



Estimating ocean tide model uncertainties for electromagnetic inversion studies

Jan Saynisch¹, Christopher Irrgang¹, and Maik Thomas^{1,2}

¹Earth System Modelling, Helmholtz Centre Potsdam, GFZ German Research Centre Potsdam, Germany

²Institute of Meteorology, Freie Universität Berlin, Berlin, Germany

Correspondence: J. Saynisch (saynisch@gfz-potsdam.de)

Abstract. Over a decade ago the semidiurnal lunar M2 ocean tide was identified in CHAMP satellite magnetometer data. Since then and especially since the launch of the satellite mission Swarm, electromagnetic tidal observations from satellites are used increasingly to infer electric properties of the upper mantle. In most of these inversions, ocean tidal models are used to generate oceanic tidal electromagnetic signals via electromagnetic induction. The modelled signals are subsequently compared to the satellite observations. During the inversion, since the tidal models are considered error free, discrepancies between forward models and observations are projected only onto the induction part of the modelling, e.g., Earth's conductivity distribution. Our study analyses uncertainties in oceanic tidal models from an electromagnetic point of view. Velocities from hydrodynamic and assimilative tidal models are converted into tidal electromagnetic signals and compared. Respective uncertainties are estimated. The studies main goal is to provide errors for electromagnetic inversion studies. At satellite height, the differences between the hydrodynamic tidal models are found to reach up to 2 nT, i.e., over 100% of the local M2 signal. Assimilative tidal models show smaller differences of up to 0.1 nT which in some locations still corresponds to over 30% of the M2 signal.

1 Introduction

The study of electromagnetic (EM) oceanic tidal signals (EMOTS) has a long history (see references in Larsen, 1968; Sanford, 1971). Since over a decade, EMOTS from the M2 are detectable in CHAMP satellite magnetometer observations (Tyler et al., 2003; Sabaka et al., 2015). Since the Swarm satellite mission's launch in 2013, satellite magnetometer observations become more precise and extended. Already, weaker ocean tides like the N2 may be detectable from space (Sabaka et al., 2016). In most use-cases EMOTS are removed from the EM observations before further analysis (e.g., Larsen, 1991; Guzavina et al., 2018). However, an increasing number of studies use EMOTS to infer EM properties of Earth's sub-systems. Kuvshinov et al. (2006) studied the sensitivity of EMOTS to lithosphere resistance. The strategy is to use discrepancies between observed and modelled EMOTS (Schnepf et al., 2014) to infer lithosphere and upper mantle resistance (Schnepf et al., 2015). Magnetometer satellites allow to conduct these studies with global coverage. Grayver et al. (2016, 2017) use EMOTS from satellite observations to constrain lithosphere, mantle conductivity, and water content profiles. Saynisch et al. (2016, 2017) propose to use EMOTS to detect changes in oceanic conductance due to salinity and temperature changes.



Many of these approaches compare or propose to compare observed and modelled EMOTS. The found discrepancies are subsequently used to update prior conductivity assumptions. Consequently, flaws of the used tidal model are inevitably projected onto the conductivity updates. Many of these inversions studies utilize a single tidal model (e.g., Kuvshinov et al., 2006; Kuvshinov, 2008; Schnepf et al., 2014). Grayver et al. (2016) compare two tidal models and state that the difference between radial magnetic field components calculated from both tidal models are below the current noise level of current satellite EM observations. However, Grayver et al. (2016) note further that both models use very similar data to estimate tidal flow and that systematic shifts cannot be fully ruled out.

Stammer et al. (2014) compared sea surface heights (SSH) and sea water velocities from 15 tidal models to observations. The authors report rms-errors from modern tidal models for the M2-SSH of 0.5-0.7 cm over the open ocean. On the shelf and in high-latitudes, the errors amount to several centimeters. Compared to coastal tide-gauges, the rms-errors can reach 15.7 cm. Comparison of modelled M2 velocities revealed rms-errors of 0.8-1.5 cm/s.

The reported errors can not directly be translated into errors of EMOTS. Tidal velocities interact with Earth's background magnetic vector field to generate tidal electric currents. This process is mathematically described by a cross product where local ocean depth and oceanic conductance have to be taken into account. The tidal electric currents subsequently generate tidal magnetic signals by electromagnetic induction. This process is described by Maxwell's equations. Here, the conductances of ocean, sediments, conductivity of lithosphere, and upper mantle have to be taken into account. To re-evaluate known tidal model uncertainties in the view of EMOTS is the main goal of this study.

As Stammer et al. (2014), our study uses an ensemble of tidal models to estimate the uncertainties of EMOTS predictions. The findings should help to evaluate, weight, and improve EMOTS-based inversions that incorporate model to observation comparisons.

In Section 2, the tidal models and the solver for the Maxwell equations are described. Section 3 presents and discusses the model-to-model differences with respect to EMOTS. The paper closes with summary and conclusions in Section 4.

2 Models

Stammer et al. (2014) identify two relevant categories of tidal models. First, forward models, which are physically consistent and model tides due to the forces generated by Earth's rotation and the movements of the respective celestial bodies. Second, empirical models, which assimilate observation data. We follow that approach and study the following currently used tidal models.

Forward Models

OMCT (Dobslaw and Thomas, 2007): Global baroclinic model with 1 degree resolution. The forcing bases on the ephemerides. Loading and self-attraction (LSA) is parameterized. Tides are calculated in combination with the global general circulation



(Thomas et al., 2001). The general circulation is forced with 3 hourly fields of wind stress and freshwater-flux.

STORMTIDE (Müller et al., 2012): Global baroclinic model of 0.1 degree resolution. The forcing bases on the ephemerides. LSA is parameterized. Tides are calculated in combination with the global general circulation. The general circulation is forced with daily wind fields from a climatological year.

Since the models are forced with full luni-solar potentials, the M2 signal has to be separated in the model output by harmonic analysis. To do this the tidal frequencies are fitted to the data. This approach has similarities to the filtering of tidal signals in real observations.

Assimilative Models

HAMTIDE (Taguchi et al., 2014): Linearized barotropic global model with spatial resolution of 0.125 degree. LSA is included. A variational data assimilation scheme is used that bases on a generalized inverse. Output from the Empirical Ocean Tide Model (EOT, DGFI-Report No.89: Savcenko R, 2012) is used as data constraints. EOT bases on multi mission satellite altimetry.

TPXO8-atlas (Egbert and Erofeeva, 2002): Global barotropic 1/30 degree model that uses the representer approach to assimilate data from multi mission satellite altimetry and tide gauges.

FES2014 (Lyard et al., 2006): Non-linear barotropic 1/16 degree global tidal model with unstructured grid. Maximal resolution of a few kilometers. FES2014 uses ensemble optimal interpolation in frequency domain to assimilate observations. Multi mission satellite altimetry data is used as constraints.

Induction model

Tidal transports from the above mentioned tidal models are regridded to an identical $1^\circ \times 1^\circ$ grid. Where tidal transports are not provided the given tidal velocities are integrated using the respective model's bathymetry. A 2D annual mean depth averaged oceanic conductivity was derived from the OMCT ocean model. OMCT oceanic conductivity ($\bar{\sigma}$), tidal transports (U) and Earth's background magnetic field (B^m , IGRF-12 Thébaud et al., 2015) are combined to estimate electric sheet current densities (J):

$$J = \bar{\sigma}(U \times B^m). \quad (1)$$

The J force Maxwell's equations, which are solved by the 3D induction solver of Kuvshinov (X3DG, 2008). X3DG calculates magnetic fields in frequency space using a volume integral equation approach. In our configuration, a thin ocean and sediment layer of spatially variable electric conductance is used (Laske and Masters, 1997; Everett et al., 2003). In addition, a 1D spherically symmetric mantle conductivity (Püthe et al., 2015) is used.

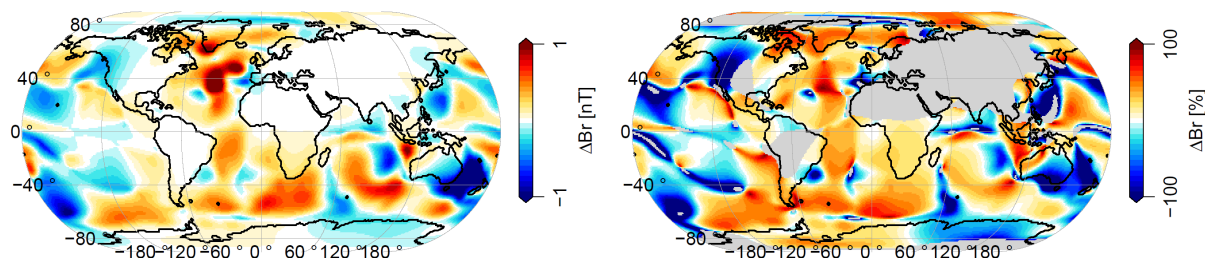


Figure 1. Differences of radial tidal magnetic field at satellite height. STORMTIDE minus OMCT amplitudes, i.e., two forward models. Left: Absolute differences. Right: Relative differences (regions of tidal signal strength below 0.1 nT are grayed out).

3 Results and Discussion

The study is restricted to tidal magnetic amplitudes of the semidiurnal lunar tide, M2. M2 has the largest magnetic amplitude and is used in the most recent satellite magnetometer based inversion Grayver et al. (2017). Only the radial M2 component of the oceanic magnetic field is presented throughout the paper.

Figure 1 shows the differences between the two hydrodynamic, i.e., the forward models.

Globally, large discrepancies of up to ± 2 nT occur, e.g. +1.5 nT in the Gulf Stream region and -2 nT around New Zealand (Fig. 1, left side). These differences are comparable in size to the actual tidal amplitudes, e.g., 80 % in the Gulf Stream region and over -100 % around New Zealand (Figure 1, right side).

Assimilation models are better in reproducing observed tidal SSH anomalies (Stammer et al., 2014). This is not astonishing since these models assimilate SSH observations (Egbert and Erofeeva, 2002; Lyard et al., 2006; Taguchi et al., 2014). However, the SSH anomalies itself are not very relevant for the magnetic signal. SSH anomalies of a few meter have to be related to the entire water depth. Consequently, SSH anomalies are only important in very shallow areas. Important to the magnetic signals are the tidal velocities. Stammer et al. (2014) compare modelled and observed tidal velocities, too. The results show that assimilative models are closer to the observations. However, with 56 moorings and 3 acoustic tomography soundings the comparison under-represents large parts of the global ocean.

In contrast to the assimilative models and in contrast to the comparisons in Stammer et al. (2014), the presented differences of Fig. 1 include baroclinic components. In addition, signals of the general wind-driven circulation are included that became aliased into the M2 tidal signal during the tidal harmonic analysis (see Sec. 2). Both contributions are included in real observations of EMOTS and should be considered in the comparison. Consequently, even if a perfect barotropic tidal model exists, it will show differences to EMOTS observations. A corresponding inversion strategy would nonetheless project these differences, e.g., on lithospheric resistivity.

Figure 2 shows the comparison of the two tidal models that were compared in Grayver et al. (2016), HAMTIDE and TPXO8-atlas. At satellite height, the two assimilative models show weak large scale differences of around 0.03 nT (Fig. 2, left side). However, locally the differences are larger. Especially around the Antarctic Peninsula (-0.3 nT) and in the Arctic Ocean

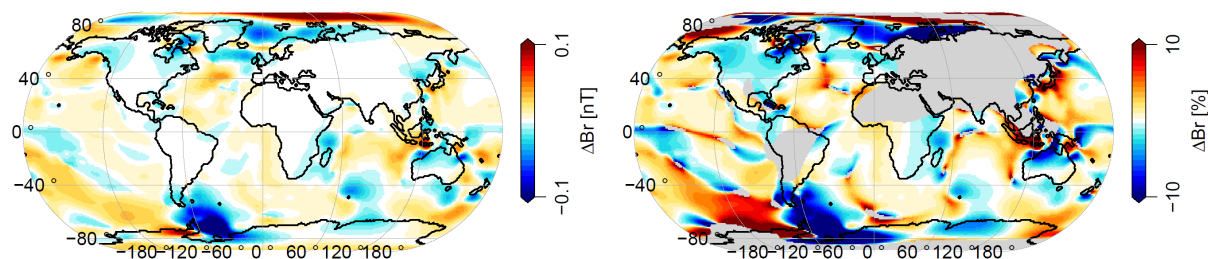


Figure 2. Differences of radial tidal magnetic field at satellite height. HAMTIDE minus TPXO amplitudes, i.e., two assimilative models. Left: Absolute differences. Right: Relative differences (regions of tidal signal strength below 0.1 nT are grayed out).

(+0.2 nT), the discrepancies are larger than Swarm's nominal noise level (0.1 nT, Friis-Christensen et al., 2006). These higher values are not present in the comparison of Grayver et al. (2016, their Fig. 4A). The reason can only be guessed to be a result of recent updates in the HAMTIDE or TPXO data sets.

The relative differences between the HAMTIDE and TPXO8-atlas amount to 10-30% in higher-latitude and around 5% elsewhere (Fig. 2, right side). Please note that all signals below 0.1 nT, i.e., the nominal Swarm precision, are grayed out in the right side plots. In these areas, even small model differences generate large relative error values. As a consequence, the plotted errors of 5-30% relate to significant, i.e., measurable tidal magnetic fields, only.

If a third assimilative model (FES2014) is taken into account, additional high discrepancies occur in other parts of the globe. Figure 3 compares the M2 signals of FES2014 and HAMTIDE. High differences over 0.1 nT occur in the central Pacific, the North Atlantic and the Indian Ocean (Fig. 3, left side). However, the fit in the Arctic Ocean is better than in Fig. 2. The relative values (Fig. 3, right side) show differences above 30% globally. Again, small signals below 0.1 nT are not considered for the relative deviations. Considering the mostly small values in Fig. 2, it is not astonishing that apart from the already mentioned Antarctic Peninsula and the Arctic Ocean, the differences between FES2014 and TPXO-atlas are very similar to the differences between FES2014 and HAMTIDE Fig. 3.

Compared to the forward models (Fig. 1), the assimilative models show smaller discrepancies (Fig. 3). This is a direct result of the assimilation of the same data, i.e., satellite height observations (Taguchi et al., 2014; Egbert and Erofeeva, 2002; Lyard et al., 2006). However, can the smaller magnetic tidal differences among assimilative models be interpreted as better magnetic signals, too? The assimilative models fit better to tide gauge data although these observations are only assimilated into TPXO8-atlas (Stammer et al., 2014). However, tide gauge data and satellite altimetry are closely related. The relevant properties for the EM signals, tidal velocities, are not assimilated into these models. A possible answer to the question can be found in comparisons of modelled and observed barotropic tidal velocities (Stammer et al., 2014). Here, the assimilative models show a better fit than the forward models, too. However, in this comparison major parts of the oceans and the baroclinic contributions are not considered (Stammer et al., 2014).

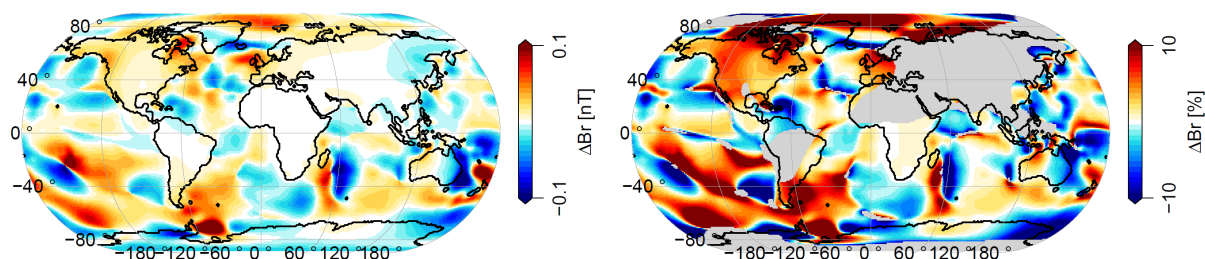


Figure 3. Differences of radial tidal magnetic field at satellite height. FES2014 minus HAMTIDE amplitudes, i.e., the assimilative models. Left: Absolute differences. Right: Relative differences (regions of tidal signal strength below 0.1 nT are grayed out).

Comparing the assimilative models directly with the forward models reveals large discrepancies of around ± 1 nT (not shown). Consequently, these differences are smaller than the differences between the forward models alone. In most parts of the globe, the tidal magnetic field amplitudes of the assimilative models lie between the two forward models.

4 Summary and Conclusions

- 5 Main goal of the study is to provide errors for inversion studies that use tidal observations from satellite magnetometers (Schnepf et al., 2014, 2015; Grayver et al., 2016, 2017; Saynisch et al., 2016, 2017).

Five momentarily used oceanic tidal models are compared with respect to their electromagnetic (EM) signal of the semidiurnal lunar tide M2. The model range includes two baroclinic, hydrodynamic forward models. Here, the tide calculation is coupled to the general circulation and bases on ephemeris forcing. Furthermore, the model range includes 3 barotropic assimilative models. These models rely heavily on satellite altimetry data.

All models provide M2 velocities or transports. These are combined with a mean 2D oceanic conductance and Earth's background magnetic field to generate electric sheet current densities. The sheet current densities are interpolated onto a $1^\circ \times 1^\circ$ grid and solved for their magnetic signal with a 3D induction solver (Kuvshinov, 2008).

- 15 At satellite height the forward tidal models globally show large scale differences of up to ± 2 nT. In most areas, the differences are larger or in the same order of the actual M2 signal. In comparison, the differences of the assimilative tidal models are smaller. Nonetheless, large scale inter-model differences over 0.1 nT occur that correspond to 30% and more of the actual M2 signal.

The differences between forward models and assimilative models are slightly smaller than but of the same order as the forward model differences.

- 20 Depending on the tidal model used in an inversion approach, the respective error budgets should be included. Locally, e.g., in polar regions, up to 30% of M2 tidal model error may be assumed.

Identifying a best tidal model for EM inversions is beyond the scope of this study. However, a follow-up study will try to derive and compile tidal EM signals from insular, coastal and bottom magnetometers (Maus and Kuvshinov, 2004; Kuvshinov



et al., 2006; Love and Rigler, 2014; Schnepf et al., 2014) and telecommunication cables (Thomson et al., 1986; Baringer and Larsen, 2001) to answer this question if possible. Such a study could simultaneously assess if modern tidal models are lacking physical processes that are relevant to tidal EM generation but which are not evident in the modelled SSH anomalies.

Competing interests. none



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