respectively. It is noteworthy that, while 96 per cent of variability in S can be accounted for by the variations in R_z and A_p, only 32 per cent of variability in L can be attributed to variations in R_z and A_p. Sources other than these are, therefore, responsible for the major part of the long-period variability in L. One probable source may be the 18.613-year variation in L, associated with the atmospheric nodal tides.

Table 5.2 also gives the Wolf ratio derived from the slope of the straight line best fitting the scatter plot of ranges against R_z. The straight lines are fitted by the least-squares method, weighing each range inversely by the square of its probable error. The probable error for smoothed lunar ranges, say for the year i, is given by :

$$\rho_i = \left[\rho^2_{i-2} + \rho^2_{i-1} + \rho^2_{i} + \rho^2_{i+1} + \rho^2_{i+2} \right]^{\frac{1}{2}}$$

Wolf ratios derived using ranges from four epochs of solar activity, classified by grouping years according to varying annual R_z, rather than yearly ranges have already been presented and discussed in Chapter 3. A comparison of the Wolf ratios presented in Table 5.2 with those given in Table 3.8 of Chapter 3 shows good agreement in respect of solar terms, but for lunar terms, particularly in the case of H and Z, there are large differences. While the Wolf ratios for L computed there were poorly determined and showed considerable scatter between the elements, the values obtained in this Chapter using yearly ranges are highly significant and are about the same in all the elements. It is seen in earlier paragraph that major part of the variability in S is attributable to the variation of regular sources, e.g. R_z and A_p, but only about one-third of the variability in L comes from such regular sources. Thus, it is likely that the effect of the variability from irregular sources on lunar variations in the four groups of solar activity of Chapter 3 may not be fully averaged out and may mask the regularity in the variation of L with R_z. However, the weighted mean value of three elements in both cases is consistent and supports the conclusion reached in Chapter 3 that solar cycle modulation of L at Alibag results primarily from the corresponding variation in the E-region conductivity.

5.4 Total daily movement and Waviness of solar and lunar daily variations

Gupta and Chapman (1970) introduced the concept of

Total Daily Movement (TDM) and Wave-parameter or Waviness (W) to bring out some characteristic features of solar and lunar daily variations. The total daily movement (TDM) in S and L is defined as the sum of successive hour-to-hour differences in a 25-hourly sequence, without regard to sign, and indicates the part of the path which the end point of a magnetic needle would be required to move in tracing solely either S or L variation in a day. The waviness parameter, W, indicates to some extent the significant harmonic in the daily variation and is defined as the ratio of TDM to twice the range, the range reckoned as the difference between the maximum and minimum values. For a nearly diurnal variation, W is close to 1 and approaches 2 for dominantly semidiurnal variation.

For computing TDM and W, a sequence of 25 hourly values are obtained for each year by synthesizing the values from the respective amplitudes and phases at intervals of one hour. The 25th value is a repetition of the 1st, which is the local midnight value. For L, these values are for the epoch of new moon. TDM and W are calculated for the elements D,H and Z for each of the years from the respective hourly values synthesized from the first four harmonics.

The value of W(S) in H is unity and remains so for the entire period, suggesting that the nature of the daily variation in H is dominantly diurnal all through the period.

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Because of the large irregular fluctuations of W(S) in D and Z and of W(L) in all the three elements, it is difficult to discern any systematic variation. To smooth out these fluctuations, five-year running averages are obtained for W in each of the elements, for both solar and lunar variations. These are presented in Fig.5.3, alongwith similarly smoothed R_z. The variations in the waviness parameter associated with solar daily variations in D and Z are related inversely with that of annual R_Z and they tend to be closer to unity with increasing solar activity suggesting that solar daily variation in D and Z becomes dominantly diurnal with increasing sunspot activity. This is probably because of the stronger dependence, on solar activity, of the diurnal amplitude rather than the amplitudes of the other harmonics, as observed in Chapter 3.

In comparision with W(S) the variation in W(L) is large and irregular and no direct association with R_z or A_p is evident. However, there is a suggestion for W(L) in H to be maximum on the declining phase of solar activity; in D, the two maxima observed are nearly 22 to 24 years apart, indicating a probable modulation of variations in D by the 22-year cycle in the polarity of the sunspots.

5.5 <u>Summary</u> :

The results of this Chapter may be summarised as follows:

(1) Both S and L belong to the elliptical population and the

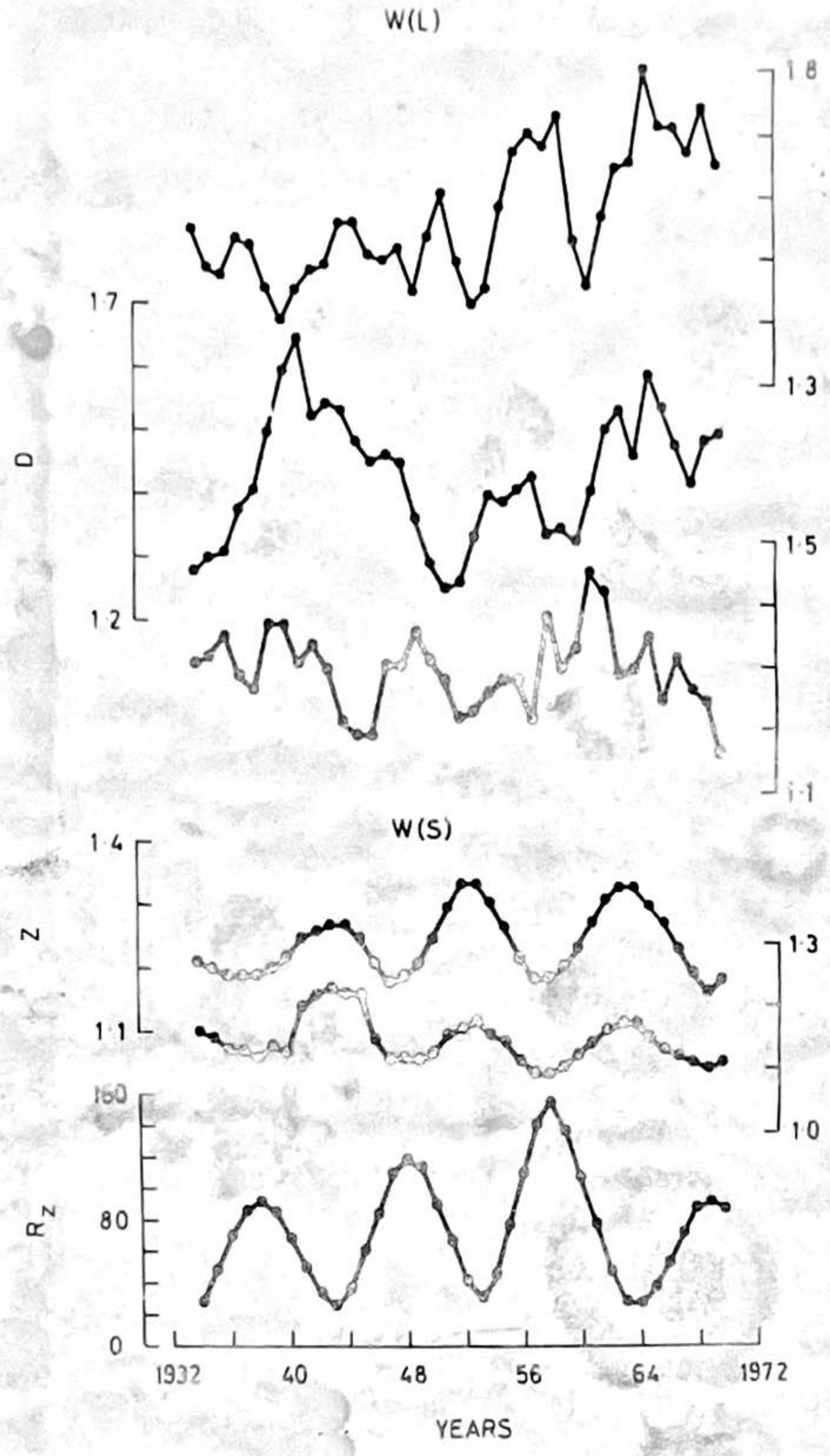

Fig. 5.3

Five-year running averages of the annual mean Waviness parameters, W(S) for solar and W(L) for lunar daily variations at Alibag during the period, 1932-1972. W(S) in H, being unity all through the period, is omitted.

assumption of Gaussian distribution of S and L vector seems to be adequate.

(ii) For solar daily variation, absolute variability is largest for the first harmonic and diminishes with increasing harmonic number. The nature of variability ellipses warrants the conclusion that principal contribution to the variability comes from changes in amplitude rather than phases. In contrast to S, harmonic dials of L show negligible ellipticity and suggest that changes of amplitude as well as phase are the sources of absolute variability.

(iii) Prominent solar cycle influence is observed in solar as well as lunar daily variations; the observed influence of magnetic activity on these variations appears to be merely a reflection of the strong correlation between solar and magnetic activities.

(iv) The variability in S is of a regular nature and about 96 per cent of the long-term variability can be accounted for by the varying effects of solar and magnetic activities. On the other hand, only 32 per cent of the variability of L is accounted by these factors. The sources for irregular variations in L are uncertain but it seems they affect phases of L most.

(V) The variation of waviness parameter reveals that S(H) is dominantly diurnal in all the phases of solar activity and in D and Z it tends to be prominently diurnal with increasing sunspot activity. There is some suggestion of a probable modulation of L(D) by the 22-year cycle in the polarity of sunspots.

CHAPTER 6

CONTRIBUTION OF OCEANIC AND IONOSPHERIC DYNAMO TO LUNAR DAILY VARIATION

Contribution of Oceanic and Ionospheric Dynamo to Lunar Daily Variation

6.1 Introduction :

The Moon exerts gravitational influence on the Earth and its environment causing tides in the atmosphere as well as in the ocean. Tidal motions in the ionized layers of the atmosphere across the main geomagnetic field constitute an ionospheric dynamo. The electric currents generated by this dynamo and the associated currents induced in the Earth and ocean are the principal sources of the observed geomagnetic lunar daily variation. Since neither the conductivity of ocean masses nor the amplitude of tidal oscillation of the ocean water is negligible, electric currents resulting from oceanic dynamo, powered by the tidal movement of the conducting waters of the ocean across the geomagnetic field, should contribute a part to the lunar geomagnetic daily variations. In fact, van Bemmelen (1912,1913), who separated the lunar magnetic variations into internal and external parts, was the first to point out that a fraction of the internal part might be due to tidal motions in the ocean. Chapman (1919), however, disagreed with this view and believed that the internal part was due merely to an external source. A number of determinations of the lunar semidiurnal variation in the vertical component of geomagnetic field, $L_2(Z)$, have, however, revealed anomalously large amplitude, e.g. at Amberley (Bullen and Cummack, 1953), Watheroo (Malin and Winch, 1968) and at Hartland, Lerwick and Valentia (Malin, 1967; 1969a).

Since all these observatories except Watheroo are within 5 kms of the coast, it would appear that the enhancement of the amplitude was associated with proximity of station to the sea (Malin, 1969a). From a comparison of the sea floor, coastal, and island observations with simultaneous continental magnetic observations, Larsen and Cox (1966) and Larsen (1968) showed that while some part of the coastal effect is due to anomalous induction effects resulting from the conductivity differences over land and sea, the most likely mechanism for anomalous $L_2(Z)$ is the dynamo process associated with the ocean tidal flow. Malin (1970), based on some reasonable assumptions, has proposed a method for the separation of the lunar daily variation into parts of oceanic and ionospheric origin. The greatest advantage of the method is that it can be readily applied to the lunar harmonics obtained by any standard procedure, without recourse to the observatory hourly mean data, and includes the evaluation of probable errors to test the significance of oceanic and ionospheric parts. The ocean contribution to L at six observatories in the British Isles were derived by this method, and these were found to be in fair agreement with theoretical values deduced by Chapman and Kendall (1970). This agreement with theory and the fact that ocean dynamo effect is of insignificant amplitude at the inland stations, e.g. Irkutsk (Malin, 1969b) and Hyderabad (Sastri and Rao, 1971), give confidence in the method of determining ocean dynamo effects. Gupta (1974) studied the variation of lunar ionospheric and oceanic dynamo parts with various geophysical parameters and showed that while the ocean effect undergoes little or no variation with season and solar activity, the ionospheric part showed large seasonal variation but very small solar activity dependence. He suggests that these features may possibly explain the disparity of large seasonal changes in L than that in S and also the lesser dependence of L on solar activity than S. Sastri and Rao (1971, 1974) have already indicated the existence of considerable oceanic dynamo contribution to L in the Indian region. In this Chapter Malin's method is applied to lunar harmonics ~~presented in~~ presented in Chapters 2 and 3 to study the manner in which the oceanic and ionospheric dynamos modulate L and its variation with season and solar activity, at Alibag.

6.2 Method and its application :

In Malin's method for the separation of L into ionospheric and oceanic parts, only the first four harmonics of Chapman's phase-law tide are considered and hence L due to M_2 tide may be written as

$$L = \sum_{n=1}^{4} l_n \sin(nt-2\nu+\lambda_n)$$

or

$$= \sum_{n=1}^{4} l_n \sin(2\tau+(n-2)t+\lambda_n) \quad \text{---} \quad (1)$$

Since the conductivity of the sea has negligible time dependence, the dynamo currents resulting from the M_2 ocean tide depend only on lunar time and are purely lunar semidiurnal in period. Ignoring the contribution from currents induced in the ionosphere by ocean dynamo, the effect of the ocean dynamo is considered to be purely of internal origin relative to the surface of the Earth and thus contribute only to the n=2 term in Eqn.(1). Hence the n=1,3,4 harmonics are from the ionospheric dynamo and the problem becomes one of separating the contributions of the two dynamos to the n=2 term.

While the ocean dynamo operates equally well by day and by night, the ionospheric dynamo is much less effective during the hours of darkness, because of the decrease in conductivity of the ionosphere in the absence of solar radiation. For this reason, it is assumed that the contribution of ionospheric dynamo to L is zero at local midnight, when the ionospheric conductivity is reduced to about one-thirtieth of its midday value.

Considering L to be lunar semidiurnal, with amplitude, l(t), and phase, $\lambda(t)$, functions of solar time, it can be expressed as

$$L = l(t) \sin [2\tau + \lambda(t)] \quad \text{---} \quad (2)$$

Equation (2) is equivalent to equation(1) and by expanding (1) and (2) and equating coefficients of sin 2τ and cos 2τ

one obtains,

$$l(t)\ \cos\lambda(t) = \sum_{n=1}^{4} l_n \cos[(n-2)t+\lambda_n] \quad \text{---} \qquad (3)$$

$$l(t)\ \sin\lambda(t) = \sum_{n=1}^{4} l_n \sin[(n-2)t+\lambda_n] \quad \text{---} \qquad (4)$$

The vector probable error, ρ, of L is, for all values of t :

$$\rho = [\sum_{n=1}^{4} \rho_n^2]^{1/2}$$

where ρ_n denotes the vector probable error of the n-th harmonic. At local midnight, when t=o in equation(2), L represents the ocean dynamo variation, L_o,

$$L_o = l_o \sin(2\tau + \lambda_o)$$

where l_o and λ_o are midnight values of l(t) and λ(t). From equations (3) and (4)

$$l_o \cos\lambda_o = \sum_{n=1}^{4} l_n \cos\lambda_n$$

$$l_o \sin\lambda_o = \sum_{n=1}^{4} l_n \sin\lambda_n$$

ρ_o, the vector probable error of L_o, is

$$[\sum_{n=1}^{4} \rho_n^2]^{1/2}$$

The ocean dynamo part contributes only to the second harmonic. Therefore, the ionospheric dynamo part, L_I of L_2 is then obtained by subtracting L_o from L_2 ; thus

$$L_I = l_I \sin(2\tau + \lambda_I)$$

where $l_I \cos\lambda_I = -(l_1\cos\lambda_1 + l_3\cos\lambda_3 + l_4\cos\lambda_4)$

and $l_I \sin\lambda_I = -(l_1\sin\lambda_1 + l_3\sin\lambda_3 + l_4\sin\lambda_4)$

The vector probable error, ρ_I, of L_I is given by

$$\rho_I = [\rho_1^2 + \rho_3^2 + \rho_4^2]^{1/2}$$

These formulae, due to Malin (1970), are applied to the lunar daily harmonics in H, D and Z obtained in chapters 2 and 3 from the data of Alibag for the period 1932-1972. The results obtained for the entire period, designated as y, as well as seasonal subdivisions, designated as d, e and j are given in Table 6.1. Similar results obtained by dividing the data into four epochs of solar activity (A, B, C and D) are given in Table 6.2. For comparison, corresponding lunar semidiurnal term L_2 results are also given in the above Tables.

6.3 Features of ionospheric and oceanic dynamo :

It is seen from Table 6.1 that all the harmonics of oceanic and ionospheric dynamo are well determined, i.e. larger than 2.08 times the corresponding pe, except the seasonal terms of $L_o(H)$. Amplitudes of the oceanic part are smaller than those of ionospheric part in all the three elements. L_o is comparable in magnitude in H and D but is smaller than that in Z. The excess of $L_o(Z)$ over the $L_o(H)$ and $L_o(D)$ is in agreement with the results of other stations. However, $L_o(Z)$ at Alibag is smaller than the corresponding values for British stations (Malin, 1970) and Watheroo (Malin and Green, 1971). This suggests that ocean dynamo is weaker in the vicinity of Alibag than that observed at the other

TABLE 6.1 Yearly and seasonal harmonic coefficient of L_2 and its constituents, L_o and L_I. (l_o, l_I, l_2, ρ_o, ρ_I and pe in units of 0.01 nT and phases λ_o, λ_I and λ_2 are in degree

Element	Season	Oceanic part			Ionospheric part			L_2		
		l_o	ρ_o	λ_o	l_I	ρ_I	λ_I	l_2	pe	λ_2
H	y	21	10	353	93	09	167	72	06	165
	j	32	24	334	67	21	165	36	12	174
	e	27	21	70	46	18	172	48	11	139
	d	32	18	323	168	15	166	139	09	171
D	y	27	05	72	51	05	311	44	03	343
	j	22	10	79	147	09	281	126	05	285
	e	29	10	52	61	08	265	40	06	288
	d	40	07	73	111	06	47	148	04	54
Z	y	52	04	173	77	04	8	30	02	33
	j	67	07	204	127	06	358	73	04	334
	e	45	06	159	82	06	331	38	03	322
	d	58	07	147	80	06	67	106	04	99

TABLE 6.2 Harmonic coefficient of L_2 and its constituents, L_o and L_I for four groups of solar activity. ($l_o, l_I, l_2, \rho_o, \rho_I$ and pe's are in units of 0.01 nT and phases ($\lambda_o, \lambda_I, \lambda_2$) in degrees).

Element	Solar Activity Group	Oceanic part			Ionospheric part			L_2		
		l_o	ρ_o	λ_o	l_1	ρ_I	λ_I	l_2	pe	λ_2
H	A	44	15	38	94	12	191	58	08	172
	B	33	22	16	103	20	175	73	09	166
	C	38	24	320	110	21	161	76	11	171
	D	08	29	319	87	25	155	80	14	156
D	A	15	09	50	38	08	326	43	05	347
	B	26	13	89	50	10	314	37	07	345
	C	35	16	67	51	13	292	36	09	335
	D	35	13	70	63	10	312	56	08	345
Z	A	49	10	170	62	09	5	19	05	45
	B	46	11	176	65	10	4	20	05	22
	C	45	10	165	75	09	354	32	04	7
	D	60	10	176	100	07	17	49	06	43

stations. The principal factors which govern the strength of ocean dynamo are the vertical component of the Earth's magnetic field, conductivity of the ocean masses and the velocity potential due to gravitational attraction. Since the M_2 gravitational potential varies as $\cos^2\theta$, where θ is the latitude, and also the conductivity of ocean water is not expected to show any marked variation with latitude, the large ocean effect at British stations as compared to Alibag can not be accounted for by these two factors. Apparently the ocean dynamo effect is weak at Alibag because of a relatively small magnitude of the vertical component of the geomagnetic field in low-latitudes.

6.4 Seasonal Variations in L_O and L_I :

6.4.1 The seasonal variations in the amplitudes and phases of oceanic and ionospheric parts together with those of L_2 are shown in Fig.6.1 by harmonic dials for the three elements. It is amply clear from Fig.6.1 and Table 6.1 that ionospheric dynamo shows considerably larger seasonal variation in amplitudes and phases than the oceanic dynamo. The seasonal variations in the amplitude of the oceanic dynamo are marginal and are not consistent in the three elements: in H, summer and winter values are equal; in D, the largest magnitude occurs during winter; in Z the largest value is reached in summer. Since the amplitudes of L_I are greater than those of L_O in all seasons, L_2 would be primarily determined by L_I and

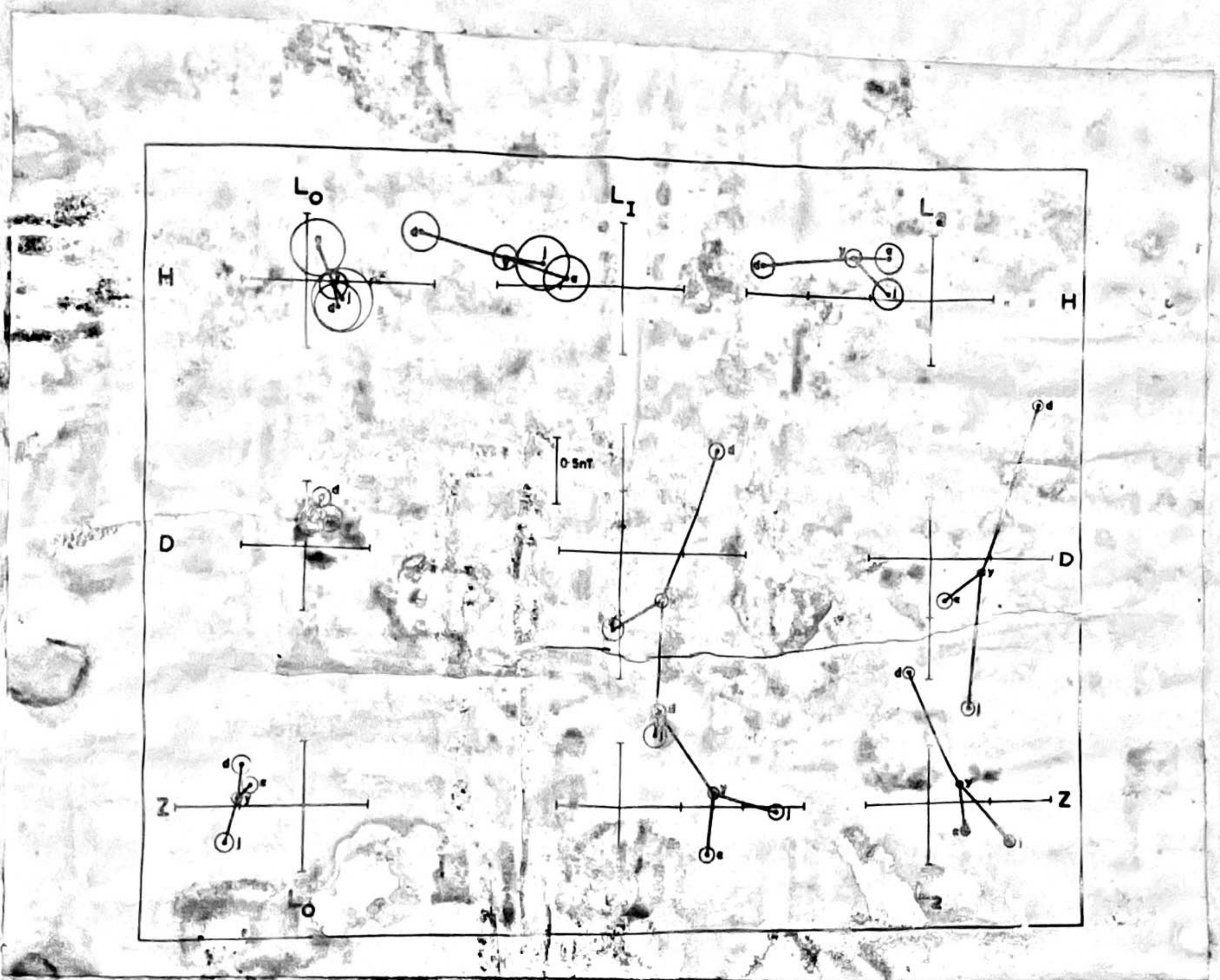

Fig. 6.1

Harmonic dials showing the seasonal progression of oceanic, L_O, ionospheric, L_I, and semidiurnal, L_2, components of L in H, D and Z. The circles around the dial points indicate the corresponding probable errors.

a close similarity in the seasonal variation of amplitudes and phase of L_1 and L_2 would be expected. Results for H fairly support this postulation. But the results for D and Z reveal that though the seasonal progression of the phase angles of L_1 and L_2 are alike, there are marked differences in seasonal behaviour of the amplitude of L_1 and L_2, i.e. while the amplitude of L_1 shows maximum in summer, maximum amplitude of L_2 is registered during winter. The large phase angle variations observed for L_1 are suggestive of complex seasonal oscillations of the current system associated with ionospheric dynamo. The absence of such changes in the phase angles of L_0 suggests that L_0 computed here is not an induced effect of ionospheric dynamo and provides a further confirmation that ocean dynamo effect is real and the method of determining it is effective. Another outstanding feature seen from Table 6.1 and Fig.6.1 is that in D and Z, L_0 and L_1 are nearly in phase during winter and nearly in phase opposition during other seasons. It seems that owing to these observed features, daily variation due to oceanic and ionospheric dynamos being nearly in phase during winter tend to add up to produce large L_2 but being in phase opposition during the other seasons of the year, they have the tendency to cancel each other. Consequently the nett L_2 is small during summer even though L_1 in D and Z has clear summer maximum as expected for a northern hemispheric station.

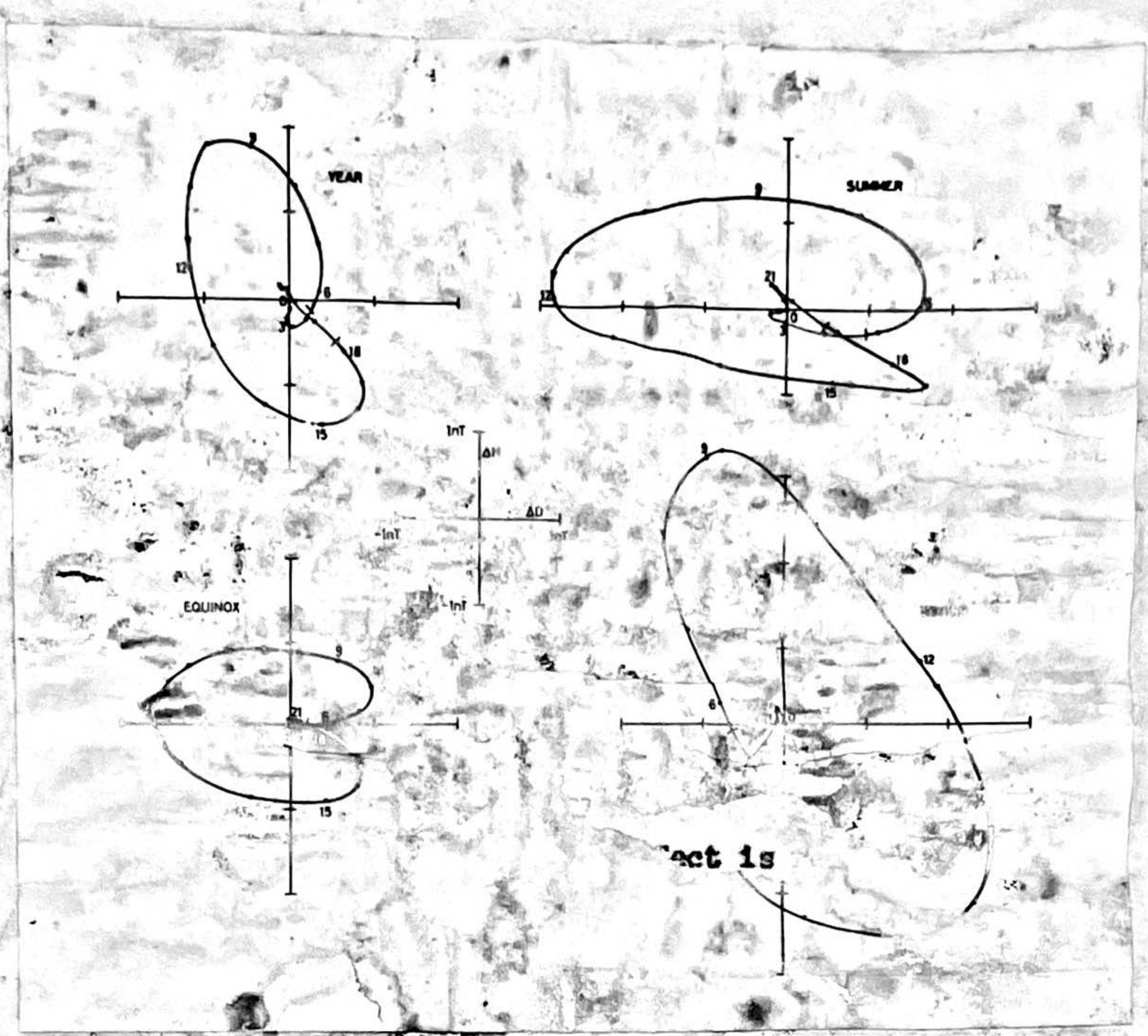

Fig. 6.2

Yearly and seasonal vectograms of L(H) after the removal of oceanic contribution from L. The curves refer to the epoch of new Moon. Some solar hour points are numbered and others are marked. Day and night portions are separated by short lines across the curve.

When l_2 and λ_2 are replaced by L_I and λ_I in eqn(1), the expression represents the L which is purely of ionospheric origin. Incorporating this change in equation(1) the lunar daily variation in the three elements for the epoch of new Moon is obtained by synthesizing the values at hourly intervals. Using these values seasonal variation in L, free from oceanic dynamo effect, is investigated by plotting vectograms in the horizontal plane. These are given in Fig.6.2. Comparison of these vectograms with those given in Fig.2.3 of Chapter 2, obtained prior to removing the oceanic effect, shows a general magnification in size both in north-south (N-S) and east-west (E-W) directions except for the winter vectogram which has diminished in the E-W direction. However, the sense of rotation of the variation vector in both the figures remains unaltered and is opposite during winter and summer. Hence the interpretation given in Chapter 2 that L at Alibag during winter is under the influence of southern hemispheric current system is credible.

6.4.2 In order to have further insight as to how the removal of oceanic contribution modulates the seasonal variation of L_2 and total lunar daily variation, the ratio of seasonal to yearly amplitudes of L_I and ranges are calculated for each element. The probable errors of these ratios are estimated by the procedure detailed in Chapter 2. The range, R'(L),

TABLE 6.3 Ratios of seasonal amplitudes to yearly mean amplitude for ionospheric part and total observed L.

	Ionospheric part L_I			Total variation L_2		
	j/y	e/y	d/y	j/y	e/y	d/
H	0.72±0.24	0.49±0.20	1.81±0.21	0.50±0.17	0.67±0.16	1.93±
D	2.86±0.23	1.19±0.18	2.16±0.18	2.86±0.23	0.91±0.15	3.36±0
Z	1.65±0.10	1.07±0.09	1.04±0.09	2.43±0.21	1.27±0.13	3.53±0
Weighted Mean	1.70±0.09	1.01±0.07	1.33±0.08	1.66±0.11	0.99±0.08	2.75±0.
	Ionospheric Range R' (L)			Total Range R(L)		
H	0.70±0.11	0.57±0.09	1.83±0.10	0.62±0.10	0.63±0.07	1.89±0.
D	2.28±0.09	1.29±0.08	1.99±0.07	2.40±0.08	1.25±0.06	2.65±0.0
Z	1.43±0.09	1.05±0.04	1.23±0.04	1.51±0.04	1.20±0.04	1.90±0.0
Weighted Mean	1.56±0.06	1.03±0.03	1.46±0.03	1.57±0.03	1.11±0.03	2.08±0.0

of lunar variation, corrected for oceanic effect, i.e. only of ionospheric origin, is calculated from the relation:

$$R'(L) = 2.0 \left[l_1 + l_I + l_3 + l_4 \right]$$

The ratios and their weighted means are given in Table 6.3. For comparison, similar ratios for L_2 and lunar range, R(L), are also given. The following features are noted: 1) in H, the ratios for L_2, R(L), L_I and R'(L) are highest in winter, but the percentage change from summer to winter is smaller in ionospheric part than in the total lunar daily variation, 2) in D and Z, the ratio of seasonal to yearly value for L_2 and R(L) with ocean effects included are maximum during winter but when oceanic effects are removed the highest ratio occurs in summer.

6.5 Solar Cycle variation :

It is seen from Table 6.2, where the yearly harmonics of oceanic and ionospheric dynamo together with L_2 are given for different phases of solar activity, that while the amplitude of L_2 and L_I exhibit, in general, an increase with solar activity, no systematic and consistent trends are discernible in regard to the amplitude of L_0 with solar activity. The sunspot cycle influence on oceanic and ionospheric parts is elaborated by computing Wolf ratios in the linear relation of R_z and amplitude of each of the parameters, L_I and L_0, in the three elements. The Wolf ratios for oceanic and ionospheric parts are given in Table 6.4. Also given are Wolf

TABLE 6.4 Wolf's ratio(m) for l_o, l_D, L_2 and lunar ranges, R' (L) and R(L).

Term	H $m \times 10^4$	D $m \times 10^4$	Z $m \times 10^4$	Weighted Mean $m \times 10^4$
Oceanic	-52 ± 102	111 ± 196	21 ± 58	10 ± 49
Ionospheric	1 ± 38	51 ± 57	60 ± 44	31 ± 26
L_2	31 ± 41	23 ± 36	195 ± 196	30 ± 27
Range R' (L)	-3 ± 14	40 ± 17	62 ± 16	30 ± 9
Range R (L)	7 ± 15	31 ± 15	84 ± 21	32 ± 9

ratios for L_2,R(L) and R'(L).

Since the conductivity of the sea is independent of the sunspot number, one might expect to find the same ocean effect in each of the divisions according to R_Z. None of the Wolf ratios for oceanic part determined here are significant and thus conforms to the above expectation.

Chapman et al. (1971) have shown that sunspot cycle variation of S measured by Wolf ratio is about three times that of L. A possible reason for this discrepancy, suggested by them, is that probably L variations contain an ocean dynamo contribution which will not vary with sunspot cycle and it is possible that the presence of this constant amplitude harmonic in the measured L could reduce the Wolf ratio for L by observed amount even though ionospheric part of L had the same Wolf ratio as that of S. In fact, Malin et al. (1975) have shown that when oceanic dynamo effects are removed from L harmonics, the Wolf ratio for L becomes comparable with the corresponding value of S. The results of present analysis for Alibag do not bear out this feature, as the weighted mean Wolf ratios for L_I as well as for ranges corrected for ocean effect are similar to those for L_2 and total range in L. However, the results obtained here are in agreement with the earlier findings of Gupta (1974), who has shown that Wolf ratios for L_I and L are nearly the same at Huancayo.

6.6 Summary :

The results of the above analysis and discussion may be summarized as follows :

(i) The ocean effect at Alibag is smaller in H and D than in Z, as also observed for other stations. But the nett magnitude of oceanic dynamo effect is also smaller than those observed for median and high latitudinal stations. This feature may be due to the small magnitude of the vertical component of geomagnetic field in low-latitudes.

(ii) Ionospheric dynamo shows considerable seasonal variation both in amplitude and phase. In D and Z, there is almost a complete reversal of phase between summer and winter. The amplitudes and phases of oceanic part show little or no variation with season, but their contribution being in phase with ionospheric part in winter and in phase opposition during equinox and summer they appear to play an important role in determining the seasonal changes of total lunar daily variation. Hence, it is important to remove oceanic part from the observed variation prior to any study of the seasonal changes in the overhead ionospheric current system responsible for L.

(iii) The oceanic terms do not show any significant change with sunspot number. Removal of the ocean dynamo part does not make any significant difference in the behaviour of L with respect to sunspot numbers and agrees with the earlier finding of Gupta (1974) that the Wolf ratios for L_1, L_2 and ranges are similar at Huancayo.

CHAPTER 7

THE O_1 COMPONENT OF GEOMAGNETIC LUNAR DAILY VARIATION

The O_1 Component of Geomagnetic Lunar Daily Variation

7.1 Introduction :

According to dynamo theory of transient daily geomagnetic variations each atmospheric tide produces a corresponding geomagnetic daily variation, the time dependence of which is determined by the product of a term representing the ionospheric movement and a sum of terms representing the variations of ionospheric electrical conductivity. In earlier Chapters the features of geomagnetic lunar daily variation, $L(M_2)$, associated with main lunar semidiurnal tide, M_2, has been discussed in detail for different seasons and with various geophysical parameters. Although M_2 is the largest of harmonic constituents in lunar gravitational tidal potential, there are a few other constituents with amplitudes not insignificant compared with that of M_2, the primary ones being O_1 and N_2. O_1 represents the largest of the lunar declinational diurnal constituents and N_2, the main lunar distance constituent. The declinational component O_1 arises because the equatorial plane of the earth and the plane of the Moon's orbit do not coincide and N_2 is due to the eccentricity of the Moon's orbit. In the lunar tidal potential (Bartels, 1957), the M_2, O_1 and N_2 are respectively in proportion to :

$$\cos^2\theta \sin(2\tau + 90^o) : 0.415 \sin^2\theta \sin(\tau - s) :$$
$$0.191 \cos^2\theta \sin(2\tau + p + s + 90^o).$$

where θ denotes geographical latitude,

τ denotes mean lunar time measured from local lower transit of the mean Moon,

s denotes the east longitude of the mean Moon and p denotes the mean longitude of the Moon's perigee.

It follows from the above expression that M_2 is symmetric with respect to the equator and attains its maximum value at the equator; the O_1 component is anti-symmetric with respect to the equator and has its maximum and minimum at latitudes $\pm 45^{\circ}$ respectively. The ratio of M_2 to O_1 is, therefore, latitude dependent.

The present chapter concerns the geomagnetic daily variation $L(O_1)$ caused by the combined effects of the lunar diurnal declinational tide, O_1, and the ionospheric conductivity. If only the first two harmonics of the time variation in the conductivity are taken into account, the time variation of $L(O_1)$ can be expressed as follows:- (Winch, 1970b)

$$L(O_1)=\sum_{n=-1}^{3} c_n \sin(nt-2\nu-h+\lambda_n) \quad \ldots \quad (1)$$

Where c_n is the amplitude of the nth harmonic, t is the mean solar time increasing by 2π per solar day, ν is the difference in the rates of solar time t and lunar time τ increasing by 2π in a mean synodic month of 29.5306 mean solar days, h is the east longitude of the mean Sun, and λ_n is the phase angle. Additional terms corresponding to n = -2, -3, 4, 5 arise from the inclusion of higher harmonics in the expression representing daily variation of electrical conductivity. For the numerical analysis of the data the range of summation is taken from n=-4 to n=4. Summands n=1,2,3,4 are referred to as phase law tides and summand n=0 as the long period tide. The summands n=-1,-2, -3,-4 are denoted as partial tides (Winch,1970a).

Chapman and Miller's (1940) method (C-M method) which was originally developed for the determination of M_2 tide, when slightly modified, would permit determination of magnetic variations associated with atmospheric tide O_1. Malin and Chapman (1970a) applied this modified method to the atmospheric pressure data of several observatories and the results revealed the existence of significant O_1 constituents in the atmospheric pressure. Tarpley (1971) analysed geomagnetic data from 12 stations for the O_1 component by C-M method and found well determined geomagnetic O_1 tides in the Z component of several stations. Winch (1970b) generalized the Chapman-Miller method, permitting the determination of partial tides and long period tide in addition to the phase law tides. This method is essentially the same as that for M_2 tides discussed in Chapter 1. It is, therefore, not proposed to discuss the method here in detail. However, some of the modifications required to make the method suitable for O_1 are as follows :

(i) For the O_1 analysis, the parameter μ' is replaced by O'. The O' numbers are constructed from the numerical expression for 2s-h, viz:

$$O' = [(261.1765 + 25.36714613\,J)/30 + 0.5] \text{ modulo } 12$$

where square brackets indicate the integral part only and J is an integer assigned to Greenwich days commencing with J=1 on 1st January 1900.

It may be recalled that in M_2 analysis the sign of A'_{psB} and B'_{psB} were changed in the secondary harmonic analysis stage (step 3 of section 1.4 in Chapter 1) because μ' numbers instead of ν' numbers were used to divide the data into 12 groups. But no such corrections are required in the present analysis because O' numbers are used directly.

(ii) The numerical values of the D_{mps} and associated matrices depend on the period of the tide that is being investigated and, therefore, the revised values are used for the O_1 analysis.

(iii) The constant in the expression for the correction of phase angles is 1/14.1915, for O_1 (see step 8 of section 1.4 in Chapter 1).

(iv) The method of computing the probable error of each of the harmonics is the same as given by Winch (1970b).

Following the above numerical procedure due to Winch (1970b), Rao and Sastri (1974) found clear geomagnetic O_1 tides at four Indian equatorial stations for the active Sun years, 1958-1961, and were led to consider these tides to be modulated by an ionospheric current like the equatorial electrojet. Later, Sastri, Arora and Rao (1975) analysed a long series of H at Alibag to study the dependence of $L(O_1)$ in H on various geophysical parameters, e.g. sunspot number, R_z, magnetic activity index, Ap, and lunar distance. They found that trends of changes in the magnitude of $L(O_1)$ with R_z and A_p are similar to those observed for $L(M_2)$. In this Chapter the relative features of $L(O_1)$ in all the three elements H, D and Z at Alibag and their seasonal variations are discussed. The results are also compared with those predicted by the equilibrium tidal theory.

7.2 Results of Analysis :

The yearly and seasonal harmonics of geomagnetic lunar O_1 tide in the three elements H, D and Z of Alibag are obtained by analysing the data for the period 1932-1972 as a whole and for the three Lloyd's seasons. These are given in Table 7.1. Most of the harmonics are found to be significantly determined as their amplitudes are greater than 2.08 times the corresponding probable errors. By virtue of using large data in the present analysis, harmonics of $L(O_1)$ in H, D and Z are better determined than those obtained by Rao and Sastri (1974) for the active Sun years, 1958-1961, but are comparable in significance, to the later results of Sastri et al. (1975). The harmonic constituents of daily variation associated with the atmospheric tide M_2 and O_1 have frequencies which differ

TABLE 7.1 Seasonal and Yearly harmonics of [illegible] are in units of 0.01 nT. Phase angles (c_n and c'_n) and probable errors (pe) (λ_n and λ'_n) in degrees are given at epoch of local midnight (t=0) and also when $\nu - s = 0$

Season	Harmonic 'n'	H Phase c_n	H Phase λ_n	H Partial c'_n	H Partial λ'_n	H pe	D Phase c_n	D Phase λ_n	D Partial c'_n	D Partial λ'_n	D pe	Z Phase c_n	Z Phase λ_n	Z Partial c'_n	Z Partial λ'_n	Z [illegible]
y	0	180	319			125	49	128			30	25	114			4[illegible]
	1	45	248	30	18	09	25	168	09	320	02	16	274	09	28	0[illegible]
	2	32	65	07	243	06	54	342	11	259	03	35	30	12	332	0[illegible]
	3	13	242	03	334	03	22	162	11	102	02	26	198	09	151	0[illegible]
	4	06	20	04	75	03	09	238	05	326	01	08	311	04	15	0[illegible]
j	0	298	337			344	128	142			100	226	100			13[illegible]
	1	14	55	54	69	15	46	175	21	264	07	51	272	29	313	05
	2	29	240	26	237	10	91	1	11	329	05	56	47	07	5	04
	3	14	77	15	355	08	60	180	14	118	02	58	242	07	165	03
	4	08	19	14	68	08	07	236	08	347	02	01	237	08	24	02
e	0	183	135			251	61	306			68	151	252			50
	1	30	304	34	275	17	27	269	11	6	07	19	350	28	117	06
	2	12	36	17	65	11	53	116	20	249	05	40	166	18	318	04
	3	10	190	11	196	06	36	321	05	75	04	26	11	06	166	03
	4	11	320	08	234	04	11	152	03	339	02	08	226	02	321	02
d	0	451	305			148	76	105			64	58	321			68
	1	134	236	65	11	13	47	124	10	337	09	18	167	17	22	06
	2	115	67	14	259	07	134	312	12	208	05	94	2	12	339	05
	3	49	255	05	07	05	52	128	15	96	04	75	163	15	142	03
	4	12	79	07	67	05	21	263	05	291	02	26	328	05	16	02

by one cycle per year. Consequently, in the sub-division of data which does not cover a complete year, e.g. seasonal sub-division, each such transient geomagnetic variation makes a contribution to the numerical estimate of the other. Hence, seasonal O_1 determinations must be interpretated with caution because of the possibility of seasonal variations in the M_2 tide introducing spurious results (Winch 1970b, 1971). In order to avoid the seasonal effect of $L(M_2)$ tide to the maximum possible extent the discussion of the primary features of $L(O_1)$ tide in the following section is based on the results obtained from the data of 1932-1972 without any sub-division into seasons denoted by y, in the Tables.

7.3 <u>General features of $L(O_1)$ tides</u> :

7.3.1 Because of the presence of partial tide term n=-1 in the equation (1) for $L(O_1)$, derived after taking into consideration only the first two harmonics of ionospheric conductivity, Winch (1970b) pointed out that partial tides might play a greater part in $L(O_1)$ than they would do in $L(M_2)$. His analysis for Toolangi data revealed that $L(O_1)$ partial tides were more pronounced in D than in H and Z, a result similar to his earlier results for $L(M_2)$ partial tides (Winch 1970a); and also in D, $L(O_1)$ partial tides were found to be greater than those of $L(M_2)$. Examination of partial tide terms in Table 7.1 shows that the amplitudes of various harmonics in H, D and Z are comparable in magnitude (except the first harmonic in H) and their comparison with the corresponding results of $L(M_2)$, given in Table 2.3 of Chapter 2, do not show predominance of these over those of $L(M_2)$. This is in conformity with the earlier observation of Rao and Sastri (1974). The amplitude of the first harmonic of partial tide term in H is comparable to those of the first two harmonics of the phase law tide. The other three partial tide harmonics are much smaller and are not significant. Unlike in $L(M_2)$, the term n=-1 in the expression for $L(O_1)$ results from the coupling effect of atmospheric tide O_1 and the first two harmonics of the conductivity (Equation 1). From the dominance of n=-1 over the partial tide terms n=-2, -3 and -4, Sastri et al.(1975) felt that $L(O_1)$ given by the equation(1), derived after taking into consideration only the first two harmonics of the ionospheric conductivity, would be sufficient to represent adequately the O_1 component of lunar geomagnetic variation at Alibag. It is seen from Table 7.1 that, in D and Z, the amplitudes of all the partial tide harmonics are of comparable magnitude and are significantly determined. However, they are much smaller than the amplitudes of the corresponding phase law harmonics. Thus, exclusion of higher harmonics in the expression representing the daily variation of ionospheric conductivity may be justified in determining $L(O_1)$ at Alibag. Abnormally high value corresponding to n=-1 in H may probably be associated with the location of Alibag with respect to the ionospheric current system, responsible for these variations.

7.3.2 The $L(O_1)$ in H,D and Z computed for the whole period shows large amplitudes for the first three harmonics of the phase-law-tide and the determinations are highly significant. As the O_1 tide is primarily lunar diurnal in period, considering only the first harmonic of phase law tide in equation (1), O_1 geomagnetic tide in H,D and Z are given by the following expressions:

$$\left.\begin{aligned} O_1(H) &= 0.45 \sin(\tau - s + 248^\circ) \\ O_1(D) &= 0.25 \sin(\tau - s + 168^\circ) \\ O_1(Z) &= 0.16 \sin(\tau - s + 274^\circ) \end{aligned}\right\} \quad \ldots (2)$$

Similar expressions for $L(M_2)$, taking only the lunar semidiurnal term, are

$$\left.\begin{aligned} M_2(H) &= 0.72 \sin(2\tau + 165^\circ) \\ M_2(D) &= 0.44 \sin(2\tau + 344^\circ) \\ M_2(Z) &= 0.30 \sin(2\tau + 33^\circ) \end{aligned}\right\} \quad \ldots (3)$$

If the geomagnetic lunar tide were simply proportional to the corresponding terms in the lunar gravitational potential, independent of their frequencies, the ratio $L(M_2)/L(O_1)$ would be 3.5789 for the latitude of Alibag. The observed ratios for H,D,Z and for the mean of these three elements are respectively 1.60 ± 0.35, 1.76 ± 0.19, 1.88 ± 0.27 and 1.77 ± 0.14.

The probable errors for the ratio are calculated by the expression given in Chapter 2. These ratios are significantly less than that predicted by the tidal equilibrium theory. Even when all the harmonics of the phase law tide are considered and ranges computed, the ratio of ranges associated with $L(M_2)$ and $L(O_1)$ are found to be 1.88 ± 0.14, 1.04 ± 0.04 and 1.58 ± 0.05 for H, D and Z respectively. The average ratio (1.24 ± 0.03) is still comparatively less than the expected value.

7.3.3 Considering the size of the zeroth and the first harmonic of ionospheric conductivity, Tarpley (1971) stated that it would be reasonable to expect in the phase law tide the c_1 term to be somewhat larger than c_2 term in the magnetic variation produced by an ionospheric O_1 tide. c_2 equal to or greater than c_1 would indicate the possibility of M_2 variation contaminating the O_1 analysis. Therefore, he suggests that stringent criteria should be used in judging whether or not the deduced magnetic variation is a genuine O_1 tide. He applied the criterion $c_1 \geqslant 1.5\ c_2$ for well determined O_1 tide. Although as per the present criterion ($c_n > 2.08 \times pe$) of significance, all the amplitudes of c_1 and c_2 at Alibag are significantly determined, they fail to satisfy the Tarpley's criterion of significance. Except in H, c_1 is generally smaller than c_2. Even many of the harmonics obtained from the seasonal sub-division of data do not satisfy his criterion. The fundamental harmonic in L(M_2) is the second phase law harmonic l_2, which is expected to be dominant amongst the harmonics. A contrary feature was observed by Sastri and Rao (1974), viz., l_2 was smaller than the corresponding l_1 in general. On removing the part of oceanic origin by Malin's (1970) method, l_2 gained dominance over other amplitudes. Thus, they attributed the apparent dominance of l_1 over l_2 in directly obtained results to the effect of oceanic dynamo contribution. Whether, contrary to expectation, a similar effect is responsible for the observed feature in L(O_1) is examined in the following section.

7.4 Separation of L(O_1) into parts of oceanic and ionospheric origin :

Like L(M_2) tide, L(O_1) also contains contributions from the dynamo action both in the ocean and in the ionosphere, due to lunar O_1 tidal movements. Since the conductivity of the ocean has negligible time dependence, the dynamo currents resulting from the O_1 oceanic tide would depend only on lunar time and will produce lunar diurnal term. By incorporating this change in the method of Malin (1970), detailed in Chapter 6, his equations, suitably modified, would be valid under the same assumptions for the separation of L(O_1) into parts of oceanic and ionospheric origin.

7.4.1 Modification of Malin's method :

Since $\tau = t - \nu$ and $\nu = s - h$, the expression for $L(O_1)$ phase law tides can be written as:

$$L(O_1) = \sum_{n=1}^{4} c_n \sin [\tau - s + (n-1)t + \lambda_n] \quad \ldots \quad (4)$$

Considering lunar variations associated with O_1 to be entirely lunar diurnal with amplitude, $c(t)$, and phase, $\lambda(t)$, functions of solar time,

$$L(O_1) = c(t) \sin [\tau - s + \lambda(t)] \quad \ldots \quad (5)$$

Eqn(5) is equivalent to eqn.(4) and by expanding (4) and (5) and equating the coefficients of $\sin(\tau - s)$ and $\cos(\tau - s)$ we obtain:

$$c(t) \cos \lambda(t) = \sum_{n=1}^{4} c_n \cos [(n-1)t + \lambda_n] \quad \ldots \quad (6)$$

$$c(t) \sin \lambda(t) = \sum_{n=1}^{4} c_n \sin [(n-1)t + \lambda_n] \quad \ldots \quad (7)$$

Further, if it is assumed that the contribution of ionospheric dynamo to lunar variation is zero at local midnight, because the ionospheric conductivity is reduced to one-thirtieth of its mid day value, then at t=0 in Eqn.(5), $L(O_1)$ represents the oceanic dynamo variation, C_o,

$$C_o = c_o \sin(\tau - s + \lambda_o) \quad \ldots \quad (8)$$

where c_o and λ_o are midnight values of $c(t)$ and $\lambda(t)$

From Eqns. 6 and 7

$$\left.\begin{aligned} c_o \cos \lambda_o &= \sum_{n=1}^{4} c_n \cos \lambda_n \\ c_o \sin \lambda_o &= \sum_{n=1}^{4} c_n \sin \lambda_n \end{aligned}\right\} \quad \ldots \quad (9)$$

ρ_o, the vector probable error of co is

$$\rho_o = \left[\sum_{n=1}^{4} \rho_n^2\right]^{\frac{1}{2}}$$

n denotes the probable error of the nth harmonic. The oceanic dynamo variation contributes only to the first harmonic. Therefore, the ionospheric dynamo part C_I, of C_1 is obtained by subtracting Co from C_1

$$C_I = c_I \sin(\tau - s + \lambda_I)$$

where

$$\left.\begin{aligned} c_I \cos\lambda_I &= -(c_2 \cos\lambda_2 + c_3 \cos\lambda_3 + c_4 \cos\lambda_4) \\ c_I \sin\lambda_I &= -(c_2 \sin\lambda_2 + c_3 \sin\lambda_3 + c_4 \sin\lambda_4) \end{aligned}\right\} \ldots (10)$$

The vector probable error, ρ_I, of c_I is given by :

$$\rho_I = \left[\rho_2^2 + \rho_3^2 + \rho_4^2\right]^{\frac{1}{2}}$$

These formulae are applied to the harmonics of yearly $L(O_1)$ phase law tide in H,D and Z and the results are presented in Table 7.2. Except for the oceanic term in H, all the oceanic and ionospheric terms are significantly determined. In H both amplitude and phase of the constituents of $L(O_1)$ are nearly equal. In D the ionospheric part dominates with largest amplitude of all the three elements, but in Z oceanic term is greater than the ionospheric term. This result supports the view of Tarpley (1971) that most probable cause of the $O_1(Z)$ variation is electric currents induced in the ocean by O_1 tide. It is interesting to note that while the

TABLE 7.2 Separation of first harmonic of yearly $L(O_1)$ phase law tide, C_1, into parts of Oceanic, C_O, and Ionospheric, C_I parts : (Amplitudes c_O, c_I, c_1 and probable errors in units of 0.01 nT and phase angles in degrees)

Element	Oceanic part			Ionospheric part			First harmonic of L(O		
	c_O	pe	λ_O	c_I	pe	λ_I	c_1	pe	λ_1
H	22	12	260	24	07	236	45	09	248
D	12	04	276	31	04	146	25	02	168
Z	17	04	314	11	04	198	16	02	274

phase difference between oceanic and ionospheric parts in D and Z are greater than 90°, in H the difference is small.

When the oceanic part is separated, the decontaminated c_1, i.e. c_I, is still less than c_2 in all the elements. This suggests that the absence of the prominence of c_1 over c_2 at Alibag is not due to the effect of oceanic dynamo contribution to c_1. An obvious alternative interpretation is that even the yearly geomagnetic $L(O_1)$, derived here, may include an unavoidable contamination from the seasonal variations of the M_2 geomagnetic tide. There are reasons to believe this because, as shown in earlier Chapters, $L(M_2)$ at Alibag, all through the year, is not under the control of northern hemispheric current system associated with $L(M_2)$. The exception in H of c_1 being greater than c_2 could be due to the fact that oceanic and ionospheric parts are nearly in phase and add up in the resultant c_1.

7.4.2 The ratios of $L(M_2)$ and $L(O_1)$ are computed for oceanic and ionospheric parts separately. The oceanic and ionospheric parts of $L(M_2)$ are taken from Chapter 6. The ratios $L(M_2)/L(O_1)$ for ionospheric parts in H,D,Z and their weighted average are 3.87 ± 1.19, 1.65 ± 0.27, 7.0 ± 2.57 and 1.80 ± 0.26 respectively. The corresponding figures for oceanic term are 0.95 ± 0.69, 2.25 ± 0.86, 3.06 ± 0.76 and 2.0 ± 0.44. The ratio for the ionospheric part in H and for oceanic part in Z are comparable to the value 3.5789, calculated on lunar gravitational potential theory, but as the determinations are of low significance no importance can be attached. The average ratio for oceanic and ionospheric parts do not show any improvement over the value obtained earlier in section 7.3.2.

7.5 Seasonal Variation of $L(O_1)$:

Fig.7.1 shows the seasonal vectograms of the $L(O_1)$ variation in the horizontal plane. The vectograms show the greatest field change during daylight hours. The variation vector during winter and year describes a clockwise loop but during summer and equinox the variation vector rotates in an anti-clockwise direction. It is interesting to note that the seasonal variation of the amplitude of $L(O_1)$ in H,D,Z and also the sense of rotation of $L(O_1)$ vector in horizontal field in different seasons are similar to the seasonal variations of $L(M_2)$. However, the sense of rotation of $L(O_1)$ variation vector during year is similar to that in winter; it is opposite to that for $L(M_2)$, suggesting that, unlike in $L(M_2)$, the yearly variation of $L(O_1)$ is dominated by the variation observed during winter. Similarity in seasonal variation of $L(O_1)$ and $L(M_2)$ may be only due to the contamination of $L(M_2)$ by $L(O_1)$ and vice versa. Winch (1971) has given a method to remove the contribution of $L(M_2)$ to $L(O_1)$ and vice versa. As per the theory, the contamination can appear only in summer and winter and,

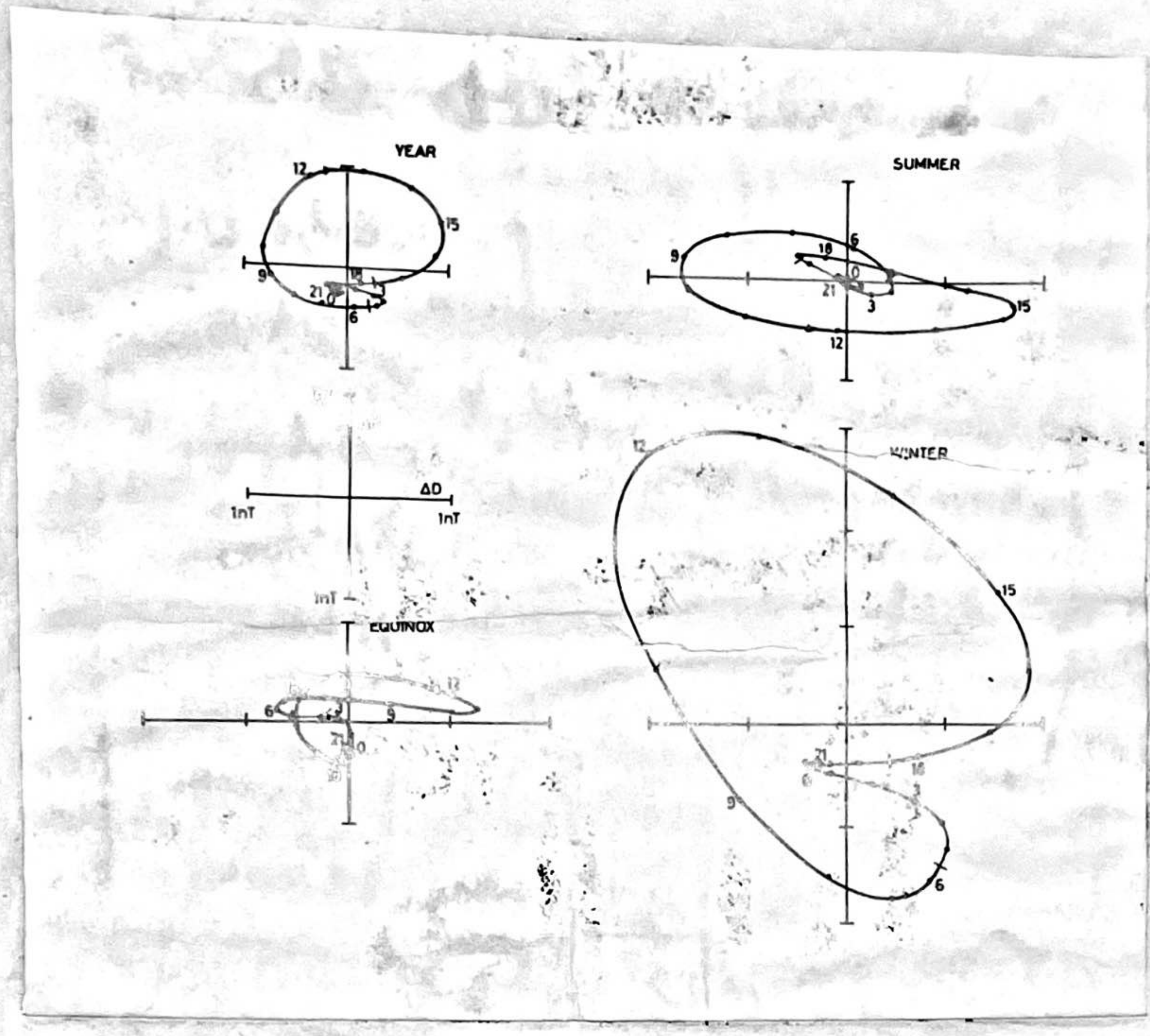

Fig. 7.1

Vectograms showing the variation of $L(O_1)$ in the horizontal plane during the year and for each season. The curves refer to the epoch when $-\nu - s = 0$. The numbers along the curve give local time. Day and night portions are separated by short line across the curve.

therefore, his equations 17, 18, 23 and 24, are applied to the harmonics of $L(M_2)$ and $L(O_1)$ in the present study. The decontaminated $L(M_2)$ and $L(O_1)$ after the removal of the $L(O_1)$ contribution from $L(M_2)$ and $L(M_2)$ contribution from $L(O_1)$ are given, respectively, in Tables 7.3 and 7.4 along with the observed harmonics for summer and winter. The probable errors of the decontaminated harmonics are also computed by the expressions given by Winch (1971). A striking feature of Tables 7.3 and 7.4 is that, though the amplitudes have improved in magnitude there is a considerable decrease in the precision of decontaminated harmonics. This supports the view of Winch (1971) that any dynamo theory devised for $L(M_2)$ and $L(O_1)$ should be able to deal with the contaminated results.

From the consideration of $L(M_2)$ and $L(O_1)$ results at Toolangi, for data averaged over all seasons, Winch (1970b) states that $L(M_2)$ results for summer months would be enhanced and for winter months diminished by the presence of the $L(O_1)$ contribution. He suggested that appropriate adjustments made for the effect of $L(O_1)$ may substantially reduce the seasonal variation of $L(M_2)$ and may offer an explanation in understanding the unduly large seasonal variation observed in global $L(M_2)$. At Alibag, when the effect of $L(O_1)$ is removed from $L(M_2)$, $L(M_2)$ during winter as well as in summer is found to increase. The winter change is of the type expected by theory but it may be recalled that during this season $L(M_2)$

TABLE ... of L(O1) contribution ...=27 in H,D and Z prior to and after the removal (Amplitudes, probable errors in units of 0.01 nT and phases in degrees) for summer and winter seasons

Element	Season	Harmonic n	Contaminated L(M_2) tide: phase l_n	λ_n	partial l'_n	λ'_n	pe	Decontaminated L(M_2) tide: phase l_n	λ_n	partial l'_n	λ'_n	pe
H	j	0	245	191			205	577	120			1177
		1	48	351	56	139	15	133	2	107	85	65
		2	36	174	18	278	12	76	216	71	211	49
		3	14	13	14	61	11	31	69	30	359	43
		4	14	286	17	132	10	25	297	37	89	40
	d	0	363	40			230	431	126			870
		1	129	340	55	250	14	208	40	142	184	59
		2	139	171	49	156	09	240	211	130	148	36
		3	57	2	12	226	05	104	46	37	206	22
		4	15	177	08	269	04	23	211	31	230	19
D	j	0	161	11			68	266	335			359
		1	65	95	34	349	08	114	123	62	330	33
		2	126	285	42	59	05	233	317	111	55	22
		3	81	105	21	160	05	150	139	63	126	11
		4	02	159	05	59	05	14	298	12	319	11
	d	0	97	226			93	233	267			357
		1	66	221	12	244	05	110	247	16	211	30
		2	148	54	21	306	04	233	101	103	308	19
		3	64	220	20	349	03	86	250	38	314	15
		4	24	8	06	75	02	41	53	32	59	09
Z	j	0	238	337			56	275	292			412
		1	56	184	33	02	05	65	223	93	316	22
		2	73	334	18	51	04	138	11	53	32	17
		3	72	172	06	358	03	142	213	27	43	13
		4	02	277	09	93	02	09	287	18	45	09
	d	0	79	302			82	318	272			332
		1	30	213	22	268	05	61	190	47	229	24
		2	106	99	23	241	04	148	141	48	225	19
		3	88	259	20	349	03	123	296	71	314	13
		4	31	71	09	355	02	52	112	26	10	09

... and after the ... contribution for summer and winter seasons (Amplitudes, probable errors in units of 0.01 nT and phases in degrees)

Element	Season	Harmonic n	Contaminated $L(O_1)$ tide: phase c_n	λ_n	partial c'_n	λ'_n	pe	Decontaminated $L(O_1)$ tide: phase c_n	λ_n	partial c'_n	λ'_n	pe
H	j	0	298	337			344	655	20			1280
		1	14	55	54	69	15	103	293	104	129	65
		2	29	240	26	237	10	66	166	79	272	47
		3	14	77	15	355	08	31	21	31	46	41
		4	08	19	14	68	08	14	234	33	139	39
	d	0	451	305			148	651	273			808
		1	134	236	65	11	13	219	183	156	56	58
		2	115	67	14	259	07	193	350	98	38	34
		3	49	255	05	7	05	89	184	31	91	22
		4	12	79	07	67	05	16	354	30	114	20
D	j	0	128	142			100	198	225			383
		1	46	175	21	264	07	77	77	38	24	32
		2	91	1	11	329	05	170	270	82	127	22
		3	60	180	14	118	02	113	92	56	187	11
		4	07	236	08	347	02	19	228	17	14	11
	d	0	76	105			64	205	34			336
		1	47	124	10	337	09	70	23	10	59	33
		2	134	312	12	208	05	203	245	98	204	20
		3	52	128	15	96	04	52	41	30	181	16
		4	21	263	05	291	02	36	193	31	311	09
Z	j	0	226	100			132	239	159			467
		1	51	272	29	313	05	50	206	89	12	22
		2	56	47	07	5	04	109	324	43	98	17
		3	58	242	07	165	03	119	166	28	129	13
		4	01	237	08	24	02	09	215	16	91	09
	d	0	58	321			68	303	7			322
		1	18	167	17	22	06	43	275	40	99	24
		2	94	2	12	339	05	117	292	31	106	20
		3	75	163	15	142	03	90	86	67	197	13
		4	26	328	03	16	02	42	252	21	273	09

is primarily determined by the southern hemispheric current system (Chapter 2). This may necessitate the inclusion of additional correction in the numerical procedure for decontamination. Hence, the observed enhancement of decontaminated $L(M_2)$ harmonics during winter may not be the true result of decontamination procedure. The increase of $L(M_2)$ during summer is contrary to the expectation by theory. It is noteworthy that seasonal variations of $L(M_2)$ and $L(O_1)$, even after the removal of the effect of one from the other, are identical which suggests that current systems responsible for $L(M_2)$ and $L(O_1)$ undergo similar seasonal changes in form and intensity.

7.6 <u>Summary</u> :

An analysis of mean hourly values of the three geomagnetic elements, H,D and Z has revealed clear and significant $L(O_1)$ tides at Alibag. The partial tide terms are small in comparison to phase law tides, suggesting that the variation resulting from the product of atmospheric tides O_1 and higher harmonics of ionospheric conductivity contribute little to the $L(O_1)$ at Alibag. As O_1 tide is primarily lunar diurnal in period, first harmonic of $L(O_1)$ phase law tide is expected to be dominant amongst the harmonics. But this is not found to be the case. The possibility that it is due to the presence of oceanic dynamo contribution to $L(O_1)$ is examined by separating $L(O_1)$ into parts of oceanic and ionospheric origin. c_1 of Ionospheric part is still smaller than c_2. It is inferred that even the yearly $L(O_1)$ harmonics include some unavoidable contribution from the seasonal variation of $L(M_2)$. This may possibly also explain why the observed ratio of $L(M_2)$ and $L(O_1)$ is less than that expected from gravitational tidal theory. In Z, the oceanic part is greater than the ionospheric part, supporting the view of Tarpley (1971) that the most probable cause of $O_1(Z)$ variation is electric currents induced in the ocean by O_1 tidal currents. Seasonal variation of $L(M_2)$ and $L(O_1)$ even after the removal of the effect of one from the other are similar, suggesting that currents responsible for $L(M_2)$ and $L(O_1)$ undergo similar seasonal changes in form and intensity.

CHAPTER 8

MODULATION OF GEOMAGNETIC LUNAR DAILY VARIATION WITH LUNAR DISTANCE

Modulation of Geomagnetic Lunar Daily Variation With Lunar Distance

8.1 Introduction :

As already stated in Chapter 7, besides the dominant M_2 and O_1 constituents in lunar tide-generating potential the other important constituent with appreciable amplitude is the lunar elliptic, i.e., lunar distance constituent, denoted as N_2 tide. This tide is associated directly with the eccentricity of the Moon's orbit and is the fourth largest term in lunar tide-generating potential, the first three in descending order of magnitude being M_2, O_1 and K_1. Geomagnetic lunar variations associated with M_2 and O_1 have been discussed in earlier Chapters. Unfortunately, the geomagnetic lunar variations related to K_1 are completely obscured by the seasonal modulation of Sq and hence their extraction is generally not possible.

In earlier studies, geomagnetic lunar daily variation, $L(N_2)$, associated with N_2 tide has been sought only indirectly, i.e., the influence of N_2 tide is determined as a modulation of the main M_2 tide with respect to lunar distance. More appropriate would be to treat N_2 as a purely periodic tide and truly harmonic analysis should be made. In the past, Bartels and Johnston (1940b) adopted this procedure in their study of L(H) at Huancayo. However, Chapman (1957) felt that their work was facilitated by the large amplitude of L(H) at Huancayo - but elsewhere, the study of N_2 tide requires much greater amount of observational data in order to obtain reliable determinations; in his analysis of L(H) at Greenwich using 66-years data for the period 1848-1913, he adopted the indirect method of estimating the influence of N_2 tide. At Alibag the amplitude of L associated with M_2 tide is only about 4-5 nT. Therefore, the significant determination of L(N_2), which is expected to be about one-fifth of L(M_2) in magnitude, may not be achieved even with 40-50 years of data. Thus, the influence of N_2 tide has been indirectly sought in this Chapter.

According to the gravitational equilibrium tidal theory, the tide producing force of the Moon varies inversely as cube of the distance of the Moon from the Earth. An estimate of L as a function of lunar distance enables one to test whether L effects are in direct proportion to the gravitational pull of the Moon or not. Considering the eccentricity of the Moon's orbit, one may expect the amplitude of L to vary in the ratio of 100:139 as the Moon moves from apogee to perigee. The results of the direct effect of the Moon on the upper atmosphere for varying lunar distance under condition of different electrical state of the ionosphere are presented and discussed in this Chapter.

8.2 Treatment of data :

The data used in the analysis are the absolute hourly values of horizontal intensity, H, at Alibag for the period

1927-1970. Following Leaton et al.(1962), each day has been coded according to lunar distance as follows: 1, for every day whose date is that of the mean Moon's apogee and three adjacent days on either side; 3, for every day whose date is that of the mean Moon's perigee and three adjacent days on either side; 2 for remaining days when the Moon is approaching perigee and 4, for the remaining days when the Moon is receding from perigee. The group of days with codes 1-4 form the lunar distance groups Apogee, Nearing, Perigee and Receding respectively. To study the variation of L with varying lunar distance for different conditions of ionospheric conductivity the data have been divided into :

(1) Three seasons; Winter, Equinox and Summer

(2) Four phases of solar activity, Quiet, Low, Medium and High, with mean annual sunspot numbers in the ranges 0-25, 26-50, 51-100 and >100, respectively.

(3) Entire period of 44 years.

Days in each of the above divisions are further subdivided according to lunar distance. Data in each of the above sub-divisions are analysed to obtain the first four harmonics of the well-known Chapman phase law tide and the partial tide of Schneider, following the numerical procedure detailed in Chapter 1. The vector probable errors for the harmonics are also calculated. Since the mean lunar distances for coded groups 2 and 4 are the same, the data of these groups are combined and the analysis is repeated. The results of the analysis are given under the lunar distance code 5. The amplitudes are considered statistically significant if they exceed 2.08 times the corresponding probable errors.

The lunar ranges, R(L), and its probable error for all the above mentioned groups are computed using the relations given in Chapter 2. The ratio of lunar range at Perigee to that at Apogee is considered as a measure of the change in lunar daily variation with lunar distance. The probable error associated with this ratio is given by:

$$pe = \frac{\left[\rho^2_{(Perigee)} + Ratio^2 \times \rho^2_{(Apogee)}\right]^{1/2}}{Range_{(Apogee)}}$$

where $\rho_{(Perigee)}$ and $\rho_{(Apogee)}$ are the probable errors associated with the range at perigee and apogee respectively.

L_2, the principal component of the M_2 tide, ranges, ratio of range at perigee to that at apogee and other associated parameters for all the groups of lunar distances in different seasons and for the entire period are given in Table 8.1. Similar results for each of the solar activity divisions are presented in Table 8.2. As three days on either side of the apogee or perigee are considered to represent the appropriate lunar distance group, the theoretically expected ratio of L at perigee to that at apogee will reduce from 1.39 to 1.29.

8.3 Results and discussion :

Table 8.1 L_2, R(L) and ratio of R(L) at Perigee to Apogee during different seasons and entire period (l_2, R(L) and pe in units of 0.01 nT and λ_2 in degrees)

	Lunar distance group	No. of days	L_2			Lunar-range		Ratio of R(L) at perigee to apogee
			l_2	pe	λ_2	R(L)	pe	
Entire period	1	4070	72	10	161	334	21	1.32 ± 0.12
	2	3958	68	11	182	322	22	
	3	4067	91	11	165	442	29	
	4	3919	78	11	145	392	26	
	5	7877	70	9	162	348	18	
Winter	1	1354	127	15	160	636	34	1.44 ± 0.10
	2	1329	150	16	180	638	33	
	3	1372	169	14	177	914	41	
	4	1298	119	16	152	672	46	
	5	2627	131	11	167	634	28	
Equinox	1	1357	49	13	148	244	32	1.39 ± 0.23
	2	1323	15	24	173	174	50	
	3	1346	69	16	141	340	34	
	4	1326	77	21	121	483	54	
	5	2649	43	16	127	312	33	
Summer	1	1359	47	17	187	402	41	0.66 ± 0.17
	2	1306	40	18	189	264	33	
	3	1349	48	29	145	264	62	
	4	1295	44	12	174	188	30	
	5	2601	42	12	181	200	24	

Table 8.2 l_2, R(L) and ratio of R(L) at Perigee to that at Apogee during different epochs of solar activity (l_2, R(L) and pe in units of 0.01 nT and λ_2 in degrees)

Solar activity group	Lunar distance group	No. of days	L_2: l_2	L_2: pe	L_2: λ_2	Lunar - range: R(L)	Lunar - range: pe	Ratio of R(L) at perigee to Apogee
Quiet	1	926	55	15	166	334	36	1.02 ± 0.14
	2	905	44	18	193	376	34	
	3	918	70	17	168	350	32	
	4	688	82	14	156	508	36	
	5	1793	60	11	169	426	19	
Low	1	923	68	17	145	410	48	1.20 ± 0.19
	2	899	60	14	172	260	49	
	3	926	79	23	164	490	53	
	4	886	71	18	154	342	44	
	5	1785	64	12	162	276	38	
Medium	1	1011	108	26	162	458	48	1.48 ± 0.21
	2	930	54	25	226	244	49	
	3	1023	148	19	164	680	63	
	4	932	60	19	141	404	50	
	5	1792	43	16	180	274	36	
High	1	1210	56	16	164	330	40	1.54 ± 0.28
	2	1174	118	19	169	606	36	
	3 / 4	1299 / 1193	198	28	[illegible]	[illegible]	[illegible]	
	5	2327	105	18	154	464	37	

8.3 Results and discussion :

8.3.1 Variation of L with lunar distance during different seasons :

While most of the phase law terms are found to be well determined, the partial terms lack significance in many cases. Many of the amplitudes of phase law and partial terms exhibit in general an increase from Apogee to Perigee. During summer, both L_1 and L_2 are poorly determined at Perigee and hence their inclusion in the determination of range, R(L), renders the change, observed from Apogee to Perigee, unreliable. The principal term of lunar daily variation, l_2, shows an increase of 33, 41 and 26 per cent from Apogee to Perigee during winter, equinox and year respectively. Similar change in ranges from Apogee to Perigee can be noticed from the results in Table 8.1. Ratio of the range at Perigee to that at Apogee during the year and in different seasons are close to the theoretically expected value of 1.29. From the analysis of the observations at high latitude stations, Chapman (1957) and Leaton et al.(1962) found that the phase angle of second harmonic (λ_2) to be smaller by 11° to 15° when the Moon was at Apogee than when the Moon was at Perigee. However, such a trend in λ_2 at Alibag, a low-latitude station, is seen only during winter. The reverse trend in λ_2 observed during summer may not be significant because of the large probable error associated with its amplitude at Perigee. Another feature of interest which emerges from examination of the results is that neither the amplitudes of the first two harmonics of phase law tide nor the range for the groups 2 and 4 are equal to each other and in many cases, their magnitudes are not of the order as would be expected by theory. The expected values for these groups should lie between the values for the groups 1 and 3. There are also marked differences between the phase angles of L_2 obtained for groups 2 and 4, and they also differ appreciably from the value for groups 1 and 3. Leaton et al. (1962) observed similar differences in the phase angles of L_2 for groups 2 and 4 at Greenwich and Abinger. They explained these differences as follows:

As per the Kepler's second law, the Moon moves faster when near perigee than when near apogee. Compared with the evenly moving mean Moon, the apparent Moon loses in the half-anomalistic month from 'Nearing' over 'Perigee' to 'Receding', and gains in the other half-month. In other words, over the part of orbit coded 2, the true Moon will be behind the mean Moon, while over the part 4 the reverse will be the case. The effect accumulates so that the tide expressed in mean lunar time τ will appear most retarded at 'Receding' [$(s-p) = 90^\circ$] and most accelerated at 'Nearing' [$(s-p) = 270^\circ$]. In the second harmonic this will produce an apparent phase shift in λ_2 of $\pm$ 11.2 while the overall relative shift between the two sets will be 22.4°. For the first harmonic the difference will be $11^\circ.2$, for the third $33^\circ.6$ and for the fourth harmonic 44.8°. When phase angles are corrected for this effect, differences are found to be small and are not systematic. Considering the uncertainty attached with phase angles, the phase differences observed can be explained in terms of the differences in the hour angle of true Moon and mean Moon. Results obtained here are thus in conformity with the findings of Leaton et al. (1962). In group 5, where days are symmetrically combined about the lines of apsides, the phase angles of l_2 are close to the values for groups 1 and 3 which further confirms that differences in the values of λ_2 for groups 2 and 4 arise from the non-coincidence of mean Moon and true Moon positions over these parts of Moon's orbit. The ranges for groups 1,5 and 3 are in the ratios of 100:128:139 and 100:104:132 during equinox and year respectively in comparison to the expected ratios of 100:115:129. The absence of such systematic changes during summer and winter may be due to the contamination of $L(M_2)$ terms by lunar declinational tide, $L(O_1)$ which contributes substantially but spuriously to $L(M_2)$ tide during these seasons (Winch 1970b).

8.3.2 <u>Variation of L with lunar distance during different epochs of solar activity</u> :

It is interesting to note that l_2 is well determined for all the divisions listed in Table 8.2 and generally increases with increasing solar activity. The general dependence of L with sunspot number at Alibag has already been discussed in Chapter 3. The tendency for l_1 and l_2 to increase from Apogee to Perigee is clearly seen in different phases of solar activity but in many cases the amplitudes are not the largest at Perigee. As noted in seasonal subdivisions, the phase angle of L_2 is nearly same for groups 1,5 and 3, but it differs appreciably between the groups 2 and 4. A marked increase in the amplitudes of the first two harmonics of lunar partial tide with diminishing lunar distance is seen, even though they are not significantly determined. It can be noticed from the results in Table 8.2 that the ratio of ranges at Perigee to that at Apogee increases with increasing activity.

For Perigee group of days, when s-p is nearly zero, L determined is $L(M_2) + L(N_2)$ and at Apogee, when s-p is equal to 180^o, it is $L(M_2)-L(N_2)$ (Malin and Chapman, 1970a). The close agreement of the ratio of lunar range at Perigee to that at Apogee, in different seasons and for total period, with that expected from gravitational tide theory not only strengthens the belief that the direct effect of the Moon on the upper atmosphere is primarily gravitational, but also suggests that the amplitude ratio N_2:M_2 departs insignificantly from that given by tidal theory, namely 0.191:1. No direct values of geomagnetic $L(N_2)$ tide for different season and for varied epoch of solar activity are available (as far as the author is aware). However, Winch and Cunningham (1972) obtained $L(N_2)$ tide for Watheroo using 40-years data without a subdivision into seasons and solar activity. It is interesting to note from their Table 8 that the second harmonic of

M_2 and N_2 are nearly in phase. It appears that at Alibag also M_2 and N_2 are in phase and their magnitudes are in the ratio as expected by the theory. The increase of the ratio of lunar range at Perigee to that Apogee with increasing solar activity would, however, suggest that the ratio $N_2:M_2$ depends on solar activity. But the absence of such a systematic increase with solar activity in the ratio of l_2 at Perigee to l_2 at Apogee would further warrant that the increase in the ratio of lunar range may not be due only to the dependence of the ratio $N_2:M_2$ on solar activity but may arise from the contamination of l_1 by $L(O_1)$. A study of the solar cycle influence on $L(N_2)$ in addition to $L(M_2)$ and $L(O_1)$tides will be essential to identify the reality of the increase of ratio of lunar range at Perigee to Apogee with solar activity.

8.4 Variation of Ionospheric and Oceanic parts of L with lunar distance :

The lunar magnetic variations from coastal observatories are found to have a significantly large part due to the oceanic dynamo. Gupta (1974) successfully applied Malin's method to Abinger and Batavia data to separate L into oceanic and ionospheric parts and showed that the observed increase of both components from apogee to perigee is close to what one would expect from theory. To examine the dependence of oceanic and ionospheric parts of L at Alibag on lunar distance, the ionospheric and oceanic parts of L for different lunar distance groups for all the sets analysed in earlier sections are

Table 8.3 Oceanic and Ionospheric parts of lunar daily variation near Apogee and Perigee (l_o, l_I and pe in units of 0.01 nT and λ_o and λ_I in degrees)

Solar activity groups	Lunar distance group	Oceanic part			Ionospheric part			Ratio of amplitude at Perigee to Apogee for			
								Oceanic part		Ionospheric part	
		l_o	λ_o	pe	l_I	λ_I	pe	ratio	pe	ratio	pe
Entire period	Apogee (1)	35	72	21	79	187	18	0.74	0.91	1.47	0.46
	Perigee (3)	26	341	27	117	164	25				
Quiet	Apogee (1)	58	79	34	78	214	31	0.50	0.64	1.08	0.56
	Perigee (3)	29	59	33	84	187	28				
Low	Apogee (1)	63	24	46	114	173	42	0.63	0.94	1.04	0.56
	Perigee (3)	40	345	52	119	164	46				
Medium	Apogee (1)	49	212	50	85	136	42	0.73	1.40	1.86	1.12
	Perigee (3)	36	264	58	158	151	55				
High	Apogee (1)	73	72	39	94	215	35	0.67	0.99	1.24	0.81
	Perigee (3)	49	350	67	116	165	61				

computed by the method of Malin (1970) detailed in Chapter 6. In Table 8.3, results for Apogee and Perigee during four divisions of solar activity and for the entire period are presented. The oceanic terms are not well determined in any of the groups. In view of the large probable errors, associated with the ratios of amplitude at Perigee to that at Apogee for oceanic and ionospheric terms, no definite cause for their behaviour can be given. However, the ratio for ionospheric part obtained using data for the entire period is significantly determined and is close to the expected value.

8.5 Summary :

The observed changes in lunar daily variation with varying lunar distance for the total period and in different seasons at a low-latitude station are in fair agreement with those expected from gravitational theory which not only confirms the tidal origin of lunar daily variation but also indicates that the amplitudes of $L(N_2)$ and $L(M_2)$ bear the same ratio in all seasons. At the same time a systematic increase of the ratio of lunar range at Perigee to that at Apogee with increase in solar activity implies that amplitude ratio $N_2:M_2$ has a measure of dependence on solar activity. Inconsistencies observed for lunar distance group 'Nearing' and 'Receding' appear to be due to the differences in the hour angle of the true Moon and the mean Moon over those parts of Moon's orbit. Change in the amplitude of ionospheric part with lunar distance, when significantly determined, is close to the expected value.

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REPRINTS AND PREPRINTS OF ADDITIONAL PAPERS

IN SUPPORT TO THE CANDIDATURE

Modulation of Geomagnetic Lunar Variation by the Sector Polarity of IMF

The interplanetary magnetic field (IMF), which originates in the Sun, has been observed to have long-lived and large-scale sectors of predominantly unipolar fields. The quasi-permanent sector structure corotates with the Sun and has profound influence on the terrestrial magnetic activity. While the southward component of IMF is the most effective component so far as geomagnetic activity as revealed by Ap, AE, Kp and Dst is concerned, the sector polarity toward and away has been used by other workers to establish relationships between the polarity and geomagnetic disturbance and field (Ref. 1-6). The sectors are identified as toward or away polarity depending on whether the azimuthal component 'By' of IMF is -ve or +ve.

Moon's influence on various geophysical phenomena has been the subject of numerous studies in the literature. Investigations of lunar effect on geomagnetic activity, in particular, are several but they have led to a number of confusing and often contradictory conclusions. It is generally assumed in studies of solar-terrestrial physics that lunar gravitational and magnetic fields are too weak to exert any significant influence on plasma clouds, sporadically ejected from the Sun, or on the solar wind. However, some evidence for a possible association of geomagnetic activity with phases of the moon was put forth by Bigg[7] and Stolov and Cameron[8]. They sought this association in the interaction that would take place by the passage of the moon through the tail of the geomagnetic cavity embedded in the flow of the solar wind. A comprehensive report on the interaction of the moon with the earth's magnetosphere is given by Schneider[9].

Since the injection of solar plasma into the terrestrial magnetosphere is regulated by the strength and polarity of IMF and in view of the fact that the geomagnetic tail extends well beyond the lunar orbit, there is a possibility that the effect of sector polarity may have a lunar component in the earth's magnetic field. In the present note we report on results of a search for such a modulation, its magnitude and equatorial enhancement in the Indian low-latitude and equatorial region.

The data sample in this note is a set of hourly horizontal intensity over a four-year period of relatively high solar activity (1958-61) at four Indian stations, Alibag (dip 24.3°), outside the equatorial electrojet, and three electrojet stations, Annamalainagar, Kodaikanal and Trivandrum with dip 5.4°, 3.0° and -1.0° respectively. All the stations were situated in the geographic longitude zone between 72°-80°E. The analysis is confined to winter season (d-months) because, in the case of lunar variations, the highest signal to noise ratio is observed during this season (Ref. 10). The re-inferred sector polarities given by Svalgaard[11] for the corresponding period are used in classifying days according to away (A) and toward (C) polarities. Lunar and solar diurnal harmonics as well as the respective probable errors (pe) are determined upto first four harmonics, separately for each of the two groups, following Chapman-Miller[12] method. The computational procedure is detailed in Rao[10]. The lunar (L) harmonic components at each of the stations for the toward and away polarities along with the number of days in each of the groups are given in Table 1. Solar (s) harmonic components are also computed and shown in Table 2. Lunar and solar daily variations obtained by synthesizing the respective four harmonics of S and L for each of the away and toward sector polarities are shown in Fig.1. All synthesized lunar day-graphs in Fig.1 correspond to zero lunar phase. It is obvious from the figure that changes in C polarity day-graphs at all the four stations in the case of lunar daily variations are appreciably large compared to those of A-polarity. It is also noticed that while the lunar day-graphs in A-polarity show little variation among the four stations, considerable enhancement of day-graphs is noticed for C-polarity at stations under the equatorial electrojet. There is also an indication of the lead in

Table 1. Lunar harmonic components

Amplitude (Amp), probable error (pe) in units of nT and phase angle (Pha) in degrees

Station	Harmonic No.	Toward (C) polarity			Away (A) polarity		
		Amp	Pha	pe	Amp	Pha	pe
Alibag		No. of days 184			No. of days 223		
	1	2.38	358	1.46	1.23	8	1.36
	2	1.82	158	0.57	1.87	151	0.49
	3	0.16	26	0.33	0.75	317	0.33
	4	0.37	308	0.28	0.22	52	0.18
Annamalainagar		No. of days 171			No. of days 211		
	1	4.42	36	1.97	1.51	29	2.20
	2	3.88	233	0.94	1.69	200	0.91
	3	2.80	93	0.69	0.54	49	0.51
	4	1.33	298	0.40	0.05	67	0.16
Kodaikanal		No. of days 183			No. of days 223		
	1	5.71	37	1.93	1.30	38	2.26
	2	5.39	232	0.91	2.19	205	0.97
	3	3.73	80	0.74	0.96	49	0.56
	4	1.42	267	0.44	0.18	73	0.22
Trivandrum		No. of days 166			No. of days 216		
	1	6.06	36	2.18	2.56	157	3.36
	2	5.91	228	1.13	2.70	201	1.11
	3	3.74	70	0.80	2.47	37	0.88
	4	1.13	272	0.47	0.24	154	0.28

Table 2. Solar harmonic components

Amplitude (Amp), probable error (pe) in units of nT and phase angle (Pha) in degrees

Station	Harmonic No.	Toward (C) polarity			Away (A) polarity		
		Amp	Pha	pe	Amp	Pha	pe
Alibag		No. of days 184			No. of days 223		
	1	24.81	282	1.35	23.68	288	1.25
	2	8.69	94	0.54	9.49	98	0.47
	3	3.44	312	0.32	3.41	309	0.32
	4	1.23	109	0.27	1.16	111	0.17
Annamalainagar		No. of days 171			No. of days 211		
	1	38.35	287	1.81	35.45	289	2.03
	2	15.64	120	0.90	15.68	116	0.87
	3	7.96	353	0.67	6.89	346	0.50
	4	2.84	201	0.38	2.55	198	0.16
Kodaikanal		No. of days 183			No. of days 223		
	1	45.82	281	1.77	42.13	282	2.07
	2	19.13	110	0.87	19.06	109	0.92
	3	8.87	341	0.72	8.03	338	0.54
	4	3.28	191	0.43	2.80	194	0.21
Trivandrum		No. of days 166			No. of days 216		
	1	48.33	278	2.00	47.15	281	3.08
	2	21.68	107	1.07	21.07	107	1.06
	3	9.66	336	0.77	7.73	335	0.85
	4	3.36	195	0.46	2.99	199	0.27

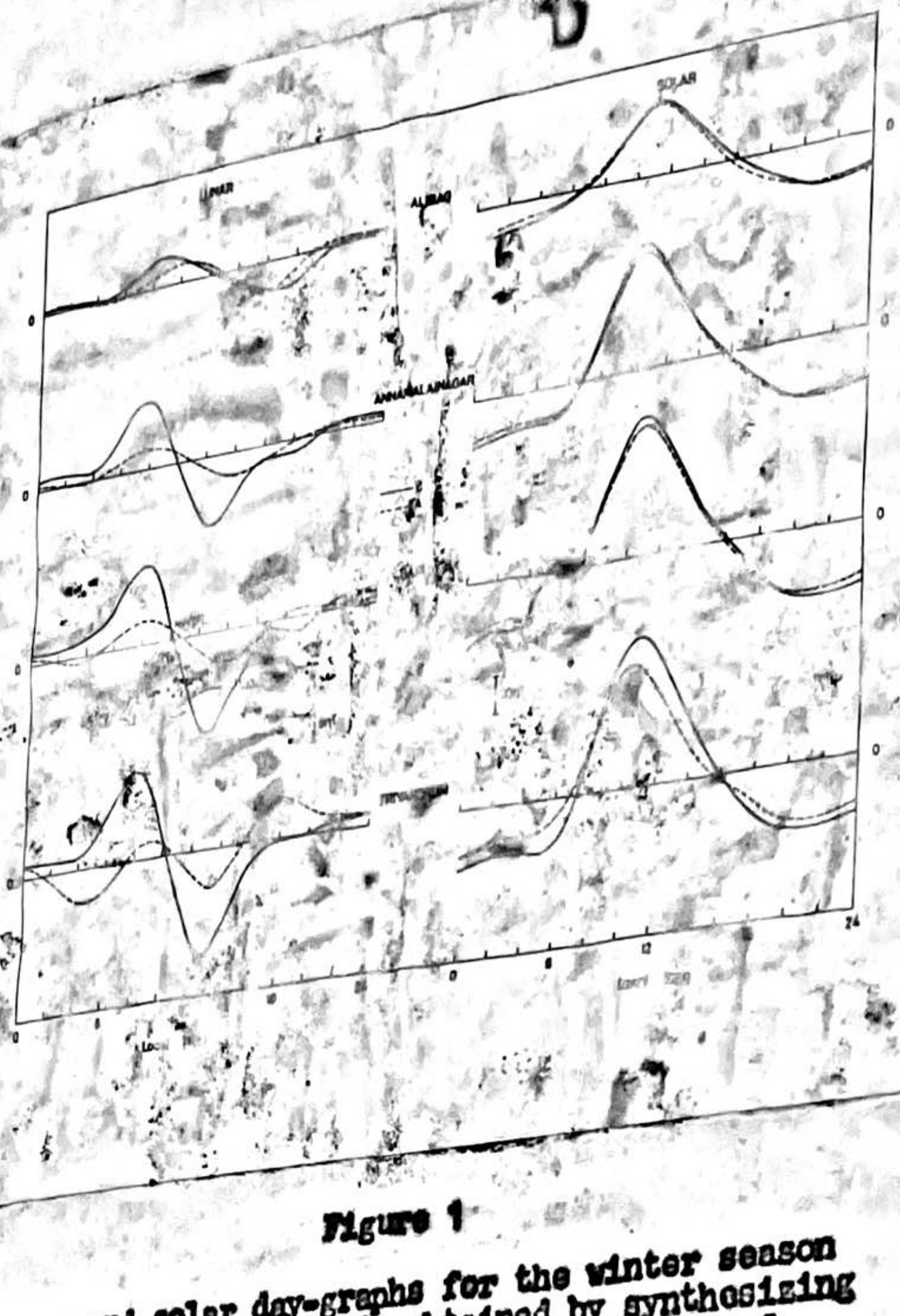

Figure 1

Lunar and solar day-graphs for the winter season during the years 1958-61 obtained by synthesizing the respective four harmonic components for C-polarity (solid line) and A-polarity (broken line) groups at the station Alibag, Annamalainagar, Kodaikanal and Trivandrum. The lunar synthesized day-graphs correspond to the lunar phase zero.

respect of C-polarity lunar day-graph over A-polarity day-graph at all the four stations. In contrast to the lunar day-graphs, the solar day-graphs surprisingly show little change in the patterns for C and A polarities at the stations except at, Trivandrum, the station closest to the dip equator. For C-polarity days, all the amplitudes of the first two lunar harmonic components given in Table 1, excepting the 1st harmonic at Alibag, are significantly determined when compared to the corresponding Pe's. For A-sector, however, only the amplitudes of the 2nd harmonic at the four stations are significant. In the equatorial electrojet region, the significant amplitudes are remarkably higher in magnitude in the C-polarity days at all the stations as compared to the A-polarity days. Even at Alibag, the amplitudes of the 1st and 4th harmonics are higher for C-polarity days compared to the A group. On the contrary, the amplitudes of solar harmonics for C group are not only similar to those of A group but also show same equatorial enhancement as for 'A' days. Only at Trivandrum the C group amplitudes are marginally higher than for the A group. For solar harmonics, the ratios of the amplitudes of C to A groups for all the four harmonics at the four stations lie between 0.95 and 1.25. In contrast, the ratios for the first two harmonics of lunar terms are very much larger and vary between 0.97 and 4.39, indicating that the lunar component is profoundly affected by the sign of the sector.

It would, therefore, appear that the behaviour of the lunar geomagnetic daily variation in the equatorial electrojet region responds to the sign of the sector polarity and that the magnitude of the lunar daily variations associated with C polarity is not only extraordinarily large but also has a greater equatorial enhancement when compared to the variation on 'A' days.

It is rather difficult to invoke a possible physical mechanism to explain the differences in the lunar geomagnetic daily variations observed here with the IMF sector polarity. According to Bigg[7] ~~(1963)~~, some possible lunar influences are (1) magnetic deflection of the ion clouds, (2) gravitational effects, including tides of the upper atmosphere (3) perturbation of plasma waves associated with the disturbances and (4) electrostatic repulsion of ion clouds carrying a net charge. Out of these, (1) and (2) are not likely to change significantly between the two polarity groups to produce the observed changes. It is quite possible that the lunar influences (3) and (4) may be playing part in producing the observed modulations. Any lunar influence on the earth's magnetosphere would be observable at ground by the secondary ionospheric effects. Because of the enhanced ionospheric conductivity at the equatorial electrojet region, these polarity modulations may have been better resolved at the stations under the electrojet.

Russell and McPherron[13] have indicated that the largest effect in geomagnetic activity, on the average, is associated with the C-sector polarity in spring and A-sector polarity in fall. Further work to examine the nature of modulation for equinoctial and summer seasons as well as in other phases of the solar activity cycle is in progress.

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High Resolution Geomagnetic Spectra In Indian Region: Lunar Tides

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Abstract:- Search for major and minor lunar geomagetic tides in the Indian region is made from high resolution power spectra, obtained by Maximum Entropy Method (MEM), at two low latitude stations. The results indicate, on the basis of frequency comparison, that only near the dip equator there is a clear evidence for the lunar tidal mechanism being the dominant factor-over the amplitude modulation mechanism. Amplitudes of the lunar terms near 1 and 2 cpd show equatorial enhancement with greater enhancement for the semidiurnal terms. The lunar semidiurnal term, M2, shows the largest enhancement.

Introduction:- In spite of the known lesser magnitude of the lunar geomagnetic variation in contrast to solar quiet day variation detection and study of various periodicities of likely lunar origin are being continuously pursued as these are potentially of more use for investigating ionospheric dynamo (Malin et al. 1975). Consequent to the introduction of an elegant method for determining lunar harmonic components by Chapman and Miller (1940), generalized later to include partial tides and other minor terms (Winch, 1970; Chapman and Malin, 1970; Winch and Cunningham, 1972) several significant contributions in the study of lunar variations have followed. Successfully applying the Blackman-Tukey approach of spectral analysis of time series to magnetic data of 54 stations, Gupta and Chapman (1969) identified several significant spectral lines whose frequencies closely agreed with that expected from lunar tidal theory. Black (1970) suggested a method of using the fast Fourier transform technique for separating signal from noise at each frequency and used this method to Abinger (Dip.lat. 54°.6N) Declination data. While Gupta and Chapman did not discuss in detail their results corresponding to minor terms, Black suggested that many of these were only due to the mechanism of amplitude modulation (AM) by the 27-day periodic term caused by recurrent disturbances. From a study of magnetic data of

Alert (Dip.lat.85°.9N) Edwards and Kurtz (1971) also arrived at same conclusion. Just recently, Currie (1975) made a significant contribution to this aspect studying the magnetic data of Hermanus (Dip lat.33.3°S). He used a radically different approach to spectral analysis, called the Maximum Entropy Method (MEM) originated by Burg (1968). Similar to Black's method, he combined the spectra derived from 39 individual one-year spans to obtain a stacked spectrum with high resolution. His results for Hermanus regarding minor terms of lunar origin were inconclusive since the deviations of the observed frequencies from expected frequencies of both tidal origin and AM mechanism were about the same. However critically examining all the available results, he concluded that both the mechanisms are equally likely but at higher latitudes the AM mechanism may tend to dominate. As an apparent latitude dependence of the significance of the AM mechanism was indicated, we have now obtained the geomagnetic spectra for two low latitude stations with one of them in the vicinity of the dip equator. In this communication the results of the spectral analysis are discussed.

<u>Data Analysis</u>:- Mean hourly values of horizontal intensity at Alibag (dip lat. 9.5°N) and Trivandrum (dip lat.1.1°S) were averaged for successive four hours to get non-overlapping means with spacing t=4 hours between adjacent data points for the years 1959 to 1973 (both inclusive). These were then detrended by application of a appropriate digital high-pass filter with unit response for periods less than 9 days. Data for each year were then spectrally analysed using the MEM. With the number of Prediction Error Coefficients (PECs) = 200, 1000 estimates were computed adopting a bandwidth of 0.003 cpd. Amplitudes at each frequency for 15 years were then combined to obtain the stacked spectrum as outlined by Currie (1975). The MEM routine used for the analysis was from Ulrich and Bishop (1975) but the amplitudes were computed by multiplying the power by the bandwidth of the estimates and taking the square root (Lacoss 1971).

<u>Results and Discussion</u>:- Fig. 1 presents the stacked spectra over the period range 8 days to 53 hours (M = 40 to 150). The indicated peaks (SR_3 to SR_8) are the harmonics of the solar rotation period signal. The mean periods of these peaks obtained from the stacked spectra for both stations are 6.94, 5.55, 4.56, 3.88, 3.51 and 3.17 days. It is interesting to note that almost all of these turn out to be exact harmonics of a fundamental signal with a period of 28.0 days. The presence of several significant harmonics of the average solar rotation signal indicates its non-sinusoidal nature which

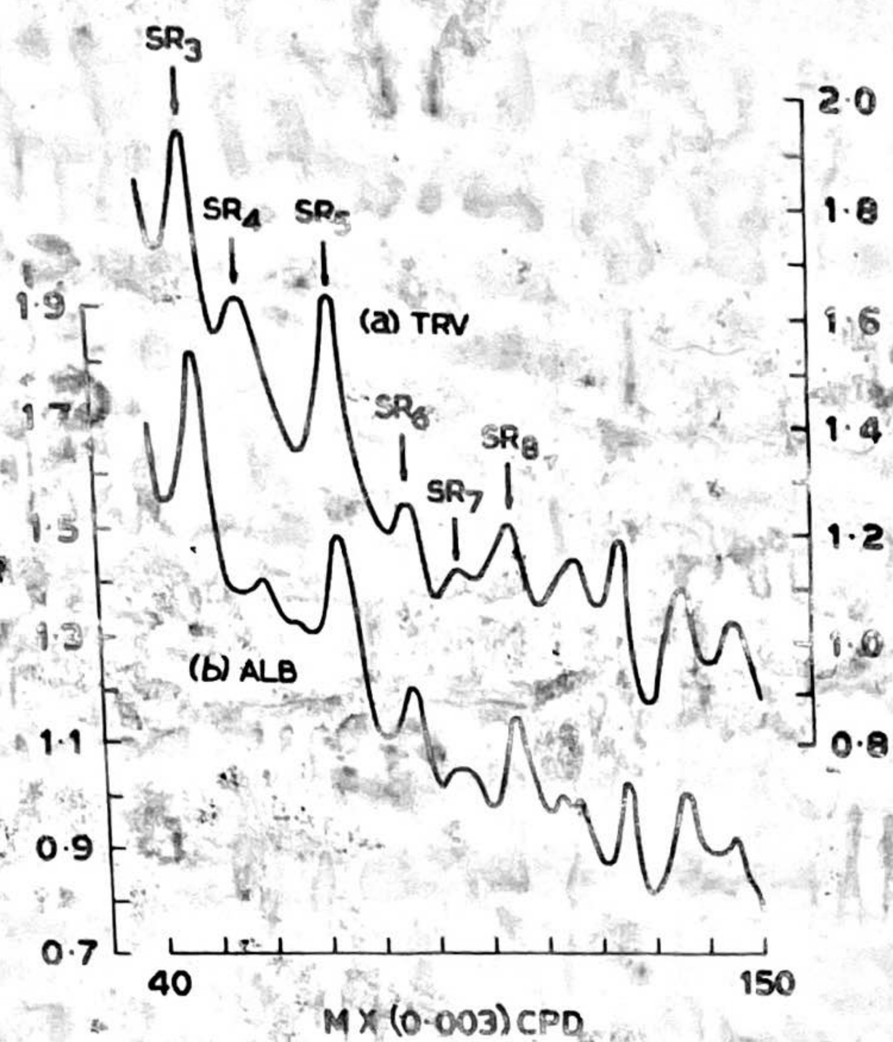

Fig. 1

Stacked amplitude spectrum from M=40 to M=150 for (a) Trivandrum and (b) Alibag. The symbols SR3 to SR8 represent the harmonics of the 28-day solar rotation signal.

should only be expected as several years of data from different phases of the solar cycle are considered to obtain the stacked spectra.

Figs.2 and 3 depict the spectra in the frequency range M=150 to M=750 for Trivandrum and Alibag respectively. The symbols point to the theoretical frequencies of lunar terms. Symbols (a) and (b) are adopted from Currie (1975). A comparison of these two figures reveals that at the electrojet station, Trivandrum all the spectral lines of likely lunar origin near 1 cpd are clearly resolved. At Alibag only O_1, M_1, J_1 and OO_1 are well above the continuum and the others are either just above the noise level or are absent. The relative order of amplitudes for different lunar terms for Trivandrum is almost the same as that of the numerical coefficients (C) of the tidal harmonics listed by Gupta and Chapman, but at Alibag there is apparently no detectable relation. Another significant aspect is that while the major term O_1 is better resolved and has greater amplitude than the adjacent term M_1 at Trivandrum, M_1 is better defined and has larger amplitude at Alibag. Since even the amplitudes of S_1 and S_2 are substantially less than the known amplitudes at both stations by a factor of about 3 (nearly same as that indicated by Currie for Hermanus) it is not clear whether this difference in the relative amplitudes for the two terms between the two stations is meaningful. Examination of the spectra presented by Gupta and Chapman (1969) around the diurnal frequency (their Fig.3a) for Huancayo and Kodaikanal shows that for both the electrojet stations O_1 amplitudes are larger than M_1 but at Honolulu, a low latitude station outside the electrojet belt, M_1 is larger in amplitude. In view of this and since identifical technique of analysis has been applied to both data strings this feature appears to be of significance. Around the solar semidiurnal frequency, at Trivandrum, the peaks of all the lunar terms are clearly above the background noise except for L_2,n_2 and (b). It is likely that the larger amplitude of S_2 signal has swamped the adjoining L_2 and n_2 signals, a feature observed by Currie at Hermanus also. At Alibag, where the half-width of the S_2 peak is narrower, L_2 appears better resolved confirming the assumption.

In their study of longer period lunar magnetic tides in the Indian region, Rao et al. (1976) found that many of the spectral lines well resolved at Trivandrum and other stations in the equatorial electrojet region were not clearly discernible at Alibag. Our results, hence, tend to show that this feature is apparently is not frequency-dependent.

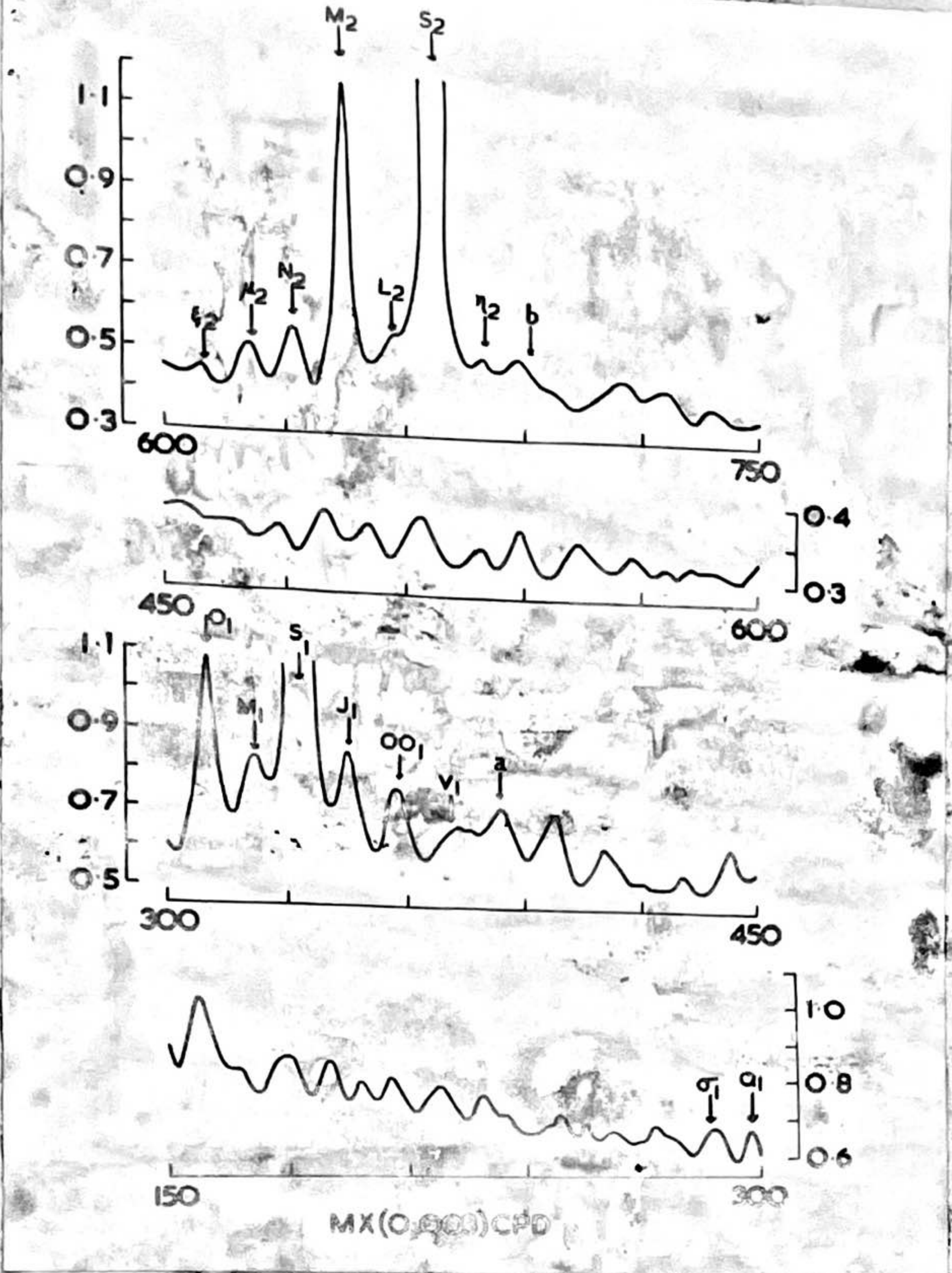

Fig. 2

Stacked amplitude spectrum from M=150 to M=750 for Trivandrum. Lunar periods are indicated by the appropriate symbols.

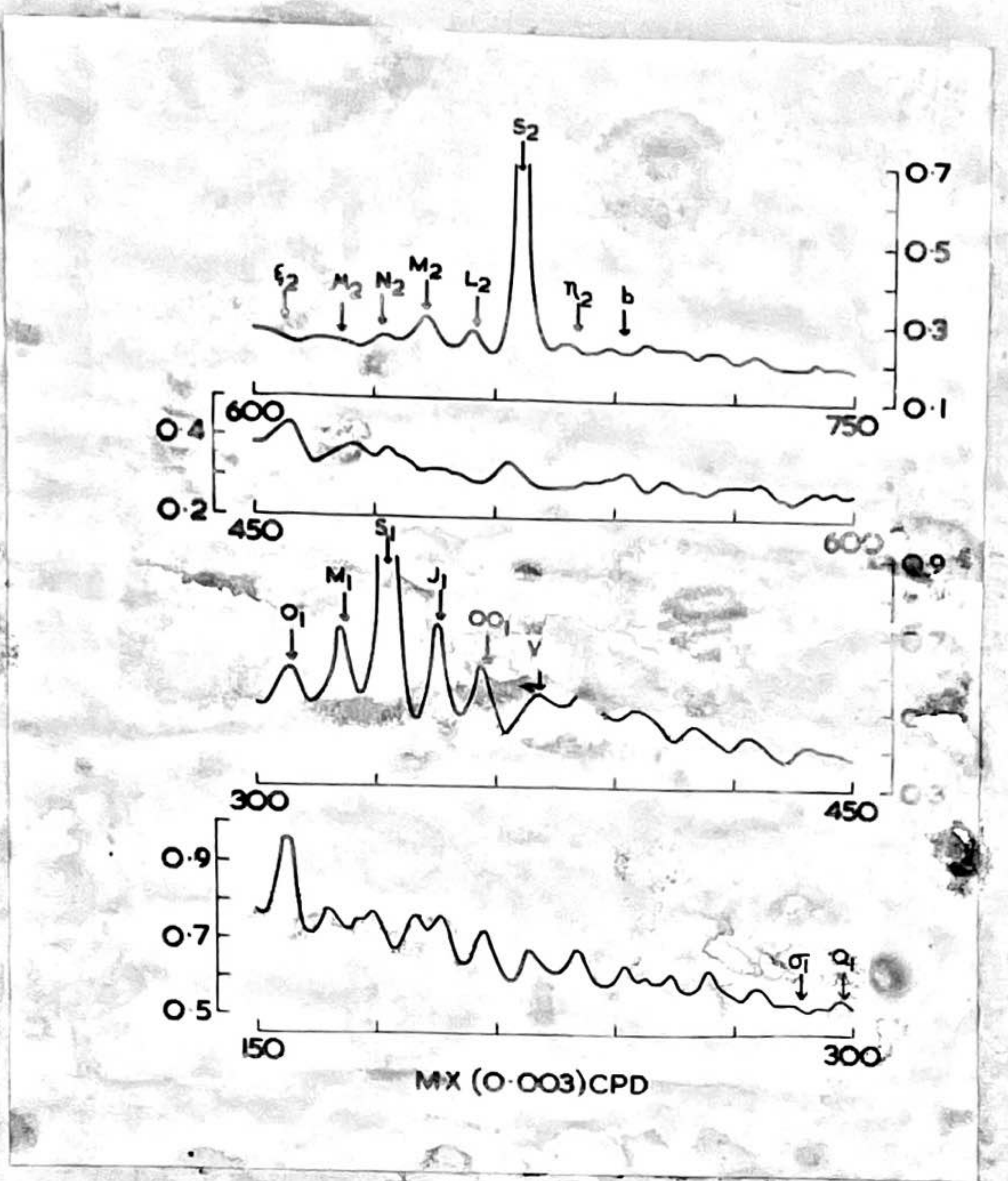

Fig. 3

Stacked amplitude spectrum from M=150 to M=750 for Alibag. Lunar periods are indicated by the appropriate symbols.

From the ratio of amplitudes for the different spectral lines of Trivandrum and Alibag, given in Table 1, it may be seen that there exists an equatorial enhancement of the spectral amplitudes corresponding to all the listed frequencies. While the amplitudes of lunar terms near 1 cpd are enhanced towards the equator by a factor of about 1.2, those near 2 cpd show a greater enhancement with a factor of about 2. This feature may be explained if the effective width of the equatorial electrojet decreases with increasing frequency resulting in greater concentration of current at the centre as envisaged by Mason (1963). Significantly, the increase in M_2 amplitude towards the dip equator is nearly four fold; similarly O_1 shows a much larger enhancement in relation to the other neighbouring lunar terms.

In Table 1 are given the frequencies of theoretical lunar tides and those observed at Alibag and Trivandrum. The observed frequencies are derived as the mean of the corresponding frequencies in each spectrum obtained by the method of parabolic interpolation suggested by Gupta and Chapman (1969). The observed frequencies in respect of O_1 and M_2 are nearly the same as that expected from theory for Trivandrum. Following Currie (1975), we found the residuals of the observed frequencies from that obtained by AM mechanism due to a solar rotation signal whose period was taken as 28.0 days in view of the significant harmonics seen in Fig.1. These residuals as also those obtained from Hermanus data (Currie 1975) are also shown in Table 1. The mean residual for all lunar terms from theoretical frequencies are 31 ± 17, 7 ± 15 and that from nominal modulation mechanism are 17 ± 11, 26 ± 11 for Alibag and Trivandrum respectively. These residuals for Alibag are comparable to those of Hermanus with values of 32 ± 11 and 26 ± 12 respectively. These figures suggest that even at a low latitude station like Alibag the generating mechanism responsible for the observed periodicities near 1 and 2 cpd can not be unambiguously determined. Only at the equatorial station like Trivandrum there is a strong bias in favour of lunar tidal potential mechanism being the dominant factor. A closer look at the residuals at individual frequencies indicates that AM mechanism can not be ruled out altogether even there.

No.	Symbol of Lunar term	Theoretical freq.	Observed frequency		Residual x 10^4 Obs.Freq. - Theor. Freq.			Residual x 10^4 Obs.Freq.-Freq.from A M		
			Alibag	Trivandrum	ALB	TRV	HER*	ALB	TRV	HER*
1.	σ_1	0.8618	0.8580±.0024(10)	0.8605±.0023(13)	-38	-13	-19	+9	+34	+78
2.	ϕ_1	0.8932	0.8907±.0013(11)	0.8925±.0011(8)	-25	-7	+76	-22	-4	+199
3.	O_1	0.9295	0.9254±.0021(13)	0.9296±.0007(15)	-41	+4	-3	-32	+10	+35
4.	M_1	0.9664	0.9643±.0019(12)	0.9651±.0012(9)	-21	-13	-44	+8	+16	-4
5.	S_1	1.0000	0.9992±.0001(15)	0.9993±.0001(15)	-8	-7	-8	-	-	-
6.	J_1	1.0390	1.0369±.0014(14)	1.0391±.0019(14)	-21	+1	-28	+16	+42	+2
7.	OO_1	1.0759	1.0700±.0012(12)	1.0745±.0013(12)	-59	-14	-36	-6	+39	-4
8.	V_1	1.1122	1.1068±.0021(11)	1.1121±.0031(10)	-54	-1	-27	+5	+58	0
9.	(a)*		1.1508±.0025(12)	1.1562±.0022(10)	-	-	-	-	-	-
10.	ϵ_2	1.8283	1.8182±.0029(9)	1.8275±.0022(11)	-101	-8	-	-	-	-
11.	μ_2	1.8645	1.8581±.0032(11)	1.8625±.0021(12)	-64	-20	-58	+5	-49	+62
12.	N_2	1.8960	1.8932±.0022(12)	1.8935±.0015(13)	-28	-25	-80	-2	+1	-13
13.	M_2	1.9323	1.9303±.0016(14)	1.9321±.0004(15)	-20	-2	+6	+12	+28	+68
14.	L_2	1.9686	1.9643±.0010(8)	1.9638±.0018(5)	-43	-48	-27	-5	-10	+31
15.	S_2	2.0000	2.0006±.0008(15)	2.0005±.0006(15)	+6	+5	-4	-	-	-
16.	η_2	2.0418	2.0424±.0025(10)	2.0451±.0024(13)	+6	+33	-67	+82	+89	-13
17	(b)*	2.0787	2.0862±.0041(10)	2.0803±.0026(10)	+75	+19	-81	+157	+84	-25
				Mean	-31±07	-7±5	-32±11	17±11	26±11	26±12

* Notation and values for Hermanus are from Currie (1975).

Figures in brackets indicate the number of individual spectra considered for obtaining the mean and S.E.

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Longer period lunar magnetic tides in the Indian equatorial region

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INDIA

Abstract - Longer period lunar magnetic tides are identified in the spectrum of geomagnetic horizontal intensity, H, in the Indian equatorial region. Computations have been carried out by the efficient method of fast Fourier transform based on Cooley-Tukey algorithm. Consistent appearance of many of the lines, corresponding to the long period lunar tidal frequencies, at all the stations confirms the reality of the lines although many of the peaks, well resolved at the electrojet stations, do not appear above the noise level at Alibag, a low-latitude station outside the equatorial electrojet. The periods of these lines are found to be close to those expected on lunar tidal hypothesis. However, they are also within the period-range of side-bands expected from the amplitude modulation of the 27-day and 13.5-day lines, which occur in the spectrum due to recurrence tendency of magnetic disturbance, by the annual and semi-annual waves. Observation of a few prominent lines in the f_oF_2 spectrum at Kodaikanal, and lines in the H spectrum, suggest that

longer period lunar tides in f_oF_2 and H are, generally, in phase opposition.

Introduction

According to dynamo theory of transient daily geomagnetic variations, each atmospheric tide produces a corresponding geomagnetic daily variation the time dependence of which is determined by the product of a term representing the ionospheric movement and a sum of terms representing the variations of ionospheric electrical conductivity. Apart from the terms of purely lunar tidal origin (M_2, N_2, O_1), terms of relatively smaller amplitudes arise from seasonal modulation of the main lunar tides by the ever changing atmospheric structure. Lunar daily geomagnetic variations can be expressed in a general form as follows (Winch and Cunningham, 1972):

$$L = \sum_{n=\ell-4}^{\ell+4} C_n \sin [(n+\omega)t + \varphi_n]$$

ℓ is a number representing the frequency of the tide in a lunar day. The summands n = ℓ to ℓ+4 are the phase law tides and summands n = ℓ-4 to -1 are the partial tides. The summand n = 0 is a long period tide with the period of $\frac{1}{\omega}$ days, where ω is the rate of change in the time argument over a solar day. Each of the lunar tides corresponding to M_2, N_2, O_1, and their higher harmonics or overtides (MM_2, OO_1, etc.) thus give rise to, in addition to phase law and partial terms, long period tides whose period is a function of ω of the corresponding tide. These long period tides are the subject of the present investigation.

Gupta and Chapman (1969) and Chapman and Malin (1970) have initiated methods of determining the tidal harmonics by spectral analysis of the data. Black (1970) and Edwards and Kurtz (1971) have, however, shown that the amplitude modulation of the diurnal line by the 27-day recurrence of magnetic activity is responsible for the minor lines in the spectrum. From an analysis of the horizontal intensity at Hermanus by the maximum entropy method of Burg (1972), Currie (1975) has confirmed the existence of most of the minor terms found by Gupta and Chapman, but has suggested that both lunar tides and amplitude modulation must be invoked to explain all the observations. Detection of long period lunar tides, corresponding to various major and minor lunar harmonics, in the spectra of both geomagnetic and ionospheric parameters will not only confirm the reality of minor tidal oscillations but will also enable one to study the role of ionospheric conductivity in the modulation of geomagnetic lunar tides.

An attempt is made in this communication to detect these long period tides in the geomagnetic horizontal component at the Indian Observatories at Alibag, a low latitude station outside the equatorial electrojet, and the three electrojet stations, Annamalainagar, Kodaikanal and Trivandrum. Computationally efficient fast Fourier transform based on Cooley-Tukey algorithm (Cooley and Tukey, 1965) has been used to compute the spectrum. A search for the corresponding tides in the noon-time critical frequency of F_2 layer, f_oF_2, at Kodaikanal is made and their phases are compared.

Analysis and Results

It has been shown that, at a station under the influence of the equatorial electrojet, the lunar semi-monthly tide corresponding to M_2 at fixed solar hours varies with solar time in the same way as the electrojet current (Trivedi and Rastogi, 1969; Sen and Rao, 1973). Consequently the signal to noise ratio can be expected to be maximum a little before local noon when the electrojet is strongest. The data chosen for the analysis are, therefore, hourly mean values at a fixed hour, 06 UT ($\sim$ 11 LT), during the 15-year period 1958-1972. Since a reliable test for the reality of the spectral peaks is consistency of the maximum among independent samples (Blackman and Tukey, 1959; Jenkins, 1961), the interval of 15 years is divided into seven blocks of three years each, with one year period overlapping in successive blocks. Each block of data is subjected to spectral analysis using fast Fourier transform. The computation requires the total number of data points in the series to be power of 2. To comply with this condition and for better time resolution, suitable number of zeros were added to one end of the series of 1095 or 1096 values after subtracting the mean, so as to bring the length of each of the series to 2048, (2^{11}) and providing spectral estimates at every 0.0005 cycles per day. The method is outlined in earlier papers (Arora and Rangarajan, 1974; Rangarajan and Bhargava, 1974). Since many of the long period lunar tides are in the period range 10 to 20 days, the stacked spectra over this range for the three stations, Alibag, Annamalainagar and Trivandrum, are obtained by averaging the seven block spectra at each of the stations, and are presented in Fig.1. It is readily seen that the nature of spectra at the three stations is nearly the same but at Alibag, many of the peaks well resolved at the electrojet stations do not appear to be above noise level. The prominent peaks are around the periods 20.28, 17.50, 16.93, 16.00, 14.73, 13.65, 12.41, 11.51 and 10.78 days. There is a suggestion of a few minor peaks around the periods 14.03, 13.13, 12.72 and 12.19 days. Examination of individual block spectra at Annamalainagar and Trivandrum has shown that these lines are present practically in all the spectra with little fluctuation in frequency, thus confirming the reality of these lines. Winch and Cunningham (1972), in an analysis of Watheroo data, have computed eleven seasonal harmonics of M_2 and O_1 group of lunar magnetic tides with time arguments

2s + mh, where the integer m takes the value from -6 to 4. s and h are the east longitudes of the mean positions of the Moon and Sun respectively. Interestingly the periods of the lines seen in Fig.1 are quite close to the periods of long period tides corresponding to these seasonal harmonics.

Examination of the possibility, that the observed lines may result from an amplitude modulation of the periodic oscillation corresponding to the solar rotation period or its first harmonic by sinusoidal functions with periods of one year and half year is complicated because of the ill-defined solar rotation period which has been found to vary between 26.4 and 28.7 days (Chapman and Bartels, 1940). Since the study extends over a solar cycle an average value of 27 days is taken as the period of solar rotation and approximate frequencies, at which the side-bands would appear as a result of amplitude modulation of 27-day and 13.5-day lines by the annual and semi-annual functions and their first four harmonics, are calculated. The periods of side-bands due to modulation of the 13.5-day line are shown, at the bottom of Trivandrum spectrum, in Fig.1 by short vertical lines pointing upwards and those due to the modulation of the 27-day line are shown by short vertical lines pointing downwards. The periods of long period tides corresponding to time arguments $\frac{1}{\omega} = \frac{1}{2s + mh}$ where m = -6 to +4 are also marked on top of the Trivandrum spectrum. It can be noticed that the periods of most of the observed peaks are very close to the periods expected on lunar tidal hypothesis. The mean and the standard deviation of the periods of the observed peaks in the period range 10 to 20 days, obtained from individual spectra of Trivandrum, are also given in Table 1. It appears from the Table that the observed mean periods, $\frac{1}{\omega}$, are closer to those expected on lunar tidal hypothesis than to those expected from the amplitude modulation mechanism, given in the last column of the Table. However, when allowance is given for the variation in the frequencies of side-bands due to changing solar rotation period, the frequencies of the observed peaks are well within the extremes. Hence little significance can be attached to the closeness of the observed peak to that expected on the lunar tidal hypothesis.

It will be noticed in Fig.1 that the amplitude of the M_2 tide (period 14.77 days) is the highest in accordance with the lunar tidal theory. But the amplitudes of some of the minor long period tides resulting from dynamo action of minor seasonal harmonics of purely lunar tides, e.g. $\delta 2$, OO_1 and MN_2, are larger than that of the main O_1 tide (period 14.19 days) which should be dominant. Gupta and Chapman (1969) also found little or no relation between the magnitudes of the terms in the lunar tidal potential and those

TABLE 1

Some lunar diurnal and semidiurnal atmospheric harmonics and the expected periods of the corresponding long period tides and the periods observed in H at Trivandrum. Periods of nearest side-bands expected from amplitude modulation of the 27-day line by annual and semiannual waves are given in the last column for comparison.

No.	Character Number	Symbol	1/ω (Period in days)	Observed period and its standard deviation in H at Trivandrum		Period of the nearest side band expected from Amplitude Modulation
				Observed period (in days)	Standard deviation (in days)	
1.	2s-6h	-	17.61	17.53	.12	17.30
2.	2s-5h	-	16.80	16.85	.08	16.52
3.	2s-4h	δ_2	16.06	16.09	.12	15.82
4.	2s-3h	τ_1	15.39	-	-	15.17
5.	2s-2h	M_2	14.77	14.76	.05	14.57
6.	2s-h	O_1	14.19	14.13	.15	14.02
7.	2s	M_f	13.66	13.60	.12	-
8.	2s+h	OO_1	13.17	13.10	.09	13.03
9.	2s+2h	MM_2	12.71	12.75	.07	12.59
10.	2s+3h	-	12.28	12.40	.07	12.18
11.	3s-6h-p	-	10.75	10.80	.07	11.08

s and h are the east longitudes of the mean moon and sun respectively, and ω is the rate of change in the time argument over a solar day.

observed in the geomagnetic spectrum. This may possibly be due to the bias of terms of lunar tidal origin from signals resulting from amplitude modulation mechanism.

An examination of the individual spectra has shown that the amplitudes of various observed lines are larger for the block of years 1958-1960 and 1968-1970 and lowest for 1964-1966, indicating a solar cycle dependence of the amplitudes.

As a step in understanding the generating mechanism of the geomagnetic lunar tides it is worth comparing the amplitudes and phases of the longer period tides in the geomagnetic field with the corresponding parameters of these tides in the ionosphere, preferably in the F-layer because tidal amplitudes are larger in the F-layer than in the E-layer (Matsushita, 1967). Spectra of series of 2048 noon-time (06 UT) daily values of f_oF_2 and the horizontal component, H, at Kodaikanal have been computed by the method described earlier. H data of Alibag, Annamalainagar and Trivandrum for the same period are also similarly analysed. The starting of each series is 1st January, 1958. Examination of these spectra has shown that the nature of H spectrum at Kodaikanal is similar to that at Annamalainagar and Trivandrum and in general there is little variation in the periods of the peaks from those of the corresponding peaks observed in Fig.1. However, many of the peaks noticed in

H spectrum are not seen in the f_oF_2 spectrum of Kodaikanal. Rastogi (1968) has earlier shown an anti-phase relationship at the equatorial stations between the fortnightly tide in f_oF_2 and that in H. Phase relationship of the few prominent lines of f_oF_2 spectrum with the corresponding lines in H spectrum is shown in Fig.2. It would appear from Fig.2 that longer period tides in f_oF_2 and in H are generally in phase opposition at all the prominent frequencies corresponding to the lunar tidal variations.

Conclusion

On the basis of signal-frequency comparison of the periods of lines observed in the stacked amplitude spectra of H at the Indian equatorial stations, obtained by averaging over seven samples, with those due to major and minor lunar tidal terms and also with those expected from the amplitude modulation mechanism, it is difficult to ascertain the source of the observed spectral lines. The mean amplitudes of various lines are, however, not in the same proportion as expected from tidal theory. Comparison of the phases of various long period tides in H with those in f_oF_2 showed an antiphase relationship. An analysis of a longer series of data from stations in the equatorial electrojet region, permitting larger number of samples than what has been used here and comparison of the association with various ionospheric parameters may lead to a better understanding of the generating mechanism of these lines.

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Lunar modulation of the diurnal variation of H at Trivandrum

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Abstract—Lunar effect on the diurnal variation of H at Trivandrum is studied by the method of Onwumechilli (1963), using the quiet-day data of the four winter months, November to February, during the period 1958-1971. The lunar tide, L, in its maximum phase is found to account for about 11 per-cent of the daily range in H and contribution of L to the departure of the hourly mean of H is about 13 percent at 10 hr and about 22 per cent at both 14 hr and 17 hr local time. These figures are comprable to those obtained by Onwumechilli for Ibadan. L is also found to contribute to the asymmetry of the diurnal variation of H at Trivandrum to the extent of about 22 per cent. Using these estimates and applying the criterion of Onwumechilli, days with different types of lunar contribution at Trivandrum are identified.

1. Introduction

Lunar daily variation, L, superposed on the solar daily variation, S, tends to modify the diurnal variation curve of the geomagnetic horizontal intensity, H. The lunar effect, though small, may be sometimes conspicuous at stations near the magnetic equator where the lunar variation is also enhanced in the day-time. Bartels and Johnston (1940) attributed changes in the shape of the diurnal variation of H at Huancayo to lunar modification. Onwumechilli (1963), using Ibadan magnetograms for quiet days in northern winter, attempted to verify their findings applying a new method of estimating L at certain hours on individual days and concluded that the existence of a wide variety of L-types would be possible which would have implications on the height of the L-field. Adopting his method the effects of various types of lunar modulation are examined here in the Trivandrum magnetograms for the horizontal component, H, on international quiet days in the winter months, November, December, January and February during the period 1958-1971.

2. Method

The method, due to Onwumechilli (1963), is in brief as follows. The departures (M_t) of the hourly mean values (H_t) of H at the local solar hour (t) from the datum-level are computed. The field averaged over 03, 04 and 05 hours LT, an interval during which field variability is found to be minimum (Bhargava and Yacob, 1974), is used as the datum-level. The departure M_t is corrected for non-cyclic variation. The greatest component of this departure is Sq, but a small part is made up of the disturbance field and the L-field.

M_t may be expressed as

$$M_t = M_{st} + M_{Dt} + M_{Lt} \quad \text{- - - - - - - - - - - - -} \quad (1)$$

On averaging M_t taken on different days of a month, M_{mt} is obtained. M_t is rationalized by dividing each with the mean, M_{mt}, so that the dominating influence of S-field is subdued. The ratio, R_t, though free from the seasonal change from month to month, still bears the imprint of Sq of the day. M_{mt} depends on Sq but the monthly mean of R_t denoted by R_{mt} is independent of Sq and should always be unity.

The ratios, R_t, for all the available days are arranged according to lunar phase, μ. $R_t(\mu)$ is the average of R_t for a selected value of μ. Following (1), $R_t(\mu)$ may be written as

$$R_t(\mu) = R_{st}(\mu) + R_{Dt}(\mu) + R_{Lt}(\mu) \quad \text{- - - - - - - - -} \quad (2)$$

Averaging for a fairly large sample $R_{st}(\mu)$ should be unity like R_{mt} because neither the S-field nor its variability depends on lunar phase, and because D-field is independent of μ and is random in lunar phase, $R_{Dt}(\mu)$ is zero. $R_{Lt}(\mu)$ then should demonstrate the dependence of R_t on lunar phase and (2) reduces to

$$R_t(\mu) = 1 + R_{Lt}(\mu) \quad \text{- - - - - - - - - - - - - -} \quad (3)$$

As can be seen from Fig. 1, which is a plot of R_t against lunar phase for the hours 10, 14 and 17, a semi-monthly wave obtained from Fourier analysis of data fits in the experimental points to a fairly good approximation so that $R_{Lt}(\mu)$ can be replaced by the expression $L_t \sin(2\omega\mu + \varphi)$, where L_t is the amplitude of the L-field at the local solar hour (t), $\omega = 2\pi/24 = 15^\circ$ and φ is the phase angle. The results obtained here for Trivandrum are as follows:

$$\left.\begin{aligned} R_{10}(\mu) &= 1.008 + .132 \sin(2\omega\mu + 179.^\circ4) \\ R_{14}(\mu) &= 1.012 + .221 \sin(2\omega\mu + 270.^\circ7) \\ R_{17}(\mu) &= 0.983 + .222 \sin(2\omega\mu + 8.^\circ6) \end{aligned}\right\} \quad \text{- - -} \quad (4)$$

The contribution by L of about 13 per cent at 10 hr and 22 per cent at both 14 hr and 17 hr is large enough for its effect to be conspicuous in the magnetograms.

It is seen from Fig. 1 that $R_{14}(\mu)$ is unity close to $\mu = 3$ or 9, indicating that lunar effect, R_{L14}, at 14 hr LT is nearly zero on all days with $\mu = 3$ or 9 and hence the variation at hour 14 may be regarded as a measure of Sq on such days. But these same days with $\mu = 3$ free of L-field near 14 hr LT are subject to minimum L-field near 10 hr LT and maximum field near 17 hr LT. Reverse is the case for days with $\mu = 9$ which are also free of L-field near 14 hr LT. In order to estimate the Sq at 10 hr and 17 hr LT, using variation at 14 hr LT as a measure of Sq, we compute the linear relation between the normalized monthly mean values of M_{mt}, S_t, at 14 hr LT and either 10 hr or 17 hr LT. It may be recalled that, since monthly mean values of M_{mt} are used, the influence of L-field present on any individual day is averaged out. Fig. 2 shows this linear relationship between the values of Sq at 14 hr LT with 10 hr and 17 hr LT respectively. Since R_{st} is a very similar measure of the same Sq as S_t, it enables one to separate the L variation, $L_t(\mu)$, at that hour. The expressions for the estimation of Sq at hours 10 and 17 are:

$$\left.\begin{aligned} R_{S10} &= 0.341\ R_{S14} + .659 \\ R_{S17} &= 1.263\ R_{S14} - .263 \end{aligned}\right\} \quad \text{-------- (5)}$$

Then the lunar variation is

$$R_{L10} = R_{10} - R_{S10}$$

$$R_{L17} = R_{17} - R_{S17}$$

comparison of these L-variations on a particular day with the expected variations from equation (4) will determine the type of L modulation on that day. The following criteria are applied (Onwumechilli, 1963):

I. Model L-day : $\left|R_{L10} - L_{10}\right| < \frac{1}{2}\sigma_{10}$ and $\left|R_{L17} - L_{17}\right| < \frac{1}{2}\sigma_{17}$

where σ_{10} and σ_{17} are the standard errors for the hours 10 and 17 respectively;

II. Big L-day : $\frac{R_{L10}}{L_{10}} > 2$ and $\frac{R_{L17}}{L_{17}} > 2$;

III. Small L-day: $\left|\frac{R_{L10}}{L_{10}}\right| < \frac{1}{2}$ and $\left|\frac{R_{L17}}{L_{17}}\right| < \frac{1}{2}$;

IV. Non-Uniform L-day: $\left|\frac{R_{L10}}{L_{10}} - \frac{R_{L17}}{L_{17}}\right| > 2$;

V. Inverse L-day: One of the ratios $\frac{R_{L10}}{L_{10}}$ and $\frac{R_{L17}}{L_{17}}$ is less than -1 and the other ratio less than $\frac{1}{2}$.

3. Results

There are 52 days in the lunar phases 3 and 9 (or 15 and 21). The frequency of occurrence of the five types of L in these 52 days is as follows:

Type	Days	Percentage
Model L-day	1	2
Big L-day	4	8
Small L-day	1	2
Non-Uniform L-day	29	56
Inverse L-day	1	2

The frequencies are comprable to those obtained by Onwumechi-lli (1963).

A selection of the magnetograms for different types of L-effects, chosen by the above criteria, is shown in Fig. 3. For lunar phase 3, L is minimum around 10 hr and maximum around 17 hr LT and for lunar phase 9, L is maximum around 10 hr and minimum around 17 hr LT. These are indicated by arrows in the diagram.

Fig. 3A represents a model L-day where the observed L-effects are of the order as expected and the diurnal variation is symmetrical about its maximum. Fig. 3B and 3D are for big L-days in the lunar phase 9 and 3 respectively. As expected, in 3B the field around 10 hr is enhanced and a depression is clearly seen around 17 hr. The reverse is the case for Fig.3D, lunar phase of that day being 3. Non-uniform days are nume-rous. On many occasions they appear to be complicated by the effects of counterelectrojet, as can be seen from Figs. 3G and 3H. In the 52 days examined in the sample of 280 days, only one day is found to be small L-day (Fig. 3E). But this day, though an international quiet day, appears to be affected by disturbance. The disturbance effect is assumed to be averaged out in arriving at the mean for a given μ. On an individual day this effect exists and it is not corrected for. Use of the long series of extremely quiet day data from Alibag may bring further support for the existence of the variety of L-days. Example for an inverse L-effect is shown in Fig. 3J, where the expected L-effect is reversed at one of the hours. Around 10 hr the field is expected to decrease, whereas an increase is seen from the Fig. 3J. In some of the examples in Fig.3, the L-effect is not easily apparent. It must be noted that the definitions here are based on the proportionate contribution of L to the hourly departure and not on the absolute value of L. In particular, on a big L-day here the absolute value of L is not necessarily high but L claims to a much higher proportion of diurnal variation than would be expected. Hence this method is advantageous in indicating days with lunar effects always not clearly visible in the magnetograms.

4. Other L effects

L affects the daily range by its magnitude near noon: suppressing the range when L is in phase opposition and enhancing it when in phase. This is examined with the daily range, M_{max}, defined as the maximum hourly mean value for the day minus the pre-dawn mean of the hours 03, 04 and 05. Fig.4 shows the expected effect and the semi-monthly wave is

$$R_{max}(\mu) = 1.008 + .105 \sin(2\omega\mu + 199^{\circ}) \quad \text{- - - - -} \quad (6)$$

Thus the L field in its maximum phase may contribute about 11 per cent of the daily range, a figure comparable to that for Ibadan (Onwumechilli, 1963) and the phase angle is same as that for the 11 hr LT, because the maximum generally occurs near about that hour.

The diurnal variation in H may be expected to be symmetrical about the hour of its maximum, which is generally around 11 hr LT at stations under the equatorial electojet. However, it is not symmetrical more often and the asymmetry is attributed to lunar modulation by Gouin (1962). The effect of the L-field on the asymmetry of H at Trivandrum is examined with the index of asymmetry formulated by Onwumechilli given by the expression

$$A_s = \frac{H_{17} - H_{05}}{M_{max}}$$

where H_{05} and H_{17} are the mean hourly values of H at 05 and 17 hr LT. The asymmetry index, A_s, for all the available days are arranged according to the lunar phase, μ. The semi-monthly wave fitting the experimental points is shown in Fig. 4b and is given by

$$A_s(\mu) = 0.997 + .219 \sin(2\omega\mu + 23.0^{\circ})$$

As can be seen from the Fig. 4b the wave does not fit the experimental points quite well, but still is the highest contributing harmonic. Only about 22 per cent of the asymmetry appears to be accounted for by the lunar effects. Thus it may be surmised that lunar modulation is not the primary cause of asymmetry of the diurnal variation of the H field about its maximum around local noon.

References

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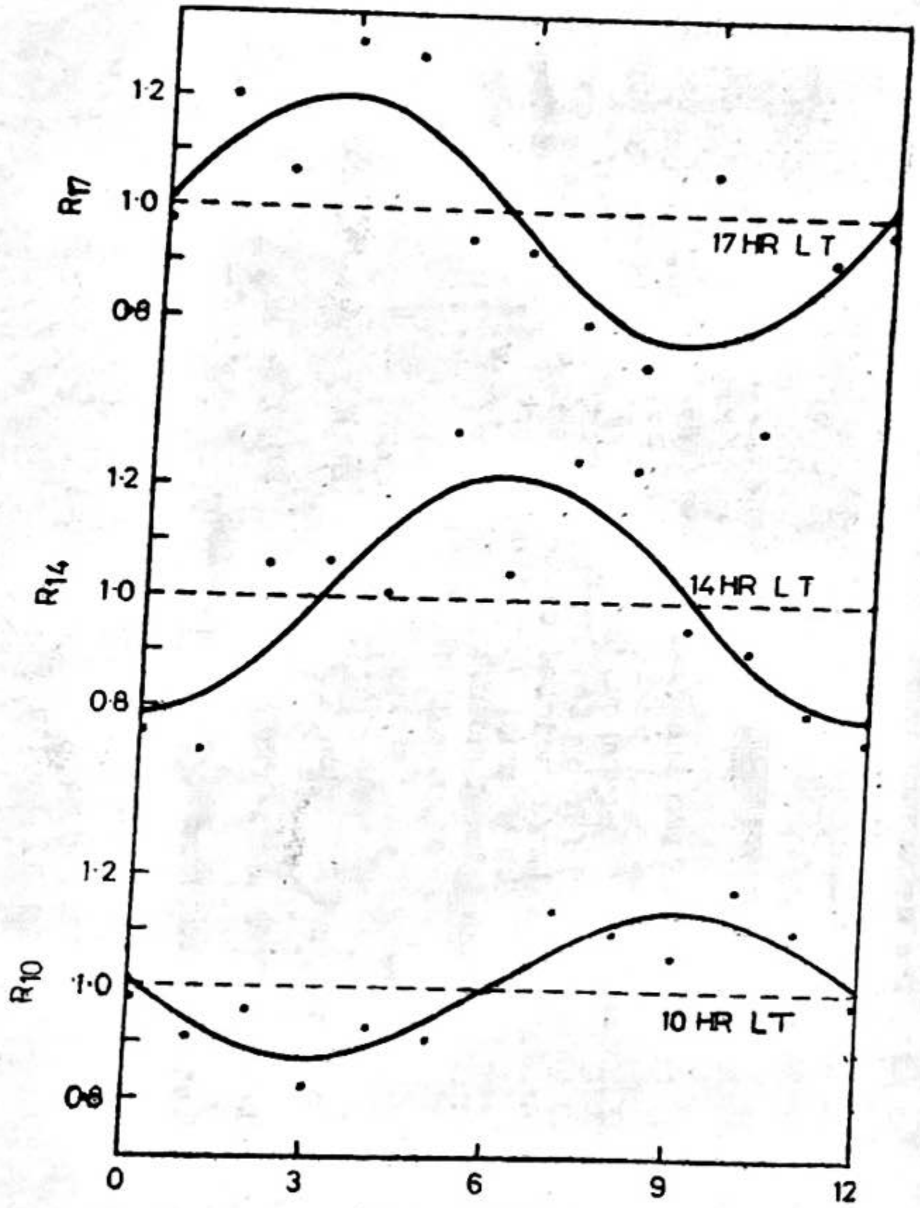

FIG. 1 VARIATION OF NORMALISED DEPARTURE (R) AT THREE SOLAR LOCAL HOURS WITH LUNAR PHASE

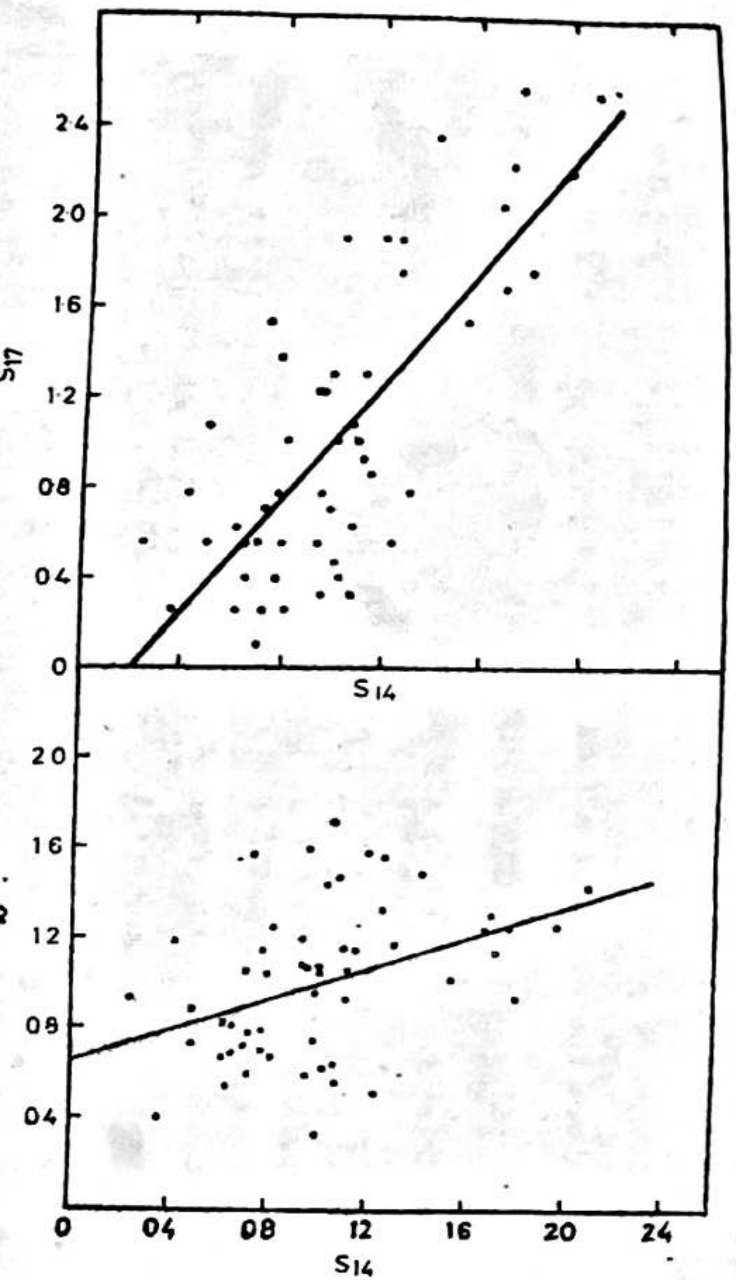

FIG. 2 REGRESSION OF NORMALIZED MONTHLY MEAN DEPARTURES S_{10} AND S_{17} AT 10 HR AND 17 HR LT RESPECTIVELY ON NORMALIZED MONTHLY MEAN DEPARTURE S_{14} AT 14 HR LT.

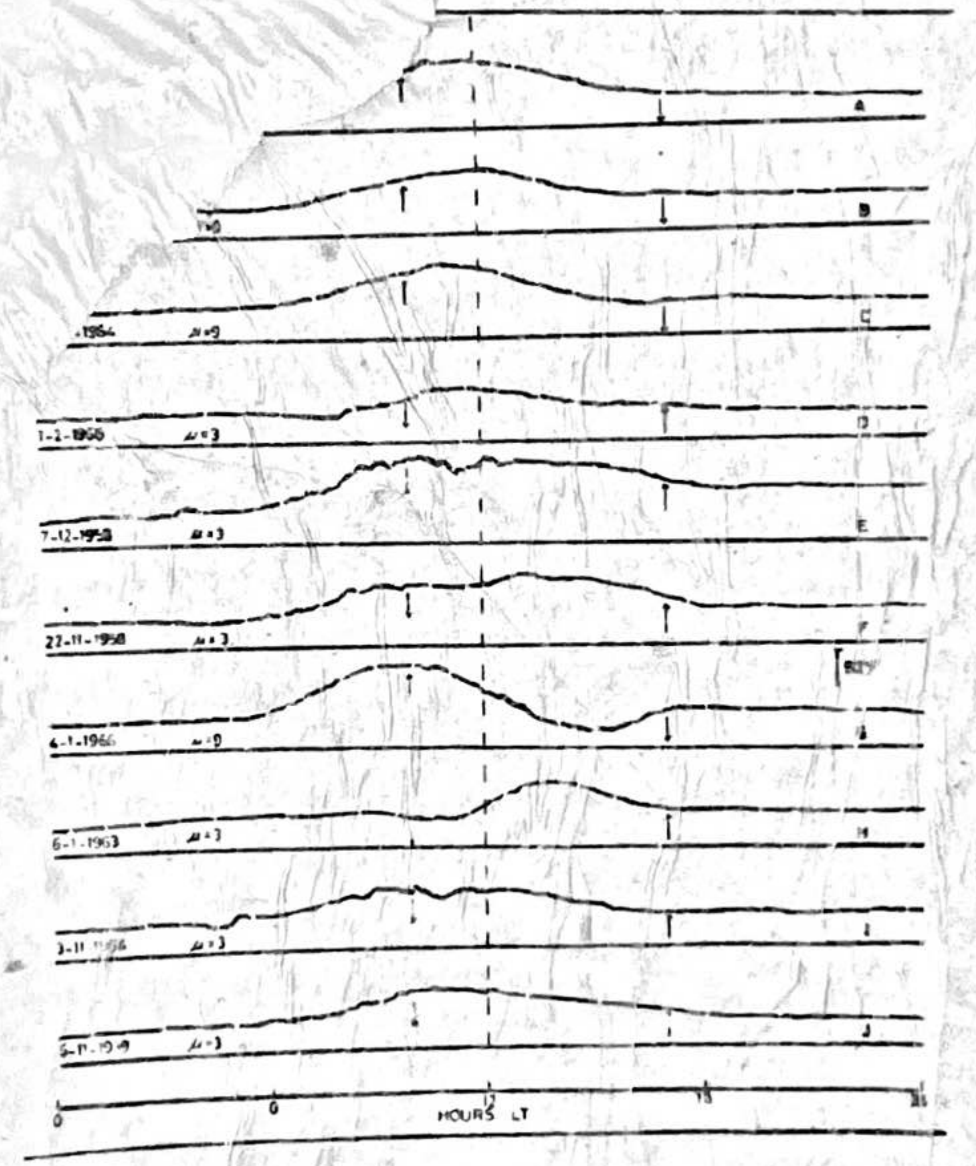

Figure 3

A selection of quiet-day magnetograms for the horizontal intensity, H, at Trivandrum in winter months of 1958-1971 for different types of L-day: A-Model L-day; B, C, D - Big L-days; E-Small L-day; F, G, H, I - Non-uniform L-days; J-Inverse L-day.

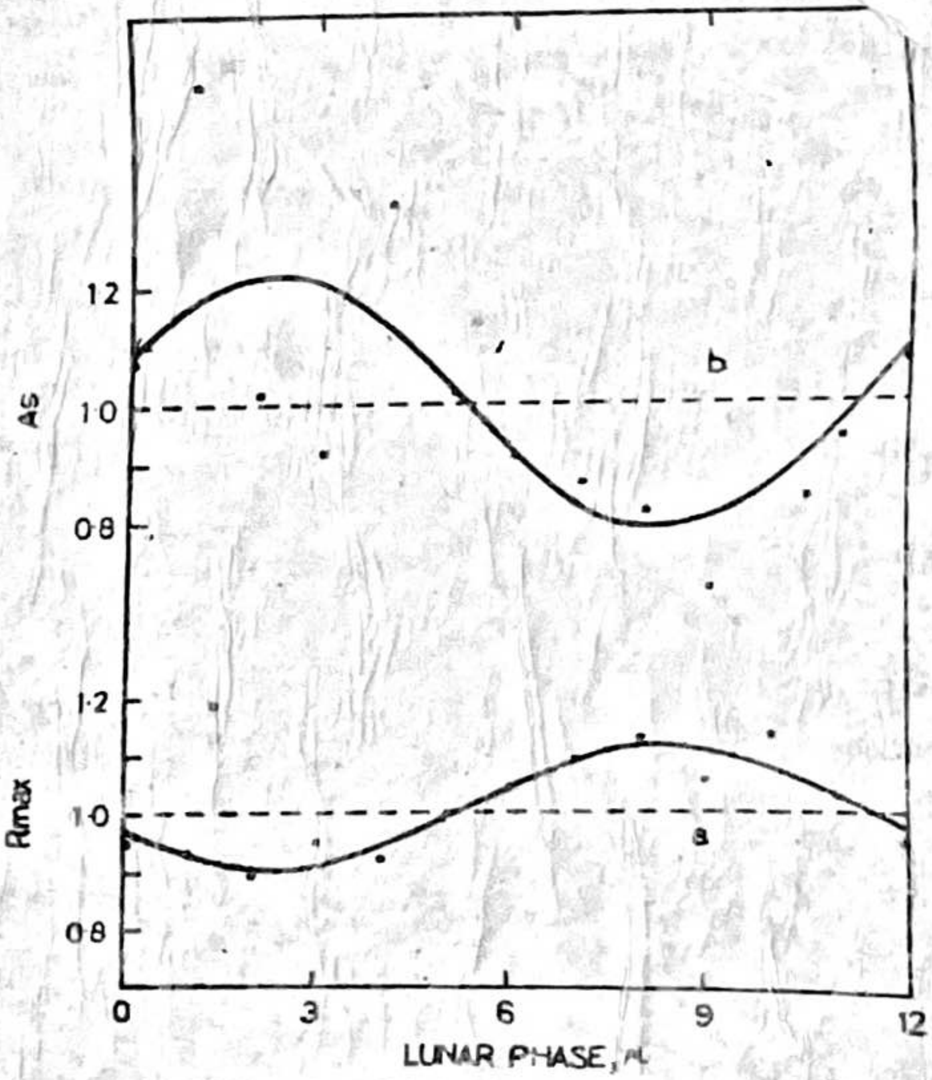

FIG-4 VARIATION OF NORMALIZED DAILY RANGE, Rmax (a) AND ASYMETRY As, (b) WITH LUNAR PHASE

Induction in Short-period Events in the Indian Peninsula

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Abstract—The amplitudes of sudden commencements, sudden impulses and bays were measured from magnetograms of all peninsular stations in an attempt to isolate the induced effect in each component. Anomalous amplitudes in Z are very marked for Annamalainagar and Trivandrum, the coastal stations under the electrojet. A comparison of the H and D amplitudes at the five observatories shows that even these elements have an anomalous part at Annamalainagar and Trivandrum. The Parkinson vectors at these two stations and Alibag point towards the nearest sea. The length of the vector for the inland station Hyderabad is comparatively small, but for Kodaikanal the vector is significantly large. Untiedt's linear regression method was employed to calculate the vectors. The results are compared with those of other workers.

INTRODUCTION

Transient variations over the Earth's magnetic field can be separated into the external part caused by ionospheric and extra-ionospheric currents and the internal part due to currents induced in turn in the earth's crust and mantle. The effect of the induced field is to add to the horizontal components (H and D) of the inducing field and oppose the vertical component. Thus, in a layered earth with radially varying conductivity, the vertical component is extinguished. But under normal circumstances, the crust and mantle have considerable lateral heterogeniety and this serves to augment the Z component so that conspicuous Z variation is the signature of lateral conductivity contrasts. The commonest of these contrasts is the land-sea or ocean-continent boundary. Of the five magnetic observatories in peninsular India, three lie on the coast. Night-time events were selected in order to obtain uniform H and D amplitudes. In Peru and Bolivia it has been shown by Schmucker et al. (1971) that for night-time bays there is very little change in amplitude over 37° of equatorial latitude. The over all variation in H is so small that the primary field can be assumed to have too small a spatial non-uniformity to make a significant contribution to Z.

ANALYSIS

In order to investigate induced variations in short period events, 40 to 50 events each of SSCs, SIs and bays occurring at night were selected. Only events recorded