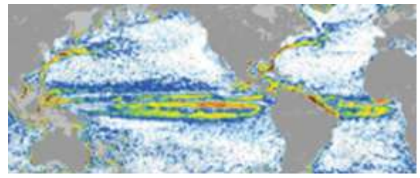

GOCE++ Dynamic Topography at the coast and tide gauge unification
GOCE ++ DYCOT

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Review of ocean dynamic topography models.

Introduction

The GRACE and GOCE missions together have dramatically improved our knowledge of the Earth's gravity field, defining the geoid to an accuracy of ~2 cm on length scales (half wavelengths) of ~100 km and larger. However, there is large variability (~30 cm RMS) remaining on shorter, unresolved length scales. The mean sea surface (MSS) is defined to comparable accuracy, and is improving particularly with CryoSat data being added. The Mean Ocean Dynamic Topography (MODT) is the difference between the MSS and the geoid. However, the MSS occurs naturally as a gridded product at high resolution, and the geoid as a spectral model with errors growing at short length scales. Optimal combination of the two is a complicated issue, and is particularly difficult at the coast.

An alternative approach is to use tide gauge measurements. In this case we have a sea level measurement *relative to a land-based datum*, exactly at the coast. To convert this to dynamic topography, we need to know the geopotential at the datum. This requires a knowledge of the geoid including all length scales, and a knowledge from GNSS measurements of the position (including vertical position) of the datum.

In this section we review the state of the art in calculating the MODT (focusing on coastal MODT) by these two methods.

Open Ocean MODT determination

Matching up the mean sea surface with the geoid requires the operation of a filter of some kind. The simplest method in the spherical harmonic domain involves conversion of the MSS (plus an extension over land and missing data, usually taken to be close to the geoid) to spherical harmonics, and then combination with the geoid followed by a (usually smooth) truncation at some chosen degree, followed be reconstitution of the harmonics in the spatial domain. The simplest in the spatial domain is to use the gridded MSS minus a spatial representation of the geoid truncated at some chosen spherical harmonic degree, and then smoothing the resulting noisy MODT using a simple isotropic (often Gaussian) kernel of chosen width.

Both of these methods involve isotropic, homogeneous smoothers (i.e. the smoothing kernel is a function only of distance from the point considered, and doesn't vary with either azimuthal angle or position of the point). However, the characteristics of the ocean circulation are such that the expected statistics of the MODT gradients are far from isotropic and homogeneous. Several recent solutions have used more sophisticated methods with more complex filters.

Rio et al (2011) used an optimal mapping technique, using an a priori ocean model/analysis product to define natural scales of the MODT as a function of region, allowing for a difference between zonal and meridional scales (i.e. an initially radially-symmetric covariance function of fixed form, stretched to different extents in the meridional and zonal directions). This permits a limited degree of anisotropy and inhomogeneity, and relies on an ocean model to determine the length scales. This satellite information was combined with a wide variety of other sources of ocean data, including surface drifters, to produce the CLS09 MODT (Rio et al., 2011), later updated to the CLS13 MODT (Rio et al., 2014). A similar method is being used in the development of the DTU15 MODT, but using currents from drifters to define the zonal and meridional length scales.

In contrast, Bingham (2010) introduced the nonlinear, anisotropic, diffusive filter. This treats the isotropic Gaussian filter as a smoothing by diffusion of the initial field, and generalises the concept by introducing diffusion coefficients which depend on direction, producing larger diffusion along currents than across them (the current directions being themselves defined by the approximate MODT). This has the effect of allowing for a smoothing of small scales without blurring the sharp gradients across strong, near-rectilinear current features. The results have been shown to have advantages over more conventional filtering in comparison with currents from drifter data (Bingham et al., 2015), though they do not completely avoid smoothing (and hence weakening) of currents. This method allows for the definition of an MODT purely based on the satellite gravity and sea surface measurements, with no additional information required.

More recently, Hughes (2015) has explored the use of a more flexible optimal mapping method based on the Wiener filter. The noise covariance function is defined based on a region known to have little large-scale dynamic variation, and a full two-dimensional signal covariance is estimated regionally (overlapping patches of 10 by 10 degrees latitude and longitude). The covariance function is taken either from a high resolution ocean model, or from a rescaled observed mean sea surface temperature field (only scales shorter than about 300 km are filtered). The two methods were found to give very similar results, and independent tests suggest a similar accuracy in the Southern Ocean to the CLS13 MODT without recourse to the additional ocean information. A significant difference, though, is that Hughes started not with a pure satellite gravity solution, but with a combined solution incorporating in-situ gravity and gravity anomalies determined from satellite altimetry over the ocean field (Fecher et al., 2015).

All of these methods have been implemented with (various releases of) GOCE gravity fields, but detailed assessments are not yet available. A point worth making, though, is that they will all be weaker in coastal regions than elsewhere, for three reasons. 1) altimeter data is poorer close to the coast, and often has gaps (see below). 2) Mapping functions based on covariance information are stronger when there is data surrounding the point in question on all sides, which is not the case at the coast. 3) The coast is special in dynamical terms, as it imposes a constraint on the direction of the flow, meaning the sea level slopes near the coast are not simply related to those nearby. In the case of this last point, it would be possible to explicitly incorporate the special nature of the coast into the anisotropic diffusion equation of Bingham (2010), but it is less straightforward to incorporate in other methods.

There are a variety of mean sea surfaces and geoids available for calculating the MODT. The primary recent MSS estimates are CLS11 (Schaeffer et al., 2012), DTU13 (Andersen et al., 2015), and the new DTU15 (Stenseng et al., 2015). Recent geoids all use the GOCE data, some in combination with GRACE, and some also in combination with in-situ data and altimetry. The GOCE data have led to significant improvements, and clear progress from Release 1 to Release 5 of the dataset – see the review by van der Meijde et al. (2015) for an overview. Rather than describe the details of the many different solutions available, we will focus (for reasons which will become apparent below) on the "combined" solutions in which some form of altimetry is incorporated into the solutions to regularise the small scales and make them compatible with a mean sea surface.

Of these combined models, the most recent are TUM13 (Fecher et al., 2015), GGM05C (Ries et al., 2016) and EIGEN6C4 (Förste et al., 2015), all of which incorporate gravity anomalies consistent with some form of the DTU MSS. TUM13 uses release 3 GOCE data together with a wide variety of in situ data and DTU10 gravity anomalies, and is provided up to degree 720 (approximately equivalent to 0.25 degree resolution). It will shortly be superseded by a model to be called GOCO05C, using the latest release 5 GOCE data and improved relative weighting of the different observations (Thomas Gruber, personal communication). GGM05C uses the DTU13 gravity anomalies (Andersen et al., 2014) and is provided to degree 360, and GGM05C uses DTU10 gravity anomalies as used in the pre-GOCE EGM08 gravity field (Pavlis et al., 2012). It is provided to degree 2190.

The DTU13 MSS has associated with it a DTU13 MODT, which is calculated using the earlier EIGEN-6C3 Geoid which is available to degree 1949 (Förste et al., 2011).

These latest data sources have moved on significantly since the initial comparison of geodetic ocean dynamic topographies demonstrated good general agreement with ocean model predictions (Woodworth et al., 2012). That comparison used Release 1 GOCE solutions with a very simple isotropic smoothing. There is clearly scope to improve on these comparisons now.

The MODT at tide gauges

A quite different methodology is necessary to calculate the MODT at tide gauges. A tide gauge is effectively a point (in space) measurement of the sea surface relative to a given land-based datum. In order to calculate the MODT from such a measurement it is necessary to know the precise position (e.g. from GPS) of the datum, and the geoid at that point (assuming the connection between datum and tide gauge zero is made by levelling). A point value of the geoid is therefore required, with full spectral content. This means that more than just satellite data is required, because geoid variability on scales shorter than those resolved by satellite gravity is typically around 20-30 cm, and can be more than 2 m in some cases (Gruber et al., 2012). The method is also limited to the relatively small number of tide gauges for which accurate GPS datum positions have been calculated.

Much of the work on this method has taken place under the GOCE+HSU study (see http://www.goceplushsu.eu/). A common approach to accounting for this "omission error" was to use GOCE-derived geoid solutions up to a chosen spherical harmonic degree, and supplement these with coefficients from EGM08 (Pavlis et al., 2012) at higher degrees. In all cases it was found that, although known to be an imperfect methodology, this produced significantly better results than simply using the solutions to low degree (typically in the range 180 to 220).

Using this methodology, Woodworth et al. (2012) showed agreement between tide gauge derived MODT and that from ocean models at the level of 6-10 cm standard deviation in favourable regions, rising to 14 cm on the Pacific coast of the Americas. At that time, this was larger than the disagreement between ocean models, and therefore demonstrated the accuracy possible with the geodetic data available. Similar levels of accuracy were found in studies with the complementary aim of defining continental vertical datums (Gruber et al., 2012; Bolkas et al., 2012).

A significant step forward has been made since then with the improved GOCE data resulting from the longer time series available, and with the emergence of combined solutions which integrate GOCE and GRACE data with in-situ gravity and altimeter-derived gravity. Hayden et al. (2015) use the Release 3 GOCE solutions in comparison with tide gauge data to determine the appropriate datum for Canada, with good consistency. More importantly, the combined solution of Fecher et al. (2015) extends the usable geoid resolution to degree 720, reducing the incompatibility with the shorter scales of EGM08. This, in combination with the collection of new GPS measurements at tide gauges (Hughes et al., 2015; Woodworth et al., 2015), has improved accuracy to the point where it is now possible to distinguish between different ocean models and see useful oceanographic features from tide gauges.

To illustrate this, Figure 1 shows observed and modelled MODT around the coast and islands of the North Atlantic and Mediterranean Sea (Hughes et al., 2015). The broad spatial pattern is in good agreement, and the difference between the two is a joint measure of the accuracy of the geoid used, the tide gauge and GPS data, and the ocean model.

To explore this further (Hughes, Woodworth and Gruber, unpublished work), we have looked at the misfit as a function of geoid and ocean model. This is shown in Figure 2, which clearly shows best agreement when using the most recent ocean models (Nemo12, NemoQ and Ecco2) and the combined geoid TUM13 (though only when extended with EGM08). The extended satellite only solutions show improvement from Release 3 (GOCO03x) to Release 5 (DIR5x). The importance of small scale geoid information is emphasised by the success of EGM08, which is only improved on by TUM2013x (which uses Release 3 GOCE data), and perhaps DIR5x. In these plots, one of the "models" (Aviso2014) is in fact the CLS13 MODT (Rio et al., 2014) which also includes Release 3

GOCE data as well as much more ocean information. The column labelled “NemoAviso” is an average of this with the two Nemo models, which gives the values shown in Figure 1.

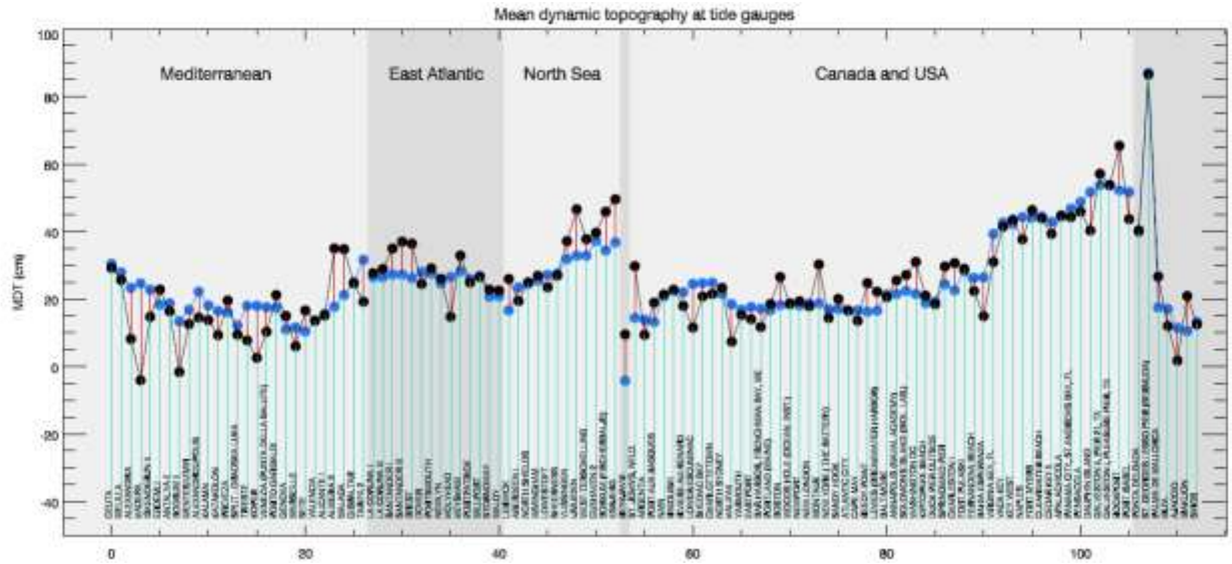

Figure 1: Mean ocean dynamic topography from tide gauges around the North Atlantic and Mediterranean (black), compared with the average of two ocean models and an observational analysis (blue). Means are arbitrary. Taken from Hughes et al. (2015).

We now see that the best combination of geoid and ocean model permits agreement on basin scales of around 8 cm standard deviation, or perhaps 5 cm if we can legitimately exclude a small number of tide gauges from the analysis. The basin scale accuracy is thus as good now as the regional accuracy was in the Woodworth et al. (2012) study. As a result of these studies it is now accepted that there are large errors in levelling over continental scales.

Outside the HSU study, other groups have also been comparing MODT estimates at tide gauges with those from ocean models, with a variety of different aims. Featherstone and Filmer (2012) showed that a large part of the tilt observed in the Australian national datum is due to ocean dynamics, and Filmer (2014) went on to use ocean models to identify levelling errors in the region. Penna et al. (2013) used a similar analysis to identify levelling errors in the UK national network. Lin et al. (2015) focused on the North Pacific, adding more tide gauges from the US, Canada and Japan, and making a partial analysis of the dynamical causes of the observed alongshore slopes. Other analyses making dynamical interpretations include Higginson et al. (2015), who showed that the steep slope along the Florida coast is a robust feature associated with the Gulf Stream, and Hughes et al. (2015) who showed that the Mediterranean inflow has far-reaching effects on the MODT of much of Europe. However, there remain some fundamental questions about how alongshore slopes of the MODT are controlled and maintained on global scales.

In most cases, the GPS measurements used in these analyses are “campaign” measurements, i.e. short duration deployments to fix a position at a single time. Little attention has been paid to the issue of vertical land motion, which is assumed to be a small factor over the time scales considered.

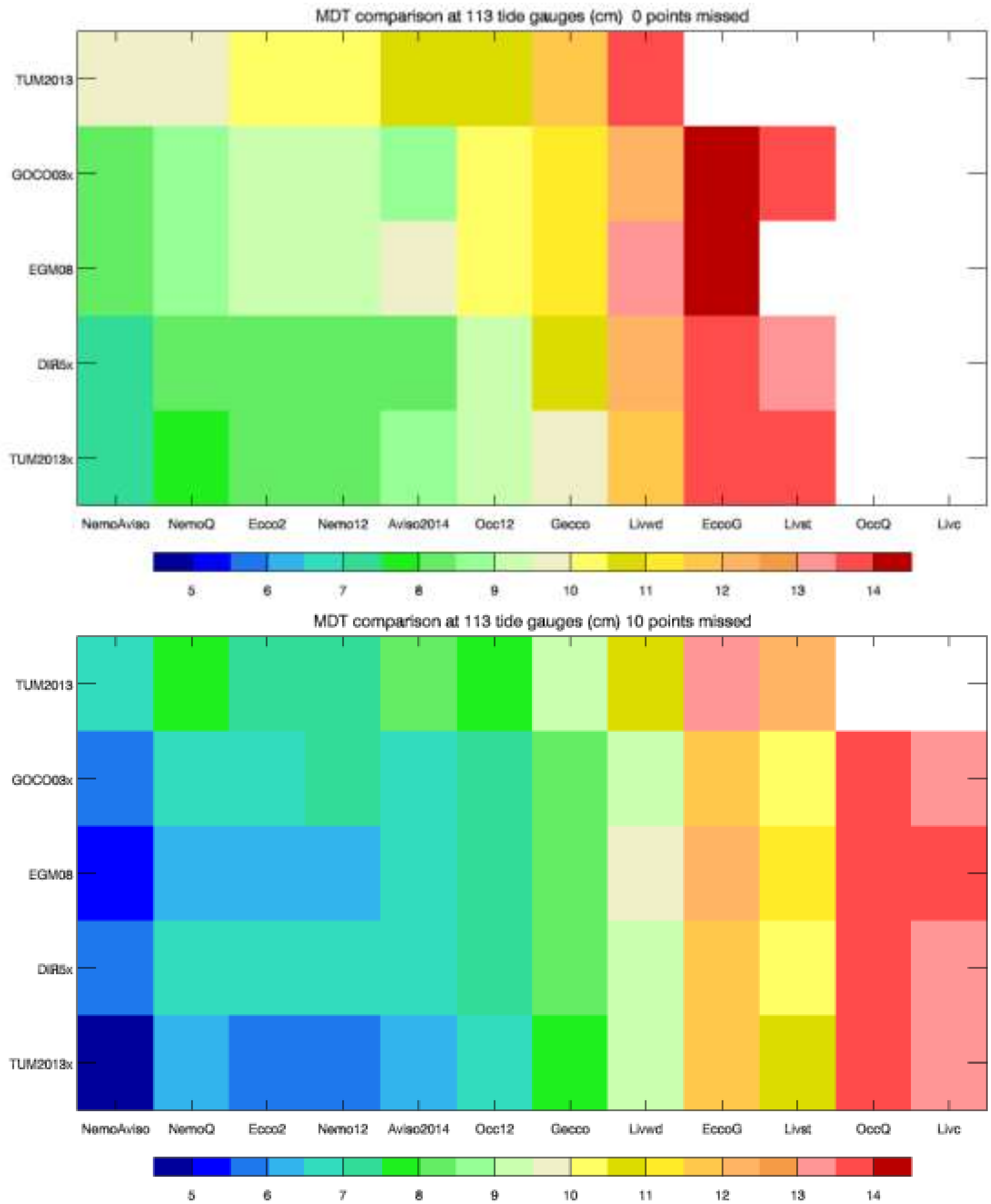

Figure 2: Standard deviation (cm) of the difference between ocean model MODTs (x-axis) and those derived from tide gauges with different geoids (y-axis). Geoids with "x" in the name are extended to higher degree using EGM08. Top uses all 112 tide gauges from Figure 1, bottom uses the "best" 102 gauges. White is off the scale.

An exception is the Lin et al. (2015) study, which used the full time-dependent GPS data. In some regions, particularly tectonically-active regions like Japan, and regions of strong Glacial Isostatic Adjustment like Canada and Scandinavia, this vertical motion can be a significant issue, and should be accounted for wherever possible. For this reason, the present study aims to use full GPS time series wherever they are available, and at least use a fitted linear trend to adjust those measurements to a common epoch. even outside these obvious regions, vertical land movement rates are observed which could contribute several cm offsets if applied a decade or so away from their measurement epoch (Santamaría-Gómez et al., 2012).

The importance of small-scale geoid structure raises a couple of possibilities which, to this point, have not generally been applied to MODT calculations. First, the dependence on the geoid at a single point can be mitigated if there are levelling connections between the tide gauge and several points rather than just one. Simple statistical averaging then means that the tide gauge level will be better determined if there are GPS coordinates for each of these points. In principle, this could mean the whole of a national levelling network. The difficulty is in working out how to weight the contributions from nearby and distant parts of the network, as it is now established that errors come to dominate the levelling over large scales. This is effectively the approach which has been taken by Ophaug et al. (2015), who have used satellite gravity data to provide a “corrector surface” to the Norwegian levelling network, thus enabling MODT calculation at far more tide gauges than the few which have good local ties to GPS measurements.

The second issue is that of smoothing along the coast. Ocean models tell us that the MODT varies gradually along the coast except in a few special cases (e.g. the Gulf Stream region, and the mouth of the Mediterranean where there is effectively a gap in the coast). Accounting for this expected smoothness could enable a better estimation of the MODT. However, it also means that we would miss any sharp gradients due to processes which are missing from ocean models or are poorly modelled (e.g. effects of river flow).

Summary

It has been shown that the coastal MODT is consistent with ocean model predictions at the 5-10 cm level. However, recent improvements and new geoid data available have not yet been fully exploited. There are two approaches: the open ocean approach using satellite altimetry, for which the next section addresses many of the issues, and the tide gauge approach. For the latter, and to a large extent also for the former approach, the inclusion of small scale gravity information is crucial. Ideally this information is incorporated into a global gravity solution in a consistent way, which is why it has been difficult to demonstrate improvements over the pre-GOCE EGM08 geoid which took this approach. The TUM13 geoid demonstrates that extension of the consistent solution to degree 720 is possible and results in significant improvements over the simple combination with EGM08, but this still requires additional information from EGM08 at higher degrees.

These consistent geoid solutions (TUM13, GGM05C, EIGEN-6C4, and the expected GOCO05C) all use versions of the gravity anomalies associated with the DTU mean sea surface, so should be compatible with that surface when calculating the MODT.

Review of satellite altimetry possibilities.

Introduction

Satellite altimetry has traditionally focused, for a number of reasons, on the open ocean. Recently there have been a number of developments with the aim of improving coastal altimetry (Vignudelli et al., 2011), involving both new techniques for exploiting old and current missions, and new kinds of satellite altimeter. Here we review the current state of understanding and development, and suggest ways in which this can be further advanced with the aim of maximising the return from satellite altimeter measurements in coastal regions, and minimising the distance to the coast from which measurements can be taken.

Traditional altimetry

Traditional, pulse-limited altimetry works by measuring the travel time of a radar pulse between satellite and sea surface, and back. Over the ocean, the reflection is from a circular area of radius typically a few kilometres (depending on wave height – the radius is larger when waves are higher), termed the altimeter footprint. As a function of time, the reflection is initially from the nadir point directly below the satellite, and spreads in concentric circles over time. Typically, data are amalgamated into one measurement per second (1 Hz), giving an along-track resolution of 6-7 km depending on satellite altitude, but higher temporal resolution (10-20 Hz) may be available, at the cost of weaker statistical averaging leading to higher noise values at individual points.

This is the mode of operation for Geosat, ERS-series, TOPEX/POSEIDON, Jason 1-2, Envisat, and other altimeters before the 2010 launch of Cryosat 2.

These altimeters suffer from various problems in coastal waters which limits their ability to measure close to the coast. There has been significant recent progress in addressing these problems, which relate to both the nature of the returned signal (the waveform) when land is included in the altimeter footprint, and also the various corrections which are used to convert travel time to sea surface height. These are the ionosphere, wet tropospheric, dry tropospheric, and sea state bias corrections (we assume a well-determined satellite orbit, though there are also subtleties to this, particularly on long time scales). More detailed descriptions of these corrections and their sizes can be found in Andersen and Scharroo (2011). In addition, there is the important issue of temporal aliasing (including tides), to which we will return below.

Corrections to the sea level measurement.

The ionospheric correction is not especially troublesome at the coast, since the ionosphere does not behave any differently at the coast compared to the open ocean. Ionospheric models are commonly used to make a path-length correction at the level of a around 1 cm accuracy, though in some cases the combination of two radar frequencies (Ku and C band in the case of Topex/Jason) allows an independent ionospheric correction to be calculated from the difference in inferred sea surface height. In the latter case, the coast is slightly more complicated, but along-track smoothing (about 100 km) is the best approach in open ocean, so extrapolation near the coast is not particularly troublesome. However, using the difference between Ku and C band ranges does make the assumption that other factors which influence the two bands differently (such as sea state and wet tropospheric correction) have been properly accounted for. This is less true in coastal than in open ocean regions, so a degree of coastal deterioration is to be expected. Recent data-based global ionosphere models appear to show sub-centimetre, but dual-frequency corrections remain better at least at distances greater than 10 km from the coast accuracy (Andersen and Scharoo, 2011). The AltiKa altimeter operates at Ka band, which is less sensitive to the ionosphere.

The wet tropospheric correction is more complicated, since it can involve quite short length scales close to the coast. The size of this correction is highly variable around the globe, with standard deviations varying regionally between more than 10 cm and less than 3 cm (e.g. Joana Fernandez et al., 2013). This problem is exacerbated by the large footprint of the radiometer which measures atmospheric column water content. The main return comes from a circle of radius 15-25 km, but points further afield can contribute, and land points can produce a large distortion of the return. For this reason, there can be a margin of as much as 50 km around the coast over which the wet tropospheric correction is not available.

One option is to use atmospheric model analyses, and this does lead to a significant improvement, but the small spatial scales and rapid temporal evolution close to the coast limit the quality of such corrections. Another very promising option is to use land-based GNSS receivers to add information on the land side of the coastal boundary, to complement the offshore radiometer measurements. This is the approach taken by Joana Fernandes et al. (2013), who conclude that total tropospheric delay can be determined at the level of about 0.6 cm, and agreement with atmospheric models (in particular, the ERA-Interim run from ECMWF) is at 1.2 cm RMS. Thus, atmospheric models can be used where GNSS data are sparse, but including GNSS data improves the accuracy to sub-centimetre. This is a similar level if improvement to that found from using the radiometer-derived wet correction rather than a model over the open ocean (Andersen and Scharroo, 2011). It is worth noting that most of this improvement comes from the wet tropospheric delay component, as the dry troposphere corrections agree at the 0.1-0.3 cm level, equivalent to 0.5-1.5 mbar errors in atmospheric pressure. The latter number becomes the relevant one when considering inverse barometer corrected sea surface height.

The last of the “corrections” is the sea state bias (SSB), which accounts for the fact that surface waves reflect radar unevenly, so that the apparent “mean” sea surface is not a true average over the distribution of heights occupied by the range from peak to trough of the waves. This correction is empirically determined (it is typically a few percent of significant wave height, but depends on the nature of the wave field so that empirical fits use both altimeter-derived wave height and wind speed inferred from radar reflection coefficient as inputs). The size of the correction may be more than 15 cm in the mean, in parts of the Southern Ocean), though typically around 10 cm in coastal regions, with temporal variability of about half that. SSB is complicated by the fact that the bias depends not just on the state of the sea surface, but on the nature of the altimeter tracker response to that state (how the instrument determines where to measure), making its determination a subtle question which must be readdressed any time there is a change in tracking methodology. In addition, it is acknowledged that the bias depends on more parameters than the two which are available from satellite altimeter measurements. Furthermore, waves change their character in shallow water as they start to interact with the sea floor, and as they come closer to a lateral boundary (so that propagation direction becomes more biased). There are good reasons to expect the SSB correction to take a different form in shallow water than in the open ocean (Vandemark et al., 2008).

A promising approach to addressing this issue is the combination of altimeter data with operational wave model analyses to supply the missing information. This method has been used to develop a correction for the Jason 1 and Jason 2 altimeters (Tran et al., 2010), and is also being used to develop a model for the AltiKa altimeter (Valledeau et al., 2015), though little detail is available about how coastal and open ocean regions differ in this correction. This is an area which would benefit from significant extra attention, as it is presently very difficult to evaluate the accuracy of the SSB corrections in coastal regions. Errors of several centimetres are possible in the mean, as well as in time dependent variations.

Improvements due to retracking.

In addition to the improved corrections discussed above, progress has been made on mitigating the polluting effects of land in the altimeter footprint, enabling improved rates and accuracy of returns in coastal regions. This is done by “retracking”, which means reanalysing the returned waveform with different software in order to improve the chances of identifying the correct ocean surface amid the noise from land and other reflective surfaces. There are a myriad of proposed and implemented retracking algorithms – see Gommenginger et al. (2011) for a discussion of the issues – but we will focus here on the ALES retracker (Passaro et al., 2014), which has demonstrated clear improvements in coastal regions while remaining consistent with more standard methods in the open ocean, thus avoiding any steps between coast and open ocean.

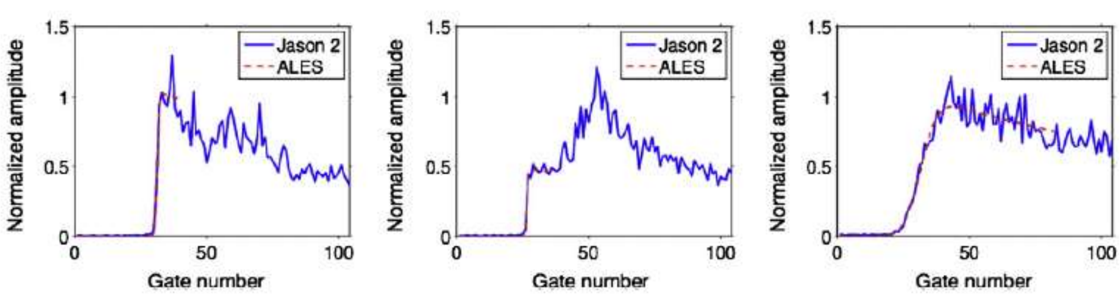

Figure 3: Example waveforms and their fits using the ALES retracker, from Passaro et al. (2014)

ALES combines a simple concept with quite sophisticated statistical methods. The idea is to identify the portion of the waveform which corresponds to the sea surface (the initial amplitude rise), and to perform a fit of the standard Brown model to this region plus the part of the tail of the waveform which is not contaminated. Figure 3 shows examples of its operation, showing how the land contamination which distorts the tail in the centre panel does not distort the fit (red), which provides the estimate of sea surface and wave height. This retracker has been implementes for Jason-1, Jason-2 and Envisat altimeters, and shows significant improvement in the number of good returns in many coastal areas. An example is shown in Figure 4, where it is compared with the standard retracker (SGDR) and results (CTOH) from an initiative to improve (without retracking) the quality of coastal altimetry by improving models and corrections (Roblou et al., 2011). The CTOH measurements are plotted at 1 Hz sampling.

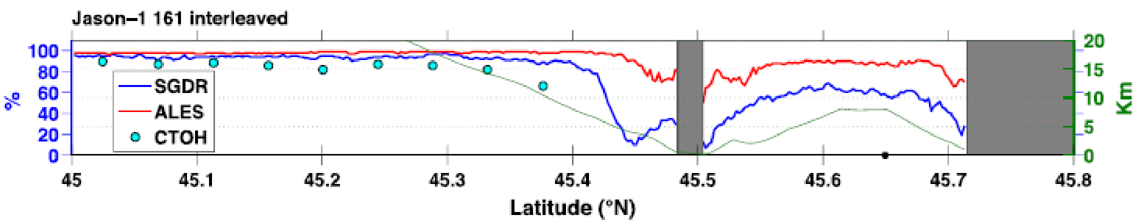

Figure 4: Percentage of returns which can be retained in order for correlation of time series with that at the tide gauge (black dot) to remain above 0.9, using three retrackers, for a Jason-1 track in the north Adriatic Sea. The green line shows distance from the nearest coast (right hand scale). From Passaro et al. (2014).

The 20 Hz sampling displayed in Figure 2 (18 Hz for Envisat) results in significant noise, seen in the point-to-point differences, which are typically 2.5 to 12.5 cm (Passaro et al., 2014). To the extent that this noise is independent at each point, averaging to 1 Hz would reduce the statistical errors to 0.4-2.0 cm.

Retracking cannot solve problems in all coastal regions. A particular exception is in the case of an altimeter moving from land to ocean, which can result in loss of track (the onboard tracker takes some time to reacquire the sea surface). Retracking cannot help in this case, as the required information simply is not recorded. However, improved strategies for onboard trackers, such as the Jason-2 DIODE/DEM tracker (based on a map of expected elevations) can greatly accelerate acquisition of the sea surface. While this is no help for historical data, it means that present and future data returns are significantly improved.

The ALES-retracked Envisat product has demonstrated its value in the complex and narrow straits separating the North Sea from the Baltic. The annual cycle of sea level in this region shows differences between mid-basin and coast (as seen from tide gauge). From the retracked product, it can be seen that the mid-basin cycle does approach that seen in the tide gauge data as the coast is approached (Passaro et al., 2015).

Aliasing of tides and other high frequencies

The above discussion concerns corrections necessary to produce a genuine measurement of the position of the sea surface. However, given the relatively infrequent sampling of altimetry (almost 10 day intervals for Jason, and longer for satellites in other orbits), there is also the question of whether the measurement is representative, or suffers from temporal aliasing. This question is most acutely felt in the case of tides which, as they have definite periods which are shorter than the sampling Nyquist period, are aliased to a variety of long periods (around 60 days for the dominant semidiurnal tides in Jason, but in many cases much longer).

In the case of tides, this is addressed by using a tide model to remove these effects. The tide models use altimetry and, in some cases, tide gauge data to constrain their predictions, and have developed significantly since the early days of satellite altimetry. For example, a recent review (Stammer et al., 2014) shows that several models now agree to better than 1 cm with open ocean observations, for the sum of 8 major tidal constituents. However, this increases to around 5 cm for shelf sea tides, and larger still for comparisons with coastal tide gauges. The situation in shallow water is not so simple though, for two reasons.

1) The statistics are skewed by small regions with large errors, so typical (median) errors are much smaller than the standard deviation - about 1.5 to 2 cm at tide gauges
2) The number of constituents needed to describe the tidal variability can be much larger in shallow water than in deep water. For example, Ray et al. (2011) shows that tides at around 3, 4, 5 and 6 cycles per day are comparable in amplitude to the diurnal tides at Calais, whereas at a deep water site they have amplitudes below the background "noise" (i.e. non-tidal ocean dynamics) level from Calais.

As a result, although tide models have improved significantly, more work remains to be done to define the nonlinear tides and the large number of constituents which are needed in shallow water. This is highly geographically variable: the relatively small tides in the Baltic region were not a large problem in the ALES retracker study mentioned above. However, around the UK, where tidal amplitudes of many metres occur, and highly nonlinear regimes are observed, errors in tidal models are still a major source of aliased variability for a comparable analysis (Simon Williams, personal communication). Furthermore, care must be taken over the sporadic large errors observed in tide models. Stammer et al. (2014) report that these are quite unpredictable, occurring in different regions of different models, and with no consistent physical cause. There is room for significant improvement, especially using regional tidal solutions, as illustrated by Ray et al. (2011), though a major limitation on such regional solutions is the poor availability of accurate bathymetry, often the limiting factor.

Aside from tides, there is also the issue of other high frequency ocean variability. In early altimeter products, this was partially dealt with via the inverse barometer correction, which serves a dual purpose: it reduces the high frequency variability, and also converts sea level to a proxy for sub-surface pressure, which is the variable of interest for ocean dynamics (for example, geostrophic flow is a result of there being a pressure gradient along a level surface). More recently, an extension to the inverse barometer correction termed the Dynamic Atmosphere Correction (DAC) has been used (Carrère and Lyard, 2003), in which a barotropic ocean model has been used to predict and remove variability at periods shorter than 20 days. This includes the dynamic response (as opposed to equilibrium inverse barometer response) to atmospheric pressure variations, as well as the response to wind stress. It merges smoothly with a pure inverse barometer correction at longer periods.

The DAC certainly reduces aliased variability. It is one of the few correction changes (in this case in comparison to simple inverse barometer) which noticeably reduces altimeter crossover variability, and it does so particularly in coastal areas (Andersen and Scharroo, 2011). This is to be expected as simple arguments show that the sea level response to a given wind stress is inversely proportional to the water depth. For this reason, aliasing of high frequency variability is a much more important issue in coastal regions than in the bulk of the ocean.

Again, however, there is clearly room for improvement. Just as for tides, improved bathymetry can make an important difference, and the DAC is a pure hydrodynamic simulation with no assimilation of observations – it could be expected that incorporating tide gauge observations would improve the model simulations. Furthermore, the model is purely barotropic (i.e. constant density). High frequency heat flux variations are likely to produce centimetric steric sea level variations in places, and narrow boundary currents have important baroclinic contributions, especially at lower latitudes. This opens up some difficulties, as any baroclinic model with sufficient resolution to simulate these boundary currents would also produce a rich eddy field, which would add noise to the sea level product (primarily a problem in the open ocean). Difficult though it may be, there would certainly be value in exploring more sophisticated modelling methods.

To give a feel for the importance of this aliasing, consider a coastal region in which sea level has a 20 cm standard deviation associated with high frequency wind and pressure driven storm surges, or an occasional 2 m surge (these are large, but not unreasonable values for a shallow, wide shelf sea). In order to remove this high frequency variability at the 1 cm level by simple statistical averaging, the 2 m surge would have to occur only once every 200 cycles (about once every 5.5 years for Jason sampling, 19 years for Envisat), and the 20 cm standard deviation would require 400 cycles (11 years for Jason, 38 for Envisat). For long time series on repeat tracks, this is not a major issue for the mean sea surface, but it means that time dependent changes are very difficult to monitor at periods shorter than a few years. For non-repeat tracks (as in the case of CryoSat-2), this becomes an important issue for the mean sea surface too.

New altimeters

A new era in satellite altimetry began with the launch in April 2010 of CryoSat 2, the first in a series of new altimeters to operate in SAR mode (in the case of CryoSat, several different modes are available). Jason 3 (launched January 2016) is a conventional altimeter, but Sentinel 3A (launched February 2016) has a SAR mode, and the future Jason Continuity Series/Sentinel 6 satellites will also have SAR mode. There are many complications and subtleties to SAR operation but, in its simplest form, Doppler shift is recorded in addition to timing of the return radar pulse. Returns from ahead of the satellite are blue-shifted, and those from behind the satellite are red-shifted, making it possible to divide the footprint into strips aligned perpendicular to the satellite track, distinguished by the Doppler shift. This enables measurements close to the coast, and in small leads within floating sea ice. SAR mode also enables an improvement in precision, with CryoSat 1 Hz noise reduced from 1.57 to 1.22 cm when SAR processing is used (Cotton, 2014).

Cryosat is not primarily an ocean altimeter, and lacks a radiometer needed for the wet troposphere correction (though alternatives are available). Nonetheless, it has clearly demonstrated the improved precision and along-track resolution expected from SAR, and has shown that good returns can be detected (with favourable orientation) as close as 100 m to the coast (Cotton, 2014). Another issue with CryoSat is that it has a nominal 369-day repeat (though small shifts mean that it can almost be considered a non-repeat orbit). While this is excellent for spatial resolution and determination of the mean sea surface, it brings the question of temporal aliasing to the fore.

Further ahead, the SWOT mission uses full SAR imaging methods to provide swath measurements of sea level to either side of the nadir track. This will provide much more data and higher spatial resolution, and has the potential to greatly improve the information available in coastal regions, including connecting coastal signals to river levels – a dynamical connection which is known to exist but is beyond the capabilities of present altimeter technology to detect. As with each new altimeter, the issue of sea state bias will need to be addressed afresh, for each kind of SAR method. Work on this is beginning with CryoSat, but it will be different again for each new altimeter.

Summary

Improved corrections are pushing to the centimetre level for coastal regions, but there remain important questions about the validity of the sea state bias correction. New techniques involving wave models are addressing part of this issue, but there are additional questions concerning the changing shape of waves in coastal regions which would benefit from further investigation.

Retracking methods are succeeding in providing more data close to the coast, though in some cases the loss of data is due to a failure of the onboard tracker as the instrument crosses from land to ocean, and these data losses are irretrievable. More recent onboard trackers do not suffer from this problem.

New SAR altimetry methods are accurate and have higher spatial resolution, allowing closer approach to the coast, but otherwise suffer the same limitations associated with corrections as traditional altimeters, including the important issue of sea state bias.

All methods suffer from important temporal aliasing effects, leading to a requirement for accurate tidal models as well as models for the high frequency response to atmospheric forcing. These issues become much more acute in coastal regions as both sources of variability increase in amplitude, and tides in particular become more complex, requiring more components than are commonly provided in tide models. This issue is mitigated for mean sea level given sufficient data (many years) for exact repeat missions, but remains an issue for the slow or no repeat CryoSat mission. The size of the problem is highly dependent on region, being particularly difficult in wide shelf seas and regions of high tides. SWOT should help in this regard, as its swath capability circumvents the classic trade-off between spatial and temporal sampling for a nadir track altimeter.

Concluding Remarks.

This report has summarised the state-of-the-art in calculation of the coastal Mean Ocean Dynamic Topography using satellite gravity in combination with either satellite altimetry or tide gauge data, with other auxiliary datasets, together with an outlook on developments and requirements for coastal satellite altimetry. The references below, together with the GOCE+HSU publication list available at http://www.goceplushsu.eu, and particularly the Tide Gauge Unification Workshop Synthesis Report available here, constitute a summary of the available scientific literature and reports. This may be supplemented for recent developments in satellite altimetry with outputs of the CryoSat+ for Ocean project at http://www.satoc.eu/projects/CP4O/.

It is clear from this report that the project partners possess expertise in all relevant aspects of the project, including development of mean sea surface and gravity products, combination with geoid to produce optimised MODT estimates, expertise in tide gauge data and GPS at tide gauges, with close links to the relevant global databases, and expertise in the synthesis and interpretation of these datasets.

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