主論文

A Study on Characteristics of Tidal Gravity Observations by Employing Superconducting Gravity Meters at Kyoto, Japan

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Contents

Abstract

Continuous observations of time change of gravity have been carried out employing two superconducting gravity meters (model TT-70) at Kyoto University since 1988. Hitherto, continuous observation employing two superconducting gravity meters over a long period at the same observation site has not been almost performed before.

In the present study, instrumental differences between the two gravity meters were determined by comparing the data obtained through simultaneous observations, confirming their high precision and stability. Comparing results obtained from the data of nine months, it was ascertained that, in the major constituents of the earth tides, δ - factors were in good agreement within 0.001 and phases were within 0.03 degree. Restricting data length to thirty days, δ - factors were in agreement within 0.002 and phases within 0.2 degree of each other for M_2 and O_1 constituents. Moreover, it was confirmed that the superconducting gravity meter kept extremely high stability for disturbances such as earthquakes, stoppage of power supply, transfer of liquid helium and displacement of a superconducting sphere. Furthermore, applying the data obtained over a period of about three years, we could detect long period tides, free core resonance and gravity changes due to polar motion, in spite of the observation site where the city noises are fairly large. We could also confirm that the superconducting gravity meter had high sensitivity and long-term stability. Until now, the detection of such phenomena was remarkably difficult when employing gravimeters of

the spring type so far available.

1. Introduction

Continuous observations of the time change of gravity employing various types of gravimeters are being carried out by many researchers at many permanent and temporal stations around the world (Melchior, 1994).

Tidal factors of gravity (δ - factors) which are the response of the earth due to the luni-solar tide-generating potential are expressed by $\delta = 1 - 3k/2 + h$, where h and k are Love's numbers. Phase lags show differences between observed and theoretical phases. δ - factors and phase lags are closely concerned with elasticity and viscosity of the solid earth, respectively. Therefore, in order to clarify the earth's structure, it is important to precisely determine both δ - factors and phase lags.

As the gravimeters employed in observations have recently become very precise, the characteristics of the earth's geodynamics such as free core resonance and so on can now also be investigated.

In Japan, continuous observations of the time change of gravity have been carried out frequently since the International Geophysical Year (1957-1958).

Nakagawa (1962a) obtained δ - factors at ten stations in Japan by means of an Askania Gs-11 gravimeter during a period of about two years from July 1957 to May 1959 As for M_2 constituent,

δ - factor was 1.142 ± 0.011 and phase lag was very small.

Furthermore, Nakagawa (1962b) obtained δ - factors through continuous observation of the time change of gravity at Kyoto by means of the same gravimeter during a period of about one year from August 1959 to August 1960. He found that there were differences of 3 % in δ - factors and of 4 degrees in phase lags during the year, so far as the M_2 constituent is concerned. He further determined that the most reliable values of δ - factor and phase lag for the M_2 constituent at Kyoto were 1.138 ± 0.005 and -2.40 ± 0.28 degrees, respectively.

In 1968, the Working Group for Comparing the Gravimeters in Japan (1969) carried out simultaneous observations of the earth tides with four Askania gravimeters and two LaCoste & Romberg gravimeters for a period of about three months from August to November 1968 at the International Latitude Observatory of Mizusawa. They found that the discrepancy among the types of the gravimeters employed existed with a large fluctuation of δ - factors amounting to about 35 % was seen in the Askania Gs-11 gravimeters. They also noted that reliable results could not be obtained in continuous observations of the earth tides when they are performed by a single gravimeter.

Nakagawa et al. (1975) determined δ - factors and phase lags employing continuous records obtained by means of an Askania Gs-15 gravimeter for a period of two years from June 1972 to May 1974 at Kyoto. They revealed that the most reliable value of δ - factor for the M_2 constituent at Kyoto was very close to 1.20, and that the K_1 constituent showed a remarkably seasonal variation in both δ - factor and phase lag. They also presented a fine spectral structure of the earth tides in the vicinity of terdiurnal and quarterdiurnal tides.

Tsubokawa et al. (1977) performed simultaneous observations of the earth tides with five LaCoste & Romberg gravimeters (model G) over a period of about three months from December 1976 to March 1977 at the International Latitude Observatory of Mizusawa. They pointed out that an offset angle should be kept at around 240 seconds and a scale constant for the gravimeter should accurately be calibrated during observations, and that the gravimeter should be installed within one second of change in tilting and 1° C of change in room temperature.

Tajima (1978) reported that an anomalous drift amounting to about 30 μgals appeared simultaneously in two LaCoste & Romberg gravimeters about one week before the Izu-Oshima Kinkai Earthquake. This observation was carried out for a period of about three months from December 1977 to March 1978 at the Aburatsubo Crustal Movement Observatory.

In 1982-1983, observation of the earth tides was performed with a Geodynamics 783 gravimeter of the International Centre for Earth Tides in Belgium for a period of 198 days at Kyoto (Melchior, 1994) He revealed that the values of the δ - factor and phase lag for the M_2 constituent were 1.2087 ± 0.0008 and -0.048 ± 0.037 degree, and for the O_1 constituent were 1.2178 ± 0.0026 and 0.207 ± 0.122 degree, respectively.

Endo (1984) and Okubo et al (1987) found the regional variation of δ - factors by employing LaCoste & Romberg gravimeters (models G and D) at nine stations in central Japan. They indicated that the δ - factors obtained showed a tendency to decrease from coastal zones toward inland ones by 1.5 % for the M_2 and by 3 % for the O_1 constituents. They suggested that the lateral heterogeneity of the earth's structure is responsible for the regional variation of δ - factors.

Ogawa et al. (1991) and Shibuya and Ogawa (1993) performed tidal gravity observations with a LaCoste & Romberg gravimeter (model G) at Syowa and Asuka stations in Antarctica in 1987. They found that diurnal δ - factors agreed with theoretical prediction, while semidiurnal δ - factors were 10 % larger than theoretical ones. They suggested that the reasons are due to the effects of inaccurate correction for oceanic tidal load and of the loading deformation of the ice sheet

For the purpose of earthquake prediction, Doi et al. (1988) carried out continuous observation of the time change of gravity at Tokai District by employing two LaCoste & Romberg gravimeters (models G and D) since 1984. They showed that the difference of δ - factors obtained from the two gravimeters' data of about eleven months at the same station was about 0.5 % and, that the fluctuation of δ - factors obtained, restricting the data length to thirty days, amounted to about 5 % for both gravimeters over a period of about eleven months.

The observations mentioned above were all carried out employing gravimeters of the mechanical spring type, with an accuracy of about $\pm$ 1 μgal On the other hand, continuous observations of the time change of gravity have recently been carried out by employing superconducting gravity meters at about twenty stations around the world.

The superconducting gravity meter applies magnetic levitation under superconductivity which is called the Meisner effect. Namely, this gravity meter is to replace the mechanical spring of previous gravimeters with the magnetic suspension (e.g., Prothero and Goodkind, 1968; Goodkind, 1991). It is expected that the superconducting gravity meter has extremely high sensitivity and long-term stability. and has efficiency to observe phenomena with an order of nanogals ($10^{-12}g$).

However, the superconducting gravity meter has one weak point : Calibration for scale factors can not easily be executed. Therefore, there exist some problems wherein the distinction between actual and apparent gravity changes due to the change of the scale factor can not be recognized. Until now, it has been almost used only as a single gravity meter in observations.

In this paper, comparing data obtained through simultaneous observations of two superconducting gravity meters installed in the same observation room, we clarified instrumental differences between the two gravity meters, and estimated their precision. Moreover, we ascertained the stability of the superconducting gravity meter for disturbances such as earthquakes and stoppage of power supply. Furthermore, employing long period data obtained, we tried to detect geophysical phenomena which have been difficult to detect with gravimeters of the spring type. We examined the high sensitivity and long-term stability of the superconducting gravity meter.

2. Observations

Two superconducting gravity meters (model TT-70), SCG-008 and SCG-009, manufactured by GWR Instruments, Inc. were installed at Kyoto University, Kyoto, Japan in March 1988. The gravity meters, as shown in Figure 1, were installed on the concrete basement perpendicular to each other in the same observation room at the ground floor of the Department of Geophysics.

The data acquisition system and the compressors of the cryogenic refrigeration system were set up in the front room to avoid any disturbance caused by entering the observation room or by the vibration of the compressors. Room temperature was controlled by an air-conditioner

After their installation, as one of the gravity meters, SCG-009, did not work because of some problems with sphere levitation, repairs and checking of the gravity sensor unit by manufacturer were made, followed by reinstallation at the end of July 1988, and the exchange of the gravity sensor unit of the other gravity meter, SCG-008, at the same time.

For these reasons, simultaneous observations of the time change of gravity with two gravity meters did not commence until the end of July 1988. As shown in Figures 2, 3 and 4, however, the following problems occurred even then :

(1) The drift of the gravity meters was too large contrary to our expectations, amounting to over 10 μgals per month.

(2) "Offset" (jumping of unknown cause) amounting to several μgals frequently occurred, the largest of which was over 50 μgals.

Furthermore, observations by the gravity meter SCG-008 were interrupted, and the gravity meter SCG-008 was sent to the manufacturer for repairs and the improvement of the gravity sensor unit in October 1989.

The following improvements were made (Warburton, 1990) :

(1) Replacement of the lead shield with one of niobiums.

(2) Changing the method for making the superconducting sphere from chemical vapor deposition to electroplating.

(3) Cooling the gravity sensor unit by fast cool down.

In October 1990, it was sent back to the University and simultaneous observations with the two gravity meters began again. However, unfortunately, an earthquake occurred near Kyoto City on November 2, 1991, and caused the superconducting sphere of the gravity meter SCG-008 to drop out, of its dynamic range being exceeded. For this reason, interruption of data from the SCG-008 occurred. Recently, however, as sphere levitation has succeeded, continuous simultaneous observations with the two gravity meters are being carried out.

Since Kyoto University, in which the superconducting gravity meters are installed, is located in a city zone, observed records are subject to various city noises, especially in the daytime. Nevertheless, there were reasons for the gravity meters being installed at the campus : We attempted to establish a method for eliminating environmental noises using the data of two gravity meters. Moreover, we could conveniently maintain and examine the gravity meters.

The data acquisition system consists of 14-bit digital recorders of the floppy disk type and pen recorders for monitoring. In addition, a 24-bit digital recorder has recently been employed to ensure a wide dynamic range.

The outputs from the gravity meters were obtained through two types of filters, namely, "TIDE" and "MODE" As shown in Figure 5, "TIDE" is a lowpass filter with cut-off frequency at about 50 cycles per hour, and "MODE" is a bandpass filter that is flat from about 1 to 50 cycles per hour (GWR Instruments, 1985) These filters are the same employed in an IDA network (Agnew et al., 1976) Presently, the outputs of "TIDE" and "MODE" are sampled at 10 minute and 10 second intervals, respectively Moreover, changes in atmospheric pressure, room temperature and humidity, which may cause noises, were simultaneously recorded as parallel observation data in the same room. In the near future, data of underground water-level changes and precipitation will be available.

The dewar housing unit can hold about 200 litres liquid helium as cryogen. As a helium level indicator is attached to the inside wall of the dewar, we can check the remaining liquid helium. As shown in Figure 6, the consumption of liquid helium was about 0.40 *l*/day for SCG-008 and 0.35 *l*/day for SCG-009, respectively. Therefore, it is possible to operate for about one and half years after filling up the dewar However, if we don't use the refrigerator system, or, if the refrigerator system is out of order, the consumption rate of liquid helium is about ten times greater than that of ordinary operation, so that the dewar would be empty in about two months.

3. Data Analysis

In order to determine the gravity value from the voltage output of the gravity meter, a scale factor must be determined. However, no simple method is available to calibrate the scale factor of the superconducting gravity meter. Until now, the following methods have been proposed for calibration :

(1) Close to a big mass near the gravity meter, taking advantage of the Newton's law of gravitation (Czipott, 1983)

(2) Use an absolute gravity meter, taking advantage of the time change of gravity (Hinderer et al , 1991).

We have not yet executed such methods. Instead, we estimated the scale factor so as to be coincident with δ - factor determined by Nakagawa et al. (1975) by employing an Askania Gs-15 gravimeter at Kyoto. They presented that the most reliable value of δ - factor for the M_2 constituent at Kyoto is very close to 1.20 Here, it was assumed that the δ -factor of the M_2 constituent obtained by the superconducting gravity meters is 1.2000. Scale factors so far obtained are as follows :

(1) SCG-008 : 109.14 μgals/volt (July 1988 - October 1989)

(2) SCG-009 : 80.42 μgals/volt (July 1988 - up to now)

(3) SCG-008 : 52.12 μgals/volt (after reinstallation : October 1990 - up to now)

In this analysis, we used hourly data from the output of "TIDE", and also used hourly data of atmospheric pressure to estimate its effect. To investigate the time change of gravity, we applied the tidal analysis program "BAYTAP-G"

(Bayesian Tidal Analysis Program-Grouping Method) (Ishiguro et al., 1981; Tamura et al., 1991) By applying the "BAYTAP-G" program to a set of hourly data, both tidal parameters and trend can be determined using ABIC (Akaike's Bayesian Information Criterion) Occasional steps and missing data are allowable if their positions are marked. In particular, it is important to be able to precisely determine the trend which includes long period gravity changes.

The data obtained through simultaneous observations with both superconducting gravity meters were taken in the following two periods, i.e., the former was from September 26, 1988 to October 20, 1989 (390 days) and the latter from October 11, 1990 to July 7, 1991 (270 days).

(A) Data analysis for the period of 1988 - 1989

Figure 7 shows tidal,irregular and trend components decomposed from the gravity data obtained during the period of 390 days from September 26, 1988 to October 20, 1989. We used the atmospheric pressure data observed in the same observation room with the gravity meters, as shown in Figure 8.

Many researchers have investigated in detail the effect of atmospheric pressure changes on gravity observations with the superconducting gravity meter (Warburton and Goodkind, 1977; Doi et al., 1991; Shi et al., 1993) In the present study, the coefficient of gravity changes to atmospheric pressure ones during the period concerned was obtained as 0.323 μgal/hPa and 0.325 μgal/hPa for SCG-008 and SCG-009, respectively. These values were estimated by applying the "BAYTAP-G" program. Both superconducting gravity meters proved to have a similar response coefficient to atmospheric pressure changes.

As shown in Figure 7, the drift (trend) increased almost linearly with the lapse of time. Here, the increase of drift means that the gravity becomes large. Drift rates were 10 - 20 μgals/month and about 20 μgals/month for SCG-008 and SCG-009, respectively. However, SCG-008 had some troubles, especially troubles of compressor of refrigerator system, since July 1989, and then, the drift rate changed nonlinearly.

(B) Data analysis for the period of 1990 - 1991

Similar results are shown in Figure 9 for which the same procedure as mentioned in the previous section was applied for the gravity data obtained during 270 days from October 11, 1990 to July 7, 1991. In Figure 9, the unit of the trend component is one-fifth of that of Figure 7.

After the reinstallation, gravity data obtained by SCG-008 were not so good, particularly in the beginning of records, because displacement of the superconducting sphere and lacks of data occurred frequently, which were caused by large offsets, earthquakes and stoppages of power supply. However, the drift rate was less than 10 μgals/month and noise level (irregular component) being less than that of the former period. These seem to be due to improvement in both the sensor unit and fast cooling method.

On the other hand, for SCG-009, observations of the time change of gravity have continued uninterruptedly since July 1988. In this period, we can point out :

(1) Drift rate increases constantly by about 5 μgals/month with almost linearity.

(2) Noise level decreases to one-third as compared with that in the former period.

(3) "Offset" did not occur at all

4. Results and Discussion

4.1. Comparison of δ - Factor and Phase

Both δ - factor and phase lag were obtained by applying the "BAYTAP-G" program. The phase lag thus obtained is hereinafter referred to as "phase" in this paper. Table 1 shows the results of analysis obtained by the two superconducting gravity meters during both simultaneous observation periods. In the analysis for short period tides, we separated fifteen tidal constituents consisting of eight diurnal, six semidiurnal and one terdiurnal constituent, and chose six major constituents (O_1, P_1, K_1, N_2, M_2 and S_2) for detailed investigation.

Two superconducting gravity meters are installed in the same observation room, and their data acquisition system and the data analysis method are the same. Therefore, errors caused by filter characteristics, clock accuracy and analysis method, and the effects by underground water-level change, rainfall and ocean tidal loading should be completely the same for both gravity meters.

According to Table 1, the six major constituents in two periods agree with each other within 0 001 for δ - factors except for the N_2 constituent of the former period and 0.1 degree for phases except for the P_1 constituent of the former period. Especially. in the latter period, there is excellent agreement, with 0.001 for δ - factors and 0.03 degree for phases. The differences of respective δ - factors obtained between the former and the latter periods were not obviously recognized in spite of the gap of about one year. On the contrary. the phases obtained in the latter period advanced by about 0.1～0.2 degree against those in the former period, except for the P_1 constituent of the SCG-008. The reason for this is not clear yet, but it might be due to the lower precision of gravity data of the former period.

In order to avoid the dependence on instrumental sensitivities, we applied the ratios of δ - factor of O_1, P_1, K_1 and S_2 constituents to that of the M_2 constituent. As shown in Figure 10, the ratios of δ - factors are coincident within ± 0.1 % for those major constituents. This result clarifies that the response of two superconducting gravity meters for the earth tides is consistent within the order of ± 0.001, and is even within ± 0.0005 in the latter period.

The ratio of δ - factors, the difference of δ - factors and that of phases of both superconducting gravity meters obtained for the former and latter periods are given with the difference of amplitudes in Table 2. According to this Table, the ratios of δ - factors for the six major constituents were coincident within an order of 0.001 except for the N_2 constituent. Furthermore, the differences of phases were in excellent agreement, being within 0.03 degree (about 7 seconds) in the latter period. This shows that there are no instrumental differences between the superconducting gravity meters so far as the phase is concerned.

As mentioned above, in the case where the data length employed in analyses was about one year, δ - factor and phase were in good agreement with each other. We then tried to clarify differences between the instruments when the data of a shorter length were employed in analyses. We examined the relationship between the length of data employed and the difference of δ - factors and phases derived from both gravity meters. The results are shown in Figure 11. In this Figure, the values of the respective tidal constituents indicate a mean value of differences between two δ - factors and phases which were obtained from the data of both gravity meters for the same periods. The length of period employed for each calculation is the abscissa, and the number of periods employed for calculating the mean values is shown in this Figure.

As can clearly be seen in Figure 11, in case of a data length of more than 90 days, the differences between the δ - factors obtained by the two gravity meters converge to 0.001 with the differences between phases being 0.1 degree. Thus, it can be seen that the results derived from data lengths longer than 90 days are reliable and sufficiently stable.

Although the period analyzed was about one year, δ - factor and phase remained in good agreement with each other over the period. Regarding the problem of the superconducting gravity meter that the scale factor can not easily be determined, the results suggest that the superconducting gravity meter has a reliable stability of sensitivity to such an order for the tidal variations of gravity.

We also ascertained that the precision of the gravity data obtained by the superconducting gravity meter achieves an order of 0.1 μgal, judging from the results of simultaneous observations at least in the tidal band. According to these results, we are certainly able to detect any gravity change within the frequencies of tidal band even under 1 μgal by employing the superconducting gravity meter. In addition, as reported by Tajima (1978), we also consider that it is possible to detect the trend changes, but not changes of δ - factor because it seems that a small local gravity change can not cause a change of δ - factor, it being the earth's response. For such determinations, however, it is most important that the characteristics of each superconducting gravity meter and especially the behavior of drift are well known.

4.2. Temporal Tidal Variations of Gravity

In order to estimate the temporal tidal variations of gravity obtained by the two superconducting gravity meters at Kyoto, we used the simultaneous observation data obtained from October 11, 1990 to July 7, 1991 because, as described above, these data are better than those for another period.

The "BAYTAP-G" program was applied to obtain δ - factors and phases from the data. The data length for each analysis was restricted to 30 days, and the period of analysis shifted every 10 days. The results of analyses obtained for every 10 days for the M_2 and O_1 constituents are shown in Figures 12 and 13. In these Figures, the temporal variation of δ - factors, phases and ratios of δ - factors (O_1/M_2) are illustrated.

Comparing the results derived from both gravity meters, the fluctuations in δ - factors and ratios of δ - factors are coincident within about 0.002 while those of phases are about 0.2 degree of each other, in spite of the period of analyses being only 30 days. Therefore, if the changes greater than these amounts occur, we will be detectable those changes. However, for the purpose of earthquake prediction, we must be able to evaluate the magnitude of any precursor of tidal variation of gravity prior to earthquake occurrence.

On the other hand, the fact that the δ - factors for M_2 and O_1 constituents obtained by the two superconducting gravity meters were coincident within ± 0.1%, though the data length was only 30 days, suggests that large changes (over a few %) in δ - factors obtained until now were probably unreliable tidal variations caused by the unstable sensitivity of the gravimeter.

4.3. Precision

Because Kyoto University at which the superconducting gravity meters were installed is located in the city, observed data are affected by various kinds of city noises such as traffic. Moreover, the geological structure in this area consists of sedimentary layers (alluvium and diluvium) thickly accumulated on a paleozoic basement (Ishida et al., 1982). There is susceptibility to various vibrations, too : For example, the concrete block on which the gravity meters were installed was not fixed to the bedrock directly. In order to clarify the noise level for each meter, the FFT method was applied to data which were obtained simultaneously during the period from October 11, 1990 to July 7, 1991. Data were divided into thirteen segments and tapered with a cosine window. Spectra obtained for the segments were averaged.

The amplitude spectra obtained for the SCG-008 and SCG-009 in the vicinity of diurnal, semidiurnal and terdiurnal tides are shown in Figure 14. Quarterdiurnal tides, however, could not be found in this Figure. According to this results, moreover, the noise level of the data for the terdiurnal tides band is in an order of about several tens of nanogals.

In order to further clarify the precision of the superconducting gravity meter, the FFT method was applied to longer data obtained by the SCG-009 during the period of three years from October 21, 1989 to October 21, 1992. The spectra shown in Figures 15 and 16 have higher precision that the tidal constituents were more clearly detected, especially, terdiurnal constituents, M_3, S_3, MO_3 and MK_3, were clearly detected. But, quarterdiurnal tides could not be detected. According to these Figures, the noise level is about 20 nanogals for the terdiurnal tidal band, and that of the subtidal band is about several nanogals.

Therefore, we consider it is difficult to detect gravity signals under a nanogal at this observation site. Nevertheless, we should endeavor to decrease the noise level, so as to be able to estimate the influence of underground water-level changes and to improve the method of data analysis.

4.4. Stability

There were sometimes lack of data, several times a year, due to the stoppage of power supply for about half a day because of the maintenance of buildings in the University. At these times, all of the gravity meter systems did not operate.

As shown in Figure 17, earthquakes occurred frequently in and around Kyoto City. The data of earthquakes were obtained using the computer program "SEIS-PC" (Ishikawa et al., 1985) However, sphere changes ("tare") didn't occur for those earthquakes with two notable exceptions over the five years of recording. One of the two exceptions occurred near Lake Biwa on January 11, 1990 (M=4.9, Δ=20km, H=11km), and the other near Kyoto City on November 2, 1991 (M=4.3, Δ=20km, H=14km). The seismic intensity for both earthquakes was 3th degrees at Kyoto City, where two big shocks occurred during observations. The epicenters are also shown in Figure 17.

Amounts of sphere changes were ;

-380 μgals for SCG-009 on January 11, 1990,

+280 μgals for SCG-008 on November 2, 1991,

-152 μgals for SCG-009 on November 2, 1991.

Here, minus sign means gravity decrease. The gravity meter SCG-008 did not operate because of its repairs in January 1990.

Several times, we made changes in the magnetic field in the gravity sensor unit, called "sphere re-centering", by which the output signals from the gravity meter were over the dynamic range for drift, offset and earthquake occurrence.

In order to ascertain the stability of the superconducting gravity meter, we examined the obtained data when sudden changes of the sphere position and stoppage of power supply occurred as mentioned above. Figure 18 shows the original data obtained by SCG-009 over the first five years of observations. It is obvious that these data were stable over this long period. Jumps twice for earthquake occurrence and three time's for "sphere re-centering" are clearly seen in this Figure.

Figures 19 and 20 show the original data and drift curve, and, δ - factor and phase which were obtained by SCG-009 during the 90-day periods before and after the occurrence of an earthquake on January 11, 1990. In the drift curve, the amount of jump was estimated and interpolated by applying the "BAYTAP-G" program. δ - factors and phases for M_2 and O_1 constituents were calculated from the 30-day data length with shifts in the period of analysis made every 10 days.

Figure 21 shows the earthquake occurrence on November 2, 1991 and the "sphere re-centering" after six days (November 8) for rectification. Sphere changes were -152 μgals and +264 μgals, respectively. δ - factors and phases are shown in Figure 22. Here, the period of data analysis was the 90 days before earthquake occurrence and after sphere re-centering ; δ - factor and phase were calculated by the same procedure as given above.

Figure 23 shows an example of the effect of stoppage of power supply which happened over an 8-hour period on December 24, 1990. δ -factors and phases are shown in Figure 24, which were similarly calculated by the above-mentioned procedure.

As can obviously be seen in all cases of these three examples, the behavior of drift was not affected and changes in δ - factor and phase were not recognized throughout before and after these events.

From these results, it was ascertained that the superconducting gravity meter maintained great stability in spite of such disturbances as stoppage of power supply and superconducting sphere change. We also obtained similar results for the SCG-008.

4.5. Observed Phenomena

(a) Long Period Tides

The long period tides are zonal functions depending on the latitude, and which have a nodal line at latitudes ± 35°16' (e.g., Melchior, 1978) Hitherto, it has been difficult to detect long period tides by employing the gravity meters at Kyoto (35°02' N) Because their amplitudes are small, and we couldn't obtain the data which maintained stability over long periods.

Especially, the data obtained by the gravimeters of spring types had always too large drift

On the other hand, Richter (1990) determined the long period tidal parameters employing uninterrupted 3-year data obtained by means of a superconducting gravity meter at the earth tidal observation station Bad Homburg (50°14' N), Germany He presented that the values of the amplitude, δ - factor and phase for the Mf constituent were 4 944 μgals, 1.1462 and +0.33 degree, and for the Mm constituent were 2.611 μgals, 1.1274 and +0.13 degree, respectively.

We attempted to detect long period tides using the data of the SCG-009, which maintained stability during the period from October 1989 to July 1992 (990 days) as shown in Figure 25. For the analysis of long period tides, we used the data of every 24 hours which were removed the short period tides (terdiurnal, semidiurnal and diurnal tides) and the short period irregulars. The power spectrum for this data is shown in Figure 26. Table 3 shows the results which were applied the long period version of the "BAYTAP-G" program, and also shows the theoretically calculated long period tides at Kyoto.

As described above, the observation site (at Kyoto) is located at latitude 35°01.7' north near the nodal line of long period tides, and therefore, it is very difficult to detect these tides. However, from these results, we consider that the Mtm, Mf and Mm constituents were certainly detected. This shows clearly that the superconducting gravity meter has high sensitivity and long-term stability.

(b) Free Core Resonance

It is well known that the free core resonances caused by the free core nutation due to the motion of a liquid core appear in the frequency dependence nearly diurnal tidal band (e.g., Lambeck, 1988)

Wahr (1981) estimated the eigenfrequency of the free core nutation for an elliptical, rotating, elastic and oceanless earth model : That period is 460.8 sidereal days in inertial frame. For the observation on the rotating earth, the frequency is 1.00217 cycle per sidereal days, i.e., 15.0737288 degrees/hour. This frequency is between the K_1 and ψ_1 constituents. According to Lambeck, for example, the δ - factor of the K_1 constituent is reduced by about 2 %, while on the contrary, that of the ψ_1 constituent is magnified by about 7 %.

Until now, the period of the free core nutation was obtained by various observations. For example, Gwinn et al. (1986) suggested that the period was 430 sidereal days analyzing the nutation data of VLBI. Sato (1991) obtained the period of 442.4 sidereal days using the data of extensometers at Esashi, Japan. Cummins and Wahr (1993) determined the period of 437.0 sidereal days using the data of tidal gravity observations at IDA network.

In order to examine the free core resonance, we used 3-year data, taken during the period from October 1989 to July 1992 by SCG-009. Table 4 shows the results of the analysis of this data. As shown in Figure 27, we investigated the influence of the free core resonance using the ten diurnal constituents except the S_1 constituent which is affected by atmospheric tides.

Here, for estimating the effect of ocean tidal loading, we applied the "GOTIC" program developed by Sato and Hanada (1984) to the observed data. The results for the O_1 and K_1 constituents were consistent with those obtained by Tsukamoto and Nakagawa (1978). The closed triangles in Figure 27 denote the δ - factors (O_1, P_1, K_1, J_1 and OO_1 constituents) which were made for ocean tidal load correction. In this Figure, the curves (solid lines) show the theoretical estimations of Wahr's model for resonance. As shown in Figure 27, we can recognize the effect of free core resonance. However, it is important to more precisely estimate the free core resonance not only from more observation data but also from more accurate tidal load correction.

(c) Polar Motion

The perturbation of centrifugal force due to polar motion induces gravity changes. Gravity changes induced by polar motion can be estimated using instantaneous position data of the rotation axis of the earth. This amounts to a maximum of about 13 μgals (Wahr, 1985) As the periods of annual and Chandler wobbles are over one year, it is necessary to obtain stable long period data in order to detect polar motion. Therefore, until now, gravity changes due to the effect of polar motion were nearly unobservable with a few exceptions.

Richter (1990) determined the gravimetric factor of polar motion using 6-year gravity data obtained by a superconducting gravity meter at Bad Homburg, Germany. He revealed that the value of δ - factor was 1.27. Seama et al (1993) suggested that the δ - factor was 1.35 using 3-year gravity data obtained by a superconducting gravity meter at Kakioka, Japan.

To ascertain such an effect at Kyoto, we also used 990-day data obtained by SCG-009. Figure 28 shows the gravity residuals (trend component) after removing the earth tides, atmospheric pressure effects, short period irregulars and "offset" from the original data. The residuals after removing the linear trend from Figure 28 are shown in Figure 29, in which some periodic variations clearly remained. In Figure 30, the gravity residuals obtained by applying the quadratic to the trend of Figure 28 are then shown.

As shown in Figure 31, gravity changes induced by polar motion were estimated by using data of 5-day intervals obtained by the IRIS-A network employing VLBI. In this procedure, we assumed that the δ - factor is to be 1.20.

Comparing the gravity residuals obtained by SCG-009 (Figure 30) with the gravity changes induced by polar motion (Figure 31), we consider that they are in good agreement with each other. The residuals after subtracting gravity changes due to the polar motion from gravity residuals are shown in Figure 32, in which some signals from the earth should be contained. Their amounts were $\pm$ 2 μgals.

In Figure 28, we can recognize that irregular gravity changes have sometimes occurred, the source of which is not clear until now, but some part of it may be due to problems of the refrigerator system, such as poor condition of the cold head system.

In particular, the large irregular changes indicated by an open arrow in Figure 28 were affected by some trouble of the compressor of the refrigerator system. In order to determine the Chandler period, it is necessary to obtain more long period and stable data.

5. Conclusions

Continuous observations of the time change of gravity were carried out by employing two superconducting gravity meters at Kyoto.

At first, comparing the data obtained by simultaneous observations of the two gravity meters, the instrumental differences between both gravity meters and their precision were clarified as follows:

(1) Although the data length was 9 months, in the major constituents of the earth tides, δ - factors agreed within 0.001 and phases were within 0.03 degree (about 7 seconds) of each other From this result, it was ascertained that there are no instrumental differences so far as the phase is concerned, and also ascertained that the precision achieves an order of 0.1 μgal at least in the tidal band. Moreover, the response of the superconducting gravity meters for the earth tides was consistent within 0.001.

(2) It revealed that the results derived from data length longer than 90 days were reliable and sufficiently stable, that

is, δ - factors could be determined within 0.001 and phases within 0.1 degree.

(3) In the case of the data length of 30 days, for the M_2 and O_1 constituents, δ - factors were coincident within 0 002, and phases within 0.2 degree. Therefore, if the changes greater than these amounts occur, it would be possible to determine any tidal variation. Furthermore, it is suggested that a large amount of changes (over a few %) in δ - factors so far obtained may unreliable, although those were interpreted as apparent tidal changes.

(4) The effects of atmospheric pressure change on gravity change showed that the two superconducting gravity meters had similar response coefficients to atmospheric pressure changes.

(5) It was ascertained that the superconducting gravity meter maintained extreme stability in spite of various disturbances, such as stoppage of power supply, transfer of liquid helium, sphere change for earthquake occurrence and "sphere re-centering".

(6) According to the consumption of liquid helium, the super-conducting gravity meter may operate for about one and half years on a filling of the dewar.

Furthermore, analyzing the long period data which were obtained by the gravity meter SCG-009, the following was clarified :

(7) The noise level was about 20 nanogals for the terdiurnal tidal band and that of the subtidal band was about several nano-gals. Therefore, it is difficult to detect the signals under a nanogal at Kyoto because the observed data are affected by

various city noises. Then, diurnal, semidiurnal and terdiurnal tides were clearly detected, but, quarterdiurnal tides could not be detected from these data.

(8) We could detect the long period tides, free core resonance and gravity changes due to polar motion. It was confirmed that the superconducting gravity meter had high sensitivity and long-term stability. Until now, the detection of these phenomena was difficult when employing previous gravimeters of the spring type.

In order to detect small gravity signals in the earth, it not only is a stable continuous observation by the superconducting gravity meter necessary, but also precise observations of the underground water-level, rainfall, atmospheric pressure, temperature and humidity. Moreover, it is strongly required to make the calibration of scale factor using an absolute gravimeter. In future, the observation from the superconducting gravity meter attached to stable bed rock and with diminution of the city noises will be of vital importance.

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Table 1. δ - factors, phases and amplitudes for six principal tidal constituents obtained by SCG-008 and SCG-009. The plus sign of phase shows that the observed tide is in advance of the theoretical one, while the minus sign shows that the former lags behind the latter

Gravity meter	SCG - 008			SCG - 009		
Constituent	δ - factor(RMSE)	Phase(RMSE) (unit:degree)	Amplitude (unit: μgal)	δ - factor(RMSE)	Phase(RMSE) (unit:degree)	Amplitude (unit: μgal)
Period of analysis : 1988.9.26. 1989.10.20.						
O_1	1.2080±0.0011	0.18±0.05	35.270	1.2070±0.0014	0.13±0.07	35.240
P_1	1.1948±0.0025	−0.48±0.12	16.235	1.1948±0.0031	−0.64±0.15	16.235
K_1	1.1847±0.0007	−0.62±0.04	48.646	1.1844±0.0009	−0.70±0.04	48.632
N_2	1.1966±0.0011	−1.08±0.05	11.533	1.1901±0.0013	−1.06±0.06	11.471
M_2	1.2000	−0.33±0.01	60.407	1.2000	−0.44±0.01	60.416
S_2	1.2032±0.0006	−1.22±0.03	28.179	1.2029±0.0006	−1.30±0.03	28.174
Period of analysis : 1990.10.11. 1991.7.7.						
O_1	1.2079±0.0003	0.28±0.02	35.265	1.2077±0.0002	0.27±0.01	35.261
P_1	1.1941±0.0007	−0.51±0.04	16.225	1.1952±0.0005	−0.48±0.03	16.241
K_1	1.1852±0.0002	−0.51±0.01	48.664	1.1855±0.0002	−0.52±0.01	48.676
N_2	1.1876±0.0004	−0.35±0.02	11.446	1.1878±0.0002	−0.36±0.01	11.448
M_2	1.2000	−0.23±0.00	60.404	1.2000	−0.23±0.00	60.411
S_2	1.2013±0.0002	−1.11±0.01	28.137	1.2020±0.0002	−1.13±0.01	28.152

Table 2. Ratio of δ - factors and difference of δ - factors and that of phases. The difference of amplitudes is also given

Constituent	Ratio of δ - factor		Difference of δ - factor		Difference of Phases (unit:degree)		Difference of Amplitudes (unit: μgal)	
	(SCG-009) / (SCG-008)		(SCG-008) (SCG-009)					
	Former	Latter	Former	Latter	Former	Latter	Former	Latter
O_1	0.9992	0.9998	0.001	0.0002	+0.05	+0.01	+0.03	+0.004
P_1	1.0000	1.0009	0.0	-0.0011	+0.16	-0.03	0.0	-0.016
K_1	0.9997	1.0003	0.0003	-0.0003	+0.08	+0.01	+0.014	-0.012
N_2	0.9946	1.0002	0.0065	-0.0002	-0.02	+0.01	+0.062	-0.002
M_2	1.0	1.0	0.0	0.0	+0.11	0.00	-0.009	-0.007
S_2	0.9998	1.0006	0.0003	-0.0007	+0.08	+0.02	+0.005	-0.015

Table 3. δ - factors, phases and amplitudes for the major long period tides obtained by SCG-009. The period analyzed is from October 22, 1989 to July 7, 1992. Theoretical amplitudes are also shown.

Gravity meter : SCG - 009 Period of analysis : 1989. 10. 22. - 1992. 7.7.				
Constituent	δ - factor(RMSE)	Phase(RMSE) (lag:negative) (unit:degree)	Amplitude(RMSE) (unit:μ gal)	Theoretical amplitude (unit:μ gal)
MSM	1.42±0.53	+2.3±21.6	0.015±0.006	0.011
MM	1.42±0.28	+2.4±11.3	0.078±0.015	0.055
MSF	1.67±0.42	+2.8±14.5	0.015±0.004	0.009
MF	1.85±0.42	+5.3±13.0	0.192±0.044	0.104
MTM	2.16±0.35	−13.6±9.4	0.043±0.007	0.020

Table 4. δ - factors, phases and amplitudes for the twenty principal tidal constituents obtained by SCG-009. The period analyzed period is from October 22, 1989 to July 7, 1992. The plus sign of phase shows that the observed tide is in advance of the theoretical one, while the minus sign shows that the former lags behind the latter

Gravity meter : SCG - 009 Period of analysis : 1989. 10. 22. - 1992. 7. 7.			
Constituent	δ - factor(RMSE)	Phase(RMSE) (lag:negative) (unit:degree)	Amplitude(RMSE) (unit: μ gal)
Q_1	1.2074±0.0035	0.86±0.17	6.750±0.020
O_1	1.2075±0.0007	0.29±0.03	35.254±0.019
M_1	1.2059±0.0090	−0.58±0.43	2.768±0.021
π_1	1.1940±0.0222	−1.69±1.06	0.951±0.018
P_1	1.1960±0.0014	−0.52±0.07	16.251±0.019
S_1	1.3276±0.0564	1.35±2.47	0.428±0.018
K_1	1.1852±0.0004	−0.55±0.02	48.663±0.017
ϕ_1	1.2455±0.0449	−0.75±2.07	0.407±0.015
ϕ_1	1.1985±0.0294	0.31±1.41	0.701±0.017
J_1	1.1938±0.0063	−1.30±0.30	2.741±0.014
OO_1	1.1886±0.0092	−1.70±0.45	1.495±0.012
$2N_2$	1.1929±0.0025	−0.07±0.12	1.522±0.003
N_2	1.1873±0.0005	−0.29±0.02	11.443±0.005
M_2	1.2000±0.0001	−0.20±0.00	60.407±0.005
λ_2	1.2896±0.0131	−3.27±0.58	0.479±0.005
L_2	1.2538±0.0047	−1.54±0.22	1.784±0.007
T_2	1.1960±0.0034	−0.90±0.17	1.642±0.005
S_2	1.2017±0.0003	−1.03±0.01	28.145±0.006
K_2	1.2047±0.0006	−0.54±0.03	7 679±0.004
M_3	1.0956±0.0029	−0.13±0.15	0.887±0.002

Figure Captions

Fig. 1 Observation room and arrangement of superconducting gravity meters at Kyoto University.

Fig. 2. Observed gravity data obtained by SCG-008 and SCG-009 during the period from July 30, 1988 to October 20, 1989. The drift behavior indicates gravity increase. The arrow shows superconducting sphere levitation which is called "sphere re-centering".

Fig. 3. An example of offset. The arrow shows offset. This occurred on December 22, 1988, at the SCG-008 (upper). The amount of offset was a gravity increase of about 51 μgals. The lower figure shows the record obtained simultaneously by SCG-009 for comparison purposes.

Fig. 4. The number of offset occurrences every month.

Fig. 5. Amplitude response (a) and phase (b) for "TIDE" and "MODE" filters. (after GWR Instruments, 1985)

Fig. 6. Consumption curves of liquid helium. 100% of the ordinate corresponds to 200 litre of liquid helium. Open and closed arrows denote the transfer of liquid helium and the stoppage of the refrigerator system, respectively.

Fig. 7. Tidal, irregular and trend components of the data obtained by SCG-008 and SCG-009 during the period of 390 days from September 26, 1988 to October 20, 1989.

Fig. 8. Atmospheric pressure changes observed from September 26, 1988 to October 20, 1989 in the same observation room.

Fig. 9. Tidal, irregular and trend components of the data obtained by SCG-008 and SCG-009 during the period of 270 days from October 11, 1990 to July 7, 1991.

Fig. 10. Ratio of δ - factor for O_1, P_1, K_1 and S_2 constituents to that for M_2 constituent.

Fig. 11. The upper figure shows the relationship between the difference of δ - factors obtained by SCG-008 and SCG-009 and the length of period employed for an analysis. The lower figure shows the same relationship for phases.

Fig. 12. δ -factors, ratios of δ -factors and phases for SCG-008 obtained every 10 days for which 30-day data were employed in each analysis.

Fig. 13. The same as in Fig. 12 for SCG-009.

Fig. 14. The amplitude spectra of 270-day gravity data obtained by SCG-008 and SCG-009 during the period from October 11, 1990 to July 7, 1991.

Fig. 15. The amplitude spectra of 3-year gravity data obtained by the SCG-009 during the period from October 21, 1989 to October 21, 1992.

Fig. 16. The amplitude spectra in the vicinity of diurnal, semidiurnal and terdiurnal tides obtained from 3-year gravity data.

Fig. 17 A seismicity map in and around Kyoto City during the period from August 1988 to December 1992. The closed square indicates the observation site at Kyoto University. Open circles denote epicenters (Magnitude: $M \geq 3.0$, Depth: $H \leq 50km$).

Fig. 18. Observed gravity data obtained by SCG-009 during the period from July 30, 1988 to February 8, 1993. Open arrows denote sphere re-centering, while closed arrows denote earthquake occurrence. The drift behavior indicates gravity increase.

Fig. 19. Observed gravity data (a) and drift curve (b) obtained by SCG-009 during the period from October 13, 1989 to April 12, 1990. The arrow denotes the earthquake of January 11, 1990.

Fig. 20. δ - factors and phases obtained every 10 days for which 30-day data were employed in the 90-day periods before and after the earthquake occurrence on January 11, 1990.

Fig 21. Observed gravity data (a) and drift curve (b) obtained by SCG-009 during the period from August 4, 1991 to February 6, 1992. The open arrow denotes the position of the earthquake on November 2, 1991 and the closed arrow denotes the position of the re-centering on November 8, 1991.

Fig. 22. The same as in Figure 20 before the earthquake on November 2, 1991 and after the sphere re-centering on November 8, 1991.

Fig. 23 Observed gravity data (a) and drift curve (b) obtained by SCG-009 during the period from September 25, 1990 to March 24, 1991. The arrow denotes the position of the stoppage of power supply on December 24, 1990.

Fig. 24. The same as in Figure 20 before and after the stoppage of power supply on December 24, 1990.

Fig. 25. Tidal, irregular and trend components of the data obtained by the SCG-009 during the period from September 26, 1988 to February 8, 1993.

Fig. 26. The power spectrum of 990-day gravity data obtained by SCG-009 during the period from October 22, 1989 to July 7, 1992.

Fig. 27. Frequency dependence of δ - factors. The open circles denote observed results. The closed triangles denote the corrected results for the effect of ocean tidal loading. The solid lines show theoretical values according to Wahr's model

Fig. 28. Gravity residuals after the removal of the earth tides, atmospheric pressure effects, short period irregulars and offsets. The arrow shows a large irregular change.

Fig. 29. Gravity residuals after the removal of the linear trend from Figure 28.

Fig. 30. Gravity residuals after the removal of the quadratic trend from Figure 28.

Fig. 31. Gravity changes due to the polar motion at Kyoto.

Fig. 32. Residuals after subtracting Figure 31 from Figure 30

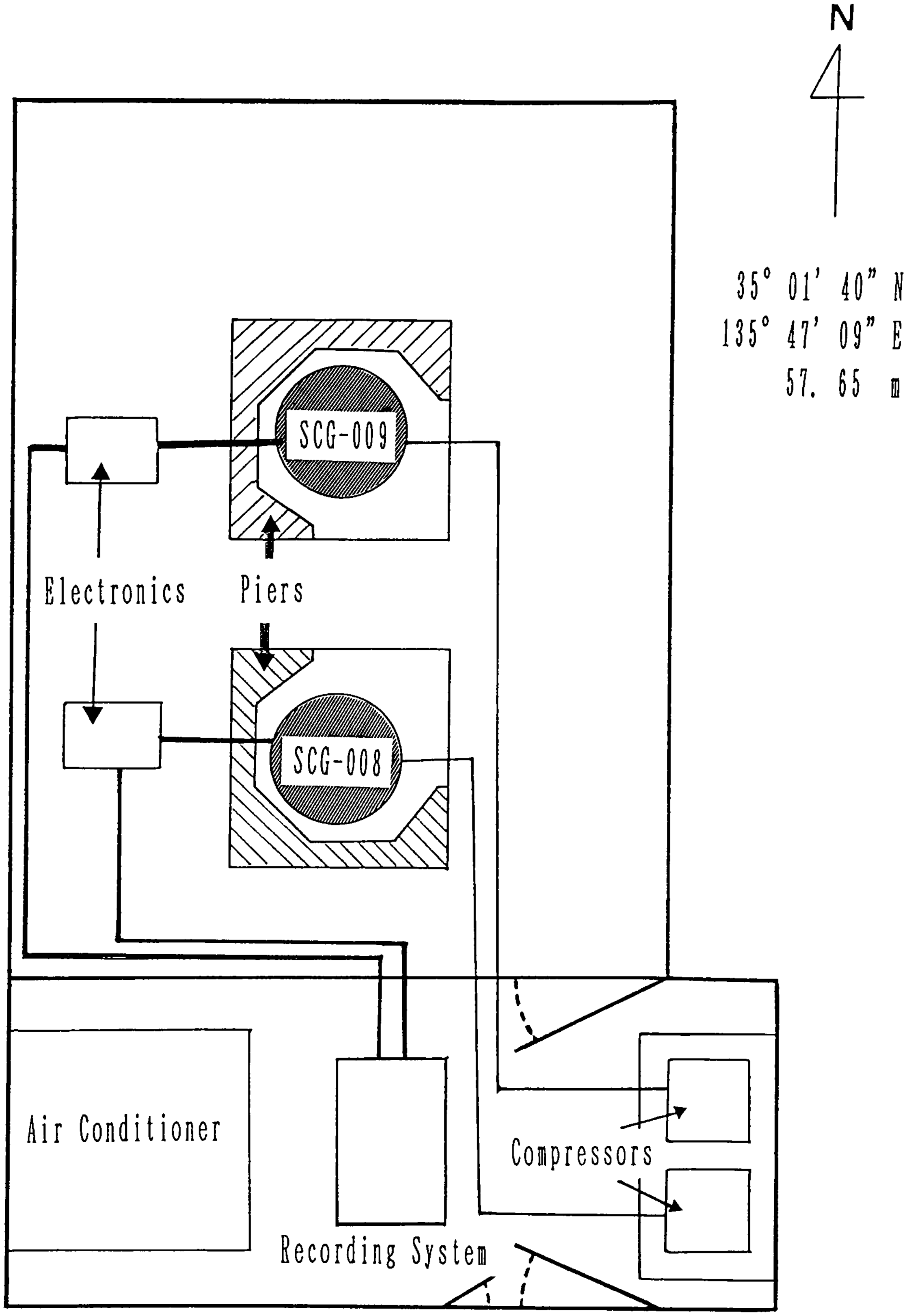

N
35° 01' 40" N
135° 47' 09" E
57. 65 m
SCG-009
Electronics
Piers
SCG-008
Air Conditioner
Compressors
Recording System

Fig. 1.

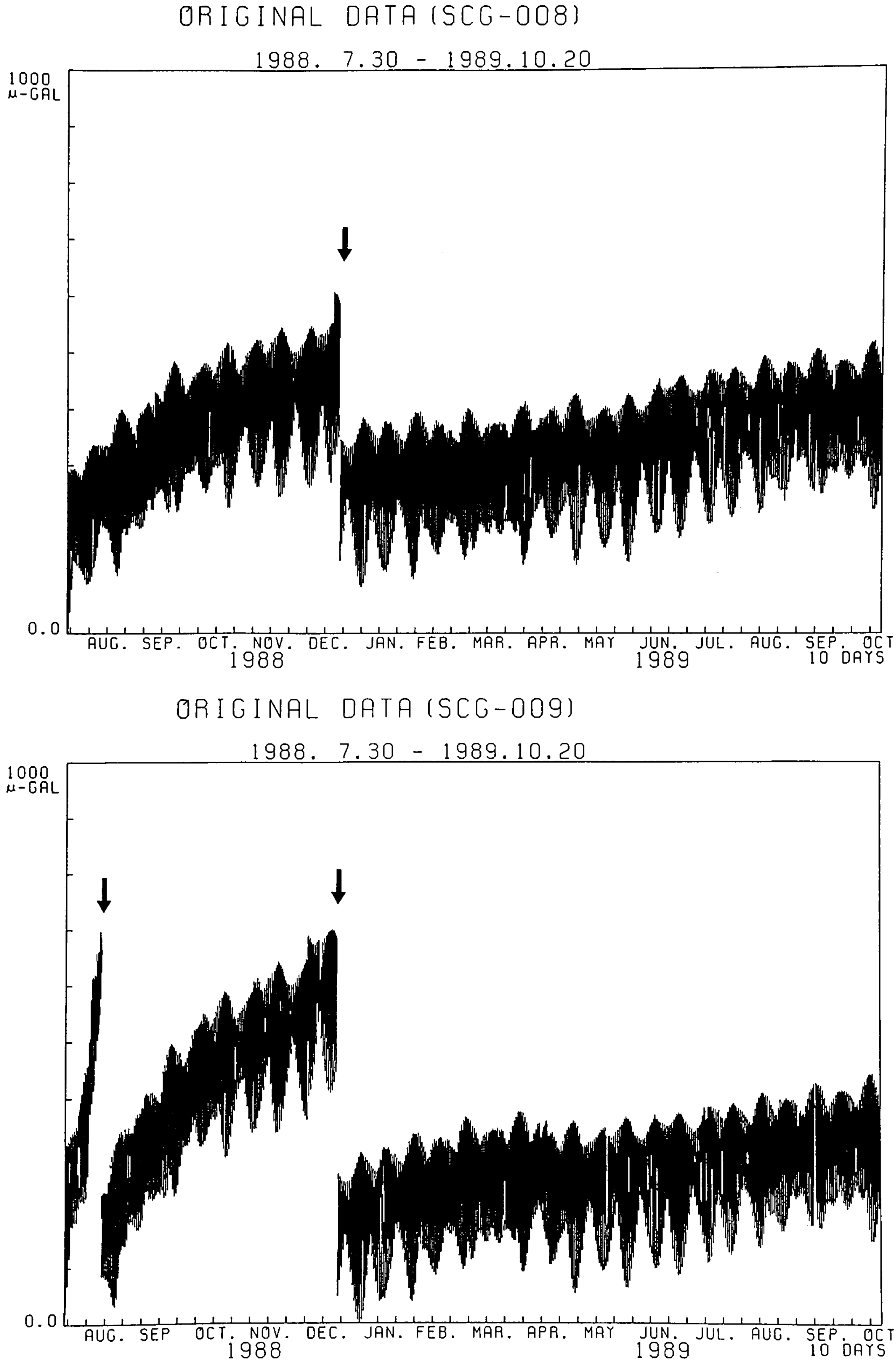

ORIGINAL DATA (SCG-008)
1988. 7.30 - 1989.10.20
1000
μ-GAL
0.0
AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT
1988
1989
10 DAYS
ORIGINAL DATA (SCG-009)
1988. 7.30 - 1989.10.20
1000
μ-GAL
0.0
AUG. SEP OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT
1988
1989
10 DAYS

Fig. 2.

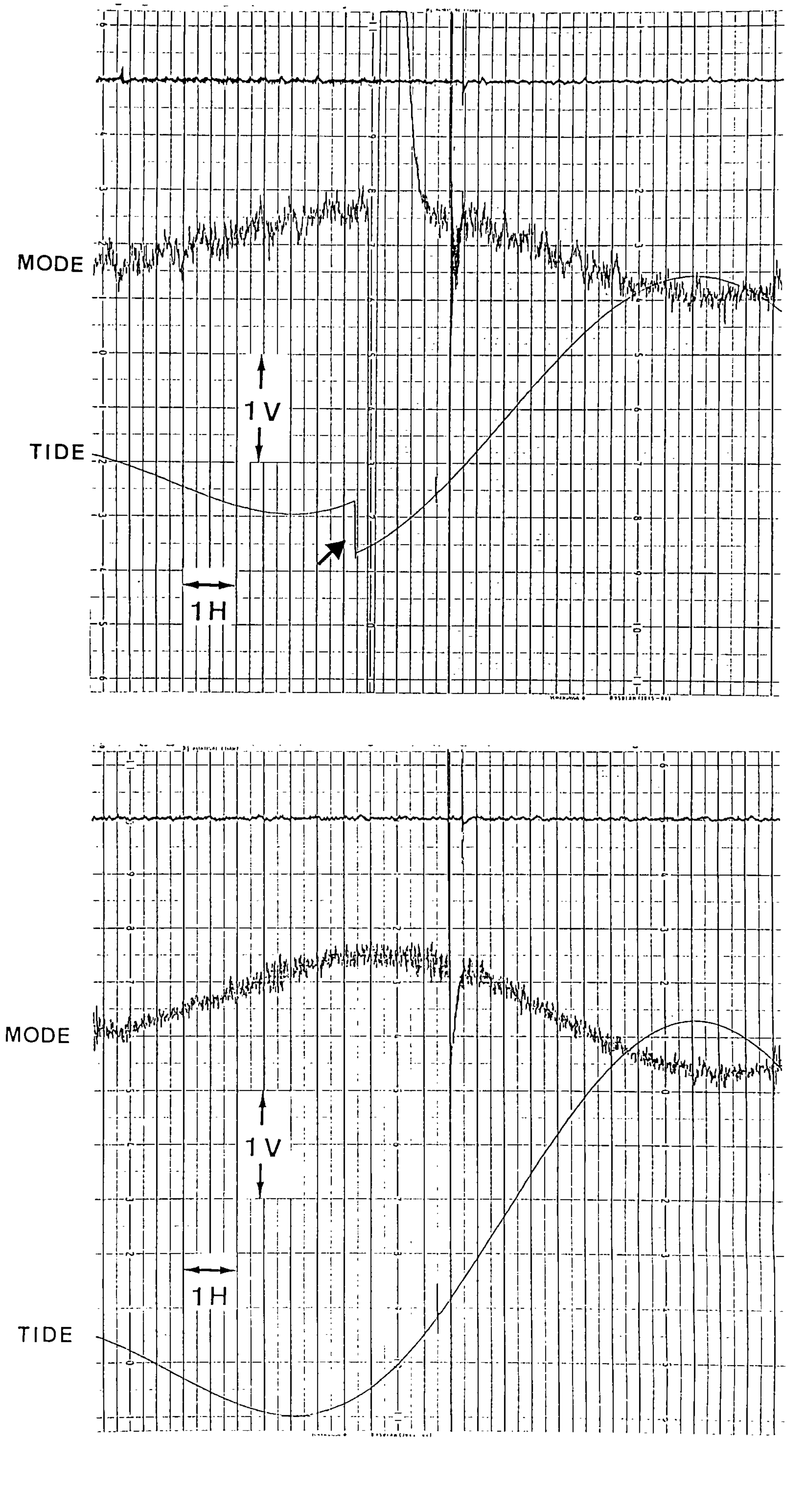
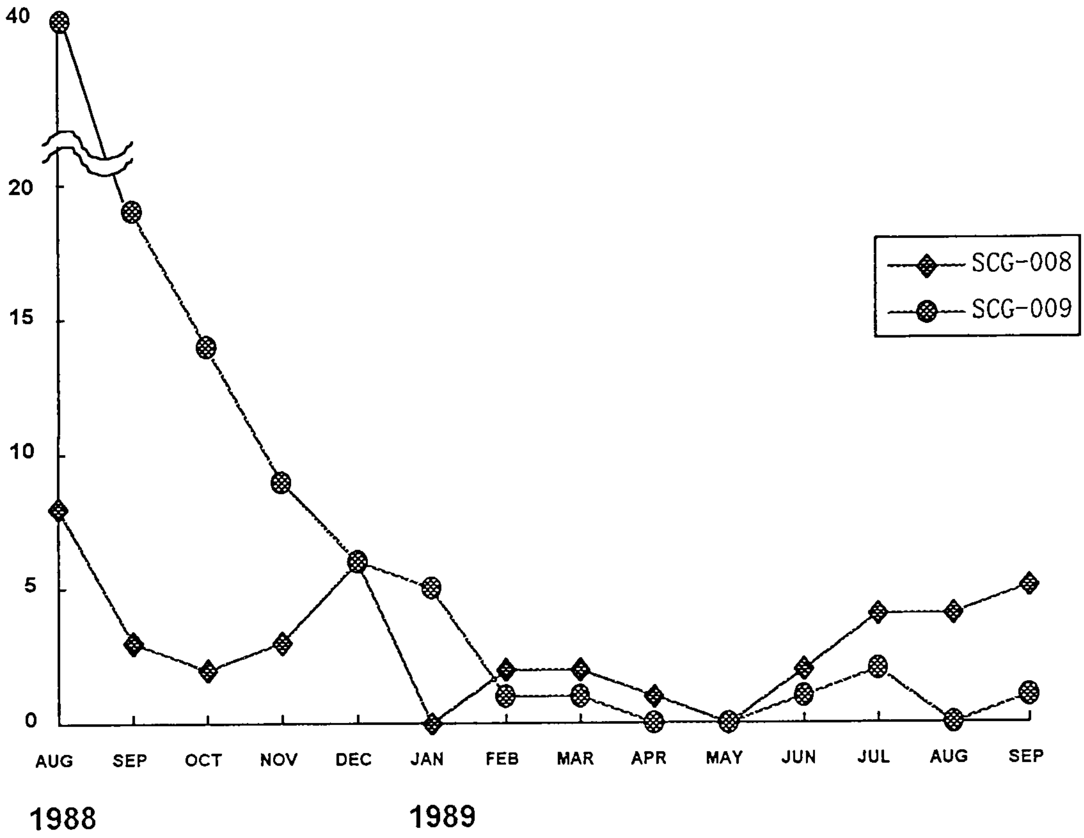


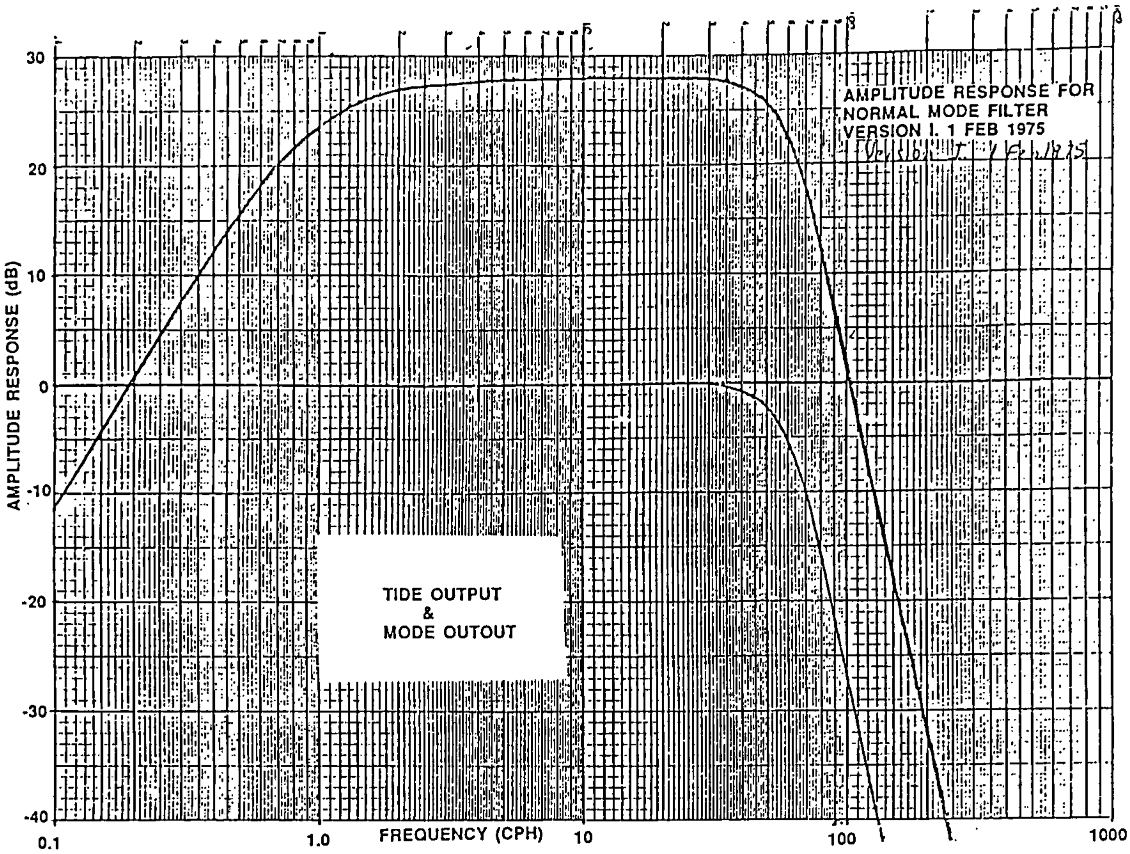
Fig. 3.



40
20
15
10
5
0
SCG-008
SCG-009
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
1988
1989

Fig. 4.

(a)


AMPLITUDE RESPONSE FOR
NORMAL MODE FILTER
VERSION I. 1 FEB 1975
Version I 1 Feb 1975
TIDE OUTPUT
&
MODE OUTOUT
AMPLITUDE RESPONSE (dB)
30
20
10
0
-10
-20
-30
-40
0.1
1.0
FREQUENCY (CPH)
10
100
1000

(b)

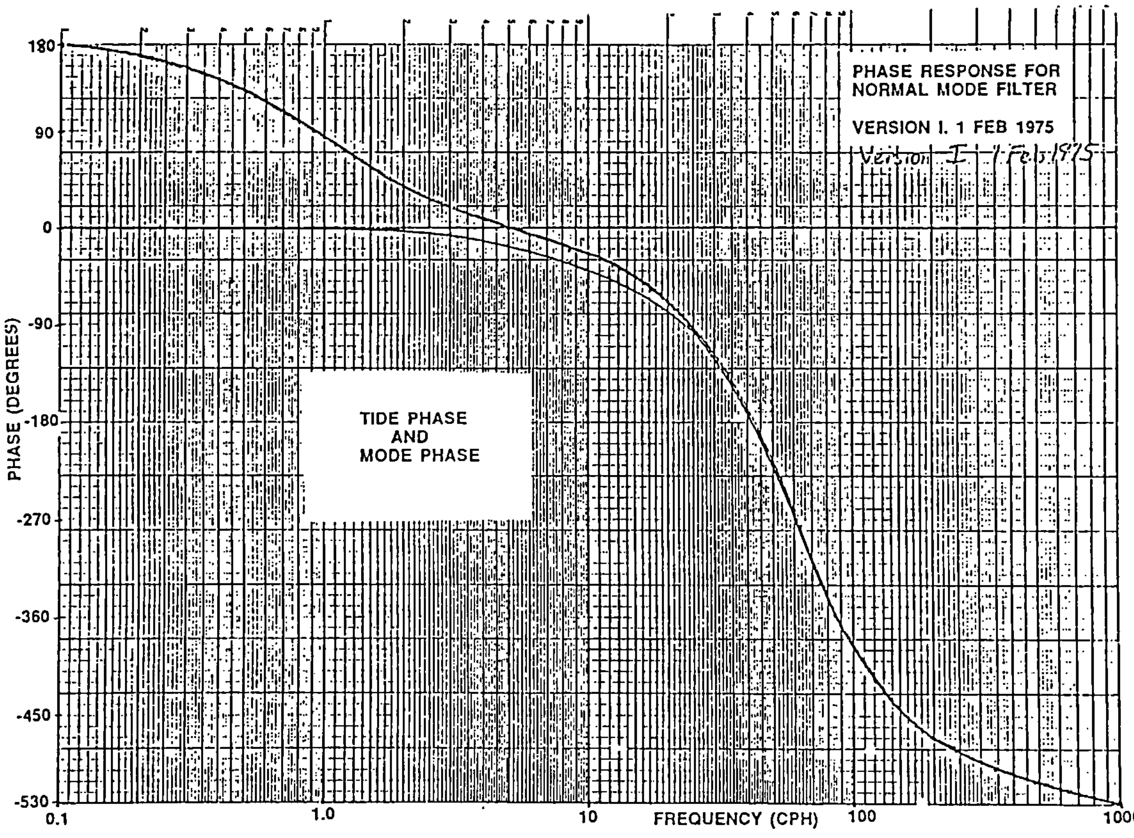

PHASE RESPONSE FOR
NORMAL MODE FILTER
VERSION I. 1 FEB 1975
Version I 1 Feb 1975
TIDE PHASE
AND
MODE PHASE
PHASE (DEGREES)
180
90
0
-90
-180
-270
-360
-450
-530
0.1
1.0
10
FREQUENCY (CPH)
100
1000

Fig. 5.

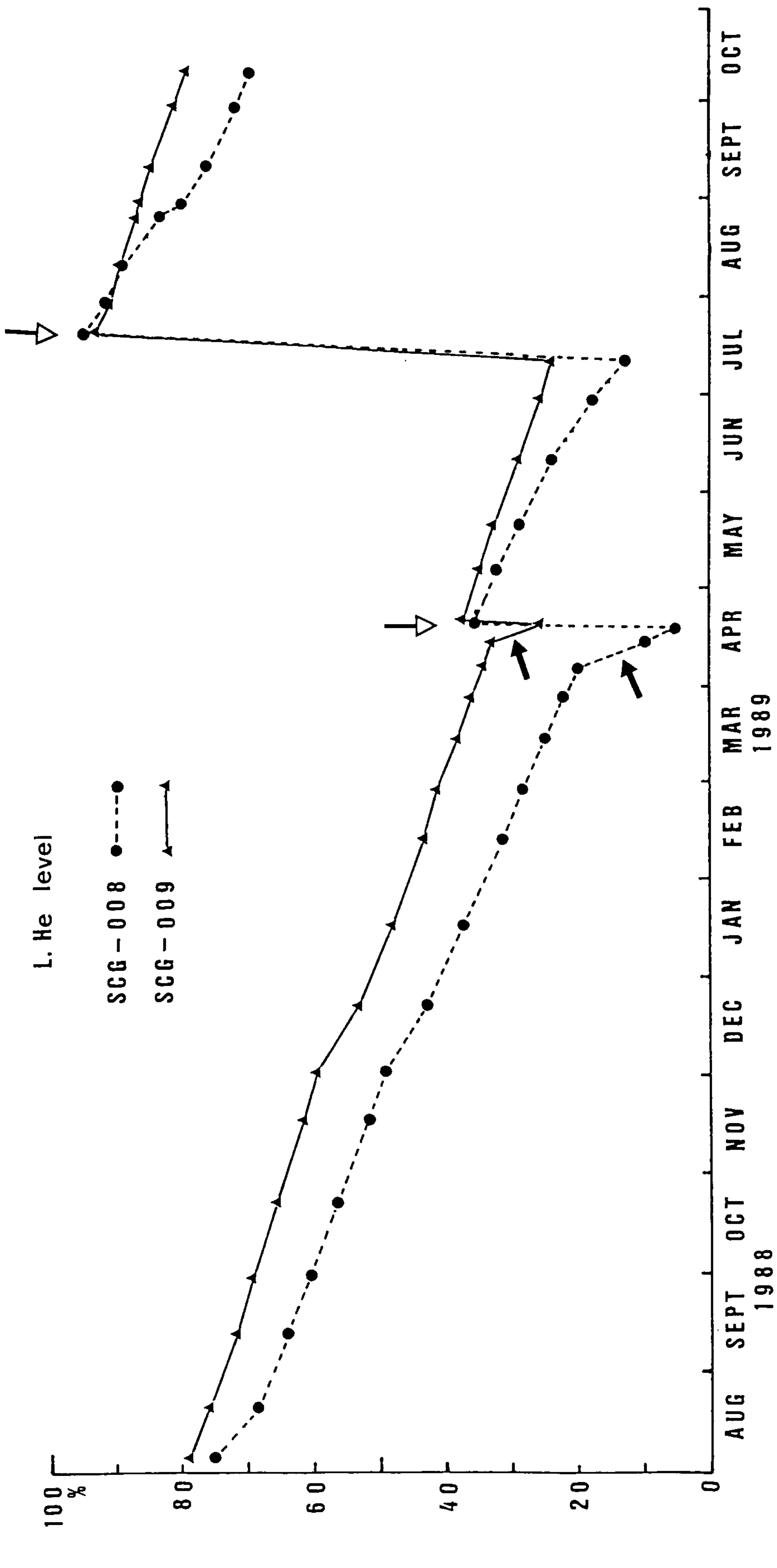

L. He level
SCG-008
SCG-009
100 %
80
60
40
20
0
AUG
SEPT
1988
OCT
NOV
DEC
JAN
FEB
MAR
1989
APR
MAY
JUN
JUL
AUG
SEPT
OCT

Fig. 6.

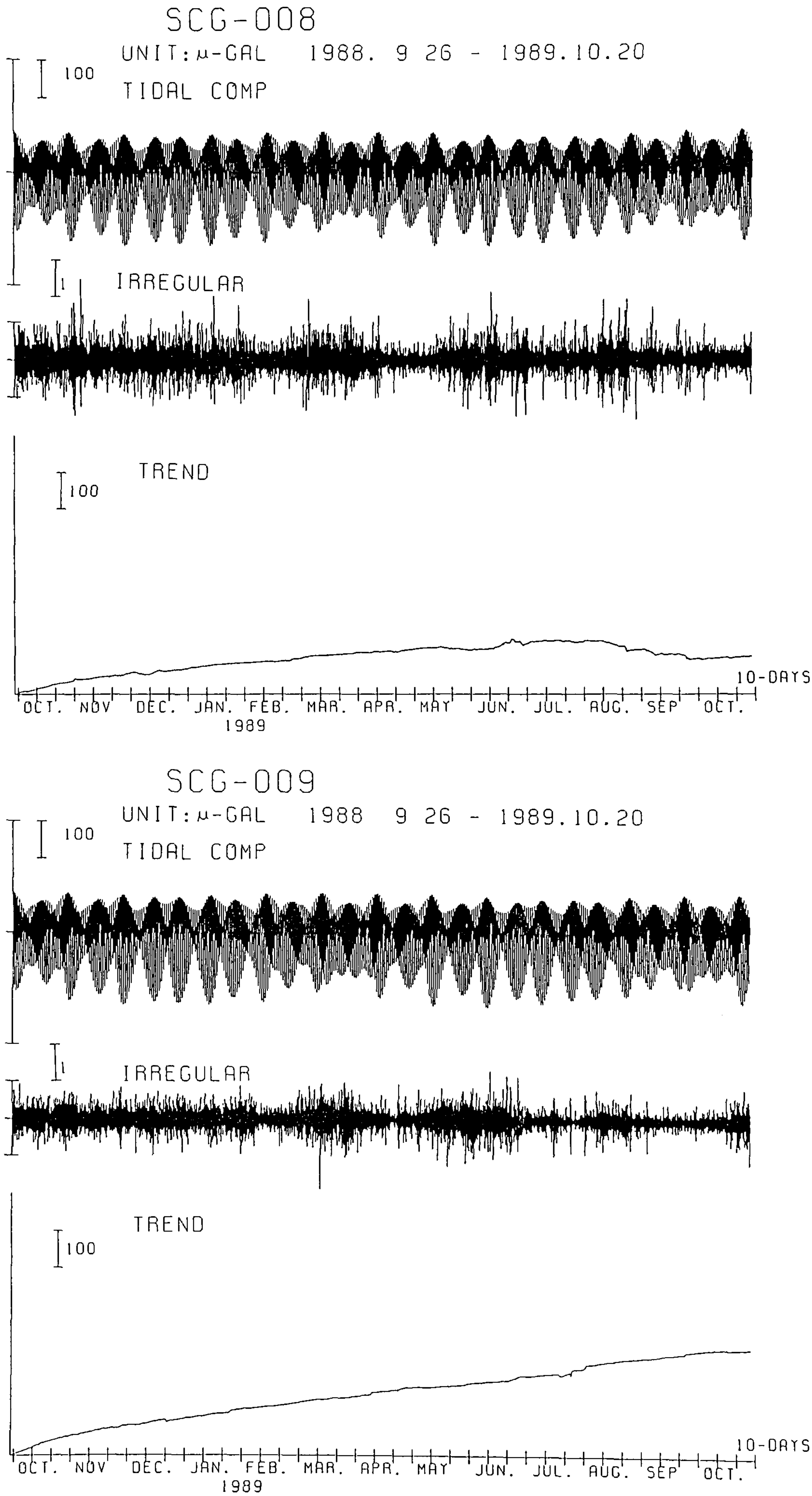
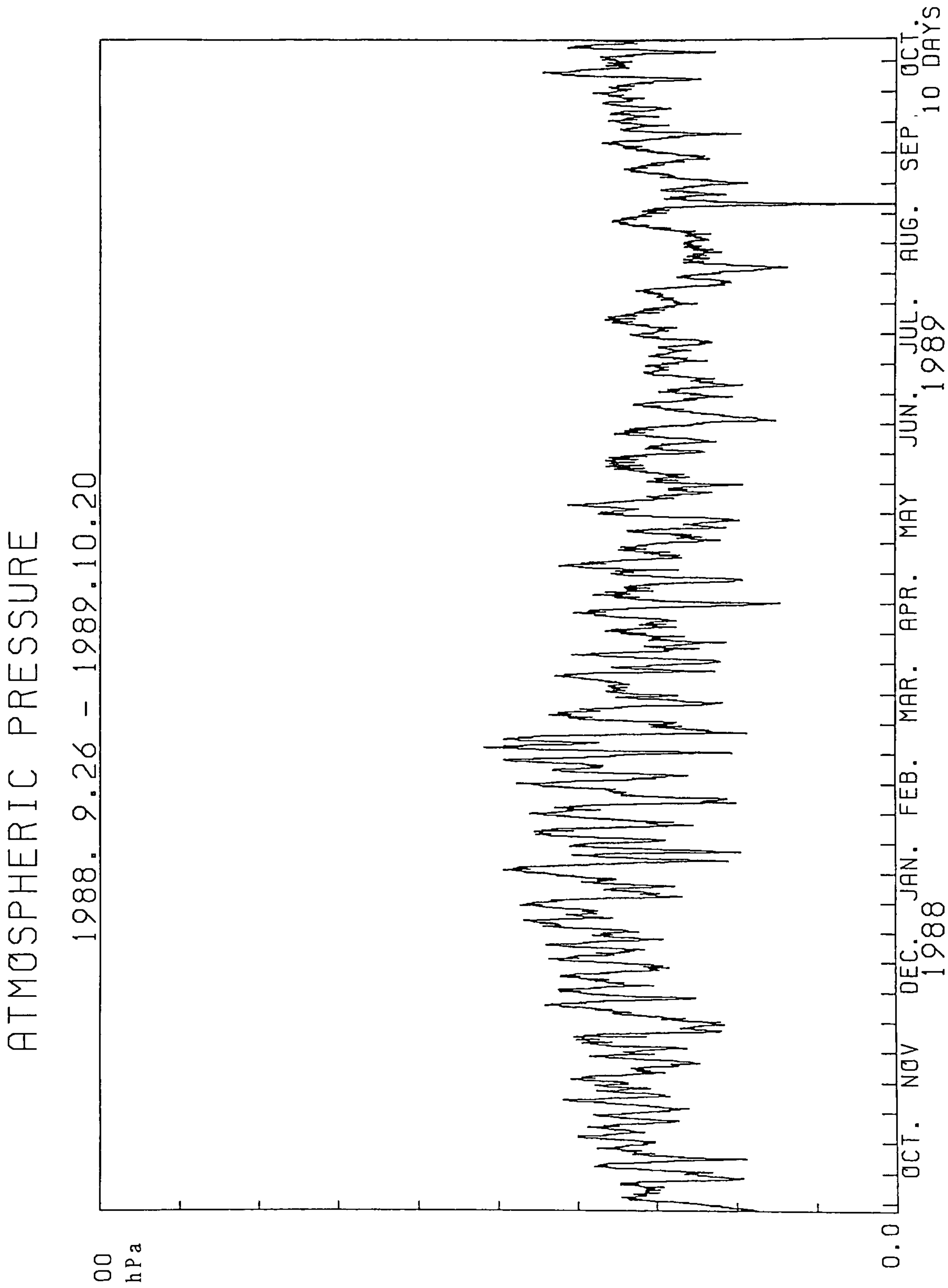
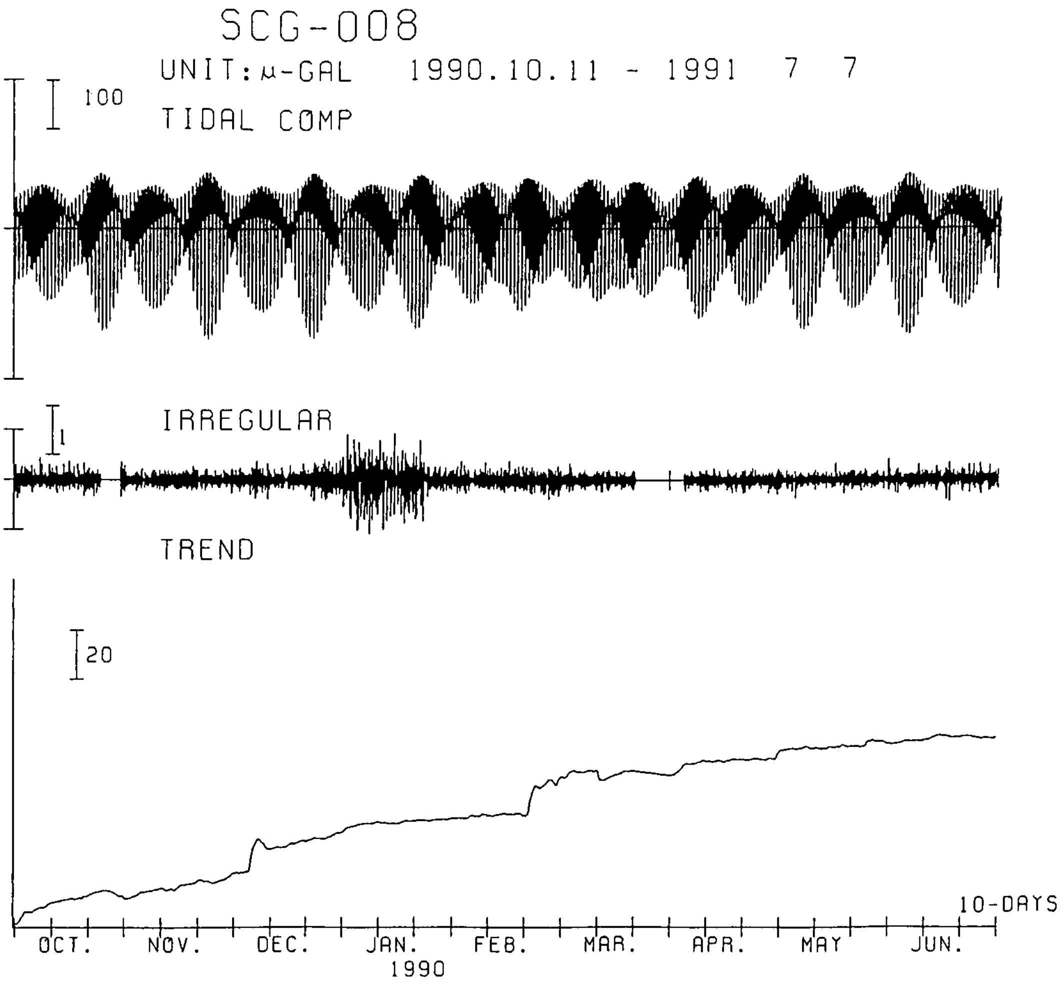

SCG-008
UNIT:μ-GAL 1988. 9 26 - 1989.10.20
100
TIDAL COMP
1
IRREGULAR
100
TREND
10-DAYS
OCT. NOV DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP OCT.
1989
SCG-009
UNIT:μ-GAL 1988 9 26 - 1989.10.20
100
TIDAL COMP
1
IRREGULAR
100
TREND
10-DAYS
OCT. NOV DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP OCT.
1989

Fig. 7.



ATMØSPHERIC PRESSURE
1988. 9.26 - 1989.10.20
100
hPa
0.0
OCT.
NOV
DEC.
1988
JAN.
FEB.
MAR.
APR.
MAY
JUN.
1989
JUL.
AUG.
SEP.
OCT.
10 DAYS

Fig. 8.


SCG-008
UNIT:μ-GAL 1990.10.11 - 1991 7 7
100
TIDAL COMP
IRREGULAR
1
TREND
20
10-DAYS
OCT.
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUN.
1990

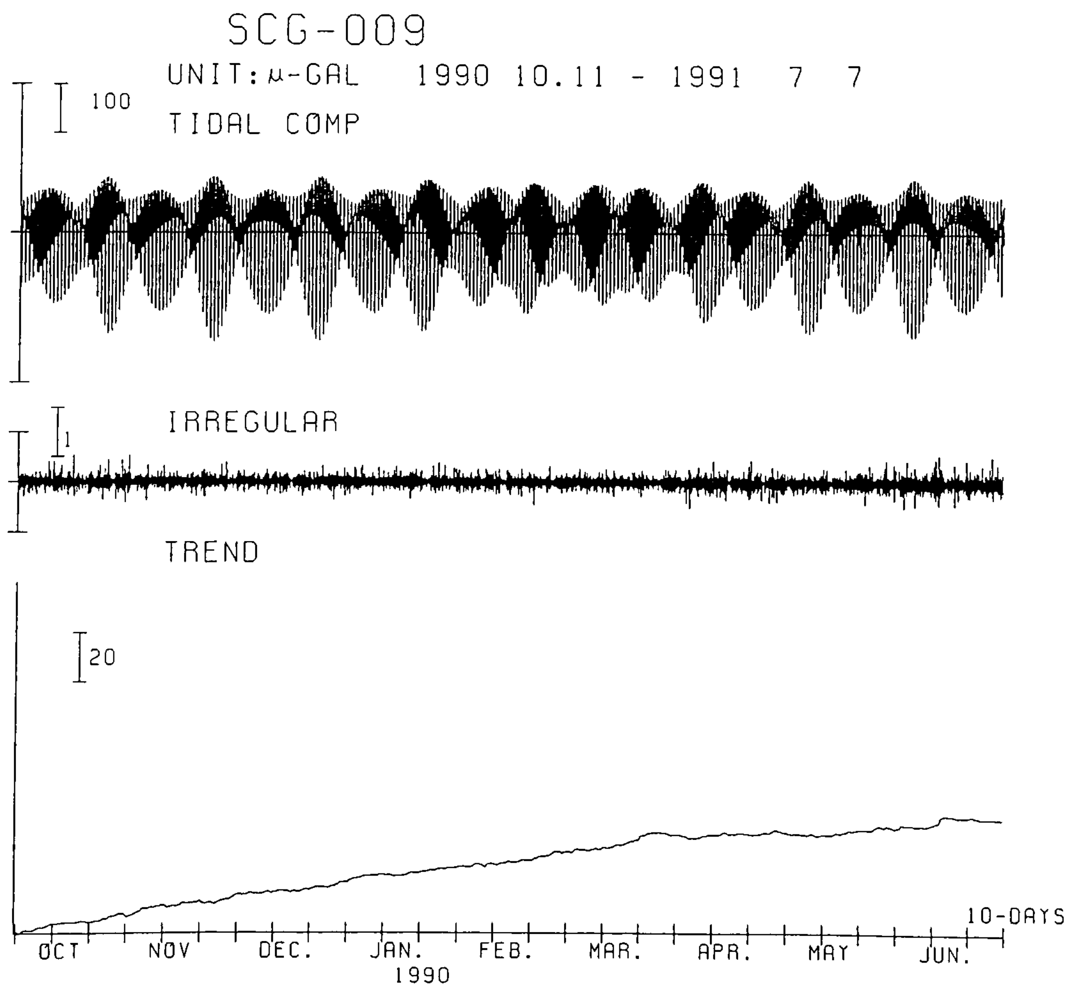

SCG-009
UNIT:μ-GAL 1990 10.11 - 1991 7 7
100
TIDAL COMP
IRREGULAR
1
TREND
20
10-DAYS
OCT
NOV
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUN.
1990

Fig. 9.

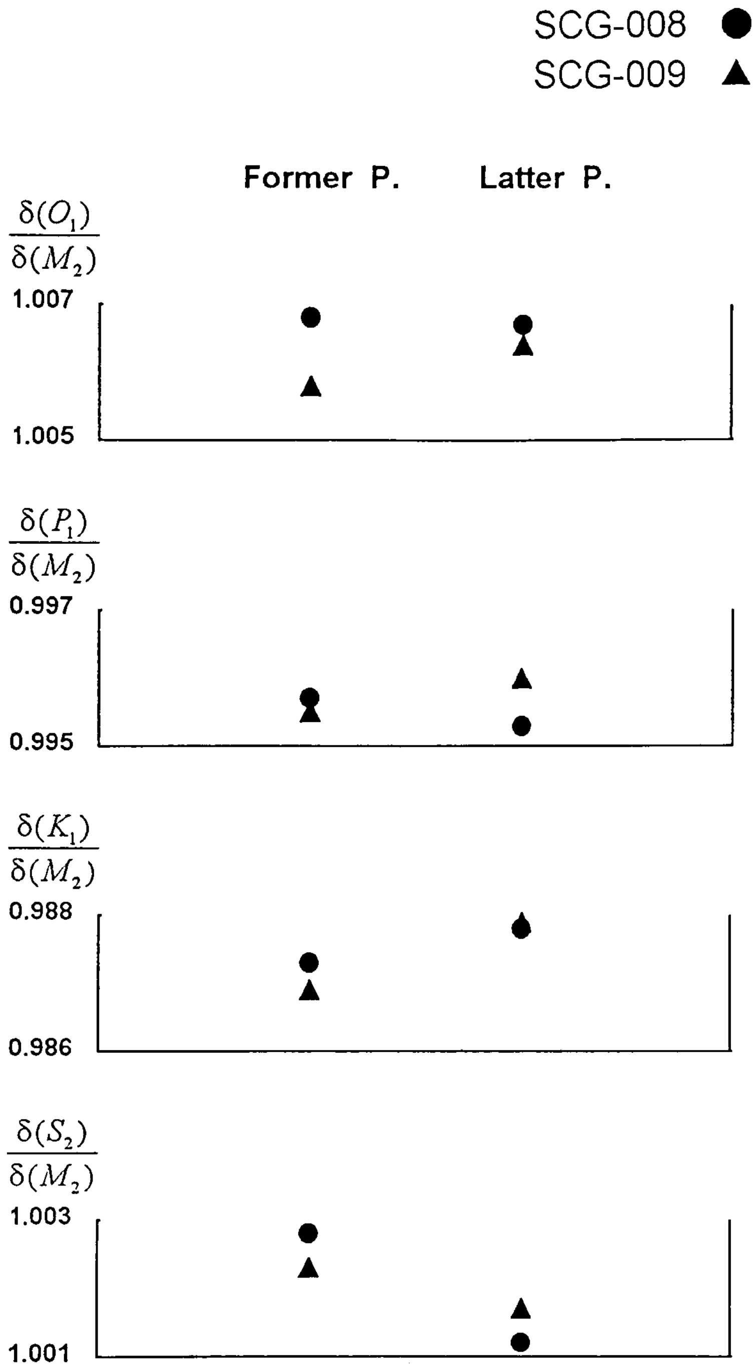

SCG-008
SCG-009
Former P.
Latter P.
$\frac{\delta(O_1)}{\delta(M_2)}$
1.007
1.005
$\frac{\delta(P_1)}{\delta(M_2)}$
0.997
0.995
$\frac{\delta(K_1)}{\delta(M_2)}$
0.988
0.986
$\frac{\delta(S_2)}{\delta(M_2)}$
1.003
1.001

Fig. 10.

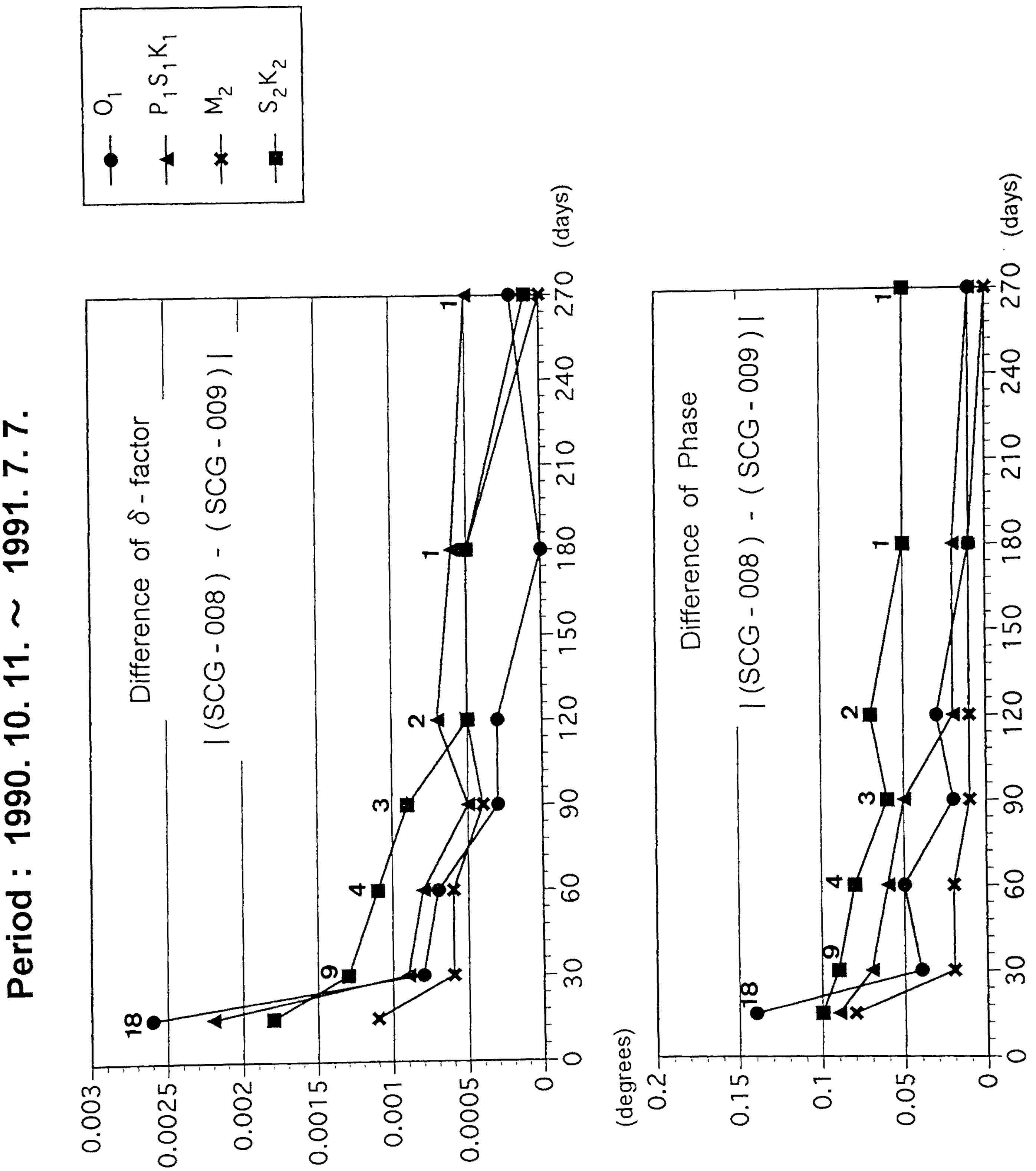
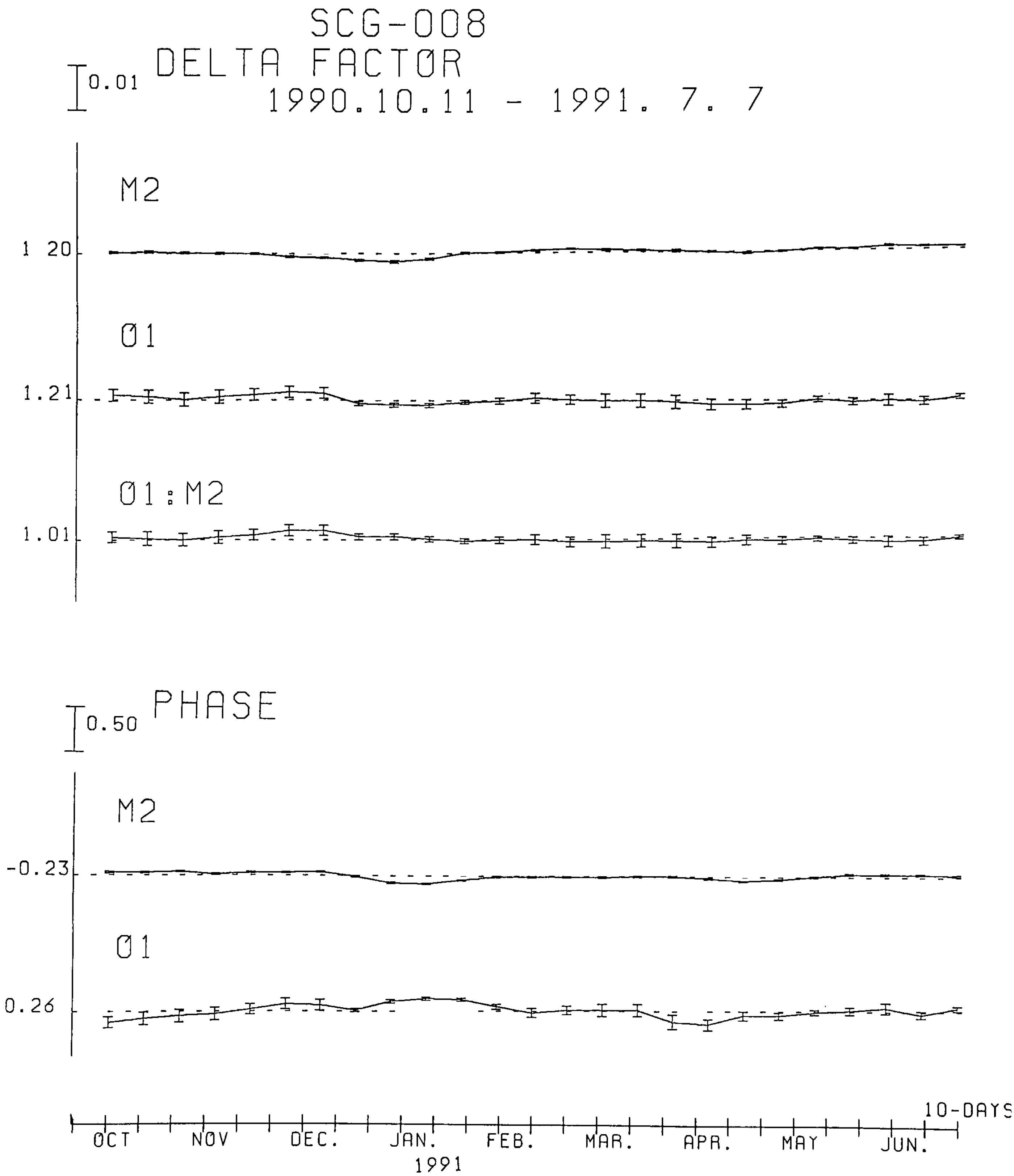
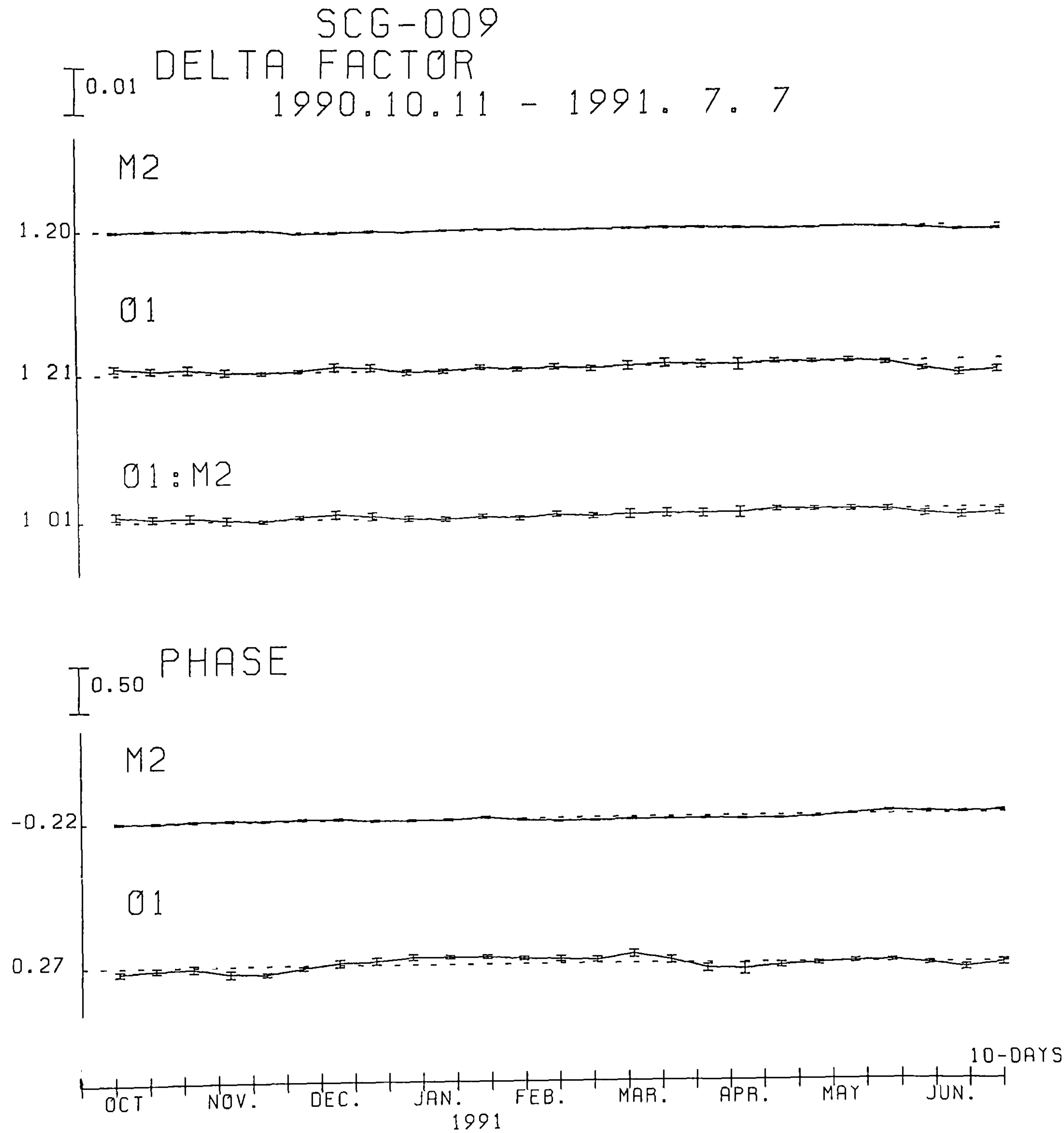

Period : 1990. 10. 11. ~ 1991. 7. 7.
Difference of δ - factor
| (SCG - 008) - (SCG - 009) |
Difference of Phase
| (SCG - 008) - (SCG - 009) |
(degrees)
(days)
O_1
$P_1S_1K_1$
M_2
S_2K_2

Fig. 11.



SCG-008
0.01 DELTA FACTOR
1990.10.11 - 1991. 7. 7
M2
1 20
O1
1.21
O1:M2
1.01
0.50 PHASE
M2
-0.23
O1
0.26
10-DAYS
OCT
NOV
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUN.
1991

Fig. 12.



SCG-009
0.01
DELTA FACTOR
1990.10.11 - 1991. 7. 7
M2
1.20
Ø1
1 21
Ø1:M2
1 01
0.50
PHASE
M2
-0.22
Ø1
0.27
10-DAYS
OCT
NOV.
DEC.
JAN.
FEB.
MAR.
APR.
MAY
JUN.
1991

Fig. 13.

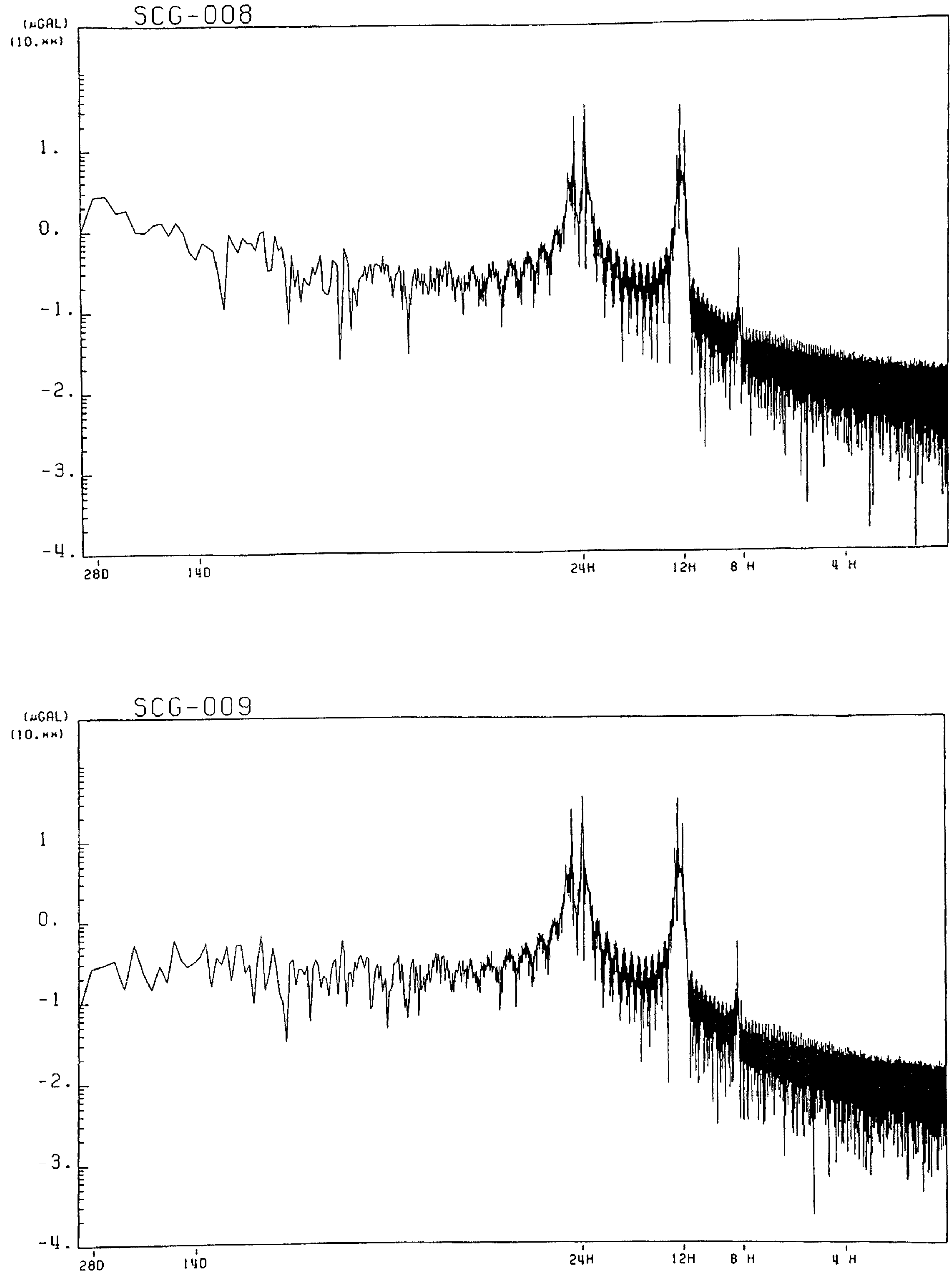

SCG-008
(μGAL)
(10.**)
1.
0.
-1.
-2.
-3.
-4.
28D
14D
24H
12H
8 H
4 H
SCG-009
(μGAL)
(10.**)
1
0.
-1
-2.
-3.
-4.
28D
14D
24H
12H
8 H
4 H

Fig. 14.

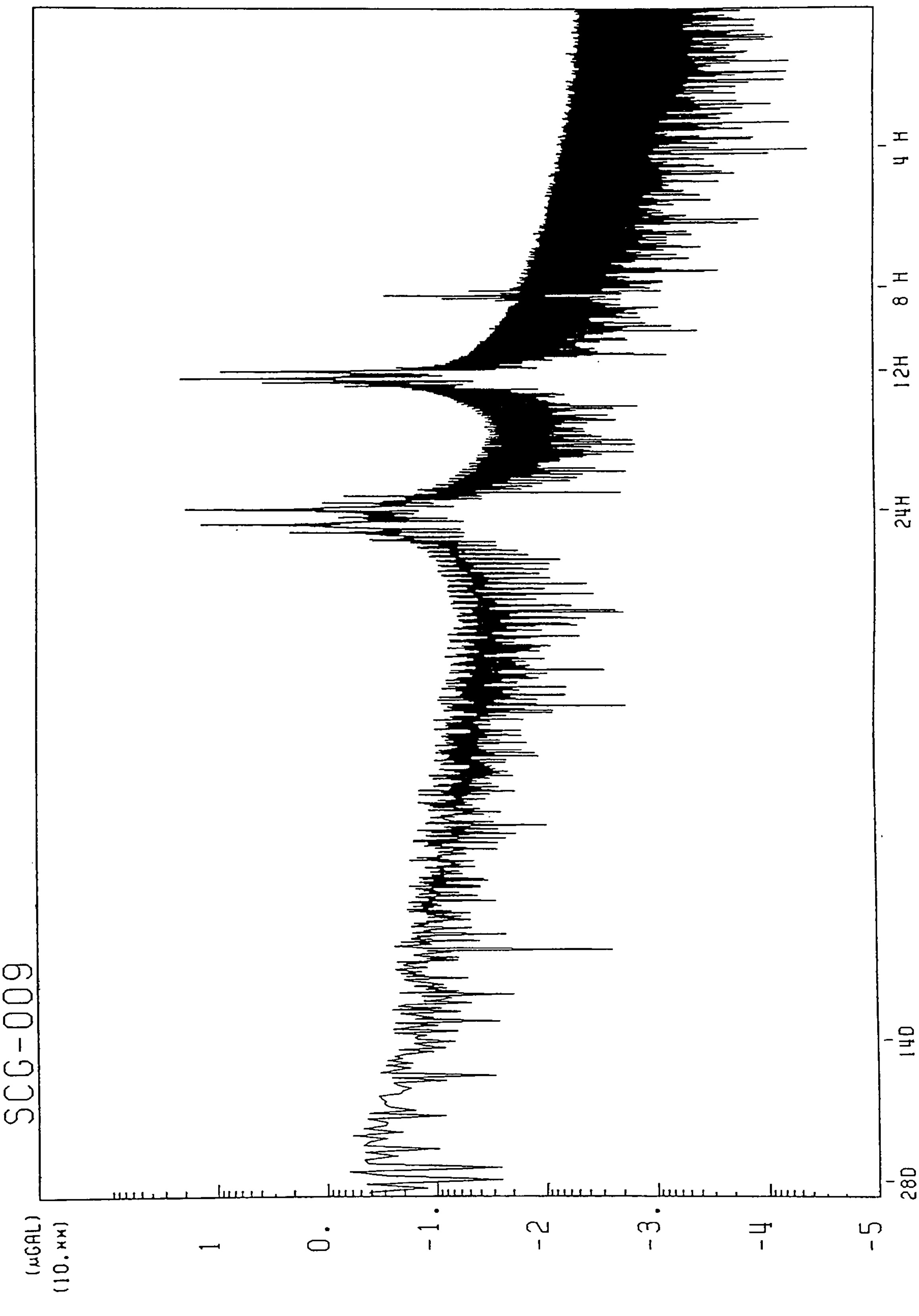


Fig. 15.

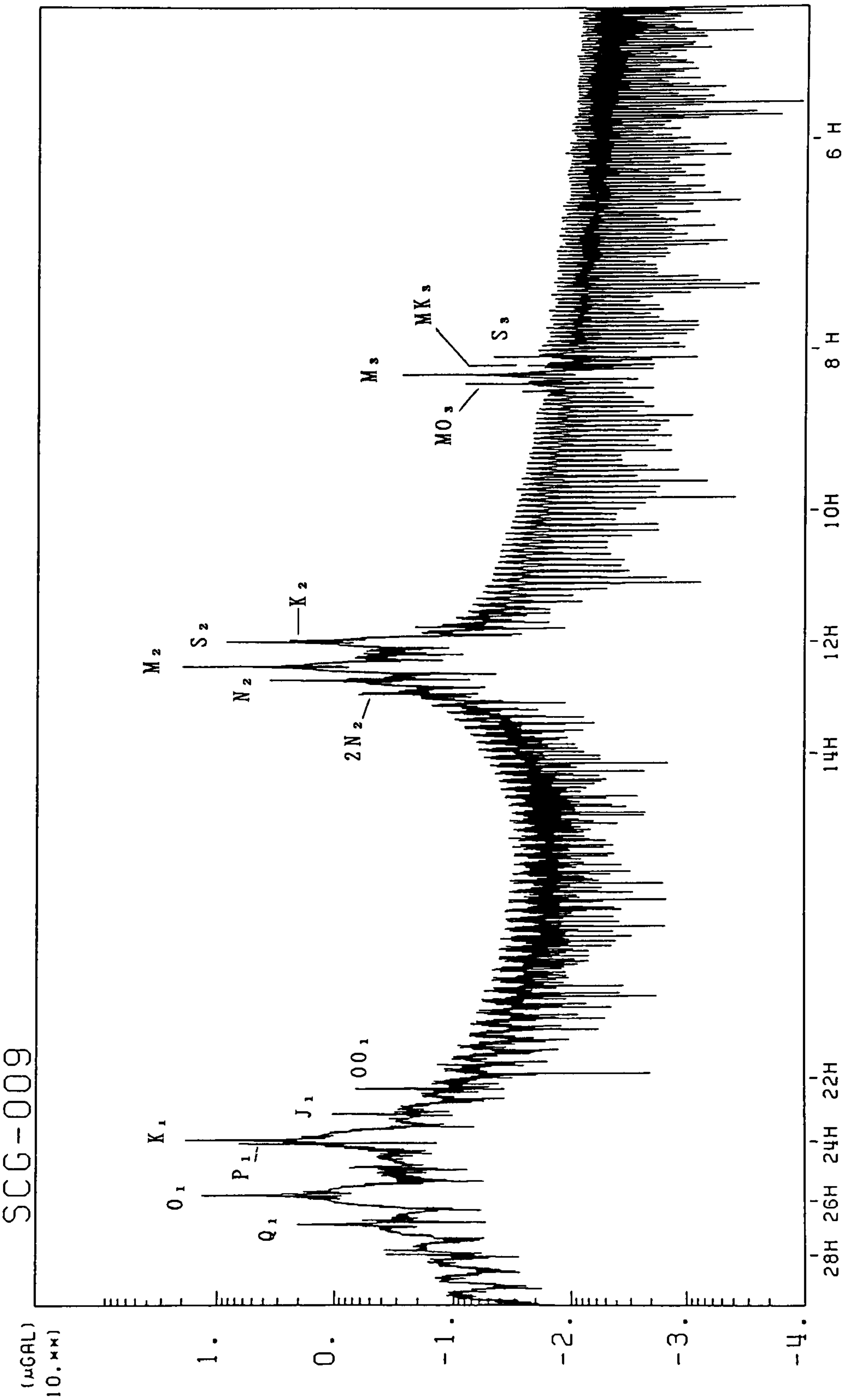
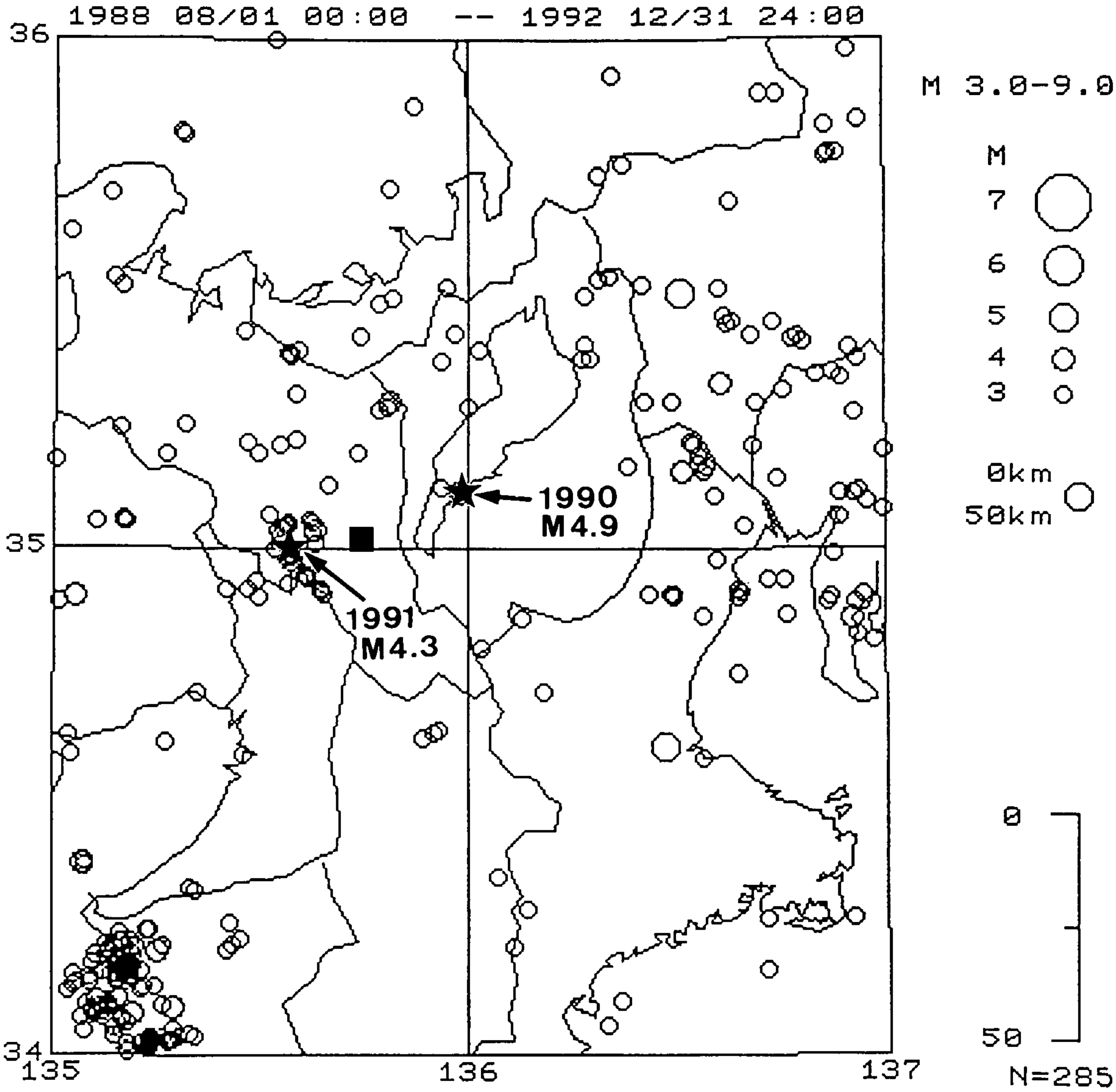

SCG-009
(μGAL)
10.**)
1.
0.
-1.
-2.
-3.
-4.
28H
26H
24H
22H
14H
12H
10H
8 H
6 H
Q1
O1
P1
K1
J1
OO1
2N2
N2
M2
S2
K2
MO3
M3
MK3
S3

Fig. 16.



1988 08/01 00:00 -- 1992 12/31 24:00
36
35
34
135
136
137
M 3.0-9.0
M
7
6
5
4
3
0km
50km
1990
M4.9
1991
M4.3
0
50
N=285

Fig. 17.

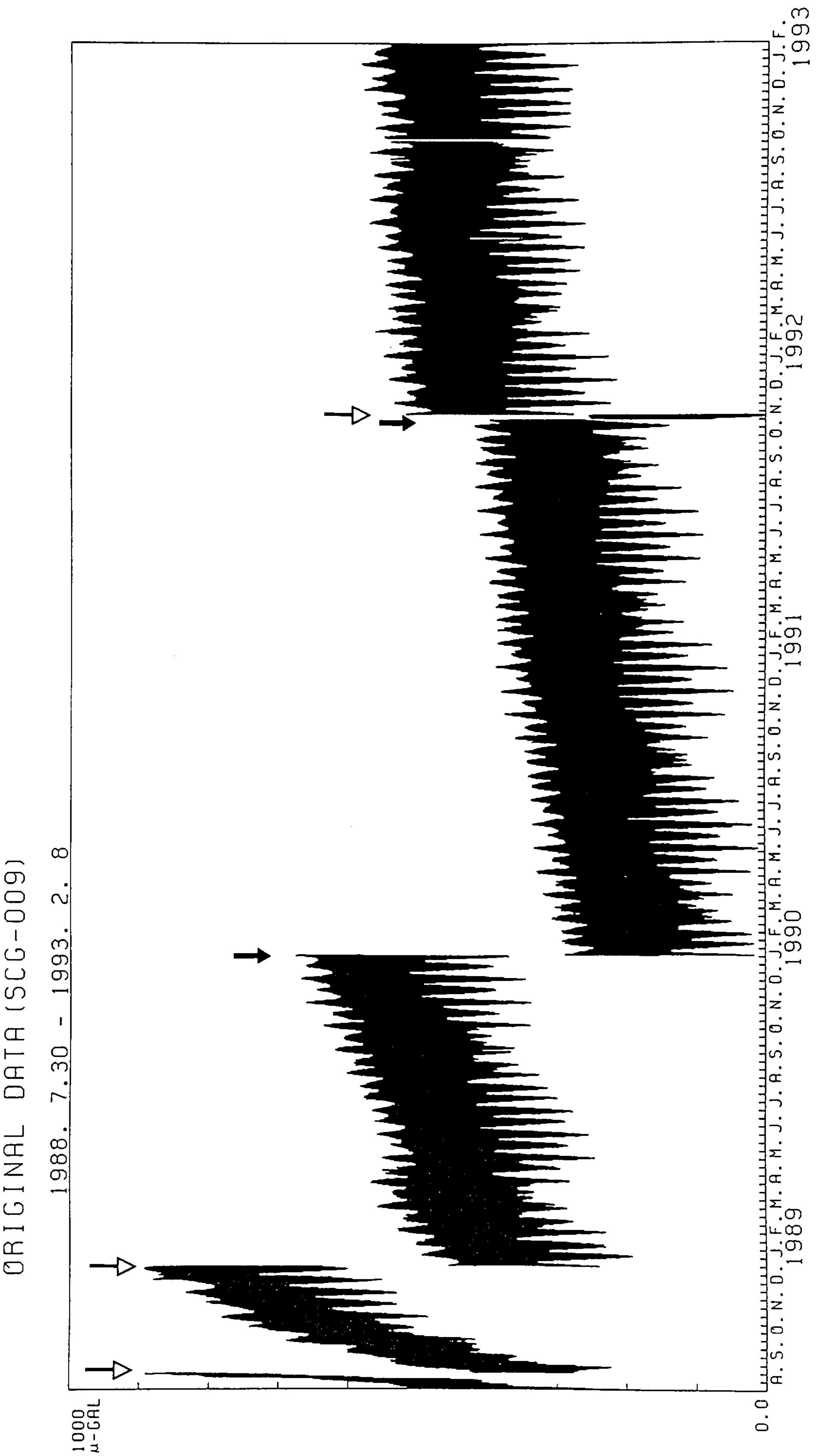

ORIGINAL DATA (SCG-009)
1988. 7.30 - 1993. 2. 8
1000 µ-GAL
0.0
1989
1990
1991
1992
1993

Fig. 18.

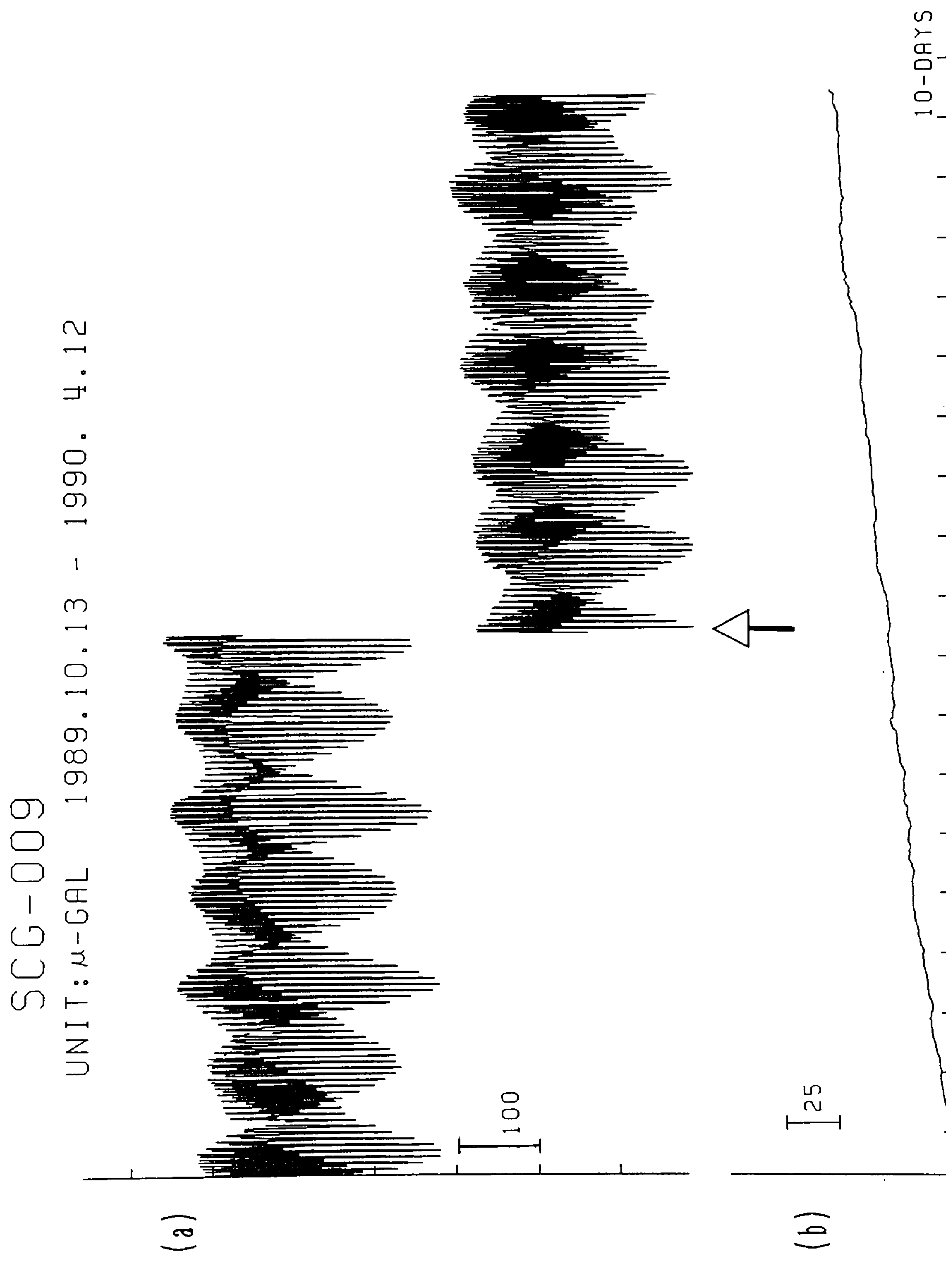

SCG-009
UNIT: μ-GAL 1989.10.13 - 1990. 4.12
(a)
100
(b)
25
NOV.
DEC.
JAN.
1990
FEB.
MAR.
APR.
10-DAYS

Fig. 19.

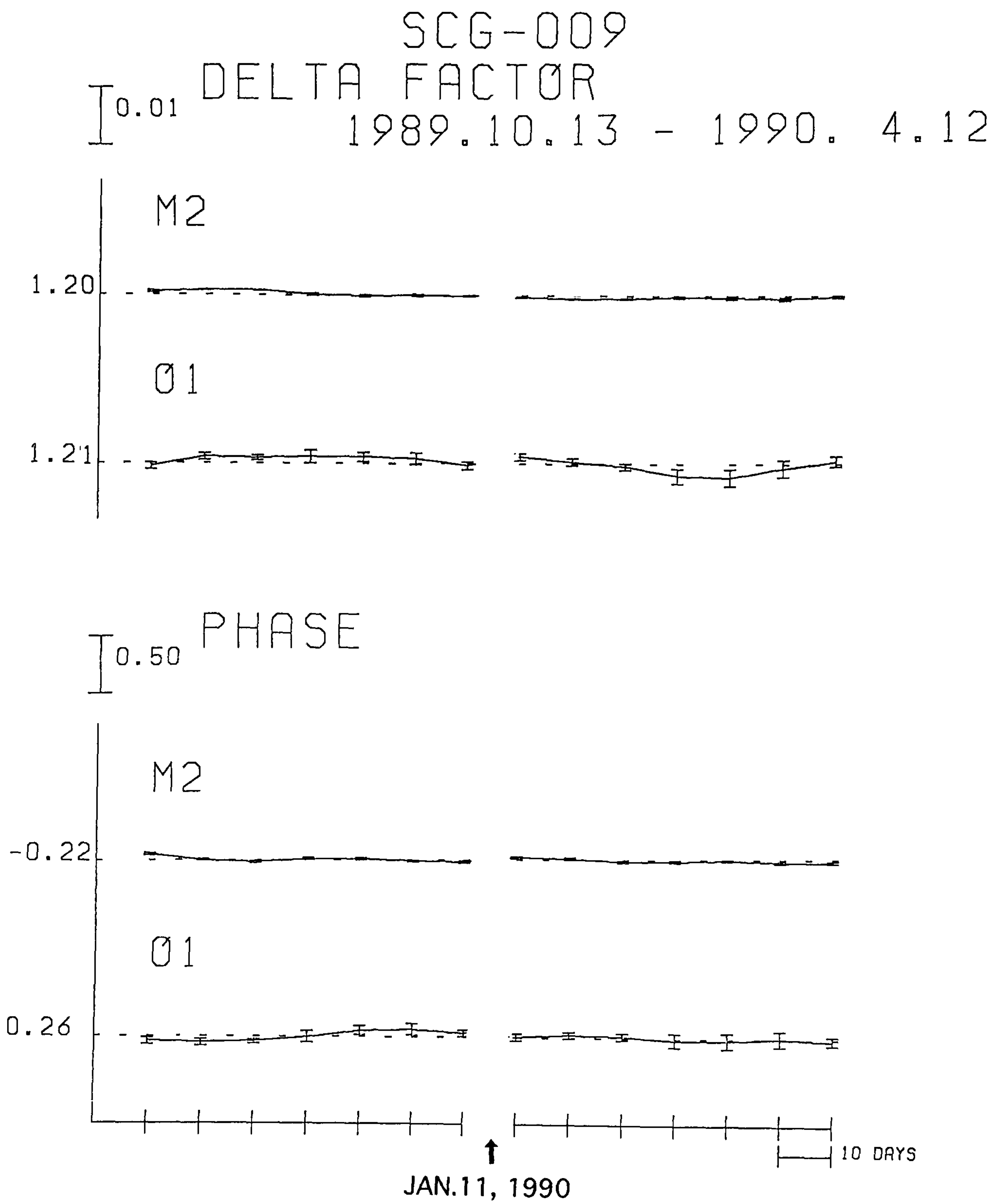

SCG-009
0.01
DELTA FACTOR
1989.10.13 - 1990. 4.12
M2
1.20
01
1.21
0.50
PHASE
M2
-0.22
01
0.26
10 DAYS
JAN.11, 1990

Fig. 20.

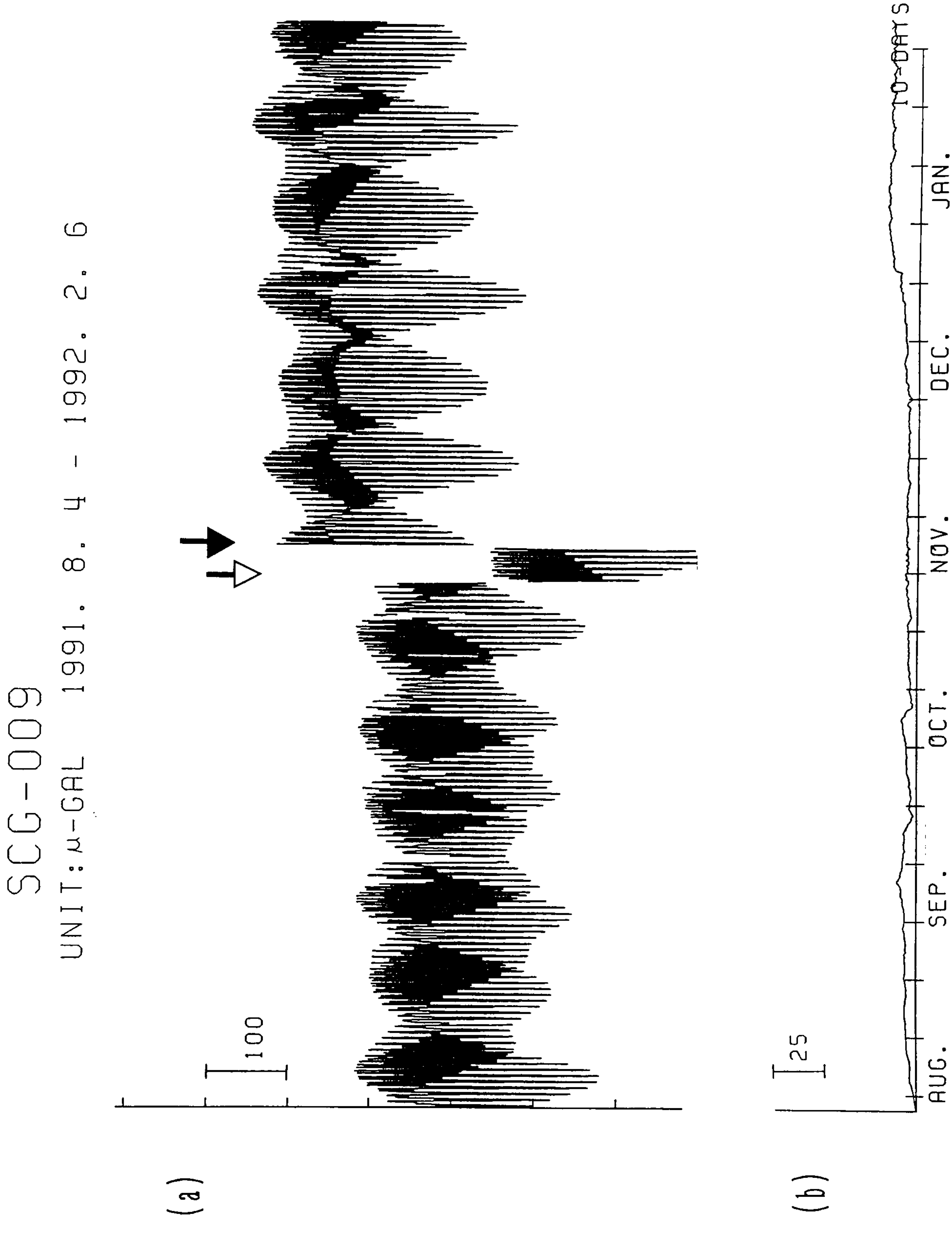

SCG-009
UNIT:μ-GAL 1991. 8. 4 - 1992. 2. 6
100
25
(a)
(b)
AUG.
SEP.
OCT.
NOV.
DEC.
JAN.
1991
10-DAYS

Fig. 21.

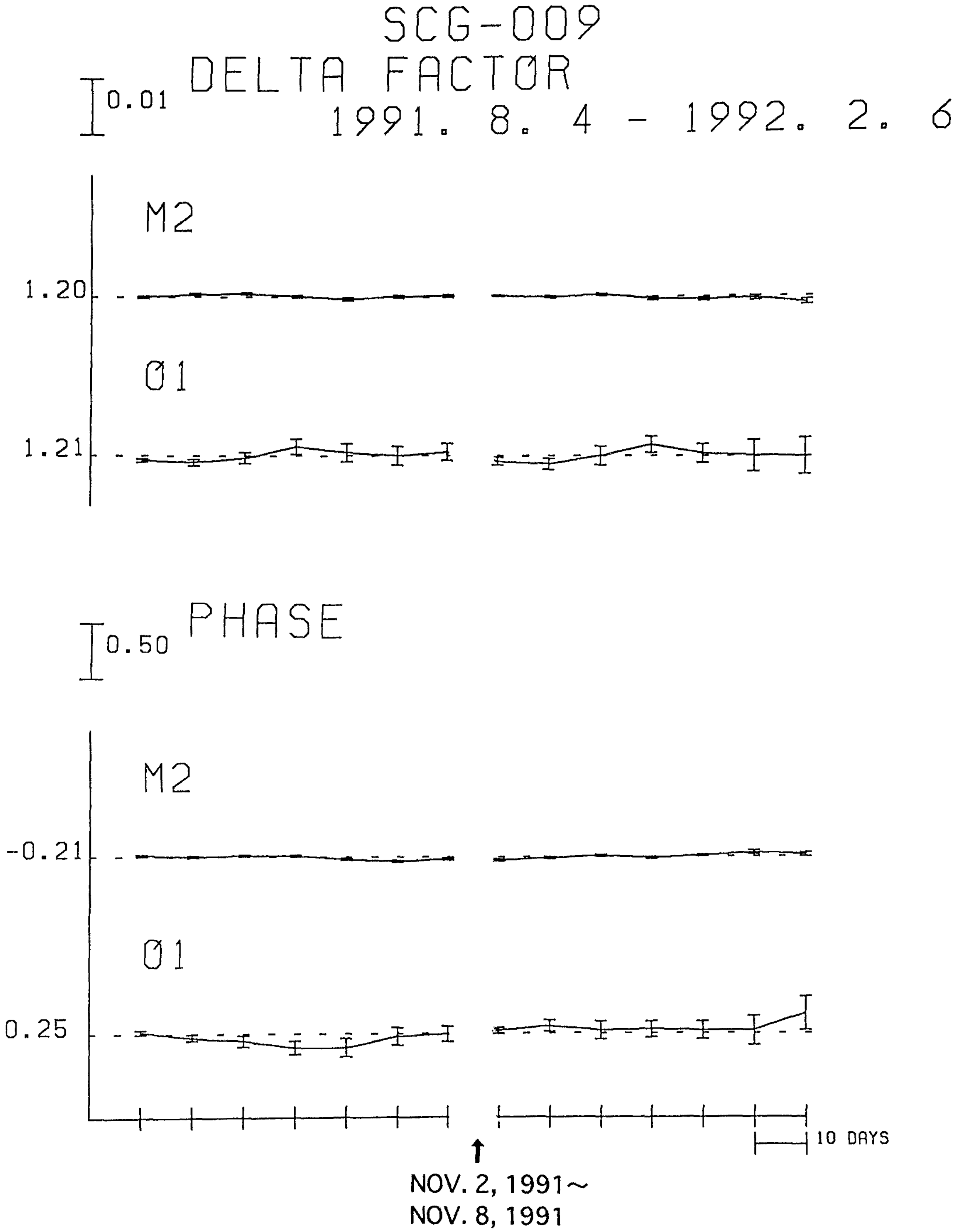

SCG-009
DELTA FACTOR
0.01
1991. 8. 4 - 1992. 2. 6
M2
1.20
O1
1.21
PHASE
0.50
M2
-0.21
O1
0.25
10 DAYS
NOV. 2, 1991~
NOV. 8, 1991

Fig. 22.

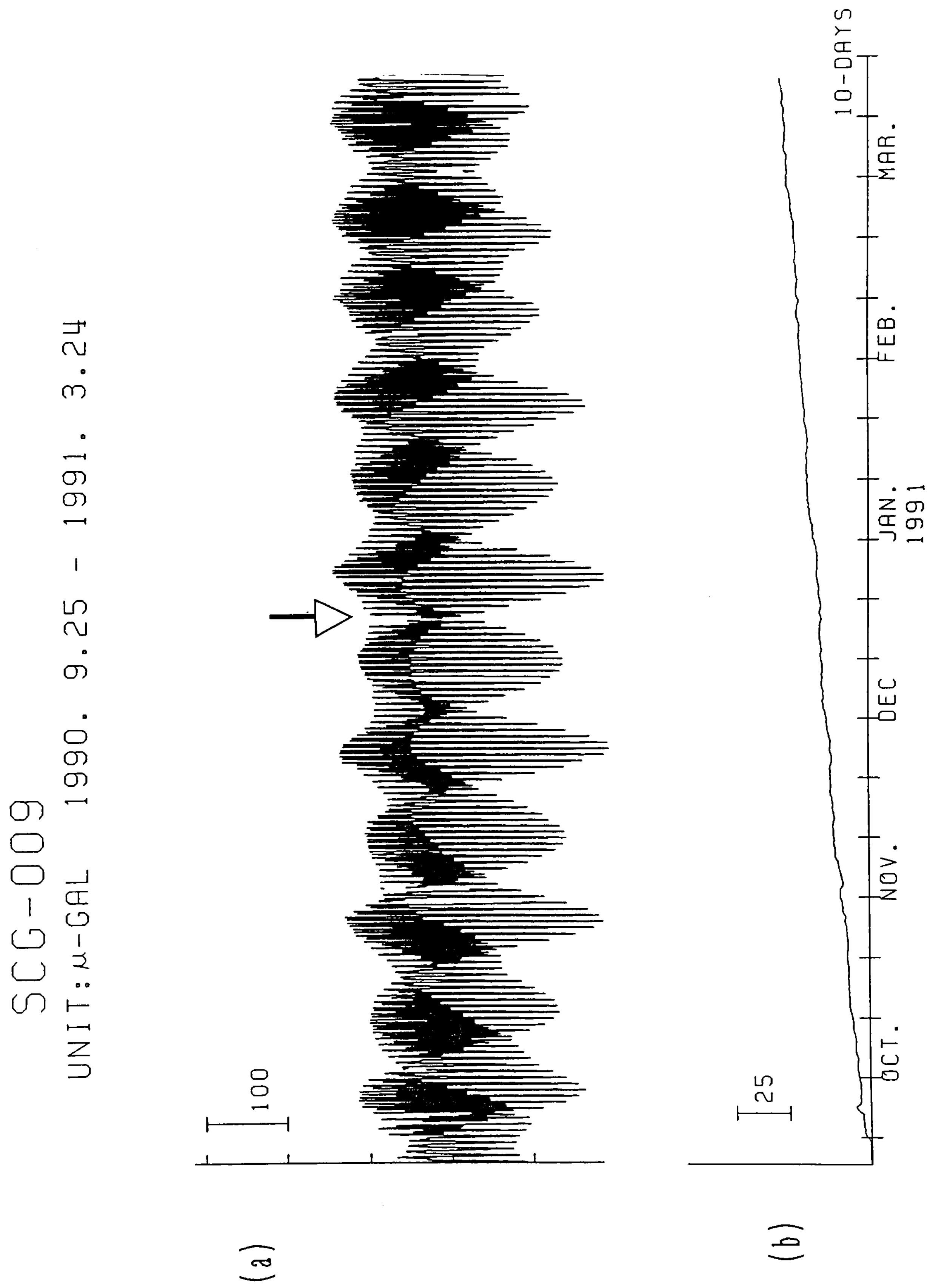
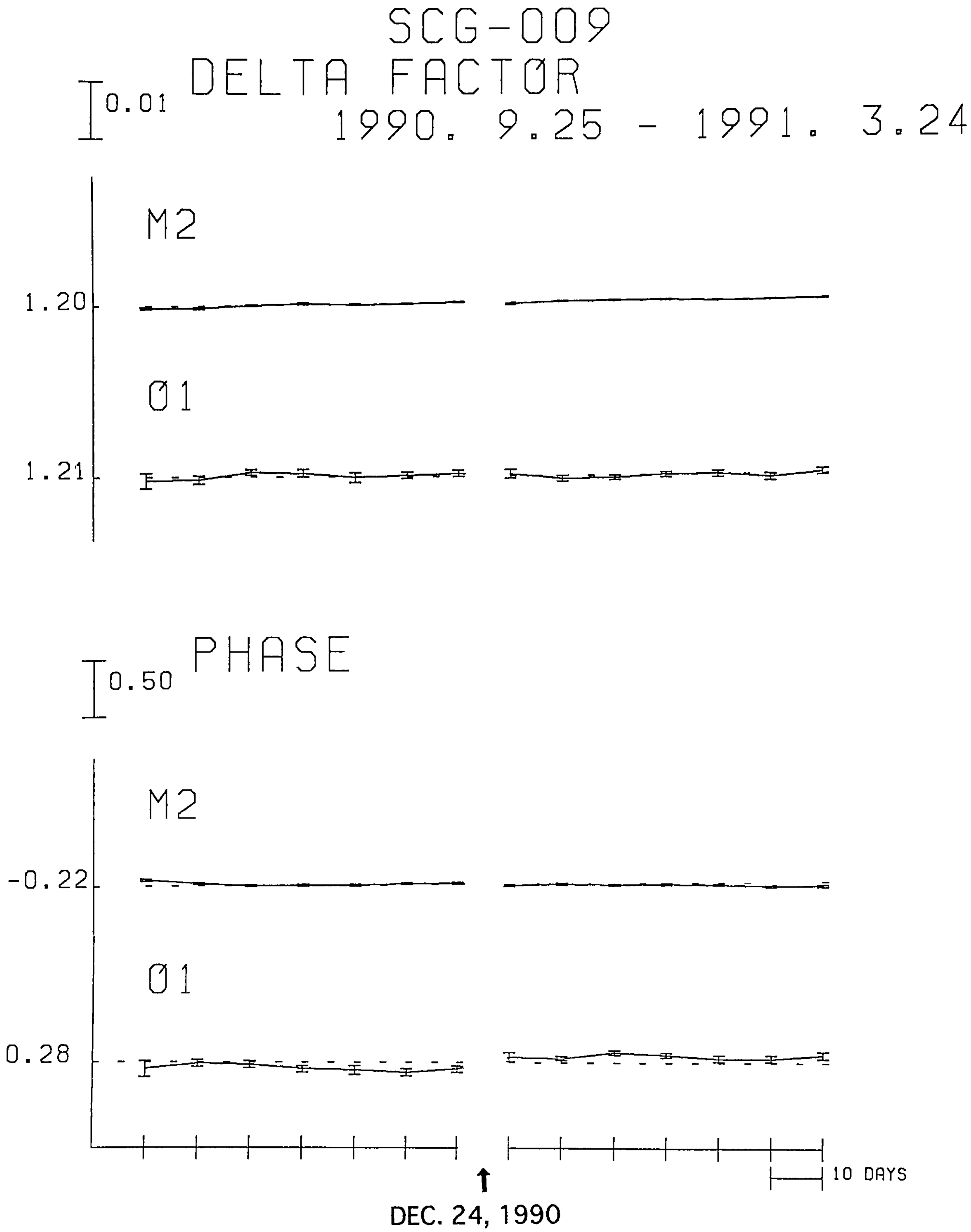

SCG-009
UNIT:μ-GAL 1990. 9.25 - 1991. 3.24
100
25
OCT.
NOV.
DEC
JAN.
1991
FEB.
MAR.
10-DAYS
(a)
(b)

Fig. 23.


SCG-009
0.01
DELTA FACTOR
1990. 9.25 - 1991. 3.24
M2
1.20
O1
1.21
0.50
PHASE
M2
-0.22
O1
0.28
10 DAYS
DEC. 24, 1990

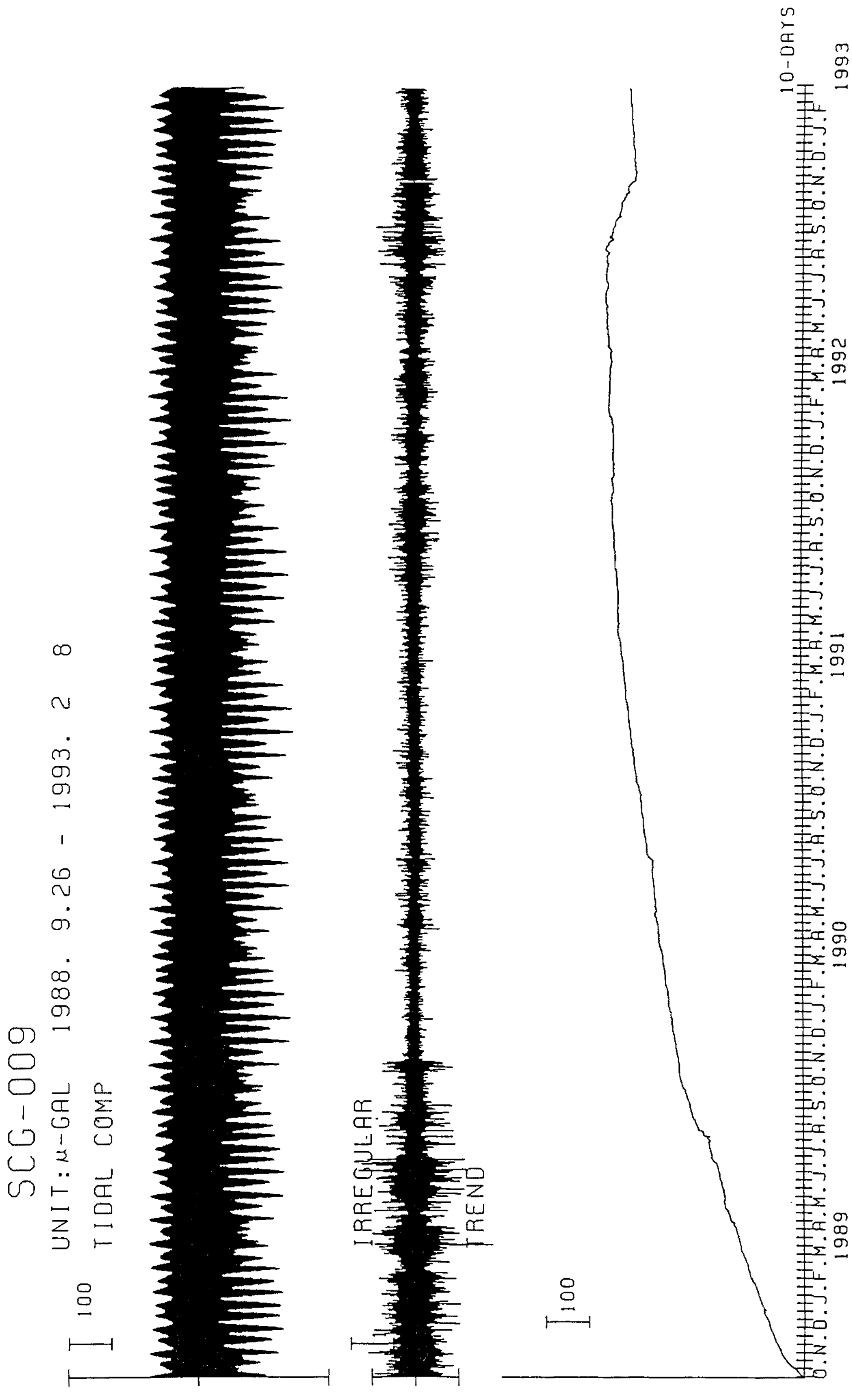
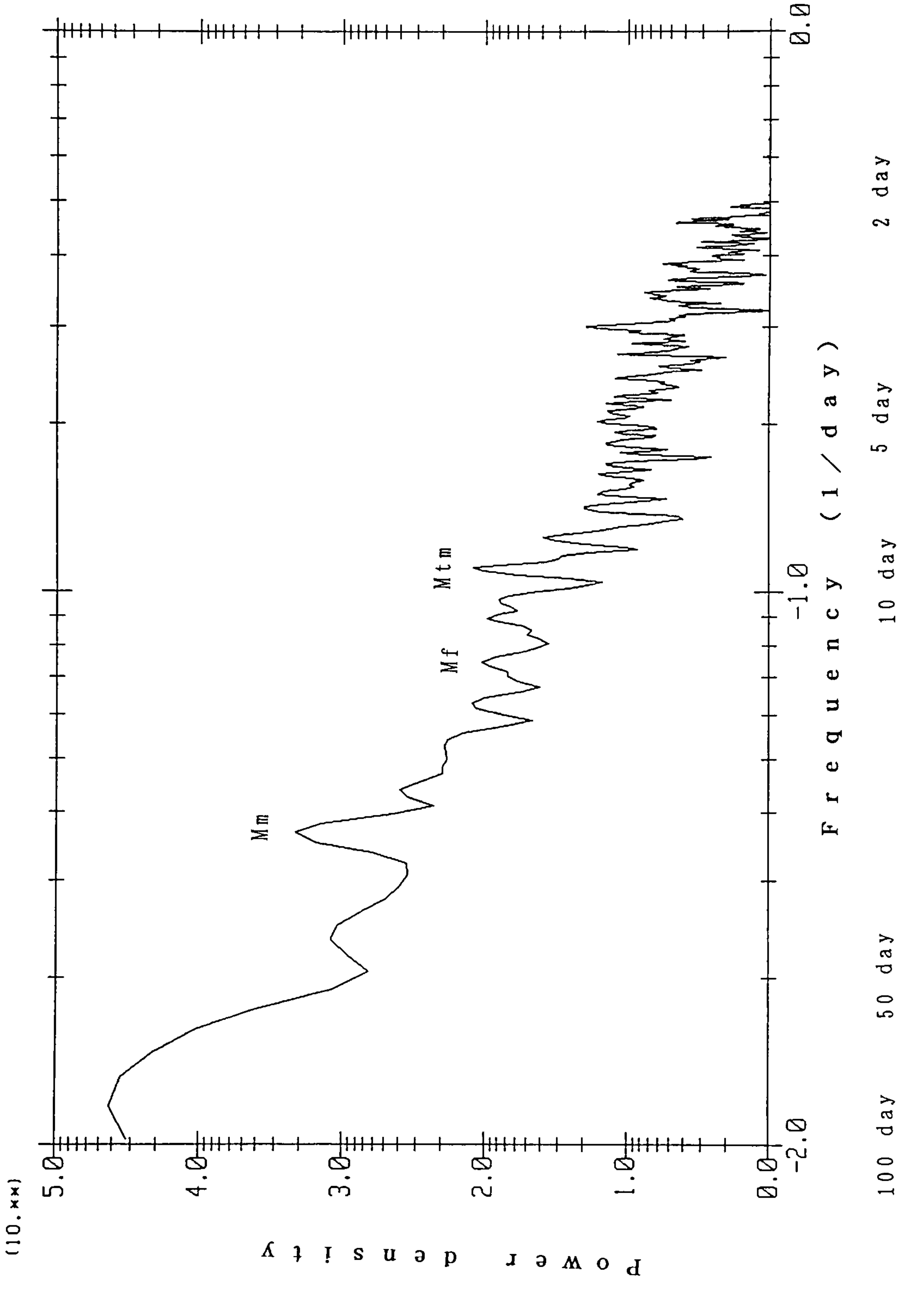
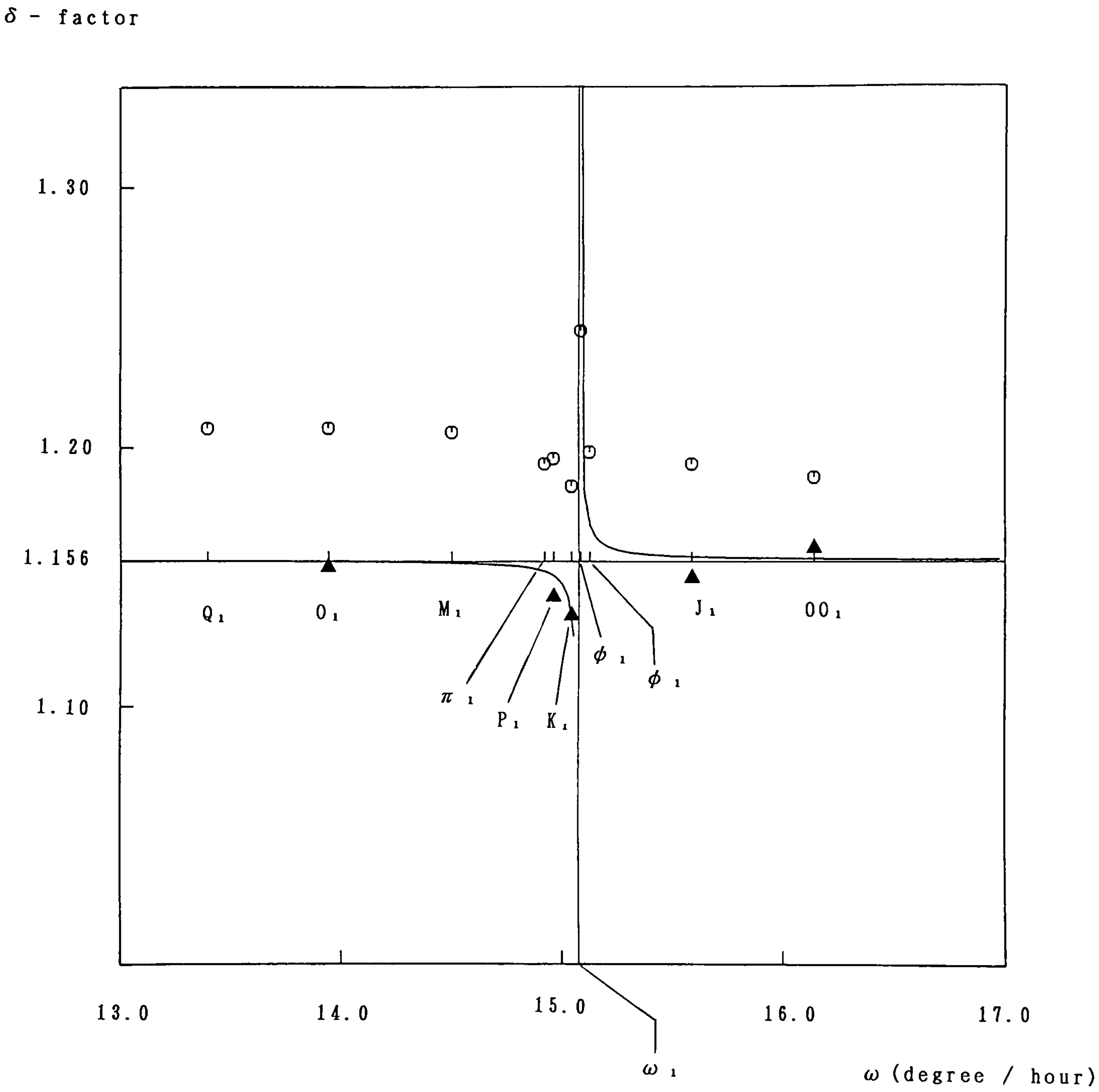

SCG-009
UNIT: μ-GAL 1988. 9.26 - 1993. 2 8
TIDAL COMP
100
IRREGULAR
TREND
100
10-DAYS
1989
1990
1991
1992
1993

Fig. 25.



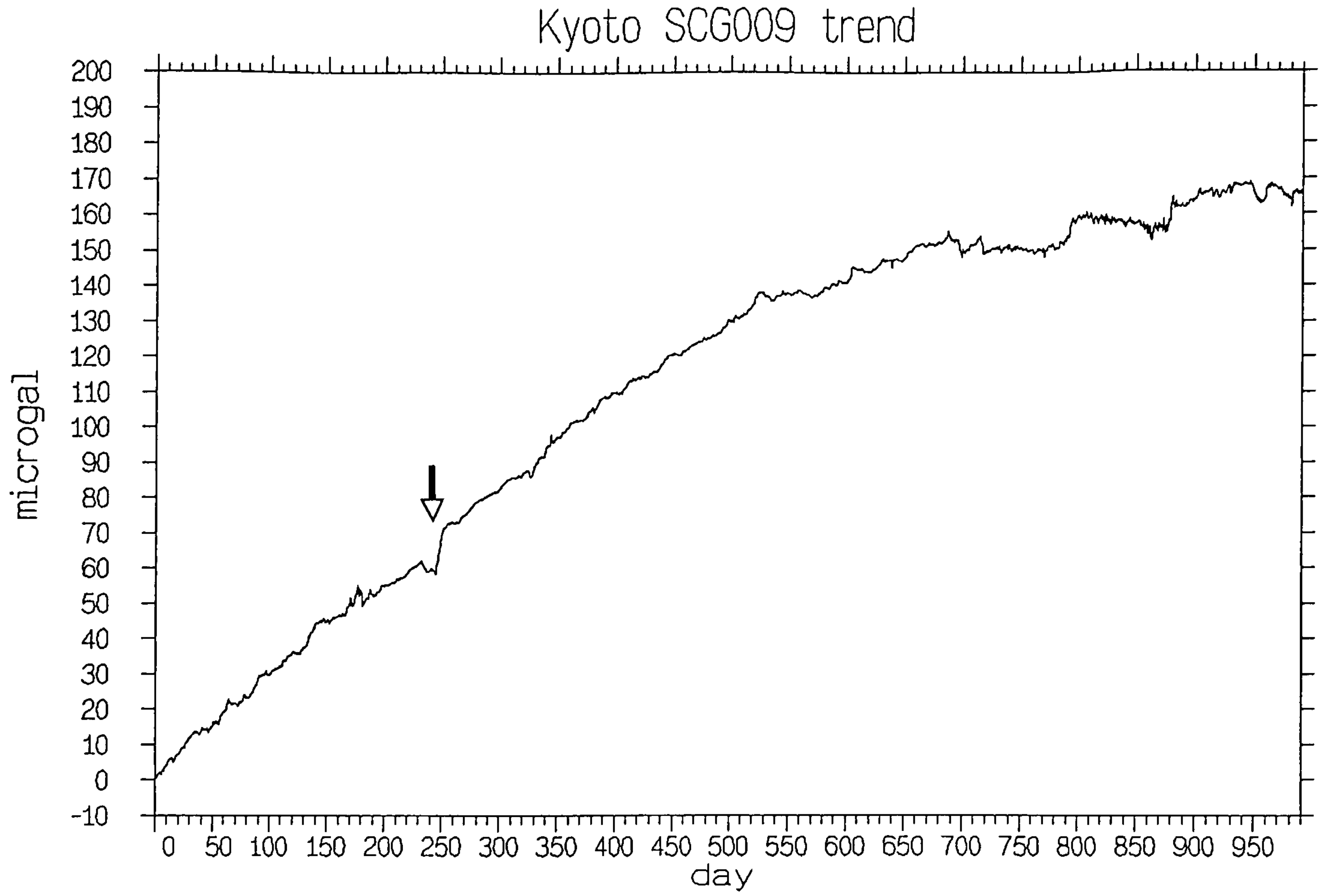
Power density
(10.**01)
5.0
4.0
3.0
2.0
1.0
0.0
-2.0
-1.0
0.0
Frequency (1/day)
100 day
50 day
10 day
5 day
2 day
Mm
Mf
Mtm

Fig. 26.



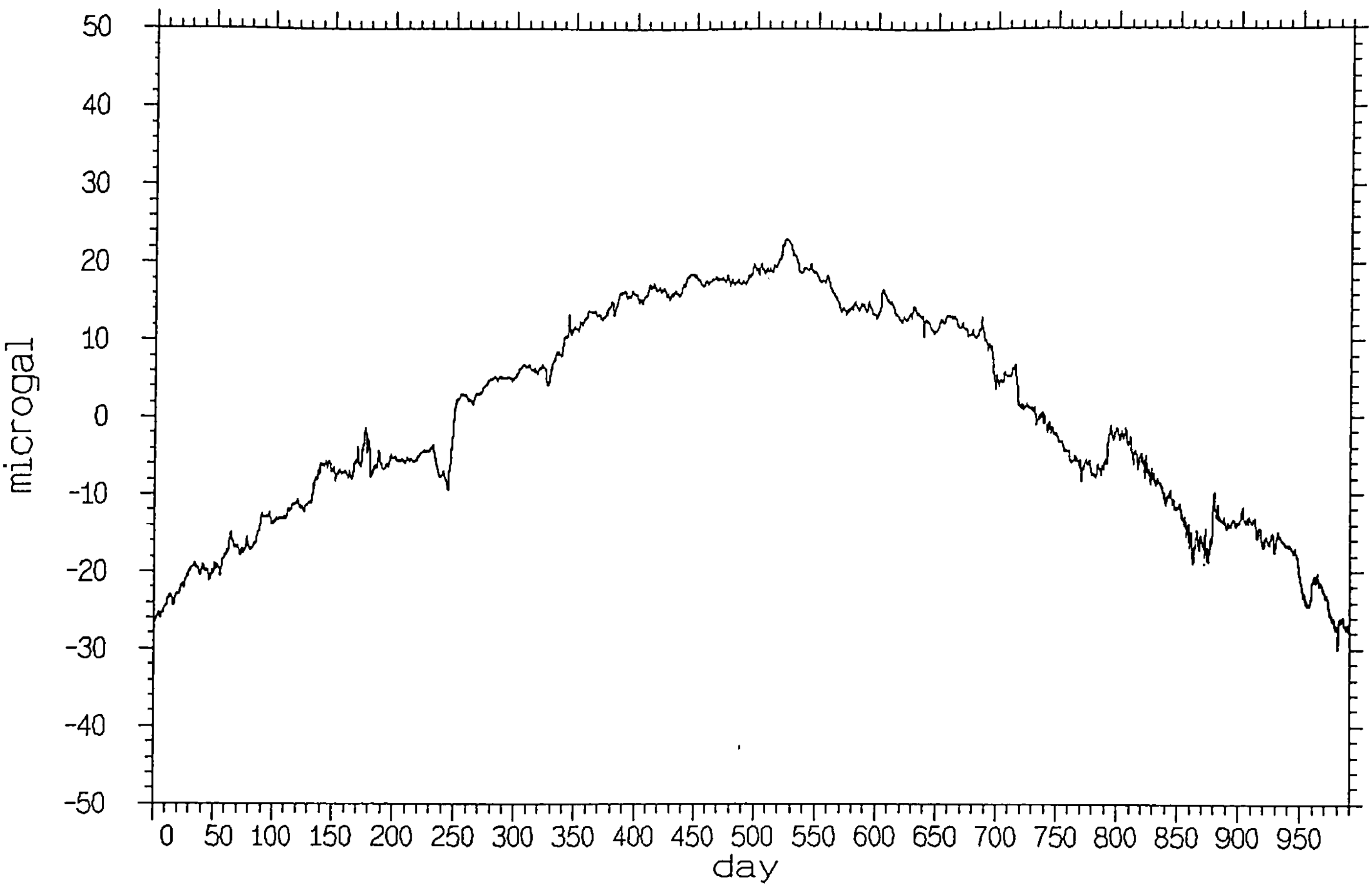
δ - factor
1.30
1.20
1.156
1.10
Q₁
O₁
M₁
J₁
OO₁
π₁
P₁
K₁
ψ₁
φ₁
13.0
14.0
15.0
16.0
17.0
ω₁
ω (degree / hour)

Fig. 27.



Kyoto SCG009 trend
microgal
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
day

Fig. 28.



50
40
30
20
10
0
-10
-20
-30
-40
-50
microgal
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 950
day

Fig. 29.

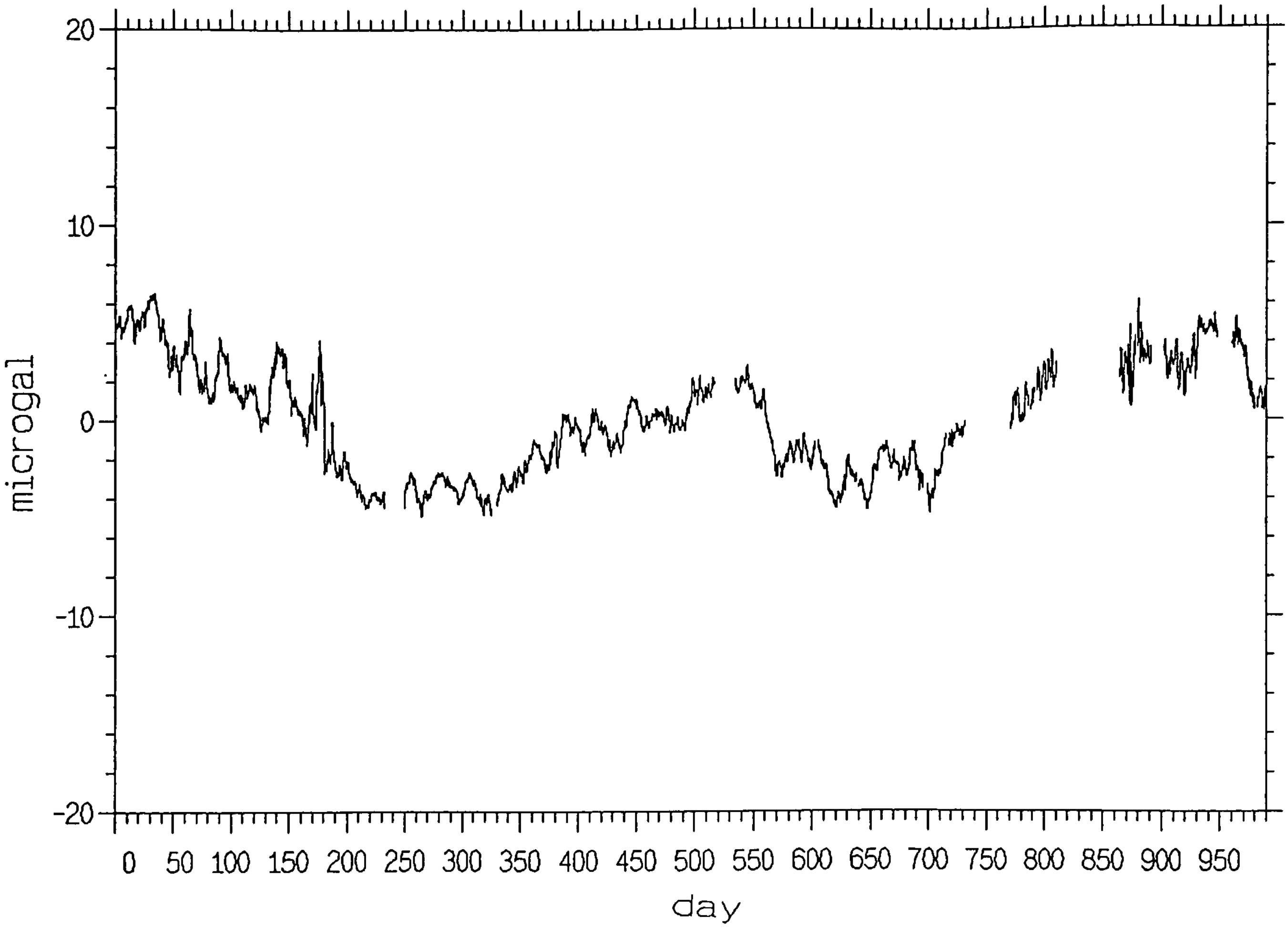

20
10
0
-10
-20
microgal
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
day

Fig. 30.

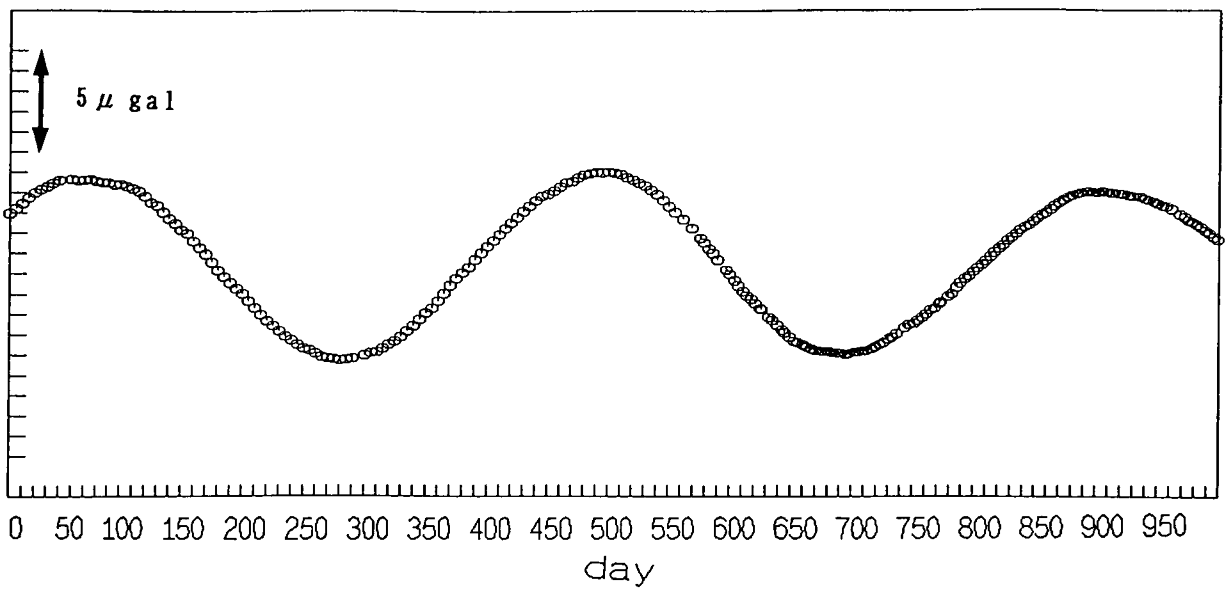
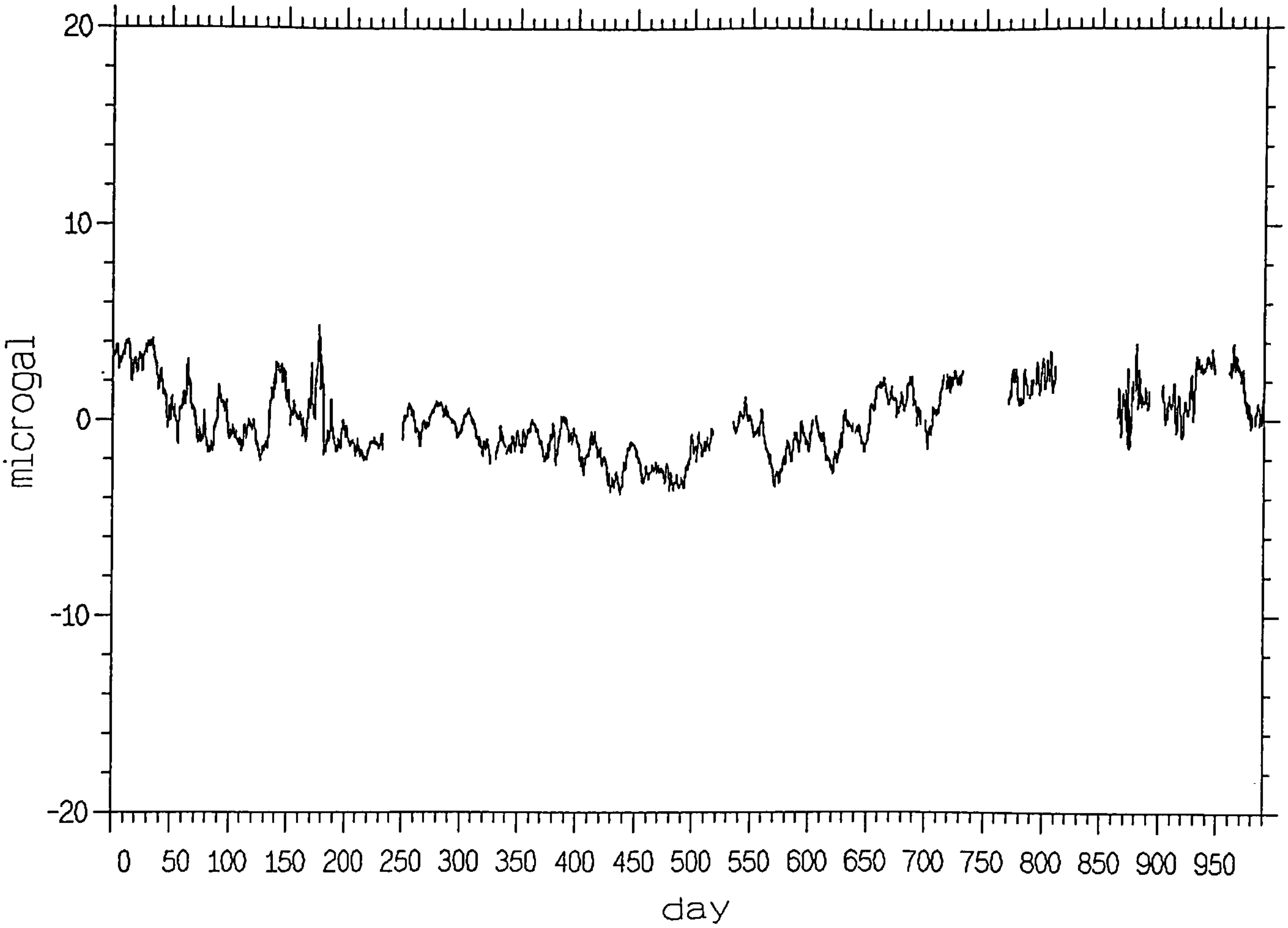

5 μ gal
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
day

Fig. 31.



20
10
0
-10
-20
microgal
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
day

Fig. 32.