# Observations of Crustal Movements by Newly-Designed Horizontal Pendulum and Water-Tube Tiltmeters with Electromagnetic Transducers (3)

## ——Time Variations of Tidal Admittance——

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(Manuscript received March 20, 1981)


### Abstract

In order to detect time variations in the amplitude and phase of earth tides, in relation to possible changes in crustal rigidity around earthquake source regions both the least squares and the time domain methods have been applied to tilt records. For the former method, it is effective for increasing the reliability of the results to analyze the observed and theoretical tides in the same way and to compare the results obtained for the $M_2$ constituent. For the latter method, it is effective to apply a band-pass filter which has dominant responses only for semidiurnal frequencies, removing meteorological influences with diurnal frequencies. For both of the methods, it is desirable to use the filtered data over one-month's duration to obtain the tidal admittance (the amplitude ratio and phase delay time) with good accuracies.

Using these two methods, the amplitude ratios and phase differences of tidal tilts have been obtained from the records of three-component water-tube tiltmeters installed at the Kamitakara station (36°17′N, 137°20′E, H=800m) in the northwestern Chubu region, Japan, during the period from September 1977 to November 1979. The results show that time variations in the amplitude ratios in three different directions (S45°W, N45°W and E) do not exceed ±4% at their maximum values and ±2% for the RMS standard deviations. These variations are estimated to be nearly equal to the error limit of sensitivity measurement.

It may be reasonable to conclude from the above results that elastic properties around the observation station have not changed significantly during the period. This conclusion may be consistent with the fact that seismic activity around this region has not been very high. In addition to the above, time variations of the tidal admittance from the water-tube tiltmeters are compared with those three-component strainmeters for the same period. No close correlations could be detected between the two types of observations. However, the tidal admittance for three-component tiltmeters and those for three-component strainmeters show consistent variations, respectively, over the entire period, although their absolute levels are different. The effects of precipitation and water discharge in the observation vault on the time variations of tidal admittance can not be clearly identified, while there are close correlations between these amounts and secular variations of ground tilts and strains. Several possibilities for these variations are discussed.

## 1. Introduction

With a view to detecting time variations in the amplitude and phase of earth tides due to possible changes in elastic properties in the crust, it is essentially important to check the reliability of the tidal admittance obtained from observed data severely.

In a previous paper[1], only the observed data were analyzed by the conventional least squares method, and the amplitudes and phases of both the $M_2$ and $O_1$ waves were normalized to the mean values for a 18. 6-year period. From this type of analysis applied to 30-days' data by successive shifting of the central epoch, it was made clear that there appear spurious periodic oscillations with a period of about half a month in the calculated tidal factors over a long period. For this reason, we suggested that a comparison between the results from the observed and theoretical tides will be useful to minimize these oscillations. In the present paper, the above refined method with a most suitable duration of analysis is investigated in more detail to estimate the amplitude and phase of $M_2$ constituent as accurately as possible.

It has been mentioned in the previous paper[1], on the other hand, that the oceanic loading effect upon $M_2$ tidal tilts is found to be considerably large at the Kamitakara station unlike the case of $M_2$ tidal strains, and hence that there is some discrepancy between the observed and theoretical waveforms of tidal tilts. In this case, it is not adequate to make direct comparison between the two waveforms before applying the time domain method. In this paper, an effective use of this method is also examined in comparison with the least squares method.

The main purpose of the present paper is to test if there are any significant time variations of the tidal admittance (the amplitude ratio and phase delay time) determined by means of both the least squares and the time domain methods. As described in a previous paper[2], it has been reported by some geophysicists[3)~6)] that the changes in elastic constants in dilatant crustal regions cause some variations in the amplitude and phase of the earth tides. For example, Beaumont and Berger[3] indicate that the amplitude of tidal strains and tilts could change by as much as 60% in the seismic source region.

Another purpose is to examine possible relationship between the time variations of the observed tidal admittances and other phenomena (secular tilts and strains, their time derivatives, the amounts of precipitation, water discharge, and seismic activity near the region under consideration).

In addition, a correlation between the secular tilts observed with water tube and horizontal pendulum tiltmeters is given.

## 2. Least Squares Method

In the present paper, secular tilts and some other drifts involved in the observed data are removed by applying the Pertzev's filter prior to the tidal analyses, and the least squares method is then applied to the 30 days' filtered data to get the amplitude and phase of 9 major constituents ($M_2$, $S_2$, $K_1$, $O_1$, $N_2$, $K_2$, $Q_1$, $P_1$ and $S_1$), while for the selection of the constituents to be included in the analysis, two cases (9 and 6 constituents) have been examined in the previous paper[1]. To what extent the accuracy of resolution of the amplitude and phase of $M_2$ constituent changes as the duration of analysis varies is also investigated here.

To discuss this problem, successive analyses are made for the records (before filtering) observed by the WT21 component over 105 days. The results show that there exist periodic fluctuations in the $M_2$ amplitude and phase, and that the amount of such fluctuations depends on the duration of analysis. To clarify possible sources of these fluctuations, the corresponding theoretical tidal tilts, which have been derived[7] from the tide-generating potential for a laterally homogeneous solid earth, are

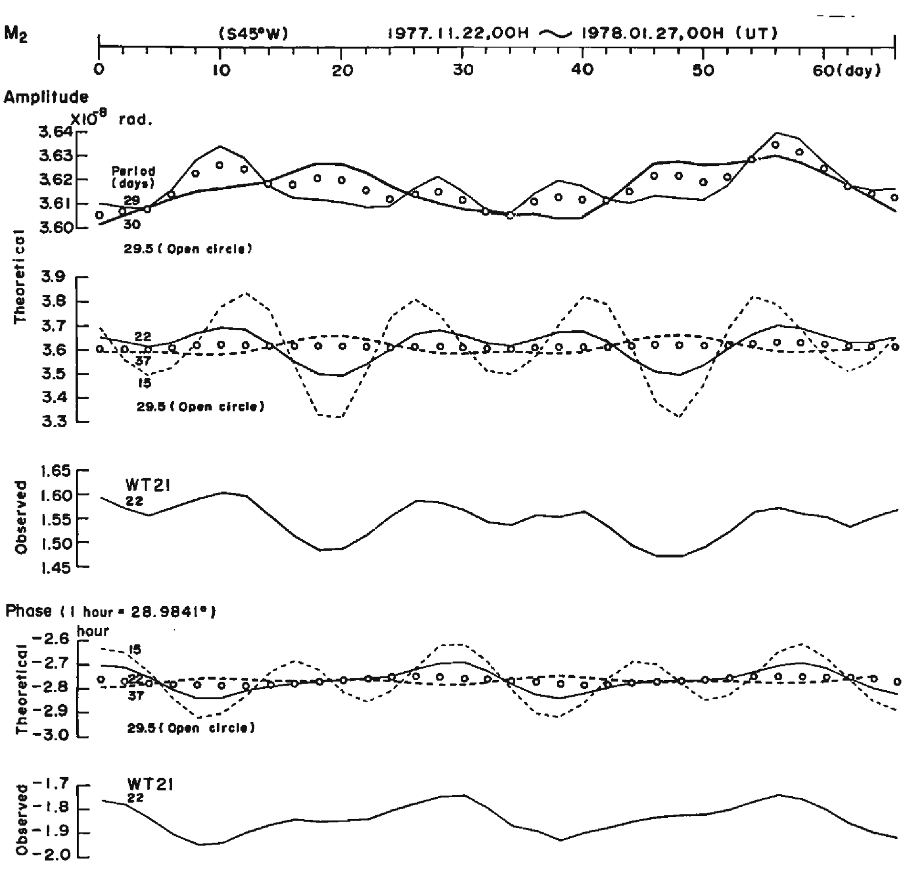


Fig. 1 Results of successive analyses for both the theoretical and observed $M_2$ tilt tides in the direction of S45°W. The phase denotes the lag (delay time) when the time origin is taken at Nov. 02, 00h00m, 1977, (UT).

analyzed by the same method for the same period. The results obtained here by analyzing the theoretical tides are summarized in **Fig. 1**, where the results for observed tides from 22 days' analysis are also included. It is noted that the phase for the $M_2$ constituent is partly represented in hours, in the present paper, for comparison with the phase from the time domain analysis. It is clear that similar periodic oscillations are also noticed in the theoretical function. Therefore, we may conclude that such fluctuations originate from the analytical method used here and might be attributed to the effects of contamination from the other constituents. It is found for the theoretical results that the amplitude of periodic oscillations is limited to within $\pm 0.5\%$ in the case when the duration of analysis is taken to be between 29~30 days. If we take the length of 22 and 15 days, the amplitude falls within $\pm 3$ and $\pm 7\%$, respectively, and in case of 37 days its fluctuation reduces to $\pm 1.1\%$.

A comparison between the results for both the observed and theoretical tides with 22 days' duration indicates similar fluctuations of the $M_2$ amplitude and phase, as seen from **Fig. 1**. If we take the ratio of the observed to theoretical amplitudes and the difference between the observed and theoretical phases, such similar fluctuations are considerably reduced. Thus it has been demonstrated here that the above method of comparing both the observed and theoretical tides in the same way is fully effective for the analysis of tidal tilts which include a considerable amount of oceanic loading tides. Mikumo and Nakagawa[8] and Nakagawa and Shiraki[9),10] have already stated the effectiveness of this type of analysis for tidal gravities. Now we attempt to examine in what pattern the fluctuations of the amplitude and phase would appear for theoretical tilts of longer duration. The results for 29.5 days' duration are shown in **Fig. 2**, which are obtained for the period from Jan. 17, 00h00m, 1978 to Jan. 12,

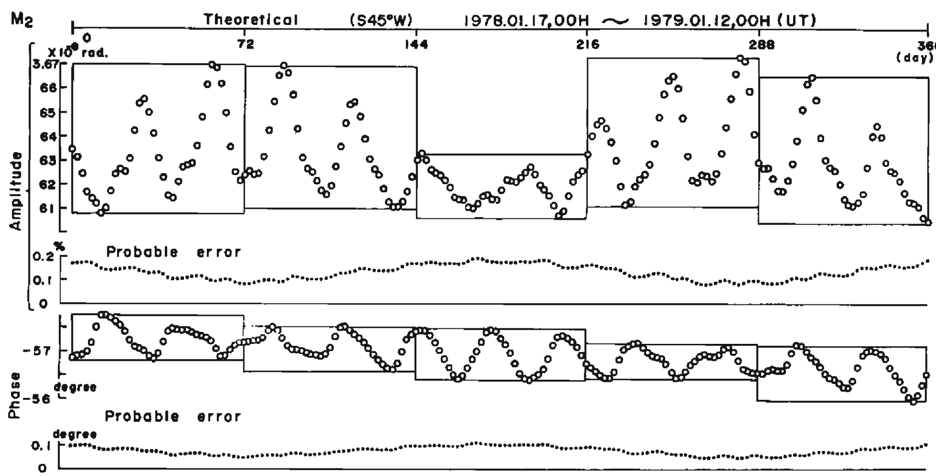


Fig. 2 Results of successive analyses for the theoretical $M_2$ tilt tide in the direction of S45°W. The duration of analysis is chosen to be 29.5 days. The phase denotes the lag (delay time) when the time origin is taken at Jan. 01, 00h00m, 1978, (UT).

00h00m, 1979 (UT) from successive analyses by shifting the central epoch by a 2-day step. In this figure the whole duration is divided into five separate periods, each of which includes 72 days. The amplitude and phase in each period vary with time, ranging between $\pm 1\%$ and $\pm 0.6°$ at their maximum fluctuations, respectively. It seems from this result that the already mentioned 105 days' period, for which both the observed and theoretical data have been analyzed, happens to correspond to the period where the fluctuations are comparatively small.

Next, in order to estimate the effect of the nodal factors, which have been applied as correction factors to the observed tides in the conventional least squares analysis, the amplitude and phase of theoretical tilt tides are computed here over a long duration of 21 years from 1968 to 1988. The results are shown by open rectangles in **Fig. 3**. The width of each rectangle indicates 72 days' interval and its length in the vertical direction shows the range of fluctuation in the amplitude and phase, which are obtained in the same way as described before. The results for the five successive periods shown in **Fig. 2** are also indicated in **Fig. 3**. Comparing these obtained rectangles with the f and u curves which have been used in the previous paper[1], it can be confirmed that the amplitude and phase computed from the theoretical tilt function by the least squares method fall almost exactly on the corresponding curves.

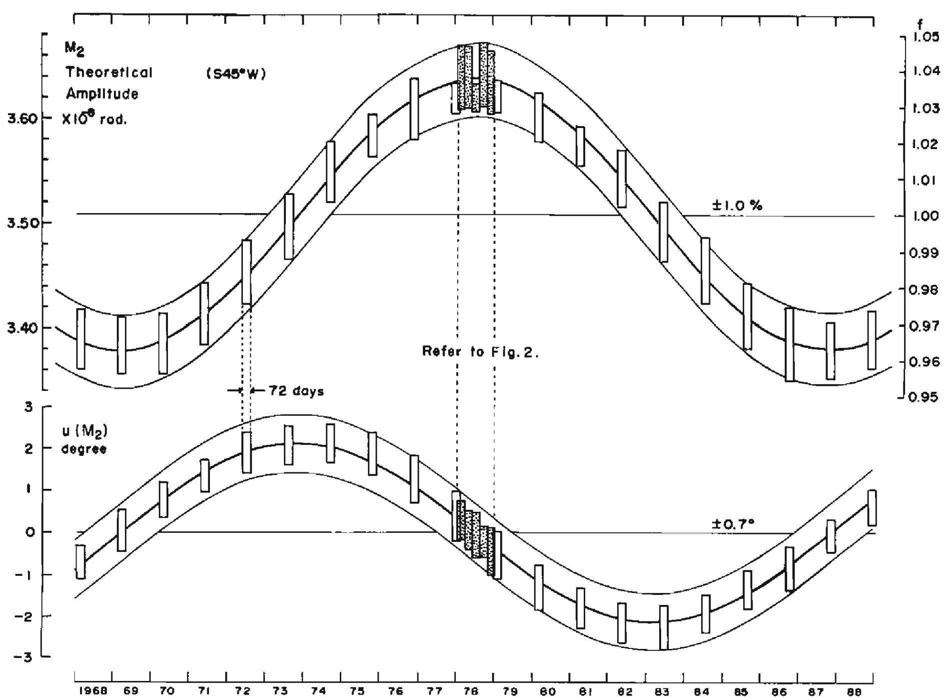


Fig. 3 Amplitude and phase from the least squares analysis of the theoretical $M_2$ tilt tide in the direction of S45°W computed over a long duration of 21 years from 1968 to 1988. The length of each rectangle shows the range of fluctuations in the amplitude and phase during 72 days. f and u curves are also shown.

The deviations of the amplitude and phase from the f and u curves are only limited to within ±1% and ±0.7° respectively, over the entire period of 21 years.

Blair[11] estimated the Fourier contamination effects from adjacent constituents on the $M_2$ in theoretical body tides, and found that their maximum value reaches 2.6% for the data with one month's duration. This value is 2.6 times as large as a maximum deviation (1%) of the amplitude from the f curve, suggesting that the least squares analysis provides better results for the $M_2$ amplitude than the Fourier analysis, as long as the length of the analyzed data is limited to one month or so.

In **Fig.4** are shown the amplitude ratios of the observed to theoretical tides and the phase differences between them for three observation directions, (E-W, N45°E-S45°W and N45°W-S45°E), respectively. Fluctuations of the amplitude ratios are estimated to be less than ±1%, slightly larger than ±1%, and ±3.5%, for the length of analyses 29.5, 22 and 15 days, respectively. The N-S component of tilt tide is not included here, because the observed amplitude is so small, being about one-fourth of the theoretical amplitude. This may probably be due to the fact that the oceanic loading effect is of comparable order with the solid tide in this direction, and it cancels out the solid tide[1].

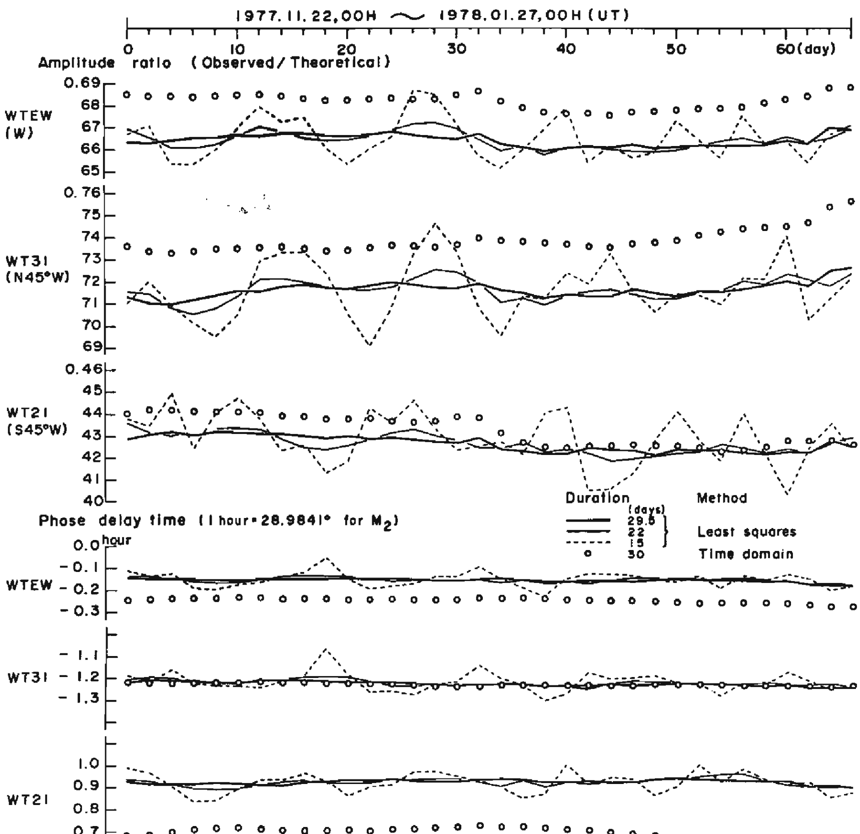

Fig. 4 Tidal admittances obtained by both the least squares and the time domain analyses.

## 3. Time Domain Method

The time domain method directly correlates the observed tidal data with the correspoding theoretical time functions predicted for a laterally homogeneous solid earth, without resolving the data into a number of tidal constituents[7]. The direct comparison between the observed and theoretical tides using the least squares in the time domain yields the overall tidal admittance averaged over all tidal frequencies, as has been described in detail by Mikumo and Kato[7]. This method can be effectively used if there is good similarity between the observed and theoretical tidal waveforms. As described in the Introduction, however, it has been pointed out[7] that there is some discrepancy between the waveforms in the case of the tidal tilts observed at the Kamitakara station ,where the oceanic loading effect is found to be considerably large and to contaminate similarity, unlike the case of tidal strains there. In this paragraph, a more effective use of this method is investigated.

The first step in the present analysis is to remove secular tilts and some other drifts involved in the observed data by applying a band-pass filter with dominant responses over semidiurnal and diurnal tidal frequencies. Then successive analyses with 30 days' data are performed by shifting the central epoch by a 2-day step. The results obtained from this preliminary analysis for the period from Sept. 29, 00h00m to Dec. 02, 00h00m, 1978 (UT) are shown in **Fig.5** (a). It is noticed that there exists a considerable amount of phase difference, which exceeds one hour in the case of

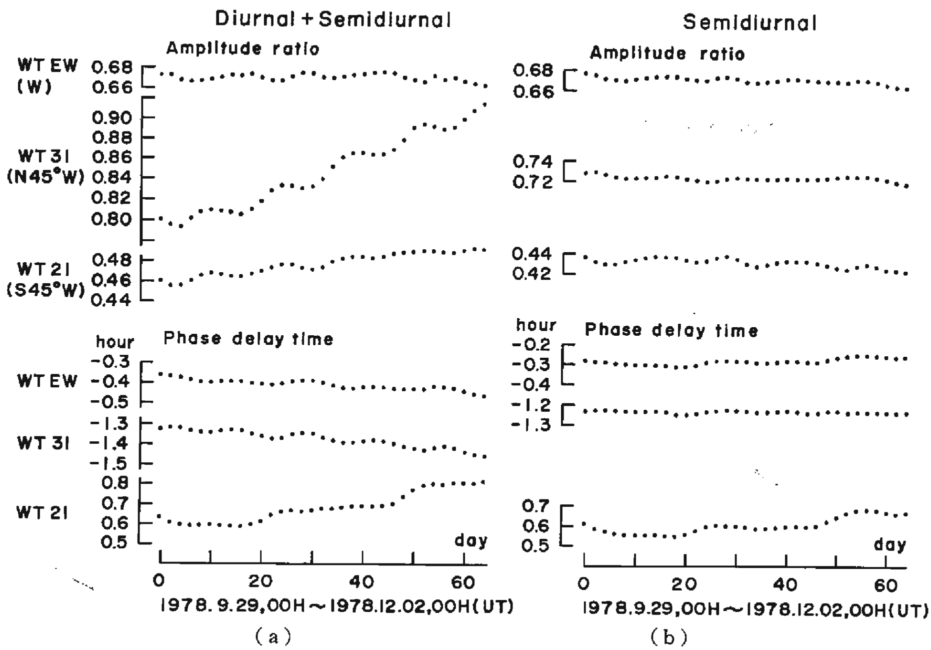


Fig. 5 Tidal admittances for the two different frequency bands obtained by the time domain analysis.

WT31 component. Since, in such cases, possible errors introduced by approximating the theoretical tides to the second term by the Taylor's expansion can not be ignored, we use a successive approximation technique to refine the amplitude ratio and phase delay time. It was found that these values nearly converge up to the third time in the successive approximation. As shown in **Fig.5 (a)**, both the amplitude ratios and phase delay times show considerably large fluctuations. The fluctuations in the amplitude ratios fall within ±1% and ±4% for the WTEW and WT21 components, respectively, while they reach ±7% for the WT31 component. The main reason for this may be due to diurnal tilts from meteorological origin,[12] which probably changes to some extent with time.

For this reason, the next step we attempted here is to remove such diurnal tides by applying a filter covering only semidiurnal frequencies. The frequency response and its impulse response of the filter used here are shown in **Fig. 6** and **Fig. 7**

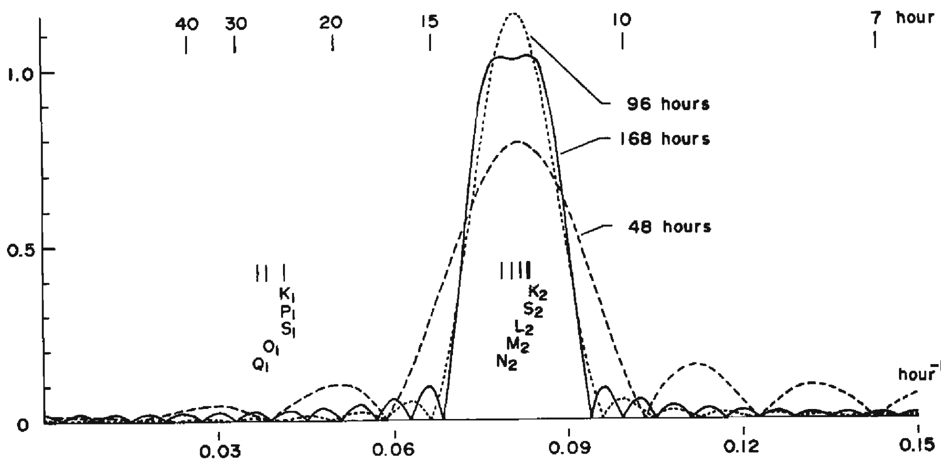


Fig. 6 Frequency response of the band-pass filter for the three different lengths of impulse response.

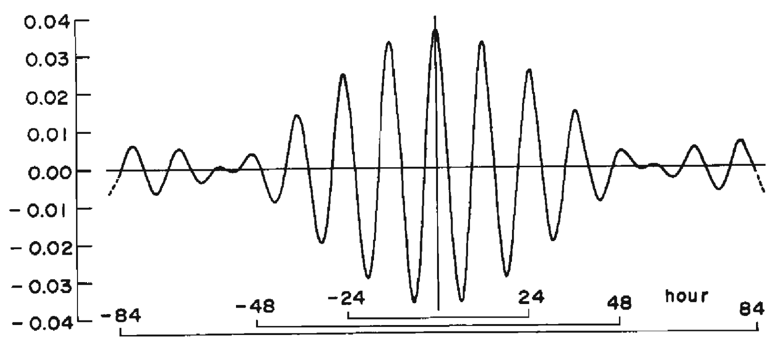


Fig. 7 Impulse response of the trapezoid-shape filter with dominant responses over semidiurnal tidal frequencies.

respectively. The length of the impulse response is taken to be 168 hours in the present analyses. The results shown in **Fig.5(b)** clearly indicate that fluctuations in the amplitude ratios and phase delay times for all the three components, particularly for the WT31 component, have been reduced to a considerable extent, as compared with those in **Fig.5 (a)**. It may be noticed, however, that their absolute levels show slight differences between the two results as shown in **Figs.5(a)** and **(b)**. This suggests that the amplitude ratio and phase delay time are weakly frequency dependent, which could take slightly different values for semidiurnal and diurnal frequencies.

Next, the observed data for the 105 days, which have been used for the analysis by the least squares method, are again analyzed here by the time domain method after applying a filter with dominant responses over semidiurnal frequencies, to compare the results from the two methods and also to examine the effects of the adopted data length. This is because we think that if the observed and theoretical tides have quite similar waveforms the resolution will not be affected by the time length of analyzed data but otherwise would be affected to some extent. In **Fig. 8** are shown all the computed results for seven different time lengths of analysis (31, 30, 29, 22, 16, 15 and

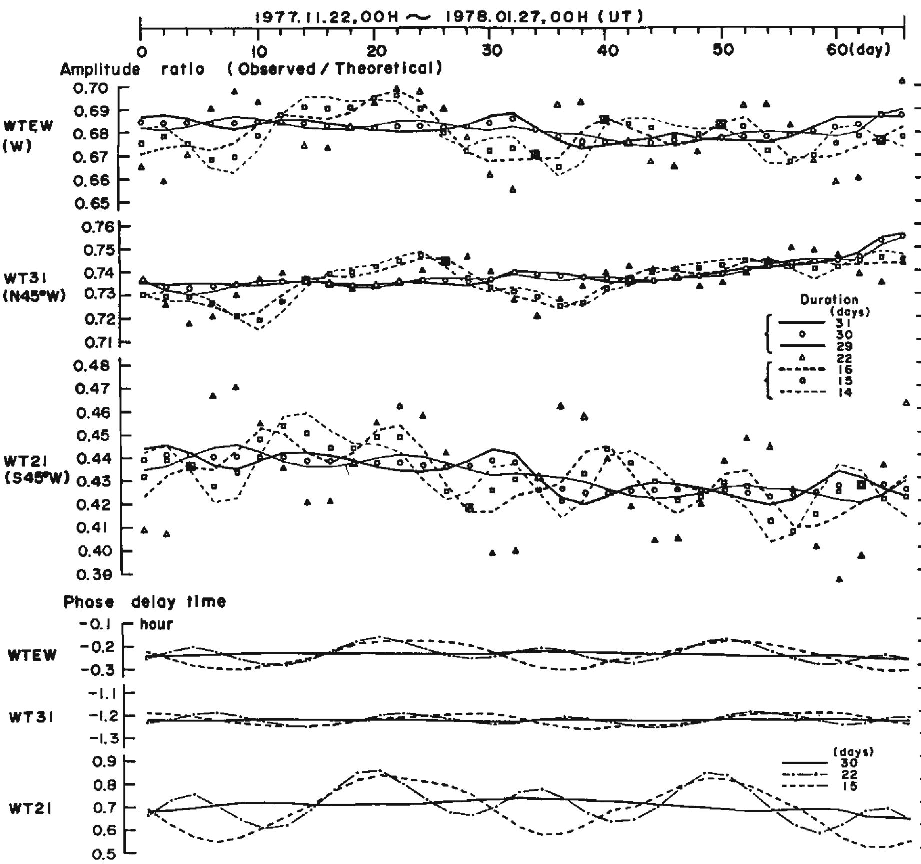


Fig. 8 Semidiurnal tidal admittances for seven different time lengths of analysis (31, 30, 29, 22, 16, 15 and 14 days).

14 days). It may be seen from **Fig. 8** that fluctuations of the amplitude ratios are minimum for the time length around 30 days and around 15 days which are limited to within ±2% and ±6%, respectively. It is to be just mentioned that the case of 22 days shows greater fluctuations than that of 15 days in spite of its longer time length of analysis.

## 4. Comparison between the Least Squares Method and the Time Domain Method

To compare the results from the least squares and the time domain methods, one of the results obtained by the latter one with the time length of analysis of 30 days are added in **Fig.4** by open circles. We immediately notice that time variations of the tidal admittance obtained by the two different methods show a very similar pattern to each other, but that there are systematic discrepancies between their absolute values. This means that the amplitude ratios and phase delay times are apparently frequency-dependent even in the narrow semidiurnal tidal band. The above discrepancies may probably result from the $S_2$ constituent which includes semidiurnal meteorological effects[12] such as atmospheric loading and temperature variations. If these systematic disrepancies do not vary with time, there is no difference whether the least squares or time domain method is chosen from the view point of detecting possible time variations of the tidal admittance. Comparing the fluctuations obtained by the two different analyses, which are shown in **Figs. 4** and **8**, it may be concluded that they are nearly the same in the case of the time length of analysis around 30 days and that in the case of 22 days the least squares method provides better results than the time domain method and vice versa in the case of 15 days.

In the time domain analysis the length of impulse response of the filter has so far been chosen to be 168 hours. In this case, 37 days' data are required to determine one pair of the amplitude ratio and phase delay time averaged over 30 days. From the view point of monitoring time variations of the tidal admittance, it is desirable to choose the length of analyzed data as short as possible. For this reason, we attempted to make similar calculations with the length of the impulse response being 96 and 48 hours for the same data as given in **Fig.5**. The frequency response and its impulse response for these filters are also included in **Figs.6** and **7**, respectively. If we adopt shorter length for the impulse response, some oscillatory side lobes tend to appear in the actual frequency response. Nevertheless, it does not appear that the obtained results depend on the length of the impulse response adopted, because the same filter is applied to both the observed and theoretical tides. This means that if we adopt the length of the impulse response of 48 hours, 32 days' data are needed.

Hereafter, in this paper, we fix the time length of analysis (for filtered data) to be 29.5 days for the least squares method and 30 days for the time domain method, as a general rule. In several cases, however, when the quantity of available data was restricted due to some interruptions or disturbances, 22 and 15 days have been adopted as the length of analyzed data for the least squares and time domain analyses, respectively.

## 5. Time Variations in the Amplitude Ratio and Phase Difference of Earth Tidal Tilts and Strains

In this paragraph, long term time variations in the tidal admittance of earth tidal tilts observed with three-component water-tube tiltmeters and one of two horizontal pendulum tiltmeters are investigated over the period from 1977 to 1979, by the two different methods described in the foregoing paragraphs. Tidal strain data which have been obtained in the same period with three-component strainmeters are also analyzed to compare with the results for the tidal tilts.

### 5.1. Sensitivity

The method of sensitivity measurements for three-component water-tube tiltmeters has been described in the previous paper[2] in detail, and it has been shown that the accuracy of absolute calibration reaches semewhat better than 1～2% and possible variation of the sensitivity of each detector is believed to be less than 0.5%/year (cf. Shichi et al.[13]).

The sensitivity of the horizontal pendulum tiltmeter used here depends on the natural period of the pendulum and the sensitivity of the electronic transducer. Since this instrument is extremely mechanically stable for the rather short period (about 6 seconds) in this case the stability of sensitivity almost depends on that of the adopted displacement transducer with a differential transformer and its related electronic circuit. The change of the sensitivity with time during two adjacent measurements, which are carried out every several months, sometimes reaches several percent.

Three components of quartz tube strainmeters, each of which has a span of 25m, are installed parallel to the water-tube and horizontal pendulum tiltmeters at the Kamitakara station[2]. These strainmeters are equipped also with a differential transformer as a displacement transducer. It has been verified that temporal changes of the sensitivity of the strainmeters during several months do not exceed a few percent.

We assumed that the measured sensitivities of both the tiltmeters and strainmeters vary linearly, to a first approximation, with time, during the two adjacent measurements. For these reasons, it may be considered that the accuracy of the carefully calibrated sensitivities of both the horizontal pendulum tiltmeter and the quartz-tube strainmmeters are within 1～2%.

### 5.2. Water-Tube Tiltmeters

The data extending over 27 months during the period from September 1977 to November 1979 are used for the present analysis. We selected several durations from the whole observation period, most of which involves complete data without any interruptions or missing. In a few exceptional cases, however, data missing for several hours have been interpolated as smoothly as possible. The results obtained from the least squares analysis are shown in **Fig. 9** and those from the time domain analysis are given in **Fig. 10**, respectively. As has been described before, it is also noticed that there are systematic discrepancies between the tidal admittances derived from the two different analyses, and that these vary slightly with time. This may probably be due to slight variations in semidiurnal meteorological effects[12].

In **Figs. 9** and **10**, it is to be noted that the amplitude ratios in two components of tilts (WT31 and WTEW) indicate consistent variations in parallel with each other. It also appears that the amplitude ratios show slightly higher values around the period from March to April. The amplitude ratios in the period from September to October in 1979 show minor fluctuations than those in the other period, which may be due to some artificial disturbances.

For the phase delay times, a parallel trend is also found between the two components (WT21 and WTEW), and there appears to exist a common pattern of semi-annual variations during 1978–1979. For example, it appears that the phase delay time calculated from the time domain analysis shows somewhat lower values in March and October and higher values in July and December. Time variations of the phase delay time for the WT31 component are extremely small in both of the two types of analysis.

As mentioned above, the existence of the parallel trend noticed between the two tilt components may not be attributed to the errors introduced from analytical

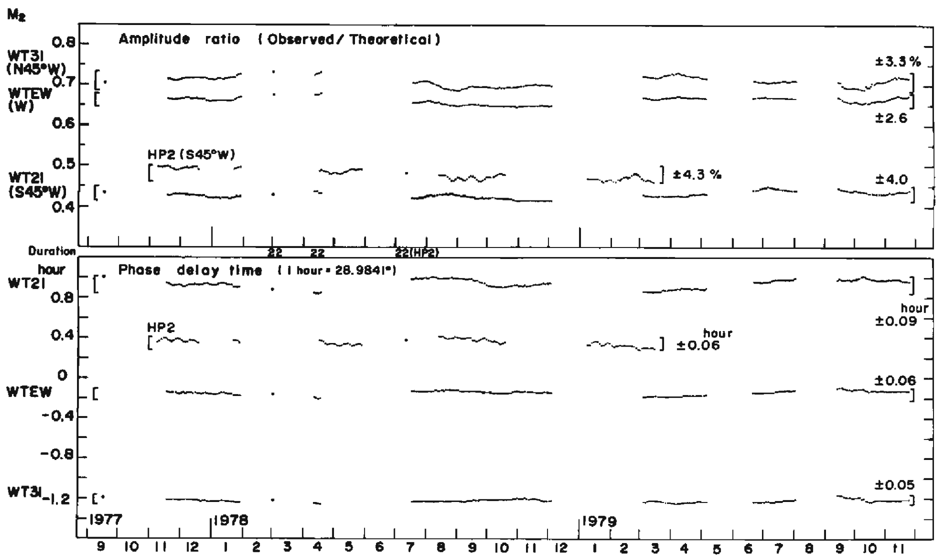


Fig. 9 Time variations in the $M_2$ tidal admittance during the period from Sept. 1977 to Nov. 1979 obtained from the least squares analysis. Both the results of three-component water-tube tiltmeters and one horizontal pendulum tiltmeter are included. The duration of analysis is chosen to be 29.5 days with some exceptions.

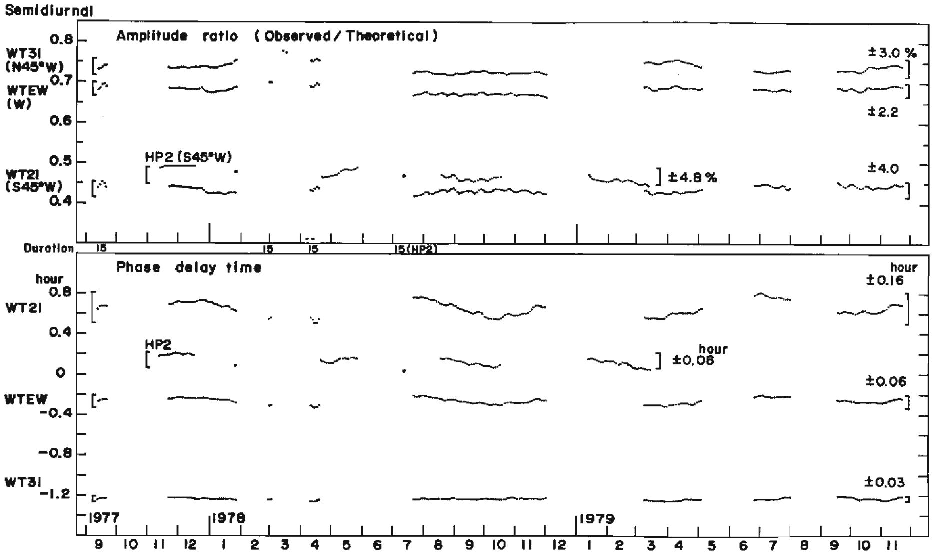


Fig. 10 Time variations in the semidiurnal tidal admittance during the period from Sept. 1977 to Nov. 1979 obtained from the time domain analysis. Both the results of three-component water-tube tiltmeters and one horizontal pendulum tiltmeter are included. The duration of analysis is chosen to be 30 days with some exceptions.

Table 1 Probable errors of the amplitude ratios for three components of the water-tube tiltmeters during the period from Sept. 1977 to Nov. 1980.

| Method | Duration of analysis | Probable error | |
|---|---|---|---|
| | | Minimum | Maximum |
| Time domain | 30 days | 0.13% | 0.5% |
| | 15 days | 0.20% | 0.6% |

problems, but probably represents real time variations. The minimum and maximum probable errors of the amplitude ratios computed from the time domain analysis over the whole observation period are shown in **Table 1.**

The ranges of maximum variations over the entire period in the amplitude ratios and phase delay times are indicated in the right end of **Figs. 9** and **10**, respectively. Since the indicated ranges for the corresponding components given in the two figures are almost the same, we may say that there is no significant difference between these two methods for the purpose of monitoring time variations of the tidal admittances at the Kamitakara station.

In the time domain analysis, the simple average and RMS standard deviation of 195 points over the entire period were also calculated for the amplitude ratio and phase delay time for all components. The results are given in **Table 2.** The standard deviation of the amplitude ratio for the WTEW component is estimated to be 1.2%,

Table 2 Simple average and RMS standard deviation of 195 points (from the time domain analysis) during the period from Sept. 1977 to Nov. 1980.

| | WTEW | WT31 | WT21 |
|---|---|---|---|
| Amplitude ratio | 0.680±0.008 (1.2%) | 0.734±0.011 (1.5%) | 0.435±0.010 (2.2%) |
| Phase delay time | −0.260±0.029$^{hour}$ (1.7$^{min.}$) | −1.231±0.011$^{hour}$ (0.7$^{min.}$) | 0.656±0.070$^{hour}$ (4.2$^{min.}$) |

which is nearly equal to the accuracy of sensitivity measurements. The phase delay time is extremely stable in the WT31 component and its standard deviation is only 0.7 minute.

## 5.3. Horizontal Pendulum Tiltmeters

As described in the previous paper[2], two horizontal pendulum tiltmeters have been installed in the same direction in the observation vault at the Kamitakara station. The distance between the two tiltmeters is only 70cm, and their direction of the pendulum makes an angle of 45° to the vault axis, with a difference within ±1° between the two instruments. Under these situations, one might expect that the observations by the two tiltmeters wo0ld give nearly the same results. In **Table 3** are given the calculated amplitudes and phases for the $M_2$ and $O_1$ constituents by the analysis of the data using the least squares method. **Table 3** indicates that there is some discrepancy in the tidal admittances obtained by the two tiltmeters. The reasons for this may be considered as follows: (1) the distance from the side wall of the vault to the two tiltmeters is different, and their pendulums are directed obliquely to the wall; this situation would give difference in the cavity effect[14),15)] on the two tiltmeters, (2) inhomogeneity of micro-geological structure in the vault. More detailed discussions on this difference will be made elsewhere in the future. In this paper, we analyze long term data only from the tiltmeter HP2.

Table 3 Comparison of the tidal tilts observed with two horizontal pendulum tiltmeters installed in the same dirction.

| Constituent | HP 2 | | HP1 | | $A_2/A_1$ | $\varphi_2-\varphi_1$ |
|---|---|---|---|---|---|---|
| | Amplitude $A_2$ | Phase $\varphi_2$ | Amplitude $A_1$ | Phase $\varphi_1$ | | |
| $M_2$ | $1.76\times10^{-3}$ | −175.1° | $1.83\times10^{-8}$ | 167.4° | 0.96 | 17.5° (36.2$^{min.}$) |
| $O_1$ | $1.06\times10^{-8}$ | 137.1° | $0.75\times10^{-8}$ | 145.2° | 1.40 | −8.1° (−34.9$^{min.}$) |

Notes : Duration of analysis; Sept. 02, 18h00m-Oct. 02, 05h00m, 1977, (JST).
The phase denotes the lag when the time origin is taken at Sept. 02, 00h00m, 1977, (JST).

The results of successive analyses during the period from November 1977 to March 1979 are also shown in **Figs. 9** and **10**, together with the results from the water-tube tiltmeters. Similar analyses have been carried out hitherto by some investigators[16)~19)]. It is found that in spite of the same direction installed, there exist systematic difference between the amplitude ratios and phase delay times from the HP2 and WT21 componen-s. A possible reason for this may be that the water-tube tiltmeter with a 30m-length is almost free from the cavity effects, while the horizontal pendulum tiltmeter tends to receive its severe local effects. Unfortunately, long-term time variations of the tidal admittances for the HP2 and WT21 components cannot be compared because of a number of interruptions of observed data, although short-period minor fluctuations are involved in the results from HP2. These are the problems to be solved in the near future.

### 5.4. Strainmeters

Mikumo and Kato[7)] have shown that there is excellent agreement in the waveforms between the tidal strains observed at the Kamitakara station and the corresponding theoretical tides. Although they used a trapezoid-shape filter with dominant responses over semidiurnal and diurnal tidal frequencies, in this paper we apply a filter covering only semidiurnal frequencies to the strain data, to compare the results for the strain and tilt tides obtained under the same condition.

In **Fig. 11** are shown the results from successive time domain analyses by shifting the central epoch by a 1-day step for the data obtained during the period from September 1977 to April 1980[20)]. Similar analyses have been carried out by a few geophysicists[21),22)]. Variations of the amplitude ratios over the whole period are limited to within ±5%, which is slightly larger than those for the case of the water-tube tiltmeters. We also notice a parallel trend between the E2 and E3 components, which is similar to the results in a previous paper[6)]. It has been described in that paper that the amplitude ratios for both the E2 and E3 components appear to show a consistent and gradual increase during 10-11 months prior to the central Gifu earthquake of 1969 (M=6.6), with a maximum variation reaching 15%, which is followed by a decrease to a normal value half a year later, and that these large variations might be interpreted as some possible changes in crustal rigidity around the source region of the earthquake. In view of the range of variations within ±5% in the present analysis, the increase in the amplitude ratio up to 15% appears to be abnormally large, more than three times the standard deviation. There remain, however, some problems in that the time length of the analyzed data was shorter than one month in several sampled intervals, and that the applied filter covered all tidal frequencies unlike that of the present analysis. These problems will be re-examined in the near future.

It may be noticed in **Fig. 11** that from February to March, 1979 both the E2 and E3 components show an appreciable increase of the amplitude after a slight decrease.

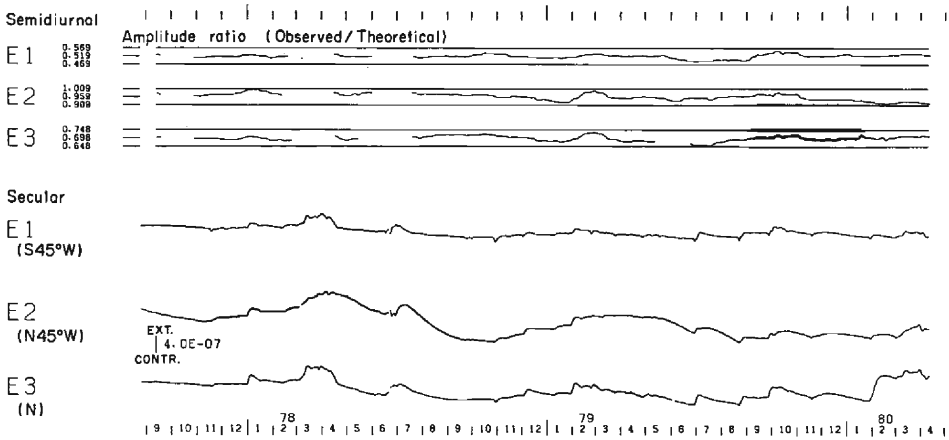


Fig. 11 Upper: Time variations of the semidiurnal tidal admittance for the strains in three different directions (E1, E2 and E3) during the period from Sept. 1977 to April 1980. The duration of analysis is chosen to be 30 days.
Lower: Secular strain changes observed with the same three-component strainmeters.

It might still be possible for us to suspect whether these amplitude variations are real changes in the tidal admittance or due to nonlinear variations of the sensitivities of the transducers used. Since all the strainmeters installed at the Kamitakara station have plural transducers, such a question will be solved in the future by comparing the results from the different set of transducers.

The observed tidal admittances for the tilt and strain data over two years and a half are not continuous but interrupted in different periods. This situation makes it difficult to compare exactly the obtained results over the long duration. It does not appear, however, that there is any particular correlation between them. Secular strain variations are also shown in **Fig. 11.** The correlation between the time variations of tidal strains and secular strains will be discussed in Paragraph 7.

## 6. Seismic Activity

In **Fig. 12** are shown the locations of earthquakes with magnitudes greater than 3.0 that occurred during the period from June 1977 to December 1979 in the northwestern Chubu region, Japan, where the Kamitakara station is denoted by KTJ (cf. Wada et al.[23]). During this period, large earthquakes ($M \geqq 4.5$) have not been observed within a distance of 50km from the Kamitakara station. The horizontal pendulum and water tube tiltmeters and strainmeters have not recorded any tilt and strain steps at the time of earthquake occurrences in this region. No correlations can be detected between the time variations of the obtained tidal admittances and the seismic activity in this region during the above period. It is to be just mentioned that the central Gifu earthquake of 1969, ($M=6.6$) which is described in the foregoing paragarph, was about 50km in the southwest direction from the Kamitakara station.

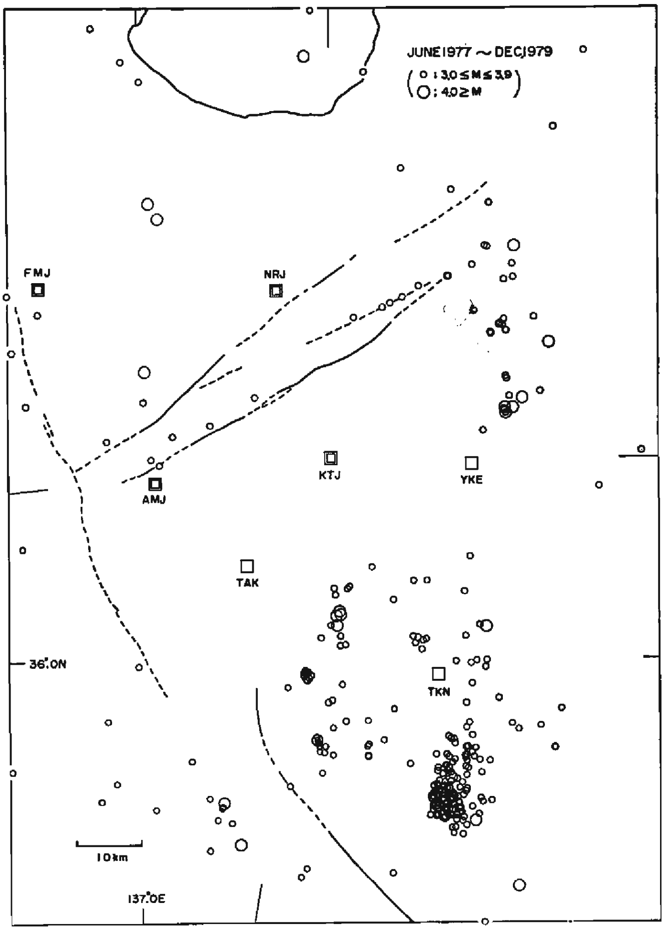


Fig. 12 Locations of earthquakes (M≧3.0) that occurred during the period from June 1977 to Dec. 1979 in the northwestern Chubu region, Japan. KTJ denotes the Kamitakara station.

## 7. Secular Variations of Crustal Tilts and Strains

In this paragraph, we attempt to investigate if there is any correlation between the time variations in the tidal admittance of tilts and strains and secular variations of crustal tilts and strains, although the secular changes at Kamitakara have so far been reported by Ichinohe et al.[24] and Doi et al.[25]. The observed tidal admittances may be considered as an average value over one month centered at its central epoch. In order to compare secular variations with the results for the tidal admittances, a filter rejecting periods shorter than one month has been applied to the data of secular tilts and strains, which are given as time series of the daily average of 24 hourly values. The frequency response of this filter is shown in **Fig. 13**.

Secular tilts of the WT21 and WT31 components, which have been filtered out

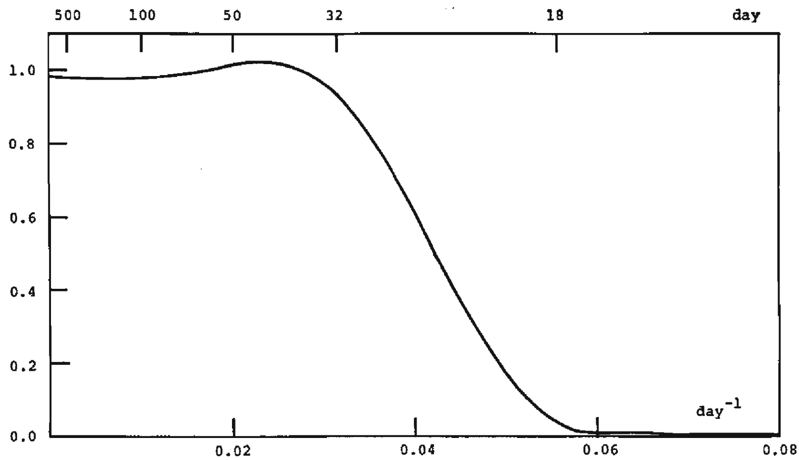


Fig. 13 Frequency response of the filter rejecting periods shorter than one month.

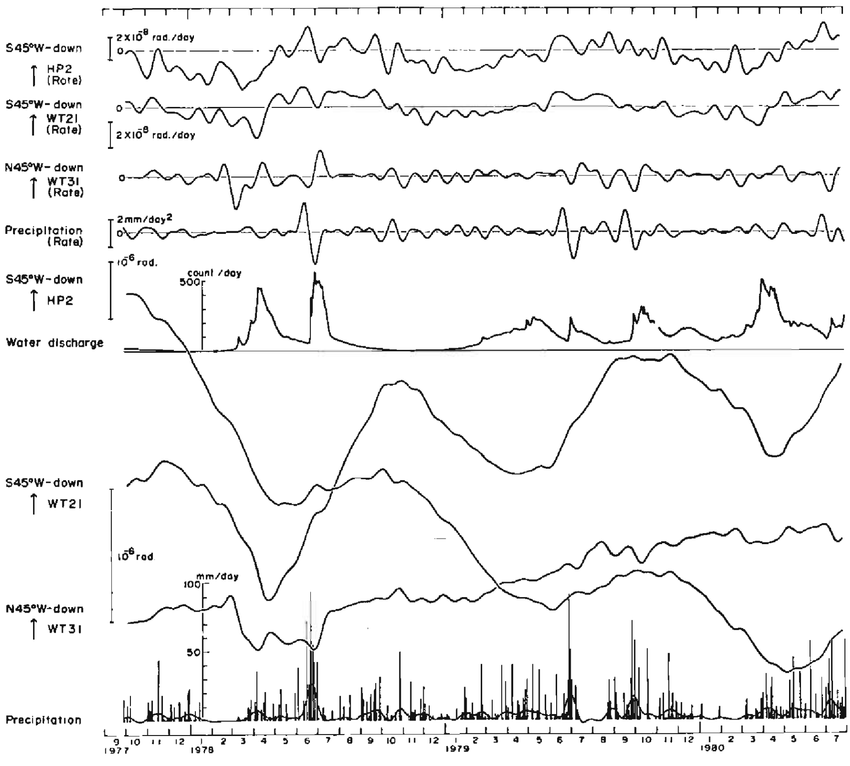


Fig. 14 Secular tilt changes observed with the water-tube tiltmeters and one horizontal pendulum tilttmeter, and their rates, together with precipitations, its rate and amounts of water discharge during the period from Oct. 1977 to July 1980.

in the above way, are shown in **Fig. 14.** It is to be mentioned that a somewhat arbitrary interpolation of missing data in March and July, 1978 might have produced spurious tilt steps. Long-term drifts in the WT21 and WT31 components over the period from October 1977 to July 1980 are estimated to be $1.2\times10^{-6}$ rad. and $0.7\times10^{-6}$ rad., respectively, and the double amplitude of annual variations of the WT21 component reaches $0.8\times10^{-6}$ rad. around 1979. The tilt rates of two components are also shown in **Fig. 14**, together with the amount of precipitation and water discharge. The water discharge is counted by the amount of waterdrop from fissures on the ceiling of the vault. It is quite natural that there exist appreciable correlations between the precipitation and the water discharge. To examine a possible relation between secular tilt variations and precipitations, the precipitation rate has also been calculated after applying the same high-cut filter to an envelope over delta-combs of precipitations. The results indicate the existense of a considerable correlation between the tilt rates and the precipitation rates, which suggests that secular variations of tilts are largely affected by the amount of precipitation.

In **Fig. 14** are also shown the filtered secular tilt and tilt rate from the horizontal pendulum tiltmeter HP2. The drift observed from October 1977 to July 1980 reaches $6\times10^{-6}$ rad., which is about 5 times as large as that observed with the WT21 component of the water-tube tiltmeter, but this value seems to be considerably small for this type of short-base instrument. The long-term trend recorded by the horizontal pendulum tiltmeter may be due to the after effects of installation. Discussion on the discrepancy between the drifts by the two types of tiltmeters should await further studies. It may be seen that the pattern of annual variations is fairly similar to that of WT21 and their double amplitude reaches $1.4\times10^{-6}$ rad. around 1979, about 2 times as large as that of the latter.

On the other hand, a rough estimate shows that daily and annual temperature variations in the observation vault at the Kamitakara station are about one-hundredth and one-tenth degrees, respectively. It seems, therefore, that the annual variations observed by both types of the tiltmeters installed in the same direction are not due to thermal effects on the instruments but reflect the tilt variations of the vault itself. A close comparison indicates that the tilt rates of WT21 and HP2 can be well correlated with each other. It may be concluded from the above described results that the horizontal pendulum tiltmeter especially designed and used here shows a high stability both for the tidal and secular observations.

We can not find any remarkable correlatio s between the secular variations of the filtered tilts shown in **Fig. 14** and the time variations of the tidal tilts described in Paragraph 5.

The high-cut filter has also been applied for the secular strain variations already shown in **Fig. 11** and we calculated the strain rates. These results are shown in **Fig. 15**, where the amount of precipitation and its rate are again included. It is clearly noticed that there exists a close correlation between the amount of precipitation and the secular variations of strains, as in the case of secular tilts, and the effect of

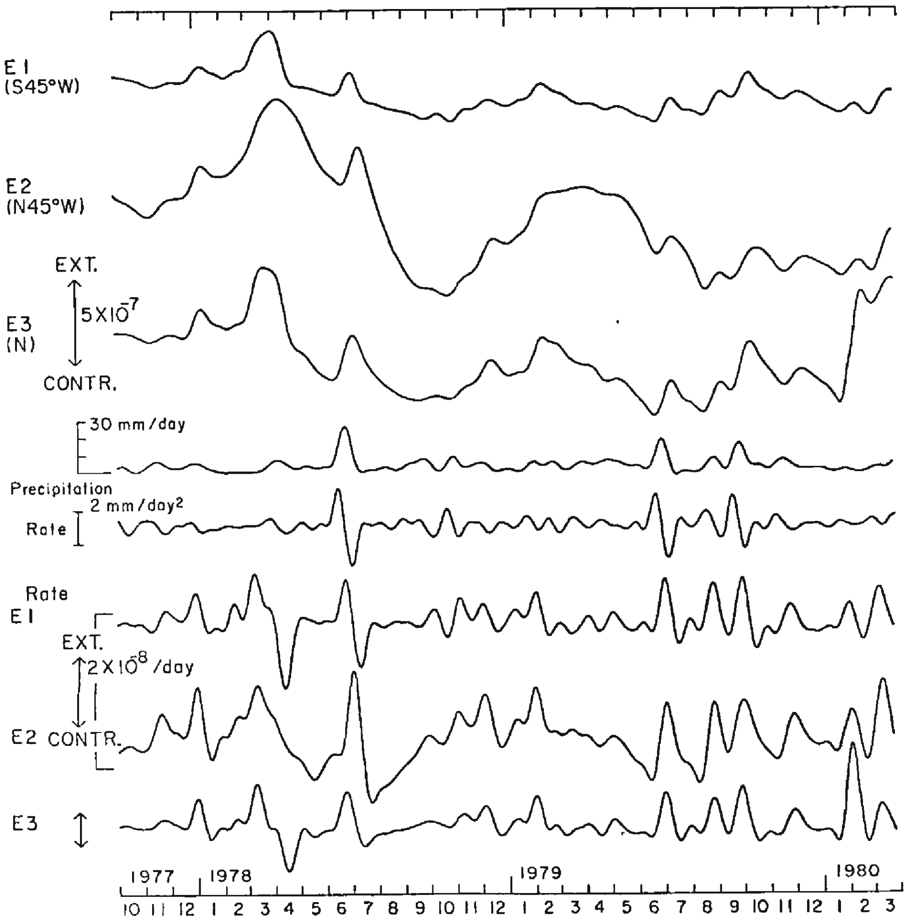


Fig. 15 Secular strain changes observed with three-component strainmeters and their rates, together with amount of precipitation and its rate during the period from Oct. 1977 to March 1980.

precipitation appears to be delayed by about 10 days. Anomalous variations in March-April, 1978 and 1979 are considered to result from a large amount of water discharge due to thawing.

From the various examinations described above, we may conclude that the amount of precipitation and water discharge provides remarkable effects on the secular variations of tilts and strains but hardly any effects on the tidal admittance.

## 8. Summary

The main results obtained in the present study and the subjects left for future studies are summarized as follows:

(1) In order to detect time variations of the tidal admittance (the amplitude ratio and phase delay time) as accurately as possible, two different methods (the Least Squares and the Time Domain analyses) have been closely examined. For the former method, it is extremely effective for increasing the reliability of the results to analyze both the observed and the corresponding theoretical tides in the same procedure. In this case, the most suitable length of analyzed data is 29∼30 days. For the latter method, it is also effective to apply a band-pass filter covering only for semidiurnal frequencies prior to the analysis to reduce meteorological effects. A suitable length of analyzed data is found to be around 30 days. It has become clear that the resolution ability is almost the same for both of the methods.

(2) Applying the least squares and the time domain methods, the amplitude ratios and phase differences of tidal tilts observed at the Kamitakara station over the period from September 1977 to November 1979 have been obtained. The results show that time variations in the amplitude ratios of the tidal tilts in three different directions (S45° W, N45° W and E) do not exceed $\pm 4\%$. This may be regarded as the maximum noise level at this station in the period of low seismic activity and quiet crustal movement. The RMS standard deviation of the amplitude ratio from the time domain analysis is estimated as 1.2% in the WTEW component of the water-tube tiltmeter. This value is nearly equal to the error limit of the present sensitivity measurements. For more detailed discussions, it is inevitably necessary to increase the accuracy of sensitivity measurements.

(3) No close correlations can be detected among the time variations of the tidal admittances obtained from three-component water-tube tiltmeters, one horizontal pendulum tiltmeter and three-component quartz-tube strainmeters. There appears to exist no prominent correlations between the time variations of the obtained tidal admittances and the secular variations of crustal tilts and strains. The amount of precipitation and water discharge provides great effects on the secular variations but no appreciable effects on the tidal admittance. We have not been able to clarify, in this paper, probable reasons for the parallel trend in the time variations of the tidal admittance which were commonly noticed in plural components. A number of physical factors, including meteorological and oceanic loading[26] effects must be considered in the future to solve these problems.

(4) Long-term drifts observed during the above period are considerably small, which are $1.2\times10^{-6}$ rad. and $0.7\times10^{-6}$ rad. for the WT21 and WT31 components of the water tube tiltmeter and $6\times10^{-6}$ rad. for the horizontal pendulum tiltmeter HP2, respectively. The tilt rates observed with the two types of instruments installed in the same direction are remarkably similar to each other. From these results it has been demonstrated that the two types of tiltmeters used here shows a high stability both for the tidal and secular observation.

## Acknowledgements

The author would like to express his deepest thanks to Professor Takeshi Mikumo for his continuing guidance and encouragement during the course of this study. The author is grateful to Professor Torao Tanaka for his helpful suggestions and estimates of the oceanic loading effect on tidal tilts observed at the Kamitakara station. The author wishes to express his sincere thanks to Professor Ichiro Nakagawa for his helpful advice for analyzing tidal data and his continuing encouragement, who also offered his computer program of the least squares method. The author is also deeply indebted to the staff (Messrs. Hikaru Doi, Yasuo Wada and Hiroo Wada) f the Kamitakara Crustal Movement Observatory of the Disaster Prevention Research Institute, Kyoto University, for their continuing maintenance of the observation system. Particular thanks are due to Mr. Hikaru Doi for his co-operation in the analysis of tidal strain data and several helpful discussions with him, and are also due to Eng. Yoshio Tsushima who constructed the mechanical parts of the observational instruments. Thanks are extended to the staff of the Research Section for Earthquake Prediction of the Disaster Prevention Research Institute, Kyoto University for their considerable assistance.

Computations involved were made at the Data Processing Center, Kyoto University and the Information Data Processing Center for Disaster Prevention Research, of the Disaster Prevention Research Institute, Kyoto University.

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