N79 21504

High Precision Tide Spectroscopy

John M. Goodkind
Department of Physics, University of California, San Diego
La Jolla, California 92093

Abstract. Diurnal and long period earth tides have been measured to high accuracy and precision with the superconducting gravimeter. The results provide new evidence on the geophysical questions which have been attacked through earth tide measurements in the past. In addition they raise new questions of potential interest. Slow fluctuations in gravity of order 10 μgal over periods of 3 to 5 months have also been observed and are discussed.

Introduction

The low noise and drift of the superconducting gravimeter have enabled us to investigate a number of phenomena at new levels of sensitivity. Most of the results described below were obtained from the first 18 months of data at Piñon Flat, California starting in September 1973, and is reported in detail in the literature[Warburton, et al, 1975, 1976, 1977, 1978]. However, we have also begun an analysis of an additional 3 1/2 years of data for which preliminary results on long period tides are discussed here. In the coming year we will begin analysis of records from a total of 6 instruments, four of which are presently in operation.

The geophysical objectives of earth tide measurements have been to measure properties of the interior of the earth by determining such things as the frequency of the core resonance, the phase shift on earth tides, or a frequency dependence of the elastic constants of the earth. In order to meet those objectives, the perturbing effects of ocean tides, the atmosphere, and other environmental influences on gravity must be understood and accounted for in the data. The measurements described here have made new and essential contributions to those objectives. However, I also wish to point out how the new levels of sensitivity can uncover new problems which may ultimately be of more interest than the original objectives.

Ocean and Atmospheric Loading

Our first investigation of the ocean loading problem is described in Warburton, et al [1975]. An accurate calibration is of crucial importance for this work since, in order to measure the ocean load part of the tide, the theoretical solid earth tide must be subtracted from the measured tide. Our instrument was calibrated, using the direct attraction of a mercury filled sphere, to an accuracy of 0.2%. A computation of expected tidal amplitudes using the best available ocean tide models for O_1 and M_2 agreed with the observations within the calibration error. The agreement is not proof that the models used were correct or unique but it does demonstrate the level at which ocean models can be tested. They will be tested even more critically when superconducting gravimeters are located at numerous sites around the world.

The atmosphere is the next largest perturbing influence on gravity tides but a quantitative investigation of its effects was not possible without the superconducting gravimeter. The dependence of the pressure-gravity admittance on frequency at tidal and non-tidal frequencies was investigated in Warburton, et al [1977]. The incoherent fluctuations due to weather and local thermal effects show an admittance which increases with decreasing frequency, reaching a maximum value of about 0.3 μgal/mbar at frequencies lower than about 5 cycles/day. At integral multiples of 1 cycle/day the thermally generated atmospheric tides are globally coherent. At up to 4 cycles/day they can be well represented by spherical harmonics as shown by Chapman and Lindzen [1970]. With this representation and the load Love numbers computed by Farrell [1973] it is possible to compute the expected admittances at the first four harmonics. The admittances computed in this way, ignoring the oceans, agree well with the observed values. However, one would expect the oceans to have a substantial effect so that it appears as if the oceans do not respond coherently on a large scale to the atmospheric tides. Additional measurements are required to confirm this effect.

Anomalous Tides

To some extent the influence of oceans and atmosphere can be eliminated by examining only differences in gravimetric factors and phases between tides which differ in frequency by only one or two cycles per year. If the frequencies are at least a few cycles per year away from 1, 2, 3, or 4 cycles per solar day, then the atmosphere will have no systematic influence. The oceans should not exhibit any resonances sharp enough to make substantial differences on tides separated by only one cycle/year. Therefore, anomalies such as this could be evidence for resonances in the interior of the earth [Warburton, et al 1978] or for a universal preferred reference frame [Warburton, et al 1976], or some other unanticipated effects. The core resonance effect is clearly observable by observation of the relative amplitudes of the P_1 and K_1 tides. However, precise determination of the frequency and determination of the Q of the resonance depend on measurement of the Ψ_1 tide which is very small. In our results this tide appears to be strongly affected by an anomalous ocean tide [Warburton, et al 1978] (which is itself a consequence of the wobble) so that results which are now being obtained at Boulder, Colorado, where the ocean loading is smaller, will be important for understanding this core effect. This inland station will also allow us to determine if the apparent anomalies at ρ_1, M_1, and J_1 [Warburton, et al 1978] were caused by the ocean, and perhaps to set more stringent upper limits on a preferred frame effect [Warburton, et al 1976].

Proc. of the 9th GEOP Conference. *An International Symposium on the Applications of Geodesy to Geodynamics, October 2-5, 1978.* Dept. of Geodetic Science Rept. No. 280, The Ohio State Univ., Columbus, Ohio 43210.

Observation of the tides in the 3 and 4 cycles/day bands is especially useful for testing for non-linearities in either the instrument or in the tides themselves [Warburton, et al 1978]. The instrument, when used in electrostatic feedback, had small quadratic and cubic terms in its response function which were measured by this means. The non-linear response of the ocean at M_4 led to an anomalous M_4 gravity tide at La Jolla, California which was substantially smaller 100 kilometers inland at Piñon Flat. This information along with that currently being obtained at 2 other inland stations in southern California could be used to determine the spatial distribution of the non-linear M_4 ocean tide along the coast of California. A peculiar feature of the 3 cycles/day band is that the measured gravimetric factor is close to the theoretical value for the solid earth. This seems to indicate that the ocean loading effect in this band is much smaller than in the 1, 2, and 4 cycles/day bands.

Another surprising feature of the data was some small temporal fluctuations of the tidal amplitudes [Warburton, et al 1978]. In the case of S_2 the fluctuations were primarily in the phase rather than the amplitude and the phase fluctuations correlated with the fluctuations in phase of the atmospheric S_2 tide. At other frequencies no such obvious identification has, as yet, been possible. Attempts to correlate the fluctuations with fluctuations in the ocean tides at La Jolla and Los Angeles have not been conclusive.

Long Period Tides

The long period tides are well above the noise level of the instrument even though Piñon Flat is close to the node at 35° latitude, but they yield surprisingly low gravimetric factors. For the fortnightly tide it is between 0.7 and 0.8, and for the monthly tide between 0.85 and 0.92. These two values for each are obtained by making different assumptions about drift as discussed below. (For the 3 year record, which has been analyzed, at present the correlations between least squares fit amplitudes of the various long period tides are finite so that it is not possible to compute simple statistical error bars.) If the low gravimetric factors continue to appear in subsequent data the most likely interpretation will be that the monthly and fortnightly tides on the ocean are far from equilibrium. If this is entirely a consequence of short wavelength responses of the oceans then the data from Boulder will be influenced less by the ocean and show larger gravimetric factors.

The longest period phenomenon which we have investigated is the Chandler wobble with period 436 days. The wobble of the pole results in a change in latitude which in turn changes the centrifugal force at a fixed position on the earth. This results in an apparent periodic variation in gravity of amplitude 2.7 μgal at Piñon Flat. A least squares fit to the data,either the IPMS data on polar motion, or a sine wave at 436 day period,leads to the same result. In both cases the resulting least squares fit amplitude is ∿6 μgal. If all other terms which are being fit simultaneously are held fixed and the frequency of the Chandler wobble term is swept, the resulting amplitude for the wobble term is independent of frequency between 0.76 and 0.84 cycles/year. This indicates that for this record we are measuring some broad band phenomenon other than the Chandler wobble.

Secular Variations of Gravity

The greatest potential contribution of this instrument to geodesy is its capability for measuring the non-periodic, long term changes in gravity which could result from tectonic uplift or subsidence. The data which is discussed here was obtained with an early version of the instrument without some additional stabilizing coils which are now in use. During the first 18 months there was a significant linear drift with slope 139 μgal/year obtained by least squares fit. At the end of this period the instrument was shut down for about two weeks. When it was started up again it was "annealed" by raising the temperature and the magnetic field above the final operating values. For the subsequent 18 months the slope was 4.8 μgal/year. Figure 1 shows the residual signal from this three year record after removal of all tides, atmospheric effects, and the linear drifts. The peak-to-peak variations are approximately 10 μgal and take place over periods of 3 to 5 months. Thus, an apparent linear drift of 4.8 μgal/year over 18 months is probably a consequence of these 3 to 5 month, non-monotonic, variations.

There are theoretical and experimental reasons for expecting the drift of the instrument to be a logarithmic function of the time. [Prothero, et al 1968] However, attempts to fit a logarithmic term

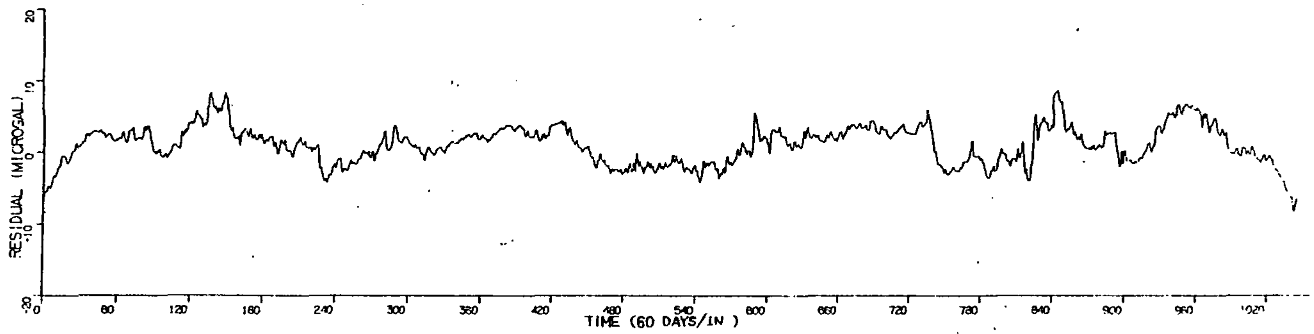

Fig. 1. Gravity residual for a 3 year record.

in place of the linear term left a large linear drift on the first 18 months of data. Including both linear and logarithmic terms in the fit resulted in a lower variance of the residual, but does not substantially alter the linear drift term. Thus the drift appears to be well accounted for by a linear term. For this record, with its two different linear drift rates, the amplitude of the long period tides and the Chandler wobble depends on whether the logarithmic term is included. The last two years of data has not yet been reduced, but since it was obtained with an instrument which had stabilizing coils, there should be no ambiguities due to instrument drift.

Conclusive evidence about instrument drift must come from two instruments run side-by-side. For approximately three months the first instrument with stabilizing coils was run alongside the instrument which obtained 3 years of data at Piñon Flat. The residual signals from each, after subtraction of tides, revealed a correlated change in drift rate during that time. [Goodkind 1979] However, the mount for the new instrument in those tests was tilting so as to generate an artificial signal. We hope to make a more valid side-by-side test of drift rate during the coming year.

Future Prospects

At present 4 instruments are in operation at Piñon Flat, Lytle Creek and Otai Mountain in California, and at Boulder, Colorado. Two more will be placed in the field in October and November at Greenbelt, Maryland and The Geysers, California. Thus we will have records from six different locations to compare during the coming year. This will allow us to improve the statistics on the Chandler wobble by stacking the records. It will also allow us to investigate regional variations in all of the phenomena discussed above. The influence of the oceans should be revealed by differences between records in Boulder and California which do not appear between the 3 records in Southern California.

The addition of our own barometric pressure gauges, recorded simultaneously with the gravity data, will allow better removal of pressure effects from the data. We are also installing our computer controlled data systems which can communicate two ways over the telephone with our laboratory minicomputer. This will ensure records with fewer interruptions and very efficient reduction of the data. Thus with the data obtained in the coming year we hope to begin to get answers to some of the questions raised above and also to discover if the slow variations in gravity which we have observed are a consequence of geophysical pressures of interest to geodesy and geodynamics.

Acknowledgments. This study was supported by the following agencies and grants: NASA NGR 05-009-246, NSF EAR 75-21621, USDI 14-08-0001-G-297, USDI 14-08-0001-G-374, and NBS 5-9013.

References

Chapman, S., and R. S. Lindzen, Atmospheric Tides, Gordon & Breach, New York, 1970.

Farrell, W. E., Phil. Trans. R. Soc. London A, 275, 253, 1973.

Goodkind, J. M., Tectonophysics, 52, 1979.

Prothero, W. A., and J. M. Goodkind, Rev. Sci. Inst. 39, 1257, 1968.

Warburton, R. J., C. Beaumont, and J. M. Goodkind, Geophys. J. R. Astr., 43, 707, 1975.

Warburton, R. J. and J. M. Goodkind, Astrophys. J., 208, 881, 1976.

Warburton, R. J. and J. M. Goodkind, Geophys. J. R. Astr., 48, 281, 1977.

Warburton, R. J. and J. M. Goodkind, Geophys. J. R. Astr., 52, 117, 1978.