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ORIGINAL ARTICLE

Quantifying FES2004 S_2 tidal model from multiple space-geodesy techniques, GPS and GRACE, over North West Australia

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Abstract Unmodeled sub-daily ocean S_2 tide signals that alias into lower frequencies have been detected in the analysis of gravity recovery and climate experiment (GRACE) space gravity fields of GRGS. The most significant global S_2 aliased signal occurs off the northwest coast of Australia in a shallow continental shelf zone, a region with high tidal amplitudes at a period of 161 days. The GRACE S_2 aliased equivalent water height grids are convolved with Green's functions to produce GRACE aliased tidal loading (GATL) vertical displacements. The analysis of hourly global positioning system (GPS) vertical coordinate estimates at permanent sites in the region confirms the presence of spectral power at the S_2 frequency when the same ocean tide model (FES2004) was used. Thus, deficiencies in the FES2004 ocean tide model are detected both directly and indirectly by the two independent space geodetic techniques. Through simulation, the admittance (ratio of amplitude of spurious long-wavelength output signal in the GRACE time-series to amplitude of unmodeled periodic signals) of the GRACE unmodeled S_2 tidal signals, aliased to a 161-day period, is found to have a global average close to 100%, although with substantial spatial variation. Comparing GATL with unmodeled S_2 tidal sub-daily signals in the vertical GPS time-series in the region of Broome in NW Australia suggests an admittance of 110–130%.

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1 Introduction

GPS observations of periodic deformations of the Earth's surface at sub-daily (e.g. Melachroinos et al. 2008; King et al. 2005), annual and semi-annual timescales (e.g. Penna et al. 2007) are used to validate ocean tide models and provide knowledge on the hydrological mass redistributions through their integrated gravitational effect (e.g. van Dam et al. 2007; Schrama 2007; Kusche and Schrama 2005). Moreover, temporal variations of the gravity field detected by the gravity recovery and climate experiment (GRACE) mission and surface loading displacements from global positioning system (GPS) networks include the combined global effect of all mass redistributions near the Earth's surface and its atmospheric and fluid envelope (e.g. Kusche and Schrama 2005).

van Dam et al. (2007) compared vertical displacements due in part to hydrological loading over Europe from GRACE and GPS estimates and found that there were large-amplitude, small-scale discrepancies between the two displacement fields. This was mostly evident for GPS stations in coastal regions. Such stations are subject to crustal deformations due to strong ocean tide loading (OTL) effects and mismodeling of the semidiurnal tides has been shown to result in spurious semi-annual signals (King et al. 2008; Penna et al. 2007). Schrama (2007) found that 59 out of 202 GPS sites studied showed a correlation greater than 0.5 in the vertical deformation loading signal observed by GRACE, with an RMS difference smaller than 3 mm.

GRACE gravity fields suffer from aliasing of high-frequency mass motions (Ray et al. 2003; Han et al. 2005; Ray and Luthcke 2006; Seo et al. 2008). The GRACE mission was

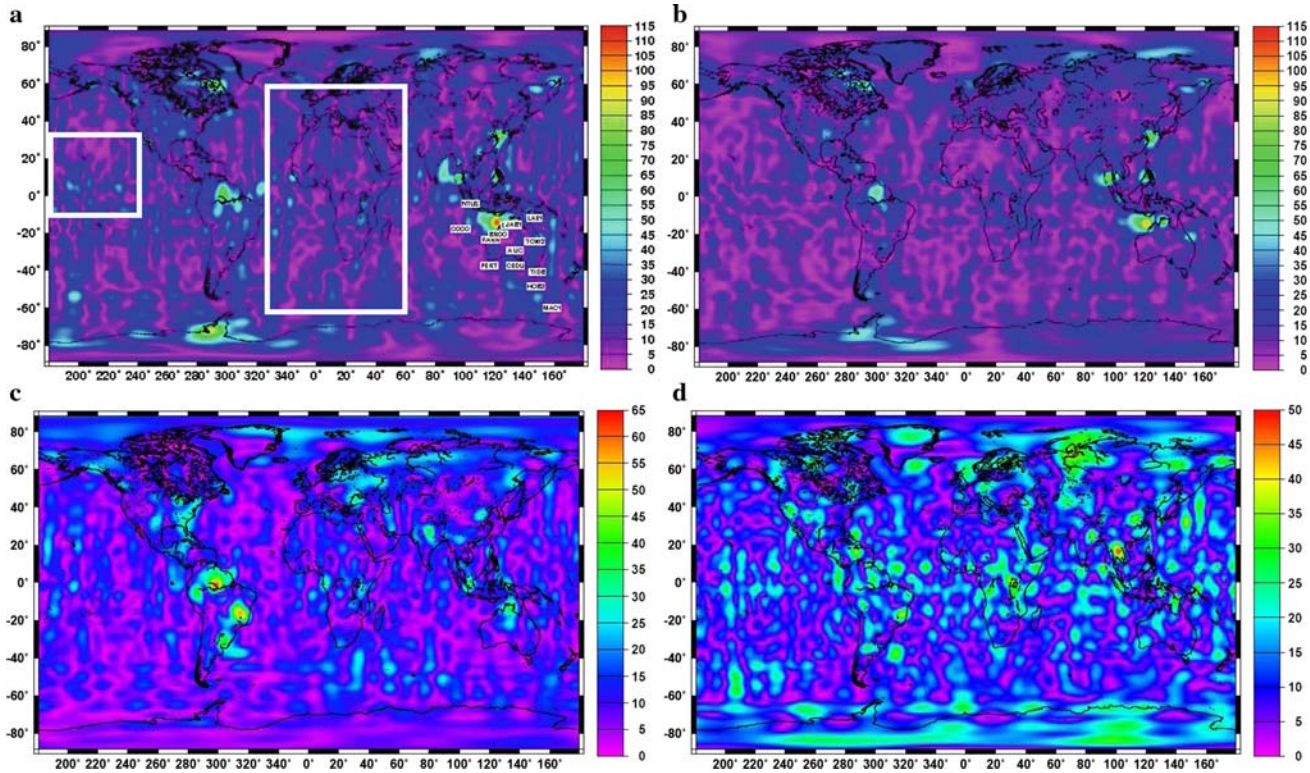

Fig. 1 **a** Amplitude (in mm) of equivalent water height of the S_2 aliasing (period = 161-days) from combined GRACE-SLR solutions. Statistics: STD: 9.6 mm, mean: 15.2 mm, min: 0.1 mm, max: 116.2 mm. The GPS sites analysed are shown. In the *white boxes* are the two regions selected for the EWH uncertainty estimation. **b** Amplitude (in mm) of equivalent water heights of the S2 aliasing (period = 161-days) from GRACE—only solutions. Statistics: STD: 8.5 mm, mean: 12.7 mm, min: 0.1 mm, max: 100.1 mm **c** Amplitude (in mm) of equivalent water heights of the S1 aliasing (period = 322-days) from GRACE—only solutions. Statistics: STD: 5.9 mm, mean: 10.4 mm, min: 0.1 mm, max: 62.3 mm **d** Amplitude (in mm) of equivalent water heights of the P1 aliasing (period = 171-days) from GRACE—only solutions. Statistics: STD: 6.3 mm, mean: 11.7 mm, min: 0.1 mm, max: 48.2 mm

not designed to sample ocean tides so during the GRACE data processing any tidal effects are removed from the analysis by applying an ocean tide model (e.g. Lemoine et al. 2007). Atmospheric tides are removed using the ECMWF atmospheric tidal model which may only be partially correct for the S_2 tide (Ray and Ponte 2003), but the maximum amplitude at these frequencies should be around 0.5–1.5 mm (Tregoning and vanDam 2005). As has been shown previously, however, ocean tide models are not yet sufficient accurate to avoid aliasing into GRACE time-series (Ray et al. 2003).

In this study, we analyze the aliased signal of erroneous S_2 tidal effects as seen in GRACE gravity fields and demonstrate that both GPS and GRACE estimates are affected similarly by shortcomings of the ocean tide model FES2004. We focus on the region of NW Australia, a coastal area that experiences large ocean tides (and hence large OTL effects). It is the region, where the highest aliased S_2 signal is detected in the release 04 GRACE 10-day gravity fields of the Groupe de Recherche de Géodésie Spatiale (GRGS) (Fig. 1a). Assuming that these errors are due to the mismodeling of S_2 ocean tides in NW Australia, they should affect the GPS solutions directly through not modeling properly the sub-daily movement of the stations.

The purpose of this study is to discover whether mismodeling of the tidal loading using the FES2004 model is affecting both space-geodetic techniques. We test this by analyzing the time-series of residual vertical loading displacements computed from GPS and GRACE equivalent water height (EWH) grids. We describe how the aliased S_2 EWH grids from GRACE solutions are obtained, including the evaluation of the uncertainty of the GRACE EWH and the admittance with which the unmodeled S_2signals alias to other frequencies in the GRACE solutions.

2 Analysis of the aliased S_2 GRACE data

In both the GRACE and GPS analyses, the effects of ocean tides are modeled using the FES2004 (Lyard et al. 2006) model, while atmospheric pressure variations are modeled using the ECMWF (http://www.ecmwf.int) models. In the GRACE analysis, it is the mass attraction effect that is

Table 1 GRACE tidal alias periods (days) (Ray and Luthcke 2006)

Tide	Alias period (days)
S1	322.1
S2	161.0
P1	171.2

important while for the GPS analysis it is the elastic deformation that results from the changes in surface loads. Pole tide effects in both analyses are modeled according to the IERS 2003 conventions (McCarthy and Petit 2003).

We used the series of time-variable Earth gravity field models published by the GRGS (e.g. Lemoine et al. 2007). These models are given in spherical harmonics, complete to degree and order 50, every 10 days. Each model is based on 30 days of GRACE data, with the first and last 10 days weighted by 0.25 and the middle 10 days weighted by 0.50. These models do not necessitate any Gaussian filtering prior to their use (e.g. Lemoine et al. 2007; Swenson and Wahr 2006; Davis et al. 2004), since the coefficients have been computed with a constraint towards a mean gravity field that optimally reduces the short-wavelength striping of the solutions. As the zonal harmonic coefficients of the second degree are especially sensitive to S_2 tide aliasing error, the latest are entirely determined from a GRACE-only solution and no satellite laser ranging (SLR) observations are added.

We have analyzed this time series over the available time span (mid-2002 to mid-2007) and performed a least squares estimation (Eq. 1) on each of the spherical harmonic coefficients of this series, solving for a bias, a drift, an annual and semi-annual term, plus three additional tidal waves, S_2, P_1 and S_1, whose aliased periods are observed by GRACE according to Eq. (1). The aliased periods for these oceanic constituents are given in Table 1 (from Ray and Luthcke 2006).

The regression equation takes the following form:

$$(C,S)_{lm}(t) = (C,S)_{lm}(t_0) + \left(\dot{C},\dot{S}\right)_{lm}(t-t_0) + (C,S)^i_{lm}\cos\left(\frac{2\pi}{T_i}(t-t_0)\right) + (C,S)^i_{lm}\sin\left(\frac{2\pi}{T_i}(t-t_0)\right) + \varepsilon^{res} \quad (1)$$

where $(C,S)_{lm}(t)$ are the harmonic coefficients at each epoch t, $\dot{C}$, $\dot{S}$ are their drifts with respect to epoch t_0 2004.0, $(C,S)^i_{lm}$ and $(C,S)^i_{lm}$ are the coefficients for the ith terms of annual, semi-annual, S_2, P_1 and S_1 signals, T_i is the period corresponding to each of these terms (see Table 1) and ε^{res} is the residual Gaussian noise.

The alias periods of Table 1 are considered for a particular orbit configuration; however, the altitude of the GRACE satellites is decreasing. Furthermore, it is possible that they may be affected by real geophysical signal occurring at seasonal periods in some unknown way. Seo et al. (2008) have implied that the orbit decay of the GRACE satellites provokes nonstationary alias error behavior. The phase sampling of any tide is controlled by the ascending node rate of GRACE's orbit plane relative to the tide-raising body and the Sun. We calculated the variation of GRACE's ascending node using the even zonals of J_2–J_{10}. The secular rate of GRACE's ascending node with respect to the sun in mid 2002 was found to be $-1.118°$/day which translates into a period of 321.9 days. In mid 2007, the same rate is $-1.114°$/day or a period of 323.017 days. Thus, there is a variation of the period of the secular change of the ascending node of 1 day in 5 years. The aliased S_2 in GRACE is half this period, that is 0.5 days in 5 years. For this study, we assume that this variation in period is negligible. The periodic terms, expressed in Eq. (1) are converted into amplitude and phase with respect to the reference date 1 January 2004. Nodal modulation is ignored, although it is zero for solar—only terms.

Then geoid heights are computed by introducing the cosinus and sinus terms for each estimated spherical harmonic coefficient according to Bruns theorem:

$$\Delta h_l^{\text{geoid}}(\cos,\sin) = \frac{T_P^{\cos,\sin}}{\gamma_Q} \quad (2)$$

where $\Delta h_l^{\text{geoid}}(\cos,\sin)$ is the equivalent geoid height corresponding to each aliasing period T_i and each prograde and retrograde coefficient C, S, γ_Q is the normal gravity at each point Q on the ellipsoid computed by

$$\gamma_Q = \gamma_0\left(1 - \frac{2}{\alpha}\left(1 + f + m - 2f\sin^2\varphi\right)h + \frac{3}{\alpha^2}h^2\right)$$

and

$$T_P^{\cos,\sin} = \frac{GM}{r}\left[\sum_{l=2}^{\infty}\left(\frac{\alpha}{r}\right)^n \sum_{m=0}^{n}\left(\bar{C}_{lm}^{\cos,\sin}\cos m\lambda + \bar{S}_{lm}^{\cos,\sin}\sin m\lambda\right)\bar{P}_{lm}(\cos\vartheta)\right]$$

is the perturbation potential at point P on the geoid, ϑ being the polar angle.

The geoid heights of corresponding to each cosinus and sinus harmonic coefficients of every aliasing constituent can then be converted into EWH anomalies using the following equation (e.g. Lemoine et al. 2007):

$$h^w_{\cos,\sin} = \frac{g}{4\pi G R \rho_w}\sum_{l=2}^{50}\frac{2l+1}{1+k'_l}\Delta h_l^{\text{geoid}}(\cos,\sin) \quad (3)$$

The total EWH amplitude of each aliasing constituent will be the square root of the summation of the two cosinus and sinus terms.

$$h^w_{\text{tot}} = \sqrt{\left[\Delta h_l^{\text{geoid}}(\cos)\right]^2 + \left[\Delta h_l^{\text{geoid}}(\sin)\right]^2} \quad (4)$$

where g is the mean surface gravity (9.8 m/s^2), G is the gravitational constant (6.72×10^{-11} m^3/kg s^2), R is the

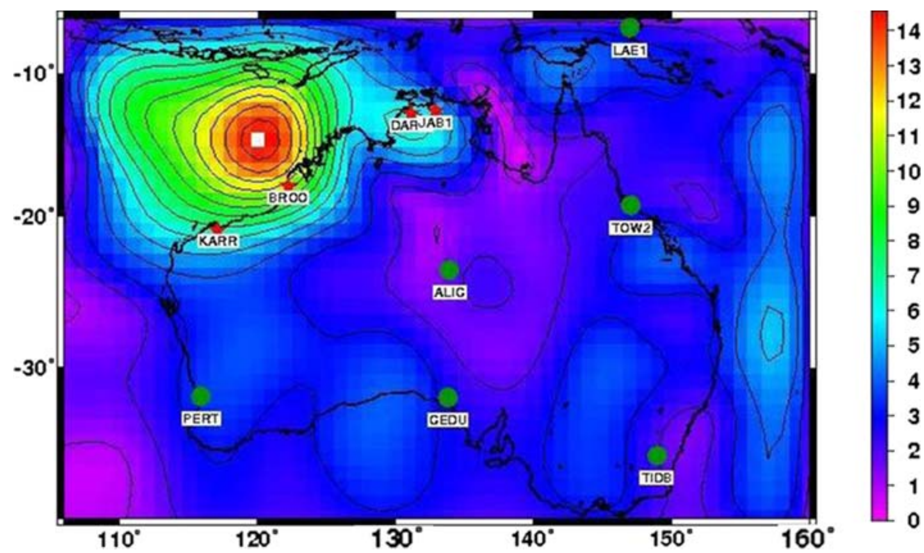

Fig. 2 Amplitudes of the S_2 GRACE aliased tidal loading grids of radial displacements in NW Australia. Resolution is $1° \times 1°$ and units in mm. The *green circles* represent the reference IGS sites while the *red stars* the stations for which position time-series are estimated

Earth radius (6378136.46 m), ρ_w is the density of water ($1,000\,\mathrm{kg/m^3}$), l is the degree, and k' are the load deformation coefficients of degree l.

The P_1 and S_1 amplitude of residual errors in the FES2004 model, as seen by GRACE, do not exceed 6 cm EWH as seen in Fig. 1c and d and are generally $\lesssim$30 mm. Characteristic is the non-tidal aliasing of the S_1 signal which its period coincides with the annual hydrological cycle over the South America. The error of the S_2 tidal signal is much larger and geographically meaningful with distinct maxima in different coastal regions around the world (Fig 1a): Ungara Bay and Foxe Channel in the Hudson Bay area; Bellingshausen Sea in Antarctica and a number of areas in Asia: the Andaman Sea, the East China Sea, Mindoro strait and the West Timor Sea. The latter is by far the strongest with a maximum of ~120 mm EWH (Fig 1a) and is the area we focus on in this paper.

The aliased S_2 EWH spans thousands of km (Fig. 1a). To assess the amount of predicted GRACE aliased tidal loading (GATL) displacements we convolved the effective load of the aliased S_2 signal with elastic Green's functions (Farrell 1972) and determined the response of the Earth on a $1° \times 1°$ grid in the NW Australian region (Fig. 2). This load translates into vertical elastic deformation of up to 11 mm along the Australian coastline. The GPS site at Broome (BROO) has the highest amplitude of around 10 mm, while sites at Karratha (KARR), Darwin (DARW) and Jabiru (JAB1) have amplitudes around ~ 7, ~ 4 and ~ 3 mm, respectively.

2.1 Omission errors

The GRGS GRACE products are complete to degree and order 50. Our gravity solutions include the FES2004 tide model in terms of orbit perturbations, complete up to degree and order 80. Therefore, there are no omission errors at higher spatial resolution affecting the GATL displacements. Nevertheless, the GRGS GRACE variable products are sensitive to wavelengths up to degree 30. In a global sense, the square root of the undulation error variances provide the cumulative RMS undulation error up to degree n. This is the commission error of the geopotential model. The fact that the GRACE 10-day variable gravity models do not extend to infinity (whereas the real gravitational spectrum of the Earth does), implies a truncation (or omission) error. This is estimated using Kaula's rule for the degree variances of the disturbing potential (Pavlis 1997). Because the errors in monthly geoid estimates rise rapidly with degree, the 10 day gravity solutions can actually only be computed accurately to about degree 30. The coefficients of degrees 31 through 50 were constrained gradually to those of the static solution of EIGEN-GL04S (e.g. Lemoine et al. 2007). As such, possible omission errors to degree 50 and beyond cannot actually be evaluated.

2.2 Propagation of unmodeled periodic S_2 tidal error into GRACE time series

In order to examine the propagation of the unmodeled S_2 tides into the GRACE gravity field time series, hence calculate the admittances of the signal (ratio of amplitude of spurious long-wavelength output signal in the GRACE time-series to amplitude of unmodeled periodic signals) observed at the aliasing period of 161 days, we have performed a simulation study. In this study, we have set to zero some of the S_2 coefficients for which we had computed the partial derivatives and which are therefore present in our normal equations of processed GRACE data. Namely, we have set to zero the prograde C coefficients from the spherical harmonic expansion of the S_2 tide (i.e. all C^+ coefficients from degree 2 to 10, plus degree 11 to 30 for order 2). An image of the amplitude

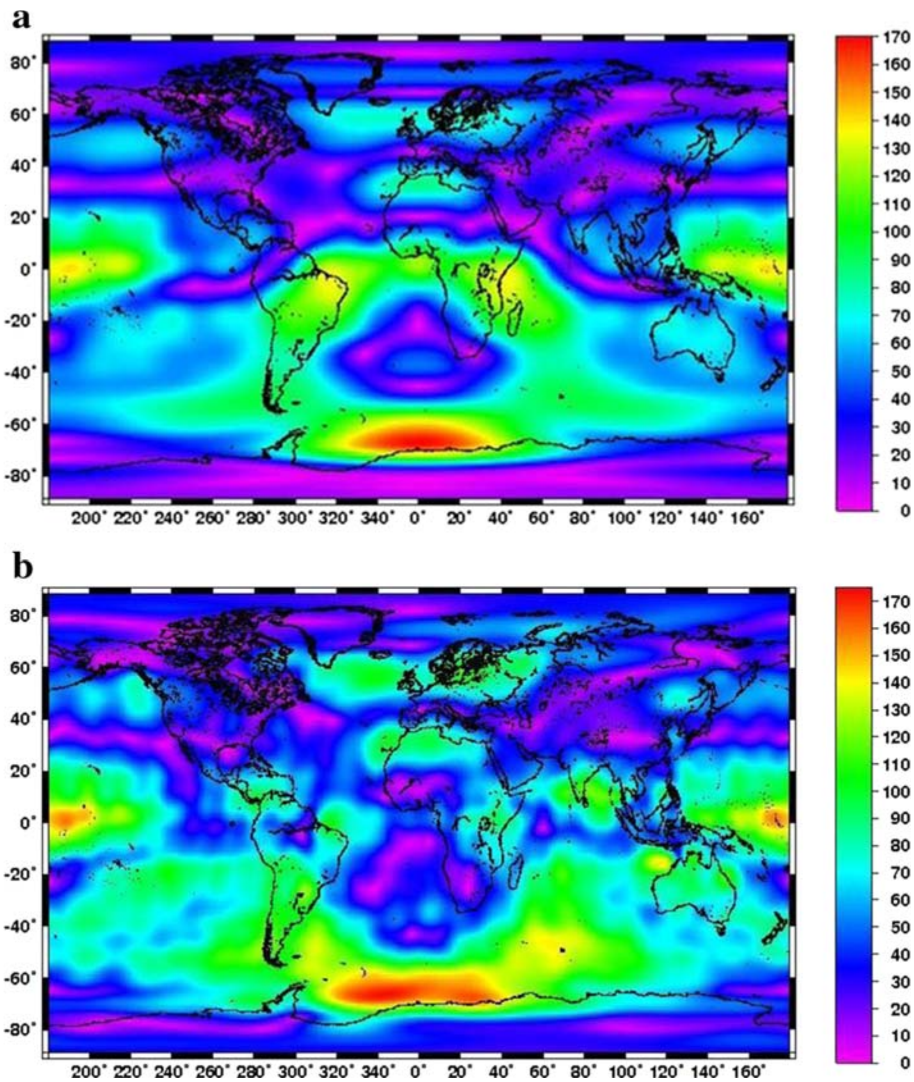

Fig. 3 **a** Amplitudes (in mm) of equivalent water height of the S_2 error introduced in the GRACE processing for degrees 2–30. The error ranges from a minimum of 0.2 mm to a maximum of 169.5 mm. **b** Simulated amplitudes (in mm) of equivalent water height of the S_2 aliasing when S_2 coefficients are perturbed for degree 2–30. Values range from 0.3 to 173.5 mm

of the S_2 error that we have introduced in such a way can be seen in Fig. 3a.

We then solved for the complete series of GRACE gravity solution in the usual way (see Lemoine et al. 2007), keeping the selected S_2 coefficients set to zero. By performing again a regression on each individual spherical harmonic coefficient of this new series, we obtained an image of the S_2 aliasing that includes the S_2 perturbation that we have intentionally introduced (Fig. 3b). Since, the S_2 perturbation introduced has a much greater amplitude than the non-perturbed S_2 aliasing, we can evaluate the response of the S_2 aliasing to a known perturbation, while forming the quadratic difference between the perturbed and non-perturbed S_2 aliasing. We have excluded from the comparison the points, where the amplitude of the perturbation is below 3 cm EWH since it leads to unrealistic admittance estimates because of the remaining noise in the GRACE solutions. By dividing this result by the amplitude of the perturbation we obtained an image of the admittance of the system (Fig. 4). The global average admittance is 1.06 ± 0.32 but it does vary spatially. It does not appear to have a particular latitude-dependency.

2.3 The $C_{2,0}$ effect on S_2 aliasing estimates

The sun and moon create a permanent tide effect that can be determined for a rigid Earth. This influence can have an important impact on the estimation of the second and third degree zonal harmonics. As such LAGEOS-1 and -2 orbits were computed over the same time period as the GRACE data in order to stabilize the gravity field solutions. The partial derivatives were calculated to degree and order 30. Finally, the normal equations from GRACE and LAGEOS were combined. In general, the $C_{2,0}$coefficients are dominated by 90 % by the LAGEOS solutions. Nonetheless, we need to verify whether the GRACE $C_{2,0}$including the S_2 aliasing has a significant effect on the computed EWH grids used to generate the GATL displacements. In order to do this we compared

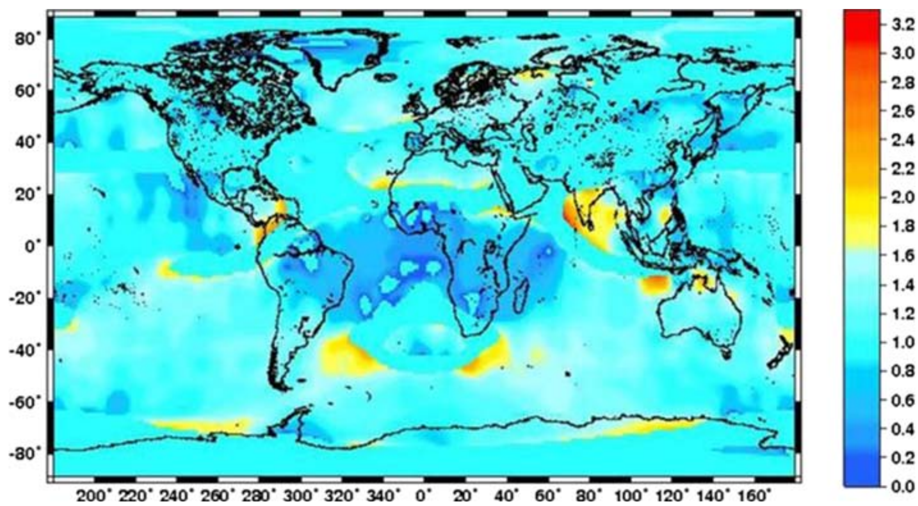

Fig. 4 Admittance of S_2 tide: ratio between introduced S_2 perturbation and retrieved 161-day signal, degree 02–30. Statistics : STD: 0.32 mm, mean: 1.06 mm, min: 0.0167 mm, max: 3.2716 mm

a combined GRACE-SLR solution with our GRACE-only solution of S_2 aliasing signal estimation (see Fig. 1a and b, respectively). The level of disagreement between the maximum values of the S_2 EWH amplitudes is about 1.5 cm, which corresponds geographically to the region of our study. This equates to about 1.3 mm in computed GATL which we regard as potential systematic error in our comparison below.

2.4 Uncertainty estimates in the GRACE EWH grids

In order to estimate the uncertainty level in the estimation of the S_2 EWH aliasing grids and hence the effect on the computed GATL, we proceeded by choosing two different geographic zones and isolated them from the S_2 EWH grids. These zones are the "Pacific zone", extending in latitude from $-30°$ to $+30°$ and in longitude from $-180°$ to $-120°$, and the "Atlantic zone", extending from $-60°$ to $+60°$ in latitude and $-30°$ to $+60°$ in longitude (see Fig. 1a). The important criteria for choosing these zones is that they neither should be contaminated by hydrologic signals (semi-annual signals are very weak over Africa) nor by any S_2 tidal errors. The overall noise (RMS of observed amplitudes) is evaluated to be of the order of 10.7 mm which equates to about 0.9 mm effect on the GATL estimates which we regard as our random error in our comparison below.

3 GPS height estimates and data set

We analyzed GPS dual-frequency phase data using the GINS software (e.g. Lemoine et al. 2007). The analysis package was recently updated and is now demonstrably capable of estimating hourly site coordinates with sufficient accuracy to undertake studies of OTL, for example in the NW region of Brittany, France (e.g. Melachroinos et al. 2008). In addition to the 4 GPS sites of interest (JAB1, DARW, BROO, and KARR), we included 9 IGS reference stations (NTUS, COCO, ALIC, TOW2, CEDU, PERT, TIDB, HOB2, MAC1) to generate a regional network (Fig. 1a). Observations from 2002.5 to end of 2004 (545 days) were used (see Table 2).

Table 2 The GPS data set of the regional IGS network

GPS data	Data span (days)	Data span(%)
ALIC	535	98
CEDU	545	100
BROO	496	91
JAB1	466	85
NTUS	489	90
DARW	532	98
HOB2	543	100
MAC1	534	98
TIDB	544	100
TOW2	545	100
KARR	545	100
COCO	545	100
LAE1	510	94
PERT	494	91

We formed double-difference (DD) baselines of the ionosphere—free combination based on a common station-pass criterion of the GPS satellites and eliminate satellite and receiver clocks. We used the IERS 2003 conventions for solid Earth tides, pole tides and the IERS Earth orientation parameters (EOPs). IGS orbits were held fixed and relative phase centre variations were used for ground-based antennae and satellite transmitters. We apply atmospheric pressure loading from 6-h (ECMWF) atmospheric pressure data (including the S_1 and S_2 tide) and OTL corrections using the FES2004 model. Thus, the surface loading effects are consistent with the FES2004 background model used in the GRACE data processing. We estimated hourly tropospheric zenith delay

(TZD) parameters using a priori values from the ECMWF model and a Marini-type hydrostatic and wet mapping function (Guo and Langley (2003)). A sampling interval of 30 s was applied and ambiguities—together with TZDs—were first resolved in daily solutions. The mean success rate of ambiguity fixing was typically about 90 %.

Then hourly solutions for each of the three GPS stations of interest (JAB1, DARW, BROO, KARR) were extracted in a subsequent step by adding additional parameters to the normal equations. We refer readers to Melachroinos et al. (2008) for more details on the estimation strategy. During this last step we applied 1 mm constraints to the a priori 3D coordinates of the 9 IGS reference sites in the geodetic frame (as transformed from the IGB00 reference frame) and, together with the fixed orbits, this defines the terrestrial reference frame.

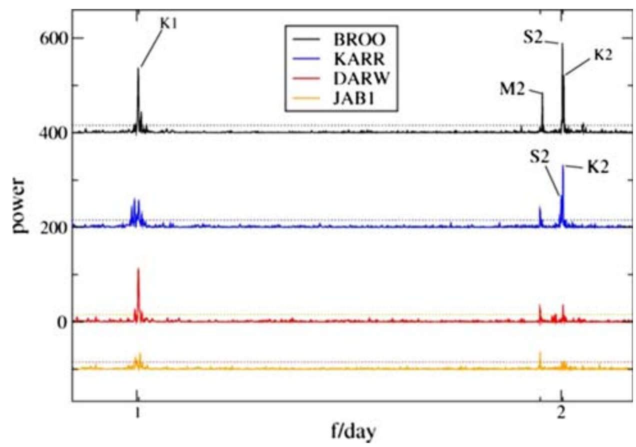

Fig. 5 The power amplitude spectra of radial displacements in the four GPS stations BROO, KARR, DARW and JAB1. 1% significance levels are denoted by the corresponding *dash-dotted lines* for each site

3.1 The OTL and GATL reference frame

GRACE S_2 EWH fields are convolved to compute GATL. These are produced in a global frame of sorts. The GPS solutions are computed using FES2004, and the S_2 residuals estimated from the time series. These are computed in a regional frame as defined by 1 mm constraints at some IGS sites.

In our case we have pinned down the GPS hourly estimates in a reference frame that may well be biased or tilted by OTL errors in FES2004 that might contain both different and common modes at each site. The common mode part would cancel out, leaving only the differenced errors. But there might well be GATL signals at each of the IGS sites that we pinned to 1 mm which again could contain both common-mode and different errors. In the GATL case, we don't pin the values down at the IGS sites, so we don't eliminate the common mode component of the GATL if there is one. This means that it might still remain in the estimates at Broome and the other GPS sites. This may cause an inconsistency, because we remove the common-mode OTL as averaged over the IGS sites from our GPS sites but we don't do the same for the GATL.

To ensure compatibility when comparing GRACE and GPS estimates, we therefore determined whether there are also any common-mode GATL signals at the constrained IGS sites. We examined the GATL at the IGS sites used to define the terrestrial reference frame and found that the common-mode signals were insignificant (<1 mm). Thus, the two reference frames are consistent.

4 Results and discussion

Firstly, we calculated the effect of whether the GRACE $C_{2,0}$ including the S_2 aliasing has a significant effect on the computed EWH grids, and found a potential systematic error of 3 mm in computed GATL. Secondly, we computed the random errors in GATL by choosing two different geographic zones and isolated them from the S_2 EWH grids. The overall noise has a 0.9 mm random effect on the computed GATL displacements.

Then, we verified the existence of periodic signals and their significance at the 99% level in the unevenly sampled GPS data time-series of each station by using the Press et al. (1992) implementation of the Scargle (1982) Lomb normalized periodogram (spectral power as a function of angular frequency) with an oversampling factor 4 (Fig. 5). Next, we estimated the harmonic content (i.e. the amplitudes of the fundamental and its multiples) of the GPS time-series. The resulting unmodeled vertical S_2 tide loading effects are significant. The power spectra of deformation amplitudes at the four GPS sites are plotted in Fig. 5.

The smallest amplitude observed is at JAB1 with 2.4 $\pm$0.3 and 3.0 mm from GPS and GATL, respectively. At DARW 3.2 $\pm$ 0.3 and 4.2 mm and at KARR 5.2 $\pm$ 0.2 and 6.7 mm from GPS and GRACE. Finally the largest signal is found at BROO station at 7.2 $\pm$ 0.3 and 10.1 mm from GPS and GRACE. In all cases, the amplitudes estimated by GRACE are ~10–30% larger than estimated from the GPS time series. However, taking into account the spatially varying admittance of unmodeled S_2, the amplitudes of GATL should be reduced and the agreement with the GPS-derived estimates can be improved. Nonetheless, there could be systematic S_2 errors which will bias our GPS-derived S_2 values in a "site-specific" way. But these are likely small (Thomas et al. 2006). Furthermore, unmodeled non-tidal signals can exhibit in the S_2 period as already discussed in Tregoning and vanDam (2005), Melachroinos et al. (2008), and lately King et al. (2008).

In addition to the S_2 spectral peaks, other harmonics are observed in the diurnal and higher spectral bands in the GPS solutions, with the most significant being the K1 spectral band with amplitude of around $\sim 5.3 \pm 0.3$ mm at BROO. At the same site, amplitudes of 4.2 ± 0.3 mm and 5.0 ± 0.3 mm are found for M_2 and K_2, suggesting that ocean tide errors in the FES2004 model in this area may not be limited to only S_2. With aliasing periods from GRACE data sampling rate of 10 days, the M_2 ($\sim$13.5 days) and K_2($\sim$1362.4 days) (Seo et al. 2008; Ray and Luthcke 2006) signals are more difficult to verify from existing GRACE data. Our time sampling of 10-days is very close to the period of 13.5 days for M2. Moreover, harmonics exhibiting signal at multiples of the K_1 frequency are probably attributed to multipath effects (e.g. Melachroinos et al. 2008; King et al. 2008; Georgiadou and Kleusberg 1988).

The deformations inferred from GRACE gravity data have no degree-1 contribution. As such GRACE data are insensitive to geocenter motions. On the other hand, the GPS vertical deformations will be sensitive to geocenter translations since the IGS orbits are held fixed. Because we used a DD approach, any geocentre motion transmitted through the orbits to the GPS height time-series will be small and we can consider the GPS and GRACE estimates of unmodeled S_2 signals to be compatible.

5 Conclusions

We showed from a simulation study that the admittance of S_2 signals aliased to 161-day period in monthly GRACE fields varies spatially, although the globally averaged value is approximately 1. We also evaluated the impact of the choice for the $C_{2,0}$ coefficients upon the S_2 aliasing product, depending on whether this coefficient is determined from combined GRACE and SLR solutions or from GRACE-only solutions. The differences have an impact of 15 mm of EWH in the area of our study, thus inducing around $\sim$1 mm uncertainty in the GATL displacements.

Vertical time-series from four coastal GPS stations in NW Australia show a geographic distribution of S_2 displacements that correspond to the distribution of the GATL displacements computed from the S_2 aliasing EWH grids. The amplitudes of the GRACE estimates of S_2 variations are found to be slightly larger than the GPS estimates by a factor of 1.1–1.3. This should reduce substantially if we account for the spatial variability of admittance factors in the aliasing of S_2 in the GRACE GATL. We conclude that the S_2 tides are not well represented in the FES2004 ocean tide model in the NW Australia region.

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