

What Can Earth Tide Measurements Tell Us About Ocean Tides or Earth Structure?

T. F. Baker

Institute of Oceanographic Sciences, Bidston Observatory
Birkenhead, Merseyside, England

Abstract. A brief review is given of the current experimental problems in Earth tides using comparisons of tidal gravity and tilt measurements in Europe with loading calculations as examples. This review shows the limitations of present day instrumentation and installation techniques and some of the ways in which they can be improved.

With these limitations in mind, we go on to a general discussion of many of the geophysical and oceanographic investigations that are possible with Earth tide measurements. In particular, we concentrate on the percentage accuracies required in the measurements in order to obtain new information about the Earth or Oceans.

1. Introduction

In recent years there has been a very significant advance in the quality of Earth tide instrumentation. Various gravimeters, tiltmeters and strainmeters are now available which, for any tidal constituent between one cycle per day and four cycles per day, give a signal/noise ratio which is comparable with, and in some cases significantly better than, that obtained with most ocean tide instrumentation. However, due to certain experimental difficulties, which are discussed in Section 2, there has not been the same degree of advance in the interpretation of the recorded signal.

On the theoretical side there have recently been some very important advances. The solution of the loading Green's function problem for a spherical, radially stratified, gravitating, elastic Earth model by Farrell [1972] and the introduction of the finite element method to model more complex local and regional structures, [Beaumont and Berger 1974, Harrison 1976 and Berger and Beaumont 1977] have now made it possible to attempt a realistic interpretation of the recorded signal.

Despite all the above advances in solving the experimental and theoretical problems of Earth tides, progress in using the Earth tide signal to obtain useful geophysical and oceanographic information has been slow and we are still at a very preliminary stage. Progress has been limited by the efforts required to solve the experimental problems discussed in the next section. Clearly, it is important to briefly review these experimental limitations before going on, in the later sections, to discuss the feasibility of some of the geophysical and oceanographic objectives.

An examination of the literature reveals essentially four stages in the development of the study of Earth tides, each associated with a different level of interpretation of the recorded signal. At the first stage there is the publi-

cation of a list of experimental tidal parameters with no interpretation other than a rough comparison with the parameters expected for an oceanless, elastic Earth and the noting of any large unexpected anomalies. The second stage is a general comparison of experimental results (usually M_2 and/or O_1) with a body tide and load tide calculation for a given standard Earth model and a single ocean tide model. The third stage is a comparison of the measurements with a range of possible given seismic Earth models and/or a range of possible given ocean tide models and thereby choosing the model(s) which give the best fit to the data. The ultimate objective is the fourth stage, the actual inversion of the Earth tide measurements in order to obtain improved models of the Earth structure or of the ocean tides. Clearly, we are particularly interested in the results from stages three and four, but unfortunately the majority of published papers are in the first two categories.

Before going on to review some of the recent developments, it is important to mention two more secondary objectives of tidal investigations. Firstly, there is an increasing demand for body tide and load tide parameters as corrections to geodetic measurements as the accuracy of these measurements increases. Corrections are required for satellite altimetry, laser ranging, VLBI, first order geodetic levelling and microgravimetric surveys. Generally corrections at the 1 centimetre and 1 microgal level are required and the above experimental and theoretical developments are now beginning to make this possible. Secondly, the improvement in instrumentation has led to increasing interest in the difficult problem of recording and interpreting long period tilt and strain signals as precursors to earthquakes. Here the resolution of a tidal signal of roughly the predicted amplitude gives some of the necessary assurance that the instrument is correctly coupled to the Earth and producing meaningful long period signals.

2. The Experimental Problems

Figures 1 and 2 illustrate the current experimental problems of Earth tides in a convenient and concise way. The M_2 observed load values are calculated by subtracting the theoretical body tide from the observations (assuming a tilt diminishing factor of 0.69 and a gravimetric factor of 1.160 with zero phase lag). The tilt observations are taken from Melchior [1976], Ostrovsky [1976] and Lecolazet, Steinmetz and Wittlinger [1970]. The gravity observations are from Melchior, Kuo and Ducarme [1976] and Baker [1977]. The contours give the computed M_2 tidal loading amplitude and phases for Europe. The Farrell [1972] Green's function for a Gutenberg-Bullen A Earth model has been used and convolved with the Hendershott M_2 world ocean tide model. It is important to

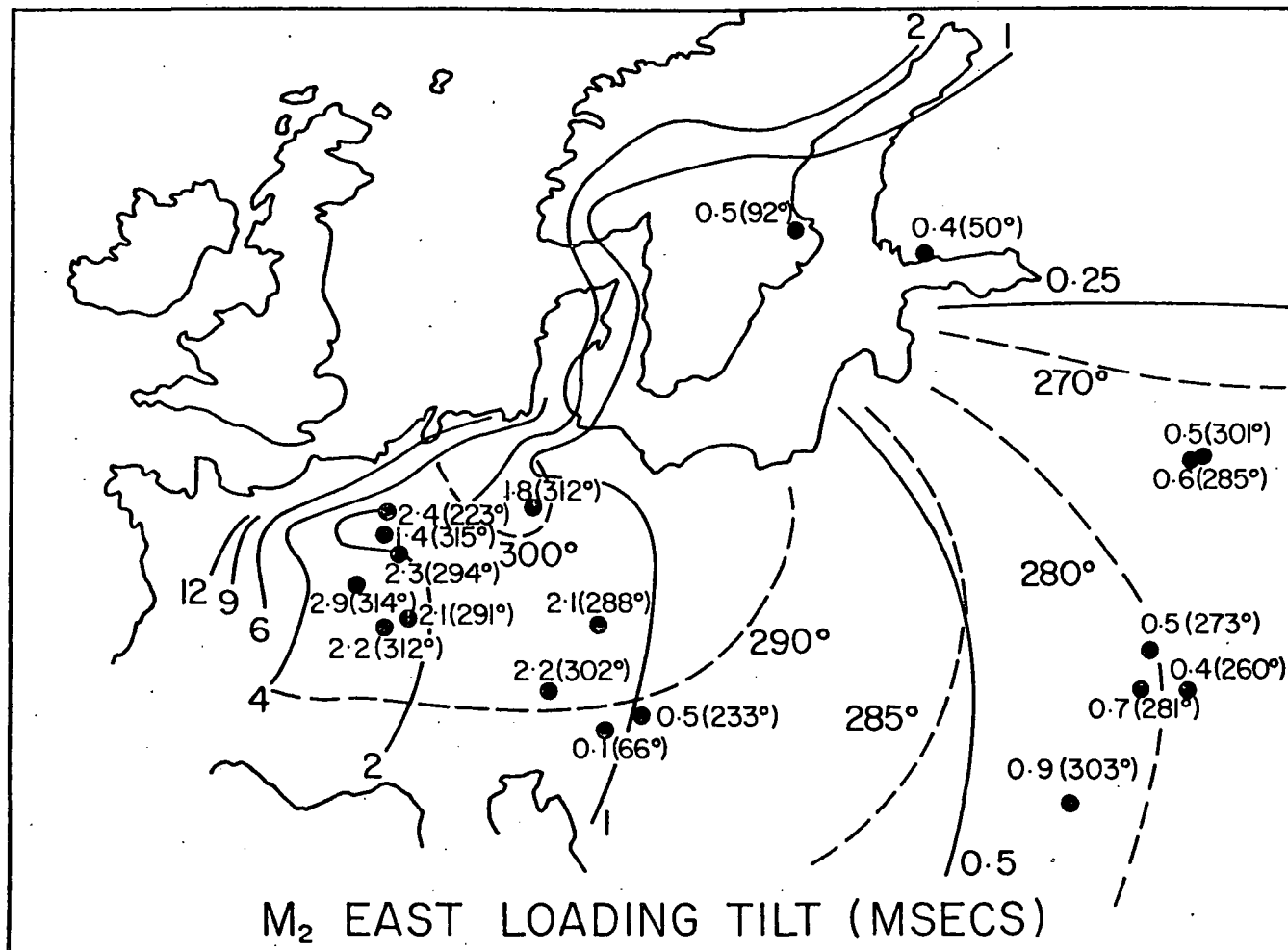


Fig. 1. The observed and calculated M_2 east loading tilt in Europe. The contours show the calculated load distribution using the models described in the text. Amplitudes are in milliseconds of arc and the phase lags are with respect to the tidal potential in the Greenwich meridian.

accurately model the large amplitude tides in the adjacent shelf seas and therefore, for the seas around the British Isles, the Hendershott model has been replaced by a more detailed hydrodynamical model of the M_2 tide [Flather 1976]. It should be noted that the Arctic Ocean and the small tides in the Baltic and Mediterranean have not been included. (For the stations immediately adjacent to the Adriatic and Mediterranean Seas the effect of neglecting these loads can be estimated from the calculations of Chiaruttini [1976]. For the two stations nearest the Adriatic we should subtract about 0.15 microgals from the amplitudes and add about 7° to the phases of our calculated loads.) Despite these limitations the calculations give a reasonable approximation to the load signal and in particular give an indication of the spatial variability of the signal. (It should be noted that for the tidal gravity map the uncertain contribution from distant oceans gives an uncertainty in amplitude and phase equivalent to perhaps ± 0.5 microgals which is fairly uniform over the geographical area).

Generally there is an overall agreement between theory and experiment. A detailed inspection

shows however that, for both the tilt and gravity, there is a large variability over short distances which is inconsistent with the expected spatial variation of the loading signal. It is this scatter of the observed data that is limiting the progress in interpretation of the Earth tide measurements in different areas of the World. The error limits as calculated from the residual spectra are usually less than 0.1 msec in tilt and less than 0.1 microgals in gravity. Therefore, systematic perturbations or systematic experimental errors are present in the data.

In the case of the east-west tilt results, strain induced tilt (strain-tilt coupling) perturbations are present due to the cavity, the topography and the local geology (see for example, Harrison 1976). The east-west rather than the north-south tilt results have been plotted for two reasons. Firstly, the load tilt is of the order of 2-3 times larger in the east-west azimuth in central Europe and secondly the strain induced tilt perturbations are usually less in this azimuth due to the small east-west M_2 body strain in these latitudes.

The typical scatter of the results in West and

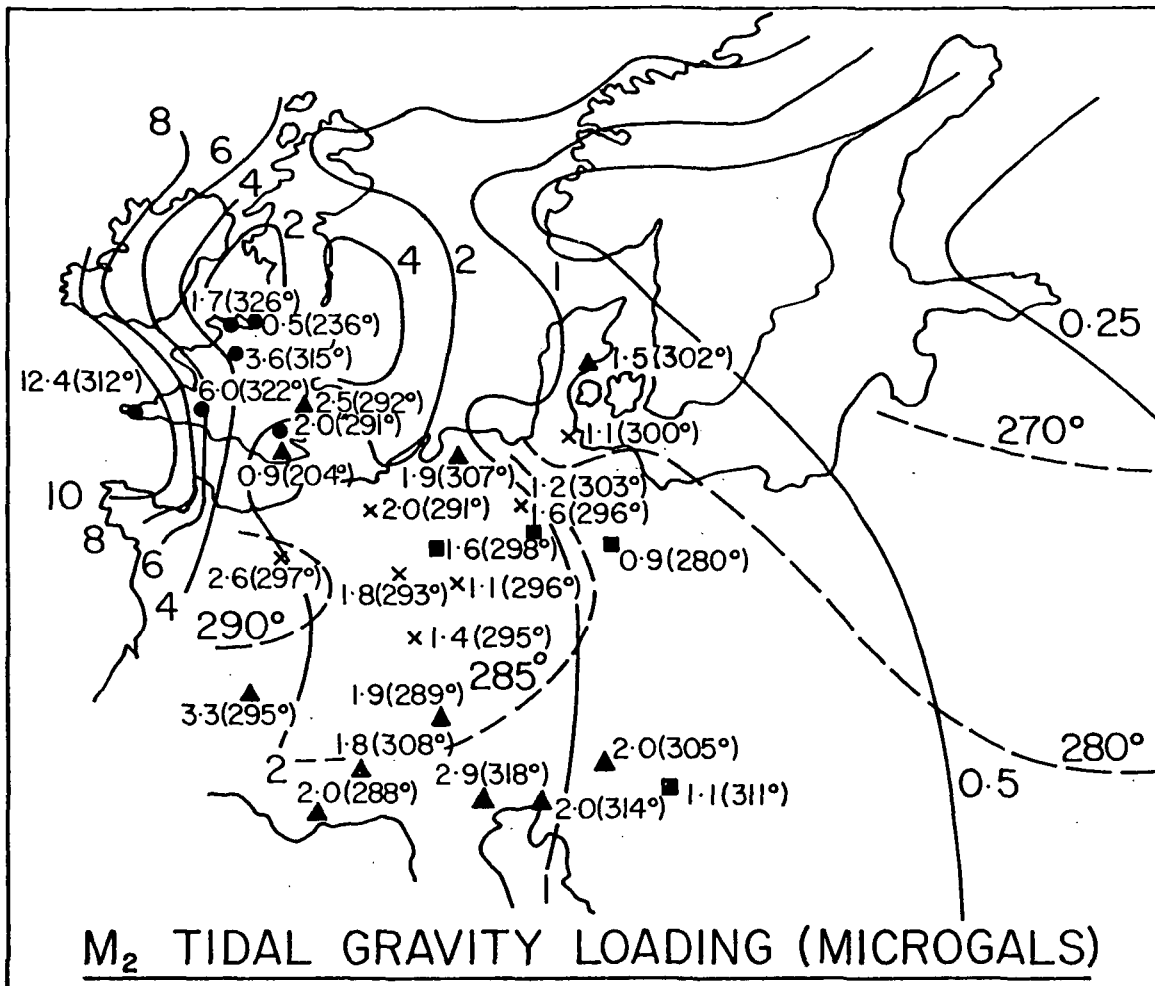


Fig. 2. The observed and calculated M_2 gravity loading in Europe. The contours show the calculated load distribution using the models described in the text. Amplitudes are in microgals and the phase lags are with respect to the tidal potential in the Greenwich meridian. ● LaCoste-Romberg tidal nulled gravimeters; ▲ Geodynamics TRG-1 gravimeters; ■ Askania gravimeters; X mean of various gravimeters.

Central Europe is of the order of ± 0.5 msec (considering both in-phase and quadrature components) which is in fact only $\pm 6\%$ of the total M_2 east-west signal (8-9 milliseconds). The extreme case is an anomaly of 16% of the total M_2 signal. These results are all in mines and tunnels.

The typical scatter of results in the Soviet Union about the mean value is only ± 0.2 msec ($\pm 3\%$ of the total M_2 signal). The Ostrovsky tiltmeters are installed at the bottom of specially constructed shafts 10-20 metres deep and 1-1.5 metres in diameter, in either bed-rock or in unconsolidated sediments. The small scatter is probably due to the symmetrical cavity. (It should be noted, however, that in the north-south direction the percentage scatter of the observations is 2-3 times larger). These results, together with those of Beaumont [1978] using metal vaults installed on the bed-rock at a depth of 5-6 metres, suggest that with near surface types of installation it may be possible to reduce unknown local strain induced tilt perturbations to less than 5% of the signal. However, these installation techniques reduce the strain induced tilt perturbations at

the expense of increased noise, particularly in the diurnal band. Future measurements with long baselength tiltmeters and strainmeters in trenches may give better results over a wider range of frequencies. The measurements of Berger and Wyatt [1973] with an 800 metre surface laser strainmeter and of Michelson and Gale [1919] with a 150 metre trench tiltmeter show that longer baselengths should give the desired improvement.

Boreholes offer another possible solution to the tilt perturbation problem. The comparison of the signals from 3 adjacent boreholes by Zschau [1976] is very encouraging since for M_2 agreement was obtained to $\pm 1\%$ for the east-west azimuth. However, as yet, there are too few published results with which to make a complete assessment of boreholes.

These new developments, as well as reducing the cavity perturbation, allow a more flexible choice of site for geophysical investigations and, where possible, for avoiding the complex topography and geology often associated with mines.

The scatter of the gravity results in figure 2 cannot be explained by local perturbations such

as the cavity, since the effects on gravity are negligible. The typical scatter of the results in Central Europe is ± 0.3 to ± 0.4 microgals which is of the order of $\pm 1\%$ of the total M_2 signal (30-45 microgals in these latitudes). These errors, however represent about $\pm 20\%$ of the M_2 load signal. This scatter is due to the uncertainty in the amplitude and phase calibrations of different instruments. Clearly we have an uncertainty of the order of $\pm 1\%$ in amplitude calibration and an uncertainty in the instrumental phase lags of the order of 1° . There are differences in the manufacturers calibrations and also in the calibration procedures of each research group. Also taking the mean value of several types of instrument at a single station leads to further confusion. Clearly we must aim for all instruments in an area to be calibrated relative to each other to an accuracy of better than $\pm 0.2\%$ in amplitude and $\pm 0.1^\circ$ in phase, so that the loading signal can then be defined to better than 5% accuracy. This can only be achieved by inter-calibrating gravimeters at regular intervals at fundamental base reference stations in each geographical area and carefully monitoring any changes in instrumental parameters during profile measurements.

In this context the measurements of Torge and Wenzel [1977] provide an interesting example. They have carefully compared most of the major types of modern gravimeter at Hannover for several months and also examined the instrumental phase lags and damping factors as functions of frequency. At the frequency of M_2 they have found instrumental lags of up to 2° and damping factor corrections of up to 2.5% . They have also found a wide range of noise levels for the different gravimeters as determined by the residual variance after tidal analysis.

This brief review of the experimental problems of tilt (strain) and gravity measurements shows that many problems still remain, but significant work is now in progress towards their solution. The importance of these experimental limitations will become clear in the later sections.

3. The Body Tide and Earth Structure

It is now well established using a range of possible seismic models that the global body tide Love numbers are only uncertain through a range of 1 or 2%. In view of the above experimental problems and the uncertainties in the ocean tide, it is therefore reasonable to assume in most work that the global Love numbers are known parameters.

The phase lag of the body tide is less well established. It is usually inferred indirectly from free oscillation Q values [Lagus and Anderson 1968]. It has often been stated that, in principle, upper bounds on the phase lag could be determined from very accurate measurements in areas where the load is small, such as in the centre of continents. However, since the expected phase lag is very small, there are severe problems due to both the experimental difficulties discussed previously and the uncertain load contributions from distant oceans.

As an example, consider the Russian tilt results in figure 1. In that area the load tilt is roughly in quadrature with the body tide. There-

fore, the mean of the observed amplitudes can be brought into better agreement with the load calculations by introducing a phase lag in the M_2 body tide tilt of between 1° and 2° . This phase lag is unreasonably large, therefore a more likely explanation is either a small uncertainty in the load calculations or a small phase lag ($1-2^\circ$) in the Ostrovsky tiltmeters.

A problem that has received a lot of interest in the last few years is the measurement of the core resonance in the diurnal band (near ψ_1) arising from the interaction of the liquid outer core with the elliptical rotating mantle. The effects of the resonance have been established for several years now by observing a decrease of the K_1 gravimetric factor relative to O_1 of the order of 1% and the increase of the K_1 tilt diminishing factor relative to O_1 of the order of 7% (see for example Lecolazet and Melchior 1977). Lecolazet and Melchior report a variation in the amplitude of ψ_1 from gravimeter data greater than the errors determined from the variance of the diurnal residuals. They suggest a possible variation of the resonance frequency. Recently, the resonance has been investigated using 2 years data from a laser strainmeter [Levine 1978] and $1\frac{1}{2}$ years data from the superconducting gravimeter [Warburton and Goodkind 1978].

Although the presence of the resonance is now well established, investigations of the detailed structure (frequency and Q value) clearly require very long series of high quality observations with careful examination of ocean loading and meteorological perturbations.

4. Earth Structure from Tidal Loading Measurements

Due to tidal loading from the adjacent sea area the tidal tilt signal within 50 kilometres of the coastline is often observed to be several times larger than the theoretical body tide tilt. If one, or more, tidal constituents in the sea area are known to a few percent accuracy from oceanographic measurements, then it may be possible to determine some parameters concerning the crustal or upper mantle structure from the tilt observations. Similarly, the tidal strain signal is larger adjacent to a sea area, although usually by a smaller factor with respect to the body tide than is the case for the tilt signal. The main difficulty has been in finding suitable sea or ocean areas where it can be assumed that the main marine tidal constituents are known to a reasonable accuracy.

Beaumont and Lambert [1972] have calculated the tilt loading Green's functions for several laterally homogeneous crustal and upper mantle models. They examine the ways in which tilt loading studies differ from or complement, seismic studies. There are three major differences: the loading signal depends upon the Earth's elastic properties averaged over an area rather than averaged along the path of the seismic wave; the loading signal is essentially independent of density; and the frequency of the tidal loading signal is several orders of magnitude lower than for the seismic signals. Beaumont and Lambert conclude that the loading tilt essentially gives information on the Young's modulus, and they suggest the

inversion of load tilt data together with seismic and gravity data in order to give improved estimates of the density and elastic parameters in layered models of the crust and upper mantle.

Continuing this work Beaumont [1978] and Beaumont and Boutilier [1978], using measurements from 5 tilt stations, have confirmed, using different seismic models, that the most appropriate model for the crust beneath Nova Scotia is that given by a seismic refraction profile along the coast of Nova Scotia. The work shows the importance of using tilt differences to eliminate the uncertain tides from distances greater than 500 kilometres. The differential tilt signal then depends upon the crustal structure and the nearby shelf tide, which for M_2 is defined to an accuracy of 2% in amplitude and 2° in phase using ocean bottom tide gauges. From the comparisons of the observations with the model results they also conclude that, except for an anomaly in the borehole results at Bedford, Massachusetts, the strain induced tilt perturbations are reasonably small.

Baker [1977], using tilt observations in a mine at Llanwrst, North Wales, finds that a crustal model from seismic investigations in the Irish Sea with a three layered, 30 kilometre thick crust, fits the observations better than the standard Gutenberg Bullen Earth model with a 38 kilometre crustal thickness. Measurements at different points within the mine, however, show that even in the tunnel azimuth there are differences in the observed tilts of the order of 10% due to strain induced tilt perturbations which make conclusive geophysical interpretation difficult.

Using the tilt Green's function for the above Irish Sea layered model, numerical experiments have been performed in order to investigate the sensitivity of the tilt Green's function to variations in the individual model parameters (P and S wave velocities, density, Young's modulus and Poisson's ratio) of the main crustal layer (depth 4 kilometres to 24 kilometres). A change in the P wave velocity of 5% gives a maximum change in the Green's function of the order of 5% but the Green's function is affected over distances up to 2 or 3 times the depth of the crustal layer. The range of distances involved illustrates the non-uniqueness of the inverse problem.

Other tests have involved the variation of the depth of the Moho, introduction of a crustal low velocity layer, the removal of the uncertain lower crustal layer and variations of the upper mantle parameters. In all these tests it has been assumed that the main crustal parameters have already been determined by explosion seismology, but the parameters are allowed to vary through their possible range of uncertainty in order to investigate how the inversion of tilt loading data can give additional information on the structure. Although it is found that the parameter variations give changes in the Green's function of up to 10% or more, the convolution of the Green's function over a sea area reduces the percentage change in the total tilt signal, due to the load contribution from distances where the Green's function is unchanged. Differential tilt measurements at a suitable separation will, of course, give a larger percentage change than a single measurement.

The convolutions for Llanwrst (16 kilometres from the Irish Sea) show that, although there is a difference of 5% between the predicted tilts with the Gutenberg Bullen model and the local seismic model, reasonable parameter variations of the seismic model only change the predicted tilt by typically 2-4%. Such small changes are difficult to detect for two reasons. Firstly, the uncertainties in the M_2 shelf tide are often of this order. Secondly, as we found in Section 2 it is difficult to guarantee that there are no unknown strain induced tilt perturbations at the 2-5% level which can bias the geophysical conclusions. A large number of tilt measurements in an area with careful topographic and local geological finite element model corrections would be required.

Where there is no previous seismic information available, or where there are large uncertainties in the structure, then tilt measurements can be used to determine the main crustal parameters. From similar tests carried out on the strain load Green's function, it is found to be of the order of 3 times more sensitive to the crustal parameters than the tilt Green's functions. It is therefore suggested that strainmeters (preferably in trenches) may provide a better means of investigating the laterally homogeneous layered Earth structure adjacent to a known tidal load (unfortunately, however, strain is susceptible to coupling perturbations over a wider spatial range than is the case for tilt; Harrison [1976]).

The load tilt signal may also provide useful ocean tide information in the first few hundred kilometres away from the coastline, if the principal crustal and upper mantle parameters are already known from seismology (see Section 6).

In all the above work we have assumed that the Earth responds elastically to the load. Zschau [1977] has pointed out that in some areas the anelastic response may be important and thus there may be a phase lag in the response. For the Irish Sea area, the anelastic response appears to be small. For the Llanwrst tunnel azimuth, 16 months Askania tiltmeter observations give an M_2 phase lag with respect to the elastic load calculations of $0.1^\circ \pm 0.2^\circ$. From the preliminary analysis of three months observations from the Askania in a borehole in the Lake District [Baker, Edge, Jeffries 1977] an M_2 phase lag of $-0.7^\circ \pm 0.3^\circ$ with respect to the elastic load calculations is obtained. (It should be noted, however, that the uncertainty in the Irish Sea M_2 tide is probably of the order of $\pm 1^\circ$.) The largest phase lags are predicted at ocean ridges where Zschau gives a tilt phase lag Green's function of nearly 5° in magnitude. If the phase lag after convolution is sufficiently large, it may be possible to detect the anelastic response using differential tilt measurements on islands on the mid-Atlantic ridge now that the tides are becoming more precisely defined from an array of temporary ocean bottom tide gauges on the mid-Atlantic ridge [Cartwright, 1977].

5. Lateral Heterogeneities in Earth Structure

In the above discussions it has been assumed that laterally homogeneous layered Earth models

are appropriate in a given area. Beaumont and Berger [1974] have shown that the tidal tilt and strain signals differ significantly from their normal values (i.e. the values on a laterally homogeneous Earth) for measurements in the vicinity of a vertical interface or discontinuity between two different elastic media. For example, they find an increase of tidal tilt of 50% over the normal tilt amplitude for a 15% contrast in P wave velocity across an interface. The effects can be detected for a distance away from the discontinuity which depends upon the depth of the discontinuity. Clearly, since the effects on the tilt and strain signal are significantly larger than those found for the changes in the layered models discussed in Section 4, then the possibilities of obtaining useful information on Earth structure are significantly larger. Experiments to investigate such discontinuities have recently commenced (e.g. Baker, Edge, Jeffries 1977, Grosse-Brauckmann, Herbst and Rosenbach 1977, Zschau and Gerstenecker 1977). One important fundamental question remains to be answered however. Since vertical discontinuities in elastic parameters are normally associated with past or present tectonic activity, the associated areas are usually very complex in terms of their geology (and topography). This may lead to significant unknown coupling perturbations over a wide range of scale lengths. Is it possible to separate the desired signal from these perturbations?

Another interesting possibility arising from a lateral contrast of elastic structure is discussed by Beaumont and Berger [1974]. This is the time variation in the tidal amplitudes due to changes in elastic parameters in a fault zone prior to an earthquake. Such precursory effects should be very easy to detect since local coupling perturbations of the regional signal are not important and all that is required is a stable calibration. Latynina and Rizayeva [1975] have investigated a possible 6% change in the observed M_2 strain before an earthquake in the Soviet Union.

6. Ocean Tides from Tidal Loading Measurements

The gravity loading Green's function for a layered Earth model is relatively insensitive to reasonable variations in the elastic parameters if the measurements are at a distance greater than 10 kilometres from the coast so as to avoid the effects of the various near surface elastic layers. Finite element calculations by Zurn, Beaumont and Slichter [1976] for a subducting lithospheric plate also show that the vertical body tide displacement only differs from its normal value by 0.8% over the edge of the plate. Calculations by Beaumont [1978] show that the gravity loading signal can be modified by at most 10% due to the lateral change of crustal thickness at a continental margin.

For most gravity measurements it is safe to assume that the Earth structure is well known and to use the tidal gravity loading signal (after subtracting an assumed body tide - Section 3) to examine the ocean tide distribution. Again the normal approach is to check the agreement or disagreement between the tidal gravity observations

and one or more ocean tide models (see for example Warburton, Beaumont and Goodkind 1975, Beaumont 1978, Beaumont and Boutilier 1978, Baker 1977). Beaumont [1978] using both tilt and gravity observations finds that an M_2 ocean tide intermediate between Tiron et. al. and Zahel's models is required for the North-West Atlantic. This conclusion is later verified with loading calculations using a new M_2 map based on several ocean bottom tide gauges and a hydrodynamical model for the Bay of Fundy - Gulf of Maine [Beaumont and Boutilier 1978]. Baker [1977] finds that the Hendershott M_2 model for the North East Atlantic gives a much better agreement with the tidal gravity measurements in the British Isles than the Pekeris and Accad or Zahel M_2 models.

Unfortunately ocean tidal maps rarely have any estimates of uncertainty attached. Differences between the maps for the major constituents of the order of 50% in amplitude and 60° in phase (or more) are found in some areas of the world. It is however important to distinguish between two types of ocean tide model. Some models [Hendershott, Bogdanov and Magarik and Tiron et. al.] constrain the tides to fit coastal tide gauges, whilst others simply allow a no flow condition across the coastlines. It is therefore perhaps not surprising that the former often give better agreement with Earth tide measurements since in the near loading area they are constrained to give a first approximation to the ocean tide.

In the introduction we discussed four stages in the development of the study of Earth tides. The third stage was the comparison of the observed signal with a range of possible Earth and/or ocean models. This is the stage of development of the work discussed in the previous sections and also for most of the published work on tidal gravity.

Jachens and Kuo [1976], Kuo and Jachens [1977] and Kuo, Jachens and Lee [1977] have, however, progressed one stage further by actually inverting their tidal gravity data in order to obtain improved models of the ocean tide distribution. In the last few years they have carried out an intensive programme of measurement in North America and Europe using Geodynamics TRG-1 tidal gravimeters.

Jachens and Kuo [1976], using a 'trial and error' method, obtained a new O_1 cotidal chart for the North Atlantic that is in better agreement with their tidal gravity observations than the starting model of Tiron et. al. This trial and error inversion is later confirmed by using a Lagrangian multiplier inversion method. Kuo and Jachens [1977] and Kuo, Jachens and Lee [1977] then go on to use the methods of linear programming in order to find the coefficients of a fourth order two dimensional polynomial which is used to correct an initial ocean tidal chart. Using 17 tidal gravity stations and 62 coastal and island tide gauges they have calculated new M_2 and O_1 tidal maps for the North East Pacific. Similarly using 25 tidal gravity stations and 90 tide gauges they obtain a new M_2 chart for the North Atlantic. No indication is given concerning the errors or the uniqueness (resolution) of the resulting solutions. Instead the new tidal maps are tested using a few ocean bottom tide gauge measurements that were not included in the original inversion. For M_2 in the North East Pacific the Tiron model has large phase

errors (50° - 80°) with respect to the ocean bottom measurements, which are reduced to less than 5° in the inversion solution. For O_1 in the NE Pacific errors of the order of 20% and 20° in the Tiron map with respect to the bottom tide gauges are reduced to less than 3% and 1° . For M_2 in the N. Atlantic errors of up to 25% and 15° in the Tiron map are reduced to the order of 5% and 5° .

Beaumont and Boutilier [1978] find that the N. Atlantic O_1 chart of Jachens and Kuo is inconsistent with their tiltmeter measurements and they suggest that the gravimeters from which the chart is derived are subject to instrumental phase lags and calibration errors.

Baker [1977] has used measurements from 8 tidal gravity stations in the British Isles to test the feasibility of the inverse ocean tide problem (see figure 2). Two LaCoste-Romberg tidal nullled gravimeters were used together with the results from a Geodynamics gravimeter [Melchior, Kuo and Ducarme 1976]. In order to ensure that their relative amplitude and phase calibrations were known, measurements were made with all 3 instruments at Bidston. For the M_2 load convolutions the Hendershott model was used together with a more detailed M_2 shelf tide numerical model for the seas around the British Isles [Flather 1976]. Comparisons with coastal tide gauges show that the typical errors in the shelf model are 10% in M_2 amplitude and 10° in M_2 phase. The M_2 tide is therefore relatively well known and this allows a useful test of the capabilities of tidal gravity.

It is found that the non-uniqueness of the inverse problem can be reduced by considering pairs of gravity stations. If the stations are suitably situated then a large (2 microgals) tidal gravity difference arises from the adjacent sea area whilst the contributions from other sea areas and distant oceans are considerably reduced. Using pairs of stations average correction factors were found for the Celtic Sea, Irish Sea and east English Channel M_2 tides. Similar results were also obtained from a least squares adjustment of the tides in the 3 sea areas. Adjustments to the tides in the other sea areas by reasonable amounts that are consistent with the oceanographic uncertainties does not affect the solution. Within the errors determined from the residuals of the least squares adjustment, the results are consistent with the known shelf model uncertainties determined from comparisons of the model with coastal tide gauges [Flather 1976]. In particular the gravity measurements require an adjustment to the amplitude of the east English Channel M_2 tide of 15% which is consistent with the tide gauge comparisons.

These results show that tidal gravity measurements can be inverted in order to obtain better tidal maps in ocean areas where the tides are less well known. Two important points are illustrated by the work. Firstly, the choice of sites is of importance in reducing the non-uniqueness of the inverse problem. Gravity stations should be chosen such that a reasonably large differential tidal gravity between pairs of stations is obtained from the ocean area of interest. Other ocean areas contributing significantly to the differential signal must be constrained either by oceanographic information or another gravity measurement. With the typical noise level of modern gravimeters

(of the order of 0.05 microgals internal error in the semi-diurnal band from a few months observations), a differential gravity signal of at least 1 microgal is required in order to obtain useful ocean tide information.

The second, and perhaps more important point, is the problem of relative amplitude and phase calibrations. Since the tidal gravity load signal is only a small fraction of the body tide signal (in most cases less than 10%) then the problem is ill-conditioned since a small calibration error represents a large error in the observed load tide. This problem was discussed in Section 2 with respect to figure 2, where it was concluded that all instruments in an area should be inter-calibrated at a reference station to better than +0.2% in amplitude and $+0.1^{\circ}$ in phase. It should be emphasised that for most problems only relative calibration of the gravimeters is important. Absolute calibrations to these accuracies are still very difficult to achieve. A small uniform error in the amplitude or phases of the observations in a gravity profile has a similar effect on the tidal gravity inversion as the effect of a small error in the assumed body tide or of an error in the calculated contributions from distant oceans.

It should be noted that the problems should be less severe for observing the diurnal loads near the Equator or the semi-diurnal and diurnal load tides near the Poles where the body tide contributions are much smaller.

It is also important to note that the required accuracy for tidal gravity implies that great attention must be paid to the tidal analysis procedures [Baker 1978 a, Yaramanci 1977 and 1978]. With different analysis methods applied to tidal gravity data, it is found that differences in amplitude of 0.5% for the major constituents can arise from incorrect use of these methods.

Even though the modern gravimeter has extremely high total signal/noise ratio the useful signal/noise ratio is far less. For this reason the limitation to gravity differences of greater than 1 microgal was suggested above. This however implies that tidal gravity can make very little contribution to defining the ocean tide for the smaller constituents or in areas where the loading from the major constituents is very small. For the small constituents tidal tilt has advantages over gravity, since within 100 km of the coastline the load tilt is comparable with, or very much larger than, the body tilt. The useful ocean tide information obtained would probably be limited, however, to the first few 100 kms away from the coastline. Of course, strain induced tilt perturbations must be reasonably small ($\leq 5\%$ of the amplitude of the constituent) and the overall crustal and upper mantle parameters (in particular the depth of the Moho and average crustal seismic velocities) must be known from seismic information (see Section 4).

Inversion of tidal gravity and tilt measurements can make a contribution to the problem of mapping the ocean tides provided attention is given to all the above experimental problems. The main contribution will probably be near 'anti-amphidromes' where the amplitude and phase of the ocean tides are such that the gravity loading signal is particularly large. The spatial averages given by loading measurements give complementary information to

oceanographic measurements. Programmes to measure ocean tides with ocean bottom pressure sensors have now commenced, but due to financial and other constraints the progress is slow [Cartwright 1977]. The additional information provided by loading measurements and eventually the developing satellite technology will help in giving the necessary global coverage.

Finally, a mention should be made of some other oceanographic problems on which loading measurements may give some information. Warburton and Goodkind [1978] have observed unexplained time variations in the amplitudes and phases of the major waves on their super-conducting gravimeter. They suggest possible variations in the ocean tides. Seasonal modulations of M_2 have been observed in short analyses of tilt at Llanrwst arising from the loading of the shallow water non-linear waves in the M_2 group [Baker 1978 b, Yaramanci 1978]. Also for measurements adjacent to a tidal loading area, the residuals and residual spectra after removing the tides may contain some interesting oceanographic information. Although there are problems with measurements in mines regarding the systematic perturbations of the signal, clearly the relatively high signal/noise ratio has some advantages for these types of problems where small signals are of interest. Measurements in mines and tunnels can also be used where the effects of perturbations of the absolute signal magnitude are of less importance. For example, the tilt loading signal can be used to examine the shape of the response function of a sea area on the assumption that the perturbing load strain has the same response function as the load tilt. Measurement of the average response function for a sea area obtained from load measurements would be relatively free of any non-linear effects that are local to an individual estuary or tide gauge.

7. Concluding Remarks

It has been shown that significant results are being obtained from the comparison of Earth tide measurements with a range of possible seismic and ocean tide models. However, in order to progress to the inversion of the measurements so as to obtain new models of the Earth's structure or of the ocean tides, various experimental errors must be reduced still further. Progress is already being made in this direction and some of the remaining problems on which future work is necessary have been emphasised.

References

- Baker, T.F., Earth tides, crustal structure and Ocean tides, Proceedings of 8th International Symposium on Earth tides, Bonn, 1977.
- Baker, T.F., A review of the objectives of tidal analysis, Bul. Inf. Mar. Terr., **78**, 4571-4578, 1978a.
- Baker, T.F., Non-equilibrium influences on the tidal signal, Bul. Inf. Mar. Terr., **78**, 4596-4610, 1978b.
- Baker, T.F., R.J. Edge and G. Jeffries, Notes on a new experimental tilt programme in the English Lake District, Proceedings of 8th International Symposium on Earth Tides, Bonn, 1977.
- Beaumont, C., Tidal loading: crustal structure of Nova Scotia and the M_2 tide in the north west Atlantic from tilt and gravity observations, Geophys. J.R. astr. Soc., **53**, 27-53, 1978.
- Beaumont, C., and J. Berger, Earthquake Prediction: modification of Earth tide tilts and strains by dilatancy, Geophys. J.R. astr. Soc., **39**, 111-121, 1974.
- Beaumont, C., and R. Boutilier, Tidal loading in Nova Scotia: results from improved ocean tide models, Canadian J. Earth Sci., **15**, 981-993, 1978.
- Beaumont, C. and A. Lambert, Crustal structure from surface load tilts, using a finite element model, Geophys. J.R. astr. Soc., **29**, 203-226, 1972.
- Berger, J., and C. Beaumont, An analysis of tidal strain observations from the U.S.A. II. The inhomogeneous tide, Bull. Seism. Soc. Am., **66**, 1821-1846, 1976.
- Berger, J., and F. Wyatt, Some observations of Earth strain tides in California, Phil. Trans. R. Soc. Lond., **A274**, 267-277, 1973.
- Cartwright, D.E., Oceanic tides, Rep. Prog. Phys., **40**, 665-708, 1977.
- Chiaruttini, C., Tidal loading on the Italian peninsula, Geophys. J.R. astr. Soc., **46**, 773-793, 1976.
- Farrell, W.E., Deformation of the Earth by surface loads, Rev. Geophys. Space Phys., **10**, 761-797, 1972.
- Flather, R.A., A tidal model of the north-west European continental shelf, Mem. Soc. R. Sci. Liège, **10**, 141-164, 1976.
- Grosse-Brauckmann, W., K. Herbst, O. Rosenbach, A tilt profile across the Harz Mountains, Proceedings of 8th International Symposium on Earth tides, Bonn, 1977.
- Harrison, J.C., Cavity and topographic effects in tilt and strain measurement, J. Geophys. Res., **81**, 319-328, 1976.
- Jachens, R.C., and J.T. Kuo, The O_1 tide in the North Atlantic Ocean as derived from land-based tidal gravity measurements, Proceedings of 7th International Symposium on Earth tides, 165-175, 1976.
- Kuo, J.T., and R.C. Jachens, Indirect mapping of ocean tides by solving the inverse problem for tidal gravity observations, Ann. Geophys., **33** (1/2), 73-82, 1977.
- Kuo, J.T., R.C. Jachens and S.S. Lee, The north eastern Pacific O_1 and the North Atlantic M_2 ocean tides as derived from inversion, Proceedings of 8th International Symposium on Earth tides, Bonn, 1977.
- Lagus, P.L. and D.L. Anderson, Tidal dissipation in the Earth and planets, Phys. Earth Planet. Int., **1**, 505-510, 1968.
- Latynina, L.A. and S.D. Rizayeva, On the changes in the tidal deformations before earthquakes, Izvestiya phys. solid Earth, **11** (9), 607-9, 1975.
- Lecolazet, R., and P. Melchior, Experimental determination of the dynamical effects of the liquid core of the Earth, Ann. Geophys., **33**, (1/2), 11-22, 1977.

- Lecolazet, R., L. Steinmetz, and G. Wittlinger, First results in a campaign to measure tidal tilt in eastern France, Proceedings of 6th International Symposium on Earth tides, Comm. Obs. R. Belg., 9, 23-29, 1970.
- Levine, J., Strain-tide spectroscopy, Geophys. J.R. astr. Soc., 54, 27-41, 1978.
- Melchior, P., Clinometric stations in Europe, Proceedings of the 7th International Symposium on Earth tides, 41-69, 1976.
- Melchior, P., J.T. Kuo and B. Ducarme, Earth tide gravity maps for Western Europe, Phys. Earth planet. Int., 13, 184-196, 1976.
- Michelson, A.A., and H.G. Gale, The rigidity of the Earth, Astrophysical Journal, 50, 330-345, 1919.
- Ostrovsky, A.Y., Results of observations of tidal tilts of the Earth's surface on the territory of the USSR for the period 1957-1972, Proceedings of 7th International Symposium on Earth tides, 121-126, 1976.
- Torge, W. and H.G. Wenzel, Comparison of Earth tide observations with nine different gravimeters at Hannover, Proceedings of 8th International Symposium on Earth tides, Bonn, 1977.
- Warburton, R.J., C. Beaumont and J.M. Goodkind, The effect of ocean tide loading on tides of the solid Earth observed with the superconducting gravimeter, Geophys. J.R. astr. Soc., 43, 707-720, 1975.
- Warburton, R.J. and J.M. Goodkind, Detailed gravity-tide spectrum between one and four cycles per day, Geophys. J.R. astr. Soc., 52, 117-136, 1978.
- Yaramanci, U., The differences between various tidal analysis methods, Proceedings of 8th International Symposium on Earth tides, Bonn, 1977.
- Yaramanci, U., A unified approach to signal analysis in Earth tides, Ph.D. thesis University of Liverpool, 1978.
- Zschau, J., Tidal sea load tilt of the crust and its application to the study of crustal and upper mantle structure, Geophys. J.R. astr. soc., 44, 577-593, 1976.
- Zschau, J., Phase shifts of tidal sea load deformations of the Earth's surface due to low viscosity layers in the interior, Proceedings of the 8th International Symposium on Earth tides, Bonn, 1977.
- Zschau, J. and C. Gerstenecker, Non local anisotropy of Earth tidal tilt in the vicinity of a deep going active thrust, Proceedings of 8th International Symposium on Earth tides, Bonn, 1977.
- Zurn, W., C. Beaumont, L.B. Slichter, Gravity tides and Ocean loading in southern Alaska, J. Geophys. Res., 81, 4923-4932, 1976.