Memoirs of the Kakioka Magnetic Observatory Vol. 17 No. 2 1978

Effect of the Oceanic Dynamo on the Lunar Daily Geomagnetic Variation at Kakioka, Memambetsu and Kanoya, Japan, 1958–1973

by

Masanori SHIRAKI

Abstract

The observed lunar daily geomagnetic variation at three Japanese observatories has been separated into parts of the ionospheric and oceanic dynamo origin, and it has become clear that the complicated features of the observed annual mean lunar daily variation at these observatories are due to oceanic dynamo effect. Moreover, it has been shown that the anomalous seasonal change of the observed lunar daily variation is somewhat revised by the removal of the oceanic dynamo effect, but its main cause cannot be attributed to oceanic dynamo effect. As to the sunspot cycle influence on the lunar daily variation, its result is much complicated even if the oceanic dynamo effect is excluded, and it is not yet evident whether the influence of the sunspot activity on the lunar daily variation is similar or not to that on the solar daily variation.

1. Introduction

It has been considered that the lunar daily geomagnetic variation is produced by the mechanism of an ionospheric dynamo (Chapman and Bartles, 1940; Matsushita, 1967). However, it was recently pointed out that the oceanic dynamo is another source of the lunar daily geomagnetic variation (Malin, 1969). Oceanic dynamo is powered by the tidal movement of the sea across the lines of force of the Earth's main magnetic field. The electric currents in the sea generated by this dynamo and the associated currents induced in the earth and in the ionosphere produce the geomagnetic variation.

In a recent paper (Shiraki, 1977, hereafter refered to as paper I) the present auther determined the lunar daily geomagnetic variation at three Japanese observatories. The interpretation of the lunar daily variation at these observatories was much complicated as compared with that of the solar daily variation at the same observatories which were simultaneously determined as a byproduct. In the paper I, most of the complicated results were interpreted by the effect of oceanic dynamo, based on the qualitative discussions.

Malin (1970) proposed a method to separate the observed lunar daily variation into parts of ionospheric and oceanic origin. In the present paper this method has been applied to the lunar daily variation at three Japanese observatories and the effect of oceanic dynamo has been quantitatively evaluated. Thereafter, the discussions given in the paper I have been reexamined.

2. Analysis

The lunar daily geomagnetic variation associated with the M_2 component in the tide generating potential is written by,

$$L=\Sigma L_n=\sum l_n \sin[2\tau+(n-2)t+\lambda_n] \quad (1)$$

where l_n and λ_n are the amplitude and phase of the n-th harmonic, respectively (Chapman and Bartels, 1940). t is the local mean solar time and τ is the local mean lunar time. By the method of Chapman and Miller (1940), the first four harmonics of Eq. (1) are usually computed from the observatory data.

According to Malin (1970), the oceanic dynamo is considered to be purely semidiurnal in period, therefore, only the second term of L is separated into the contribution of the ionospheric origin (L_I) and that of the oceanic origin (L_O). L_I and L_O are written by,

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

$$L_O=l_O \sin(2\tau+\lambda_O) \quad (3)$$

where (l_I, λ_I) and (l_O, λ_O) are the amplitude and phase of geomagnetic vectors due to ionospheric and oceanic dynamo origin, respectively. With an assumption that the contribution of the ionospheric dynamo to L is zero at local midnight, when the conductivity in the ionosphere is negligibly small as compared with that at local midday, the amplitude and phase of L_I and L_O are calculated by,

$$l_I \cos\lambda_I=-l_1\cos\lambda_1-l_3\cos\lambda_3-l_4\cos\lambda_4 \quad (4)$$

$$l_I \sin\lambda_I=-l_1\sin\lambda_1-l_3\sin\lambda_3-l_4\sin\lambda_4 \quad (5)$$

$$l_O \cos\lambda_O=l_1\cos\lambda_1+l_2\cos\lambda_2+l_3\cos\lambda_3+l_4\cos\lambda_4 \quad (6)$$

$$l_O \sin\lambda_O=l_1\sin\lambda_1+l_2\sin\lambda_2+l_3\sin\lambda_3+l_4\sin\lambda_4 \quad (7)$$

Moreover, if ρ_n denotes the vector probable error of the n-th harmonic, those of L_I and L_O are respectively given by,

$$\rho_I=(\rho_1^2+\rho_3^2+\rho_4^2)^{1/2} \quad (8)$$

$$\rho_O=(\rho_1^2+\rho_2^2+\rho_3^2+\rho_4^2)^{1/2} \quad (9)$$

Details of the derivation of these formulas are found in the paper of Malin (1970).

Above formulas are applied to the lunar daily geomagnetic variation at three Japanese observatories, Kakioka [36°14′N, 140°11′E], Memambetsu [43°55′N, 144°12′E] and Kanoya [31°25′N, 130°53′E]. In the paper I the lunar daily variation at these observatories were determined by the Chapman-Miller method using hourly mean values of magnetic declination D, horizontal intensity H and vertical intensity Z for the period 1958–1973. The separation of the ionospheric and oceanic dynamo parts is carried out for all results tabulated in Tables 2L, 3L and 4L in the paper I. Results of the separation are given in Table 1.

Table 1. The ionospheric and oceanic dynamo parts of the lunar geomagnetic semidiurnal harmonic. Unit of amplitude is 0.01 γ and that of phase is degree.

	D						H						Z					
	l_I	ρ_I	λ_I	l_O	ρ_O	λ_O	l_I	ρ_I	λ_I	l_O	ρ_O	λ_O	l_I	ρ_I	λ_I	l_O	ρ_O	λ_O
Kakioka																		
all	62	9	288	38	10	328	95	17	56	31	18	167	47	8	42	69	8	247
winter	76	11	56	82	13	347	169	27	98	45	30	255	68	11	201	33	13	265
equinox	80	21	300	17	22	282	69	27	8	53	30	139	71	12	41	85	14	250
summer	169	15	261	29	17	294	130	34	28	49	37	141	132	11	32	90	13	238
quiet	46	12	288	44	13	312	82	21	47	50	22	157	52	9	37	77	10	242
active	78	10	287	34	12	348	110	30	62	16	32	199	42	11	48	61	13	254
Memambetsu																		
all	64	12	301	23	13	15	105	18	43	48	19	181	13	4	3	33	4	282
winter	62	15	59	75	16	10	138	24	107	50	27	252	60	5	204	44	6	322
equinox	98	23	316	22	25	136	105	29	18	67	31	167	36	7	46	47	8	273
summer	146	18	267	14	20	312	177	34	16	70	37	153	67	7	360	28	8	236
quiet	46	14	312	22	15	333	97	19	35	65	21	169	19	6	10	35	7	274
active	83	13	295	34	16	40	115	32	48	34	34	202	8	6	347	31	7	290
Kanoya																		
all	79	8	280	34	9	12	78	16	85	34	17	203	50	9	22	60	10	185
winter	79	12	49	76	14	16	175	31	112	59	33	257	15	16	204	63	19	153
equinox	89	20	282	12	21	27	31	28	17	42	31	166	63	13	20	62	14	195
summer	208	17	261	18	19	342	84	35	48	42	39	171	100	13	22	68	14	204
quiet	66	11	269	36	13	356	60	22	76	51	24	185	49	11	23	63	12	190
active	94	11	287	34	13	28	97	29	91	25	33	241	51	11	19	57	13	179

The separation of L_I and L_O causes a considerable decrease in the precision. The vector probable error of L_I and L_O is roughly two times larger than that of the corresponding L_2. The harmonic L_I or L_O is considered to be significant at the five percent level when the amplitude exceeds 2.08 times its vector probable error (Leaton, Malin and Finch, 1962). Using this criterion all but 3 out of the 54 harmonics of L_I and 33 out of the 54 harmonics of L_O are significantly obtained.

3. Discussions

3.1. Annual mean variation

The ionospheric dynamo part (L_I) and oceanic dynamo part (L_O) of the annual mean lunar semidiurnal harmonic, which correspond to "all" in Table 1, are shown in Fig. 1 by harmonic dials, together with the total lunar semidiurnal harmonic (L_2).

The amplitude of L_O is generally much smaller for D and H than that of L_I. By the removal of the oceanic dynamo effect, the difference among three observatories, which was remarked in the paper I to be more notable for L_2 harmonic than those for L_1 or L_3 harmonic, is somewhat reduced for L_I harmonic in comparison with that for L_2 harmonic. However, as its reduction is not so large, it may be concluded that the major part of L_2 harmonic for D and H is the ionospheric dynamo origin. Therefore

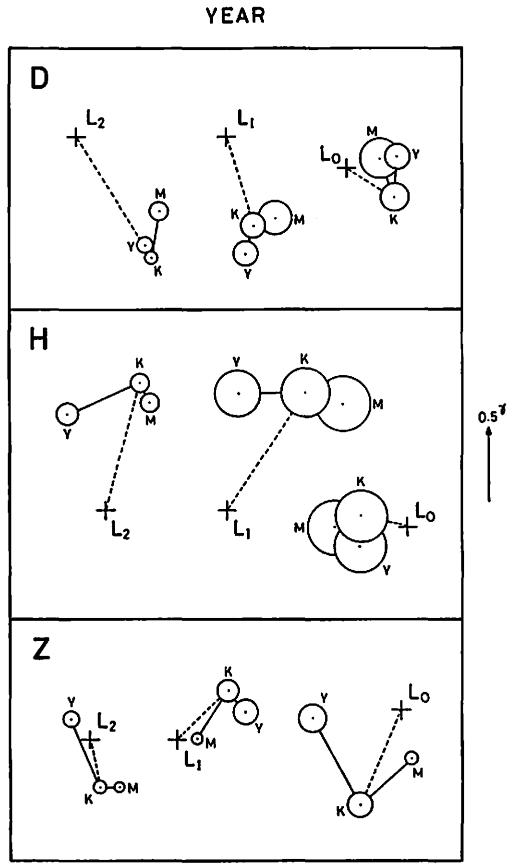

Fig. 1. Harmonic dials of L_2, L_I and L_O at Kakioka (K), Memambetsu (M) and Kanoya (Y) for D, H and Z. The dial vector is drawn only for Kakioka. Vectors for Memambetsu and Kanoya are indicated by their end points. The vector probable error circles are drawn at the end points of vectors.

the discussions in the paper I given for D and H are slightly changed for the ionospheric dynamo part of the lunar daily variation.

Not in accordance with D or H, it is clear that the oceanic dynamo effect for Z is remarkably large. The amplitude of $L_O(Z)$ is larger than that of $L_I(Z)$ for all observatories. And the vectors of $L_I(Z)$ and $L_O(Z)$ are rather in opposite direction at Kakioka and Kanoya. The complicated results of the observed lunar daily variation of Z, which were noted in the paper I, are clearly due to the oceanic dynamo effect. First, the main lunar harmonic of Z is not L_2 at Kakioka and Kanoya, but when only the ionospheric dynamo part (L_1, L_I, L_3, L_4) is considered, the main harmonic becomes L_I as being expected from the ionospheric dynamo theory. Secondly, the phase of L_2 at Kakioka does not lead those at Memambetsu and Kanoya being different from the phase of L_1 and L_3, and in the paper I it was suggested that for L_2 harmonic the oceanic dynamo part may conceal such a phase relation as seen for L_1 and L_3. Really, by the removal of the oceanic dynamo part, the phase of L_I harmonic at Kakioka leads those at Memambetsu and Kanoya similarly as L_1 and L_3 harmonics and also similarly as the harmonics of solar daily variation. This phenomenon for the phase is explained by the anomalous electrical conductivity distribution beneath central Japan (Rikitake, Yokoyama and Sato, 1956). On the other hand, looking at the phase relation of $L_O(Z)$, such a phenomenon is not seen for oceanic dynamo part; the phase of $L_O(Z)$ increases from Kanoya to Memambetsu with increasing latitude. This fact suggests that the oceanic dynamo part of the lunar daily geomagnetic variation is mainly caused by the dynamo currents in the sea and is little affected by the associated currents induced in the earth though the ionospheric dynamo part of the lunar daily variation are much affected by the induced currents in the earth. This fact may be consistent with the fact that the oceanic dynamo part is not so large for D and H and it is very large for Z.

3.2. Seasonal change

Seasonal mean harmonics obtained as M_2 component of the lunar daily geomagnetic variation have contributions of O_1 component, because the frequencies of the harmonic constituents of M_2 and O_1 components in the geomagnetic variation differ by an amount corresponding to only one cycle per year (Schneider, 1963; Winch, 1970). However, the contribution of O_1 component is ignored throughout the discussion in this section.

Fig. 2 illustrates by the harmonic dials the annual mean and seasonal mean harmonics of L_I and L_O at Kakioka, together with those of L_2. In the paper I it was found that the seasonal change of the lunar daily variation at Kakioka and the other two observatories is surprisingly anomalous as compared with that of the solar daily variation at the same observatories. Such an anomalous seasonal change is clearly seen in Fig. 2; the amplitude of L_2 harmonic is smallest at equinox for all elements and the phase difference of L_2 between winter and summer is very large.

By the removal of the oceanic dynamo part, the anomalous seasonal change of the amplitude is somewhat revised for D and Z but is rather amplified for H. And the seasonal change of the phase of L_I is essentially unchanged for D and H from that of L_2. However the phase of $L_I(Z)$ decreases from winter to summer similarly as the phase of L_I or L_2 of D and H, though the phase of $L_2(Z)$ reversely increases from winter to summer. The features of the seasonal change of L_I at Memambetsu and Kanoya are not appreciably different from those at Kakioka.

For the numerical comparison of the seasonal change of the ionospheric dynamo part of the lunar daily variation $L(I)$ with that of the solar daily variation S, the similar manner in the paper I is used here. As a measure of seasonal change the ratio of seasonal to annual mean ranges of $L(I)$ is calculated for each of three elements and three observatories. The range of $L(I)$ is defined here by,

$$R(L)=2(l_1+l_I+l_3+l_4) \tag{10}$$

The weighted mean ratios from three observatories are given in Table 2 together

KAKIOKA

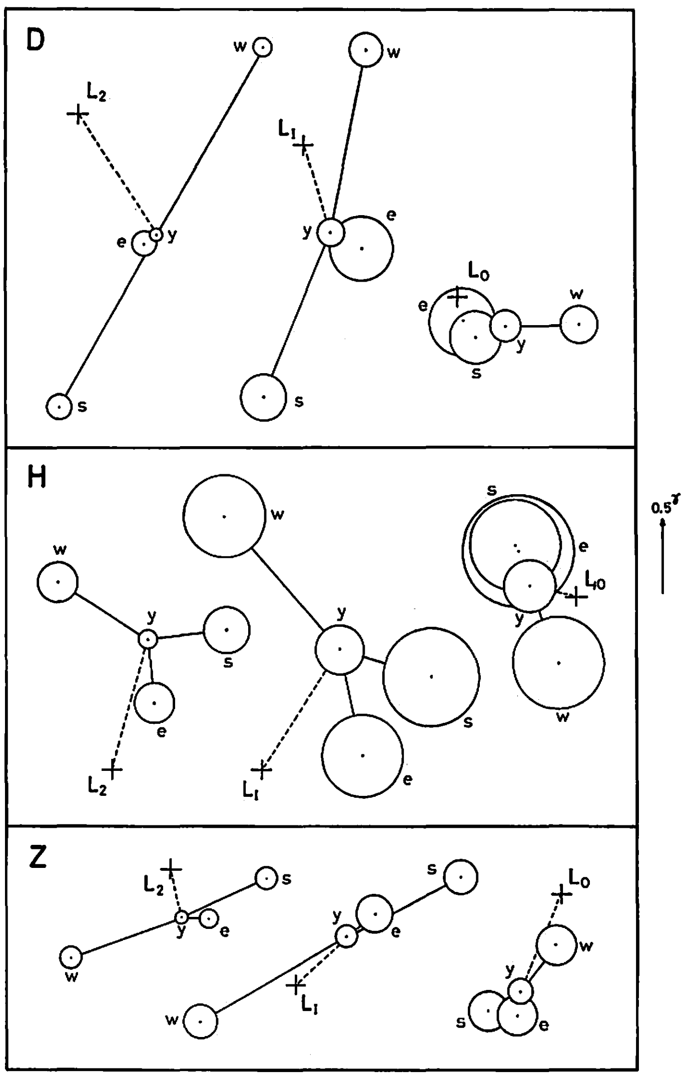

Fig. 2. Harmonic dials of L_2, L_I and L_O for the annual mean and seasonal mean harmonics at Kakioka for *D*, *H* and *Z*. The dial vector is drawn only for the annual mean harmonic, but not drawn for the seasonal mean harmonics; they are indicated only by their end points. The dial points *y* refer to the annual mean, those marked *w*, *e*, *s* to the winter, equinox and summer. The vector probable error circles are drawn at the end points of vectors.

Table 2. The weighted mean ratio from Kakioka, Memambetsu and Kanoya of seasonal to annual mean range of $L(I)$, $L(I+O)$ and S.

	D	H	Z	$D+H+Z$	$D+H$
winter/annual					
$L(I)$	1.15±0.05	1.58±0.08	1.33±0.08	1.28±0.04	1.27±0.04
$L(I+O)$	1.40±0.04	1.54±0.07	2.09±0.08	1.54±0.03	1.43±0.03
S	0.51	0.75	0.76	0.67	0.63
equinox/annual					
$L(I)$	1.42±0.07	0.80±0.07	1.53±0.08	1.23±0.04	1.11±0.05
$L(I+O)$	1.31±0.05	0.74±0.06	1.37±0.06	1.16±0.03	1.08±0.04
S	1.12	1.38	1.07	1.19	1.25
summer/annual					
$L(I)$	2.31±0.08	1.39±0.09	2.21±0.10	1.98±0.05	1.90±0.06
$L(I+O)$	2.19±0.05	1.38±0.08	2.08±0.08	1.98±0.04	1.96±0.04
S	1.50	1.25	1.27	1.34	1.38

with the result for the lunar daily variation not removed the oceanic dynamo effect $L(I+O)$ and the result for S which are given in Tables 6L and 6S in the paper I. The ratios of $L(I)$ at equinox and summer are nearly equal to those for $L(I+O)$. On the other hand, at winter, the ratios of $L(I)$ of D and Z and also the mean ratio of $L(I)$ from all elements or from D and H are smaller than those of $L(I+O)$. Consequently the anomalous seasonal change, which is mainly seen as the large ratio at winter, is somewhat revised for $L(I)$ (about 20%), but is very different from the seasonal change of S as yet. Therefore it is concluded that the main cause of the anomalous seasonal change of the lunar daily variation at three Japanese observatories cannot be attributed to the effect of oceanic dynamo.

On the other hand, the seasonal change of L_O is also noteworthy. In Fig. 2 the vector of L_O at winter is very different from those at equinox and summer for all elements. Such a feature is common to all three observatories. The contribution of O_1 component to the seasonal change of M_2 component, which is ignored throughout discussions, may be considerable as one of the causes. However, its real explanation of the cause is a future problem.

3.3. Sunspot cycle influence

Fig. 3 illustrates by the harmonic dials the sunspot cycle influence on the annual mean harmonics of L_I and L_O at Kakioka together with those of L_2. The amplitude of L_I increases for D and H and decreases for Z with increasing sunspot number. The amplitude of L_O decreases for all elements from quiet group to active one. The same statements are also true at Memambetsu and Kanoya except for two cases ($L_I(Z)$ at Kanoya and $L_O(D)$ at Memambetsu).

The sunspot cycle influence are numerically evaluated in a similar manner as the paper I using the Wolf's formula,

$$r=A(1+mR) \tag{11}$$

where r is the amplitude of harmonic or the range of daily variation and R is the sunspot number. The values of m for the amplitudes of L_I and L_O and the range of $L(I)$ are calculated for each of three elements and three observatories. And the weighted mean values from three observatory are given in Table 3 together with those for L_2, $L(I+O)$ and S obtained in the paper I. It is noted that the m values of L_I and $L(I)$ for Z are negative and are very different from those for D or H.

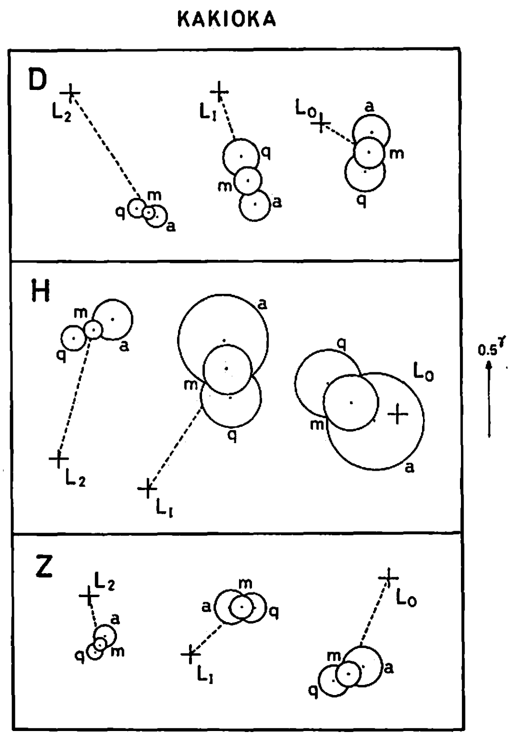

Fig. 3. Harmonic dials of L_2, L_I and L_O for the annual mean harmonics at Kakioka with respect to the sunspot actiyity for D, H and Z. The points marked q and a represent the harmonics determined from groups of sunspot active years and of sunspot quiet years, respectively. The point marked m represents harmonic derived from group "all". The dial vector is drawn only for the group "all", not for quiet or active group. They are indicated only by their end points. The vector probable error circles are drawn at the end points of the vectors.

Table 3. The weighted mean values of $10^4 m$ from Kakioka, Memambetsu and Kanoya

	D	H	Z	$D+H+Z$	$D+H$
L_I	84 ± 38	40 ± 40	-21 ± 22	12 ± 17	63 ± 27
$L(I)$	62 ± 10	59 ± 17	-5 ± 8	26 ± 6	62 ± 9
L_2	23 ± 10	30 ± 17	-11 ± 12	13 ± 7	25 ± 8
$L(I+O)$	39 ± 6	59 ± 13	$-1+7$	26 ± 5	42 ± 6
S	52	62	72	62	57
L_o	-15 ± 37	-54 ± 44	-18 ± 17	-22 ± 15	-31 ± 28

As far as the mean values from D and H are concerned, the m values of L_I and $L(I)$ are much larger than those of L_2 and $L(I+O)$, respectively. It is clear that the m value of the observed lunar daily variation is much reduced due to the effect of the oceanic dynamo as suggested in the paper I. By the removal of the oceanic dynamo part, the value of L_I shows the median value of L_1 (74±52) and L_3 (55±12) and they decrease with increasing harmonics similarly as the case of S. Moreover the m value of $L(I)$ is close to that of S. Therefore it may be concluded that, when the effect of the oceanic dynamo is removed, the lunar daily variation is similarly affected by the sunspot activity to the solar daily variation, though this conclusion is obtained at present only from D and H.

On the other hand, due to the negative m value for Z, the mean values of L_I and $L(I)$ from all elements are not so different from those of L_2 and are much smaller than that of S. Therefore, contrary to the conclusion from D and H, the conclusion from all elements is that the lunar daily variation is affected much less by the sunspot activity than the solar daily variation, even if the oceanic effect is excluded.

It is not yet known which of these conclusions is true. It should be clarified why the m value for Z is very different from those for D and H. Considering the results of the section 3.1. the effect of the oceanic dynamo seems to be well separated for Z. However, as the method of separation is not perfect because of some assumptions, the overestimate or underestimate of oceanic dynamo effect may be considerable as one of causes. Further improvement of the method and its application to the observed lunar daily variations as many as possible are very desirable.

4. Conclusions

Applying the method of Malin (1970), the observed lunar daily geomagnetic variation at three Japanese observatories has been separated into parts of ionospheric and oceanic dynamo origin, and it is found that the complicated features of the observed annual mean lunar daily variation at these observatories, especially for Z, are due to the oceanic dynamo effect. Moreover, it becomes clear that the anomalous seasonal change of the observed lunar daily variation is somewhat revised by the removal of the oceanic dynamo effect, but its main cause cannot be attributed to the oceanic dynamo effect. As to the sunspot cycle influence on the lunar daily variation, its result from D and H and that from all elements are quite unlike, even if the oceanic dynamo effect is excluded, and it is not yet evident whether the influence of the sunspot activity on the lunar daily variation is similar to or not to that on the solar daily variation. In general, the observed lunar daily variation at three Japanese observatories seems to be well separated into the ionospheric and oceanic dynamo parts, but further improvement of the method is clearly needed for the more satisfactory and better separation of the ionospheric and oceanic dynamo origin.

Acknowledgements

The author thanks Prof. H. Maeda of Kyoto University for his interest in this study and his critical reading of the manuscript. Thanks are also due to Dr. M. Kawamura, the Director of the Kakioka Magnetic Observatory, for his encouragement.

References

Chapman, S. and J. Bartels (1940): Geomagnetism. Oxford Univ. Press (Clarendon), London and New York.

Chapman, S. and J. C. Miller (1940): The Statistical Determination of Lunar Daily Variation in Geomagnetic and Meteorological Elements, Month. Not. Roy. Astr. Soc., Geophys. Suppl. **4**, 649-669.

Leaton, B. R., S. R. C. Malin, and H. F. Finch (1962): The Solar and Luni-Solar Daily Variation of the Geomagnetic Field at Greenwich and Abinger, 1916-1957. Roy. Obs. Bull. London, No. 63, D273-D318.

Malin, S. R. C. (1969): The Effect of the Sea on Lunar Variations of the Vertical Component of the Geomagnetic Field. Planet. Space Sci., **17**, 487-490.

Malin, S. R. C. (1970): Separation of Lunar Daily Geomagnetic Variations into Parts of Ionospheric and Oceanic Origin. Geophys. J. Roy. Astr. Soc., **21**, 447-455.

Matsushita, S. (1967): Solar Quiet and Lunar Daily Variation Fields. Physics of Geomagnetic Phenomena. Academic Press, New York and London, 301-424.

Rikitake, T., I. Yokoyama, and S. Sato (1956): Anomaly of Geomagnetic Sq Variation in Japan and Its Relation to the Subterranean Structure. Bull. Earthquake Res. Inst. Tokyo Univ., **34**, 197-235.

Schneider, O. (1963): A Generalization of the Phase-Law of Lunar Geomagnetic Tides. Nature, **199**, 548-550.

Shiraki, M. (1977): Solar and Lunar Daily Geomagnetic Variations at Kakioka, Memambetsu and Kanoya, Japan, 1958-1973. Geophys. Mag., **38**, 37-70.

Winch, D. E. (1970): Geomagnetic Lunar Tides, O_1 Component. J. Geomag. Geoelectr. **22**, 319-328.

柿岡，女満別および鹿屋の地磁気太陰日変化に及ぼす海洋ダイナモ効果

白 木 正 規

概 要

先の論文 (Shraki, 1977) で得られたわれわれの観測所の太陰日変化を電離層ダイナモが起因の変化と海洋ダイナモが起因の変化に分離し，先の論文の議論を調べなおした。