TIDAL PERTURBATIONS IN ASTRONOMICAL OBSERVATIONS

N.P.J. O'Hora
Royal Greenwich Observatory, Herstmonceux

T.F. Baker
Institute of Oceanographic Sciences, Bidston Observatory

SUMMARY. Twenty years of time and latitude observations made with the Herstmonceux Photographic Zenith Tube have been analysed to determine the phase and amplitude of deflexions of the local vertical at the frequency of the semi-diurnal M_2 tide. The results have been compared with predictions incorporating new calculations of the gravitational attraction due to the M_2 tides in the surrounding seas. The effects of the zonal M_m and M_f tides on the time observations have also been determined and compared with existing theory. In both cases the agreement is reasonably good.

Group results of the time and latitude observations made with the Herstmonceux Photographic Zenith Tube (PZT) have been analysed to determine their tidal components. The data analysed extend over the years 1958-1977; they are based on observations of 36000 star transits giving 5800 group results. The time observations are expressed as measures of UT0 - TA (RGO), where TA (RGO) is the atomic time scale of the Royal Greenwich Observatory. The latitude observations have been corrected for the diurnal drift in latitude at Herstmonceux (Thomas and Wallis, 1971). The two sets of observations were smoothed by the Vondrák method (Vondrák, 1969) to obtain smooth values that are almost unaffected by periodic terms of less than 30 days period. Observational residuals, in the sense "observed minus smoothed" were then calculated.

Tidal deflexions of the vertical that affect PZT observations are primarily due to the global body tide of the Earth and are the direct effect of variations in the tidal force as the direction of the Moon changes. There is also an oceanic effect due to variations in the horizontal gravitational attraction, caused by the tidal variation in sea level. In the case of the Herstmonceux PZT, the changes in the direction of the vertical caused by the oceanic effect are of the same order of magnitude as those due to the direct effect. For the principal lunar semi-diurnal component M_2, the deflexions are periodic functions of 2H, where H is the hour angle of the Moon and, in the case of the

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direct effect, they are proportional to Λ, where $\Lambda = (1+\kappa-\ell)$ and κ and ℓ are body tide Love numbers.

The amplitudes of deflexions affecting the PZT observations in the East-West and in the North-South directions were determined by least-squares analyses of the time and latitude residuals of the group results respectively. Earlier determinations of the deflexions (O'Hora, 1973; O'Hora and Griffin, 1977) were obtained by analyses of plate residuals. But since a plate residual represents an average value based upon several hours of observation, the effects in a plate result of semi-diurnal term are diminished by smoothing. Group results represent, on average, slightly more than an hour's observing time so they conserve the effects of such a term virtually free from smoothing. The deflexions of the downward vertical given by the new analyses of the time and latitude residuals are, in units of milliseconds of arc, respectively:

$$16.1 \cos (2H - 118^\circ) \text{ towards the West}$$
$$\text{and } 22.0 \cos (2H + 31^\circ) \text{ towards the South}$$

with standard errors of 1.0 in amplitude and 4° in phase.

The deflexions due to the oceanic effect in these directions were evaluated by dividing the surrounding seas into sections and calculating for each the amplitude and phase of the horizontal component of the gravitational attraction at Herstmonceux due to the M_2 ocean tide. Figure 1 shows the M_2 tidal attractions at Herstmonceux from the different sea areas. The largest North-South contribution arises from the eastern English Channel only 7 kilometres distant; significant East-West contributions arise from the southern North Sea, the English Channel, the Celtic Sea and the North Atlantic Ocean. Figure 2 shows M_2 phasor plots of the observations and the theoretical calculations for the west and south directions respectively. The amplitudes of the deflexions in milliseconds of arc are plotted radially and the phase lags (α) with respect to the argument of the direct tidal potential at Herstmonceux are plotted anti-clockwise. The uncertainty in the theoretical global body tide due to the range of possible seismic Earth models is less than ±1% (see, for example, Farrell 1972). For these calculations a value of $\Lambda = 1.22$ has been used. In the plots, the total theoretical deflexion (body tide + sum of attractions of the different sea areas) is compared with the observed values. The observed error circles are standard errors calculated from the least-squares solutions.

The importance of the oceanic tidal attractions is very clear and, in both directions, their inclusion considerably improves the agreement between theory and observation. The main uncertainty in the theoretical calculations arises from the uncertainty in the amplitudes and phases of the M_2 ocean tides. These are of the order of ±10% in amplitude and 10° in phase (Baker 1977). The effects on the PZT of the tidal deformation of the Earth due to ocean-tide loading have been neglected.

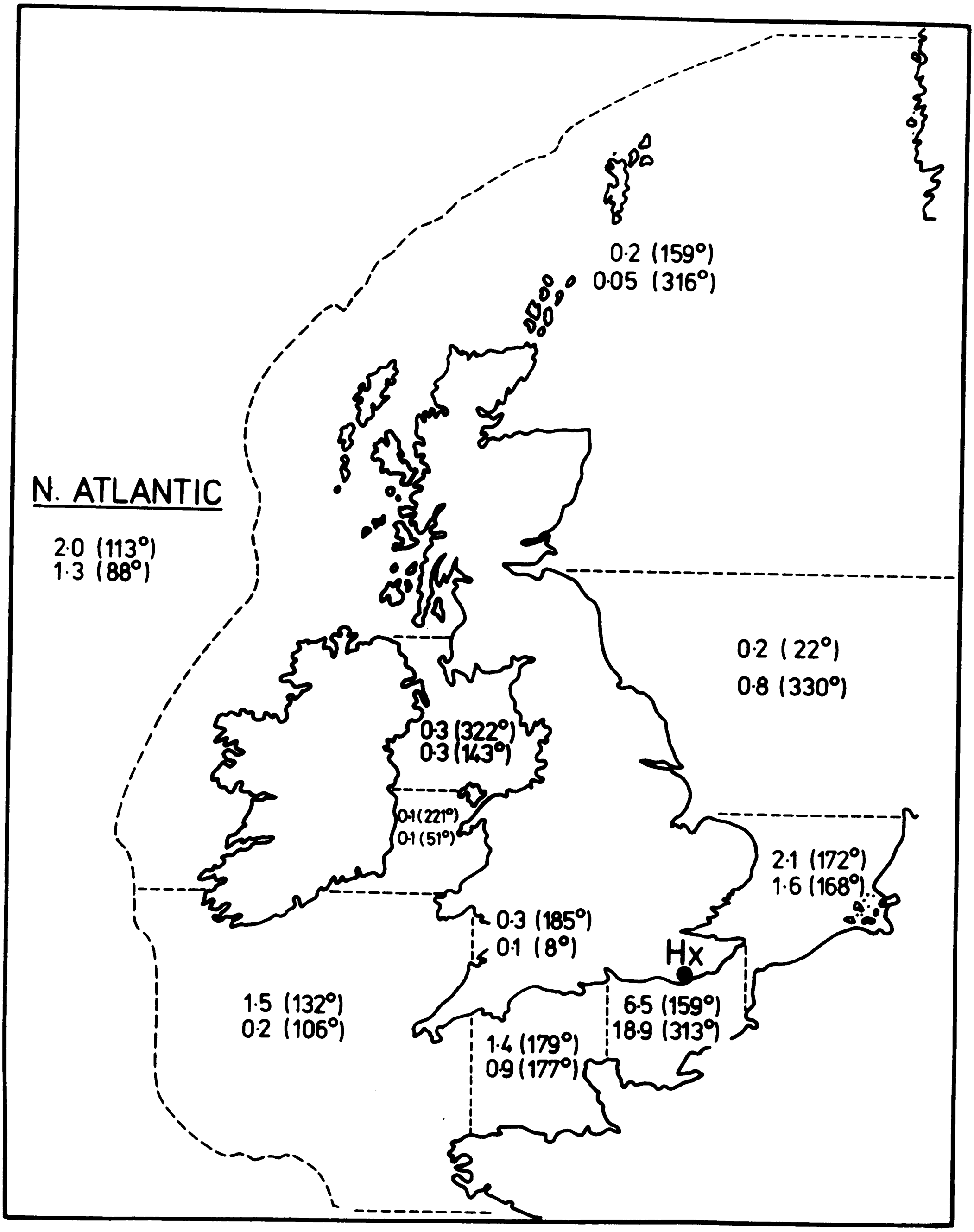

Figure 1: Deflexions of the downward vertical at Herstmonceux (Hx) due to the M_2 tide in different sea areas. Amplitudes are in milliseconds of arc and phase lags are with respect to 2H, the argument of the tidal potential at Herstmonceux. Upper lines are west deflexions, lower lines are south deflexions.

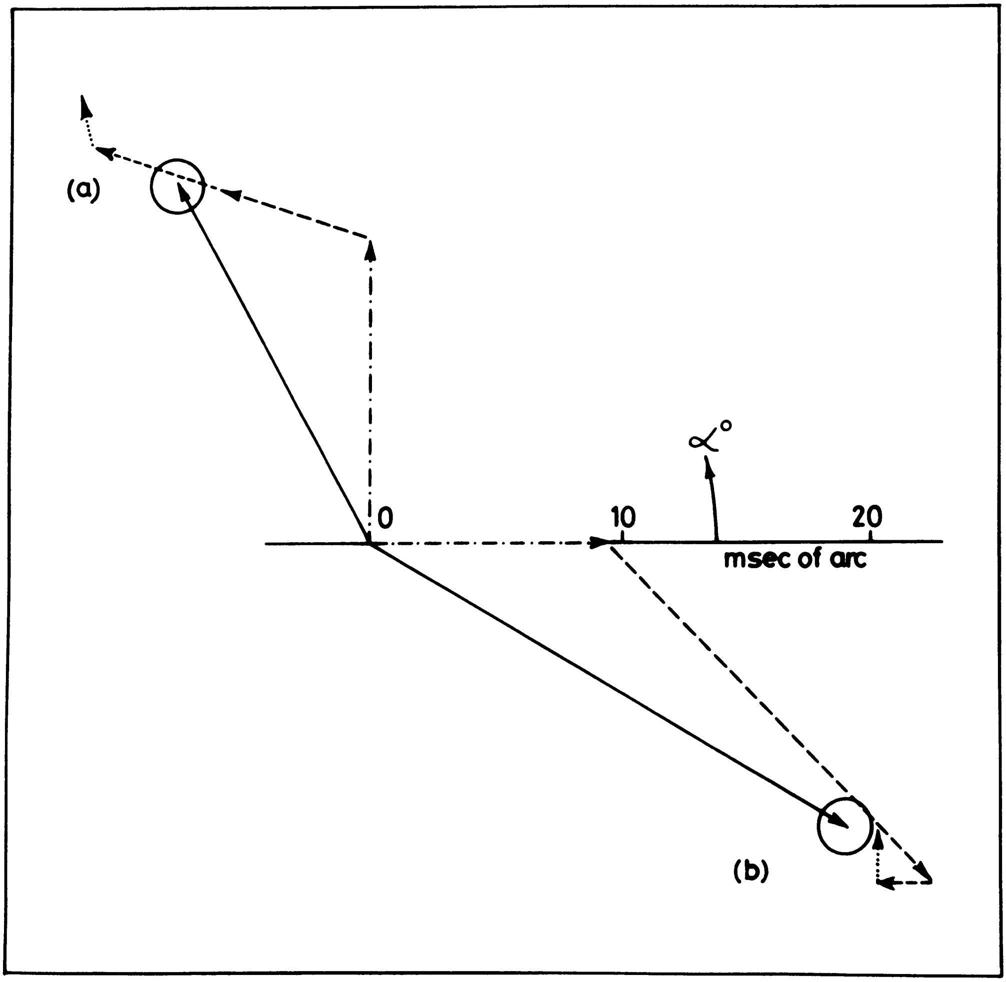

Figure 2: The solid lines show the observed deflexions for (a) time and (b) latitude, while the broken lines show calculated deflexions as follows:- (a) West deflexion; tilts are positive when a mass on a plumb line moves towards the west. (b) South deflexion; tilts are positive when the plumb line moves towards the south. In both cases the deflexion is in msec of arc and α is the phase lag with respect to the argument of the direct tidal potential at Herstmonceux.

—·—·—·—·—·	theoretical global body tide, Λ = 1.22
— — — — — —	east English Channel attraction
- - - - - - - - - - - -	rest of continental shelf attraction
....	N. Atlantic attraction

Firstly, the change in potential of the deformed Earth gives rise to a horizontal attraction described by the load Love numbers k_n (Farrell 1972). Secondly, the horizontal displacement of the PZT gives a deflexion of the vertical described by the load Love numbers ℓ_n. These effects of the loading deformation are small compared to the gravitational attraction of the ocean tide which produces them. Order of magnitude estimates based on the load Love numbers of Farrell show that the total oceanic effects in Figures 2 (a) and (b) should be reduced by approximately 10% and 5%, respectively. Allowing for the above uncertainties in the oceanic effects there is very good agreement between theory and observation, particularly in the North-South direction.

The zonal tides induced by the Moon cause the moment of inertia and, consequently, the speed of rotation of the Earth to vary, and the variations are reflected in the time observations. These tides do not influence the position of the pole of inertia so the latitude observations are not affected. Melchior has recently tabulated theoretical values for the terms in the time observations (Melchior, 1978). The amplitudes of these terms are all proportional to k, and assuming $k = 0.30$, the amplitudes of the principal terms are 0.75, 0.31 and 0.80 ms with periods, in days, of 13.661 (M_f term) 13.633 and 27.555 (M_m term), respectively. The PZT time residuals were analysed to determine the amplitudes of the periodic terms corresponding to the M_f and M_m tides. Before the least-squares analysis the residuals were corrected for the semi-diurnal deflexions found above, and also for the effects of a 14.19-day term, with amplitude 1.27 ms, due to nutation and aliasing of the O_1 diurnal tide. The amplitudes obtained for the M_f and M_m terms are 1.06 ± 0.12 and 0.84 ± 0.12 ms respectively. The disparity in the results was investigated analysing the first and third quarters of the data separately from the second and fourth quarters.

These solutions yielded amplitudes of 1.12 and 0.93 for M_f and 0.58 and 1.15 ms for M_m, all with standard errors of about 0.17. For each term the phases given by the half-data solutions are in much better agreement than the amplitudes. The influence of excessive residuals in the data was examined by rejecting all residuals outside the range $0 \pm 40n^{-\frac{1}{2}}$ ms where n is the number of stars in the group observation and 40 ms is approximately 4 times the standard error of unit weight. Analyses of the remaining 99% of the data gave amplitudes of 0.98 and 0.85 for M_f and 0.55 and 1.03 ms for M_m. Adopting the means of these results, the values obtained for k are 0.37 ± .04 from M_f and 0.30 ± .04 from M_m. Within the observational uncertainties k is consistent with the theoretical value of 0.30 derived from a range of seismic models (Farrell 1972). It should be noted that there are also oceanic contributions to the M_m and M_f terms which have not been taken into account. A least-squares analysis of the data for the 13.633 day term gave effectively zero amplitude as compared with the theoretical value of 0.3 ms.

CONCLUSIONS

20 years of PZT time and latitude observations have been analysed for the principal lunar semi-diurnal constituent M_2. Within the experimental and theoretical uncertainties these observations are consistent with a theoretical model including both the body tide and ocean tides.

Analysis of the time observations for the long-period tides M_m and M_f gives amplitudes which, within the experimental uncertainties, are consistent with the expected value for the body-tide Love number k.

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