COASTALT: Improving radar altimetry products in the oceanic coastal area

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ABSTRACT

Fifteen years of global altimetry data over the coastal ocean lie, largely unexploited, in the data archives, simply because intrinsic difficulties in the corrections and issues of land contamination in the footprint. These data would be invaluable for studies of coastal circulation, sea level change and impact on the coastline. Amongst some initiatives, we describe here the COASTALT Project, funded by ESA. The main objective of the COASTALT Project is to contribute towards making the status of pulse-limited coastal altimetry operational. In this paper we will first illustrate the first project phase, based on the assessment of user requirements, and summarize those requirements. Then we will describe the COASTALT methodology and objectives. Finally, we will illustrate and discuss the various options for coastal waveform retracking, and present a plan for the validation of the retracked data. The first results in the radar altimeter waveform analysis show the complexity of the coastal signals due to land contamination and calm/rough waters.

Keywords: Coastal altimetry, radar altimeter, waveform, retracking.

1. INTRODUCTION

Over 10 years of continuous altimeter measurements have revolutionized the use of altimetry for ocean circulation and climate research. Part of this revolution lies in the steady progress in the quality of the altimeter data, but also in the availability, since Topex, of dual-frequency measurements at Ku and C band. This has led to rapid improvements in the geophysical corrections and has allowed better estimates of the mean sea level, and thus a better understanding of the ocean circulation. In addition, new altimeters and new technologies are now available to the scientific community (SIRAL, SAR-altimetry). Recently, new applications have been developed, mostly related to rivers' and lakes' levels estimation [1, 2]. As a matter of fact, we now know more about the Earth, the ocean dynamics and the cryosfere, thanks to the use of radar altimeter data. Also, three disciplines can now work together exploiting altimeter measurements: Geodesy, Geophysics and Oceanography.

Two of the key points regarding radar altimetry lie firstly in the development of better and more precise geophysical corrections in order to improve the quality of the data and secondly in the study of new scientific applications, which should help the understanding of the processes related to abrupt climate changes. As an example, the contribution of radar altimetry to the studies of mean sea level variations and their trends (mean sea level rise of 3.2 mm/years in the last 15 years estimated from the available radar altimeter data) and their relation to climate change. The accuracy of the measurements for this kind of application needs to be globally below 2-3 cm. This has been already achieved for radar altimeter measurements. However, the accuracy of the mean sea level estimates and significant wave height, mainly at local scales (coastal areas), still needs to be improved specially due to the lack of good geophysical corrections in these areas and an inappropriate radar signal processing scheme due to land contamination of the signals.

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The first attempt to retrieve nearshore altimetric data by custom processing was that of [3], who recomputed the wet tropospheric correction for ERS-1 altimeter data over the Corsica Channel by recalibrating the model correction with the closest available radiometric estimate; they also recovered measurements that had been flagged as bad due to the sigma0 value being high (in turn due to a smooth sea surface). [4] reviewed the potential of Topex/Poseidon over the coastal ocean, using both 1 Hz and 10 Hz data but with no improvements in the corrections, and noticed that over flat coastal topography the useful signal is retrievable closer to shore than in the case of rough terrain. An extensive study of coastal altimetry, taking into account all the issues in the reprocessing, was carried out by [5]. They describe the generation of coastal altimeter data and are the first to analyze in detail various retracking algorithms and their implementation. The idea of customized tidal modelling was followed by [6] in another study over the Corsica Channel, this time using 1 Hz Topex/Poseidon data in combination with current meter and tide gauge data. Results were encouraging, showing that with simple improvements in the processing, the signal recovered at seasonal time scales was in good agreement with the in situ measurements and allowed the inference of useful oceanographic conclusions. This paper prompted the joint French-Italian ALBICOCCA initiative for coastal altimetry; one of its outcomes was the generation of a coastal product in the Northwest Mediterranean by adopting ad hoc filtering and screening techniques [7] in combination with state of the art tidal and atmospheric modelling.

Several other studies have dealt with the limitations of, and possible improvements to, coastal altimetry in recent years, including, [8, 9, 10, 11] and [12]. The Cooperative Institute for Oceanographic Satellite Studies [13], in cooperation with NOAA, has been looking into 10-Hz Geosat data [14] and 20-Hz Jason-1 data, using model wet troposphere corrections to avoid the land contamination in the data from the on-board microwave radiometer [15]. From several of the studies mentioned above, a reasonable consensus emerges on the fact that further improvements of the nearshore altimetric records will have to rely not only on post-processing of higher rate data, but more importantly on pre-processing, i.e. retracking of the waveforms, or use of retracked higher rate data; one example of this for ERS-2 data has recently been proposed by [16]. Another example, by [17], successfully uses Ku-band T/P data, with various retrackers, to measure water level changes over Louisiana wetlands. Retracking has also been used for geodetic purposes, i.e. for gravity field modelling in coastal areas. The coastal complications in deriving the marine gravity field from satellite altimetry were first examined by [18]; retracking was used over the Taiwan straits by [19], and recently by [20] using ERS-1 GM mission data.

Finally, the RAIES Project [21] is an ESA-funded study for the scientific exploitation of Envisat RA2 Individual Echo and S-band data for ocean, coastal, land and ice applications. One of the RAIES outcomes has been an updated retracker for RA2 data [22].

The growing demand for readily available, reprocessed coastal altimetry data has already stimulated a number of initiatives. These are the first seeds in order to move coastal altimetry to operational status, and are therefore of great relevance for the Coastalt project, which will build on the experience gathered in some of these initiatives: ALTICORE (value-added ALTImetry for COastal Regions – www.alticore.eu) is an international initiative whose main objective is to encourage the move towards an operational use of altimetry over coastal areas, by improving the quality and availability of altimetry data in the coastal region of some pilot areas in the Mediterranean, Black, Caspian, White and Barents Seas. A parallel project devoted to improvement of altimetry in coastal areas is ReCoSeTo (Regional Coastal Sea Level Change and Sea Surface Topography in Europe), funded by DFG and carried out at IPG-TUD Darmstadt. This project is based on higher rate (10 Hz) data and on improved altimeter corrections better suited for coastal areas, with an extension into retracking [23].

The generation of improved altimeter products in coastal areas is based on three main aspects: (i) Improvement of the geophysical corrections applied to the radar altimeter measurements. (ii) Development of a new retracking scheme for altimeter signals nearshore. (iii) Validation of the new altimeter products.

2. THE COASTALT PROJECT

The main objective of the COASTALT Project is to contribute towards making the status of pulse-limited coastal altimetry operational, by defining, testing and implementing the new coastal radar altimeter product so that ESA can routinely generate and distribute the Envisat coastal altimetry product.

On the way to this overall objective the COASTALT partners also aim to: (i) Carry out an extensive study of the possible improvements in geophysical corrections, and identifying the best strategies. (ii) Revisit the whole approach to waveform retracking, by assessing the capabilities of physically-based retrackers in the coastal ocean, testing novel retracking schemes and strategies, identifying the best candidate strategy for immediate operational application and producing a fully usable prototype of that retracker, while at the same time seeding the research into the next generation or retrackers for Sentinel-3. (iii) Assess the performance of the new retracked products over two regions with different characteristics, where a host of in situ measurements are available for validation. (iv) Provide full documentation on the new product in a way that is consistent with – and can be integrated in – the Envisat User Handbook

The proposal has also a significant element of capacity building, outreach and dissemination, both for the approach based on the assessment of user requirements, for presence of a dedicated workpackage on outreach, and for the creation of a Coastal Altimetry Science Working Team which will act as a scientific and operational forum as well as an incubator of new ideas in this novel field of altimetry. The project is divided into 6 main work packages summarized as follow:

2.1 User Requirements for Coastal Altimetry Products

This first workpackage has been already done and the main results and conclusions obtained are presented in the next sections.

User requirements survey which was based on Coastal Zone oceanographers contact. Coastal Zone experts have been interviewed for product requirements and the information has been gathered in the form of surveys or questionnaires. Some experts have been interviewed in person, and others have contributed in the form of electronic questionnaire.

User requirements evaluation which was focused on the analysis of the experts' feedback achieved under the previous task. From the evaluation a final product detailing the minimum requirements has been produced as a deliverable.

2.2 Improvement of Corrections

(i) Investigate the potential of improving the wet and dry tropospheric corrections from the ECMWF model in the coastal zone. (ii) Investigate the availability and applicability of new radiometer wet tropospheric corrections in the coastal zone. (iii) Investigate the performance of the dual frequency ionospheric correction in the coastal zone, and how this correction may be improved. (iv) Study the effect of the inverse barometer correction and high-frequency signals on coastal zone altimeter signals. (v) Investigate the accuracy and suitability of available coastal tide models to coastal altimetry products. (vi) Report on the results of these investigations and provide recommendations for wet and dry topographic corrections, dual frequency ionospheric correction and coastal tide corrections for inclusion in a coastal altimetry product.

2.3 Coastal waveform retracking: model development and prototyping

The specific objectives of this work package are as follows: (i) To perform a comprehensive and systematic analysis of the return waveforms in the coastal zone. (ii) To develop one or more new ad-hoc coastal retracking algorithms to process coastal waveforms. (iii) To develop and deliver a prototype software for the processing of waveforms in the coastal zone. (iv) To design a test plan and independently validate the selected retracking algorithm/s in accordance with the proposed test plan, including an assessment of the improvement of geophysical corrections dependent on the output (SSH, SWH) of the new retracker.

2.4 Validation and Performance Assessment

The objectives are: (i) To define a set of protocols for the validation of altimetric products in the coastal ocean. (ii) To assess the performance of the coastal altimetry product to reproduce the variability observed in the ground-based measurements in the proposed regions. (iii) To obtain sufficient in-situ information from coastal tide/wave gauges and other instrumentation and numerical models to enable an adequate comparison of existing and improved altimetric data sets near to the coast and thereby an evaluation of the improvement in performance.

2.5 Outreach and publications

(i) To develop web-based promotion material demonstrating a range of applications of the new coastal zone product(s). (ii) To provide web-based information on the principles behind coastal altimetry, the new data products and the oceanography of the product validation regions, in a format suitable for informing potential users and for aiding interpretation of the new data products. (iii) To provide a tutorial using the BRAT software, with hands-on actitivities suitable for beginners, advanced and expert users, based on example datasets from the validation regions with relevant background information.

2.6 Project Management and Science Working Team management

The last work package of the COASTALT project concerns the creation of group of scientists expert in coastal altimetry that can act as: (i) A discussion forum for technical issues. (ii) An independent review body for some of the deliverables of this proposal. (iii) An incubator for future initiatives in the field of coastal altimetry.

The SWT will be open to all parties interested in coastal altimetry but the initial list of invitees will be selected on the basis of existing contacts. SWT scientists will also be invited to attend (at their own expenses) the two Project Workshops foreseen.

3. RESULTS

We present here the first results obtained in the frame of the COASTALT Project. We will be focused only on two of the milestones of the project: (i) User Requirements for Coastal Altimetry Products (section 2.1); and (ii) Coastal waveform retracking: model development and prototyping (section 2.3)

3.1 User Requirements for Coastal Altimetry Products

After the survey we can conclude that we have valuable information to draw the user requirement for the new altimetry product. Twenty institutions responded to the COASTALT questionnaire while a further thirty three responded to the PISTACH questionnaire. It has to be taken into account that the major proportion of both the COASTALT and PISTACH communities are public research institutions. The public institutions working on operational products are well represented in both communities, but there is a lack of participation from the private sector: just 8% of both communities represent private industry. The integration of the results of PISTACH project and COASTALT project has been very useful in providing a more consistent analysis. The COASTALT results in all cases have confirmed the indications drawn from the PISTACH sub-sample and can be seen as an independent validation of the PISTACH survey, and vice versa. As a general indication, we can say that remote sensing data are used as a valuable tool alongside modelling and data assimilation for the purposes of research or operational services. These applications are of varying natures, with Near Real Time and delayed mode studies being more common among the community. The length of the datasets needed/used depends on the application. In the case of operational services, some of them near-real-time, the data required in most of the cases is one day long or shorter, while for research studies the dataset more requested is between one and ten years. For the observation zone there is no clear preference among near shore, coastal zone and Open Ocean, and in consequence the typical distance to the shoreline varies in a balanced way.

The answer about the purpose for the altimetry products reveals that for the research community the main focus is on the analysis of ocean processes, while the operational community tends to require altimeter data more for model validation or assimilation into models. The physical processes most frequently studied in the community are the Sea Surface height and the Sea Level Anomaly, and as it can be foreseen, the most frequently used parameter is the Surface elevation. It is important to highlight that wind and wave parameters are of great interest for operational forecasting centres. Currents where also suggested despite not being an option in the initial list. The analysis of the current and preferred accuracy and precision requirements for different classifications of users has been very helpful; in many occasions the current product does not satisfy clearly the user in terms, for instance, of the accuracy of the SWH or the radiometric accuracy on sigma nought. Concerning required supplementary data, the community prefers quality controlled data for its purposes, complementing the altimetric information in most cases with Optical, SAR or infrared data equally. Finally, preferred formats among the community are NetCDF and ASCII while ftp and OPeNDAP are the most desirable delivery options. The preferred latency of data is the best achievable (~daily) for the whole the community, independently of the nature of the centre.

3.2 Coastal waveform retracking: model development and prototyping

We will show the first results obtained in the first step of this work package: To perform a comprehensive and systematic analysis of the return waveforms in the coastal zone. The main objective of this preliminary study is a local analysis of Envisat RA-2 ocean waveforms as the satellite approaches to the coast from land to ocean and from ocean to land. We will focus on the effect of land contamination and calm/rough waters on the shape of the waveforms. To do this, we selected two pairs of ascending/descending tracks over the coast of Livorno. The frame work is in the Italian North-Western Mediterranean coast at East Longitude: 8º - 11º and North Latitude: 40º - 45º. In this particular location of the Mediterranean Sea a set of ascending (5) and descending (5) Envisat RA-2 orbits are available (Fig. 1). We made use here of the *Sensor Geophysical Data Records* (SGDR) orbits which provides information at 18 Hz frequency (20 measurements per data block at 1.1 s intervals approximately). We show here the results obtained in the Livorno and Ligurian coastal transitions.

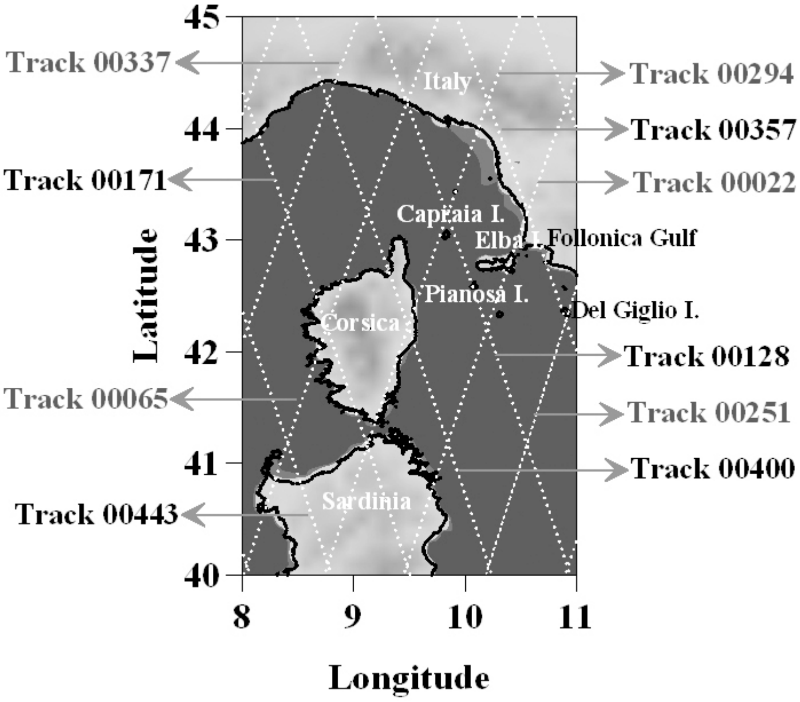

Fig. 1. Location of the ascending (5) and descending (5) tracks in the study area: Italian North-Western Mediterranean Sea. Tracks are depicted with white dots showing the position of the 1 Hz measurements.

Descending track 00022 (13/07/2005) and ascending track 00357 (05/08/2005) from cycle 39 were used. The position of the two tracks at 1 Hz is highlighted in Fig. 2 (upper figure). The amplitudes of 620 waveforms are plotted in the lower figure for the two orbits analyzed (descending and ascending respectively). Particularly interesting is track 00022 as presents two land to ocean transitions and one ocean to land transition in the study area. This is due to this track is the only RA-2 orbit overflying the Elba Island. The effect of this island in terms of land contamination is clearly seen in the amplitudes of the waveform (from signal 450 to 500 approximately). There is also an asymmetry in the shape of the waveforms between the ocean to Elba and Elba to ocean transitions. The amplitudes of the waveform for track 00357 are also presented. Here, the small effect of Del Giglio Island is clearly observed (first 20 waveforms). Particularly interesting is the effect of the Follonica Gulf (around waveform 175 to 200) as it connects with the ocean to land transition. This will be analyzed in detail further.

We propose now a deeper analysis of the land to ocean transition in terms of waveform shape. To do this, Fig. 3 shows the transition of track 00022 approximately over Cecina (Livorno). The upper left figure shows the position of the 80 18 Hz waveforms analyzed. Lower figure is a zoom view of the waveform amplitudes presented in Fig. 2 for this track (cycle 39). The solid line in gray indicates the position of the first waveform located at ocean (waveform number 24 in the upper figure). The exact position of this waveform was possible thanks to the availability of the high precision coastal line. The first waveforms present the maximum amplitude in the final gates (from 80 to 100), but as the satellite approaches to the coast this maximum moves toward gates 35 to 45. We also present in Fig. 3 the shape of the closest 18 Hz waveforms to the coast (upper right figure): signals number 22, 23 and 24 (which represents the first 18 Hz signal centered over ocean). Signal nb. 22 shows the maximum amplitude (higher than 7000 FFT counts) over gate 37. Signal nb. 23 presents a similar shape but the maximum amplitude is 20 times smaller and is now on gate 36. Finally, waveform nb. 24 has the smallest amplitude (10 time lower than the previous one) on gate 37. However, the shape of this signal is completely different to the other two analyzed. Coming back to the lower figure in Fig. 3, once the radar starts to measure over ocean the shape of the waveforms denote ocean-like signals with the probable effect of land contamination over almost 15 signals (waveform nb. 25 to 40 in Fig. 3). It is also clearly seen how the tracking point is moving towards the nominal value expected for ocean waveforms (gate 46). The cycle to cycle variability of this transition should also be analyzed taking into account that the cycle to cycle position of the orbit can oscillate and the effect of rougher/calmer waters could add more noise to the signals depending on their spatial temporal variability.

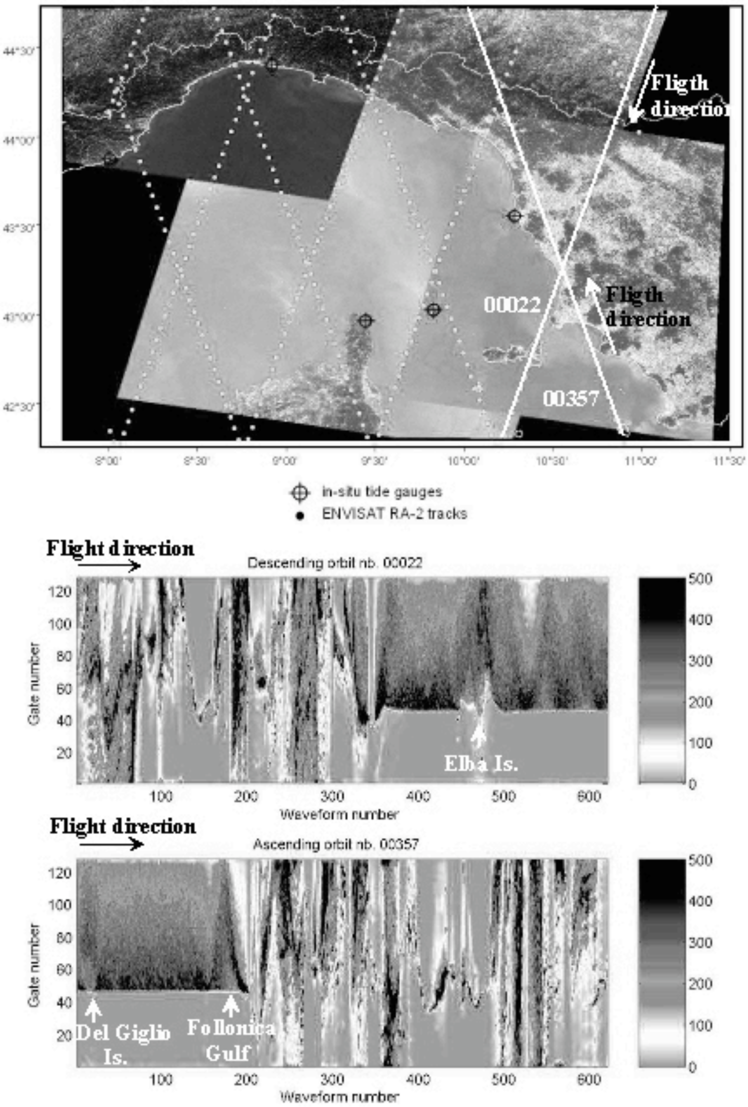

Fig. 2. Upper figure: location of the two tracks analyzed in the Livorno coast (descending orbit segment 00022 and ascending orbit segment 00357). Lower figure: amplitude of 620 waveforms corresponding to the orbit segments shown in the upper figure. The SGDR cycle used was number 39.

Upper figure in Fig. 4 shows the location of the two orbits analyzed in the Ligurian coast: descending track 00065 (16/07/2005) and ascending track 00128 (20/07/2005) (upper figure) corresponding to the SGDR cycle 39. The amplitudes of the 620 waveforms analyzed are presented in the lower figure. On descending track 00065, the land to ocean transition is clearly seen in the first 50 waveforms. Then pure ocean waveforms are observed until the satellite reaches Northern Corsica Island. On ascending track 00128 we observe typical ocean waveforms until the satellite overpasses Pianosa Island (Fig. 1). The modification in the amplitudes is clearly seen (waveforms from 90 to 100 approximately). Also, it seems that Capraia Island (Fig. 1) could be the responsible of the land contamination observed between waveforms 190 and 210. This could be confirmed analyzing the descending track 00294 (Fig. 1), which is also close to the island. The two tracks analyzed in this section are particularly interesting as they have the crossover point in the last waveform (number 37: ascending track 00128) and first waveform (number 17: descending segment 00065) 18 Hz ocean measurements of the two orbits. Further analysis should analyze the shape of the waveforms in this crossover point in order to determine the effect of land contamination over waveform located approximately in the same location but with different flight directions.

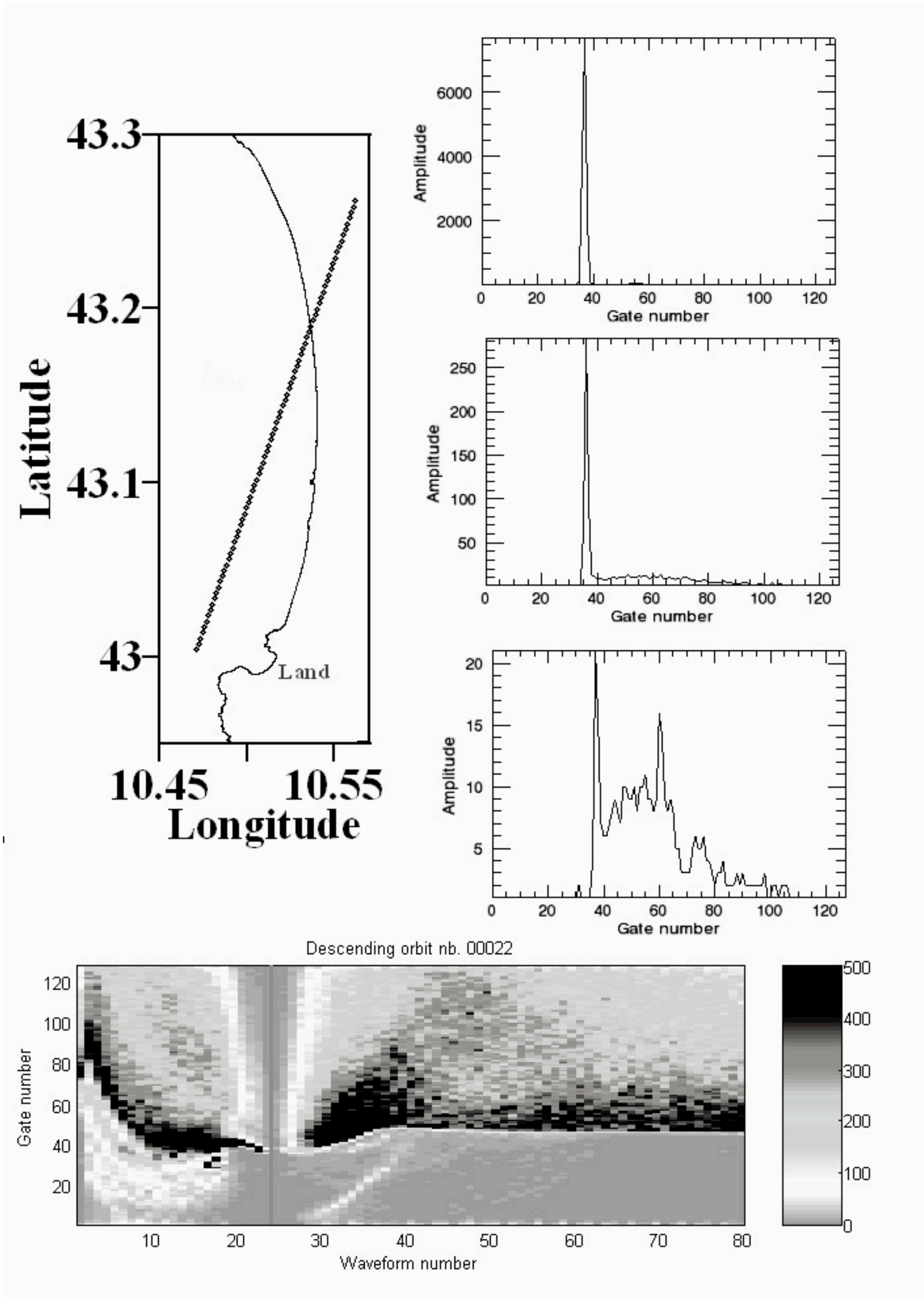

Fig. 3. Upper left figure: location map of the 80 18 Hz waveforms (descending track 00022) in the transition coastal zone over Cecina (Livorno coast). Upper right figure: shape of waveforms number 22, 23 and 24. The third one represents the first signal measured over ocean. Lower figure: Zoom view of the transition zone over Cecina (solid magenta line showing the position of the coastal line).

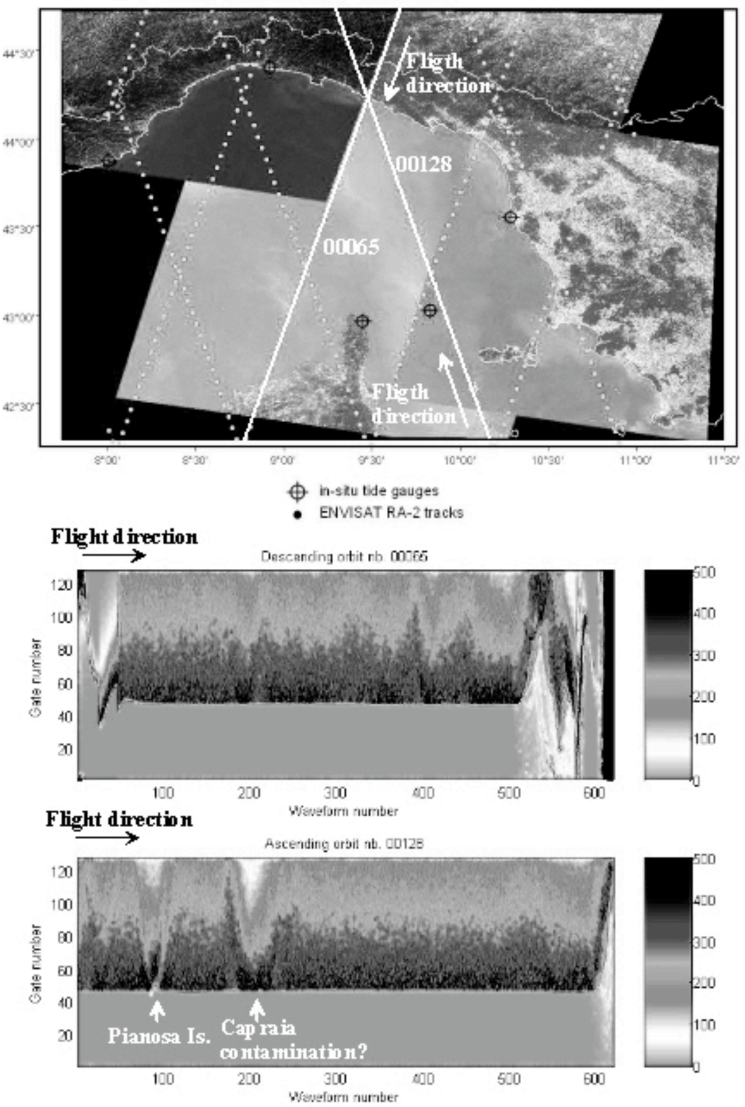

Fig. 4. Same as Fig. 6 but for descending track 00065 and ascending track 00128.

4. CONCLUSIONS

The outcome of the COASTALT and PISTACH surveys has to be a list of recommendations (below) for the definition of the new product, i.e. a list of characteristics that the new product should have. To draft this list of characteristics we, COASTALT partners, have decided to follow a *supervised* approach: rather than deriving the recommendation solely from the raw, results of the COASTALT and PISTACH questionnaire, we interpret these results on the basis of our previous (10-year) experience in the field. We believe that this approach will prove the most successful in that it ‘filters’ the results of the questionnaire, moderating some indications that could be biased due to incomplete familiarity of the users with the existing or planned products, as well as to incomplete (or difficult to find) information/documentation. A good example of how we interpret the results in order to draw recommendations would be the precision issue: a non-negligible share of the users believes that the current SSH product available for the coastal environment has a precision better than 3 cm. For these users, therefore, there would be little scope to improve the product precision. However, a quick informal survey between few expert altimetrists does immediately show that this is a very optimistic – and unrealistic -view. We therefore conclude that precision improvement is a requirement, even if it is being overlooked by some (actual or potential) users. Another example is on data formats: although some replies would still favour ASCII over NetCDF, experienced users can testify that metadata (easy to add to NetCDF – not so easy to account for in simple ASCII files) are often essential to many applications, so our recommendation goes definitely towards NetCDF as the format to adopt.

The main recommendations for the Coastal Altimetry Products are:

(1) The product should be provided along-track. (2) Include not only sea surface height, but also significant wave height and wind speed which will constitute a very valuable asset to coastal managers and modellers. (3) Include both the 1 Hz posting rate and the maximum posting rate compatible with an acceptable signal-to-noise ratio; the upper boundary on this is obviously 18 Hz for Envisat. (4) Include data as close to the coast as possible, even when none of the main estimated parameters (height, significant wave height and wind) are considered reliable. (5) Initially be developed as a delayed product, but with a processing chain compatible with the delivery of near-real-time (with daily distribution) and real-time data, as there is a clear requirement for those. (6) Put in place all those improvements in corrections (including local corrections) and retracking so that accuracy and precision are optimized. (7) Provide the users with an error budget and clear documentation on the characteristics and limitations of the products. (8) As far as the height measurement is concerned, provide not only the SSH, but also anomaly and mean value, and a coastal *Mean Dynamic Topography* where possible. (9) Provide quality flags together with all the separate corrections. (10) Be easy to merge across missions, with a common correction scenario that should make possible the cross-calibration of Sea Surface Height, wind and wave information from Envisat with those from other altimetric missions. (11) The product must be in NetCDF format and distributed both via FTP and OPeNDAP. (12) However DVD distribution should be retained for the benefit of those users with bandwidth constraints.

A preliminary coastal waveform analysis has been done in the Italian North-Western Mediterranean coast. Several high resolution products (hot shown here) have been used in the analysis, together with some ascending and descending Envisat RA-2 SGDR tracks. The study was focused on the analysis of ocean to land and land to ocean transitions in the Livorno and Ligurian coast. The transitions were analyzed using the 18 Hz waveforms available in the SGDR cycle 39. From the results obtained we outline the following conclusions. Brighter targets from land and/or calm waters, and the noise due to rough waters in coastal areas strongly affect the shape of the closest ocean waveforms to the coastline. The number of ocean waveforms affected by land contamination might differ depending on the topography. Thus, the land to ocean transition over Cecina (descending track 00022) with smoother topography is totally different to the transition over Genoa coast (descending track 0065) with more rapidly change topographic features. A high resolution DEM could be used to confirm this. The analysis of the Genoa-Ligurian coast shows that the land to ocean transition adds higher contamination on waveform shapes with respect to the ocean to land transition located at approximately the same location.

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