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Assessing the accuracy of predicted ocean tide loading displacement values

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Abstract The accuracy of ocean tide loading (OTL) displacement values has long been assumed to be dominated by errors in the ocean tide models used, with errors due to the convolution scheme used considered very small (2–5%). However, this paper shows that much larger convolution errors can arise at sites within approximately 150 km of the coastline, depending on the method used to refine the discrete regularly spaced grid cells of the ocean tide model to better fit the coastline closest to the site of interest. If the local water mass redistribution approach is implemented, as used in the OLFG/OLMPP software recommended in the IERS 2003 conventions, OTL height displacement errors of up to around 20% can arise, depending on the ocean tide model used. Bilinear interpolation only, as used in the SPOTL and CARGA softwares for example, is shown from extensive global and regional comparisons of OTL displacement values derived from the different methods and softwares to be more appropriate. This is verified using GPS observations. The coastal refinement approach used in the OLFG/OLMPP software was therefore changed in August 2007 to use bilinear interpolation only. It is shown that with this change, OTL displacement values computed using OLFG/OLMPP, SPOTL and CARGA invariably agree to the millimetre level for coastal sites, and better than 0.2 mm for sites more than about 150 km inland.

Keywords Ocean tide loading (OTL) · Displacement · Ocean tide models

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1 Introduction

The periodic distribution of water due to the ocean tides loads the Earth, such that in some areas such as South-West England the surface moves through a (predominantly) vertical range of over 100 mm in around 6 h. The measurement of this ocean tide loading (OTL) displacement with GPS and VLBI has seen much progress in recent years, with studies by Allinson et al. (2004), King et al. (2005), Thomas et al. (2007) and Petrov and Ma (2003) demonstrating an attainable measurement quality of around 1 mm at discrete sites where many years of GPS/VLBI data are available. Ideally the OTL displacement should also be predicted (modelled) to this accuracy or better, in order to remove the phenomenon adequately from geodetic measurements so as not to bias the resulting coordinate and baseline time series.

Ocean tide loading displacements can be modelled by convolving a global ocean tide model with a Green's function that depends on the elasticity of the Earth. Errors in the different available ocean tide models have long been considered to dominate the errors in the OTL values (Scherneck 1993; Bos and Baker 2005). The numerical errors in the convolution scheme have been studied by Agnew (1997) by comparing the output of different OTL programs with the same input. He found that the differences (at an unspecified number and distribution of sites) were usually less than 5%

and often less than 2%. Bos and Baker (2005) undertook a similar investigation with newer loading programs that included SPOTL v3.1 (Agnew 1997), GOTIC2 (Matsumoto et al. 2001), OLFG/OLMPP (Scherneck 1991) and CONMODB (the program used at the Proudman Oceanographic Laboratory), and selected from each program the best methods to construct a new program called CARGA. On considering ten globally distributed superconducting gravimeter sites all at least, but invariably much more than 50 km inland, they demonstrated a 2–5% (better than 1% for inland European sites) numerical error for the OTL convolution procedure. Although the accuracy of the ocean tide models has improved dramatically during the 1990s (Shum et al. 1997), they are still considered to cause most of the uncertainty in OTL values.

Modern global ocean tide models are provided on evenly distributed grids ($0.125°, 0.25°$ or $0.5°$ spacing typically) and therefore the grid cells do not fit the coastline perfectly. This results in a misrepresentation of the tidal water mass that is causing the OTL. To improve the accuracy of the OTL computation it is therefore necessary to refine the ocean tide model grid locally, i.e. by interpolating the model to a finer grid. The tidal values in the refined grid are mostly determined with bilinear interpolation. Scherneck (1991) describes a further requirement whereby local water mass redistribution (MRD) is undertaken in order that the water mass within the area of refinement remains constant. This MRD approach was used in the "OTL web provider" (http://www.oso.chalmers.se/~loading/) from its inception in 2001 until August 2007, when it switched to using bilinear interpolation only, as a result of the findings described in this paper. The methods used in the OTL web provider are important since it facilitated the wide and easy access to modelling OTL displacement by the space geodetic community, and is the approach recommended in the IERS 2003 conventions (McCarthy and Petit 2004). Therefore many GPS, DORIS, SLR and VLBI-based research projects have used such values, including both global (Urschl et al. 2005; Thomas et al. 2007) and local (Melachroinos et al. 2007) comparisons of predicted OTL displacement values with GPS observations. What has never been tested, however, is whether MRD should be carried out when using modern global ocean tide models or if bilinear interpolation alone is sufficient, and what the influence of this choice is for both coastal and inland sites when millimetre or better accuracy is desired. This is investigated in this paper. Also detailed are global and regional comparisons of OTL displacements computed from different software packages that use different refinement methods for ocean tide model grid cells that overlap land. The sensitivity of the choice of model refinement method to the particular ocean tide model input is illustrated, and an indication provided of the quality of the different ocean tide models, for both coastal and inland sites.

2 Ocean tide loading computation and softwares

2.1 Ocean tide loading computation

For each tidal frequency (the M2 constituent with period 12.42 h usually dominates) the OTL displacement u at the discrete site at r can be computed with the following convolution integral (Longman 1962, 1963):

$$u(r) = \int_{\Omega} \rho G(|r - r'|) Z(r') \mathrm{d}\Omega. \tag{1}$$

In Eq. (1), ρ represents the density of sea water and Z is the tide at r', whilst G is a Green's function that depends only on the distance between r and r'. The integral is taken globally over all water areas Ω, thus requiring the use of a global ocean tide model.

A focus of this paper is the influence of the near ocean tides on the computed OTL values. To illustrate the effect of the tides near the site of interest, consider an example in which the coastline is straight, the site is exactly on this coastline and that only the loading due to the tides within a radius of r around the site (which thus forms a half circle) is taken into account. Using the equation for a point load on an homogeneous half-space (Farrell 1972), the amplitude of the OTL height displacement u at the site is given by:

$$u = \frac{3\rho}{4\rho_E a} h_\infty Z r \quad \approx -1.1 \times 10^{-7} Z r \quad (\mathrm{m}) \quad \text{for } r < 10\,\mathrm{km} \tag{2}$$

where ρ_E is the mean density of the solid Earth, a is the mean radius of the Earth (assumed spherical), Z is the amplitude of the ocean tide and h_∞ is the Love number for a homogeneous half-space (Farrell 1972). The units of Z and r are m. Similarly, the horizontal displacement v, perpendicular to the straight coastline, due to a half circle, is given by:

$$v = \frac{3\rho}{2\pi\rho_E a} l_\infty Z r \approx 0.24 \times 10^{-7} Z r \quad (\mathrm{m}) \quad \text{for } r < 10\,\mathrm{km} \tag{3}$$

where $l_\infty = 1.673$. Thus the height displacement is about 4.7 times larger than the horizontal displacement.

Equation 2 illustrates that the contribution of a 1 m tide to the OTL height displacement within a 10 km radius of the site is around 1 mm, showing that the near tides can have a significant contribution to the loading value. For a larger radius of 100 km one should take roughly half the value of h_∞, to take into account the fact that the Earth is not homogeneous but consists of different elastic layers, which results in a 5 mm displacement for a 1 m tide. Consequently, within this radius the amplitude of the tides must be known to better than 20 cm to reach a 1 mm accuracy threshold. These examples demonstrate that both near and far tides must be considered when computing OTL values, with the near tides being the most important.

2.2 OTL softwares

The different OTL software packages all compute Eq. (1). Since near tides have the biggest contribution to the loading at a site yet the global ocean tide models are only provided as discrete values on regularly spaced grids, an important feature of each package is how the grid is refined and interpolated to a finer resolution in the cells nearest the site considered, to better fit the coastline. A finer grid near the site of interest also helps assure that the approximation of the continuous loading by point masses best represents reality. The effect of coastal grid refinement on OTL values decreases for more inland sites.

Three different software packages are considered in this paper (OLFG/OLMPP, SPOTL and CARGA), chosen since they are widely used and freely distributed or use different approaches to ocean tide model refinement at the coast. Key features of each package are now précised, particularly regarding their methods of coastal model refinement. Further details on each package are provided in Bos and Baker (2005).

OLFG/OLMPP was selected since it is used by the popular OTL web provider recommended in the IERS 2003 conventions. The area of coastal model refinement comprises a $3° \times 3°$ box around the site considered, and within this box interpolation and extrapolation is performed by considering all tides within a $5° \times 5°$ box surrounding the site. The box boundaries are not defined from exact centreing about the site however, but instead are chosen to fit the nearest grid lines of the ocean tide model. A further (unique) feature is the use of MRD across the $3° \times 3°$ box, i.e. to avoid creating or destroying water within the box, the excess tidal water mass is redistributed equally over all water surfaces. Thus, if the water area is larger after refinement of the grid, then the tidal amplitude will locally be reduced and vice versa. Outside the $3° \times 3°$ box the model is not refined, meaning that for sites far enough (more than ~150 km) inland, no attempt is made to compensate for model cells imperfectly fitting the coastline. The value for the density of sea water used is 1,030 kg/m^3.

SPOTL is a freely distributed package that uses concentric rings around the site considered to represent the integration mesh. The width of the rings and number of subdivisions is dependent on the distance from the site, but within a 10° radius bilinear interpolation is used to refine the mesh to better fit the coastline, whilst outside the tide value for a given location simply takes the value of the model grid cell that covers that location. This means that for sites far enough inland (defined as a 10° radius, i.e. approximately 1,000 km), no model coastal refinement takes place. The value for the density of sea water used is 1,025 kg/m^3.

CARGA uses bilinear interpolation to refine the model for every cell across the globe that imperfectly fits the coastline, rather than only refining the model locally. Bilinear interpolation is also used to compute the tide in the open ocean, rather than the SPOTL approach of using the value of the nearest grid cell. The OTL displacement value output from CARGA is a mean of 18 runs, in which three mesh layouts, two different coastlines and three coastal interpolation techniques are varied. The value for the density of sea water is kept fixed to 1,030 kg/m^3. Global tidal water mass is conserved (to ensure that no water mass is created or destroyed during the tidal cycle) by removing a small uniform layer, whose thickness is different for each ocean tide model and constituent considered (Bos and Baker 2005).

This section has considered OTL displacement. The effects of gravity OTL at (near) coastal sites are more complicated since the direct gravitational attraction of the tidal water mass dominates the OTL value. A very high resolution coastline is necessary together with a very accurate value of the ocean tides in front of the site (Bos et al. 2002). The gravity OTL computation cannot yet be accurately automated for (near) coastal sites and therefore is not considered in this paper.

3 Ocean tide models

The global ocean tide models (“maps”) input to OTL softwares are mostly computed with the use of the Laplace tidal equations which are depth integrated (Hendershott and Munk 1970). For each tidal constituent, a global map of tidal amplitudes and phase-lags relative to the tidal gravitational potential at the Greenwich meridian is obtained. These hydrodynamic solutions do not represent the true tides perfectly and for that reason the solutions are adjusted to fit tidal observations. The Schwiderski (1980) tide model was one of the first successful examples of using tide gauge data to improve the model. The most recent models assimilate tide gauge and (usually TOPEX/POSEIDON) satellite altimetry data to improve the accuracy of their tide model, and a short description of the most used ones is given below. Each of the models described is distributed to the community as a set of amplitude and phase values on discrete, regularly spaced global grids.

NAO.99b (Matsumoto et al. 2000) is based on the same hydrodynamics as the Schwiderski model but includes the assimilation of TOPEX/POSEIDON data. It is provided (and directly computed) on a 0.5° grid and hence the misfit with the coast can be as large as 25 km. The Ross Sea is not modelled.

FES94.1 (Le Provost et al. 1994) is a pure hydrodynamic tide model tuned to fit tide gauges globally. It has been calculated on a finite element grid with very fine resolution near the coast but has been transformed on to a regular 0.5° grid for its distribution. It is no longer used because it has been superseded by FES99 (Lefévre et al. 2002) which includes the assimilation of tide gauge and TOPEX/POSEIDON data. FES99 is transformed to a 0.25° grid for distribution, and although its resolution is better than FES94.1, it has too many grid cells over land. FES99 does not have any tidal information in the Baltic Sea, the Black Sea, the Persian Gulf or the Red Sea. The most recent FES version is FES2004 (Lyard et al. 2006) which has a very good fit to the coastline (although the ice shelf in the Ross Sea is modelled ∼100 km inland of the grounding zone) and is provided on a 0.125° grid.

GOT00.2 (Ray 1999) was developed by adjusting the hydrodynamic model FES94.1 using TOPEX/POSEIDON and ERS 1/2 satellite altimetry observations. It is provided on a 0.5° grid and incorporates local models of the tides in the Gulf of Maine, the Gulf of St Lawrence, the Persian Gulf, the Mediterranean Sea and the Red Sea.

TPXO.6.2 (Egbert and Erofeeva 2002) is a model into which tide gauge (from the Arctic Ocean and around Antarctica) and TOPEX/POSEIDON data have been assimilated using the procedure described by Egbert et al. (1994). It is provided (and directly computed) on a 0.25° grid and does not contain the Black Sea.

A further model is CSR3.0 (Eanes and Bettadpur 1996) which applies long wavelength corrections to FES94.1 via 2.4 years of TOPEX/POSEIDON data, whilst CSR4.0 is an update using a longer data span. It is provided on a 0.5° grid. Outside the ±66° TOPEX/POSEIDON coverage limits, the model defaults to FES94.1.

4 Global comparison of OTL softwares

To investigate the effects of the ocean tide model coastal refinement method used and the sensitivity of both coastal and inland sites to it, all 387 sites (as of August 2007) of the IGS (Dow et al. 2005) network were selected. This provided a global distribution of sites often analysed by the space geodetic community. M2 OTL height, East and North displacements were computed using the OLFG/OLMPP (applying MRD), SPOTL v3.2 and CARGA softwares. For each software, the computed OTL values represent displacements of the Earth's surface relative to the centre of mass of the undeformed solid Earth without atmosphere and oceans (this convention was used throughout this paper). Firstly the FES99 model was input since it is one of two (the other being GOT00.2) recommended in the IERS 2003 conventions for the computation of OTL. Then the more recent FES2004 model was input, that has a very good fit to the coastline and a finer grid resolution of 0.125° than the 0.25° resolution FES99 model. The agreements between the OTL displacements computed per software for each model were assessed by computing, per component per site, the vector difference:

$$d = \sqrt{(A_1 \cos\varphi_1 - A_2 \cos\varphi_2)^2 + (A_1 \sin\varphi_1 - A_2 \sin\varphi_2)^2} \quad (4)$$

where d is the vector difference and A_i, φ_i, respectively, represent, per software, the OTL displacement amplitude and Greenwich phase lag.

For the height component, vector differences were computed between the OLFG/OLMPP (MRD) and CARGA values, and between the SPOTL and CARGA values, which are plotted in Fig. 1. It is immediately apparent that the SPOTL and CARGA values invariably agree at the sub-mm level for both the FES99 and FES2004, models. In fact, as can be seen from Table 1, the agreement between CARGA and SPOTL is better than 0.2 mm at 298 sites when using FES99, and at 318 sites when using FES2004. At only five and six sites is the agreement worse than 1 mm for FES99 and FES2004 respectively. For FES99 the maximum difference is 2.43 mm at VESL (lon. 357.1583, lat. −71.6738) in Antarctica, followed by 1.53 and 1.36 mm at NANO (lon. 235.9135, lat. 49.2948) and ALBH (lon. 236.5126, lat. 48.3898), respectively, which are both on Vancouver Island. For FES2004 the maximum difference of 2.23 mm also occurs at VESL, followed by 1.57 mm at EPRT (lon. 293.0079, lat. 44.9087) on the Bay of Fundy. The difference at VESL is due to a newer coastline in SPOTL (v3.2) than CARGA (which uses the SPOTL v3.1 coastline), whilst around Vancouver Island the large FES99 differences are likely to be caused by a large gap between the model grid and land, resulting in much extrapolation by CARGA.

The differences shown in Fig. 1 between the OLFG/OLMPP (MRD) and CARGA height values are strikingly much greater for the FES99 model than the equivalent SPOTL minus CARGA differences. Table 1 details that 34 of these differences are greater than 1 mm, which all arise at coastal sites. Meanwhile, only 199 (compared with 298 for SPOTL-CARGA) of the differences are less than 0.2 mm. However, when using FES2004, at only four sites are the differences greater than 1 mm, and at 350 sites the differences are less than 0.2 mm. This clearly suggests that the model refinement method employed by OLFG/OLMPP (MRD) is not equivalent to those of SPOTL and CARGA for coastal grid cells when using the FES99 model, although all three methods work equivalently for the FES2004 model. The striking FES99 OLFG/OLMPP (MRD) discrepancies arise since many of the FES99 grid cells overlap the land (due to an inaccurate transformation from the irregular grid in the computed version to the regular global grid in the distributed version), and the MRD approach requires this excess to be redistributed evenly across the 3° × 3° refinement box. This can change the model's tidal amplitude for cells within about

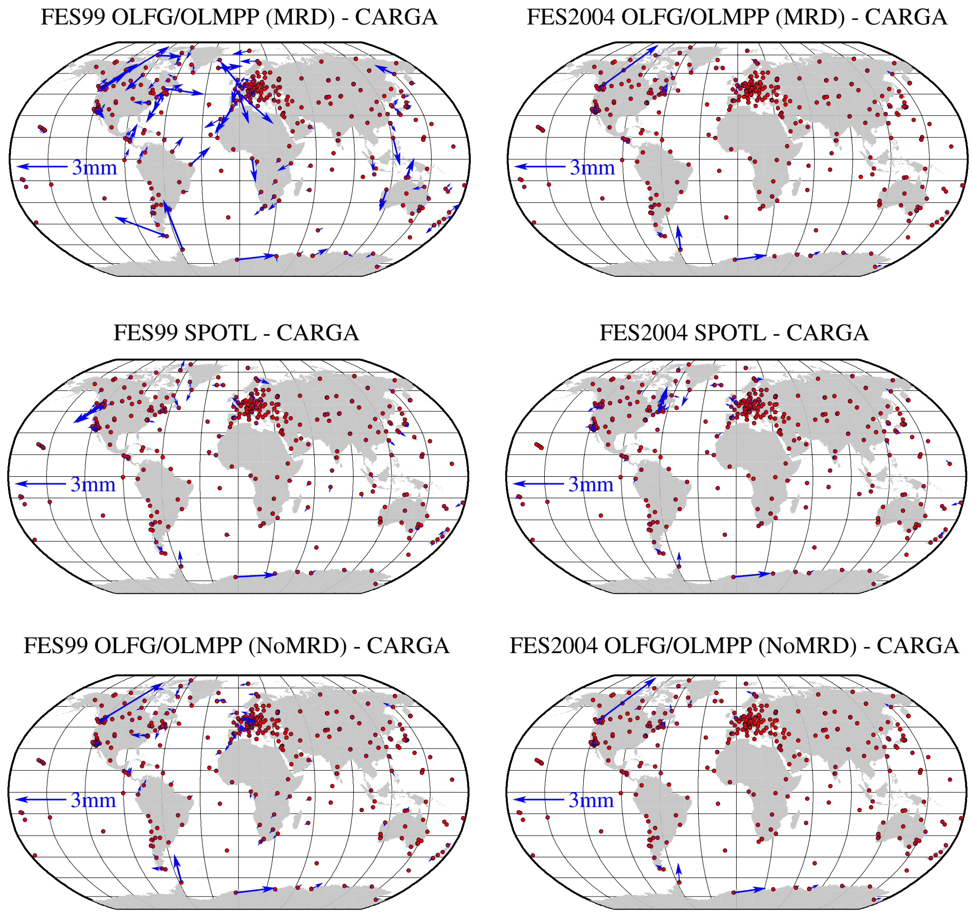

Fig. 1 M2 OTL height displacement vector differences between the OLFG/OLMPP, SPOTL and CARGA softwares for 387 IGS sites when using the FES99 and FES2004 ocean tide models

Table 1 Tally of M2 OTL height displacement vector differences between the different softwares for 387 IGS sites when using the FES99 and FES2004 models

Vector difference magnitude (mm)	FES99			FES2004		
	OLFG/OLMPP (MRD)—CARGA	SPOTL—CARGA	OLFG/OLMPP (No MRD)—CARGA	OLFG/OLMPP (MRD)—CARGA	SPOTL—CARGA	OLFG/OLMPP (No MRD)—CARGA
<0.2	199	298	286	350	318	358
<0.5	305	369	364	378	373	381
>1.0	34	5	5	4	6	3

150 km of the site by up to about 20% and hence the near tide loading effect changes. The FES99 model tendency for the grid cells to overlap the land is not exhibited in FES2004. Thus little excess water mass arises and applying MRD has little effect on the loading values compared with those computed using bilinear interpolation of the model's grid cells alone. In addition, the finer 0.125° grid of FES2004 also diminishes the difference of using the nearest grid cell (SPOTL) instead of bilinear interpolation (CARGA and OLFG/OLMPP) to determine the tidal amplitude in the open ocean.

To confirm that the large discrepancies between OLFG/OLMPP (MRD) and CARGA (and implicitly also SPOTL) height values when inputting the FES99 model arise from employing MRD, the OLFG/OLMPP values were recomputed but without employing MRD when refining the land overlapping model cells in the 3° × 3° box around the site. Thus only bilinear interpolation was carried out. These solutions are referred to as OLFG/OLMPP (NoMRD). The OLFG/OLMPP (NoMRD) minus CARGA differences when using both the FES99 and FES2004 models are also shown in Fig. 1. The discrepancies between the OLFG/OLMPP and CARGA FES99 values are clearly now much smaller and, as detailed in Table 1, 286 sites have differences less than 0.2 mm, and only five sites have differences greater than 1 mm. As with the SPOTL minus CARGA comparisons,

Table 2 Tally of M2 OTL East displacement vector differences between the different softwares for 387 IGS sites when using the FES99 and FES2004 models

Vector difference magnitude (mm)	FES99			FES2004		
	OLFG/OLMPP (MRD)—CARGA	SPOTL—CARGA	OLFG/OLMPP (No MRD)—CARGA	OLFG/OLMPP (MRD)—CARGA	SPOTL—CARGA	OLFG/OLMPP (No MRD)—CARGA
<0.2	366	383	374	383	383	383
<0.5	383	387	385	387	387	387
>1.0	–	–	–	–	–	–

Table 3 Tally of M2 OTL North displacement vector differences between the different softwares for 387 IGS sites when using the FES99 and FES2004 models

Vector difference magnitude (mm)	FES99			FES2004		
	OLFG/OLMPP (MRD)—CARGA	SPOTL—CARGA	OLFG/OLMPP (No MRD)—CARGA	OLFG/OLMPP (MRD)—CARGA	SPOTL—CARGA	OLFG/OLMPP (No MRD)—CARGA
<0.2	355	383	371	383	384	383
<0.5	384	384	385	385	384	385
>1.0	–	–	–	–	–	–

the biggest differences arise at NANO (due to much CARGA extrapolation) and VESL. The VESL differences arise since OLFG/OLMPP uses the GMT (Wessel and Smith 1998) coastline which, in Antarctica, follows the ice shelves instead of the land-sea interface followed by the CARGA (SPOTL v3.1) coastline. For the FES2004 model, the OLFG/OLMPP (NoMRD) values are practically identical to the OLFG/OLMPP (MRD) values, as can be gleaned by comparing the similarity in the CARGA comparison statistics listed in Table 1. In the FES2004 distribution the grid fits the coast much better, without the tendency to always overlap the coast.

The equivalent horizontal displacement vector differences are shown in Tables 2 and 3 for the East and North components, respectively. It is clearly apparent that the four approaches are in much closer agreement (as judged by the absolute values of the vector differences) for the horizontal components than the height, and the effect of MRD is less pronounced. For both the FES99 and FES2004 models, none of the OLFG/OLMPP (MRD) minus CARGA, SPOTL minus CARGA or OLFG/OLMPP (NoMRD) minus CARGA differences exceed 1 mm, all but 3–4 are less than 0.5 mm, and for at least 90% of sites the differences are less than 0.2 mm (invariably substantially so). For the North component, the biggest differences arise for the Antarctic sites OHI2 (lon. 302.0987, lat. −63.3211), RIO2 (lon. 292.2489, −lat. 53.7855) and VESL, which is attributed to the different OLFG/OLMPP and CARGA coastlines. Meanwhile, the largest differences (0.7 mm) between the OLFG/OLMPP (MRD) and CARGA East component values arise for the Southern England sites HERS (lon. 0.3362, lat. 50.8673), HERT (lon. 0.3344, lat. 50.8675) and NPLD (lon. 359.6604, lat. 51.4210) with the FES99 model. This is attributed to firstly, the fact that the East component OTL values are large at these locations (around 6 mm); secondly, the MRD effect causes a difference of 0.2–0.3 mm; and thirdly, the $3° \times 3°$ box is too small to remove all FES99 grid cells overlapping the land in the region which at these locations have large tidal amplitudes. The last effect is around 0.3–0.4 mm. Invariably the effect of MRD on the horizontal displacements is smaller than for the height in a relative sense also. In almost all cases, only tiny changes of <5% arise, usually much less so.

The global discrete IGS site comparisons have shown that OTL displacements are sensitive to the grid cell refinement method adopted to make the ocean tide model better fit the coastline, which in turn is model dependent. The largest differences between the CARGA and the respective OLFG/OLMPP (MRD), OLFG/OLMPP (NoMRD) and SPOTL values all arose at coastal sites. This is to be expected since the near tides have the biggest contribution to the loading at a site, and no model fits the coastline perfectly. However, only a few of the discrete sites of the IGS network are located on complicated coastlines and therefore do not necessarily provide an indication of the biggest discrepancies that can arise, or the spatial scales over which the discrepancies can change. This is considered in the next section, which focuses on the height component, since it exhibits much bigger differences than the horizontal components.

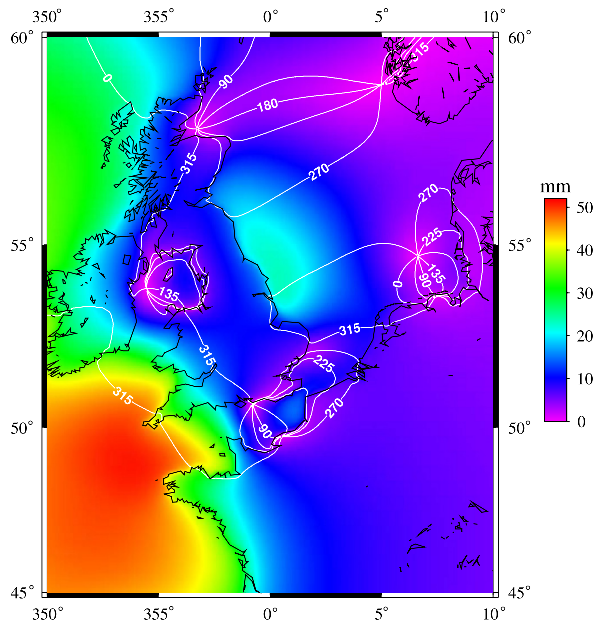

Fig. 2 M2 OTL height displacement amplitudes and Greenwich phase lags for a 0.125° grid across North-West Europe, computed using CARGA with the FES2004 ocean tide model

5 Regional comparison of OTL softwares

To further test the methods of coastal ocean tide model refinement, M2 OTL height displacements were computed per point of a 0.125° grid across North-West Europe, extending from 10°W to 10°E and 45°N to 60°N. The region was selected since it encompasses complicated coastlines (which the model grid cells do not perfectly fit) around Great Britain and Brittany, which are surrounded by shallow seas where the modelling of ocean tides is challenging. The region extends several hundred kilometres inland to substantial portions of Eastern France, Germany and Switzerland, enabling the effect of coastal model refinement methods on inland sites to be determined also. Furthermore, the region encompasses a very wide range of M2 OTL height displacement values, from over 5 cm off South-West England to near zero in Norway. This is illustrated in the M2 OTL height displacement map shown in Fig. 2, computed for the FES2004 model using the CARGA software. As for the IGS site comparisons, vector differences were formed, namely OLFG/OLMPP (MRD) minus CARGA, SPOTL minus CARGA and OLFG/OLMPP (NoMRD) minus CARGA, which are shown in Figs. 3, 4 and 5, respectively. In addition to the FES99 and FES2004 models used for the IGS sites, displacements were also computed for the GOT00.2 and NAO.99b models. These were chosen since they are both distributed on a 0.5° grid, i.e. a coarser spacing than FES99, and GOT00.2 is also recommended in the IERS 2003 conventions.

It is clear from Fig. 3 that the vector differences between the displacements computed by OLFG/OLMPP (MRD) and CARGA are substantial around Great Britain when the FES99, GOT00.2 and NAO.99b models are input. FES99 results in the biggest differences, greater than 5 mm across all of South-West England and across much of Wales, reaching about 8 mm in and around the Bristol Channel. Expressed as a proportion of the displacement amplitude, these differences are approximately 10–20%, much greater than the <5% differences previously reported by Agnew (1997) and Bos and Baker (2005). These differences are even larger than occurred at the global IGS sites, which is attributed to many of the FES99 model grid cells overlapping the complicated Great Britain coastline which causes a large MRD effect. With the exception of East Anglia and parts of Scotland around the Caledonian Canal, the vector differences everywhere in Great Britain are about 1–3 mm, even 100 km and more inland. Similarly, at least 1–3 mm vector differences arise throughout Brittany and parts of Normandy, peaking at about 7 mm. The differences arising using NAO.99b are almost as large as with FES99, reaching 7–8 mm in Northern Brittany (about 20%) although somewhat smaller in South-West England and Wales (2–3 mm), but reach around 4 mm in Western Scotland. The differences are greater than 1 mm throughout all of inland Brittany, Normandy, the Netherlands and Southern England. Whilst the vector differences arising using the GOT00.2 model are not as large as when using FES99 or NAO.99b, they are still greater than 1 mm throughout Brittany, Normandy and Scotland. Maximum differences reach around 4 mm near to Glasgow and on the Normandy coast. There is a pronounced gridded pattern to the differences, which is attributed to the OLFG/OLMPP 3° × 3° refinement box incrementing in steps equal to the grid spacing of the tide model, rather than being exactly centred around the site. Thus since the resolution of the GOT00.2 and NAO.99b models is 0.5° and the displacement differences have been computed at a 0.125° resolution, a gridded pattern results. It is notable that, despite the coarser grid of GOT00.2 compared with FES99, the OLFG/OLMPP (MRD) minus CARGA differences are not as pronounced. This shows that the model's grid resolution itself is not the sole contributor to how much MRD must take place, but more important is how many grid cells, on average, overlap the land. As GOT00.2 and NAO.99b have the same 0.5° grid resolution, the smaller differences arising with GOT00.2 suggest that on average, it has fewer grid cells overlapping the land. As for the IGS sites, the differences obtained when using FES2004 are very small across all of North-West Europe, peaking at only about 1 mm around the Channel Islands. This suggests that FES2004 has, on average, a very good fit to the coastline. With the exception of the FES2004 model, the differences generally only reduce to the sub-0.5 mm level seen for the majority of IGS sites when further than ∼150 km inland.

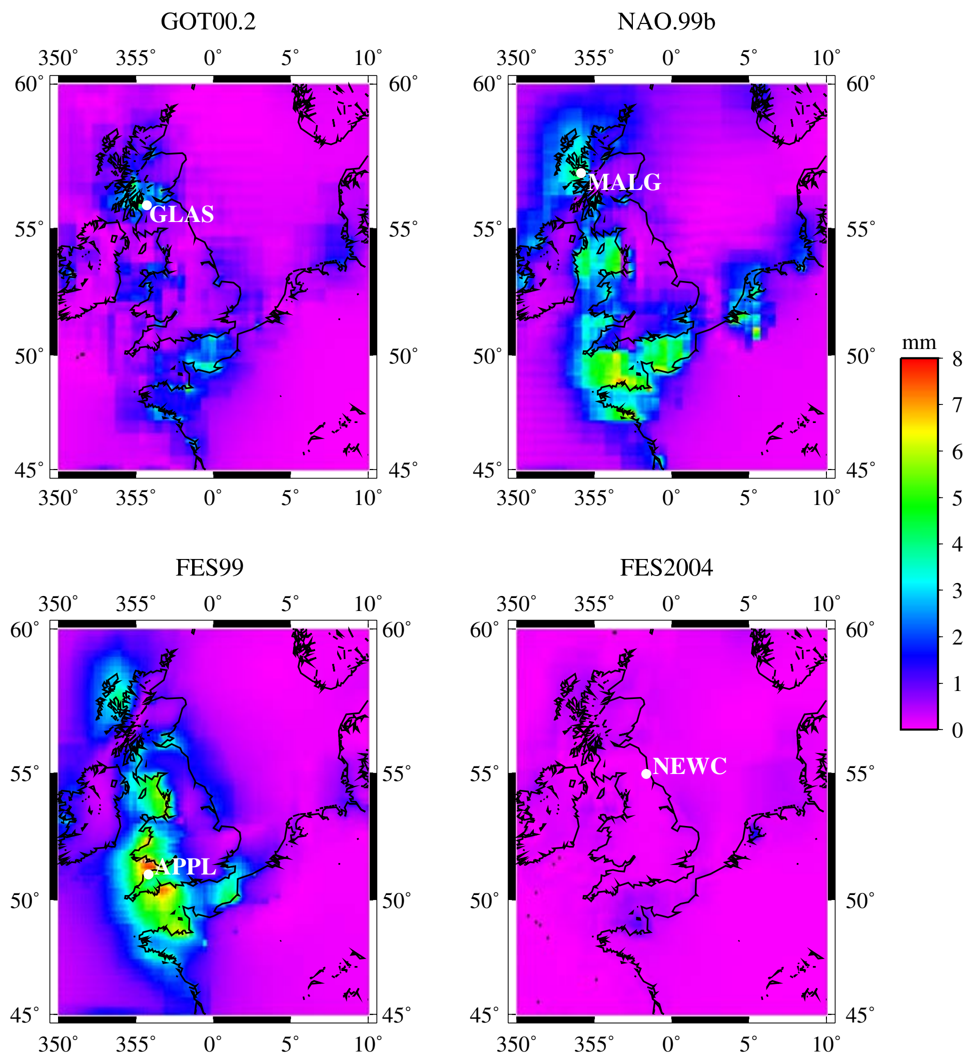

Fig. 3 OLFG/OLMPP (MRD) minus CARGA M2 OTL height displacement vector differences for a 0.125° grid across North-West Europe when using the GOT00.2, FES99, NAO.99b and FES2004 ocean tide models

From Fig. 4, it can be seen that the vector differences between the SPOTL and CARGA estimates are much smaller than the OLFG/OLMPP (MRD) minus CARGA differences, for each of the four models considered. The differences between the SPOTL and CARGA values are invariably less than 0.5 mm for all four models for all but sites right on the coastline, at which the differences are usually no more than about 1 mm. These larger coastline differences are attributed to CARGA taking the average of three extrapolation schemes near the coast, whilst SPOTL uses only one; the differences are smaller over the open ocean since CARGA and SPOTL both use simple bilinear interpolation of the four surrounding tidal values. Besides sites right on the coastline, differences greater than 0.5 mm only arise for the NAO.99b model in a small (few tens of km) section of the Bristol Channel, reaching up to about 6 mm. This is again attributed to having too many grid cells overlapping the land. The CARGA values are slightly larger than those of SPOTL over water because the integral over the water only starts at 0.02° from the site considered in SPOTL, while in CARGA this gap does not exists.

As found above for the IGS sites, it can be seen from inspection of Figs. 3 and 5 that the agreement between the OLFG/OLMPP and CARGA displacements dramatically improves for the NoMRD values than when applying MRD. The differences are approximately sub-millimetre for all four models everywhere except around the Channel Islands for the FES99, GOT00.2 and NAO.99b models, parts of Southern England for FES99, and parts of North-West England for NAO.99b. For FES2004 the differences are less than 0.5 mm everywhere except around the Ijsselmeer. Thus in general, the very close agreements between the OLFG/OLMPP NoMRD and CARGA values (and hence also SPOTL values) suggest that for millimetre level displacement quality, model refinement of local land overlapping cells only is adequate, rather than refining all land-overlapping cells globally as is done in CARGA. This is the case for all the models, whether provided on a 0.5°, 0.25° or 0.125° resolution grid. It should

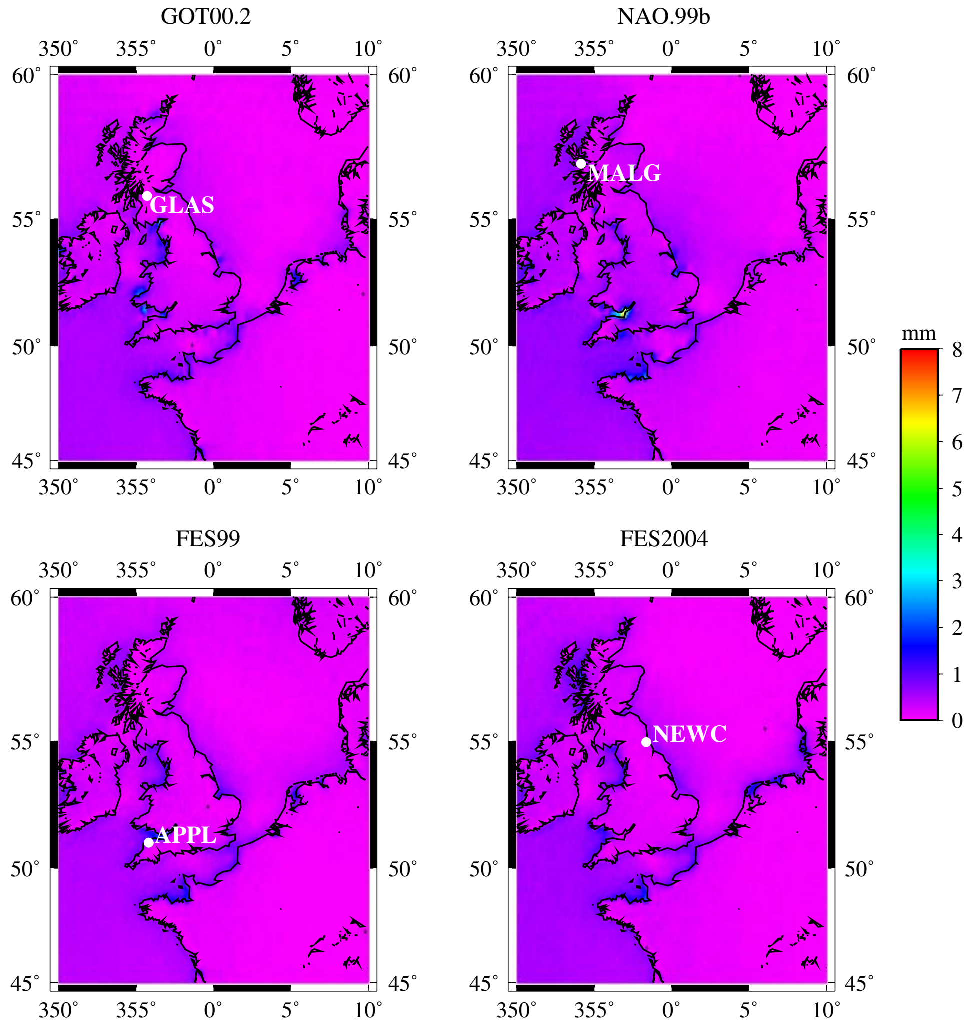

Fig. 4 SPOTL minus CARGA M2 OTL height displacement vector differences for a 0.125° grid across North-West Europe when using the GOT00.2, FES99, NAO.99b and FES2004 ocean tide models

be noted however that this is only the case for millimetre level displacement, with Bos and Baker (2005) finding the more global refinement used by CARGA is necessary for high quality gravity sites.

It can be seen from Figs. 3, 4 and 5 that the agreement between the OLFG/OLMPP (MRD), OLFG/OLMPP (NoMRD), SPOTL and CARGA displacement values improves on moving further inland. This is expected since the near tides have the biggest influence on a site's loading value, and therefore the effect of errors due to model cells not perfectly fitting the coastline, and inadequate model refinement, reduces. All four solutions agree at the sub-0.2 mm level for each of the four models input when greater than about 100–200 km from the coast. Indeed, at distances greater than approximately 150 km inland the OLFG/OLMPP MRD and NoMRD solutions are identical and use the global ocean tide models in their distributed form, since no model refinement is carried out as the $3° \times 3°$ box surrounding the site encompasses no water. Such inland sites provide a pure indication of the numerical differences between each of the three softwares.

6 GPS testing of OTL softwares

The OLFG/OLMPP (MRD) M2 OTL height displacements have been shown to be highly discrepant (up to about 8 mm) compared with the OLFG/OLMPP (NoMRD), SPOTL and CARGA values when either of the FES99, GOT00.2 or NAO.99b models are used. To test whether the OLFG/OLMPP (MRD) discrepant values are erroneous, a GPS verification was carried out. A GPS site was selected as close as possible to the part of North-West Europe where the maximum OLFG/OLMPP (MRD) minus CARGA disagreement arose for each model. Hence as illustrated in Fig. 3, GLAS was selected for GOT00.2, MALG for NAO.99b and APPL for FES99. NEWC was arbitrarily selected to verify the FES2004 displacements, even though no large discrepancies arose. All available data between 2005.00 and 2007.00 were obtained for the four sites from the NERC BIGF (http://www.bigf.ac.uk) GPS facility. Location details for these sites are listed in Table 4, together with OTL displacement values computed using each different software package.

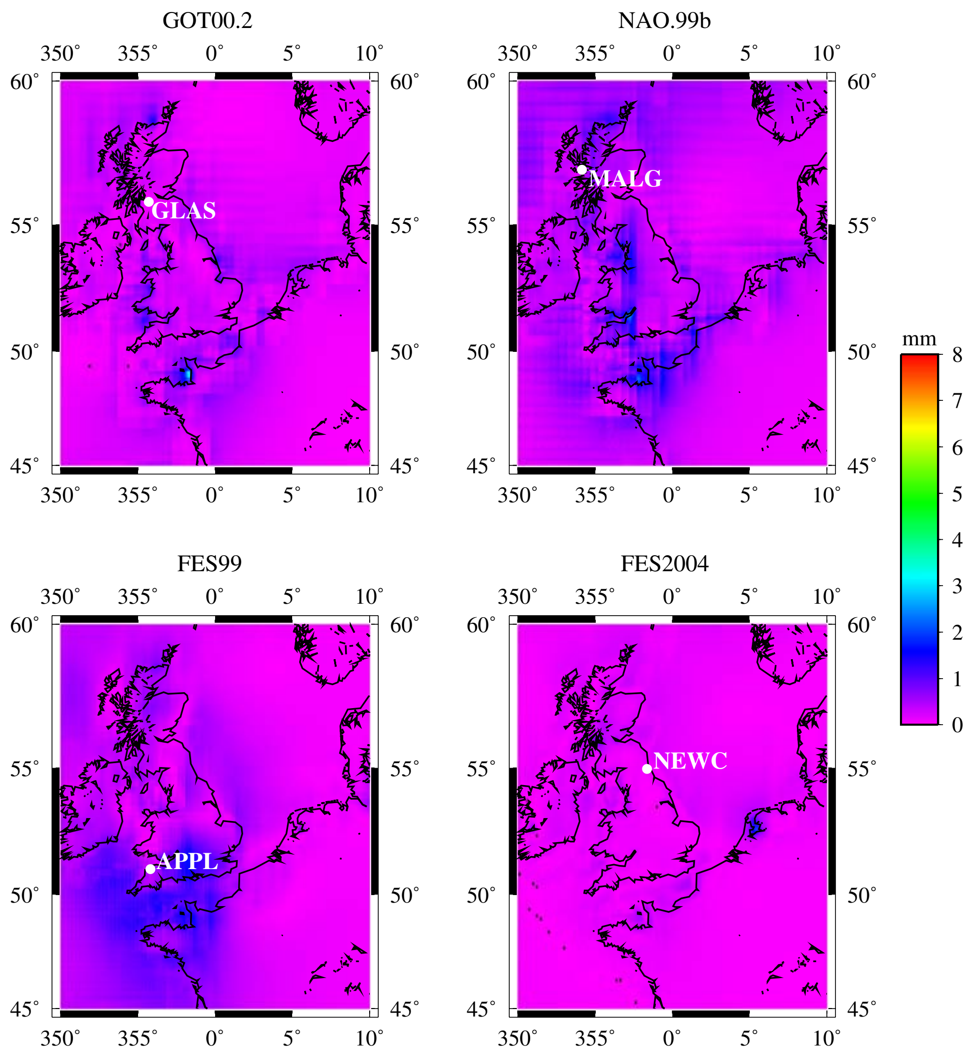

Fig. 5 OLFG/OLMPP (NoMRD) minus CARGA M2 OTL height displacement vector differences for a 0.125° grid across North-West Europe when using the GOT00.2, FES99, NAO.99b and FES2004 ocean tide models

Table 4 North-West Europe site details and M2 OTL height displacement amplitudes (A) and Greenwich phase lags (Φ) for different softwares

Site	Lon. (°)	Lat. (°)	Model	OLFG/OLMPP (MRD)		CARGA		SPOTL		OLFG/OLMPP (NoMRD)	
				A (mm)	Φ(°)	*A* (mm)	Φ(°)	*A*(mm)	Φ(°)	*A* (mm)	Φ(°)
APPL	355.8003	51.0569	FES99	38.20	327.5	32.21	322.5	32.16	322.5	32.77	323.0
GLAS	355.7035	55.8540	GOT00.2	12.39	312.1	9.76	309.2	9.69	309.4	9.67	309.4
MALG	354.1716	57.0061	NAO.99b	23.96	341.8	19.94	337.9	19.40	337.9	19.77	338.8
NEWC	358.3834	54.9791	FES2004	13.88	287.0	13.80	287.0	13.97	286.4	13.92	286.7

Latitudes and longitudes are positive in the North and East directions, respectively

The GPS data were processed using GIPSY/OASIS v4 software in a kinematic precise point positioning strategy outlined by King (2006) and refined by King et al. (2008). This involved processing in 30 h batches with site coordinates, zenith wet delays and receiver clocks estimated every 5 min, whilst holding fixed final JPL fiducial orbits and Earth rotation parameters. Ambiguities were not fixed to integers and a 7° elevation cut-off angle was adopted. The 30 h batches were centred on the UT day (3 h overlap either side), with the site coordinates whose time-tags matched the central UT day extracted to form continuous time series and to minimise day-to-day edge effects. OTL displacements were firstly modelled using OLFG/OLMPP (MRD) values, and the processing then repeated applying the CARGA values. The estimated site coordinates per solution were thinned to a spacing of 30 min, and linear trends and outliers (defined as greater than 5 times the inter-quartile range) removed. Amplitude spectra of the height time series were then computed according to the Press et al. (1992) implementation of Scargle (1982), which are shown in Fig. 6.

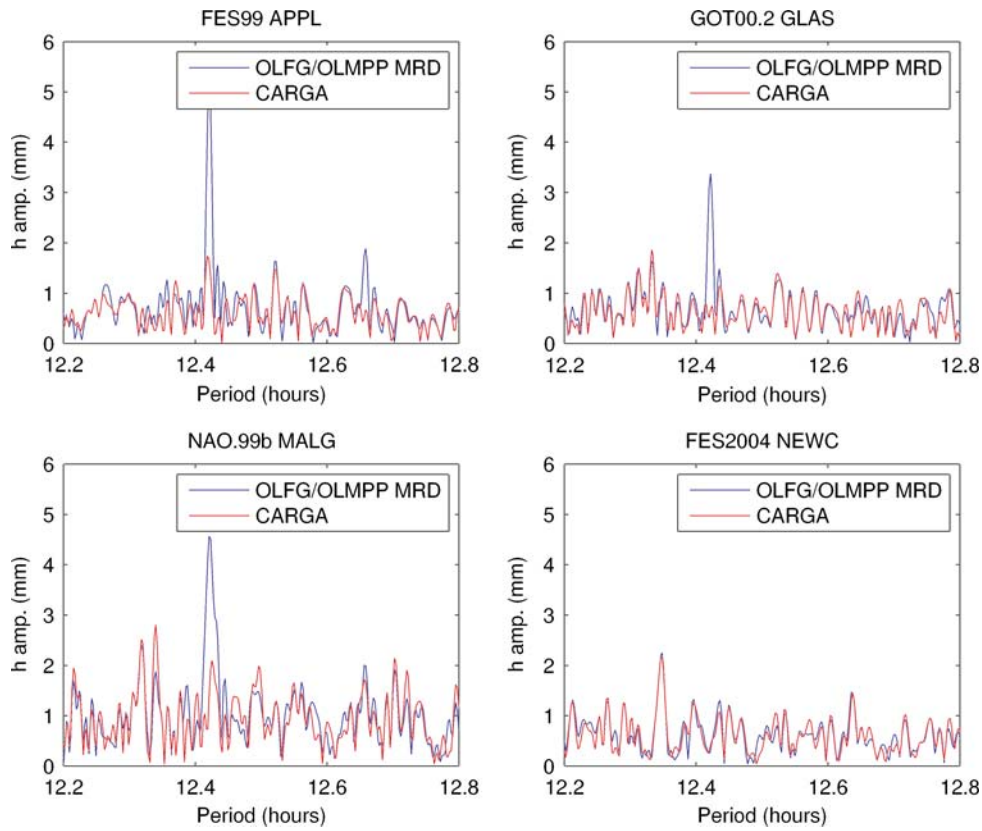

Fig. 6 GPS height amplitude spectra for OLFG/OLMPP (MRD) and CARGA solutions for ocean tide models FES99 at site APPL, GOT00.2 at GLAS, NAO.99b at MALG, and FES2004 at NEWC

The GPS height time series amplitude spectra shown in Fig. 6 clearly indicate that modelling M2 OTL displacements computed using CARGA reduces 12.42 h (M2) periodicities to the height time series noise level, whereas substantial energy remains when OLFG/OLMPP (MRD) is used. This is obvious for the APPL, GLAS and MALG sites, located in areas where there are large differences between the OLFG/OLMPP (MRD) and CARGA displacements for the respective FES99, GOT00.2 and NAO.99b ocean tide models. Given that the OLFG/OLMPP (NoMRD) displacements are in such close agreement with the CARGA values at these sites, it strongly suggests that MRD is inappropriate when the FES99, GOT00.2 and NAO.99b models are used. However, when the FES2004 model that better fits the coastline is used, it can be seen from Fig. 6 that modelling M2 OTL displacement using OLFG/OLMPP (MRD) or CARGA reduces the energy at the 12.42 h M2 period to the noise level. This suggests that when using the FES2004 model, MRD may be implemented in the OLFG/OLMPP solutions without loss of accuracy because the MRD effect is small.

7 OTL displacement sensitivity to different ocean tide models

For the M2 constituent and height component, the three OTL softwares considered have been shown to output displacements with vector differences invariably no greater than 1–2 mm for sites adjacent to complicated coastlines and shallow seas (provided MRD is not used in OLFG/OLMPP), and often better than 0.2–0.5 mm when more than ∼100 km inland or close to straighter coastlines and the deep oceans. This can therefore be considered the noise level of the convolution procedure. The horizontal displacement vector differences were considerably less. In this section an indication is provided of the magnitude of the commonly assumed biggest component of the OTL displacement error budget, namely ocean tide model quality.

M2 OTL height displacements were computed for the 387 IGS sites considered in Sect. 4 using the CARGA software and inputting each of the six modern ocean tide models CSR4.0, FES99, FES2004, GOT00.2, NAO.99b and TPXO.6.2. The CSR4.0 model used here is a filtered version—CSR4.0 grid cells over land were eliminated using the grid of the GOT00.2 model. Vector differences between each model value and the six model mean value were computed and the RMS of these differences (i.e. inter-model agreement) used to assess model quality, which are plotted in Fig. 7. It can be seen that for a great many sites, particularly those inland, the OTL displacement is insensitive (<0.4 mm) to the choice of model, although discrepancies of nearly 3 mm arise for some coastal sites. Table 5 details the sites for which a discrepancy of greater than 1 mm arises, including the M2

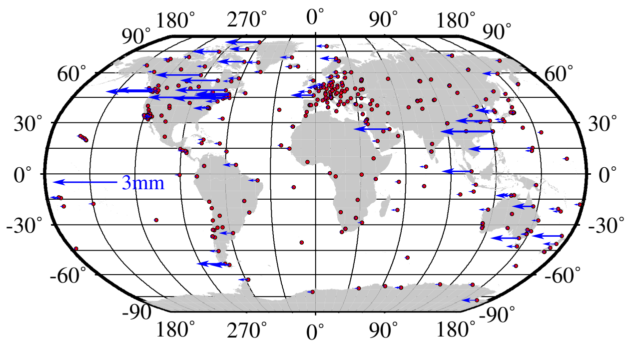

Fig. 7 RMS vector differences of M2 OTL height displacements for 387 IGS sites, computed using CARGA and the CSR4.0, FES99, FES2004, GOT00.2, NAO.99b and TPXO.6.2 ocean tide models

amplitudes and Greenwich phase lags computed per model. It can be seen from Table 5 that for some sites such as TNML it is just one particular model (FES99) causing the inter-model discrepancy, although the discrepant model differs depending on global location. For example at PARC the discrepant model is NAO.99b, at TOW2 it is GOT00.2 and at AUCK it is FES2004. At some sites such as ALBH, BAIE and NTUS, no one model is discrepant and the large RMS agreement is simply due to a larger scatter of the amplitude and phase values across all the models.

It is clear from Fig. 7 and Table 5 that OTL displacement values are sensitive to the choice of ocean tide model at the several millimetre level at some coastal sites. Furthermore, Penna et al. (2007) showed that RMS agreements between M2 height amplitudes computed using the SPOTL software with the CSR4.0, FES99, GOT00.2, NAO.99b and TPXO.6.1 models input can be as high as 8 mm in some regions such as the Weddell and Ross Seas, where there are no IGS sites. Which model is discrepant is location dependent, suggesting that it is not necessarily appropriate to use just a single model in global analyses, as was also suggested by Baker and Bos (2003). However, the IERS 2003 conventions do not stipulate any regional dependency in their recommendation to use either FES99 or GOT00.2. Meanwhile, the working version of updates (unratified) to these conventions available at http://tai.bipm.org/iers/convupdt/convupdt.html has changed the recommended model for global use to either FES2004 or TPXO.6.2, whilst recognising that other models might be preferred for internal consistency.

8 Discussion and conclusions

It has been clearly demonstrated that M2 OTL displacements (especially the height component) are sensitive to the refinement method adopted when the near ocean tide model grid cells do not perfectly fit the coast. If the local water mass redistribution approach of Scherneck (1991) is implemented and if the site is adjacent to complicated coastlines and shallow seas, errors of around 8 mm or 20% can arise for the height component, depending on the ocean tide model used. Particularly large errors have been shown to arise if the FES99 (0.25° resolution) or NAO.99b (0.5° resolution) models are used, attributed to their grids consistently overlapping the coastline which means that when MRD is applied, a large change in loading arises. Meanwhile, 4–5 mm errors arise using the 0.5° resolution GOT00.2 model, which are less than when using NAO.99b despite the models' equivalent grid spacing. Thus the effect of MRD is dependent not just on the model's grid resolution, but on how much the grid overlaps the coastline. On average the GOT00.2 grid cells overlap the land as much as they leave a gap between the grid and the land, whereas the NAO.99b and FES99 grid cells overlap the land too much, resulting in loading errors when applying MRD. These errors have been confirmed using GPS measurements, since substantial energy remains at the M2 period in the GPS height time series amplitude spectra when using MRD, yet the energy reduces to the noise level when using CARGA (whose displacement values agree very closely with the OLFG/OLMPP NoMRD and SPOTL values). However, the grid of FES2004 has on average as many grid cells overlapping the coast as cells leaving a gap to the coast. This causes the MRD effect to be small for the FES2004 model.

Provided the MRD option is not used by the OLFG/OLMPP software package, this package, SPOTL and CARGA all compute M2 OTL height displacements that invariably agree at better than the 1–2 mm level at coastal sites adjacent to complicated coastlines and shallow seas, and invariably better than 0.2 mm for sites more than ∼100 km inland for all four models considered. When more than ∼150 km inland, the OLFG/OLMPP MRD and NoMRD values are identical because no local refinement is applied at all. Expressing the inland differences as a proportion of the loading amplitude translates to ∼2–5% (often less), which is in agreement with the comparisons of Agnew (1997) and Bos and Baker (2005), but contradicts the statement of Boy et al. (2003) that convolution errors of 10% can arise at Strasbourg (lon. 7.6838, lat. 48.6218) in North-East France. In order to model OTL displacement to an accuracy of around 1 mm, the three packages OLFG/OLMPP, SPOTL and CARGA can be considered practically interchangeable. The different model refinement methods for coastal cells when computing the OTL produce equivalent outputs, and suggest that for a displacement accuracy level of about 1 mm, it does not matter if bilinear interpolation or the nearest grid cell value is used to determine the tidal amplitude at distances of more than 10° from the site. For the 387 IGS sites tested, the sensitivity of the horizontal displacements to the refinement method used was less than for the height component.

Aside from model refinement at the coast and interpolation of model grid cells in the open ocean, contributions to

Table 5 Predicted M2 OTL height displacement amplitudes (A) and Greenwich phase lags (Φ) from six ocean tide models using the CARGA software for IGS sites for which the RMS of the vector differences (mm) from the six model mean was greater than 1 mm

Site	Lon (°)	Lat (°)	CSR4.0		FES99		FES2004		GOT00.2		NAO.99b		TPXO.6.2		Vector
			A (mm)	Φ(°)	*A* (mm)	Φ(°)	*A* (mm)	Φ(°)	*A* (mm)	Φ(°)	*A* (mm)	Φ(°)	*A* (mm)	Φ(°)	RMS Diffn.
ALBH	236.5126	48.3898	17.0	72	20.8	68	16.1	78	17.0	72	15.5	73	19.8	69	2.2
ALRT	297.6596	82.4943	0.6	111	0.9	261	0.9	220	0.4	111	3.7	88	1.0	236	1.6
AUCK	174.8344	−36.6028	27.7	56	27.9	55	24.9	59	27.5	56	27.4	59	27.7	54	1.4
BAHR	50.6081	26.2091	5.2	253	3.4	296	6.6	259	6.1	256	7.1	257	6.2	258	1.7
BAIE	291.7367	49.1868	5.9	146	2.9	106	4.4	84	5.7	148	4.0	84	3.9	94	2.4
BARH	291.7783	44.3950	9.5	211	13.4	227	13.4	236	13.9	235	13.8	235	12.4	231	2.3
CHUR	265.9113	58.7591	6.4	198	5.6	182	10.8	181	9.4	182	10.3	187	9.1	177	2.1
EPRT	293.0079	44.9087	9.5	205	13.8	222	16.0	242	16.3	238	15.9	234	13.3	229	3.6
ESCU	295.2013	47.0734	6.3	154	6.7	116	5.9	154	6.6	157	6.3	142	6.2	145	1.6
HLFX	296.3887	44.6835	13.7	169	13.5	169	13.2	180	14.0	176	12.7	180	13.5	171	1.2
KUUJ	282.2546	55.2784	7.3	168	4.9	165	9.9	158	9.1	157	8.7	157	8.3	153	1.8
LROC	358.7807	46.1589	27.5	281	28.2	282	27.6	287	27.8	282	27.2	282	27.5	281	1.1
MOBS	144.9753	−37.8294	6.8	172	3.7	153	6.2	164	7.1	170	7.1	172	6.5	172	1.3
NANO	235.9135	49.2948	18.4	72	17.5	74	15.8	76	18.4	73	15.9	75	20.4	71	1.7
NTUS	103.6799	1.3458	5.1	196	4.9	180	6.1	184	5.6	186	4.3	197	5.3	153	1.4
PARC	289.1201	−53.1370	5.9	143	6.1	152	5.8	150	5.6	144	6.8	127	5.4	118	1.4
PIMO	121.0777	14.6357	8.1	139	6.7	145	9.9	134	9.1	136	10.3	134	9.5	135	1.3
QIKI	295.9663	67.5593	13.7	119	11.8	117	13.2	117	13.6	117	11.0	125	12.7	112	1.3
RESO	265.1067	74.6908	7.6	35	4.5	35	5.3	26	7.5	35	5.1	41	6.0	32	1.3
SHAO	121.2004	31.0996	7.0	193	4.1	212	6.7	202	8.4	210	7.8	211	7.8	199	1.6
SHE2	295.4480	46.2207	7.9	164	7.5	155	7.2	192	8.3	178	7.1	175	7.6	163	1.6
TCMS	120.9874	24.7980	10.2	209	7.4	235	12.2	209	11.8	208	12.0	207	11.7	201	2.4
TNML	120.9873	24.7980	10.2	209	7.4	235	12.2	209	11.8	208	12.0	207	11.7	201	2.4
TWTF	121.1645	24.9536	10.6	200	7.3	224	12.3	202	12.0	201	12.2	200	12.1	194	2.4
UNBJ	293.3583	45.9502	7.3	172	6.9	179	6.8	199	7.5	194	6.8	197	6.8	183	1.3

Latitudes and longitudes are positive in the North and East directions, respectively

the small differences between the OLFG/OLMPP, SPOTL and CARGA displacements arise from the choice of Green's function and the value for the density of sea water. To assess the effect of the Green's function used, the FES99 CARGA height values for the 387 IGS sites were recomputed using the Green's function of a Gutenberg–Bullen A Earth model (Farrell 1972), in addition to the default PREM Green's function of Francis and Mazzega (1990) which is used by CARGA throughout the paper. For coastal sites, this changed the displacements by ∼0.25 mm, although by about 0.8 mm at RIO2, whilst the change at inland sites was very small (<∼0.1 mm). Regarding the effect of sea water density, the average water density value for a column of water can change by 1%. For sites with very large OTL displacement values of 20–30 mm this corresponds to an error of 0.2–0.3 mm.

Whilst convolution errors have been shown, in general, to be not more than 1–2 mm, errors in the available ocean tide models remain a bigger contributor to errors in OTL displacement values. Height errors of up to around 3 mm RMS between the different modern models arise at IGS sites and up to around 8 mm in areas such as the Weddell Sea and Ross Ice Shelf where there are no IGS sites. No one model can yet be considered to best represent the tides in all regions of the world, with further research required to evaluate which model is most appropriate in different parts of the world. The models themselves still need some improvement. Notably some of the current global models lack any information on certain seas (e.g. NAO.99b omits the Ross Sea, TPXO.6.2 omits the Black Sea), which will cause problems for nearby sites. A possible solution is to develop regional tide models for these uncovered regions which is the approach adopted by SPOTL.

The widely used OTL web provider recommended in the IERS 2003 conventions (and suggested in the unratified updates) is driven by the OLFG/OLMPP software. MRD was implemented for near coastal cells from 2001 until August 2007, when the option was switched off for the reasons outlined in this paper and bilinear interpolation only is now used. Therefore, for any GPS, DORIS, SLR or VLBI analyses that have applied OTL web provider generated displacement corrections computed during this window for sites within ~150 km of the coast, biased parameters will result. The size of such biases will depend on the distance of the site from the coast, the resolution of the model used, the shape of the nearby coastline, how much land overlap arises for the model's grid cells, and whether the site is adjacent to shallow seas or the deep oceans.

In this study, the OTL values represented displacements at the Earth's surface relative to the centre of mass of the undeformed solid Earth without atmosphere and oceans. In the ocean loading problem the distance between the solid Earth centre and the joint centre of mass of the Earth system (i.e. solid Earth and oceans) undergo tidal translations that are generated by hemispherical ocean mass exchange. In sensitive orbit calculations, this offset should be taken into account. From the perspective of a user of orbital products, for example those provided by the IGS in the case of GPS, it appears more practical if the translations are removed from the orbital products disseminated by the analysis centres. Many applications, such as relative GPS and VLBI, are insensitive to such translations anyway, and there is not yet clear evidence that the translation parameters are crucial and that they can be verified by orbit analyses. Since these parameters are somewhat uncertain in ocean tide modelling and also difficult to determine in altimetry, most space geodetic analysis centres do not apply them at present. Thus the assumption of the solid earth centre as a reference is consistent with the JPL fiducial orbit products used in this study. Any error would have to be tracked to second-order dynamic effects of the neglected offset to the joint mass centre. (Sensitive tests of orbit anomalies due to ocean tide mass induced frame centre translation are encouraged).

A centre of figure frame, as discussed in Blewitt (2003), did not need to be considered here—the centre of figure frame concept relates to unknown deformations and fits an undeforming surface to the station positions. Included in the modelling of ocean loading are degree-one load Love numbers, which can be decomposed into a translation and a deformation part. However, this translation arises in the Earth's interior and does not displace the solid Earth's mass centre. From observations at the Earth's surface, this particular translation component cannot be distinguished from additional translations involving the mass centre.

This study only considered the (usually dominant) M2 constituent. Moreover, only a sample of globally distributed sites (the IGS network) was considered, along with a single more detailed test region (North-West Europe) that encompassed complicated coastlines and shallow seas, for which the (dominant) height component was considered only. High resolution intercomparisons of OTL softwares and ocean tide models should be undertaken for other coastal regions for height and horizontal displacements and various tidal constituents.

Acknowledgments The providers of the CSR4.0, FES99, FES2004, GOT00.2, NAO.99b and TPXO.6.2 ocean tide models are gratefully acknowledged, together with Duncan Agnew for making the SPOTL software freely available to the public. The UK NERC BIGF facility (http://www.bigf.ac.uk) is thanked for GPS data provision, and JPL for the GIPSY software and orbital products. Thanks to Matt King for his initial development of the GPS data processing method. Many of the figures were produced using the GMT v4.2 software (Wessel and Smith 1998). Penna was funded by UK NERC grant NE/C003438/1 and Bos by Fundação para a Ciência e a Tecnologia (FCT), through grant SFRH/BPD/26985/2006. Constructive reviews by Duncan Agnew and Jean-Paul Boy are acknowledged.

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