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OCEAN TIDE LOADING CONSIDERATIONS FOR GPS PROCESSING AROUND AUSTRALIA

Nigel T. Penna

Western Australian Centre for Geodesy
Curtin University of Technology
Perth AUSTRALIA
email: nigel.penna@curtin.edu.au

Trevor F. Baker

Proudman Oceanographic Laboratory
Bidston Observatory Merseyside UK
email: tfb@pol.ac.uk

ABSTRACT

Ocean tide loading (OTL) effects are not always modelled in static GPS data processing. In some parts of North West Australia, models suggest that (predominantly vertical) OTL induced site displacements as large as 10 cm in range can occur over the course of about 6 hours. The correct mitigation of OTL effects is consequently important if station coordinates and tropospheric delays are to be estimated from GPS data with millimetric accuracy. However, adequately modelling the site displacement due to OTL is not trivial and, in addition, displacement is not necessarily largest nearest the coast, or negligible hundreds of kilometres inland. This paper reviews how OTL site displacements are modelled, and outlines some major advances made in the modelling of the ocean tides during the last decade. Expected site displacements at a selection of sites in Australia are detailed, and the paper outlines the effects of incorrect mitigation of the OTL site displacement on GPS derived parameters, with some references to existing scientific literature.

1. INTRODUCTION

The oceans move periodically due to the gravitational attractions of the moon and the Sun, and in turn the solid Earth responds periodically due to the change in the mass distribution of the water of the oceans. This is the *ocean tide loading (OTL) displacement*, which is spatially very variable and difficult to model, since it depends on the global spatial distribution of the amplitudes and phases of the ocean tides relative to the observation point, and upon the elastic / inelastic structure of the Earth (Baker 1984; Baker, 1991). In addition, this mainly vertical OTL displacement is not simply a function of distande from the coast, and its range can be more than 10 cm in some parts of the world (Baker et al, 1995), such as the coast of North West Australia.

For high accuracy GPS applications, namely when millimetric tolerances are required, the OTL induced site displacement can have a significant effect on the geodetic parameters estimated. Such applications include the monitoring of crustal dynamics, the establishment of zero order geodetic control and GPS meteorology, in which GPS estimated tropospheric delay parameters are converted to an estimate of atmospheric water vapour. OTL effects include the manifestation of ocean tidal periodic signatures in geodetic time series, or increased noise of the observations and the estimated parameters. Appropriate mitigation techniques to overcome the effects of OTL site displacement are often necessary, namely differencing and/or modelling, depending on the baseline length and OTL site displacement characteristics at the ends of the baseline.

2. OCEAN TIDE LOADING PARAMETERS

The effects of OTL site displacement on GPS data may be corrected (modelled) using OTL displacement coefficients, hereafter termed *OTL parameters*, that model the different tidal constituents of the displacement. These tidal constituents arise due to the periodic motions of the moon and Sun. The tidal displacements can be expressed as sums of series of harmonics of known amplitudes and phases and these harmonics are called tidal constituents. Each constituent represents an astronomical motion and takes the form of a sinusoid of known frequency with an amplitude that is independent of time. The main, dominant, tidal constituents were given symbols comprising a letter and suffix by George Darwin (son of Charles) with the lunar and solar constituents represented by letters near to 'M' (eg M, N, O) and 'S' (eg S, P) respectively in the Roman alphabet. A suffix represents the speed of the constituent and is termed the *tidal species*. If the species has one or more cycles per day, the number of daily cycles (eg 2 for semi-diurnal tides) is used, and for low frequency species, the abbreviation of the period itself is used (eg '$_f$' for fortnightly tides, $_{sa}$ for semi-annual tides). The 11 main tidal constituents are listed in Table 1 and, of these, M_2, S_2, K_1 and O_1 generally dominate (Baker et al, 1995).

Darwin Symbol	Name	Period (h=solar hours, d=solar days)
Semi-diurnal tides:		
M_2	Principal lunar	12.42 h
S_2	Principal solar	12.00 h
N_2	Major lunar elliptical	12.66 h
K_2	Luni-solar declinational	11.97 h
Diurnal tides:		
O_1	Principal lunar	25.82 h
K_1	Luni-solar declinational	23.93 h
P_1	Principal solar	24.07 h
Q_1	1st order elliptic	26.87 h
Long-period tides:		
M_f	Lunar fortnightly	13.66 d
M_m	Lunar monthly	27.55 d
S_{sa}	Solar semiannual	182.62 d

Table 1: The main tidal constituents (after Baker et al (1995))

The OTL parameters comprise an amplitude and phase lag (with respect to a reference phase, typically that for the constituent at Greenwich). The amplitude indicates the maximum displacement and the phase provides the time of maximum displacement compared with the tide generating force. The parameters are most commonly computed per site per constituent, by evaluating the displacement caused by the effect of the ocean tides across the entire globe. Consequently, this so called '*convolution method*' (section 4.1) requires the best models possible of the ocean tides globally, and of the Earth's rheology, enabling the response of the Earth to the tidal loading to be computed. An alternative approach is based on the response of an Earth model that is considered to be loaded by a spherical harmonic surface mass layer. However, this approach requires a very high degree spherical harmonic expansion, especially near the coasts, rendering it somewhat impractical due to computational resources. A third method, developed by, for example Schenewerk et al (2000b), enables OTL parameters to be estimated directly using several months of continuous GPS data, as described in section 4.2.

The OTL parameters computed for a particular set of ocean tide and Earth models (or from GPS data) for a particular location, are time invariant. The parameters can then be used to compute (model) the actual site displacement for any particular instance in time. Typically, the time varying displacement, Δc, is computed within geodetic software packages according to IERS 1996 Conventions (McCarthy, 1996), in which the OTL parameter amplitudes and Greenwich phase lags, plus the time of observation, are input to equation (1):

$$\Delta c = \sum_j f_j A_{cj} \cos(\omega_j t + \chi_j + u_j - \Phi_{cj}) \qquad (1)$$

where: A_{cj}, Φ_{cj} are the amplitudes and Greenwich phases at the site for each tidal constituent j

ω_j is the tidal frequency

χ_j is the astronomical argument

f_j, u_j are the nodal factor and angle respectively

Computation of the tidal frequency and astronomical argument listed in equation (1) are dependent on the positions of the moon and Sun, and are detailed in McCarthy (1996). The nodal factor and angle are computed according to Doodson (1928).

As illustrated in equation (1), the total site displacement at the epoch considered is obtained by simple summation of the displacements due to each tidal constituent considered. In GPS least squares processing software, the approximate station coordinates are then corrected by the displacement (Δc) at each processing epoch. Hence the mathematical model of the observation (evaluated using the approximate values of the unknown parameters) accounts for the ocean tide loading displacement.

3. OCEAN TIDE MODELS

When computing OTL parameters using the convolution method, the main error arises due to uncertainties in the models of the ocean tides, not the Earth model (Farrell, 1972). The Earth can be assumed elastic at tidal periods for the accuracies needed for GPS measurements (Dodson et al, 1999), whereas Baker et al (1995) state that errors of at least 10 to 20 % of the ocean tide amplitude are common, even for the larger tidal harmonics. However, much research has been done in the last decade to improve the ocean tide models. This largely coincided with the development of satellite altimetry missions, such as ERS-1 and TOPEX/Poseidon (launched in August 1992), whose data could be used in the modelling of the ocean tides.

Ocean tide models comprise a set of amplitudes and phases at discrete locations that attempt to describe the different constituents of the ocean tides, analogous to the OTL parameters. Often maps for each constituent are plotted for a region, with contours (cophase lines) shown, which indicate locations of equal phase, at which high waters occur simultaneously. Contours (coamplitude lines) also join locations with equal amplitude (and hence tidal range).

As stated in section 2, the computation of OTL parameters via the convolution method relies on knowledge of the tides throughout all oceans and seas on Earth. Hence any *ocean tide model* adopted must provide *global coverage* for the constituents considered, with sufficient *accuracy* and *spatial resolution*. The spatial resolution criterion is vital, since although the tide characteristics vary only gradually over the open oceans, they are highly variable in shallow waters such as along coastlines and on continental shelves, due to local resonance that causes regional amplifications. Since the waters adjacent to the observing site have the largest influence on the OTL displacement, accurate modelling of the tides in the surrounding seas is crucial when computing OTL parameters for near coastal sites (Baker et al, 1995). Similarly, Scherneck (1991) states that about half the tidal loading effect arises from tides within 2000 km of the site considered. This causes problems when global ocean tide models do not represent the tides in local waters sufficiently, so often the global ocean tide models are augmented with specific regional and local tide models (Scherneck, 1991).

There are essentially 3 types of ocean tide models, as defined by the method of creation:

(i) Empirical models - derived from data such as tide gauge records or satellite altimetry, and to extend the coverage to areas where no measurements are available, interpolation is used.

(ii) Theoretical or hydrodynamic numerical models - models in the purest form, evaluated using only bathymetry information and the mathematical modelling of the ocean tides.

(iii) Combination of technique models – usually based on a combination of (i) and (ii).

A brief overview of some ocean tide models that can be considered appropriate for the computation of OTL parameters is now given. This is not intended to be exhaustive, but highlights some important developments in ocean tide modelling. The models discussed all have global coverage, a prerequisite for OTL parameter estimation. The Schwiderski (1980) model was the only viable option for OTL parameter computations before 1991, and was the model recommended in the IERS 1992 Standards (McCarthy, 1992) for use in GPS processing software. The Cartwright and Ray (1991) model was developed based solely on GEOSAT1 satellite altimetry data, but did not have fully global coverage, being restricted in latitude to ±69°. Several new models were produced from 1994 onwards, following the launch of TOPEX/Poseidon in 1992. A notable model was the purely hydrodynamic FES94[1] model (LeProvost et al, 1994), that was then recommended in the IERS 1996 Conventions (McCarthy, 1996) for use in GPS processing software. At a similar time, the TOPEX/Poseidon generated CSR2.0 model was developed by Eanes (1994), but was restricted to latitude coverage of ±66°. A natural research progression involved the combination of the techniques that had been used to produce the FES94 and CSR2.0 models. This culminated in the release of the FES95 model (LeProvost et al, 1998), which was a hydrodynamic model that assimilated tidal estimates based on altimetry data, and also the CSR3.0 model (Eanes and Bettadpur, 1996), which used altimetry to provide long wavelength corrections to FES94. Thereafter, further research has been carried out on models produced from the combination of techniques, resulting, for example, in one of today's state-of-the-art models FES98 (Lefevre et al, 2000). This is based on a hydrodynamic model with the tidal constituents from about 700 tide gauges assimilated in order to improve the modelling of the ocean tides in the problematic shallow seas and near coastlines. The latest model, FES99, assimilates both these tide gauge data and TOPEX/Poseidon altimetry data (Lefevre et al, 2002).

3.1 The Schwiderski model

Until 1991, the only ocean tide model suitable for computing OTL parameters was Schwiderski (Schwiderski, 1980). This global model, with no latitude restrictions, was generated using the 'combination technique', whereby the mathematical representation of the ocean tides was constrained in deficient areas with information from over 2000 coastal, island and bottom-pressure empirical tide gauges, via a hydrodynamic interpolation technique. In the areas where empirical data are incorporated, the accuracy of this model matches that of the data used, but in the remaining areas degrades due to

[1] FES=Finite Element Solution

deficiencies in the purely hydrodynamic solutions. The model incorporates the 11 major tidal constituents listed in Table 1 and is provided at a 1° by 1° global resolution. A rough indication of the model's accuracy was obtained by Cartwright and Ray (1991), who compared the model's tidal estimates with 80 assumed 'ground truth' observations situated on the ocean bottom or at small oceanic islands. The agreements found between the data and the model were about 4 cm RMS for M_2 and 2 cm RMS for S_2, K_1 and O_1.

3.2 The FES94 model

FES94 (LeProvost et al, 1994) is a purely hydrodynamic global model (0.5° by 0.5° spatial resolution) that addressed the previous limitation of hydrodynamic models, namely lack of resolution over shelf areas, by using finite element techniques. The elements ranged in size order from about 200 km in the deep ocean to 10 km along the coastlines to account for the greater variability of the tides in shallow waters. Due to computational resources, the global model was computed in sections, although this limited the accuracy of the model due to the necessity to stipulate boundary conditions across sections (Lefevre et al, 2000). The constituents M_2, S_2, N_2, K_2, K_1, O_1 and Q_1 are provided in the model, and its quality was assessed by comparison with tidal data available from 78 'ground truth' stations of the archive of the International Association for Physical Sciences of the Oceans (IAPSO) and the International Hydrographic Bureau (Le Provost et al, 1994). The model agreed with the data to a few centimetres for the larger constituents M_2, S_2, K_1 and O_1, and a few millimetres for the remaining constituents, with increased differences over shallow waters.

3.3 The FES95 model

FES95 (Le Provost et al, 1998) is a combination technique global model (0.5° by 0.5° spatial resolution), whereby values from the empirical TOPEX/Poseidon satellite altimetry model CSR2.0 (Eanes, 1994) in oceanic areas with depths greater than 1000 m were assimilated into the purely hydrodynamic FES94 model. It was assumed that a large part of the errors in FES94 came from limitations in the hydrodynamic model, which requires knowledge of ocean depth, which are insufficiently determined, or classified, over many areas. Hence by assimilating values derived from TOPEX/Poseidon, an improved solution was expected, since comparisons with tide gauge observations indicated that the TOPEX/Poseidon derived values are closer to reality than the hydrodynamic estimates.

Whilst FES95 is an excellent model for most of the oceans, there are some problems in a few local areas. These were caused by the assimilation method giving spurious resonances in a few areas (Lefevre et al., 2000). One of the problem areas is the Arafura Sea to the north of Australia, so some caution is required when using this model to compute OTL parameters for this region. This problem has been eliminated in the more recent models (FES98 and FES99).

3.4 The CSR3.0 and CSR4.0 models

CSR3.0 (Eanes and Bettadpur, 1996) is a combination technique global model developed at the University of Texas, whereby the first 2 years of data from TOPEX/Poseidon were used to make long wavelength adjustments to the FES94 hydrodynamic solution. The resulting model was available for constituents M_2, S_2, N_2, K_1, O_1, P_1, K_2 and Q_1, with a global resolution of 0.5° by 0.5°. CSR4.0 is a recent updated version of CSR3.0 using a longer set of TOPEX/Poseidon data.

3.5 The FES98 model

FES98 (Lefevre et al, 2000) is based on a single global hydrodynamic solution and is improved in shallow water areas by the assimilation of data from about 700 tide gauges carefully selected from the numerous tide gauges along the world's coastlines. The use of a single global hydrodynamic solution overcomes any undesirable computational boundary effects suffered by FES94. The model excludes satellite altimetry derived data, that are traditionally beneficial in open oceans but not over the coast. The resultant global model is available at a 0.25° by 0.25° resolution, and includes constituents M_2, S_2, N_2, K_2, O_1, K_1 and Q_1.

3.6 Other ocean tide models

In addition to the above there are several other ocean tide models. Many of these are reviewed in Shum et al (1997) and Le Provost (2001). Since these articles were written, other ocean tide models have been produced. Amongst these recent ocean tide models, the FES99 model (Lefevre et al, 2002) and the NAO99b model of Matsumoto et al (2000) are particularly useful for OTL computations, since they assimilate both altimetry and coastal tide gauge data.

4. COMPUTATION OF OCEAN TIDE LOADING PARAMETERS

4.1 The convolution method

For particular ocean tide and Earth models, convolution is the most feasible method for computing OTL parameters for any particular site, regardless of location. This involves the convolution of the ocean tide with the loading Green's function to give the OTL displacement. The convolution integral is evaluated for the particular numerical global model of the ocean tides and Green's functions for the particular Earth model. The Green's functions are related to the properties of the Earth by so-called load Love numbers, computed according to a particular model of the Earth's seismic properties. Farrell (1972) provides further details.

For a particular Earth model, such as Gutenberg-Bullen A (Farrell, 1972), the Green's function gives the response of the Earth model, $L(\underline{r})$, to a point mass load:

$$L(\underline{r}) = \rho_w \iint G(|\underline{r} - \underline{r}'|)\xi(\underline{r}')dA \qquad (2)$$

where: $L(\underline{r})$ is the loading effect (OTL parameter) at site r

$\underline{r}$ is a position vector on the Earth's surface

ρ_w is the density of sea water

$\xi(\underline{r}')$ is the height of the ocean tide over the surface area dA at position vector r'

$G(|r - \underline{r}'|)$ is the appropriate loading Green's function

Equation (2) illustrates that the OTL parameter at site $\underline{r}$ involves the summation of the effects of the ocean tides over all the oceans. In practice, it is usually assumed that $\xi(\underline{r}')$ can be approximated by some uniform tide over a limited area (Baker, 1984). The subsequent response of the Earth at site $\underline{r}$ to a uniform ocean tide load on a cell of limited area dA at position vector $\underline{r}'$, is computed according to the site to cell separation distance. Repeating the calculation and summing for all cells covering the oceans, gives the OTL parameter at site $\underline{r}$.

The convolution method is performed for both radial (vertical) and tangential (horizontal) displacements, with tangential displacements generally being about one third of the order of the radial displacements (Farrell, 1972).

4.2 Use of GPS observations

An alternative approach to the convolution method is the direct estimation of the OTL parameters using several months of continuous GPS data per site. Since this recently developed GPS-only approach requires neither ocean tide nor Earth models used conventionally, it can be useful in areas where the ocean tides are poorly modelled.

The GPS-only approach has been used by Schenewerk et al (2000b) to estimate the vertical OTL parameters for over 300 sites distributed worldwide (mainly North America) for the 8 semi-diurnal and diurnal tidal constituents listed in Table 1. The PAGES double difference GPS processing software (Schenewerk et al, 2000a), developed by the US National Geodetic Survey, was modified to achieve this. Although simulations indicated that only a few weeks of data were needed to reliably estimate the 8 constituents considered, Schenewerk et al (2000b) used data from every third day of 1997-1999, to alleviate concerns that multipath and diurnal and seasonal site dependent effects may affect the estimated OTL parameters. 90 % of the GPS estimated OTL parameter amplitudes agreed with the equivalent Schwiderski (1980) global model estimates to within 5 mm or less. However, Schenewerk et al (2000b) found that the GPS only method does not estimate the K_1 and K_2 parameters very well. K_1 and K_2 have periods of a sidereal day and half a sidereal day so multipath effects and the period of the orbit of the GPS satellites effectively renders the reliable estimation of these particular OTL parameters from GPS observations impossible (Schenewerk et al, 2000b).

It is also possible to directly estimate OTL parameters from GPS data using JPL's GIPSY software with a single receiver precise point positioning strategy, as detailed by Scherneck et al (2000).

4.3 Interpolation of ocean tide loading displacement contours

If the convolution or GPS-only approaches are used to compute OTL parameters at a given resolution over the region of interest, a simple approach to obtaining site-specific OTL parameters is to interpolate load maps of amplitude and phase lags.

This is feasible since, as stated above, OTL parameters are time invariant for a particular combination of ocean tide and Earth tide models. This approach could be particularly useful in web-based on-line GPS processing services. Such services may not have the time, data or software capabilities to generate the OTL parameters 'on-the-fly' for the station considered using the convolution or GPS methods, but the correction of OTL site displacements may still be desirable.

5. OCEAN TIDE LOADING SITE DISPLACEMENTS IN AUSTRALIA

Australia experiences OTL site displacements varying in range from almost zero to over 10 cm, ie some of the largest in the world. Although Australia is mainly surrounded by deep oceans, the presence of shallow seas along the North West Shelf causes significant OTL site displacements, and the OTL site displacement is also large on the South East coast (Baker, 1991). The variation of the OTL effect in Australia is illustrated in Figure 1, which shows contours of the OTL amplitudes and Greenwich phase lags for the principal tidal constituent, M_2, computed using the convolution method with the Schwiderski global ocean tide model.

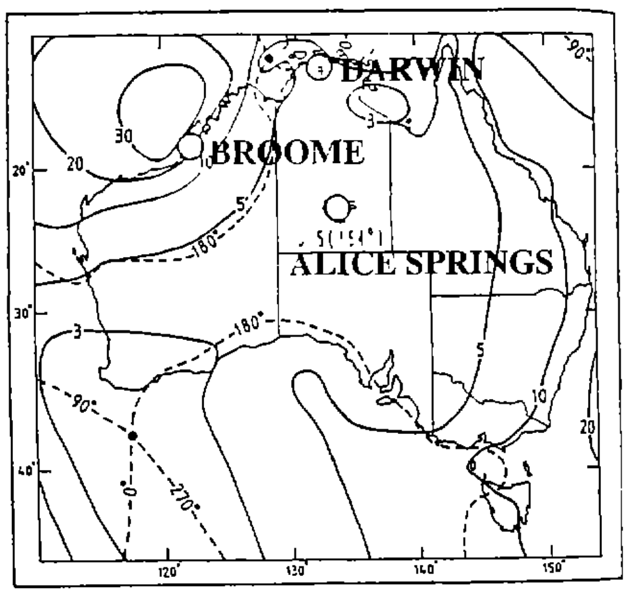

Figure 1: The M_2 amplitudes (solid contours in mm) and Greenwich phase lags (dashed contours in degrees) across Australia, using the Schwiderski ocean tide model (Baker, 1991). Also shown are the amplitude and phase lag for Alice Springs.

The sites Broome, Darwin and Alice Springs are highlighted in Figure 1. Broome is subject to about the maximum OTL site displacement in Australia, whilst the OTL site displacement at Darwin is much smaller, despite being a coastal site, since it is close to an M_2 amphidrome (point of zero tidal loading). Alice Springs is highlighted to show the magnitude of the OTL site displacement that can still arise hundreds of kilometres inland.

OTL parameters were obtained for Broome, Darwin and Alice Springs from Scherneck (2000), who has computed OTL parameters for a number of sites worldwide, using the convolution method (Scherneck, 1991) with different ocean tide models. OTL parameters selected were based on several different ocean tide models. These were the Schwiderski model, to comply with the IERS Standards 1992 (McCarthy, 1992), the FES94 model, to comply with the IERS Conventions 1996 (McCarthy, 1996) and also the CSR3.0 model, to show the effect of a model that was partly derived from satellite altimetry data. The 11 constituents listed in Table 1 were obtained and the height amplitudes and phase lags for the main constituents (M_2, S_2, K_1, O_1) are listed in Table 2.

Site	Constit.	FES94		Schwiderski		CSR3.0	
		Amp.	Phase	Amp.	Phase	Amp.	Phase
Broome	M_2	28	-139	27	-140	28	-128
	S_2	15	-75	14	-76	16	-64
	K_1	10	-2	9	-7	10	-5
	O_1	7	-20	7	-18	7	-14
Darwin	M_2	4	87	2	130	5	63
	S_2	1	91	0	138	2	68
	K_1	7	22	5	-8	8	17
	O_1	5	-7	4	-20	6	-3
Alice Springs	M_2	4	149	4	154	3	150
	S_2	1	-111	1	-83	1	-62
	K_1	2	8	2	3	2	5
	O_1	2	-3	2	2	3	6

Table 2: Height OTL parameters from Scherneck (2000) using the FES94, Schwiderski and CSR3.0 ocean tide models and convolution method. Amplitudes are in mm and Greenwich phase lags in degrees.

Each constituent contributes to the total OTL site displacement at each observational epoch. This is not constant in time due to the different periods of each constituent causing the constituents to move in and out of phase with each other. The combined effect of all 11 constituents for the FES94 derived OTL parameters are illustrated for the height, North and East coordinate components of OTL site displacement for Broome, Darwin and Alice Springs for March 2001 in Figures 2, 3 and 4 respectively. The displacements shown were generated according to the IERS Conventions 1996 (McCarthy, 1996) by generating an estimate every 15 minutes.

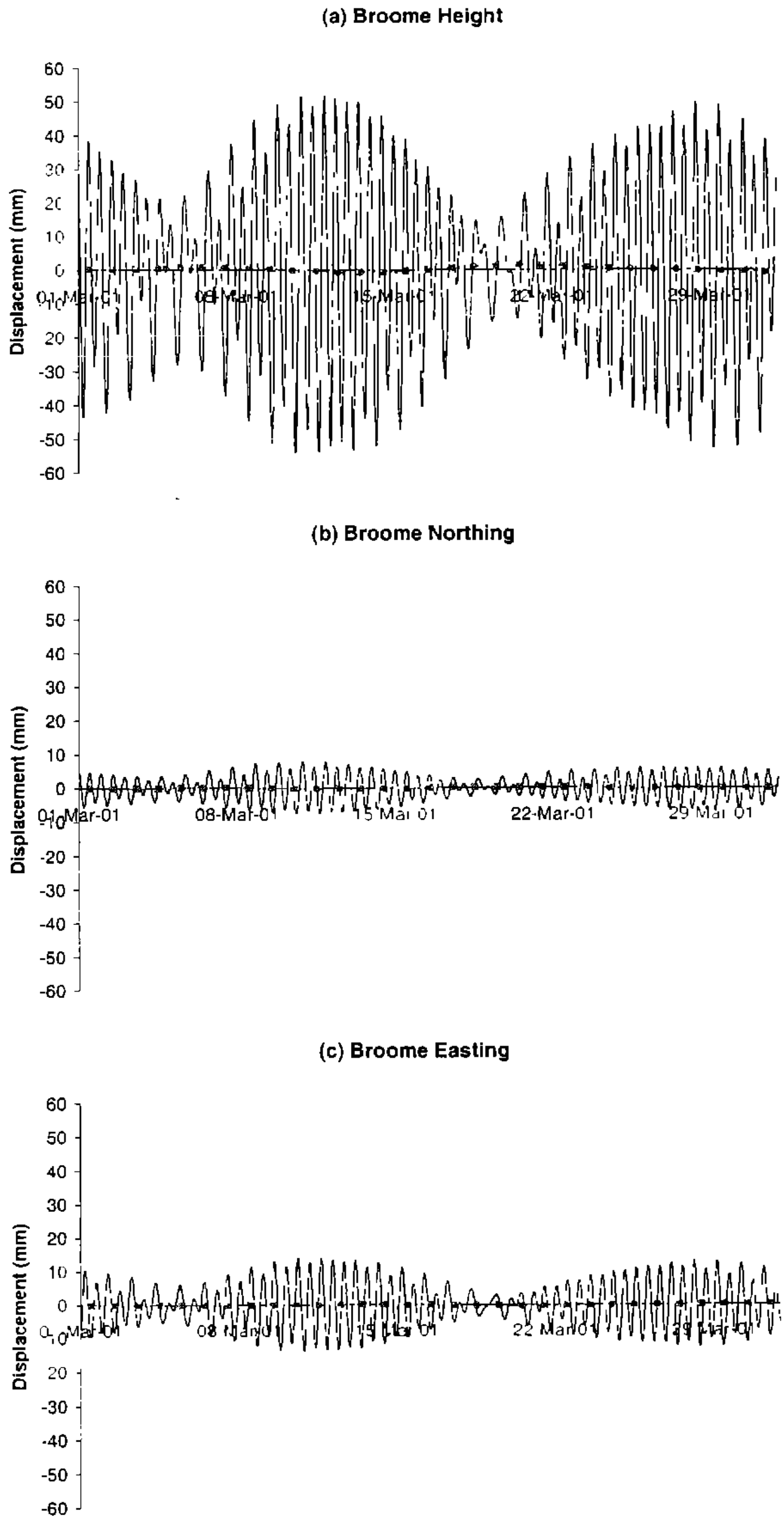

Figure 2: OTL displacement for March 2001 at Broome using the FES94 ocean tide model, in height (a), Northing (b) and Easting (c) components, indicated by the unmarked line. The rectangles indicate average daily displacements, centred about 1200 UT.

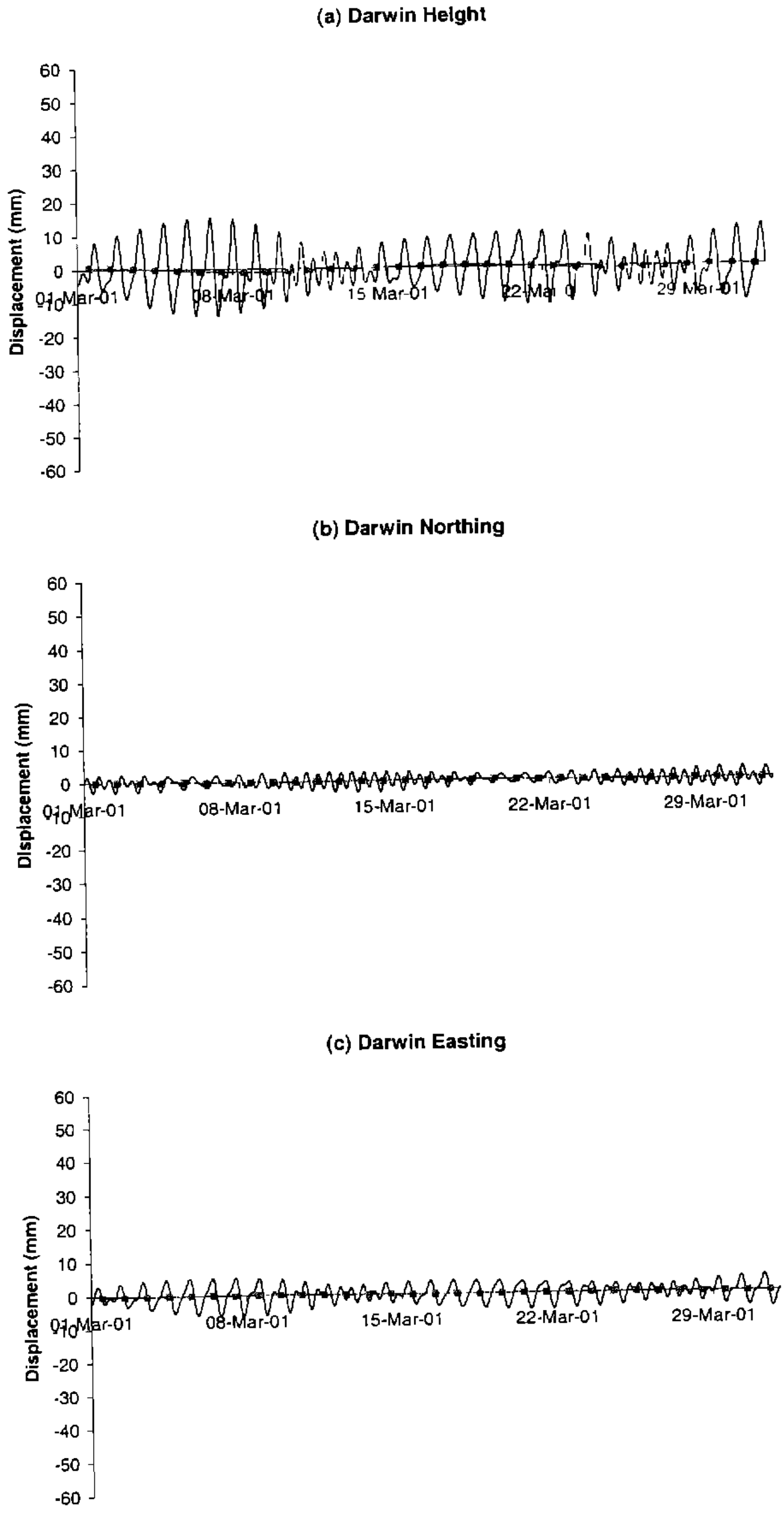

Figure 3: OTL displacement for March 2001 at Darwin using the FES94 ocean tide model, in height (a), Northing (b) and Easting (c) components, indicated by the unmarked line. The rectangles indicate average daily displacements, centred about 1200 UT.

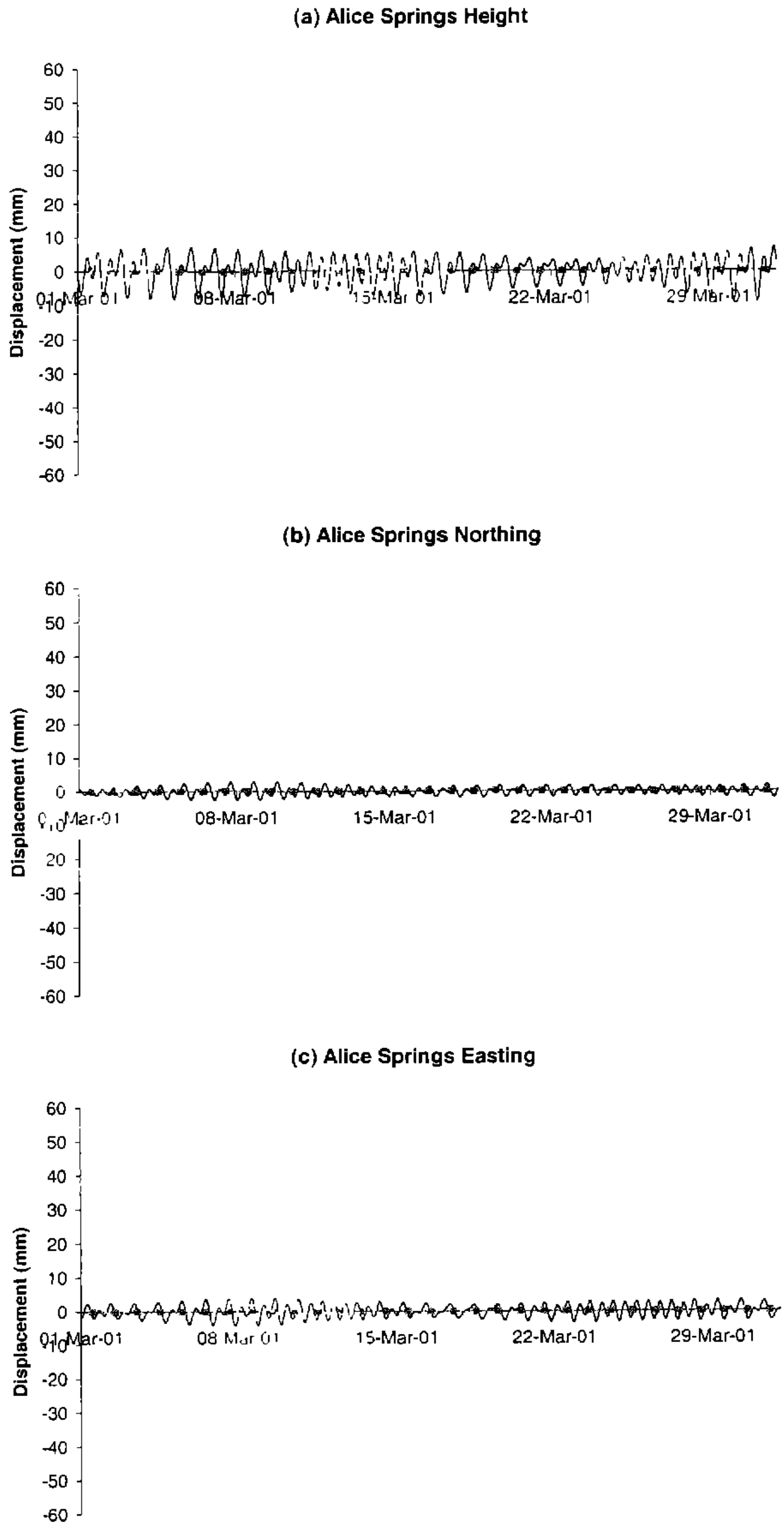

Figure 4: OTL displacement for March 2001 at Alice Springs using the FES94 ocean tide model, in height (a), Northing (b) and Easting (c) components, indicated by the unmarked line. The rectangles indicate average daily displacements, centred about 1200 UT.

A range in OTL height displacement of over 100 mm for Broome is apparent from Figure 2(a), with ranges of over 15 mm in the Northing component and nearly 30 mm in the Easting component apparent from Figures 2(b) and 2(c) respectively. The effect of the different periods of the M_2 and S_2 constituents to the resultant displacement is clearly apparent, causing fortnightly displacement peaks (spring tides when the moon and Sun are in direct alignment, ie M_2 and S_2 in phase) and troughs (neap tides when the moon and Sun are 90° apart, ie M_2 and S_2 out of phase). The variation between successive high and low tidal displacements is also apparent in Figure 2, caused by the diurnal constituents and termed the diurnal inequality. Also shown for each of the 3 displacement components is the average OTL site displacement over 24 hours per solar day, which has a maximum range of displacement of only 4 mm in height. This implies that the OTL site displacement effect may be considerably reduced if averaging techniques are used, which might be expected in routine global or regional IGS GPS processing when 24 hour sessions are generally used. This phenomenon arises due to the closeness of the periods of many of the tidal constituents to either half or a whole solar day.

The OTL height displacement range for Darwin shown in Figure 3 is about 30 mm, with ranges of about 7 mm and 12 mm in the Northing and Easting components respectively. This confirms that the OTL displacement at coastal sites can be small, and illustrates the non-generality of the OTL mitigation issue. The fortnightly spring-neap cycle that was evident at Broome is also apparent for Darwin, and averaging the OTL site displacements to single values per day reduces the range of displacement to about 2 mm.

A range in OTL height displacement of about 15-20 mm for Alice Springs is apparent from Figure 4, with only about a 5 mm range in Northing displacement and about a 10 mm range in Easting displacement. The fortnightly spring / neap cycle is much less apparent for Alice Springs than for Broome. By inspection of Table 2, this can be attributed to the almost negligible S_2 amplitude of 1 mm at Alice Springs compared with the M_2 amplitude of 4 mm, whereas at Broome, the S_2 amplitude of 15 mm is over half the magnitude of the M_2 amplitude of 28 mm. Averaging of the OTL site displacements to one value per day at Alice Springs makes the range of displacement almost zero.

To demonstrate the effect of computing OTL parameters using different ocean tide models, the Broome OTL height displacement time series for March 2001 was also computed using both the Schwiderski and CSR3.0 ocean tide models. The resulting differences between FES94, Schwiderski and CSR3.0 are plotted in Figure 5.

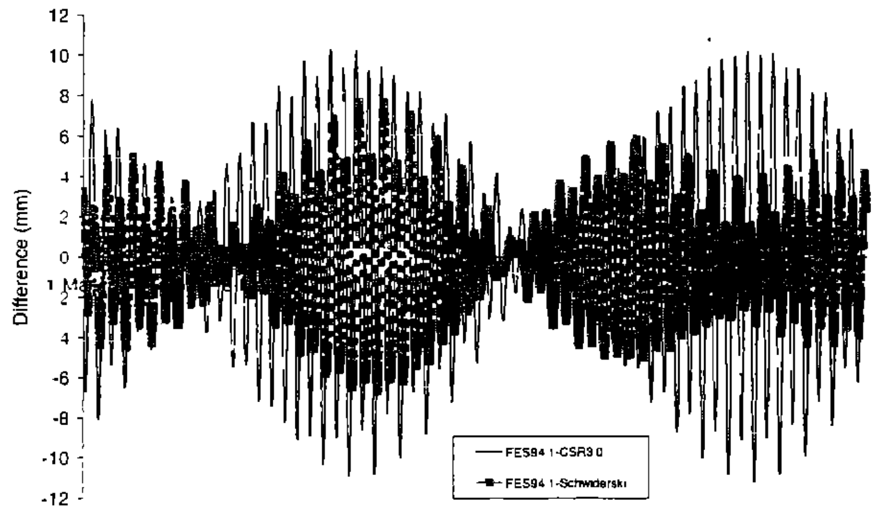

Figure 5: OTL displacement height differences obtained for Broome for March 2001 using different ocean tide models. Differences are FES94 minus CSR3.0 and FES94 minus Schwiderski respectively

It can be seen from inspection of Figure 5 that the 3 ocean tide models considered result in OTL height displacement estimates for Broome that differ by several millimetres during March 2001. These are quantified in Table 3, with the percentage of differences less than 3 mm incremented values listed.

Displacement Diffn (mm)	FES94 - CSR3.0 (%)	FES94 – Schwiderski (%)
=0	1	1
<3	43	67
<6	73	98
<9	94	100
<12	100	100

Table 3: Percentage of height displacement differences for Broome for March 2001 by comparing models FES94 minus CSR3.0 and FES94 minus Schwiderski

Table 3 shows that at any instant in time, there is a probability of at least 33 % that the OTL height displacement estimated from 1 of the 3 models will differ by more than 3 mm from the other models. The comparisons shown in Table 3 can be summarised as RMS differences between the FES94 and CSR3.0 models of 5.0 mm, and between the FES94 and Schwiderski models of 2.8 mm.

6. EFFECT OF OCEAN TIDE LOADING ON GPS PARAMETERS

It has been shown and discussed above that OTL site displacement is variable both spatially and temporally. To ascertain the significance of OTL site effects on GPS estimated parameters, such as station coordinates and tropospheric delay, the target accuracy, processing techniques, network design and time and observational session length must all be considered.

6.1 Target accuracy

The most important consideration for the mitigation of OTL effects in GPS data processing is the target accuracy of the estimated parameters. For example, if a station height estimate is required at a lower accuracy than the range of the OTL height displacement, there is little need to model the OTL site displacement. However, when 3-dimensional millimetric position tolerances are desired, the correct mitigation of OTL site displacements with only a few millimetres range can be important. Otherwise, ocean tide signatures in coordinate time series can arise with resulting decreased precision and a biased mean. The appropriate mitigation of OTL effects is becoming ever more important in GPS meteorology, in which estimates of tropospheric delay are converted with very little additional uncertainty to estimates of the amount of water vapour in the atmosphere above a receiver (precipitable water), using surface pressure and temperature measurements. Precipitable water is typically required to an accuracy of 1 mm, if used in meteorological forecasting. Since an approximate method of converting from zenith wet tropospheric delay to precipitable water is to multiply by 0.16 (Bevis et al, 1992), the zenith wet delay must be accurate to about 6 mm. For the contribution of OTL effects to this error budget to be less than 20 %, any OTL effects on tropospheric delays must be mitigated to an accuracy of about 1 mm. Brunner and McCluskey (1991) provide a rule of thumb that a tropospheric delay error is proportional to a station height error, scaled by the sine of the elevation cut-off angle adopted. For a 15° cut-off, this suggests that about 30 % of the station height error maps to the tropospheric delay error. Hence in the case presented here, the OTL site displacement would need to be modelled with an accuracy of 3 mm.

6.2 Positioning mode

The positioning mode is an important factor when considering OTL effects. If single receiver precise point positioning is adopted, for example with GIPSY software as outlined by Zumberge et al (1997), any unmodelled OTL site displacements will propagate directly to the geodetic parameters. When relative positioning is performed, common OTL signals at the two ends of the baseline will be removed. This is generally successfully used to mitigate OTL effects on short baselines. However, it was shown in section 5 that the OTL site displacement effects are complex, vary slowly over the oceans but are highly variable on coastlines adjacent to shallow waters. Thus it is difficult to generalise what constitutes a 'short' baseline. For example, Baker et al (1995) showed that a height estimate time series from continuous 3 hour sessions over a week. for a 300 km long baseline in the south of England, included a strong ocean tidal signal The corresponding standard deviation of the heights reduced from 39 mm to 21 mm when OTL site displacements were modelled. Although this is an extreme case, with a 120 mm range of OTL displacement at one end of the baseline, and a 20 mm range of OTL displacement at the other end, it is a useful illustration. However, for the Australia context, the baselines lengths between permanent reference stations are generally hundreds, or even thousands of kilometres, so differencing alone will seldom mitigate OTL effects.

6.3 Session length

The effect of unmitigated OTL site displacement on estimated geodetic parameters can, in some cases, be reduced by increasing the observational session length. As shown in Table 1, the semi-diurnal and diurnal tidal constituents have periods close to 12 and 24 hours respectively. Consequently, the adoption of a 24 hour session length that equals or doubles these periods, as used in routine processing of IGS global and regional networks, has been suggested by previous works to enable the effects of these constituents to be mitigated without actual modelling. For instance, Dragert et al (2000) showed for a single baseline in North West Canada, on which the range in differential OTL site displacement was about 60 mm, the scatter (over 30 daily, 24 hour solutions) when not modelling OTL effects was 7.6mm in height but which only improved to 7.3mm when OTL effects were modelled. Dragert et al (2000) did not consider this change to be significant, concluding, for this case, that OTL site displacement effects were adequately mitigated using a 24 hour data span alone. Meanwhile, Lambert et al (1998) state that, when processing 24 hour data sessions, not modelling OTL site displacements should result in only a small increase in the variance of the height estimates.

The technique of averaging over a session to mitigate OTL effects is only applicable if parameters are assumed constant over the entire session, such as station coordinates. If parameters are variant at a higher frequency than the data session length, then this mitigation approach may be invalid. Tropospheric delays for example, are often estimated per station as piecewise constant parameters over intervals ranging from 15 minutes to 3 hours. The period of these is clearly less than the 12 and 24 hour tidal periods, so data time averaging alone will not mitigate OTL effects and models are needed. In addition, Dragert et al (2000) considered the implications of unmodelled OTL site displacements on estimated tropospheric delays, when station coordinates were also simultaneously estimated. They found that for a 3 hour session length in which hourly tropospheric delays were estimated, the station coordinates absorb most of the OTL signal, but in a 24 hour session length, since the station coordinates are constant throughout the session, most of the OTL signal is absorbed in the tropospheric delay estimates. Furthermore, modelling OTL site displacement in such instances should enable a better evaluation of multipath effects (Baker et al, 1995). Also, GPS processing software generally uses the principle of least squares to compute the desired parameters, assuming the observational residual errors to be Gaussian (normally distributed). Any unmitigated OTL effects (systematic error) present in the observational residuals could lead to a biased solution and increased noise.

The correct mitigation of OTL site displacement is particularly important in episodic surveys, when the duration of the session observed may be less than the shortest period of the OTL constituents. Dodson et al (1999) provide examples where the coordinate time series from the episodic sessions of 3-4 hours (when OTL was not modelled) result in erroneous, aliased trends, in which the OTL displacement signal is not averaged away.

6.4 Effect of OTL on GPS time series

GPS is a very popular technique for the monitoring of crustal deformation (eg Blewitt et al, 2001) by the formation of time series (often spanning several years) from the processing of continuous GPS (CGPS) data. This usually involves discrete coordinate solutions from 24 hours of GPS data, from which coordinate time series are formed. The significance of the OTL effect on such long-term coordinate time series, for instance the solar-semi annual effect with a period of 6 months, is the topic of a subsequent paper.

6.5 Verification of OTL parameters

Given the number of different ocean tide models that are now available, and the different methods of computing OTL parameters, it is important to determine their resultant applicability to GPS data processing. Simple methods of assessing the quality of the OTL parameters include the precision of any coordinate time series computed, such as the session-to-session repeatability, plus the accuracy of the estimated coordinates with respect to assumed 'truth' values.

The quality of OTL parameters used in the estimation of tropospheric delay may be assessed by firstly converting the tropospheric delay to precipitable water, then comparing with external measurement techniques. These include radiosondes and water vapour radiometers, that provide estimates of precipitable water unaffected by OTL site displacement. An alternative method is proposed by Dach and Dietrich (2000), whereby an OTL scale factor is estimated as an additional unknown in the GPS processing. If the OTL site displacement is correctly modelled, the OTL scale factor will equal unity, and conversely, if the OTL site displacement is completely mismodelled, the scale factor will be zero. However, it is likely that the introduction of such scale factors could absorb some of the desired tropospheric signal unless properly relatively constrained.

Another technique that has been used (Lambert et al, 1998) to identify any unmitigated OTL signatures on a parameter time series is spectral analysis, since OTL signals have well defined periods.

7. CONCLUSIONS AND DISCUSSION

This paper has reviewed some of the considerations associated with OTL effects in GPS data processing, with likely OTL site displacements in some parts of Australia shown. The effect of OTL site displacement on GPS estimated coordinates and tropospheric delays have been highlighted, indicating that the decision whether to model OTL site displacement depends on the target accuracy, the characteristics of the OTL site displacement at the two ends of the baseline considered, and the session length. The methods of computing OTL parameters have been discussed, especially the method of the convolution of a global ocean tide model with a model that gives the dynamic response of the Earth, to obtain the OTL displacement at a site.

Highlighted in the paper were several different ocean tide models, including the resultant increased research activity in this area in the last decade, largely coinciding with the availability of data from satellite altimetry missions such as ERS-1 and TOPEX/Poseidon. However, this has raised the question of which ocean tide model is the most applicable for computing OTL parameters in certain areas. For instance, tests by Shum et al (1997) indicate that more than 20 recent global ocean tide models all agree within 20-30 mm of each other in the deep ocean, and offer an improvement of about 50 mm RMS over the classical Schwiderski model. What is more difficult to decide is which model should be used in shallow water areas where the models may be deficient, or if a particular model should be supplemented with more localised models. Such a situation arises in parts of Australia, for instance at Broome and, additionally, the issue of obtaining such data and routinely computing the desired OTL parameters requires extremely specialist software and is not trivial. Since about mid-2001 however, OTL parameters for any site world-wide for several ocean tide models have become more easily obtainable following the launch of web-based OTL parameter computation facilities such as that of Bos and Scherneck (2001). Once OTL parameters are obtained though, before a user applies them in geodetic GPS processing software, it is clearly essential that their source and computation method are clearly understood, and they should not necessarily be assumed perfect.

The paper has highlighted that OTL site displacements are significant over some parts of Australia and should not be ignored in high accuracy GPS positioning. It is of note that in the analysis of the GPS data by Morgan et al (1996) from the Australian National GPS Network to define the major zero order network in Australia ie GDA94, OTL site displacements were not modelled. Additionally, regional GDA94 densifications, such as the STATEFIX project in Western Australia (Stewart et al, 1997) also did not model OTL site displacements. It is of interest that Stewart et al (1997) reported quality degradations in height estimates for stations near the North West shelf when using sessions of a minimum of 12 hours, and suggested OTL site displacement as a likely cause.

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