Solid tidal tilting observed in the West Australian goldfields

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Summary. Experimental tidal tilts were obtained in the Eastern Goldfields region of Western Australia. Spectral data are given for the total tilt in one direction only and the results compared with the theory. The main semi-diurnal ($M_2$) component is extracted by Fourier techniques and it is shown that analysis of a data length 57 periods of the $M_2$ wave (or 29.50 sidereal day) yields less uncertainty in the estimation of the $M_2$ amplitude than does analysis of a longer data length of 70 $M_2$ periods (or 36.23 sidereal day). Furthermore it is shown that use of a simple rectangular gate time window yields less uncertainty in the Fourier estimation of the $M_2$ amplitude than that obtained using the well-known Hanning and Hamming windows. Phasor plots of the $M_2$ tilt tide are also given for two distinct methods of tilt meter mounting to the bedrock. In the present investigation tilt-strain coupling due to both the cavity effect and local topography is considered negligible, however tilt-strain coupling due to the geological effect is not necessarily negligible and is evaluated using a boundary integral method.

Introduction

Previous to the present investigation, solid tidal deformations had not been measured in Western Australia, and in fact, such deformations have been measured in only a few isolated regions of the Australian continent. Langdon & Thomas (1974) attempted to measure the solid tidal strain in South-eastern Australia, however, their strain meter was located only about 15 m below the surface, hence their measurements were influenced by a rather large thermal contamination. Blair & Sydenham (1976) reported measurements of multidirectional tidal strain components obtained in the Cooney Observatory, Eastern Australia. The latter measurements were not significantly influenced by thermal effects since the instruments were located about 400 m or so below the surface.

With the exception of the present study, the solid tidal tilt, in particular, has been measured in only one location within the Australian continent. These measurements, reported by Tanaka & Sydenham (1977), were made in the Cooney Observatory and consisted of a study of the $M_2$ solid tides for gravity, tilt and strain.
There are several methods of obtaining the amplitudes of the main solid tidal constituents from a finite length of experimental data (see, e.g. Levine & Harrison 1976), however the simplest method is to perform a discrete Fourier analysis. With the implementation of the Fast Fourier Transform (FFT), the simplicity and speed of Fourier analysis offers a distinct advantage over other methods of tidal analysis. However the FFT analysis of experimental data results in contamination of the Fourier estimates due to the finite length analysed. Quite recently, the author (Blair 1979) has shown theoretically that for a careful choice of the length of data analysed, the resulting Fourier estimates of the main tidal constituents are quite reasonable. The present work, in particular, analyses experimental solid tidal tilts in the light of such Fourier estimates.

**Tilt meter installation**

The tidal tilts were detected using an ANAC tilt system installed 62 m below the surface in the Hainault Gold Mine on the Golden Mile, Kalgoorlie. The geographic location of the site being 30.503° S and 121.775° E. The mine had ceased operations over 10 years ago and now functions solely as a tourist attraction. The particular location chosen within the mine was remote from the influence of tourists and consisted of a vault formed by bricking in a small niche set into the side of a reasonably long drive. The vault door was sealed with layers of sponge and polystyrene foam in order to achieve adequate thermal stability.

The ANAC system consisted of a model 305 precision tilt transducer coupled to a model 301 tilt indicator. This system was designed at the University of Queensland and is described by Stacey et al. (1969).

In order to ensure minimum thermal contamination, both the transducer and indicator were installed in the vault, the output from the latter being fed into a dual TOA recorder model EPR-200A external to the vault. This set up ensured a minimum number of entries into the vault since most adjustments could be performed using the recorder itself. The recorder was set on a paper feed rate of 1 cm hr⁻¹ and displayed both temperature and tilt variations. The temperature variations were recorded using a calibrated thermistor probe and over the period of interest daily temperature variations never exceeded 10 mK with a long-term average drift of about 5 mK/100 hr.

The entire system was powered by ±12 V DC delivered by two car batteries located outside the vault. The mine itself was powered by a 32 V AC system which was switched off overnight, however this supply was used to trickle charge the car batteries during the day.

The surface rubble within the vault was removed and the tilt indicator mounted on the bedrock. Two distinct methods of mounting were studied. The first being a sand-mount in which the tilt meter was placed on a granite slab resting horizontally on fine compacted sand. The second method was implemented by mounting the tilt meter directly onto the bedrock. A gyro-theodolite was used to determine the tilt meter azimuth as 76.79° west of north.

**Experimental results**

The tilt system was taken underground prior to the construction of the vault and allowed to attain equilibrium with the thermal environment of the mine. About a month later, after the completion of the vault the indicator was sand-mounted on the bedrock and the recording commenced. Fig. 1 shows a plot of the initial tilt drift for the system over the first 550 hr. At the end of the run, the tilt drift was determined to be 5.5 nrad hr⁻¹. The tilt meter was allowed to stabilize further and, commencing at 7.93 hr UT 1977 August 23, an uninterrupted
Solid tidal tilting in Australia

Figure 1. Initial tilt drift for the ANAC system.

A record of tidal tilt for 25 day duration was obtained. In the subsequent analysis a data length of 47 period of the M2 wave (24.32 sidereal day) was used.

The instrumental drift and long-period tides were isolated using a low-pass digital filter implemented as a third-order recursion algorithm. This algorithm was derived by applying the bilinear transform to a Butterworth response. The phase response of the filter was zero for all frequencies and achieved by passing the waveform twice through the same filter in the manner specified by Shanks (1967); the amplitude response of the filter approached the square of the amplitude function of a sixth-order Butterworth filter. The 6 db point of the filter was set at 0.5 cycle day\(^{-1}\) (cpd) and had attenuation of approximately 75 db octave\(^{-1}\) beyond this frequency. In the pass band attenuations of less than 0.1 db were present for frequencies up to 0.35 cpd.

Fig. 2(a) shows the original tidal record while Fig. 2(b) shows the low-pass filtered record consisting of instrumental drift and long-period tides. From the latter figure the total drift is estimated at approximately 2.8 nrad hr\(^{-1}\). Fig. 2(c) shows the drift-free (experimental) tidal tilt obtained by subtracting the low-pass filtered values from the original record. The Fast Fourier Transform (FFT) was then applied to the drift-free results yielding an amplitude of 57.2 nrad of tilt for the M2 component.

Due to failure in the recording equipment a longer length of record could not be obtained for the sand-mounted tilt meter. It was then decided to mount the device directly on to the bedrock and so, commencing at 4.12 hr UT 1978 October 5, a continuous record of tidal

Figure 2. Elimination of the long-period drift using a low-pass digital filter.
tilt for 60 day duration was obtained and a data length of 114 period of the $M_2$ wave (59.00 sidereal day) employed in the subsequent analysis. The low-pass filter was used to isolate the drift and long-period tides; in this instance the average drift was found to be approximately 0.8 nrad hr$^{-1}$. FFT analysis of the drift-free data yielded 55.7 nrad of tilt for the $M_2$ component.

In the study of both mounting methods the analysed records were obtained 2 month after the mounting of the tilt meter and thus the drift rates given are considered to be primarily a function of the mounting technique, with the direct bedrock mount providing superior low-drift properties.

In order to obtain an idea of the uncertainty involved in the FFT analysis of a finite length of experimental data, a rectangular time window of length equal to 42 period of the $M_2$ wave was then chosen and the variation of its $M_2$ component calculated as the window was moved through the entire data train of the bedrock mounted device. The results are shown in Fig. 3(a). The analysis was then repeated for rectangular windows of lengths 57 and 70 $M_2$ period and the results shown in Fig. 3(b) and (c) respectively.

From Fig. 3 it is quite obvious that the uncertainty in the estimation of the $M_2$ component for a data length of 70 $M_2$ period is, in fact, nearly twice as large as that for a data length of 57 $M_2$ period.

Comparison of theory with experiment

The experimental results of Fig. 3 are in general agreement with the theory of Blair (1979) who shows that an increase in the length of tidal data analysed by discrete Fourier techniques does not necessarily guarantee a decrease in the uncertainty of estimation of a tidal constituent. The theory only predicts the maximum possible uncertainty of estimation, and Table 1 shows a comparison of such with an analysis of the present experimental data for the case of the $M_2$ tidal component.

Table 1. Maximum deviations in the $M_2$ amplitude.

<table>
<thead>
<tr>
<th>Data length ($M_2$ periods)</th>
<th>Average $M_2$ amplitude (n rad)</th>
<th>Max. observed deviation (per cent)</th>
<th>Theory (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>56.1</td>
<td>23.3</td>
<td>39.2</td>
</tr>
<tr>
<td>57</td>
<td>55.8</td>
<td>10.0</td>
<td>5.2</td>
</tr>
<tr>
<td>70</td>
<td>54.9</td>
<td>17.7</td>
<td>24.4</td>
</tr>
</tbody>
</table>
Overall the theoretical predictions are quite reasonable and for a data length of $57M_2$ period, only, does the observed maximum deviation shown in Fig. 3 exceed the maximum allowable by theory. This is due, in part, to the noise level ($\pm 3$ per cent at most) on the experimental records; such noise will affect the value of the $M_2$ amplitude obtained by Fourier analysis.

Fig. 4 shows an FFT spectral analysis of the experimental tidal tilt of length 114 period of the $M_2$ wave, and Fig. 5 shows a similar spectral analysis for the theoretical tilt, based upon a Gutenberg-Bullen earth model, and generated for the azimuth and period of time applicable to the observed results. In both cases the major diurnal and semi-diurnal waves are indicated.

It should be appreciated that the spectra of Figs 4 and 5 both suffer from Fourier contamination effects since they are obtained from a finite length of data. From Fig. 5, the Fourier estimate of the $M_2$ amplitude for the theoretical tilt tide is given as 46.6 nrad. Alternatively, the theory of solid tides (see, e.g. Melchoir 1978) provides an analytical expression for the $M_2$ amplitude that does not involve Fourier techniques. In fact, in the azimuth of $76.7^\circ$ for the Hainault location on Earth, the analytical expression yields a value of 44.6 nrad for a Gutenberg-Bullen earth model in which the diminishing factor, $\gamma$, is given as 0.6926. The difference of 4.5 per cent between the Fourier estimate and the analytical result is due mainly to the Fourier contamination effect.

Before a direct comparison can be given between theory and experiment for the amplitudes and phases of the $M_2$ tide, an estimate of the ocean load and local perturbation effects on tidal tilt must be made (see, e.g. Harrison 1976).

The $M_2$ component of the ocean load effect on tidal tilts was calculated by applying the Green's function method of Farrell (1972) to the $M_2$ ocean tidal model of Hendershott (1973). For the location and azimuth of present interest the amplitude of the oceanic effect

![Figure 4. FFT spectrum of the experimental tilt tide.](image)

![Figure 5. FFT spectrum of the theoretical tilt tide.](image)
was calculated to be 10.6 nrad and its phase $-22.1^\circ$ with respect to the theoretical north-south body tide (Tanaka, private communication).

The topographic influence on tidal tilts is assessed from a knowledge of the surface region of Hainault which is a gentle slope of about 1.5$^\circ$ at most. The results of Harrison (1976) indicate that small horizontal tilt-strain coupling factors (well below 0.05) exist beneath the surface of a hill with such a slope. Hence the topographic effect on tidal tilts at the Hainault mine is considered to be negligible.

The ANAC device is a short baselength tilt meter and hence is subject to cavity effects. However, the installation niche was set in the centre of a long drive and the tilt meter placed on the floor in the centre of the niche, with tilts being measured along the axis of the drive. This is the optimum installation procedure required to minimize the cavity effect (Harrison 1976) and hence tilt-strain coupling factors due to this effect are considered negligible.

In the present investigation, however, it is important to determine the magnitude of the tilt-strain coupling due to the geological effect since the rock structure near the measurement site is non-uniform. The inset of Fig. 6 shows a representative cross-section of the region with the tilt meter location indicated; the tilt axis being along the line AB. The two main rock types involved are Paringa Basalt for region 1 and Golden Mile Dolerite for region 2 and any contrast in the elastic properties of these two main types will cause geological tilt-strain coupling at the measurement site.

I determined the elastic properties of these two rock types in a series of experiments conducted in the rock mechanics Laboratory at the Kalgoorlie School of Mines. Elastic deformations in stressed rock cores were measured by both Kyowa resistive strain gauges and TESA GT 41 displacement transducers attached to the cores, both methods yielding similar results. For the Golden Mile Dolerite the average value of Young's modulus was determined to be $E_2 = 8.28 \times 10^{10} \text{N m}^{-2}$, and for the Paringa Basalt an average value of $E_1 = 5.71 \times 10^{10} \text{N m}^{-2}$ was obtained. In both cases average values of 0.25 were obtained for Poisson's ratio.

These elastic properties were then used in a Boundary Integral Method (BIM) employing the discretized cross-section shown in Fig. 6 (inset). The BIM offers several advantages over alternative Finite Element solutions in that only the relevant boundaries need be discretized, and solutions obtained at any desired points either on the model boundaries or at interior regions. This enables fine discretization at moderate cost and so is advantageous for the calculation of tilt-strain coupling for regions of high gradients in tilt. Furthermore the BIM gives solutions for the loaded boundaries located at infinity and hence errors due to the size

![Figure 6. Tilt strain coupling due to the local geological effect.](https://academic.oup.com/gji/article-abstract/67/2/293/596087)
of a finite model are not introduced. For the present model only a uniform horizontal normal stress was applied at infinity and the **BIM** program of Crotty & Wardle (1980) used to obtain the model displacements from which the tilt-strain coupling factors were calculated. Fig. 6 also shows a plot of the tilt-strain coupling factor as a function of the arbitrary distance along the horizontal line AB of the model, yielding a factor of −0.111 for the measurement site. The total strain (solid tide plus ocean load) along the tunnel axis is 5.4 nanostrain having a phase of +34.1° with respect to the theoretical north—south tilt tide; hence the amplitude of the strain induced tilt is −0.6 nrad in phase with the total strain.

The values of $E_1$ and $E_2$ given previously were obtained for groups of competent rock cores taken from drill holes located away from the contact area of regions 1 and 2 (Fig. 6, inset). However, analysis of both dolerite and basalt cores from drill holes intersecting the contact regions show a marked decrease in the elastic properties of both. In fact in this region, even at considerable depth, the dolerite had undergone severe ‘bleaching’ in which the ferromagnetites had been replaced by some carbonates, chlorites and mica, thus considerably weakening its structure. Tests on the bleached cores yielded values of Young’s modulus less than $2.5 \times 10^{10}$ N m$^{-2}$ and for the basalt from the contact region values less than $10^{10}$ N m$^{-2}$ were obtained. The present results together with the local geology suggest a region of considerably weakened rock on the contact of both major rock types. Such a weakened zone could well have a dominating influence on the strain-induced tilt at the measurement site irrespective of the material properties in the central area of region 1 (Fig. 6, inset).

In view of the overall uncertainty of the geological model, Fig. 7 shows a plot of the tilt-strain coupling factor at the observation site as a function of the elastic contrast $E_1/E_2$. From these results it can be seen that large, negative tilt-strain coupling factors could arise if the altered rock types in the contact zone were a dominating influence in regional tilting. It is also interesting to note that for very small values of the elastic contrast, $E_1/E_2$, the coupling factor becomes positive with a limiting value of +1.691 for $E_1/E_2=0$.

Fig. 8 shows phasor plots of the $M_2$ component of tidal tilt observed for both the sand-mounted and direct bedrock-mounted tilt meter. In both cases the amplitudes and phases were determined by Fourier techniques, the theoretical tidal tilt series being generated for the same period of time relevant to the particular experiment. For the sand-mounted case the theoretical amplitude was found to be 49.4 nrad and phase $-97.00^\circ$ with respect to the theoretical north—south tilt tide; for the direct bedrock-mounted case these values were found to be 46.5 nrad and $-96.75^\circ$ respectively.
The theory of Blair (1979) was used to calculate the effect of Fourier contamination on the $M_2$ amplitude; it could be much more difficult to obtain a general theory for the associated phase contamination inherent in the Fourier analysis of a finite length of data and so each particular case of interest should be separately evaluated. The analytical approach (see, e.g. Melchior 1978) yields a phase of $-96.79^\circ$ for the azimuth of interest ($76.79^\circ$). Thus the present results indicate that Fourier contamination of the phase is much less significant than the corresponding amplitude contaminations.

A tilt-strain coupling factor of about $-0.8$ is possible for the present geology and would produce a strain induced tilt of $-4.3\,\text{nrad}$ having a phase indicated by the dashed lines of Fig. 8. Such a tilt-strain mechanism would yield excellent agreement between theory and experiment for the sand-mounted device as indicated by Fig. 8(a), but could not yield improved agreement for the case of the direct bedrock mounted device as indicated by Fig. 8(b). In fact for the latter mounting case it is impossible to invoke any two-dimensional tilt-strain coupling mechanisms at all which would improve the agreement between theory and experiment. With the three-point mount of the tilt meter directly installed on the bedrock it is quite possible that any small discontinuities in the rock near a mounting point could affect both the amplitude and the phase of the measured solid tide (see, e.g. Harrison 1976). In this aspect the tilting of a long slab of granite placed on a large pile of sand should obviously be less sensitive to the existence of small discontinuities in the bedrock. Thus the experimental results are consistent with the supposition of a geological tilt-strain coupling factor of approximately $-0.8$ and the existence of small-scale rock effects on the performance of the tilt meter directly mounted to the bedrock. However, it should be noted that there were no obvious inhomogeneities visible at the site.

General window functions

In tidal analysis it has been acceptable to use special cosine windows to get a rounded or tapered signal that avoids the high frequencies introduced by the sharp rise and fall of the rectangular window (see, e.g. Godin 1972). If a cosine window is to be used then it is worthwhile investigating the Fourier contamination effect on a finite length of data that has been multiplied by such a window.

If $w(t/l)$ is the time representation of the window, then the experimental tidal results of a finite time duration, $l$, for the semi-diurnal components, must be related to the tapered function

$$f(t) = w(t/l) \sum_n A_n \cos 2\pi n (t + \phi_n)$$

(1)
where \( l \) is the total length of the record in units of the \( \mathbf{M}_2 \) wave period, \( t \) the time variable, \( A_n \) the relative semi-diurnal tidal amplitudes, \( \kappa_n \) the corresponding frequencies and \( \phi_n \) arbitrary phase terms; The numerical values for \( A_n \) and \( \kappa_n \) are given by Blair (1979).

For the general cosine windows

\[
w(t/l) = a + b \cos(2\pi t/l) \quad \text{for } |t| < l/2
= 0 \quad \text{for } |t| > l/2
\]

where \( a \) and \( b \) are positive constants. For the rectangular gate window \( a = 1, b = 0 \); for the Hanning window \( a = b = 0.5 \) and for the Hamming window \( a = 0.54 \) and \( b = 0.46 \).

If the rectangular window, \( \operatorname{rec}(t/l) \), is replaced by \( w(t/l) \) then the entire theory of Blair (1979) can be readily reworked to estimate the Fourier contamination of a windowed tidal data series. In fact, if \( A_m \) is the maximum Fourier amplitude obtained for the \( \mathbf{M}_2 \) component from a finite length of data then the theory yields

\[
A_m = 0.5 \left( a A_1 + \sum_{n=2}^{6} A_n \left| \operatorname{sinc}(l(1 - \kappa_n)) + 0.5b \operatorname{sinc}(l(1 + 1/l)) + \operatorname{sinc}(l(1 - 1/l)) \right| \right)
\]

where the summation is taken over only six main tidal constituents and, for any variable \( x \), \( \operatorname{sinc} x = [\sin(\pi x)]/\pi x \). The previous theory involving the rectangular gate function was derived to a second-order approximation (accurate to 0.04 per cent). However in the present case the algebra becomes quite lengthy hence only a first-order approximation (accurate to 2 per cent) is given by equation (3).

Before a direct comparison between different types of windows can be made, the Fourier amplitudes must be normalized. Since

\[
\int_{-l/2}^{l/2} w(t/l) \, dt = a l
\]

then the normalized amplitudes are given by \( a^{-1} A_m \). The percentage difference between such normalized amplitudes and the exact \( \mathbf{M}_2 \) amplitude \((0.5 A_1)\) is thus given as

\[
E = 100 \sum_{n=2}^{6} A_n |\operatorname{sinc}(l(1 - \kappa_n))| + \frac{50b}{a} \sum_{n=2}^{6} A_n |\operatorname{sinc}(l(1 + 1/l)) + \operatorname{sinc}(l(1 - 1/l))|,
\]

where \( E \) is the maximum percentage error involved in obtaining the amplitude of the \( \mathbf{M}_2 \) component of a tidal series by discrete Fourier analysis. In the case of the rectangular window \((a = 1, b = 0)\) the second term of equation (5) becomes zero and the remaining expression is identical to that derived previously (Blair 1979) for a first-order approximation.

Equation (5) quite clearly indicates that the use of either the Hanning or Hamming windows will increase the maximum percentage error possible in estimating the \( \mathbf{M}_2 \) amplitude; this increase is given by the second term of the equation.
Figure 9. $M_2$ Fourier contamination of a finite length of tidal data due to both rectangular and Hanning windows.

Table 2. The window effect on the uncertainty of the $M_2$ amplitude.

<table>
<thead>
<tr>
<th>Data length (M$_2$ periods)</th>
<th>Rectangular window (per cent)</th>
<th>Hanning window (per cent)</th>
<th>Hamming window (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>19.6</td>
<td>52.3</td>
<td>47.7</td>
</tr>
<tr>
<td>47</td>
<td>14.1</td>
<td>40.0</td>
<td>36.2</td>
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<tr>
<td>57</td>
<td>2.6</td>
<td>15.3</td>
<td>13.4</td>
</tr>
<tr>
<td>70</td>
<td>12.2</td>
<td>32.3</td>
<td>29.5</td>
</tr>
<tr>
<td>114</td>
<td>2.4</td>
<td>5.2</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Fig. 9 shows a plot of equation (5) as a function of the data length $l$ for both the rectangular and Hanning windows. For all windows, the theoretical results for the data lengths of present interest are summarized in Table 2 which shows the maximum percentage errors involved.

The experimental results of Fig. 2(c) for the sand-mounted tilt meter were then multiplied by a Hanning window and FFT analysis yielded an $M_2$ amplitude of 45.9 nrad. This value deviates by 24.6 per cent from the previous value of 57.2 nrad obtained by applying the rectangular gate time function. According to the phasor plot of Fig. 8(a) an experimental value of 45.9 nrad would yield poor agreement with theory. The fact that the Hanning window underestimates the $M_2$ amplitude in this particular case is obvious since this window preferentially weights the central portion of the time series, which, according to Fig. 2(c) is the region of small amplitude tilt tides.

Furthermore the experimental analysis resulting in Fig. 3(b) was then repeated with a Hanning window replacing the rectangular window. This yielded an increase of the maximum total deviation in the Fourier amplitude from 10.0 to 11.9 per cent. The results of both these experimental analyses show quite clearly that a rectangular gate time window provides a more accurate estimate of the $M_2$ amplitude than that obtained using a Hanning window, and so is in agreement with the present theoretical ideas.
Conclusions

Since the tidal frequencies have no common multiple, Fourier analysis is not an ideal method of analysing tidal records and analyses aimed at high accuracy or recovery of the weak tidal lines are generally done by other techniques such as the response method of Munk & Cartwright (1966). However, Levine & Harrison (1976) have shown that both Fourier and response methods give reasonable agreement for the main solid tidal components. The usefulness of the Fourier method has been emphasized further by the present work which shows both experimentally and theoretically that careful choice of the data length of a tidal series can result in a reasonable Fourier estimate of the $M_2$ tidal component and so preserves the value of the FFT technique for the rapid processing moderate length tidal data.

The sensitivity of the Fourier estimated $M_2$ amplitude to the tilt meter mounting technique has been discussed in detail and it appears that the tilt meter mounted on a sand bed is less susceptible to the effects of small-scale rock inhomogeneities than the tilt meter mounted directly on to the bedrock; the sand-mounted device exhibiting the higher tilt drift. In the present work the sand-mounted tilt meter is considered to give the superior performance, since it is an easy matter to remove drift from an experimental record, it is not always a simple matter to account for small-scale mounting effects.

In obtaining the Fourier amplitude it has also been shown that a more reasonable estimate is obtained if no special time window is applied to the tidal series, this is equivalent to using the rectangular gate time window.

Acknowledgments

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References