The COASTALT Project: Towards an Operational use of Satellite Altimetry in the Coastal Zone

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***Abstract*- In this paper, we will showcase the main outcomes of the COASTALT project, including improved corrections (with special emphasis on the tropospheric effect) and novel re-tracking techniques built on established research results and the processing chain development with the generation and validation of ENVISAT test data sets over a selection of regional sites. We will also dive in further and explore how coastal altimetry might be exploited to its full potential in the coastal zone. This should be of interest to a broad range of data integrators that have an interest in using these improved altimeter data in their operational products or services.**

I. INTRODUCTION

The coastal zone is the unique part of the Earth where land, sea, air and people meet. By its nature it is a complex system where all the processes that influence its functioning, whether physical, biological, chemical, social, climatological or geological, are interconnected. So it makes sense an integrated approach benefiting of a synergy of modeling tools and multiple datasets created from space, air, land and ocean-based earth observing systems. Right now, there are several environmental satellites orbiting in space providing one of the most extensive and continuous archives and interoperability standards are removing the barriers to information flow that have traditionally separated disciplines and domains.

II. SATELLITE ALTIMETRY IN THE OPEN OCEAN

Satellite altimetry is capable of providing a detailed global picture of sea level and track its change regularly. The launch of the TOPEX/Poseidon in 1992 provided the greatest impetus for satellite altimetry research in the 20th century. Its launch was followed by the Jason-1 (2001) and Jason-2 (2008). ESA satellites were launched in 1991, 1995, 2002 (ERS-1, ERS-2, Envisat) and the US Navy Geosat Follow-On was launched on 1998. Whilst several of these missions are still in active orbit and expected to continue operation in the future, new missions are planned to be launched by space agencies over the next few years (CryoSat-2, AltiKa, Sentinel-3). Satellite altimetry has had exceptional success over the open ocean, the domain for which it was originally designed. In this endeavor, the unique combination of day/night and all weather operation, global coverage and collection of high resolution data along tracks with the possibility of revisiting the place makes it a key component of the Global Earth Observing System of Systems.

III. SATELLITE ALTIMETRY IN THE COASTAL ZONE

The processing strategy used in the open ocean has not been of much success in getting sea level in the coastal zone. The advantage of current radar altimetry for coastal studies is that it can fill gaps in the vast areas around tide gauges which are running continuously, but in only a few places. The coastal domain represents a challenging target for processing of satellite data in general; for satellite altimetry, the data retrieval is required to address some problems including: (1) re-tracking which is important for the last 10 km next to the coast; (2) a more accurate wet troposphere path delay correction; (3) better modeling of tidal and atmospheric effects. A global record of length 17 years of raw data from a series of altimetry missions is presently available and represents a unique resource for retrospective analysis in the coastal zone. The future missions will be designed with higher resolution capabilities than predecessors, benefiting from advances in technology (e.g. Delay- Doppler and Interferometry) in concert with emerging multiple orbital configurations and possible instrument miniaturization.

IV. COASTALT: AN INITIATIVE FOR COASTAL ALTIMETRY

The recent advances in waveform processing schemes and improvement in corrections combined with developments in how the data are treated [1], make it possible to increase the quality and quantity of data in the coastal zone. A great impetus has been given to the field by the recent launch of two major projects devoted to the development of coastal altimetry products for specific missions: PISTACH, funded by the French Space Agency (CNES) concerning coastal altimetry processing for Jason-1 and Jason-2; COASTALT (www.coastalt.eu), funded by the European Space Agency (ESA) to design and implement a prototype coastal altimetry processor for Envisat, paving the way for the development of algorithms for the Cryosat-2 and Sentinel-3 missions. In parallel, NASA recognizing the importance of the topic is sustaining coastal altimetry research through specific R&D projects in response to the last OSTST call. This new "coastal altimetry" community, inherently interdisciplinary, has already had two well-attended international workshops (see http://www.coastalt.eu/pisaworkshop08/) and is contributing to a topical book (see http://www.alticore.eu/book). COASTALT is producing a global coastal dataset at a resolution of around 350 m along track for the period from 2002 to now. Its main objective is to prepare altimeter data to aid coastal ocean monitoring, e.g., in a form which facilitates timely assimilation into numerical coastal ocean forecasting models. In addition, climatologists can use the data to better understand and quantify sea level rise.

V. THE COASTALT PROCESSOR

The COASTALT project is contributing to the development of a coastal prototype processor. It consists of a suite of programs, modules and functions written in Fortran and C. An important aspect of the COASTALT processor which differentiates it from other altimeter services is its customization: users can incorporate their local correction and test new retrackers. This approach takes into account the need for a global product (based on corrections available globally) and the need of users for customizable regional coastal products (given that the best corrections are often only available locally). The processor has two functional units: (1) the baseline module and (2) the optional User-defined Coastal Geophysical Corrections (UCGC) module. The UCGC module is provided as a stand-alone program for users with access to local geophysical corrections. Examples of such user-defined corrections include: tidal corrections from regional models, GPS-derived ionospheric corrections, land emissivity based wet tropospheric correction.

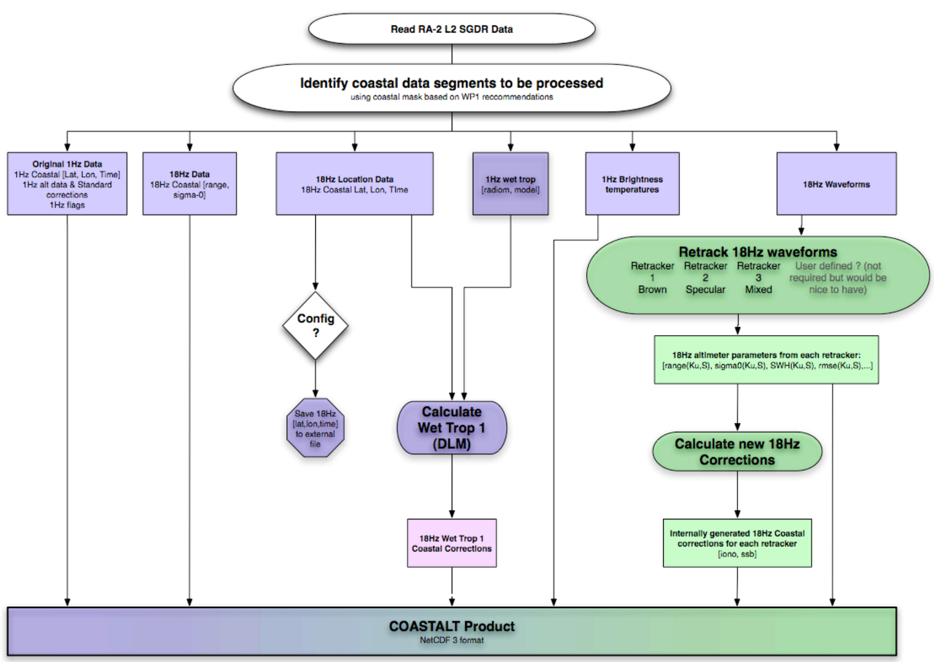

Figure 1: Logical framework of the Baseline Processor

The COASTALT processor can ingest the ESA ENVISAT level-2 SGDR products and reprocess the waveform data, using a number of alternative retrackers to generate high resolution (18Hz) data. Figure 1 shows the software logical model of the baseline processor, which illustrates the data flow for the main fields extracted from the SGDR file and their use in the processing algorithms. The processor can also generate new geophysical corrections from these new data as well as higher data rate geophysical correction data, by interpolation, as necessary for correcting the higher rate range data. The output consists of all the relevant original and new fields into a single file per pass, in a self describing format. The basic coastal product includes fields that can be determined for any coastal region, using the data from the altimeter itself, or instruments mounted on the same platform, and global models. This product does not include fields that would require specific auxiliary information, such as a region specific tidal model, or in situ observational data. However, such additional fields may be added to the product, using the standalone product enhancer. The output product has been designed to allow use of the new, retracked, range, significant wave height and backscatter values, together with the geophysical corrections that rely on them (such as ionospheric correction and sea-state bias corrections). They also contain the comparable original data, to enable users to readily compare the SGDR and COASTALT values. One enhancement of the source data, is to provide all geophysical corrections fields at the higher (18Hz) data rate. This involves interpolation of the existing 1Hz values.

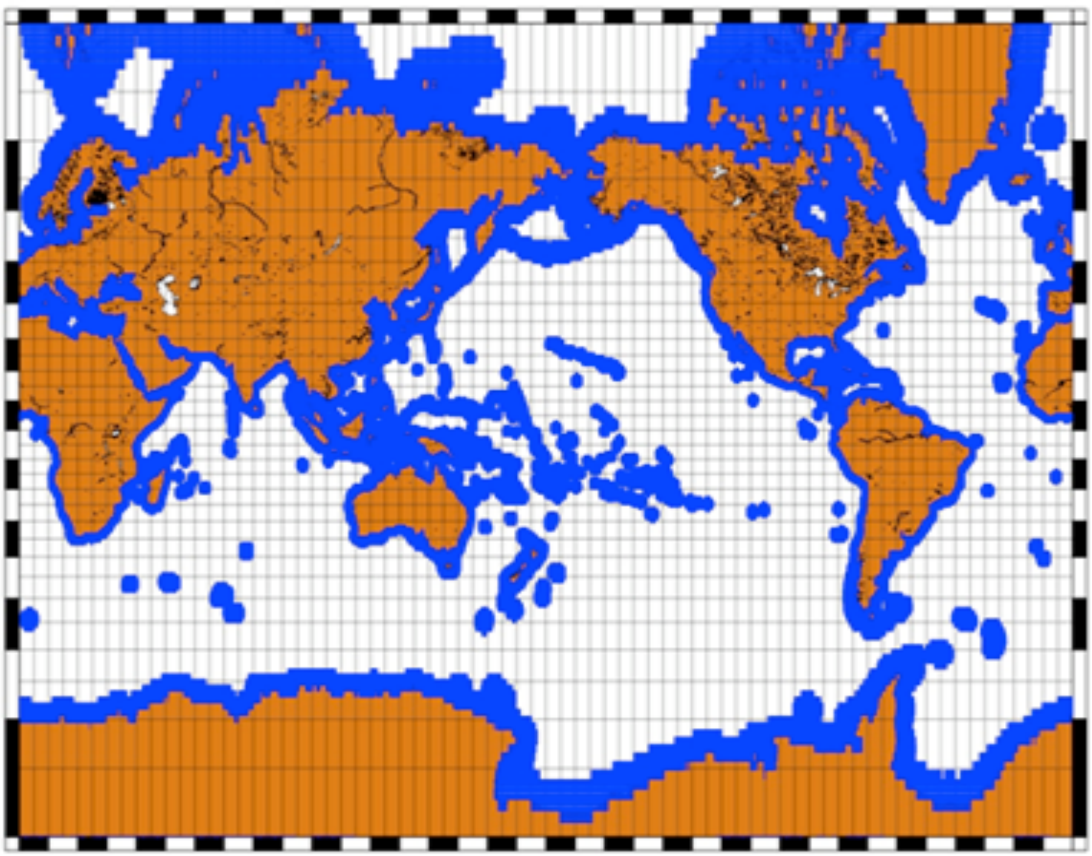

Figure 2: Global Coastal Mask

A coastal mask identifies those data segments in the SGDR file, which require coastal processing. The COASTALT mask (Figure 2) is global and time independent. It consists of a 1/10th by 1/10th deg latitude and longitude bit map based on GSHHS (Global Self-consistent, Hierarchical, High resolution Shoreline Database; see http://www.soest.hawaii.edu/wessel/gshhs). Its spatial coverage is chosen to be deliberately conservative to ensure that all data in the coastal zone are included at all time (i.e. accounting also for temporal changes in coastline position and water depth due to e.g. tides). The coastal mask identifies coastal data segments in the SGDR file, which are subsequently processed, retracked and exported to the COASTALT output product. Only data within the coastal mask are included in the COASTALT output product. However, several coastal data segments can be present in the output for any given SGDR file.

VI. WAVEFORMS AND RETRACKING

A comprehensive and systematic analysis of the return waveforms in the coastal zone was done. The main objective was a local analysis of Envisat RA-2 ocean waveforms as the satellite approaches to the coast. The joint use of DEM, coastline and Landsat images helped in the prospect of assessing waveforms at land to ocean and ocean to land transitions. We used a DEM obtained from SRTM 3-arc second product (90 m in the horizontal) (USGS web page). Note that it may also be possible to get high resolution DEM for Tuscany (including islands) and Ligurian with a tolerance around 10 m. It is a matter of discussion what level of accuracy is really necessary for coastal altimetry. We present here some examples from the NW Mediterranean Sea (Figure 3).

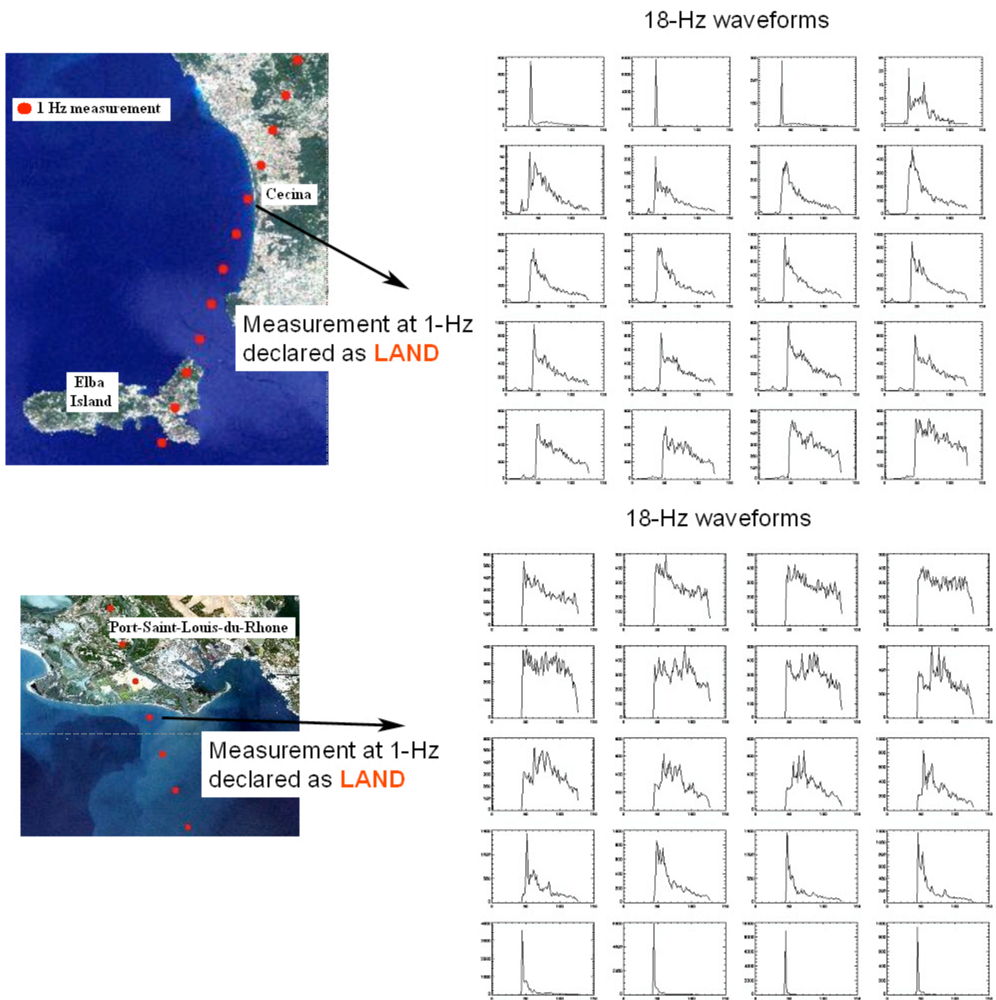

Figure 3. Two examples of bad categorization of 1 Hz measurements. Upper left figure: Track segment of descending orbit 00022 over Italy showing the position of the 1 Hz measurement. Upper right figure: Shape of 20 18 Hz waveforms corresponding to the first 1 Hz measurement over ocean. Lower-left figure: Track segment of an ascending orbit over France. Lower right figure: Shape of 20 18 Hz waveforms corresponding to the last 1 Hz measurement over ocean.

In this analysis we show the discrepancies between the ocean/depth elevation available in the GDR 1 Hz product and the land/ocean flag. Thus negative depths (denoting ocean) were found in the positions in which the land/ocean flag was declared ‘land’. Fig. 3 shows two examples of this in the Western Mediterranean. Upper-left figure is a segment of the descending orbit 00022 crossing Cecina (Livorno-Italy) and the Island of Elba (Italy). The 1 Hz measurement analyzed is declared as ‘land’ in the GDR flag, but a visual analysis of the shape of the twenty 18 Hz measurements (upper-right figure) shows the number of ocean waveforms. The same can be observed in the ascending orbit over Port-Saint-Louis-du-Rhone (France) (lower-left figure) with the 1 Hz measurement analyzed being considered as 'land'. The shape of the 20 18 Hz waveforms (lower right figure) shows that most of them are ocean, but with a clear land contamination. Three physically-based waveform retrackers are implemented and run in parallel in the COASTALT processor. The first one is the conventional Brown theoretical Ocean Retracker: This is the well-known Brown [2] ocean waveform retracker which works properly for altimeter waveforms over the open ocean and (typically) up to ~10km from the coast. The second one is the Specular Beta-parameter retracker with exponential trailing edge. This functional form is well suited to fit waveforms with a rapidly decaying trailing edge. The algorithm fits a 5- or 9-parameter function to the waveform reflected from one or two scattering surfaces. Finally, the third one is an experimental Mixed Brown Specular retracker which aims at addressing the retracking of coastal waveforms, which exhibit a specular peak embedded within a Brown-type ocean waveform. Such highly variable waveform shapes were observed frequently during the analysis of waveforms in the coastal zone.

VII. WET TROPOSPHERIC CORRECTION

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 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 centimeter level [3]; 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: (1) model the correction from some atmospheric model (such as ECMWF), adjusting the correction values so that there is continuity with the openocean radiometer-derived correction (this is the so-called Dynamically Linked Model approach); (2) 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 [4] and (3) use maps of path delay derived from GNSS/GPS observations.

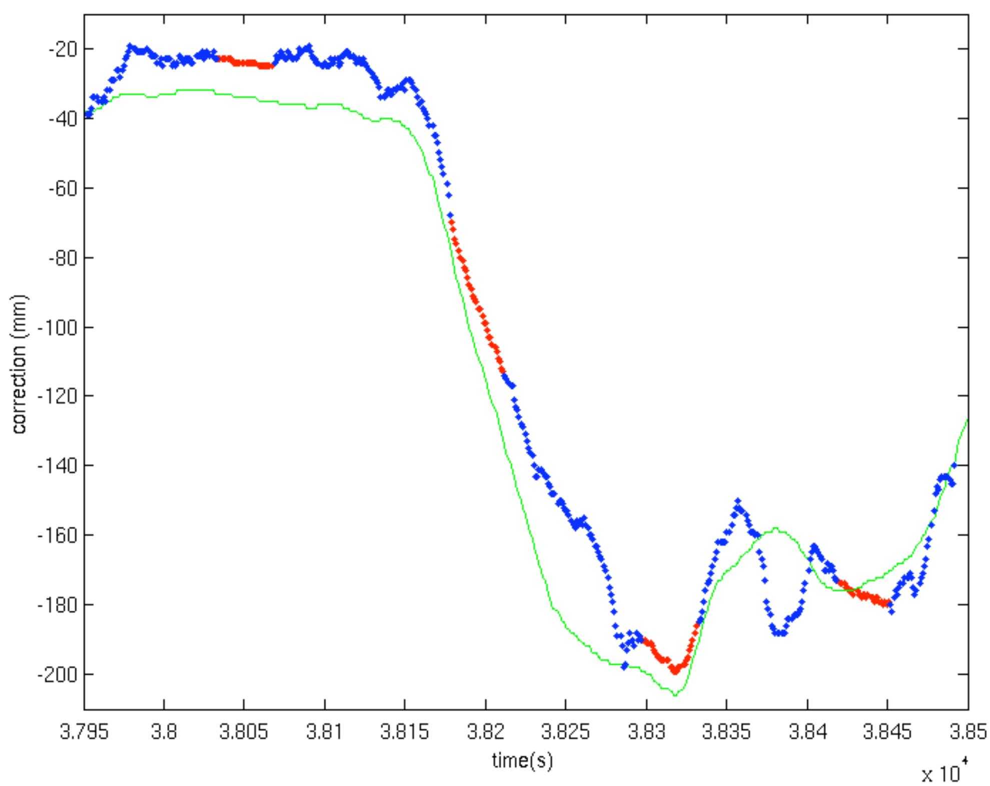

Figure 4: Example of Wet tropospheric correction behaviour in the coastal zone. Comparison of MWR (blue), Model (green) and DLM (red)

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 without any doubt 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. Figure 4 shows an example of the DLM approach compared to wet tropospheric correction derived from MWR and ECMWF

VIII. APPLICATIONS OF COASTAL ALTIMETRY

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, but the 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. 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). It is clear that the form of processing depends on the particular application, and indeed no marine correction at all may be still be useful. The COASTALT and PISTACH initiatives for the establishment of a multi-mission global coastal altimetry record are still at relatively early stage of development. When the existing 17-year archive of altimetry data is reprocessed, the most immediate application of coastal altimetry is to look at the coastal sea level. This has two interrelated aspects: long-term sea level change due to climate change, and tides. Thanks to reliable estimates of sea level and its gradient over the continental shelf, an immediate application will be the construction of a global atlas of the statistics of sea level and surface current variability over the continental shelves of the world. But the most ambitious application of the surface dynamic topography from coastal altimetry is to estimate and forecast the three-dimensional ocean state through data assimilation. At the most general level, coastal altimetry in synergy with modelling tools and other data sources is essential for applications such as monitoring surges and coastal setup, measuring long term coastal sea level variation, and providing current observations for erosion and sediment transport studies, ship routing and coastal defence design and operation.

IX. CONCLUDING REMARKS

A decade of research in coastal altimetry has provided some insights into the possible use of existing altimeter data sets in an oceanic coastal environment. Traditionally, altimeter data close to the coast were discarded because the processing was difficult and some corrections were inaccurate. Given the proximity to land, the satellite-retrieved results might be also contaminated (within 10 km from land). Recently, however, development of new techniques for reprocessing these data has begun, including local, accurate models for their correction. Improvements in the retrieval of information from the shape of radar altimeter ocean averaged waveforms (retracking) have been identified. The COASTALT initiative is contributing to the generation of consistent, high-quality coastal altimeter data from the ENVISAT mission through a series of actions including the retracking and new operational corrections. The new coastal altimetry products will constitute a crucial input for coastal observing systems: the experience gained in optimizing existing coastal altimetric data will guide the design of the future instruments, so that the multi-decadal record is not only continued, but also improved in quality and quantity.

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