DEVELOPMENT OF RADAR ALTIMETRY DATA PROCESSING IN THE OCEANIC COASTAL ZONE

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Technical Note on

Improvement of Corrections in Coastal Areas

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Introduction

This technical note summarizes the work done in COASTALT Work Package 2 on the improvement of various corrections for the altimetric record in the coastal zone, and provide recommendations for wet and dry tropospheric corrections, ionospheric corrections and coastal tide corrections for inclusion in a coastal altimetry product.

The recommendations specified for each correction are needed in particular for the work carried out in Work Package 3 on the design and prototyping of a coastal altimetry processor for Envisat. The recommendations include specification of algorithms and potential model sources, for inclusion in the coastal altimeter product, but in some cases we also recommend further avenues of investigation into potentially beneficial correction techniques that are still not at the operational level.

1 Wet tropospheric correction (D2.1)

1.1 Introduction and state of the art

The wet tropospheric correction is at present, together with the tidal correction, one of the two largest obstacles in deriving a good quality altimetric measurement of sea surface elevation in the coastal zone. While for the tidal models (see section 5) the issue is the accuracy of the correction based on global models, as these models are prone to large errors in the coastal zone, for the "wet tropo" the very first issue that one has to face is the complete *absence* of the microwave radiometer-derived correction in a strip of a few tens of kilometres along the coast.

The microwave radiometer-derived correction is at 1 Hz rate and over the open ocean its expected error is at centimetre level (Obligis et al, 2005); we will obviously use that information up to the along-track point where it is available (i.e. where land starts impinging on the radiometer footprint), at some tens of km from the coast. But landwards of that point, we need to either extrapolate the correction or use a model. The options are basically three:

- model the correction from some atmospheric model (such as ECMWF), adjusting the correction values so that there is continuity with the open-ocean radiometer-derived correction (this is the so-called Dynamically Linked Model approach);
- model, and hence remove, the influence of land for specific coastal areas in the radiometer readings such as the methods described by Desportes *et al* (2007);
- use maps of path delay derived from GNSS/GPS observations.

1.2 Dynamically Linked Model approach

The Dynamically Linked Model (DLM) is the most obvious approach. Fundamentally, it relies on using corrections interpolated from a large-scale atmospheric reanalysis model, and somehow 'linked' to the last few values of the available radiometer-derived correction before land starts entering the radiometer footprint. The model of choice is the ECMWF model, which is readily available in the GDRs and also chosen as reference by PISTACH for the tropospheric correction. The question is then on which particular strategy to adopt to ensure the continuity in the transition region between radiometer and model. This problem is being investigated in detail by University of Porto in the COASTALT contract extension, and a full description of the optimal strategy will be given in a later document. Here we describe a simple baseline version of the DLM approach for implementation in the prototype of the COASTALT processor.

The wet tropospheric correction derived from the ECMWF large-scale atmospheric reanalysis model may be in error in 3 ways; there can be a bias in the modelled values of the correction, a mis-location of atmospheric features or an absence of small-scale features from the model. It is not possible within the scope of this study to address the mis-location or missing scale issues, but we will compensate for the bias. There are two strategies depending on the configuration of the track segment over which the radiometer wet tropo is missing (or flagged as bad), which we refer to as the *wet tropo gap*. The algorithms implementing these two strategies are described below.

1.2.1 "Single-ended" wet tropo gap

In this case the gap is such that there is no valid measurement on the other side of the gap in the segment that is being processed. This is the case in which there are missing wet tropo data at the beginning or end of the whole segment being processed: one typical example is when the satellite is approaching or receding from a large land mass, illustrated in fig. 1.1 below, where the data segment ends.

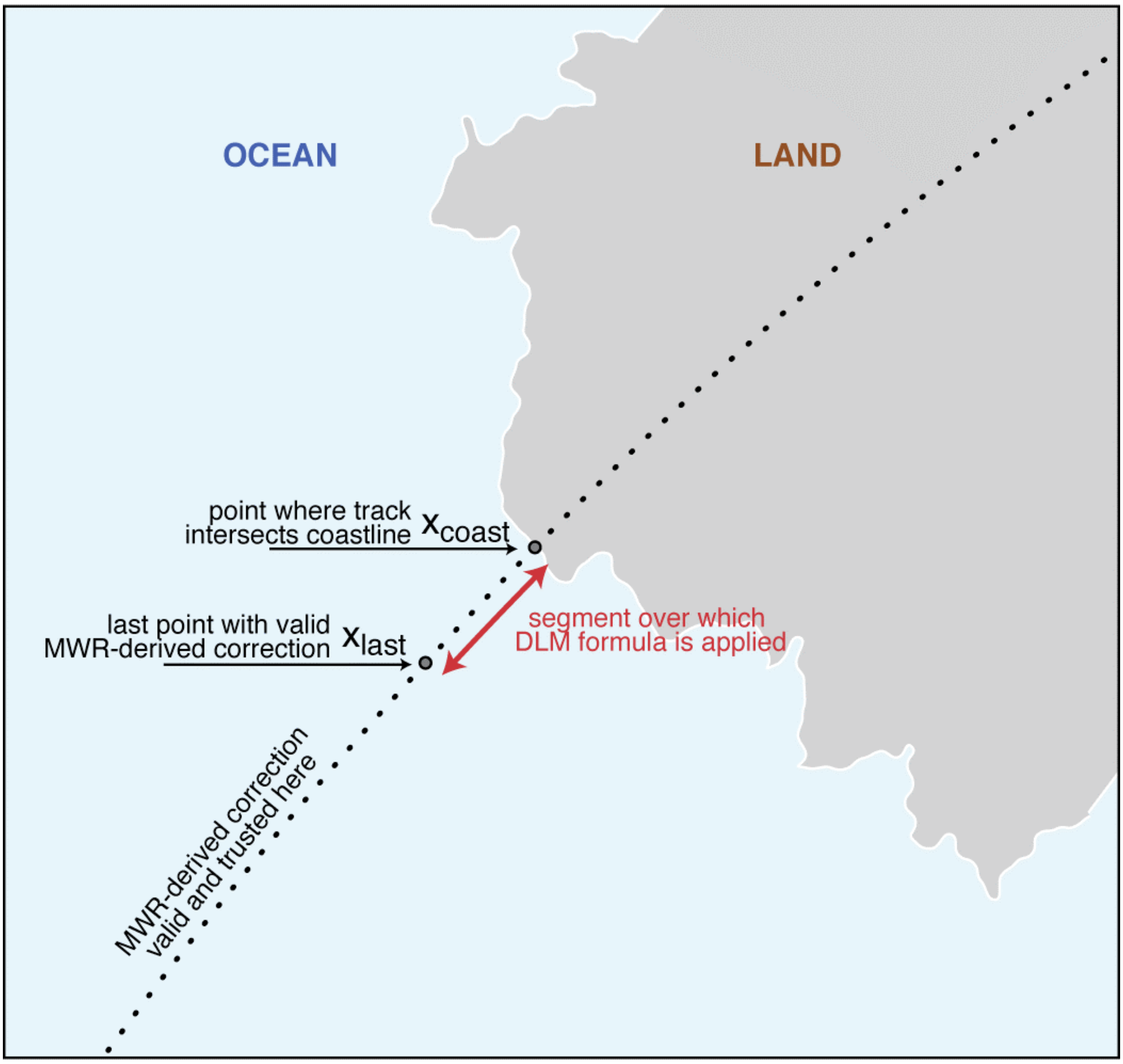

Figure 1.1 – a typical configuration for a "single-ended" wet tropo gap

First we compare the microwave radiometer-derived wet tropospheric correction R_{MWR} and modelled wet tropospheric correction R_{MOD} at the last location x_{last} of the radiometer-derived record deemed to be 'valid'. We propose that validity is initially estimated based on the MWR flag; further refinements can more directly account for the distance of the along-track point from the closest land mass. From the comparison we estimate the bias in the model correction with respect to the observed (radiometer-derived) correction:

$$bias = R_{MOD}(x_{last}) - R_{MWR}(x_{last}) \qquad (1.1)$$

then we remove that bias from the model correction up to the coastline x_{coast}:

$$R_{wettropo}(x) = R_{MOD}(x) - bias \quad \text{for } x = x_{last} \text{ to } x_{coast} \qquad (1.2)$$

1.2.2 "Double-ended" wet tropo gap

In this case the gap with missing or bad MWR-derived correction R_{MWR} values has valid values at both ends; the gap may include land or be completely over the ocean, as illustrated in figure 1.2.

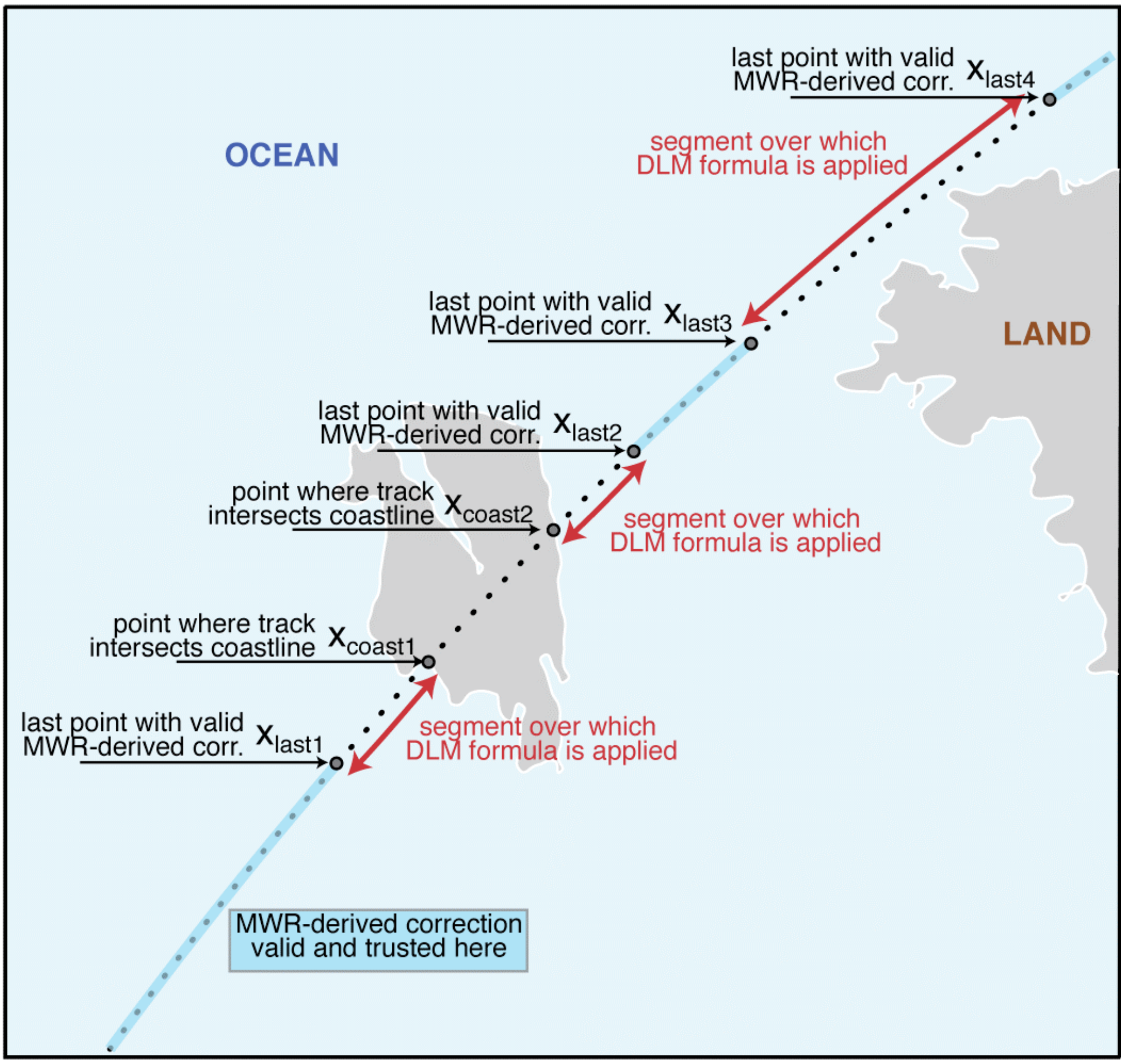

Figure 1.2 – typical configurations for a “double-ended” wet tropo gap (between x_{last1} and x_{last2} over the island in the centre and between x_{last3} and x_{last4} in the top right where lands approaches the track)

The strategy for the correction is at first similar to the one for the single-ended gap: we compare the microwave radiometer-derived wet tropospheric correction R_{MWR} and modelled wet tropospheric correction R_{MOD} at the last location x_{last} of the radiometer-derived record deemed to be valid, and from that we estimate the bias in the model correction with respect to the observed (radiometer-derived) correction. But this time we do this bias computation at both ends of the gap:

$$bias_1 = R_{MOD}(x_{last1}) - R_{MWR}(x_{last1}) \quad (1.3)$$

$$bias_2 = R_{MOD}(x_{last2}) - R_{MWR}(x_{last2}) \quad (1.4)$$

then we compensate the model correction with a combination of the two biases, varying linearly from *bias1* at x_{last1} to *bias2* at x_{last2}:

$$R_{wettropo}(x) = R_{MOD}(x) - [\, (1-\alpha)\bullet bias_1 + \alpha\bullet bias_2 \,] \quad (1.5)$$

where

$$\alpha = (x - x_{last1}) / (x_{last2} - x_{last1}) \quad (1.6)$$

and the correction is obviously only applied up to the coastlines x_{coast1}, x_{coast2}.

The same equations (1.3) to (1.6) apply to the ‘ocean-only’ gap (such as the one between x_{last3} and x_{last4} in figure 1.2, and in this case the correction $R_{wettropo}(x)$ is applied to the whole segment where the wet tropo is missing.

Finally, we note that this simplified DLM strategy leads to a deliverable wet tropospheric correction for the coastal areas that can be readily implemented everywhere in the global coastal ocean. This is the version of the correction that we recommend to be implemented in the first prototype of the COASTALT processor.

1.3 Removal of land contamination

The rationale behind this approach is that the contamination of the microwave brightness temperatures due to land entering the footprint can be modelled and removed from the measurement. To illustrate this concept, see figure 1.3 which shows the value of the microwave-derived wet tropospheric correction for all cycles of Envisat pass 343 in the region of the Agulhas Current, along the eastern South African Coast (see fig 1.4). This ascending track hits the land (in grey in the figure) at 33.28°S. It can be seen that, on top of the cycle-to-cycle variability, all cycles (except very few ones with anomalously varying wet tropo) display a characteristic decrease (increase in magnitude) of the correction on approaching land, whose influence starts at about 20 Km from the coast. This feature is mainly due to the change in emissivity over the footprint due to the land, which has a much higher emissivity than the sea (the net result of this on the correction is an overestimation of the correction magnitude). It is exactly the land surface contribution that, in theory, could be modelled and ultimately removed from the microwave measurement, leading to a correction that can be applied up to the coast. This technique has been described in detail by Desportes et al., 2007, and is being tested extensively by the PISTACH project so we will not reiterate its description here.

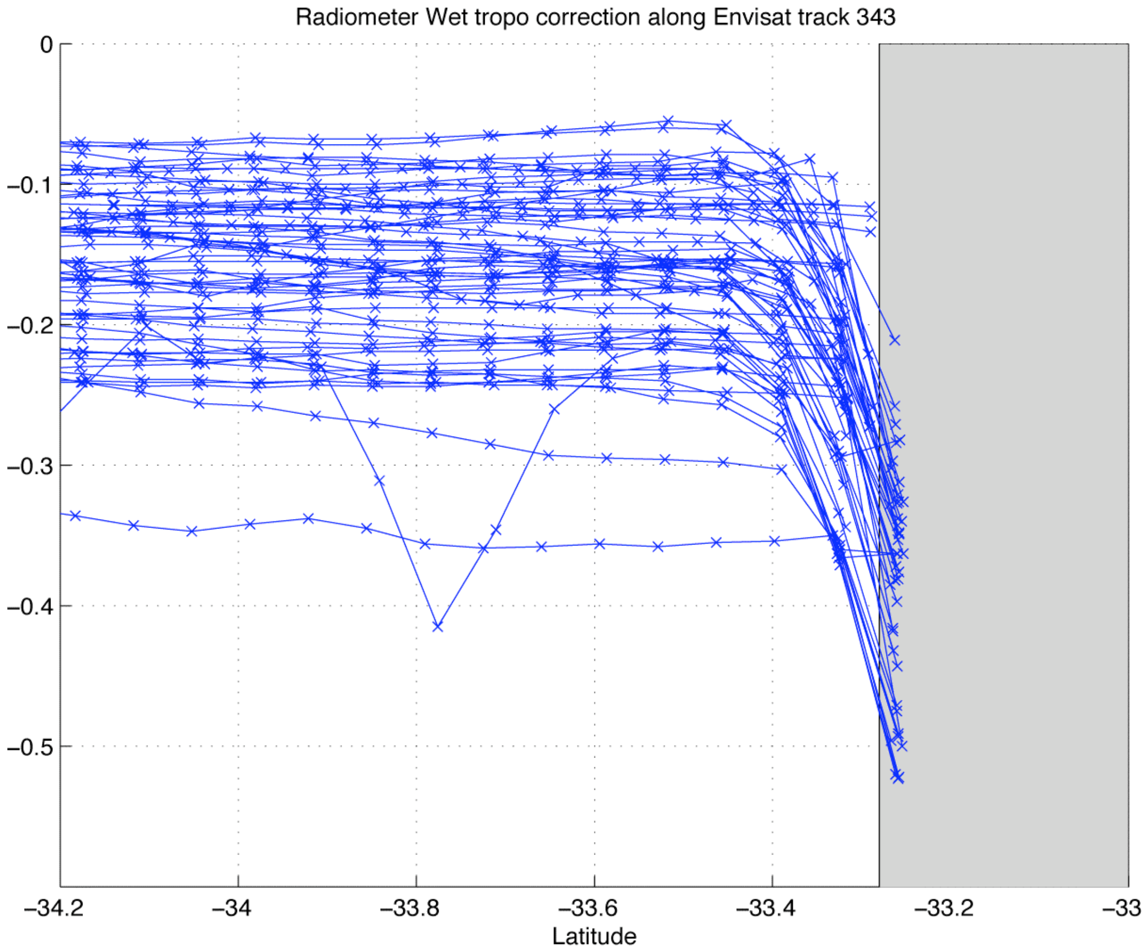

Figure 1.3 – Microwave-radiometer-derived wet tropospheric correction along ground track 343 of Envisat (figure by Joseph Maina Mbui for ALTICORE-Africa)

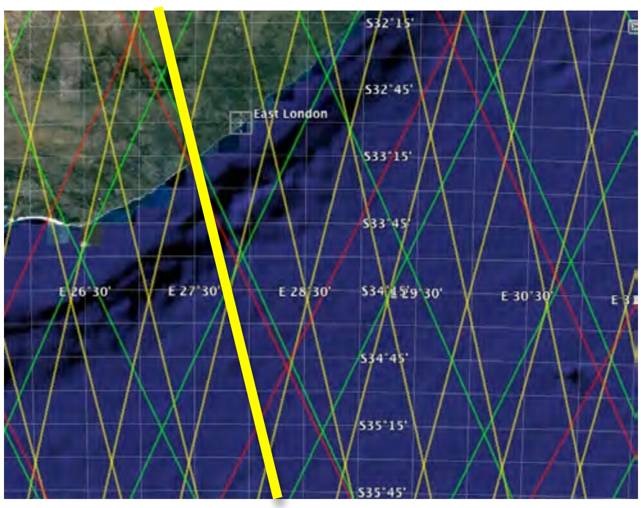

Figure 1.4 – Eastern Coast of South Africa with altimeter tracks: Envisat (yellow), T/P-Jason (red), GFO (green). Envisat track 343 is highlighted in bright yellow.

1.4 GPS derived path delay approach

This approach to the wet tropo correction employs tropospheric observations of Zenith Tropospheric Delay and Integrated Water Vapour from continuous GPS stations. Such GPS-meteo observations are becoming used widely so in principle this is a viable correction, however there are issues on how point-wise information from these stations can be extrapolated to the various altimeter tracks, and also on what ancillary information is needed for an accurate estimation of the correction. This approach is being investigated in detail by University of Porto in the COASTALT contract extension, and a full description of the optimal strategy will be given in a later document as planned in the project CCN.

1.5 Recommendations for COASTALT processor

1.5.1 Recommendation table

Correction: Wet tropospheric – operational (baseline) algorithm

Model or Algorithm	Dependence (input)	Domain (global/regional)	Res.	Where from?	Format
DLM (Eq. 1.1 to 1.6 in this section)	ECMWF reanalysis	Global	N/A	GDRs	netCDF

Correction: Wet tropospheric – research algorithm

Model or Algorithm	Dependence (input)	Domain (global/regional)	Res.	Where from?	Format
Removal of Land contamination of MWR	Emissivity Maps or climatologies	Global	N/A	CLS/PISTACH (F. Mercier /E. Obligis)	CLS to advise
GPS Wet tropo	-	Initially Portugal, W Britain	N/A	GPS community	UP to Advise

1.6 References for Section 1

Desportes, C., E. Obligis, and L. Eymard (2007) On the Wet Tropospheric Correction for Altimetry in Coastal Regions, *IEEE Transactions On Geoscience And Remote Sensing*, vol. 45, no. 7, 2139-2149.

Obligis, E., L. Eymard, N. Tran, S. Labroue, and P. Femenias, “First three years of the microwave radiometer aboard ENVISAT: In-flight calibration, processing and validation of the geophysical products,” *J. Atmos. Ocean. Technol.*, vol. 23, no. 6, pp. 802–814, 2005

2 Dry Tropospheric correction (D2.2)

2.1 Introduction and state of the art

The "dry tropo" is the correction for the effects of gas molecules in the troposphere (0-12 Km altitude) and although it is by far the largest adjustment to altimeter measurements (around 2.26 m, see Chelton et al., 2001), it is also the easiest to compute for the coastal area as it is – with very good approximation – proportional to sea level pressure P_0 :

$$R_{drytropo} \approx 222.74\ P_0/g_0(\varphi) \approx 0.2277 P_0\ (1 + 0.0026 \cos(2\varphi)) \qquad (2.1)$$

where P_0 is in millibar, $g_0(\varphi)$ is the gravitational acceleration in cm/sec^2 and φ is latitude, yielding $R_{drytropo}$ in cm (for more details see Chelton et al., 2001).

Therefore the problem of computing this correction converts into the problem of securing the best possible measurements of Sea Level Pressure. With the current widespread use of the ECMWF reanalysis fields at ¼° and 6-h resolution the accuracy of this correction is of the order of 1 cm, and remains of the same order even in coastal areas as the spatial scales of variability of air pressure are barely affected by the ocean/land transition (contrarily to what happens to water vapour for the wet tropo correction).

With the current status of the art, the dry tropo is less critical than other corrections, however this should not be intended to imply that the dry tropo is a closed issue. Improvements are still possible, and research is welcome in future projects, for instance to investigate shear at the land/sea interface, Gibbs effects in the models, effects of night/day mass transport and effects of higher temporal resolution in the models.

2.2 Recommendations for COASTALT processor

An ECMWF-based dry tropo correction has been adopted for long time by the altimetric community, is the current choice by the PISTACH Projects and therefore we also recommend it for COASTALT. However we will follow closely the development and availability of other models like ALADIN.

2.2.1 Recommendation table

Correction: **Dry tropospheric – operational (baseline) algorithm**

Model or Algorithm	Dependence (input)	Domain (global/regional)	Res.	Where from?	Format
Eq. 2.1	ECMWF reanalysis	Global	N/A	GDRs	netCDF

2.3 References for Section 2

Chelton B., Ries J., Haines B. J., L.L. Fu L. L., and P.S. Callahan, *Satellite altimetry. In: Satellite Altimetry and Earth Sciences: A handbook of techniques and Applications* [L.L. Fu, and A. Cazenave (eds.)]. 49 Vol. 69. Academic Press, San Diego, pp. 1-131, 2001.

3 Ionospheric correction (D2.3)

3.1 Introduction

The speed of a radio pulse transmitted from an altimeter is less than the velocity of light by an amount proportional to the number of free electrons in the ionosphere (Total Electron Content, TEC) and inversely related to the square of the radio pulse frequency. The amount varies from day to night, from summer to winter, and as a function of the solar cycle. The TEC can be estimated from measurements at two frequencies. Such measurements include:

1. Dual frequency range measurements by the altimeter itself (e.g. the dual frequency instruments on board TOPEX, Jason-1 and -2, and Envisat)
2. Dual frequency DORIS measurements as provided for T/P, Jason-1 and -2 and Envisat.

Early experience in the T/P Science Working Team demonstrated that corrections (1) and (2) appeared to be consistent at the 1 cm level in the open ocean, with an absolute accuracy for both also of the order of 1 cm (e.g. Zlotnicki, 1994). If this level of accuracy were to apply also in coastal areas, then either technique would certainly be adequate for COASTALT, given the magnitude of the uncertainty of other correction terms in coastal areas. The near-global coverage of DORIS beacons means that estimates of ionospheric correction based on (2) would be available virtually worldwide, including most coastal areas. However, more recent experience has demonstrated that (1) and (2) are less consistent at periods of high solar activity (several cm difference, R. Scharroo, private communication).

The effect can also be estimated from:

3. GPS Ionosphere Maps (GIMs), such as the ionosphere correction based on GIMs provided on Envisat GDRs.

The Jet Propulsion Laboratory GIM model provides 2-hourly global TEC maps based on GPS measurements. As GPS and altimeter satellite altitudes are different, the total TEC values from the GIM maps are scaled to altimeter altitudes using the International Reference Ionosphere 95 (IRI-95) model (Ho et al., 1997; Komjathy et al., 2000; Otten and Dow, 2002). Up until now, the GPS-derived GIM models have proved to be more representative of the TEC than the DORIS equivalents.

Other ionosphere information is available from climatologies of TEC information from various sources. These include the long-standing Bent model (Bent et al., 1976) and a more recent model from Scharroo et al. (2007) based on the GIM information, which has become available in recent years. (In the Delft RADS database, this ionosphere climatology model is called NIC08.)

How will one use the ionospheric information in coastal areas? The dual frequency altimeter information provided on GDRs tends to be noisy and it is common practice for users of altimeter data in the open ocean to smooth the data with a filter of typically 100 km. For coastal applications, such smoothed altimetric ionospheric information could be extrapolated along-track from the open ocean to the coast (e.g. by interpolating smoothed 1 Hz values to 20 Hz to reduce noise considerably).

Alternatively, in a procedure similar to the Dynamically Linked Model (DLM) approach proposed for the COASTALT wet tropospheric correction, one could make use of a reference model (e.g. from GIM), to which the altimetric ionospheric correction could be compared in the nearby open ocean to derive an offset (and possibly a trend), enabling GIM data to be employed for altimetric correction near to the coast instead of the altimeter-derived information. This approach is only worthwhile if one has reason to believe that the altimeter-derived information (1) is intrinsically more accurate away from land than the GIM-derived information (2), otherwise there is no advantage to the use of GIM data directly.

We understand that in the case of Envisat, the S-band measurement has not been available for some time. In processing these data for coastal use, the only possibility is to use GIM data (or DORIS data, or less desirably a climatology) directly. Of course, the same procedure would have to be followed for the coastal use of data from a single frequency altimeter. We will choose DORIS as our baseline option given its widespread use, but at the same time we will provide GIM and possibly a climatology such as NIC08.

3.2 Recommendations for COASTALT processor

The best choice for reference ionospheric correction model for COASTALT would appear to be that from GIM. This choice enables global coverage, commonality between the T/P, Jason and ESA missions and potentially those of other agencies, and access to the considerable experience of the GPS community.

As Envisat (the main altimeter to be used for COASTALT) is now effectively a single frequency altimeter, the only option is to use GIM (or DORIS) directly. For processing of earlier Envisat coastal data, when both frequencies were functioning, it is proposed that when dual frequency ranges become available from the retracking in WP3, that comparisons are made between altimeter-derived ionosphere corrections using GIM as a reference model in the DLM approach, to direct GIM information. In each case, long-term consistency in the use of GIM data can be tested with the use of data from DORIS or with the ionospheric climatologies.

3.2.1 Recommendation table

Correction: Ionospheric correction – baseline algorithm

Model or Algorithm	Dependence (input)	Domain (global/regional)	Resolution	Where from?	Format
DORIS dual frequency ionospheric correction	-	Global	20 Hz	ESA or RADS	NetCDF

Correction: Ionospheric correction – research algorithms

Model or Algorithm	Dependence (input)	Domain (global/regional)	Resolution	Where from?	Format
Dual frequency altimeter determination of the ionospheric correction	Retracked altimeter ranges	Global	20 Hz	COASTALT WP3	NetCDF
GIM ionospheric correction	-	Global	20 Hz	ESA or RADS	NetCDF
Bent and NIC08 climatologies	-	Global	20 Hz	Delft RADS experts	NetCDF

3.3 References for Section 3

Bent, R.B., Llewellyn, S.K., Nesterczuk, G. and Schmid, P.E. 1976. The development of a highly successful worldwide empirical ionospheric model, in Effect of the Ionosphere on Space Systems and Communications, ed. J. Goodman, pp.13-28. Natl. Tech. Inf. Serv., Spingfield, Va.

Ho, C.M., Wilson, B.D., Mannucci, A.J., Lindqwister, U.J. and Yuan, D.N. 1997. A comparative study of ionospheric total electron content measurements using global ionospheric maps of GPS, TOPEX radar, and the Bent model. Radio Science, 32(4), 1499-1512.

Komjathy, A., Born, G.H. and Anderson, D.N. 2000. An improved high precision ionospheric total electron content modeling using GPS. Geoscience and Remote Sensing Symposium, 2000. Proceedings. IGARSS 2000. IEEE 2000 International, 7, 2858 – 2860.

Otten, M and Dow, J. 2005. Envisat altimeter calibration and validation. Proceedings of the 2004 Envisat and ERS Symposium, Salzburg, Austria, 6-10 September 2004 (ESA SP-572, April 2005).

Scharroo, R., Smith, W.H.F. and Lillibridge, J.L. 2007. A new climatology for he total electron content of the ionosphere. Geophysical Research Abstracts, 9, 05845. Sref-ID: 1607-7962/gra/EGU2007-A-05845.

Zlotnicki, V. 1994. Correlated environmental corrections in Topex/Poseidon, with a note on ionospheric accuracy. Journal of Geophysical Research, 99, 24907-24914.

4 Air pressure (IB) and Wind corrections (D2.4)

4.1 Introduction: Accuracy Requirements for Coastal Studies

The objective of expanding the use of altimetry in coastal areas has to be considered in the context of the applications in which the altimeter data are to be employed, and of the magnitudes and spatial scales of the physical processes involved, together with the magnitudes and scales of the various correction terms.

Some coastal work is already possible with existing corrections. For example, the study of slope currents requires a precision of the order of 1 cm/10 km over perhaps 100 km (John Huthnance, personal communication). At first sight this is impossible to address given that some correction terms have uncertainties much larger in magnitude e.g. the surge correction described below with an uncertainty of typically 5-10 cm. However, the uncertainty in the correction in this case will have a much larger spatial scale than the signal of interest, and so studies of slope currents are already quite feasible. Another example is the computation of a Mean Sea Surface (MSS) Quasi-Geoid (QG), which is an important reference surface for many applications, in which one applies tide and surge corrections to the altimeter data. In this case the inaccuracy of the tide and surge modelling can be considerably reduced by time-averaging. Consequently, it is clear that one must always judge how effective the corrections terms might be in determining the physical signals of interest in coastal areas, and if it is possible to tolerate those uncertainties in an analysis.

Nevertheless, while some coastal studies are already possible, our objective is to expand the range of possible applications of altimeter data. That can only be done by reducing the uncertainties of the various correction terms. In this section, we discuss one of the largest corrections in coastal areas, that due to air pressure and wind effects (the storm surge).

4.2 Air Pressure and Wind Effects

Sea surface elevations in shallow seas and coastal areas can depart considerably from those predicted by the tide and by the 'inverse barometer' model of sea level response to air pressure changes. These departures are due to the role of winds, with wind setup proportional to wind stress divided by water depth, and to dynamical adjustments to air pressure forcing (e.g. Ponte et al., 1991). Surges can be metres in magnitude.

A number of schemes can be found in the literature which employ distant and lagged air pressure measurements in order to parameterise the wind field, and a regression parameterisation between such meteorological data and local elevations (e.g. Amin, 1982). Indeed, such a scheme formed the basis for flood warning in the UK for many years (Flather, 2000). However, since the computer age a more rigorous approach has been possible through the use of numerical surge models forced by air and wind fields provided by meteorological agencies (Heaps, 1983).

Operational storm surge models now exist for many parts of the world (Table 1). These employ forecast wind and air pressure information in order to predict likely surge elevations and currents up to several days ahead. In shallow areas with large tides, the models are often run once in tide-only mode and then a second time with both tidal and meteorological forcings, so as to account for tide-surge interaction, and with the difference between the two model outputs defined as the 'surge'.

The same models have also been used successfully for research purposes, using extended sets (perhaps 50 years) of hindcast meteorological information to compute variations in surge levels over a long period. Examples include Flather et al. (1998) and Bernier and Thompson (2006). The accuracy of such computed surge fields is probably of the order of 10 cm, as we discuss in detail below, although accuracy would be expected to be much worse where model spatial and temporal resolution (either meteorological and/or surge) is insufficient. Examples would include surges initiated by tropical cyclones or by polar lows.

4.3 Recommendations for COASTALT processor

The baseline prototype COASTAL processor will initially apply a pure inverse barometer, which is available globally, however several possible options are available for a specific regional correction, to be applied at a later stage:

1. To use archived regional surge fields from operational agencies based on the most recent forecast meteorological information (typically a few hours old).

In principle, it would be feasible to combine together in one place the outputs from operational surge models from different regions. Indeed, such an activity was proposed long ago as part of Coastal GOOS, now subsumed within COOP (the IOC Coastal Ocean Observations Panel) but this proposal has never been taken forward. Surge forecasts from several groups are available for Europe through the SEPRISE demonstration project http://www.eurogoos.org/sepdemo/) and, of course, from the individual agencies. A reservation about this approach is that, while it might be feasible in some areas, it is clear that large regions would not be represented (e.g. the African coastline).

2. To use hindcast information several weeks later (or however later is considered acceptable for the altimeter data processing), assuming that the hindcast data are by then of higher quality than the stored forecast information (probably unlikely as meteorological re-analyses are usually performed over a considerable time later).

3. To use a global barotropic model forced with global meteorological information. Such **global models** include:

- MOG2D (T-UGO) - this is a finite element 2D model with a high spatial resolution at the coastline (Carrère and Lyard, 2003) (e.g. 15 km elements for the global model, 4 km for regional models). This model is now used for routine processing of Jason and Envisat altimetry and is available to the COASTALT partners. The T-UGO incarnation can also be used in 3D mode.

- OCCAM barotropic version from POL, the highest resolution version at present being 0.25 degree. This model has been used for 50 years runs with ECMWF forcing up to 2004 (global routine runs up to the present day would require additional investments)

- The barotropic model of Pacanowski (and Ponte et al.) implemented by Ali, Zlotnicki and others to provide high-frequency (periods shorter than 20 days) corrections to earlier T/P and Jason GDRs (Aviso, 2002) with a primary emphasis on the deep ocean.

Of the three global models above, the one that can be readily employed is MOG2D, however there are disadvantages to the use of a global model over regional ones in that the latter are often based upon considerable local knowledge and experience, especially with regard to the accuracy of the essential bathymetric information, and in the quality of regional meteorology, and tend to be of higher resolution.

It is possible that both the regional-combination and global model approaches could be followed with regard to a global coastal product if considered desirable.

For the COASTALT test areas, therefore, we will start from the baseline of the pure inverse barometer, but then when we start plugging more sophisticated models into the processor it makes sense to use **regional models** like the following ones, all available as they come either from COASTALT partners of institutes (LEGOS) with which COASTALT partners have ongoing collaboration and information exchange:

NW Mediterranean study area – regional MOG2D-MedSea surge model with data sets based on (slight) hindcast information. This model has been shown to provide broadly similar information to an alternative model (HIPOCAS, see Pascual et al., 2008).

West of Britain – POL/Met Office regional surge model with data sets based on operational (forecast) information.

West of Portugal – Mohid primitive equation model developed at IST (see www.mohid.com).

Now let us discuss the accuracy of the surge models. The POL model can be taken as a case in point. For most of the year the performance of the model will be at an accuracy better than 10cm, but the performance is inevitably worse during bigger events and 10 cm overall is considered a representative figure by POL.

For Mog2D (for which a detailed model assessment can be found in Lyard and Roblou (2003)), a specific assessment of the HF correction over 31 tide gauges around the Mediterranean can be found in table 2 of Cipollini et al. (2008). Quoting from that table, the global version of the model leaves a residual variance at ~7 cm^2, while the regional version improves that figure to 5.1 cm^2. Comparable results are in Jan et al, (2004), Mangiarotti and Lyard (2008) and Benjamin-Martinez et al, (2004). All these papers use the same regional model outputs.

It is clear that the 'average' (in time) behaviour of the Mog2D model is very good (standard deviations of 2-3 cm), but the same warning as for the POL model applies: in big events the performance of the model will be worse.

It must be noted that those models we mentioned above represent the state of the art by virtue of the many years' experience that went into their development. Regional models in other parts of the world may do worse than that, also depending on the quality of bathymetry and meteorological forcing.

4.3.1 Recommendation table

Correction: Improved air pressure and wind corrections – baseline option

Model or Algorithm	Dependence (input)	Domain (global/regional)	Resolution	Where from?	Format
Inverse Barometer		Global		L2GDR 1Hz Inv Barometer	

Correction: Improved air pressure and wind corrections – research options

Model or Algorithm	Dependence (input)	Domain (global/regional)	Resolution	Where from?	Format
MOG2D (T-UGO)	Meteorological fields (preferably recent hindcast)	global	15 km hourly	Florent Lyard and colleagues, LEGOS	NetCDF
NW Mediterranean MOG2D-MedSea model	Ditto	Mediterranean	Hourly or more frequent	Florent Lyard and colleagues, LEGOS	NetCDF
POL/Met Office operational surge model	Ditto	NW European continental shelf	Ditto	Kevin Horsburgh and colleagues, POL	Unix/Linux binary
West of Portugal Mohid model	Ditto	West of Portugal	Ditto	Henrique Coelho, Hidromod (COASTALT partner)	HDF

4.4 Final Remark

When one uses altimetry to study shelf sea dynamics, there is no clear distinction between tide/surge/inverse barometer, and the clearest interpretation is possible only for sea level (uncorrected except for path-delay corrections and sea state bias) or for sub-surface pressure (sea level corrected with a pure inverse barometer correction). This returns to the issue referred to in the Introduction, namely a form of processing depends on the particular application, and indeed no correction at all may be still be useful. Of course, given the strong temporal aliasing of high-frequency forms of variability in coastal waters, such an uncorrected sea level product would not be very meaningful in gridded form, but would be a valuable along-track product (as for COASTALT).

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Table 1: JCOMM Survey of Operational/Preoperational Storm Surge Models (not to be reproduced without permission from JCOMM/WMO)

Model	Area	Type	Grid	Country
HAMSOM/Nivmar	Med.sea and Iberian Peninsula	Vertically integrated barotropic	10 minutes	Spain

cont.

Model	Area	Type	Grid	Country
Mike 21 pre-op. 3-D 2-D finite element MOG2D	North Sea, Baltic Sea	2-D hydrodynamic	finite diff. 9nm-3nm-1nm-1/3nm	Denmark
Coupled Ice-Ocean NPAC	Grand Banks, Newfoundland, Labrador NE Pacific 120-160W, 40-62 N	3-D circulation based on Princeton Ocean Model	20 km x 20 km aprox. finite diff. curvilinear c-grid 1/8 deg.	Canada
JMA Storm Surge	23.5 N-46.5 N 122.5 E-146.5 E	2 D linearized shallow water	staggered Arakawa C-grid 1 min. latitude/longitude	Japan
KMA Storm Surge	20 N-50 N 115E-150E	2-D barotropic surge and tidal current based on Princeton Ocean Model	8 km x 8 km aprox. finite diff. curvilinear c-grid 1/12 deg.	Korea
NIVELMAR	Portuguese mainland coastal	Shallow water	1min. latitude/longitude	Portugal
SMARA storm surge	shelf sea 32-55 S 51-70 W Rio de la Plata	2-D depth averaged	geographical Arakawa C 1/3 degree latitude/longitude 1/20 degree, latitude/longitude	Argentina
BSH circulation (BSHcmod) BSH surge (BSHsmod)	NE Atlantic, North Sea, Baltic Sea	3-D hydrostatic circulation 2-D barotropic surge	Reg. spherical North Sea, Baltic 6 nm German Bight, Western Baltic, 1nm Surge North Sea 6nm NE Atlantic 24 nm	Germany
Caspian Storm Surge	Caspian Sea 36-¦ ¦ 48.5 N, 45¦58 -¦ E North Caspian Sea 44.2 48-¦N, 46.5 -55.1 E	2-D hydrodynamic, based on MIKE 21 (DHI Water & Environment)	10km 2 km	Kazakhstan
HIROMB/NOAA	NE Atlantic, Baltic	3-D baroclinic	C-grid, 24nm	Sweden
WAQUA-in-Simona/DCSM98	continental shelf 48N-62N, 12W-13 E	2-D shallow water, ADI method, Kalmanfilter data assimilation	latitude/longitude, 1/8 degree longitude x 1/12 degree latitude	Netherlands
	Near Europe Atlantic (Gulf of Biscay, Channel and North Sea) 8°30' W - 10° E,		Arakawa c grid;	

Model	Area	Type	Grid	Country
derived from MOTHY oil spill drifts model	43°N - 59°N; West Mediterranean basin (from the Gibraltar Strait to Sicily) Restricted area in oversea departments and territories	shallow water equations	5' (5 to 9 km) finer meshes	France
SLOSH (Sea, Lake and Overland Surges from Hurricanes)	sea south of Hong Kong within 130 km	finite difference	Polar, 1km near to 7 km South China Sea	Hong Kong, China
Short-Term Sea Level and Current Forecast	Caspian Sea and near shore low lying zones	3-D Hydrodynamic baroclinic	3 nm horizontal, 19 levels	Russia
IIT Delhi, IIT Chennai, NIOT Chennai	east and west coasts of India and high resolution areas	non-linear finite element explicit finite element	Eg. for inundation model average spacing of 12.8 km offshore direction and 18.42 km along shore	India
CS3 tide-surge	NW European shelf waters	Finite difference, vertically averaged	C grid 12 km nested finer resolution	United Kingdom

5 Tides (D2.5)

5.1 Introduction: Accuracy Requirements for Coastal Studies

In this section we consider how coastal tide corrections for altimetry might be improved. However, we can first refer the reader to the accuracy requirement comments in the “Air Pressure and Wind” section (section 4). An important point is that whether one needs improved models or not depends upon the application, and that one might already be able to perform some studies with an appreciation of the limitations of the capabilities of existing models.

A first issue to address with regard to tide models concerns their sources of inaccuracy. This topic is discussed below, followed by mention of available models, and then by recommendations on how the present situation might be improved.

5.2 Errors in Tidal Predictions from Tidal Models

Numerical models of the ocean tide are usually formulated as a combination of harmonic components. Most models (whether global or regional) contain a limited number of the main semi-diurnal and diurnal components, and some include shallow-water and long period constituents. In principle, summation of the various components yields an estimate of the total water elevation at a given location and time (e.g. Pugh, 1987).

The models will be inevitably imperfect for two sets of reasons which we term ‘commission’ and ‘omission’ errors.

5.2.1 Commission Errors

Commission errors result from the fact that the tidal harmonic ‘constants’ (amplitude and phase) at each model grid point will have an associated error. These errors follow from the imperfect representation by the model of the real ocean tide, due to inadequate knowledge of bathymetry, inaccurate lateral boundary information (for regional models) and imprecise parameterisation (e.g. friction). The role of bathymetric errors can be easily visualised, given that the tide propagates at roughly sqrt(*gh*), and one might have say a 1 m error in a 10 m depth in coastal areas. Moreover, coastal evolution could mean that bathymetric information is not only imprecise but time-dependent. Another commission error will arise from the finite spatial resolution of a model, with imprecise interpolation of tidal information between grid points resulting in an error in total elevation.

Commission errors can be estimated at a limited number of positions by comparison to constants determined from tide gauge data, although the latter will have their own uncertainties.

One notes that, even if a tidal model is successful in predicting accurately the tidal signal near the coast, as verified by comparison to tide gauge data, its usefulness for the COASTALT project will depend on whether the model can also accurately represent the tides along the satellite tracks so as to determine long-shore tidal gradients. This is, in practice, difficult to assess as there are large gradients in bathymetry near the coast resulting in large gradients in tidal propagation.

5.2.2 Omission Errors

Numerical models rarely derive more than a dozen constituents and often omit sizeable semi-diurnal and diurnal components as well as smaller shallow water and long period terms. This contrasts with analysis of tide gauge data in which typically 60 constituents are calculable given a one-year time series. Consequently, errors are bound to occur in the use of models to compute total water elevation from the omission of such additional terms.

An example of the importance of omission errors in models can be given with the use of tide gauge data from Newlyn. In this example, we can assume a typical situation in we have a model which adequately simulates the major semi-diurnal and diurnal components (Q1, O1, P1, K1, M2, S2, K2, N2 in the case of Flather et al., 1998), which account for a large part of the tidal variance. However, we can consider what might be missing from this simplified description of the total tidal elevations.

Table 1 shows that, in this example of a model to correct altimetry near to Newlyn, there would be a residual error of 21.5 cm, due to that part of the variance unexplained by the 8 main terms (assumed perfect). In practice, some of this residual tidal variability will be in the semi-diurnal and diurnal band (representing 14.0 cm in this case) and this can be parameterised to some extent using admittance relationships with respect to the original 8. (In Jason processing, for example, admittance relationships are employed for 18 additional constituents.) However, in practice this procedure will not be perfect and one might imagine that an error of order 5-10 cm will remain from imperfect representation of the residual semi-diurnal and diurnal variability.

5.2.3 Shallow Water Constituents

Table 1 shows that many shallow water constituents in combination can contribute (in the example of Newlyn) an important tidal signal, and that the omission of third-diurnal and higher frequency components would lead to a combined error of 14.9 cm.

Table 2 indicates that the larger of the higher-frequency terms tend to be stable from year to year, and are reliably known from one year of tide gauge data, as might be expected. However, it is more difficult to verify the individual accuracies of the many smaller terms. Part of the accuracy with which they are known will be determined by instrumental factors (timing errors, data gaps etc.).

The larger shallow-water terms (e.g. M4) are sometimes included in numerical models but are often poorly determined and inconsistent with tide gauge data due to imprecise parameterisation of friction and inaccurate bathymetry in the models. The level of knowledge of these terms from gauges sets the ultimate accuracy that can be claimed for the models. In terms of the present study, there are few models, either global or regional, which could claim to account for shallow water constituents adequately.

5.2.4 Seasonal Dependence

The tide of the NW European continental shelf is dominated by semi-diurnal components having a seasonal dependence that is often (or indeed usually) neglected in modelling studies. The source of the seasonal variability is partly astronomical (seasonal sidebands of M2 existing in the tidal potential) and is partly related to tide-surge interaction. The seasonal dependence of M2 (represented by terms MA2 and MB2) and of S2 (represented by R2 and T2) comprises 3.5 of the 14.0 cm of the 'Other semi-diurnal and diurnal' constituents in Table 1 and is typically 1% of the corresponding main terms around the UK (Amin, 1985; Pugh and Vassie, 1992; Huess and Andersen, 2001). However, a large part of this seasonal variation is still poorly understood and is highly irregular from year to year. It is likely that such irregular seasonal dependence exists in other shelf areas.

5.2.5 Interannual Variability

It has been known for many years that tidal 'constants' vary slightly from year to year, depending upon the amount of non-tidal variability in the area and internal tidal processes. The resulting 'tidal cusps' in the tidal power spectrum were first identified by Munk and Cartwright (1966). Such variations are also considered to be of the order of 1%, although the percentage could vary considerably between locations. In addition to interannual variability, tidal 'constants' can also contain a secular component (in addition to that due to the secular changes in lunar and solar ephemerides) (e.g. Woodworth et al., 1991).

5.2.6 Summary

To the extent that models are validated by comparison to tide gauge data, which tend to be available as records of one or a few years, then it can be seen that there is no way of validating the major components in the models locally better than typically at the 1% level (commission errors). When coupled with omission errors, stemming from unmodelled tidal variability, it can be seen that within this example for Newlyn, one would not be able to reliably simulate the total elevation using a model to better than a couple of decimetres.

5.3 Available Global Tide Models

Global tide models improved in accuracy with the availability of precise altimetry from T/P and Jason-1 (Andersen et al., 1995; Shum et al., 1997). Of the typically dozen models now available (e.g. for a recent list see http://amcg.ese.ic.ac.uk/index.php?title=Local:Global_Tidal_Models), two models (GOT00.2 and FES2004) were selected for processing of Envisat and Jason and Envisat data (ESA, 2006; Aviso, 2008). However, these two and other models have continued to evolve, with GOT4.7 and TPX0.7, for example, now available. Most recently, EOT08a from the DGFI, Munich has been developed using data from many altimeter satellites, including the ESA sun-synchronous ones, which in principle should help with regard to density of information in coastal areas; the improvement in accuracy in coastal waters using altimeter data less precise than T/P remains to be confirmed.

Differencing of solutions for the major tidal constituents between models tends to show high accuracy in the deep ocean but large variations near to the coast, and at this stage it is not clear which of the competing models is the more correct. Validation requires independent information from tide gauges and possibly other devices (e.g. current meters).

Some models also assimilate data from coastal tide gauges and from relatively sparse off-shore measurements obtained from scientific programmes (www.pol.ac.uk/psmsl/gloup) and from the off-shore industry (e.g. www.simorc.org). Such assimilation is clearly desirable for development of coastal models. Models need to account precisely for tidal loading effects, depending on whether one is considering the pure or geocentric ocean tide.

5.4 Available Regional Tide Models

Regional models have been devised by different authors using different methods. In the classical modelling case, a large area (even global) tide model is used to provide boundary conditions to a regional model for which a higher resolution bathymetric grid has been constructed. Flather et al. (1998) is such an example. Altimeter data analysts have employed satellite data to determine a grid of empirical tidal information within a region (e.g. Woodworth and Thomas, 1990). In other cases, altimeter and tide gauge data have been assimilated into a classical modelling scheme for a region (e.g. Mourre et al., 2004).

Current regional tidal models represent propagation of tidal energy well (provided an adequate representation of bathymetry is used, discretisation always being a limitation) and generation of higher harmonics (if the equations represent the right physics). Limitations of regional models are that parameterisation of friction may not be adequate, generally density is not considered variable (at least in 2-D) and so there is no internal tide, 3-D models are available and could be more widely used even if density evolution is imperfect. There are now unstructured grid models for better resolution of coastal boundary and bathymetry. More constituents than hitherto could be included if reliable offshore boundary conditions are available. Direct effects of tidal potential and loading can be better employed in coastal models.

Table 3 provides a list of some regional models. As stated above, most include only a limited number of constituents. This can be adequate for application to surge modelling, for which one requires only a good first-order determination of tidal elevations and currents (Flather et al., 1998). In other cases, it is not clear why authors chose to limit the number, as additional constituents within the semi-diurnal and diurnal bands at least can be added to the determined constituents by means of response analysis. In some models, bathymetric and other parameters have been adjusted to provide an adequate representation of the tide on the coastline of interest, and the models may be far from accurate off-shore.

A generic problem with many of these models, in addition to omission errors, is the probably inadequate accuracy in many cases for intended altimetry applications. In particular, owing to the smaller spatial scales involved in coastal tides than in deep ocean tides, models derived from T/P-Jason information might contain inaccuracies between the coarse ground tracks.

5.5 Recommendations for COASTALT processor

5.5.1 Reprocess altimeter data with a more recent global model

This is the simplest approach and at the time of writing either the GOT4.7 (Richard Ray) or EOT08a (Wolfgang Bosch) models would be recommended. Both are multi-mission models. This is the only way at the present time of obtaining a 'global coastal' product. As far as the accuracy of these models is concerned, Richard Ray at the recent Pisa Coastal Altimetry Workshop (Nov 2008) has quoted RMS differences (with a shallow water validation dataset) of 8.1 cm for GOT4.7 and 9.0 for EOT08a; however EOT08a seems to perform slightly better over the 'truly coastal' subset of stations.

5.5.2 Employ a global model with additional tidal analysis/filtering

Even with the most recent global models, subtraction of their tidal elevations from altimeter data is likely to leave a significant amount of semi-diurnal and diurnal energy in coastal areas, in addition to the omission errors discussed above.

However, if altimeter data sets are long enough, it should be straightforward to further filter (or harmonic analyse) their time series to remove some of the remaining tidal energy, a procedure tantamount to developing a new tide model for the coastal area. For example, Dong et al. (2002) and Woodworth et al. (2004) readily removed residual variance for M2, S2, N2, K2, MU2, NU2, M4, O1 and K1 in studies of T/P and Jason-1 altimeter calibration. As always in such studies, this procedure is less rigorous in along-track studies of altimeter data from a sun-synchronous satellite, and is at the expense of also removing some non-tidal energy which occurs within the bandwidth of the selected tidal terms.

This is also an obvious approach to follow towards a coastal product in a relatively short time. A tidal group could be contracted to derive an optimised model for coastal areas, based on harmonic analysis of residual tidal signals after subtraction of global model information.

5.5.3 Assemble a set of regional tide models

An obvious approach is to assemble a (incomplete) set of existing regional models such as those of Table 3 to supplement the information from the global models. However, there are some reservations with this approach:

- First, the job could take several years to do properly

- Second, the fact that a model is a regional one does not imply that it is more accurate than a global one: a set of detailed regional validations would be required
- Third, the models will continue to contain a similar set of omission errors as the global models for the reasons discussed above.
- Fourth, the set of models collected would vary considerably in the number of constituents, spatial resolution etc.

Nevertheless, one could imagine following this approach.

5.5.4 Develop a complete set of new regional models with consistent standards

The best approach in the long-term, instead of employing existing models as in 5.3, would be to develop a consistent set of new regional models, probably with assimilation and based on the findings of 5.2, which would be dynamically consistent at their boundaries with the global models. Given the experience with MOG2D in this regard (Table 3), it might be optimum to base a community effort on this model, although the use of alternative regional models for comparison would be desirable, in particular to benefit from local modelling insights. Generic problems of lack of bathymetry and validation data sets are likely to apply. This work is likely to take some years.

For the COASTALT test areas the regional model approach will be followed:

- NW Mediterranean study area – regional MOG2D-Medsea model (Florent Lyard). Some figures on the accuracy of this model in the Mediterranean Sea have been reported by Cipollini et al. (2008) in their Table 1; the accuracy for the different tidal constituents is at centimeter level or better.

- West of Britain – newly developed POL 2 nm model for the NW European shelf. (This has a delivery date of end of 2008 so it should be ready for WP5. Failing that, we shall use the POL 12 km model or FES2004.). The model errors in this area of very large tides will be mainly omission errors, of the order 10 cm

- West of Portugal – Mohid multi-nested tide model validated by tide gauge data. Comparisons of Mohid results with data in several tide gauges along the Iberian margin has shown errors of the order of 10 cm (down to 5 cm for some stations)

These regional models will be used with additional filtering (as per 5.5.2) in each case.

However, if COASTALT is to be considered as providing a global product, then in the short term the only approach is that of 5.5.1, with additional filtering in some regions as described in 5.5.2 if considered appropriate to their analyses by altimeter users. The GOT4.7 model might be chosen as providing some consistency of heritage of tide models used for altimetry. However, the higher spatial resolution of EOT08a (it being derived from FES2004) would appear to make for a more suitable choice for coastal use. The intrinsic accuracy of this unpublished model has, however, yet to be demonstrated for each region (and one might have made a different recommendation if this study was being performed after community experience with new models). Nevertheless, one might expect it to be not less accurate than FES2004 from which it is derived.

5.5.5 Recommendation table

Correction: COASTALT Operational (baseline) Model

Model or Algorithm	Dependence (input)	Domain (global/regional)	Resolution	Where from?	Format
Open Ocean Tide GOT 00 or GOT 4.7		Global		L2 GDR 1Hz Tides	

Correction: COASTALT Research & Regional Tide models

Model or Algorithm	Dependence (input)	Domain (global/regional)	Resolution	Where from?	Format
EOT08a	-	Global	Hourly or as required	Wolfgang Bosch, DGFI	NetCDF and FES2004 format
MOG2D-MedSea (T-UGO)	-	Mediterranean	Hourly or as required	Florent Lyard and colleagues, GRGS	NetCDF
POL best model (2 nm model remains to be validated. If not available we shall use 12 km model or FES2004)	-	NW European continental shelf	Ditto	Kevin Horsburgh and colleagues, POL	Unix/Linux binary
West of Portugal Mohid model	-	West of Portugal	Ditto	Henrique Coelho, Hidromod	HDF

Table 1: Magnitude of Different Subsets of the Ocean Tide at Newlyn

Subset	Root-sum-square (cm)
Total	186.1
8 main semi-diurnal and diurnal	184.8
Other semi-diurnal and diurnal (not including the 8)	14.0
Seasonal M2 and S2	3.5
Third-diurnal and higher freq.	14.9
Long period	7.3
Total less the 8	21.5

Table 2: Amplitude and phase of selected larger high-frequency constituents at Newlyn determined from data for different years (cm, degrees).

	M4	MS4	MK4
1950	11.1, 169	7.4, 219	2.1, 224
1960	10.7, 171	7.1, 221	1.8, 217
1970	11.4, 170	7.3, 224	2.2, 221
1980	11.1, 170	7.5, 222	2.1, 223

Table 3: Some Regional Tide Models

Mediterranean:

Tsimplis et al., JGR, 1995. Lyard et al. – FES2004 with assimilation (and see below). Alvarez Fanjul et al, 2001 – based on Hansom.

North Sea:

see Flather (2000) for a list of POL, DMI, BSH and other models

NW Atlantic:

Bernier and Thompson, JGR, 2006

Canada Various Regions:

Greenberg et al. see:
http://www.mar.dfo-mpo.gc.ca/science/ocean/coastal_hydrodynamics/WebTide/webtide.html

Southern Ocean:

King and Padman, GRL, 2005 (and various other papers)

Arctic Ocean:

Padman, GRL, 2004. Lebedev et al., Russian J. Earth Sc., 2008.

Various Regions with MOG2D (T-UGO) models:

Bering Strait, NE Atlantic, NW European shelf, Mediterranean, Amazon delta, S. Indian Ocean, Indonesia.

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