Tides and the SWOT mission: Transition from Science Definition Team to Science Team

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As the SWOT wide-swath satellite altimeter mission transitions from the Science Definition Team to the Science Team, it is an opportune time to review the progress that has been made with respect to tides, and the work remaining to be done. As with previous altimeter missions, tides present both an opportunity and a challenge for the SWOT mission. The TOPEX/Jason class of altimeters have allowed high-accuracy mapping of open-ocean barotropic tides over their coverage latitudes (66°S to 66°N), but the inter-track spacing of these missions (~150 km) has limited their ability to map smaller-scale features such as shelf tides, coastal tides, and open-ocean internal tides. Because SWOT will measure sea surface height at unprecedented horizontal resolution, SWOT offers the chance to map shelf tides, coastal tides and open-ocean internal tides in unprecedented detail. In addition, the inclination of SWOT offers the chance to improve tide estimates poleward of 66°, up to the SWOT orbit inclination of 78°. At the same time, shelf tides, coastal tides, open-ocean internal tides, and high-latitude tides must be accurately removed from SWOT data before SWOT can be used to examine non-tidal signals such as mesoscale and submesoscale eddies, the main target of the SWOT oceanography mission. Shelf tides, coastal tides, and open-ocean internal tides will be difficult to remove not only because of their small horizontal scales but also because of their inherently more challenging predictability compared with open-ocean barotropic tides. For shelf and coastal tides one aspect of this is the greater number of constituents that must be considered because of possible compound tides and overtides generated by nonlinear interactions in shallow regions. An especially great challenge will be in estuaries, where the hydrology and oceanography mission interests intersect, and where the tides can be quite nonlinear and nearly unpredictable, with nonlinearity sometimes manifested by impressive tidal bores (Dronkers, 1964; LeBlond, 1978; Godin, 1999; Jay et al., 2011; among other works on river tides and their changes).

Below, after reviewing the successes with open-ocean barotropic tides enabled by previous altimeter missions, we briefly review the progress-to-date, and work remaining, on shelf tides, coastal tides, open-ocean internal tides, and high-latitude tides as they pertain to the SWOT mission. In addition, we also discuss plans for tidal correction algorithms, the need for better bathymetry, especially in coastal regions, and the need for a coordinated effort to evaluate tidal models. Finally, the document concludes with some recommendations for SWOT-related tide model development efforts.

Open-ocean barotropic tides

As noted above, the most accurately known tides are open-ocean barotropic tides in the latitude band covered by the TOPEX/Jason class of altimeters (equatorward of 66°). In Stammer et al. (2014), a review paper that five of us participated in as co-authors, several state-of-the-art assimilative tide models—that is, tide models that assimilate altimeter data in some way—were compared to each other and to validation data derived from tide gauges and other instruments. The modern state-of-the-art assimilative tide models have an M_2 RMS elevation difference of about 0.5-0.7 cm with respect to the 151 open-ocean tide gauge and bottom pressure stations used in Stammer et al. (2014). The 0.5-0.7 cm error should be compared to a signal of 30 cm; the relative error (RMS difference over signal) is thus about 2%.

The data-constrained tide models examined in Stammer et al. (2014) include purely empirical models and barotropic hydrodynamic models employing some form of data assimilation. The three barotropic assimilative hydrodynamic models examined in Stammer et al. (2014) are the TPXO model (Egbert et al. 1994, Egbert and Erofeeva 2002), the FES model (Le Provost et al. 1994, Lyard et al. 2006, Carrère et al. 2012), and the HAMTIDE model (Taguchi et al. 2014, Stammer et al. 2014).

Over the latitude bands covered by T/P and Jason satellites, the deep-ocean barotropic tide models needed by SWOT are satisfactory. This is not the case, however, in higher latitudes. More progress is needed in such regions. Fortunately, even before SWOT launches, there are already new satellite missions that are providing some useful data for improvements (see below).

Shelf and coastal tides

With very low errors in open-ocean barotropic tides, attention has recently turned to the harder problem of shelf and coastal tides—see, for instance, Ray et al. (2011). Stammer et al. (2014) compared state-of-the-art assimilative barotropic tide models to shelf and coastal stations, in addition to the open-ocean stations described above. The shelf comparisons were divided into the European Shelf, which has a great number of the stations, and elsewhere. For the "elsewhere" comparison, the RMS difference in M_2 elevations between the assimilative models and the validation stations ranged from 3-5 cm. Measured against a 54 cm signal, the relative errors of shelf tides range from 6-10%, much higher than for open-ocean barotropic tides. Furthermore, the 3-5 cm difference is significantly larger than the 1 cm error that is taken as a target error for the SWOT oceanography mission. For coastal stations, the M_2 elevation errors range from 4-16 cm, again larger than the SWOT target error of 1 cm, with a signal of 60 cm. The relative errors range from 7-27%, higher still, and the differences between tidal models are much greater than in the open-ocean, underscoring the need for improvement before adequate prior models of shelf and coastal tides can be released for the SWOT mission. However, as Stammer et al. (2014) noted, the errors in shelf and coastal tides in present-day models are already much smaller than the errors in models during the early days of the TOPEX mission. Therefore there is reason to believe that shelf and coastal tide estimates will continue to improve as we move towards the SWOT mission. SWOT itself is likely to lead to improved coastal and shelf tide estimates, due to the higher spatial resolution of SWOT and the smaller footprint (which reduces land contamination errors) relative to contemporary altimeters.

It has long been community wisdom that accurate bathymetric datasets are especially critical for modeling of shelf and coastal tides. It is also a fact that coastal geometries and bathymetry impact the deep ocean tides significantly. Arbic et al. (2007), Arbic et al. (2009), and Arbic and Garrett (2010) show, for instance, that removal of the Hudson Strait from the global tidal system increases the global mean amplitude of the largest tidal constituent (M_2) by 10%. It stands to reason then that improvements in coastal bathymetric datasets are likely to improve the open-ocean tides in purely hydrodynamic tide models, which form the backbone of some of the state-of-the-art assimilative tide models such as FES and TPXO. One of us (Florent Lyard) has been making substantial efforts in this regard. Lyard and collaborators have utilized local navigation charts, where they are available, to improve bathymetric datasets in about 40 different shelf areas around the globe. They have found that incorporation of these improved shelf bathymetries greatly increases the accuracy of their purely hydrodynamic global tide solutions, not only in the shelf/coastal regions, but also in the open ocean. It is quite clear that gathering and assembling improved bathymetry datasets is a critical pre-requisite, and must be addressed at an international level to coordinate the efforts of the tidal and geodetic communities.

Another difficulty in shelf/coastal tide modeling is that physical parameters such as the bottom friction coefficient need to be spatially modulated to accurately represent tides in shallow waters, especially in near-resonant areas. Spatial resolution must be increased, and the larger tidal spectrum, including non-linear tides, must be resolved. In sum, the deployment of an accurate tidal model needs intensive efforts for each significant shelf/coastal area. Because the relative density of tidal data is lower in shelf/coastal areas (due to the reduction of typical wavelength and the variety of tidal regimes in those regions), the accuracy of the prior hydrodynamic solutions needed to perform efficient data assimilation must be carefully controlled. Moreover, owing to coarse sampling and sometimes unfavorable aliasing, many non-linear constituents are barely observed with current altimetry, and the assimilated dataset reduces to sparse tide gauge datasets, making the accuracy of the prior solutions even more critical.

The interests of tide modelers, geodesists, and hydrologists overlap at the coastline and within tidal estuaries. The deficiencies in tide models are a significant source of error in the marine geoid near the coastline (Sandwell et al., 2013), which leads to uncertainty in the pressure gradient associated with freshwater transport across the land-ocean boundary. Conventional practice in hydrodynamic river and estuary modeling involves adjusting the bottom drag coefficient and mean sea level to achieve agreement with observed river transport, a procedure which mixes vertical datum errors with model parameter error. There will be difficulty interpreting SWOT data in estuaries where the mean water level, geoid, and tides are uncertain, and the nonlinear coupling of tides and river flows in estuaries suggests that progress will result from the collaboration of specialists in all three areas.

In consequence, regional modeling of shelf/coastal areas should be encouraged, either to provide regional patches for, or to be later integrated into, global ocean tide models.

High-latitude barotropic tides

The accuracy of high-latitude tides is limited by the lack of coverage of the TOPEX/Jason class of altimeters, the lack of good bathymetric data in polar areas especially under the Antarctic Ice Shelves, the presence of seasonal and/or persistent ice cover, and the relative paucity of validation data in polar areas. Stammer et al. (2014) documented some progress in the accuracy of high-latitude tide models constrained by the TOPEX/Jason class of altimeters. The RMS M_2 elevation discrepancy between the assimilative barotropic models and a set of 20 Arctic tide gauges ranges from 4-6 cm, larger than the SWOT 1 cm target error and a 20-30% relative error with respect to a signal of 20 cm. The situation is similar though somewhat better in the Antarctic, with a 3-4 cm RMS M_2 elevation discrepancy between the assimilative barotropic models and a set of 49 Antarctic tide gauges, representing a 10% relative error with respect to a signal of 38 cm. But these statistics are not definitive because of the general lack of useful validation data.

As noted in Stammer et al. (2014), between now and the launch of SWOT, analysis of data from several planned polar-focused missions such as CryoSat-2, HY-2A, Sentinel-3, and ICESat-2 will help to improve estimates of high-latitude tides. They recommended deployment of validation measurements, such as bottom pressure sensors in high-latitude regions with large inter-model discrepancies such as Nares Strait and GPS records in locations such as the Ross Ice Shelf where the validation records used are older and have greater uncertainties. GRACE gravity data were also used by Stammer et al. to assess model accuracies, and GRACE may be especially useful in polar regions owing to its more complete spatial coverage (as opposed to sparse tide gauges), but the data are also limited by the coarse spatial resolution of satellite gravity. Nonetheless, GRACE data may also still prove useful in directly improving models if further work in the difficult problems of gravity inversion and gravity assimilation is forthcoming (Egbert et al., 2009).

As noted above, a difficult issue in high-latitude seas is the seasonal sea ice cover. Not only does the acquisition rate reduce to a fraction of the nominal mission observational performance, but ithe loss of observations is not random. In consequence, the formal Shannon-Rayleigh criterion used to identify and separate tidal constituents may fail to quantify the accuracy of the harmonic analysis of altimetry time series, and uncertainties of harmonic constants increase greatly. Some approaches have been developed to tackle the problem (inspection of the harmonic matrix, multi-mission data binning), and these efforts should be continued in a more coordinated manner.

Tidal harmonic analysis in high latitude seas, required by the empirical models as well as the data assimilation models, should be identified as a specific issue of interest.

Open-ocean internal tides

The coherent component of open-ocean internal tides is detectable by satellite altimetry; the internal tide signal can reach several cm in some locations (Ray and Mitchum, 1996). As such, the internal tides will be an important signal in SWOT, which, because of its ability to resolve small horizontal scales, is expected to help immensely in mapping coherent internal tides globally. At the same time, accurate removal of internal tides is necessary before the non-tidal signals of interest in SWOT data—e.g., the mesoscale and submesoscale eddy field—can be examined reliably.

In the coming years before launch, there are three major work efforts that the SWOT tide community should address concerning open-ocean internal tides: (1) Preparations must be made for how the initial SWOT tide corrections will be computed. New models of internal tides must be developed and algorithms worked out for how the models will be applied and the predictions computed, leading eventually to detailed Algorithm Theoretical Basis Documents. (2) Plans must be developed for determining how SWOT data themselves will be used to refine and improve our initial models. What approaches can be taken and how much SWOT data must be collected before realistic improvements can be obtained? It seems evident that item (1) is more critical than (2) at this juncture, because all other SWOT oceanography users will be depending on these corrections from the beginning of the mission. Moreover, aspects of (2) are more research-oriented and will no doubt proceed in many different directions depending on the individual investigators as they think about these issues in the coming years. Finally, (3) research is needed to understand the degree to which open-ocean tides—and specifically their surface elevations—maintain sufficient coherence in time to be amenable to prediction. Because the surface elevations are dominated by the lowest baroclinic modes, it is reasonable to expect they are far more coherent than the very incoherent high-mode internal tides observed with current meter moorings and other in situ measurements (e.g., Wunsch, 1975). But the degree of coherence and what this implies about SWOT tide corrections are open research questions much in need of clarification. Both observational studies based on present-day altimeter data (Ray & Zaron, 2011) and other data (e.g., Chavanne & Klein, 2010; Nash et al., 2012), as well as process studies based on high-resolution ocean models (Zaron & Egbert, 2014; Dunphy & Lamb, 2014; Shriver et al., 2014) are needed.

Notwithstanding questions of possible incoherence, it is already clear from present-day altimetry that significant energy remains coherent and can to some degree be predicted and removed from the SWOT data. Following (1) above, the SWOT project should develop models for this. Several approaches can be envisioned for developing the required models. It is not a priori evident which approach is best and several should and will be explored in the coming years.

The simplest SWOT tide correction algorithms are likely to be based on using fixed sets of global harmonic constants (possibly extended to seasonal sidelines), based on some kind of empirical analyses of past altimetry, with prediction algorithms similar to standard tidal prediction methods. A number of different mapping approaches are already being investigated and have recently been published or presented at meetings (Dushaw et al., 2011; Zhao et al., 2011, 2012; Egbert et al., 2012; Zaron, 2013). The most complicated algorithms are likely to be based on analyzing the outputs of high-resolution general circulation models that incorporate tidal astronomical forcing (Arbic et al. 2010, 2012; Shriver et al., 2012; Müller et al., 2012, 2014). The latter class of models can potentially yield both coherent and incoherent tides as a function of time, and can also inform us about the tidal versus non-tidal contributions to mission-critical quantities such as the wavenumber spectrum of sea surface height (Richman et al., 2012). Such models have thus far been run in forward (non-assimilative) mode. Initial simulations done by the Naval Research Laboratory HYCOM group with an Ensemble Kalman Filter show improvements in tidal accuracy over simulations done with purely forward tidal dynamics, although both still lag empirical methods in accurately reproducing observed tides. One can also envision developing internal-tide corrections based on approaches between these two extremes. The SWOT project should use the pre-launch years to develop several of these approaches further. Like models for barotropic tide corrections, a suite of different internal-tide correction algorithms could be developed and then compared against each other and against independent data. This should be a high priority in the years leading up to launch.

Such efforts to develop internal-tide correction algorithms are also likely, as a byproduct, to lead to useful insights into how best to incorporate eventual SWOT data into such models. There will likely be clear inadequacies in the pre-launch corrections that SWOT data themselves will do much to highlight as well as to alleviate. Among these are likely to be improvements to models of solar tides; past sun-synchronous altimeter missions (ERS, Envisat) have been useful almost exclusively for lunar tides and yield very limited information on solar tides.

Tidal correction algorithm

In the end, for all the tidal motions discussed above—open-ocean barotropic tides, shelf and coastal tides, high-latitude barotropic tides, and open-ocean internal tides—the SWOT project will require tidal corrections in the form of sea surface height maps. As the mission draws nearer the project will have to consider whether such maps are to be generated by time-stepping models or via standard atlases of amplitudes and phases of major tidal constituents. Each approach has advantages and disadvantages. For internal tides, the choice may depend on whether the temporally incoherent components can be predicted with any degree of confidence. Nonlinear effects in shallow water and estuaries and the modeling of tide and storm-surge interactions would call for time-stepping approaches. Time-stepping approaches have not generally been utilized in satellite altimetry, even for current research programs in coastal altimetry, because of the difficulties involved and the limited accuracy improvements in most regions. The standard path of using (high resolution) global atlases of amplitudes and phases for a (reasonably large but still limited) set of tidal constituents is clearly the most straightforward and well-understood approach, for which current tidal data-assimilation methods apply, and we envision that initial correction algorithms will probably follow such a course.

Recommendations

We reiterate that at the present time it is difficult to know which approaches will result in the most accurate pre-launch prior open-ocean internal tide model for SWOT. To some extent the same is true for shelf and coastal tides, and for high-latitude barotropic tides. Therefore, exploring a diversity of efforts offers the best chance for finding accurate prior models. We recommend that the SWOT project support a number of complementary approaches to developing the needed tide models for SWOT. For internal tides, this includes empirical mapping approaches (based on analyses of historical altimetry data) and various types of data-assimilation (e.g., reduced gravity models) as well as tidal syntheses based on general circulation models that include tidal forcing.

We recommend that regional studies and process studies of internal tides be encouraged alongside global correction models. Regional models offer greater spatial resolution than global models. Process models offer important insights into mechanisms of interest. For instance, process studies (e.g., presented by Ponte and Klein at the 2014 Toulouse SWOT meeting; also Zaron and Egbert, 2014; Dunphy and Lamb, 2014; Shriver et al., 2014), on the propagation of tides through an eddy-rich environment, offer useful glimpses into how internal tides become incoherent.

We recommend that efforts to improve barotropic tide models in high latitudes be undertaken with greater urgency, concentrating especially on the gap between 66° (the limit of T/P-Jason) and 78° (the limit of SWOT). Such efforts can exploit recent and future satellite data, including Cryosat-2, ICESat-2, Sentinel-3, and possibly GRACE.

Following previous experience with T/P and Jason altimetry, we recommend that plans be implemented for adopting two or more models for tidal corrections in the SWOT GDRs, since this allows users to easily compare corrections and to check sensitivity to their adopted corrections.

The tidal estuarine issue is extremely challenging and it is difficult at present to foresee a global ocean tidal correction being adequate for those regions. However, we recommend that the project provide adequate inputs (such as appropriate boundary conditions) to support modeling/data assimilation efforts by dedicated groups. The coupling of estuary tides to river discharge suggests that interpretation of SWOT data in tidal estuaries will require collaboration amongst tide modelers, geodesists (for bathymetry and the coastal marine geoid), and hydrologists.

Because improvements in shallow-water and near-coastal tides are so dependent on accurate bathymetry, we recommend that frequent discussions of bathymetry, and a repository for improvements to bathymetric databases, be encouraged. In this regard SWOT project support to ease cooperation with institutional bodies such as hydrographic databases would be welcomed.

We recommend that a coordinated effort to evaluate global internal-tide models be undertaken. The Stammer et al. (2014) review paper undertook a comprehensive review of barotropic tides, but did not review baroclinic tides. Similar assessment work with baroclinic models will highlight useful progress as well as likely inadequacies in modeling.

We recommend that a coordinated effort to improve shallow-water and coastal tide-gauge datasets for both model development and model validation be undertaken. The datasets available and used by Stammer et al. (2014) were spatially very limited and were completely inadequate for work with truly global models. Some regions, of course, will always remain poorly sampled. However, careful, detailed work with historical data could recover useful data, and greater efforts at international collaboration could also extend the network used by Stammer et al. (2014).

Finally, we note that discussions of tidal processing technology are needed for the project. Because hourly output is standard for tidal processing, and because internal tides have short spatial scales, the output of global internal tide models, for instance, is very large, thus expensive to store and to analyze. Frequent discussions of improvements in efficiencies of analysis methods could prove very useful for the project. More generally, algorithms dedicated to submeso/mesoscale and internal tide surface signal separation will be needed as well for realistic numerical simulations and SWOT data processing.

References

Arbic, B.K., P. St-Laurent, G. Sutherland, and C. Garrett, 2007: On the resonance and influence of tides in Ungava Bay and Hudson Strait. Geophysical Research Letters 34, L17606, doi:10.1029/2007GL030845.

Arbic, B.K., R.H. Karsten, and C. Garrett, 2009: On tidal resonance in the global ocean and the back-effect of coastal tides upon open-ocean tides. Atmosphere-Ocean 47, 239-266, doi:10.3137/OC311.2009.

Arbic, B.K. and C. Garrett, 2010: A coupled oscillator model of shelf and ocean tides. Continental Shelf Research 30, 564-574, doi:10.1016:/j.csr.2009.07.008.

Arbic, B.K., A.J. Wallcraft, and E.J. Metzger, 2010: Concurrent simulation of the eddying general circulation and tides in a global ocean model. Ocean Modelling 32, 175-187, doi:10.1016/j.ocemod.2010.01.007.

Arbic, B.K, J.G. Richman, J.F. Shriver, P.G. Timko, E.J. Metzger, and A.J. Wallcraft, 2012: Global modeling of internal tides within an eddying ocean general circulation model. Oceanography 25, 20-29, doi:10.5670/oceanog.2012.38.

Carrere, L., F. Lyard, M. Cancet, A. Guillot, and L. Roblou, 2012: FES 2012: A new global tidal model taking advantage of nearly 20 years of altimetry. Proceedings of the symposium “20 years of progress in radar altimetry”, Venice.

Chavanne, C. P., and P. Klein, 2010: Can oceanic submesoscale processes be observed with satellite altimetry? Geophysical Research Letters, 37, L22602.

Dronkers, J.J., 1964: *Tidal Computations in Rivers and Coastal Waters*, North-Holland, Amsterdam.

Dunphy, M., and K. G. Lamb, 2014: Focusing and vertical mode scattering of the first mode internal tide by mesoscale eddy interaction. Journal of Geophysical Research Oceans, 119, 523-536.

Dushaw, B. D., P. F. Worcester, and M. A. Dzieciuch, 2011: On the predictability of mode-1 internal tides. Deep Sea Research Part I 58(6), 677–698, doi:10.1016/j.dsr.2011.04.002.

Egbert, G.D., A.F. Bennett, and M.G.G. Foreman, 1994: Topex/Poseidon tides estimated using a global inverse model. Journal of Geophysical Research 99, 24821-24852.

Egbert, G. D., S. Y. Erofeeva, S.-C. Han, S. B. Luthcke, and R. D. Ray, 2009: Assimilation of GRACE tide solutions into a numerical hydrodynamic inverse model. Geophysical Research Letters 36, L20609, doi:10.1029/2009GL040376.

Egbert, G.D., and S.Y. Erofeeva, 2002: Efficient inverse modeling of barotropic ocean tides. Journal of Atmospheric and Oceanic Technology 19, 183-204.

Egbert, G. D., S. Y. Erofeeva, and E. D. Zaron, 2012: Mapping M2 internal tides using a data-assimilative reduced gravity model, Ocean Sciences Meeting, Salt Lake City.

Godin, G. 1999: The propagation of tides up rivers with special considerations on the upper Saint Lawrence River. Estuarine, Coastal, and Shelf Science., 48, 307–324.

Jay, D. A., K. Leffler, and S. Degens, 2011: Long-term evolution of Columbia River tides. Journal of Waterways Port Coastal Ocean Engineering, 137, 182–191.

LeBlond, P. H., 1978: On tidal propagation in shallow rivers. Journal of Geophysical Research, 83(C9), 4717–4721.

Le Provost, C., M.L. Genco, F. Lyard, P. Vincent, and P. Canceil, 1994: Tidal spectroscopy of the world ocean tides from a finite element hydrodynamical model. Journal of Geophysical Research 99, C12, 24777-24798.

Lyard, F., Lefevre, F., Letellier, T., and Francis, O., 2006. Modelling the global ocean tides: modern insights from FES2004. Ocean Dynamics, 56:394–415, doi:10.1007/s10236-006-0086-x.

Müller, M., J. Cherniawsky, M. Foreman, and J.-S. von Storch, 2012: Global map of M2 internal tide and its seasonal variability from high resolution ocean circulation and tide modeling. Geophysical Research Letters, 39, L19607, doi:10.1029/2012GL053320.

Müller, M., J. Cherniawsky, M. Foreman, and J.-S. von Storch, 2014: Seasonal variation of the M2 tide. Ocean Dynamics 64(2), 159-177, doi:10.1007/s10236-013-0679-0.

Nash, J.D., E.L. Shroyer, S.M. Kelly, M.E. Inall, T.F. Duda, M.D. Levine, N.L. Jones, and R.C. Musgrave. 2012: Are any coastal internal tides predictable? Oceanography 25(2):80–95

Ray, R.D., G.D. Egbert, and S.Y. Erofeeva, 2011: Tide predictions in shelf and coastal waters: Status and prospects. In Coastal Altimetry, Eds.: S. Vignudelli et al., Springer-Verlag, Berlin, pp. 191-216.

Ray, R. D., and G. T. Mitchum, 1996: Surface manifestation of internal tides generated near Hawaii. Geophysical Research Letters 23, 2101–2104.

Ray, R. D., and E. D. Zaron, 2011: Non-stationary internal tides observed with satellite altimetry. Geophysical Research Letters 38, L17609, doi:10.1029/2011GL048617.

Richman, J.G., B.K. Arbic, J.F. Shriver, E.J. Metzger, and A.J. Wallcraft, 2012: Inferring dynamics from the wavenumber spectra of an eddying global ocean model with embedded tides. Journal of Geophysical Research 117, C12012, doi:10.1029/2012JC008364.

Sandwell, D. T., E. Garcia, K. Soofi, P. Wessel, and W. H. F. Smith, Towards 1 mGal Global Marine Gravity from CryoSat-2, Envisat, and Jason-1, The Leading Edge, 32(8), 892899. doi: 10.1190/tle32080892.1, 2013.

Shriver, J.F., B.K. Arbic, J.G. Richman, R.D. Ray, E.J. Metzger, A.J. Wallcraft, and P.G. Timko, 2012: An evaluation of the barotropic and internal tides in a high resolution global ocean circulation model. Journal of Geophysical Research 117, C10024, doi:10.1029/2012JC008170.

Shriver, J.F., J.G. Richman, and B.K. Arbic, 2014: How stationary are the internal tides in a high-resolution global ocean circulation model? Journal of Geophysical Research Oceans 119, 2769-2787, doi:10.1002/2013JC009423.

Stammer, D., R.D. Ray, O.B. Andersen, B.K. Arbic, W. Bosch, L. Carrere, Y. Cheng, D.S. Chinn, B.D. Dushaw, G.D. Egbert, S.Y. Erofeeva, H.S. Fok, J.A.M. Green, S. Griffiths, M.A. King, V. Lapin, F.G. Lemoine, S.B. Luthcke, F. Lyard, J. Morison, M. Müller, L. Padman, J.G. Richman, J.F. Shriver, C.K. Shum, E. Taguchi, and Y. Yi, 2014: Accuracy assessment of global barotropic ocean tide models. Reviews of Geophysics 52, 243-282, doi:10.1002/2014RG000450.

Taguchi, E., D. Stammer, and W. Zahel, 2014: Inferring deep ocean tidal energy dissipation from the global high-resolution data-assimilative HAMTIDE model. Journal of Geophysical Research 119, 4573-4592, doi:10.1002/2013JC009766.

Wunsch, C., 1975: Internal tides in the ocean. Reviews of Geophysics 13, 167-182.

Zaron, E.D., and G.D. Egbert, 2014: Time-variable refraction of the internal tide at the Hawaiian Ridge. Journal of Physical Oceanography 44, 538-557, doi:10.1175/JPO-D-12-0238.1.

Zaron, E.D., 2013: Can geodetic-mission altimetry be used to improve maps of the internal tide? NASA OSTST Meeting, Boulder, CO.

Zhao, Z., M. H. Alford, J. Girton, T. M. S. Johnston, and G. Carter, 2011: Internal tides around the Hawaiian Ridge estimated from multisatellite altimetry. Journal of Geophysical Research 116, C12039, doi:10.1029/2011JC007045.

Zhao, Z., M. H. Alford, and J. B. Girton, 2012: Mapping low-mode internal tides from multisatellite altimetry. Oceanography 25(2), 42–51, doi:10.5670/oceanog.2012.40.