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# Characteristics of Gravity Spectra in the 1–8 Hour Band

By

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**Abstract**

Characteristics of gravity spectra in the 1–8 hour band were examined by employing data obtained from two superconducting gravity meters in Kyoto, Japan. Spectral analyses were executed by applying FFT to the gravity data. Windowed segments in time series were successively shifted and the time variations of gravity spectra were investigated. Contour maps for amplitudes of gravity spectra were drawn on a time-period diagram. Such contour maps enabled not only the period dependence of gravity signals but also the time variation of gravity spectra to be visually understood. A result derived from one of the gravity meters was variation of the spectral level at some periods such as 8, 6, 5, 4 and 3–1 hours. Some of them might have been caused by insufficient removal of atmospheric pressure effect, but excitations of gravity spectra without relations with atmospheric pressure changes were also recognized. Some of these excitations might be caused by oscillations in deep interior of the earth. In a result obtained from the other gravity meter, many spectral peaks might have been derived from instrumental noised. The excitations of gravity spectra were then compared with sequence of large earthquakes. However, correlation between them was not so clarified.

## 1. Introduction

Gravity meters heretofore in use have been able to detect gravity changes in broad bands from earth tides longer than 8 hours to free oscillations of the earth shorter than 1 hour. As the former has an amplitude of a few hundreds microgals and the latter has that as large as a few microgals just after a great earthquake, gravity changes in such bands have been examined in detail so far. Meanwhile, there have been few studies in the 1–8 hour band, in which no significant signals in gravity changes were expected. This band, however, has begun to be given attention from viewpoints such as searching the interior of the earth and so on.

Mansinha *et al.* (1990) reported some characteristics of gravity spectra by employing data from a superconducting gravity meter in Brussels. They suggested that excitations of gravity spectra at about 8 and 4.8 hours might be associated with an earthquake sequence. On the other hand, Linkov *et al.* (1991) analyzed data from horizontal seismometers, and reported that spectra in the 1–5 hour band had been excited just before great earthquakes such as the Spitak (M=7.0; 1988) and Loma-

Prieto (M=7.1 ; 1989) earthquakes.

From a theoretical point of view, some of eigen periods in core modes were introduced in the band of about 4 hours by numerical calculations carried out for a realistic earth model (Smylie *et al.* 1992). These core modes consisted of the translational oscillation of the inner core as well as the resulting fluid movement in the outer core. Further, Smylie (1992) compared the observed core modes with those theoretically estimated for different earth models, and indicated that the periods of those modes were distributed in the band from 2.6 to 4.1 hours for both observed and calculated results. However, there are also critical views for those observations of core modes.

On the other hand, Melchior *et al.* (1988) analyzed data from a superconducting gravity meter in Brussels, and detected the decaying spectra identified as a core mode at about 13 hours. Its amplitude was 10 nanogals level. On the analogy of this result, the core modes with periods of about 4 hours, which were identified by Smylie (1992), might have a similar order of amplitudes.

As mentioned above, there may be some oscillations in the 1–8 hour band excited by large earthquakes and so on. However, the amplitudes of such oscillations are considered to be very small. Thus, if we want to search for signals in the 1–8 hour band, continuous observation of gravity should be performed at the precision of nanogal level. A superconducting gravity meter satisfies this necessity.

In the present study, we examined characteristics of long-term variation in gravity changes in the 1–8 hour band by employing gravity data obtained from two superconducting gravity meters installed in Kyoto, Japan. Contour maps for the spectral amplitudes were drawn on a diagram of time in the abscissa and period in the ordinate. Such contour maps enabled us to visually understand not only the period dependence of gravity signals but also the time variation of gravity spectra. Such a study will contribute to investigate the earth interior such as searching for core modes at about 4 hours.

## 2. Observations

Two superconducting gravity meters (GWR Model TT-70: Nos. 8 and 9) were installed at the basement of a building in Kyoto University, Kyoto, Japan. As shown in Fig. 1, these meters were installed side by side, each turning 90 degrees on the same base in the observation room. Simultaneous observations of gravity changes with those meters have been carried on by employing pen-recorders since March 1988. In addition to the analog recordings, digital recordings by TEAC DR-F1 recorders have been taken since September 1989. In routine observation, the sequence of eleven digital data at the interval of 1 second was successively recorded every 10 minutes, and then the total eleven data were averaged. The gravity data thus obtained were employed for analyses as the 10-min. sampling data. Resolution of the recordings was about 20 nanogals. Unfortunately, observation by gravity meter No. 8 was interrupted for about one year from October 1989 to October 1990 due to the repair of the gravity meter's sensor. Moreover, the output from gravity meter No. 8 has drifted over the

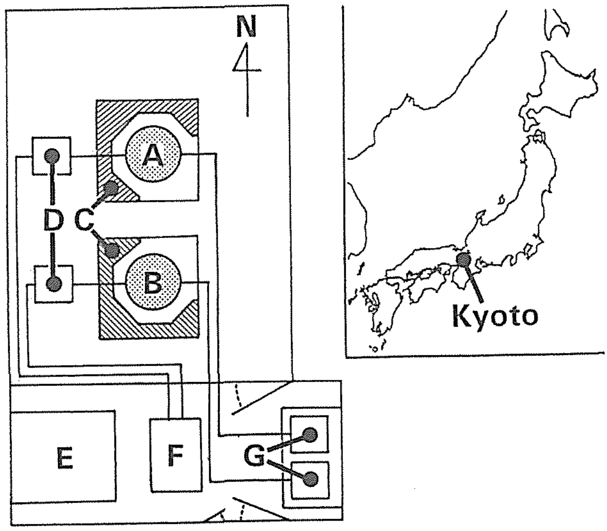


Fig. 1. Location of the observation site and arrangement of two superconducting gravity meters at Kyoto University in Kyoto, Japan. A: Superconducting gravity meter 009 (No. 9), B: Superconducting gravity meter 008 (No. 8), C: Supporting piers, D: Electronics, E: Air conditioner, F: Recording system, G: Compressors.

maximum range of the digital recorder since November 1991, so that the digital data from gravity meter No. 8 have not been obtained since then. Two barometers were attached to both gravity meters, and digital recordings of atmospheric pressure changes have been performed as 10-min. samplings in parallel with the observations of gravity changes. During the repair of gravity meter No. 8, observation by barometer No. 8 was also interrupted.

## 3. Precaution of Data Analyses

Outputs from the gravity meters have been obtained through the 50-sec. low pass analog filters which were included in gravity meter systems themselves. The routine data of 10-min. samplings could not be employed to search for signals in the 1–8 hour band without consideration about the effect of aliasing on analyses. We thus obtained 10-sec. sampling data from gravity meter No. 9 during the period from November 1991 to November 1992 by using an 8-digit digital voltmeter together with a personal computer (NEC PC9801F). Resolution of the recording was about 0.01 nanogals. As the low pass filter of 50 seconds had provided gains less than −50 dB at 20 seconds, 10-sec. sampling data were almost free from aliasing. The 10-sec. sampling data were passed through a low pass digital filter of 20 minutes and then sampled every 10 minutes. A new data set of 10-min. samplings as well as the 10-min. sampling data routinely obtained from gravity meter No. 9 were then passed through high pass digital filters of 48 hours after the removal of tidal components and atmospheric pressure effects. Using these data sets, spectral analyses were performed with FFT (Fast

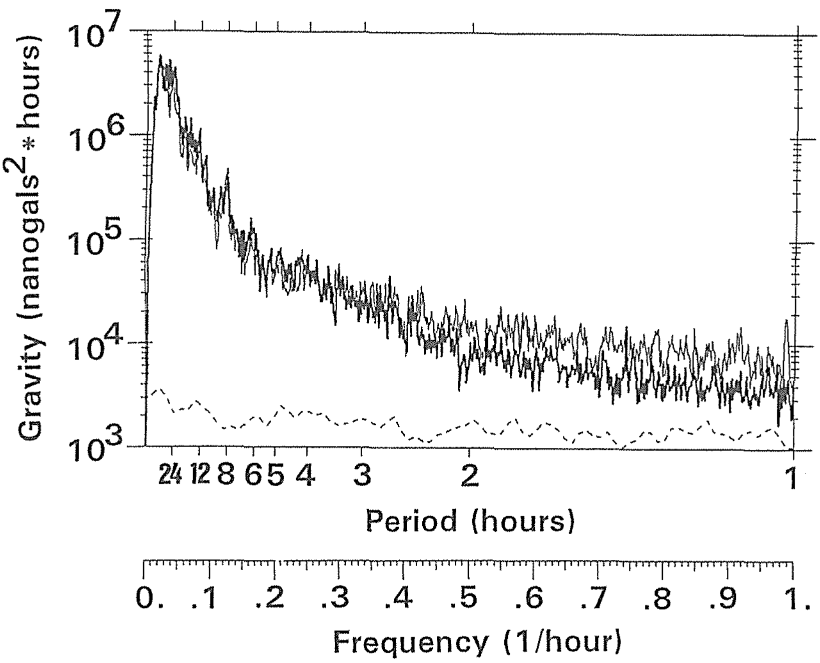


Fig. 2. Influences of aliasing on gravity spectra averaged in the period from November 1991 to November 1992. Heavy and light lines show the gravity spectra obtained from the data free from aliasing (10-sec. samplings) and contaminated with it (10-min. samplings), respectively. Broken line shows levels enhanced by aliasing with employing original 10-sec. sampling data.

Fourier Transform). In detail, the time series were divided into some segments, each of which consisted of 8,192 data (about 56.9 days) and was shifted by 25% of its own value (about 14.2 days) from the preceding one. Each segment was tapered with a cosine window. Spectra obtained for the segments were averaged. Two sets of averaged gravity spectra thus obtained are shown in Fig. 2, in which heavy and light lines correspond to spectra obtained from the sampling data of 10 seconds and 10 minutes, respectively. The latter spectrum might be affected by aliasing, while the former one was free from aliasing. Therefore, discrepancies between two spectra should be mainly caused by aliasing. Meanwhile, influences on spectra by aliasing were also numerically estimated from spectra in periods shorter than 20 minutes, which were obtained from original 10-sec. sampling data. The results are shown as a broken line in Fig. 2. In this figure, enhancements by aliasing were almost constant through the band of 1–8 hours to be estimated approximately $2\times10^3$ nanogals$^2$*hours.

As shown in Fig. 2, discrepancies between two spectra shown as heavy and light lines were very small in periods longer than 3 hours, and the spectral levels in these periods were higher than 10 times of the enhancements by aliasing. Therefore, we considered that the influences of aliasing were able to be ignored at least in the 3–8 hour band.

On the other hand, the spectral levels of 10-min. sampling data were in some

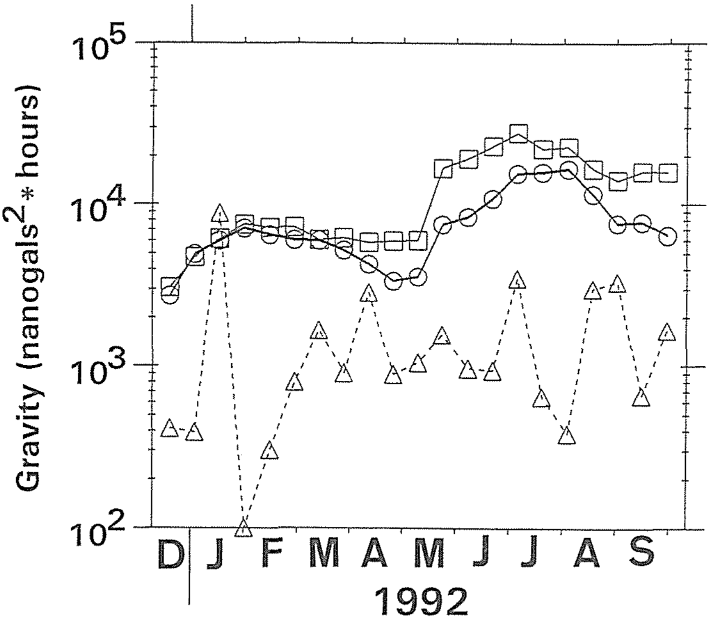


Fig. 3. Influences of aliasing on time variations of gravity spectra in 1–3 hour band. Heavy (○) and light (□) lines show the gravity spectra obtained from the data free from aliasing and those contaminated with it, respectively. Broken line (△) shows levels enhanced by aliasing.

degrees higher than those of 10-sec. sampling data in the 1–3 hour band, and these discrepancies might be caused by aliasing. Fig. 3 displays variations of spectral levels, each of which was calculated for a segment of 8,192 data and then averaged all over the 1–3 hour band. Heavy and light lines correspond to the sampling data of 10 seconds and 10 minutes, respectively. Variation of enhancements due to aliasing is also shown as a broken line in Fig. 3. We can recognize from this figure that variations of spectral levels of two data sets had a similar tendency in the 1–3 hour band and enhancements of spectral levels due to aliasing were almost lower than 50% of signal levels. Therefore, we considered that the influence of aliasing in the 1–3 hour band was not so serious in the present investigation to search for variations of spectral levels.

Consequently, 10-min. sampling data of gravity can be used to search for signals in the 1–8 hour band. We, thus, employed the 10-min. sampling data of both gravity and atmospheric pressure for the present analyses. Tidal components in gravity and atmospheric pressure were estimated by applying 'BAYTAP-G' (Bayesian Tidal Analysis Program-Grouping Model: Ishiguro *et al.*, 1984). These tidal components contained diurnal and semidiurnal tides as well as $M_3$ constituent. They were firstly removed from the original data. Linear drifts in the gravity data were estimated to be about 240 and 100 microgals/year for the gravity meters Nos. 8 and 9, respectively, and these drifts were removed. Spikes caused by earthquakes could distort spectra in the 1–8 hour band, so that they were also removed. As for these data, we executed a linear interpolation. The time series of 10-min. samplings thus obtained are shown in Fig. 4

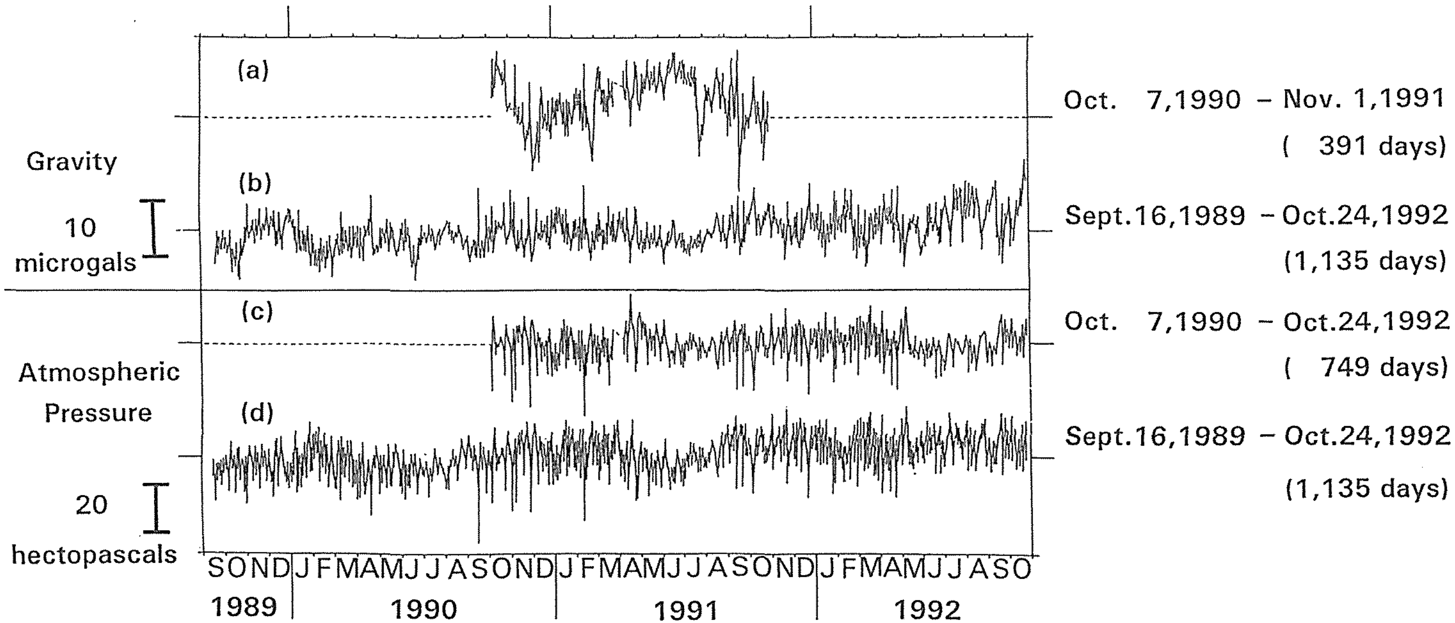


Fig. 4. Time series of gravity and atmospheric pressure after the removal of the major tidal components and linear drifts. The period of analyses for each data is shown at the right side of its figure. Broken lines indicate the interrupted intervals of observations. (a) Gravity data (No. 8), (b) Gravity data (No. 9), (c) Atmospheric pressure data (No. 8), (c) Atmospheric pressure data (No. 9).

together with the periods of analyses.

## 4. Influences of Atmospheric Pressure Changes on Gravity Observations

Using the time series of 10-min. samplings shown in Fig. 4, spectral analyses were performed with FFT. The time series were passed through a high pass filter of 48 hours and divided into some segments, each of which consisted of 16,384 data (about 113.8 days) and was shifted by 25% of its own value (about 28.4 days) from the preceding one. Each segment was tapered with a cosine window. Spectra obtained for the segments were averaged, and the spectral features of gravity and atmospheric pressure over the whole period of analyses were examined. The results are shown in Fig. 5.

Although spectral peaks corresponding to tidal components were almost removed from original data, there remained some significant peaks in the 1–8 hour band on both the spectra of gravity and atmospheric pressure (Fig. 5). These peaks were existing at 8.0, 6.0, 4.8, 4.0, 3.4, 3.0, and 2.7 hours, though signal levels at the last two periods were considerably low. It was supposed that these peaks in gravity spectra had been largely derived from atmospheric pressure changes. In the case of the spectrum obtained from gravity meter No. 8, there were several high peaks besides the periods mentioned above. The spectral peaks of gravity meter No. 8 were wide spread and much higher than those from No. 9. One of the reasons to be considered was that the spectral energy might focus on those particular bands due to changes of instrumental and electronic factors of gravity meter No. 8 itself.

Noise levels of the atmospheric pressure spectra in the 1–8 hour band were $10^{-2}-5\times10^{-1}$ and $4\times10^{-1}-8\times10^{-1}$ hectopascals$^2$*hours for barometers Nos. 8 and 9, respectively. When the data from barometer No. 9 were employed for reduction of atmospheric pressure effect, noise levels in gravity were enhanced by about $10^4$ nanogals$^2$*hours in periods shorter than 3 hours. On the contrary, reduction with the data from barometer No. 8 did not enhance noise levels in gravity. Thus, the data from barometer No. 8 were suitable for the reduction of atmospheric pressure effect. However, those from barometer No. 9 were also employed for the reduction during the interrupted interval (before October 1990) of observation with barometer No. 8. Reduction of atmospheric pressure effect was executed by employing the least squares method. Fig. 6 displays residual gravity changes after removal of atmospheric pressure effect. In this figure, (a), (b) and (c) are the gravity changes of Nos. 8, 9 and 9, which were obtained by executing the reduction with the atmospheric pressure data of Nos. 8, 9 and 8, respectively. By employing such gravity data, averaged spectrum over each period of analyses was obtained with the same method as that applied to obtain curves in Fig. 5. The results are shown in Fig. 7, in which (a), (b) and (c) correspond to the data shown as (a), (b) and (c) in Fig. 6, respectively.

In Fig. 7(a), the gravity spectrum of No. 8 is not so much improved as compared with that of Fig. 5(a), because large spectral peaks still remained at about 12, 8, 6, 5 and 4 hours. However, there are not so large spectral peaks in the gravity spectra of No. 9 shown in Figs. 7(b) and 7(c) except at 8 hours. Thus, apparent spectral peaks of No. 8

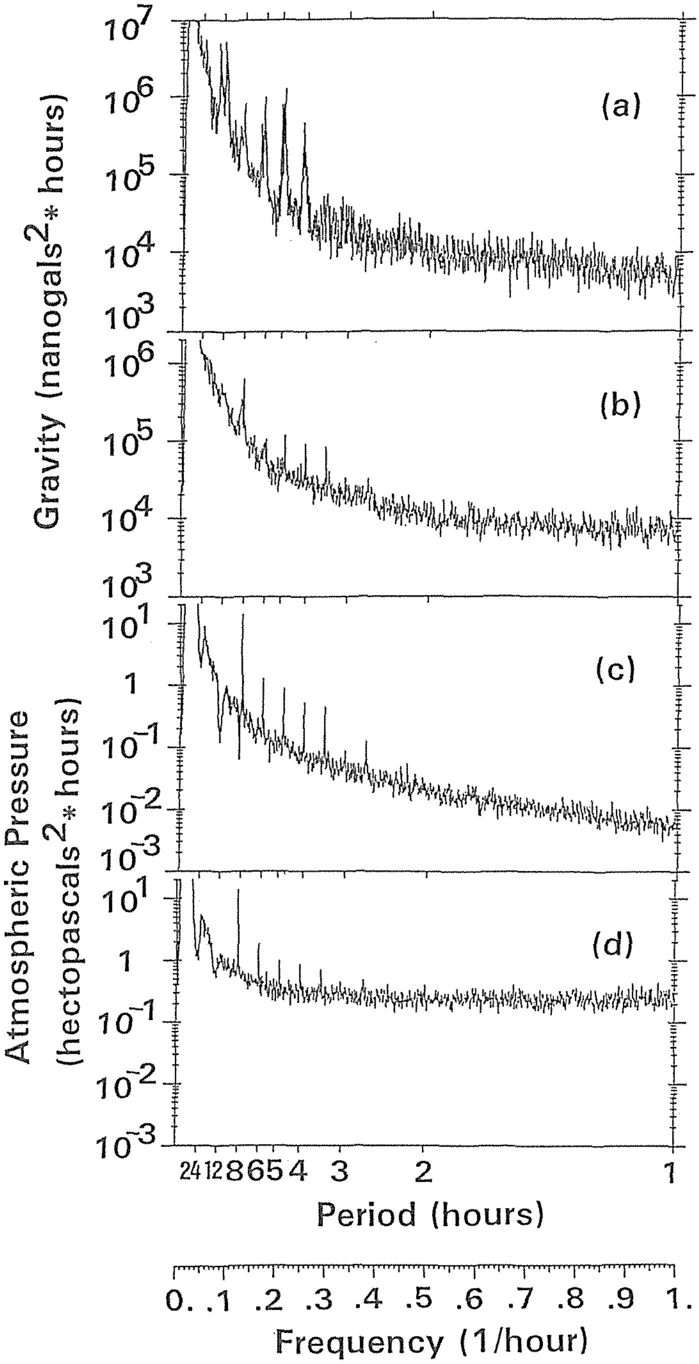


Fig. 5. Spectra obtained from the corresponding data of Fig. 4.

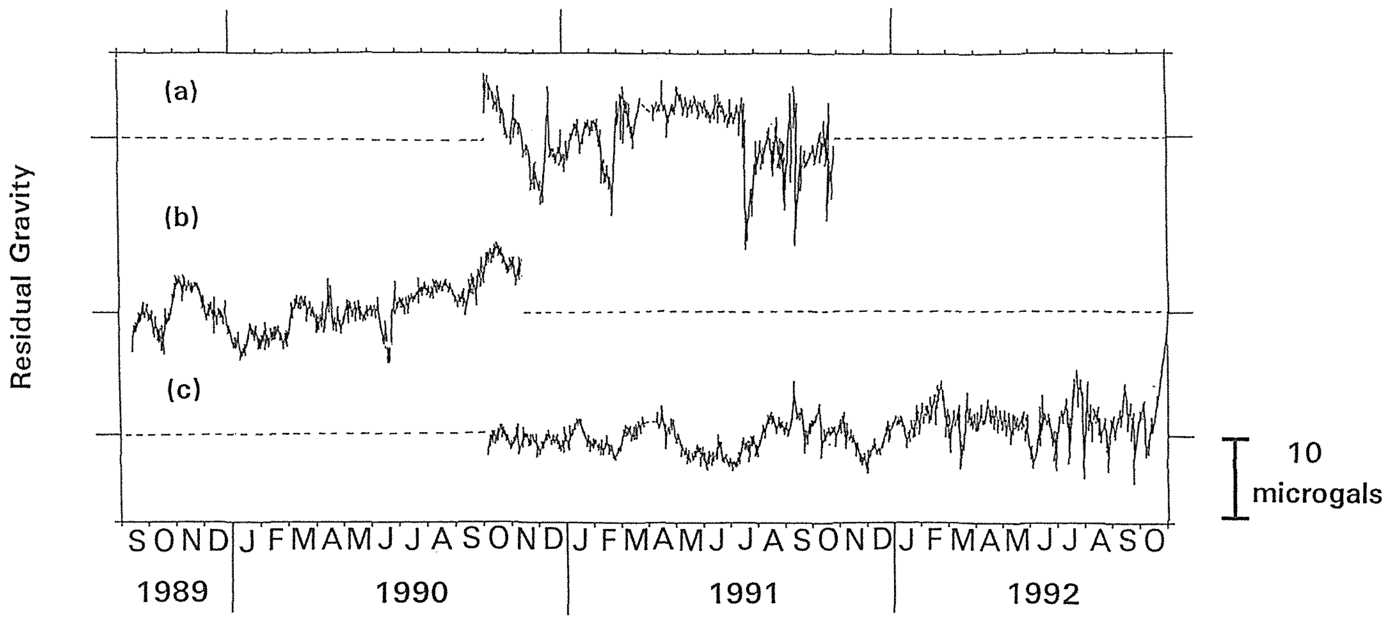


Fig. 6. Time series of gravity after the removal of atmospheric pressure effect. Broken lines indicate time intervals with no data, or those not involved in the present analyses. (a) No. 8 : After the reduction employing the atmospheric pressure data of No. 8, (b) No. 9 : After the reduction employing the atmospheric pressure data of No. 9, (c) No. 9 : After the reduction employing the atmospheric pressure data of No. 8

might have been caused by the instrumental noises of gravity meter No. 8 itself. Noise levels of gravity meter No. 8 in the 1–8 hour band were $10^4$–$10^5$ nanogals$^2$*hours and were similar to those of gravity meter No. 9.

As for the gravity spectra of No. 9, although the spectral peaks were significantly seen at 8.0, 6.0, 4.8, 4.0 and 3.4 hours before the reduction of atmospheric pressure effect (Fig. 5(b)), these peaks were almost removed after the reduction (Figs. 7(a) and 7(b)).

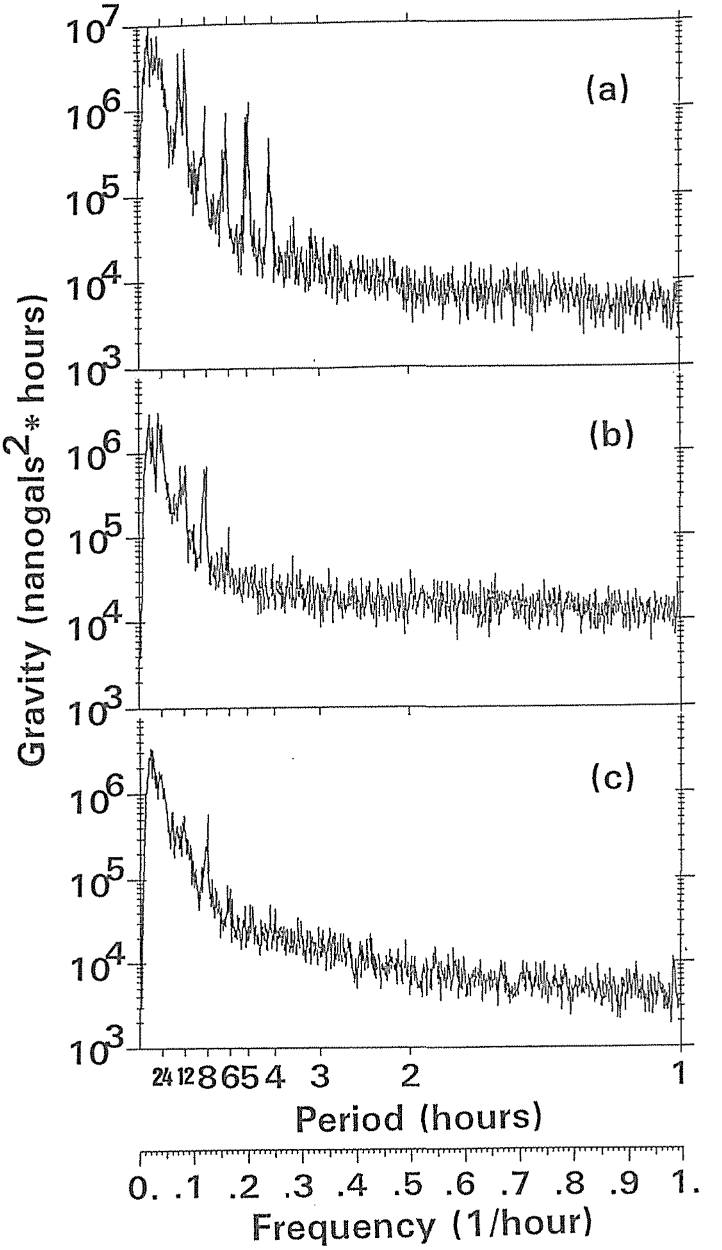


Fig. 7. Spectra obtained from the corresponding gravity data of Fig. 6.

It was, thus, confirmed that those peaks in Fig. 5(b) had been almost derived from atmospheric pressure changes. Significant spectral peaks remained at 8.0 hours in Figs. 7(b) and 7(c), and also at 6.0 hours in Fig. 7(b). These peaks at 8.0 and 6.0 hours are situated close to the sum frequencies of the principal tidal waves and might have been caused by nonlinearity in either the instrumental response or the response of the earth and its oceans (Mansinha *et al.,* 1990), or by the insufficient removal of atmospheric pressure effect.

In Fig. 7(b), noise levels were enhanced by about $10^4$ nanogals$^2$*hours in a shorter period band than 3 hours after the reduction with the atmospheric pressure data of No. 9. This was because this reduction induced high noise levels in the short period band. On the other hand, noise levels in Fig. 7(c) were slightly lower after the reduction with the atmospheric pressure data of No. 8. The noise levels in the 1–8 hour band were $2\times10^4$–$10^5$ and $10^4$–$10^5$ nanogals$^2$*hours for the spectra shown in Figs. 7(b) and 7(c), respectively. These noise levels at Kyoto were 40–4 times larger than those at the PINON PLAT station reported by Agnew and Berger (1978) in the 1–8 hour band.

## 5. Variation of Gravity Spectra

If eigen oscillations were excited or damped, spectral levels would rise or fall, respectively, with the lapse of time in narrow bands centered on the eigen periods. In such cases, when a contour map for spectral amplitudes was drawn on a diagram of time in the abscissa and period in the ordinate, eigen oscillations would be revealed as contour lines extending in the direction of the time axis in narrow bands.

FFT spectral analyses were excuted with the same procedure as described in the previous section for the segments, each of which consisted of 8,192 data (about 56.9 days) and was shifted by 25% of its own value (about 14.2 days) from the preceding one. Contour maps thus obtained are shown in Figs. 8(a) and 8(b) for gravity spectra of Nos. 8 and 9, respectively. The middle time of each segment was set to time in its contour map. The whole period of analyses of No. 9 was divided into two; that is, October 1989–October 1990 and November 1990–September 1992. Contour maps in the former and the latter periods were obtained from the gravity data shown in Figs. 6(b) and 6(c), respectively. Thus, the contour map shown in Fig. 8(b) has gaps between those two periods. Contour lines were drawn on the basis of spectral amplitudes with 80, 90 and 95% confidence levels, which were determined from the noise levels of spectra averaged over the whole period of analyses on the assumption of Gaussian noises.

As clearly shown in Fig. 8(a), the spectral levels of No. 8 largely change over the whole 1–8 hour band; particularly, at about 6, 5 and 4 hours after July 1991. These features are consistent with those shown in Fig. 7(a). Such large spectral variations are not recognized in No. 9 (Fig. 8(b)), so that those variations of the gravity spectrum of No. 8 might have likely been caused by instrumental noises of gravity meter No. 8 itself. Coherences between two gravity data from Nos. 8 and 9 were obtained in the following two periods; that is, November 1990–April 1991 and May 1991–September 1991. Coherences in the former and the latter periods are illustrated in Figs. 9(a) and

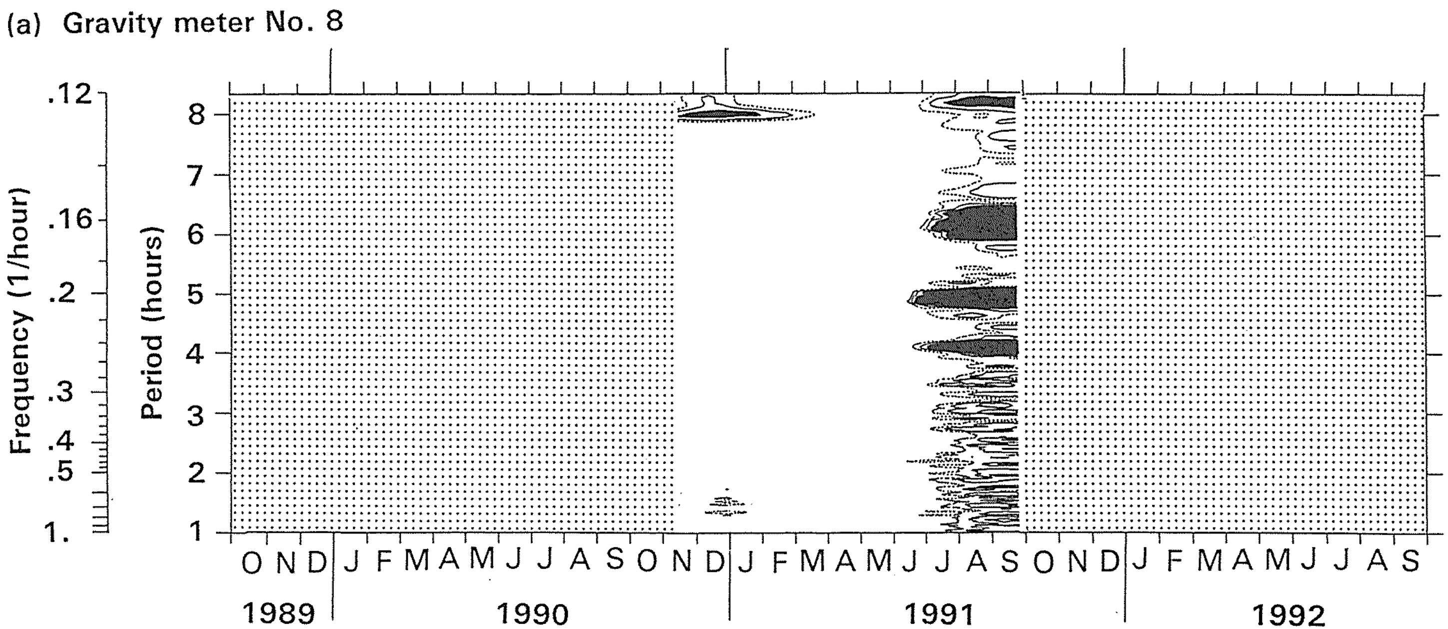


Fig. 8(a). Contour map illustrating for the amplitudes of gravity spectra on time-period diagrams in 8.3–1.0 hour band. Dotted and solid lines show 80 and 90% confidence levels, respectively. Painted portions show the confidence level over 95%. Shaded portions indicate time intervals with no spectral data for the Gravity meter No. 8.

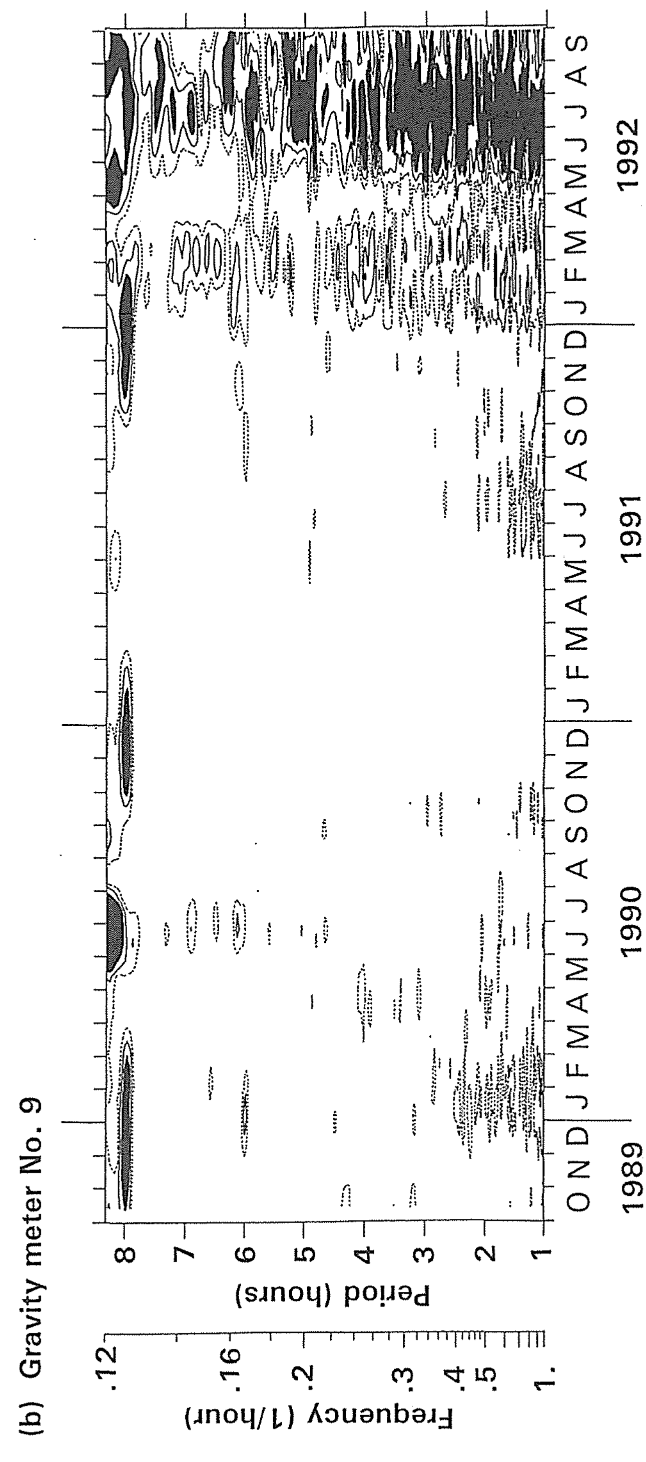


Fig. 8(b). Contour map illustrating for the amplitudes of gravity spectra on time-period diagrams in 8.3–1.0 hour band. Dotted and solid lines show 80 and 90% confidence levels, respectively. Painted portions show the confidence level over 95%. Shaded portions indicate time intervals with no spectral data for the Gravity meter No. 9.

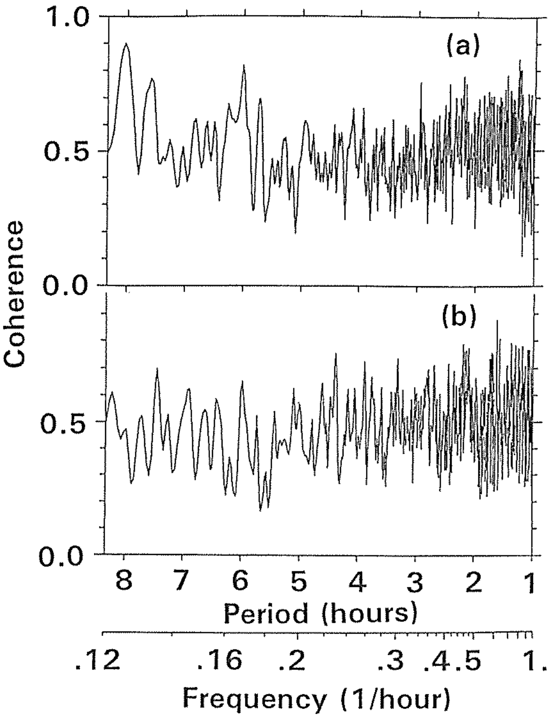


Fig. 9. Coherences between gravity data from Nos. 8 and 9. (a) Coherence in the period from November 1990 to April 1991, (b) Coherence in the period from May 1991 to September 1991.

9(b), respectively. Averaged levels of coherences in both periods are not so high in the 1–8 hour band. Following reasons can be considered that continuous signals over noise levels did not exist in that band and the most parts of the noises were dependent on the instruments. As for the noises depended on instruments, Goodacre *et al.* (1993) reported that a significant reduction of noises had been attained by enclosing a superconducting gravity meter's system with thick Styrofoam so as to insulate it from room temperature fluctuations. Influences of temperature fluctuations on gravity meters should be investigated in the near future. Coherences in the latter period are lower than those in the former period at about 8 and 6 hours. This seems to support that the large enhancements shown in Fig. 8(a) after July 1991 were caused by instrumental noises of gravity meter No. 8 itself.

In Fig. 8(b), contour map of No. 9 shows the enhancements of spectral levels in the 1–8 hour band after December 1989, June 1990, June 1991, January 1992 and May 1992. At those times, there often exist spectral peaks at some particular periods. For example, significant spectral peaks are frequently shown at about 8 hours. This is consistent with the features shown in Figs. 7(b) and 7(c). However, some of those peaks tend to annually appear in common with atmospheric pressure changes. Thus, the influence of atmospheric pressure might not have been removed sufficiently. Excitations of spectra are also shown in periods shorter than 8 hours, though there are no significant spectral peaks in this band in Figs. 7(b) and 7(c) , except at 6.0 hours in

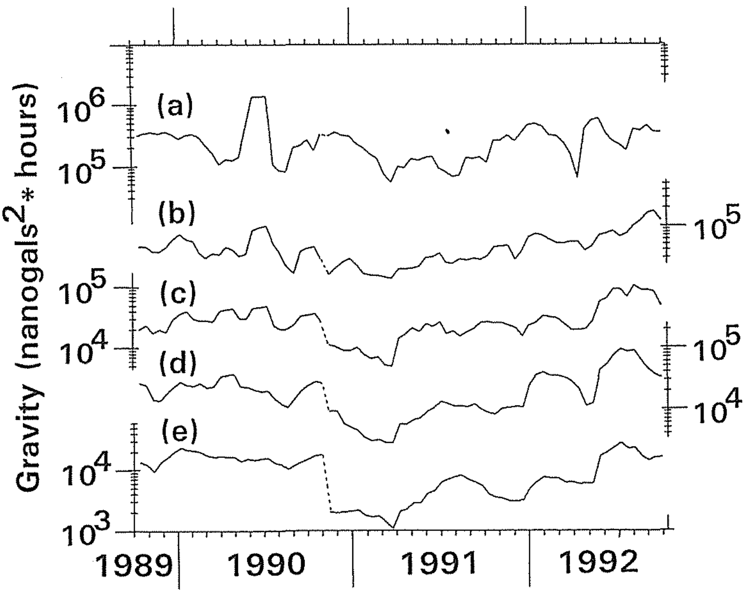


Fig. 10. Time variations of gravity spectra averaged in some bands. (a) 8.3–7.9, (b) 6.2–5.8, (c) 5.1–4.7, (d) 4.2–3.6, and (e) 3.0–1.0 hour bands.

Fig. 7(b). Spectral levels were often enhanced at about 6, 5, 4 and 3–1 hours.

Variations of gravity spectra in the periods of about 8, 6, 5, 4 and 3–1 hour were investigated in detail. Gravity spectra for the segments, which were employed to obtain the contour maps, were averaged in narrow bands containing those periods. Variations of spectra thus obtained are shown in Fig. 10, in which (a), (b), (c), (d) and (e) are variations of gravity spectra averaged over the 8.3–7.9, 6.2–5.8, 5.1–4.7, 4.2–3.6 and 3.0–1.0 hour bands, respectively.

### *5.1. Residual Effect of Atmospheric Pressure Spectra*

Variations of atmospheric pressure spectra were estimated with the same procedure as that used to obtain those of gravity. The results are shown in Fig. 11. Spectra before and after November 1990 were obtained from the data of barometers Nos. 9 and 8, respectively, so that gaps exist in November 1990. As shown in Fig. 11, spectral levels were annually enhanced, and maximum peaks appeared around January every year. The annual variations are remarkable in the longer period, particularly at about 8 hours. This tendency of annual variation can also be shown in the variation of gravity spectra at about 8 hours (Fig. 10(a)), so that the annual variation shown in gravity spectra might be caused by residual components of atmospheric pressure changes, which were remained as a result of insufficient removal of atmospheric pressure effect. As for removal of atmospheric pressure effect, Sato *et al.* (1991) reported that atmospheric pressure distribution at least over a 30 degree cap centered at the observation site had to be considered, so as to reduce with high precision below 1 microgal. Thus, it might be necessary to execute more precise reduction for atmospheric pressure effect. In the 1–3 hour band, the variation of gravity spectra

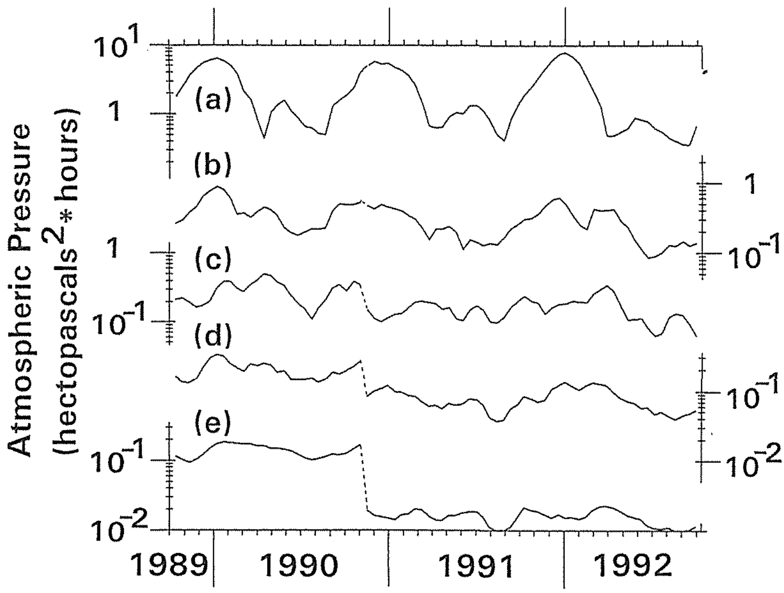


Fig. 11. Time variations of atmospheric pressure spectra in the same bands as used in Fig. 10.

shown in Fig. 10(e) is similar to that of atmospheric pressure spectra shown in Fig. 11(e) before November 1990. This is because noise levels in gravity were enhanced by the reduction with atmospheric pressure data of No. 9 in a shorter period than 3 hours.

As mentioned above, influences of atmospheric pressure changes might be remained in gravity data at some periods even after the reduction executed in the present study. However, excitations of gravity spectra could be seen at some times when atmospheric pressure spectra were not so excited, for example, at about 6 and 8 hours in June 1990. in the 1–3 hour band around August 1991, at about 4 hours around January 1992 and in the 1–8 hour band in May 1992.

### *5.2. Comparison with Large Earthquakes*

The variations of gravity spectra shown in Fig. 10 were compared with sequence of large earthquakes (M≧6). Energy radiated by the large earthquakes was summed up in each segment which was used to obtain the contour maps. Fig. 12 displays time variation of energy thus obtained. In this figure, enhancements of the energy are shown around June 1990, April 1991, December 1991 and May 1992. These times of enhancements are close to those of excitations of gravity spectra shown in Fig. 10, so that it seems to suggest that there were some correlations between them. Coefficients of cross correlation between the variation of gravity spectra and that of energy radiated by large earthquakes were obtained in the period from November 1990 to September 1992 by employing the values shown in Figs. 10 and 12. The values before November 1990 were not used, because the gravity spectra in the shorter period band were contaminated by noises in atmospheric pressure data from No. 9. Coefficients obtained are shown in Fig. 13, in which (a)–(e) were obtained by employing Figs.

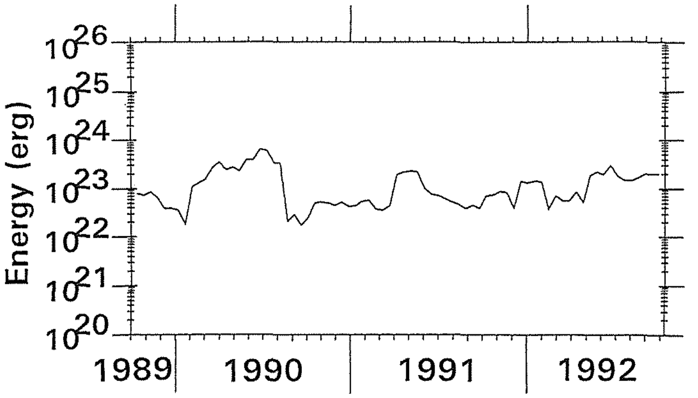


Fig. 12. Time variations of energy radiated by large earthquakes of M≧6.

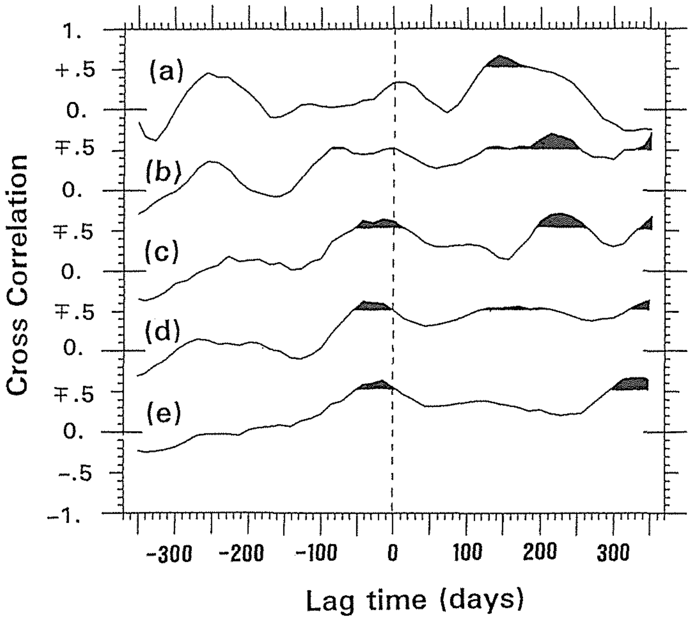


Fig. 13. Cross correlations between variation of gravity spectra shown in Fig. 10 and that of enegy radiated by large earthquakes shown in Fig. 12. Variation of gravity spectra precedes or follows that of energy radiated by earthquakes at positive or negative lag times, respectively. Painted portions show the correlations higher than +0.5.

10(a)–10(e), respectively. Variation of gravity spectra precedes or follows that of energy radiated by the earthquakes at positive or negative lag times, respectively. If gravity spectra in the 1–8 hour band were excited by earthquakes, high correlations would be shown at negative lag times. Although correlations at about 8 and 6 hours are lower than +0.6 at negative lag times, those over +0.6 exist around a lag of −30 days in a shorter period than 5 hours.

Meanwhile, gravity spectra might be also affected by spikes caused by earthquakes whose focuses were located near the observation site, mainly through the effect of aliasing. However, the influences on spectra by such earthquakes were reduced by using long segments to obtain spectra. In the present study, spectra were obtained by using relatively long segments (about 56.9 days) and the data just after earthquakes were removed from analyses, so that the influences by the earthquakes occured near the site were considered to be low.

Significant correlations over +0.7 are not seen at negative lag times, and it is unknown if there are some mechanisms that large earthquakes enhance gravity spectra in this band. Therefore, correlations between excitations of gravity spectra and large earthquakes could not be clarified.

## 6. Concluding Remarks

Gravity spectra in the 1–8 hour band were examined by employing gravity data obtained from two superconducting gravity meters (Nos. 8 and 9) installed in Kyoto, Japan. Major tidal signals and linear drifts were removed from the original gravity data as well as atmospheric pressure data obtained simultaneously. Because outputs from gravity meters were obtained through only low pass filters of 50 seconds, 10-min. sampling data were contaminated with aliasing. But, spectral levels in periods longer than 3 hours were considerably higher than enhancements due to aliasing, so that influences of aliasing could be ignored in this band. In periods shorger than 3 hours too, the influence of aliasing was not so serious to investigate the tendency of time variation of gravity spectra averaged over the 1–3 hour band. Therefore, in the 1–3 hour band, only averaged levels were discussed.

The averaged gravity spectra over the whole period of analyses showed that there were some spectral peaks at 8.0, 6.0, 4.8, 4.0, 3.4, 3.0 and 2.7 hours. Many peaks in those periods were derived from atmospheric pressure changes and were almost removed by executing the reduction of atmospheric pressure effect especially for gravity meter No. 9.

Windowed segments were successively shifted by 25% of its own value in time series, and the FFT spectral analyses were performed. In order to visually understand simultaneously both the period dependence of gravity signals and time variation of spectra, contour maps were illustrated on a time-period diagram. In those maps, the enhancements of the spectral levels were shown over the whole period of 1–8 hours. In particular, there existed relatively significant spectral peaks at about 8, 6, 5, 4 and 3–1 hours. Although some of them might be caused by insufficient removal of atmospheric pressure effect, excitations of gravity spectra without relations with atmospheric pressure changes were also recognized. Some of them might be caused by oscillations in deep interior of the earth such as core modes. In this respect, more detailed investigation is necessary.

Some excitations of gravity spectra seemed to have correlation with large earthquakes ($M \geqq 6$). However, the coefficients of cross correlation between them were lower than +0.7 at negative lag times, and at the present stage, such correlation can not be concluded. In order to ascertain this, it is necessary to accumulate as much data as possible and to clearly distinguish between signals and noises.

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