SIMULTANEOUS MEASUREMENTS OF EARTH TIDES IN OSLO AND BERGEN*)

by

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Abstract

The gravimetric earth tide was observed simultaneously in Oslo and Bergen for a period of one week in September 1970. The experiment was repeated in Bergen in September 1971.

The experiment indicates that a tectonic feature such as the Oslo graben responds to the tidal forces, that the ocean tide and the ocean loading are important indirect effects, and it showed how gravity tide measurements feel the ocean at great distances. An important finding is that the resultant gravity effect of the ocean tide and the ocean loading had a time lag (delay) of about two hours compared to the ocean tide at the coast in the 1971 experiment, while the time lag was approximately zero in the 1970 experiment.

1. *Introduction*

The response of the earth to tidal forces can be observed by recording the tidal variation of gravity, the tilting of the earth's surface, and the variation in linear strain. KANESTRØM [3] attempted to measure the gravimetric earth tide with an ordinary gravimeter (Worden Master), and the results of the experiment were so promising

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that we decided to repeat the experiment using two observational sites and with at least two or more instruments at one of the sites.

The object of the experiment was not only to determine the solid earth tide, but also to gain insight into the importance of the indirect and secondary effects in earth tide measurements. The indirect effects are those which have the same periods as the tidal forces such as the ocean tide. The secondary effects are those which do not have these periods such as the barometric pressure. Another aim of the experiment was to determine if earth tide measurements can be used for investigating regional tectonic features in the crust.

A geological model for the Oslo graben has been given by RAMBERG and SMITHSON [7] from gravity data. Their model suggests that the crust beneath the graben is quite different from that beneath adjacent precambrian basement rocks. Seismic measurements also indicate that the physical properties of the crust in terms of seismic velocities and intra-crustal boundaries associated with the graben differ from what is found outside the Oslo graben (KANESTRØM and JOHNSTAD, [4]). Such a major regional tectonic feature as the Oslo graben might affect the earth tides. Thus we set up this experiment in an attempt to detect this effect, and Oslo was chosen as one of the recording sites. With the other recording site in Bergen, both the near and distant effect of the ocean tide and ocean loading could be studied.

2. *General aspects of earth tide*

The deformation of the solid earth caused by the tide-raising potential depends on the rigidity within it. It is well known that the observation of the response of the earth to tidal forces is one of a number of observations which lead to the interpretation that the outer core is liquid. Neglecting dynamic effects in the treatment of the earth tide and using equilibrium theory, the deformation of the earth caused by a tide-raising potential of the second degree is conveniently expressed in terms of the two quantities h and k, known as Love's numbers. The total disturbed potential (W) at a point on the earth can be expressed by

$$W = W_0 + W_t + W_m - gu \tag{1}$$

where W_0 is the undisturbed potential due to the gravity and the rotation of the earth, W_t is the tidal potential due to the sun and the moon, W_m is the potential due to the redistribution of the material of the earth in the tidal deformation, u is the radial displacement at the point, and g is the gravity. With the notations used above, the quantities h and k are defined by

$$u \quad = h \frac{W_t}{g} \tag{2}$$

$$W_m = k\, W_t \tag{3}$$

The tidal component in gravity (g_t) may be written

$$g_t = -\left(1 + h - \frac{3}{2}k\right)\frac{\delta W_t}{\delta r} = -\delta\,\frac{\delta W_t}{\delta r} \tag{4}$$

For details, the reader is referred to MELCHIOR [5]. For a completely rigid earth the gravimetric factor $\delta = (1 + h - 3/2\, k)$ would equal one, because g_t would be given by $-\delta W_t/\delta r$. Thus the gravimetric factor gives the magnification of the variations in g due to the yielding of the earth. The potential due to the redistribution of the mass of the earth tends to reduce the magnification caused by the displacement of the observer.

Observations show that only a general agreement exists between the theory of earth tides in terms of h and k and the observational determinations of h and k. In theory, it is assumed that the earth is spherically symmetrical with no oceans on its surface and that its physical properties vary only as a function of radius. It is obvious that these assumptions are not fulfilled. The measurements of the pure tidal deformation of the solid earth are complicated by the contribution of the indirect and secondary effects. Perhaps one of the most important indirect effects is the ocean tide, which disturbs the gravitational field through the direct attraction of the water, and further through the distortion of the earth by the load of water. The interpretation of the measurements of the earth tide is complicated by the fact that our present knowledge of the correction for indirect and secondary effects is incomplete. It is not unreasonable that crustal fractures or other tectonic features will cause effects that will complicate the global pattern of the earth tide. On the other hand, earth tide measurements may become a method for investigating tectonic features as faults and crustal blocks in the future.

3. *The experiment*

The gravity effect of the earth tides was measured simultaneously at Bergen and Oslo for one week in September, 1970. One gravimeter was operated in Bergen and three at the same station in Oslo. Additional measurements were made in Bergen in September, 1971, where two gravimeters were in operation. For both series of measurements, the gravimeters and the temperature in the observation room were read every 30 minutes. In Bergen the instruments were operated in the seismometer room at the Seismological Observatory, and in Oslo a suitable room was available in basement of the Mineralogisk-Geologisk Museum. Three types of instruments were used: Two Worden Masters, one Worden Pioneer and one LaCoste-Romberg. A thermostat was in operation only on the LaCoste-Romberg gravimeter. Data for the stations, instruments and periods of observation are given in Table 1.

4. *Analysis of the tidal gravity data*

As a first approximation we assumed the instrumental drift to be linear during the period of observation. The temperature variation was less than 2°C for the whole period. The assumed linear drift was determined by using the method of least squares and is given in Table 1. A computer plot of the original data is shown in Figure 1 which demonstrates clearly the instrumental drift. As can be seen from Table 1 and Figure 1, the instrumental drift is much less for the LaCoste-Romberg gravimeter (2.6 μgal/hour) than for the Worden gravimeters (14 μgal/hour). KANESTRØM [3] used one of the same Worden gravimeters in his tidal gravity experiment in 1967 and observed a linear drift of 18 μgal/hour, which shows that there is no great change in the mean instrumental drift over period of a week.

The presence of microseisms caused the beam to vibrate about the null line on the reticle, making the gravity readings troublesome sometimes. Sufficient time

Table 1. Instruments, sites and periods of recording.

<table>
<tr><th>Site</th><th>Instrument</th><th>Instrumental drift (μgal/hour)</th><th>Temperature (°C)</th><th>Recording period (Time in GMT)</th></tr>
<tr><td rowspan="3">Oslo
59°55′07″ N
10°45′37″ E
Elevation: 31 m</td><td>LaCoste-Romberg</td><td>2.6 ± 1.5</td><td rowspan="3">20 ± 1</td><td rowspan="4">1970
Start: 14. September
08 h 00 m
Stop: 21. September
07 h 30 m</td></tr>
<tr><td>Worden Master</td><td>13 ± 4</td></tr>
<tr><td>Worden Pioneer</td><td>14 ± 7</td></tr>
<tr><td rowspan="3">Bergen
60°23′13″ N
05°19′33″ E
Elevation: 22 m</td><td>Worden Master</td><td>14 ± 4</td><td>15 ± 0.5</td></tr>
<tr><td>Worden Master</td><td>14 ± 4</td><td rowspan="2">15.5 ± 0.5</td><td rowspan="2">1971
Start: 26. September
15 h 30 m
Stop: 2. October
15 h 00 m</td></tr>
<tr><td>Worden Pioneer</td><td>17 ± 6</td></tr>
</table>

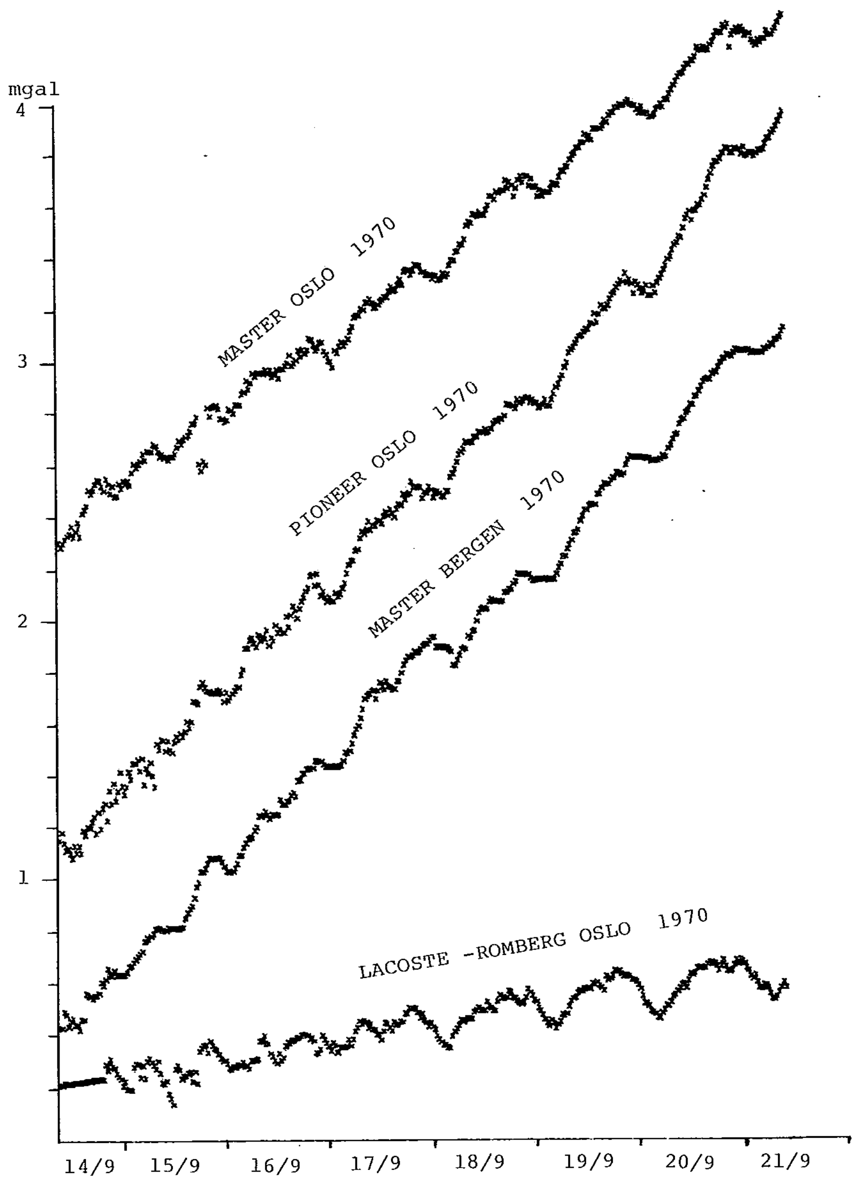

Figure 1. Computer plot of the gravity earth tides measured in Oslo and Bergen, September, 1970.

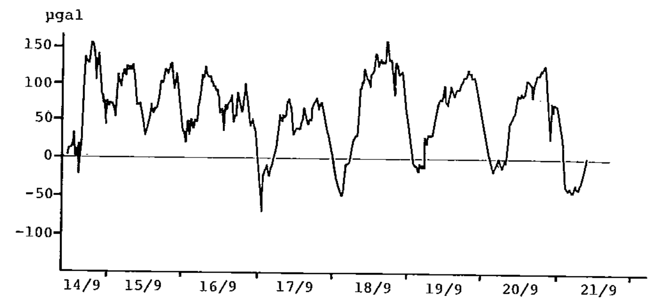

Figure 2. Earth tide (unfiltered) measured by a Worden Master gravimeter, Oslo, September, 1970.

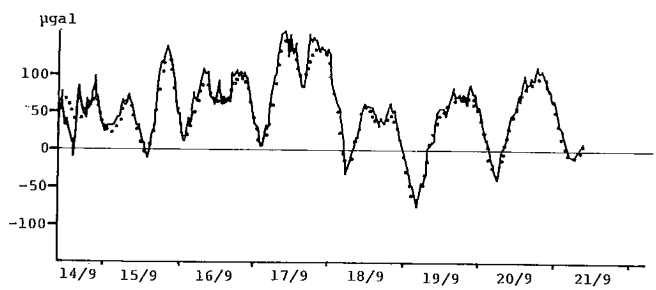

Figure 3. Unfiltered (solid line) and filtered (dotted line) earth tide measured by a Worden Master gravimeter, Bergen, September, 1970.

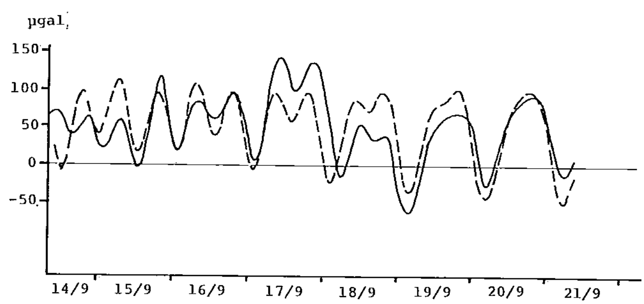

Figure 4. Observed earth tide uncorrected for ocean tide (solid line) and predicted earth tide (dashed line) for Bergen, September, 1970.

was taken in positioning the beam at the null line, however, and the average null position of the dial was read. The uncertainty in the positioning of the beam occurs as high frequency noise in the earth tide as shown in Figure 2. The noise was effectively removed by using a digital low-pass filter (0–0.125 $hour^{-1}$). An example of unfiltered and filtered data is shown in Figure 3. An accurate comparison of the observed and predicted tides demands exact coincidence of their zero lines, but the gravimeters do not indicate the zero points of the observed tides. The location of the zero line of the observed tides was attained through equalization of the data. By using the same process on the predicted tides as well, the zero lines of the two tides were brought in coincidence. A comparison between the observed and predicted tide for Bergen 1970 is shown in Figure 4. The predicted earth-tide is calculated for a yielding earth with $(1 + h - 3/2\,k) = 1.20$. As is clear from Figure 4, the tides do not coincide, and there are at least two important effects which cause the discrepancy. First we have not corrected for the ocean tide, which affects the local gravity field in two ways. The major effect arises from the variation of the attraction of the water masses, and a smaller influence is produced by the change in station elevation accompanying the variation of the ocean loading. The two effects are acting in the same way. Second, we have assumed that the instrumental drift is linear over the period of observation.

The ocean tide affects the recordings of earth-tide most seriously in Bergen since the recording site is located at the coast. The correction for the ocean tide was obtained by calculating the attraction of the sea water from coastal tide gauge data (Fig. 5). The calculation was simplified by dividing the ocean into plane sectors of constant thickness. The calculated gravimetric effect of the ocean tide together with the residual between the observed earth tide (uncorrected for ocean tide) and the predicted earth tide are shown in Figure 6. The striking agreement between the two curves, indicates that the ocean tide is an important indirect effect in the measurement of earth tide at sites close to the coast. The maximum correction for the water masses in the Oslofjord and a sector of 40° as seen from Oslo into the Skagerrak, amounts to less than 2.8 μgal. The predicted tide and the observed earth tide corrected for the ocean tide are shown in Figure 7 for the experiment in Bergen, 1970. The deviation between the equilibrium or zero points of the two tides can be explained by the existence of an non-linear component of instrumental drift, or by secondary effects. If the earth tide had been observed over a sufficient period of time, the non-linear instrumental drift could be eliminated with a high-pass filter. An exact coincidence of the zero lines of the predicted and observed tides can be obtained only after the elimination of the instrumental drift from the observed tides.

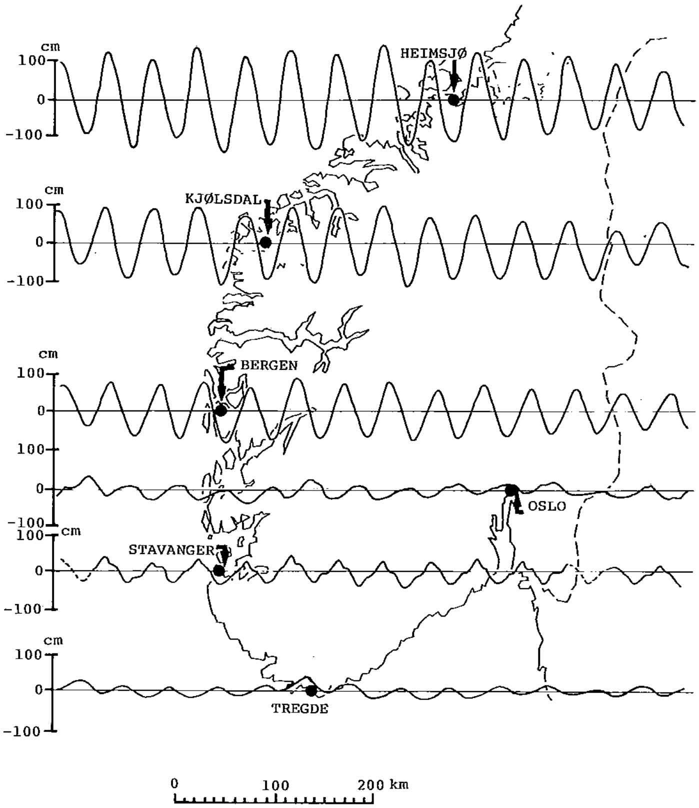

Figure 5. Recordings of the ocean tide along the Norwegian coast from September 14th to September 21st, 1970.

In the present study, the non-linear component of the instrumental drift is eliminated by a method based on the following assumption: The ratio between the amplitude measured from the zero line (peak or trough) to the total amplitude for the observed tide shall be equal to the corresponding ratio for the predicted tide. By this adjustment of the zero line for the observed tide, the non-linear component of the instrumental drift was removed from the observed tide. The non-linear component of the instrumental drift for the three gravimeters used in Oslo is shown in Figure 8 together with the barometric pressure for the Oslo area and the temperature variation at the observation site.

The non-linear component may be explained by secondary effects as mentioned above. The three gravimeters in Oslo were placed at the same site, and thus they

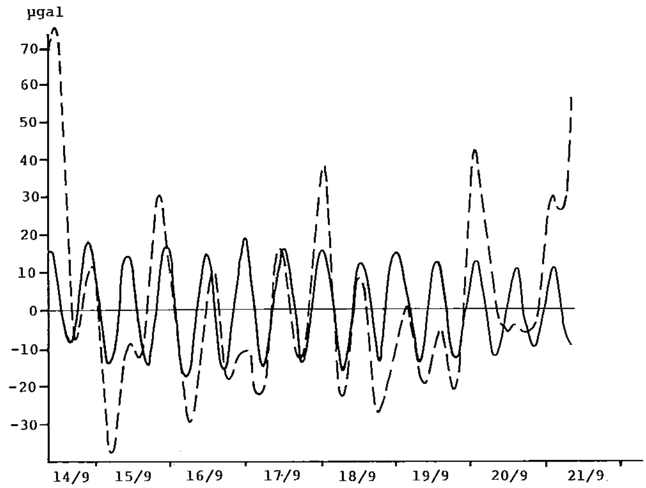

Figure 6. Tidal residual uncorrected for ocean tide (dashed line) and the gravimetric effect of the ocean tide (solid line) for Bergen, September, 1970.

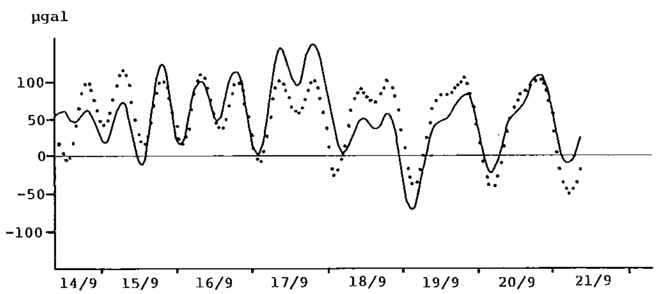

Figure 7. Observed earth tide corrected for the ocean tide (solid line) and predicted earth tide (dots) for Bergen, September, 1970.

recorded the same geophysical phenomena. If the secondary effects are the main reason for the non-coincidence of the observed and predicted tide, the three curves in Figure 8 should have been approximately equal. The same argument may be used to exclude the effect caused by changes in the barometric pressure, and indeed the canges in the barometric pressure (Fig. 8), affect the local gravity field by only 10 μgal (see appendix). This effect is almost completely removed from the data together with the linear instrumental drift, because the barometric pressure varies almost linearly over the period of recording. The remaining barometric effect amounts to less than 2 μgal. We conclude that the differences among

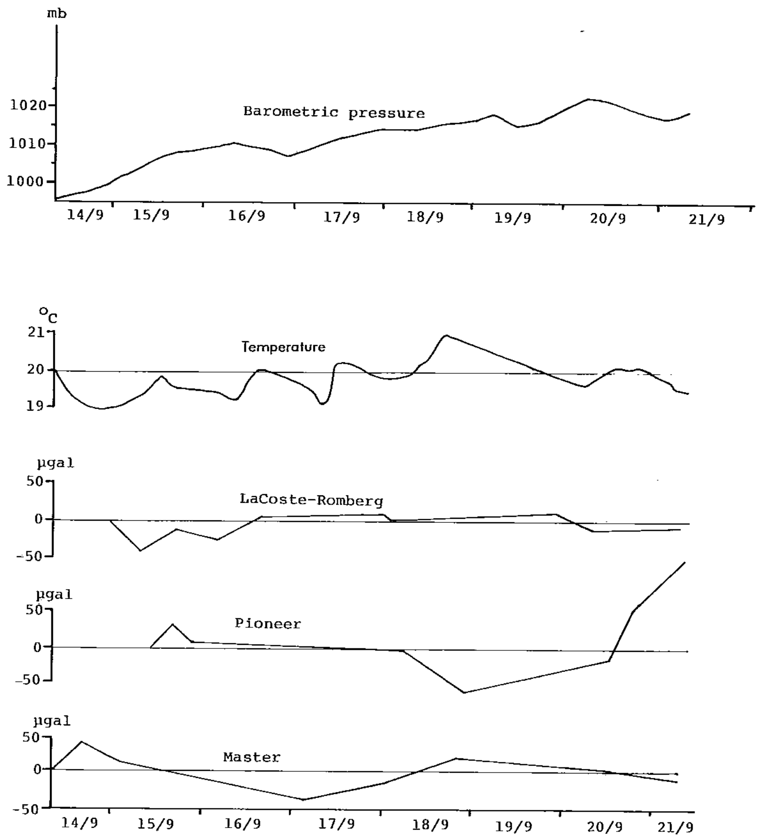

Figure 8. Non-linear instrumental drift in Oslo, 1970, together with the barometric pressure and the temperature variation at the observation site.

the curves in Figure 8 are mainly a result of changes in the instrumental drift. Changes in ambient temperature in this experiment are small (see Fig. 8 and Table 1), and inside the instrument the changes are delayed and reduced by the insulating bottle. It is unlikely, therefore, that the drift rates shown in Figure 8 reflect only the temperature drift. The tides measured by the three instruments in Oslo are averaged to obtain a »mean observed tide» in Oslo.

5. *Determination of the gravimetric factor*

The gravimetric factor was determined using four different procedures to obtain a check on the methodical differences in treating the data.

Method I.

Equation 4 shows the gravimetric factor (δ) to be a ratio of the observed and predicted tides. The accuracy of δ decreases when the amplitudes become smaller, and it will be especially serious when a time (or phase) lag occurs. To reduce this effect one can leave out all points where the predicted amplitudes are less than a given value. To reduce the effect of a phase lag for all amplitudes, we have calculated δ from the mean absolute amplitudes of the observed and predicted tide by the following equation:

$$\delta = \frac{\sum_{i=1}^{N} |AO_i|}{\sum_{i=1}^{N} |AP_i|} \tag{5}$$

where AO_i and AP_i are the amplitudes of the observed and predicted tides respectively. N is the number of amplitude values. By this procedure we have avoided the indeterminant points and the extremely large or small values of δ in connection with small amplitudes of the observed and predicted tides.

Method II.

The gravimetric factor can be determined as the regression coefficient of the observed and predicted tides. This method has been commonly used to determine the mean value of δ (TOMASCHEK, [8]; BAARS, [1]). A modification of the method was used by PAN [6]. In the present study the straight line was restricted to pass through the origin to reduce the influence of the small amplitudes.

Method III.

The mean gravimetric factor was also obtained using the gravimetric residual (R_i) which is defined as the difference between the observed and predicted tide:

$$R_i = AO_i - AP_i \cdot \delta \tag{6}$$

The value for δ is obtained using equation 6, by requiring that $\sum_{i=1}^{N} |R_i|$ be a minimum.

Method IV.

The gravimetric factor was also calculated from harmonic analysis of the observed and predicted tides, and is given by the equation

$$\delta = \frac{SO_j}{SP_j} \tag{7}$$

where SO_j and SP_j are the spectral amplitudes of the observed and predicted tides for the constituent j. In our experiment the observation time was relatively short, therefore tidal constituents with closely spaced periods are not completely separable. Because the lengths of the observed and predicted tides are identical, however, the effect of tidal constituents with close period on the amplitude of a single constituent is approximately equal in the spectra of the observed and predicted tides. In the present study, the value of δ was determined for the diurnal and semi-diurnal constituents.

6. *Results and discussion*

The obtained values for the gravimetric factor are given in Table 2. The four methods described above were used on the tide recorded on each of the gravimeters, and on the »mean observed tide» in Oslo obtained by averaging the data from the three instruments used in Oslo. In the experiment carried out in Bergen 1971, the Worden Pioneer gravimeter had a breakdown, and the tidal data recorded by this instrument is not presented here.

As seen from Table 2, the values of δ obtained by the different methods are quite consistent except for the values obtained from the spectral amplitudes of

Table 2. Calculated values of the gravimetric factor using different procedures.

Site	Instrument	The gravimetric factor $\delta=(1+h-3/2k)$ obtained by different methods					
		Method I	Method II	Method III	Method IV		Mean value of δ
					Diurnal constituents	Semi-diurnal constituents	
Oslo 1970	LaCoste-Romberg	1.29	1.26	1.26	1.32	0.85	1.28 ± 0.03
	Worden Master	1.23	1.25	1.24	1.25	0.97	1.24 ± 0.01
	Worden Pioneer	1.27	1.27	1.25	1.25	1.06	1.26 ± 0.01
	»Mean earth tide»	1.24	1.26	1.25	1.28	1.05	1.26 ± 0.02
Bergen 1970	Worden Master	1.19	1.24	1.19	1.07	1.11	1.17 ± 0.06
Bergen 1971	Worden Master	1.11	1.10	1.13	1.17	0.62	1.13 ± 0.03

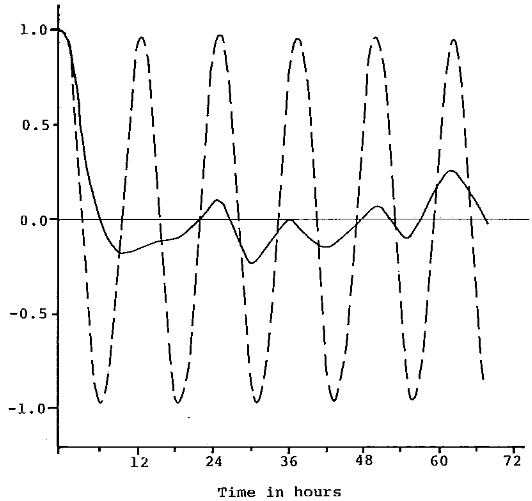

Figure 9. Autocorrelation functions of the ocean tide, Bergen, (dashed line) and of the tidal residual (Worden Master, Oslo). September, 1970.

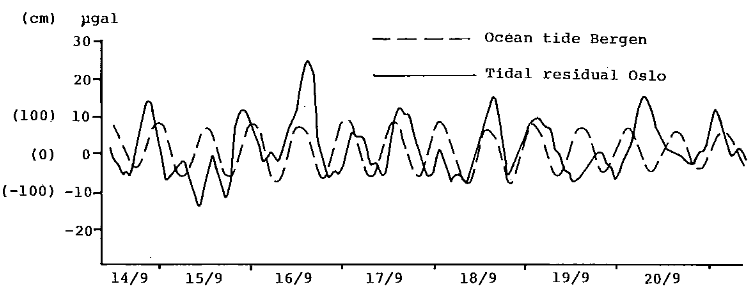

Figure 10. Ocean tide, Bergen, and the tidal residual for the »mean earth tide» in Oslo, September, 1970.

the semi-diurnal constituents. The tidal data recorded by the Worden Master in Oslo give systematically lower values of δ than do the data recorded by the Worden Pioneer and LaCoste-Romberg gravimeters. This difference may be explained as a result of incorrect instrumental conversion factor (dial constant).

An interesting result of the analysis of the observed tides is the difference between the values of δ obtained in Oslo and Bergen. As already mentioned, we applied a correction for the attraction of the water masses in Bergen. This correction is undoubtly incomplete because of lack of information on the ocean

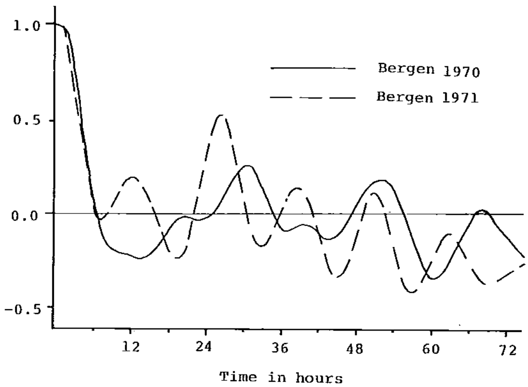

Figure 11. Autocorrelation functions of the tidal residuals in Bergen 1970 and 1971.

tide off the coast, and because of the unknown effect of the ocean loading still remaining in the observed earth tide.

The tidal residuals were analysed and were found to contain periodic components. The most prominent component has the same period and phase as the ocean tide along the west coast of Norway. Figure 9 shows the autocorrelation functions of the ocean tide recorded in Bergen and of the tidal residual for one of the gravimeters in Oslo. The tidal residual for the »mean earth tide» in Oslo is plotted in Figure 10 together with the ocean tide recorded in Bergen. The effect of the ocean on gravity tide measurements, even at great distances, is demonstrated in Figures 9 and 10. The tidal residual reflects not only the attraction of the water mass, but also the loading effect of the ocean tide. As seen from Table 2 the calculated values for the gravimetric factor (Method IV) are systematically lower for the semidiurnal constituents than for the diurnal constituents in Oslo. A reasonable interpretation of this result is that it is an effect of the ocean tide. It should be remarked that we have not performed any contamination correction in Method IV, but this is not essential because the contamination effects are the same on spectra of both observed and theoretical tides.

There is a change in the ratio between the gravimetric factors obtained for the semi-diurnal and diurnal constituents in Bergen 1970 and 1971. A significant geophysical interpretation of this observation is that the correction for the ocean tide in 1970 was almost successful or even overestimated, while the ocean tide correction in 1971 was underestimated. The autocorrelation functions of the tidal residuals in Bergen 1970 and 1971 show that a distinct semi-diurnal component is present in the tidal residual for 1971 (Fig. 11). Support for this interpretation is shown in Figure 12 where the tidal residual is compared with the ocean tide. For

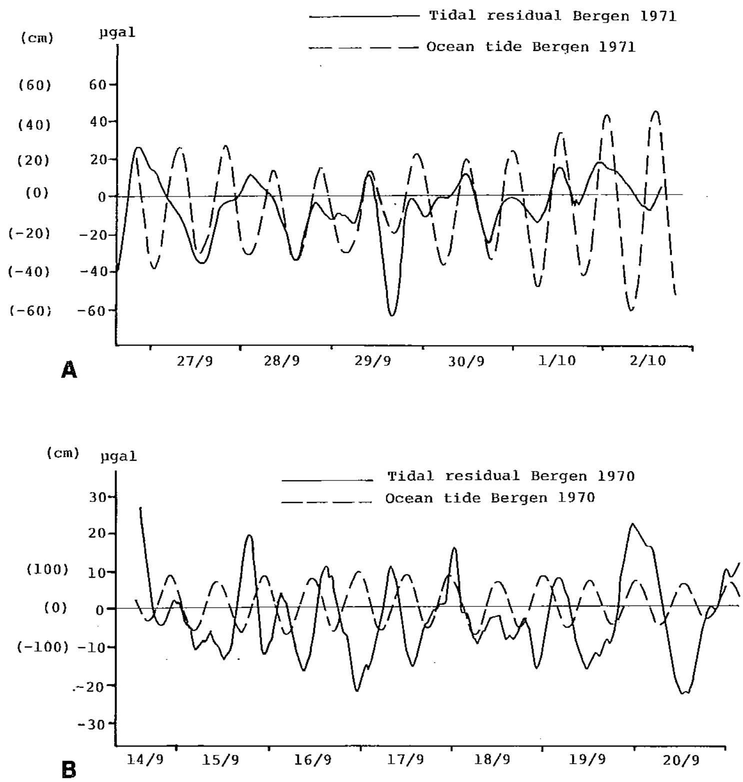

Figure 12.
A) Ocean tide and tidal residual, Bergen 1971.
B) Ocean tide and tidal residual, Bergen 1970.

the experiment in 1971 (Fig. 12A), there is a striking agreement between the periods of the tidal residual and the ocean tide at the coast when a time delay of about four hours was applied to the tidal residual with respect to the ocean tide at the west coast of Norway. The corresponding curves for the experiment in 1970 (Fig. 12B) do not show this agreement, and to a certain degree the two curves are opposite in phase. A zero time lag between the ocean tide and the tidal residual does not alter this, and we find that an overestimation of the ocean tidal correction in the 1970 experiment is a reasonable interpretation. The lack of information on the ocean tide off the coast does not permit a further investigation into this point in the present study.

The time lag between the ocean tide (recorded at the coast) and the tidal residual uncorrected for ocean tide for the 1971 experiment was determined by the cross-

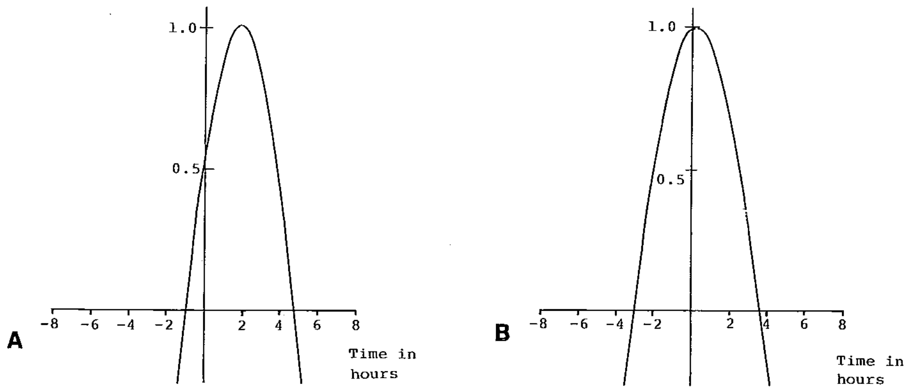

Figure 13.
A) Crosscorrelation function between the ocean tide (recorded at the coast) and the tidal residual (uncorrected for ocean tide) for Bergen 1971.
B) Crosscorrelation function between the ocean tide (recorded at the coast) and the tidal residual (uncorrected for ocean tide) for Bergen 1970.

correlation function and shows that the resultant effect of the ocean tide and the ocean loading is delayed by about two hours compared to the ocean tide at the coast (Fig. 13A).

This demonstrates the difficulties of performing a satisfactory correction for the ocean tide in earth tide measurements, and the situation is further complicated by the fact that the time lag between the tidal residual (uncorrected for ocean tide) and the ocean tide at the coast was approximately zero for the 1970 experiment in Bergen (Figs. 6 and 13B). At present we feel to be in no position to enter a detailed discussion of this phenomenon, and we limit ourselves to suggest that the ocean tidal conditions for the two periods of observations were different as referred to the ocean tide at the coast. The experiments show that earth tide measurements carry with them much information about the ocean tides.

Despite the difficulties and uncertainties in correcting for indirect effects, we consider the difference in the gravimetric factor obtained in Oslo and Bergen to be significant. The most important support for this is the values of δ obtained from the spectral amplitudes of the diurnal constituents which, in this experiments, were less affected by indirect effects than the semi-diurnal constituents.

The Worden Master gravimeter used in Bergen was checked against the Worden Pioneer used in Oslo, and the observed difference in δ cannot be explained by discrepancies in the dial constants for the two instruments. The interpretation of this observation is that a tectonic feature as the Oslo graben responds to the tidal forces.

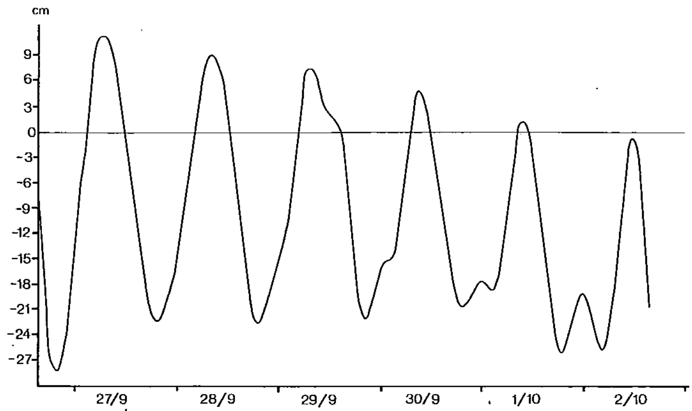

Figure 14. Vertical movement of the earth's surface in connection with the earth tide (Bergen 1971).

The limited amount of data and the low sampling rate do not permit a satisfactory analysis of the phase difference between the observed and the predicted earth tide.

Out of curiosity, we computed the ground amplitude in connection with the earth tide from the observed earth tide in Bergen, 1971. The amplitudes were computed by adopting $(1 + k - h) = 0.65$ and are shown in Figure 14. Since the gravimeter follows the movements of the earth's surface, the observed variation in gravity is influenced by the acceleration of the ground. However, in this case it will not exceed $0.4\,\mu$gal which is far below the accuracy of measurement.

7. *Conclusions*

Despite the relative low precision of the instruments used in this experiment, the data permit some conclusions.

1) A significant difference in the gravimetric factor was observed between Oslo and Bergen, and this indicates that a tectonic feature as the Oslo graben responds to the tidal forces.
2) Earth tide measurement is not just a method for determining the solid earth tide, but may give information about offshore ocean tides. The present study gives an examplification of this.

Like other geophysical phenomena, the observed response of the earth to tidal forces varies over the earth in ways not completely predicted by theory. Earth tide measurements contain considerable information about the earth, and it is to be hoped that we will learn to interpret the observations in the near future. Undoubtedly, this will require that systematic earth tide measurements including gravity, tilt and strain, should be carried out all over the earth.

APPENDIX

THE BAROMETRIC EFFECT

The local gravity field is affected in two ways by changes in barometric pressure. The variation of the attraction of the air mass caused by changes in the density of the air mass is the most prominent effect. A smaller effect, of opposite sign, is caused by the change in the station elevation accompanying the variation of the atmospheric loading.

The attraction of the excess mass in the atmosphere is satisfactorily expressed by the formula for the attraction of an infinite plan slab of thickness h and density ρ:

$$\Delta g_A = 2\pi G \rho h$$

Here G is the gravitational constant. By ordinary hydrostatic theory, the expression for Δg_A can be given by

$$\Delta g_A = 2\pi G \frac{\Delta B}{g_0} = 0.43 \frac{\mu\text{gal}}{\text{mb}} \Delta B$$

where g_0 is the local value of gravity and ΔB is the pressure change in millibars. To obtain a more complete expression for the barometric effect, we have to take into account the vertical displacement of the station caused by the pressure load. CAPUTO [2] has calculated the radial surface displacements of a spherical earth model consisting of a solid homogeneous mantle and a liquid core (radii r_1 = 3473 km and r_2 = 6371 km) in the case that the deforming forces arise from a mass distribution of constant thickness over a single spherical surface cap of arbitrary size. Using the tables of Caputo, keeping the elastic parameters $\lambda_2 = 14\mu_2/11$, $\mu_2 = 10^{12}$ and $\lambda_1 = 8 \cdot 10^{12}$, $\mu_1 = 0$, for the mantle and core, respectively, the central displacement (ΔR) caused by a cap of mass with a semiamplitude of 4 degrees is given by

$$\Delta R = 0.0304 \frac{\text{cm}}{\text{mb}} \Delta B.$$

Applying the free-air correction to correct for the change in the local value of gravity caused by the change in station elevation, we arrive at

$$\Delta g_L = 0.09 \frac{\mu\text{gal}}{\text{mb}} \Delta B.$$

The total barometric effect, Δg_B, (attraction of the air mass and atmospheric loading) is then given by

$$\Delta g_B = (\Delta g_L - \Delta g_A)\, \Delta B = -0.34 \frac{\mu\text{gal}}{\text{mb}} \Delta B.$$

This means that an increase in the barometric pressure of 1 mb reduces the value of gravity by 0.34 μgal.

The principles outlined here can also be applied to the ocean loading.

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