CRYOSAT TO SENTINEL–6: OCEANOGRAPHIC ADVANCES AND COASTAL INCURSIONS

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1. INTRODUCTION

CryoSat's SIRAL altimeter, the first altimeter in orbit with Synthetic Aperture Radar (SAR) mode capability (albeit only on a few regions over the ocean) has initiated a significant evolution in the way we observe the oceans with altimetry, which is continuing with the forthcoming Sentinel–3 (Sentinel–3A to be launched in late 2015, followed by Sentinel–3B in two years' time) and then with the Sentinel–6 (also known as Jason–CS) pair from 2020. In this contribution we review several aspects of this evolution (i.e. evolution in processing, evolution in products, evolution in sampling skills over the ocean). Then we discuss the expected impact of SAR altimetry on oceanography at different scales and in different domains, and finally we examine some of the unprecedented capabilities of SAR altimetry in the coastal zone.

2. CRYOSAT TO SENTINEL–6: EVOLUTION OF SAR ALTIMETRY

CryoSat, whose primary mission objective is to observe the cryosphere, is clearly also demonstrating the potential of SAR altimetry over the ocean, as shown by many presentations at CryoSat Workshops, Ocean Surface Topography Science Team meetings and Coastal Altimetry Workshops in recent years (see for instance Gommenginger et al., 2011; Cipollini et al., 2013; Fenoglio–Marc et al. 2015). CryoSat's oceanographic success is even more remarkable as its design lacks several features normally desired for an oceanographic mission: it is a single–frequency (Ku–band) altimeter that requires a separate ionospheric correction and it lacks a microwave radiometer on board, therefore requiring an ancillary wet tropospheric correction.

Sentinel–3's SRAL instrument, which contrarily to CryoSat's SIRAL will be operated in SAR mode over the entire globe, is similar in concept to SIRAL but without interferometric capability and with the addition of a second frequency (C–band) for ionospheric correction. Sentinel–3 is also equipped with a dual frequency microwave radiometer (an evolution of the radiometer on Envisat) to provide accurate wet tropospheric correction over the open ocean, so it is fully geared up to provide accurate oceanographic observations of sea surface height (as well as significant wave height and winds).

The evolution will continue with Sentinel–6's POSEIDON4 altimeter: not only will it be the first SAR altimeter used on one of the reference missions (i.e. on the 10–day reference orbit established by TOPEX/Poseidon in the early 1990s and flown subsequently by Jason–1, Jason–2 and soon by Jason–3), it will also be the first altimeter that operates in a continuous high–rate pulse mode, such that there is no longer the need to wait 2/3 of the time for pulses to be received, while transmitting only 1/3 of the time, like the altimeters of CryoSat and Sentinel–3. On top of that, Sentinel–6 will be operating in this mode 100% of the time. This particular operating mode, also known as the 'interleaved' mode, allows simultaneous production of low–resolution mode (LRM) measurements on–board as well as the processing of SAR echoes on–ground, and brings some unique opportunities for cross–calibrating and cross–validating the two modes. POSEIDON4 will also be a dual–frequency (Ku and C band) altimeter and Sentinel–6 will also carry a three–frequency microwave radiometer for accurate wet tropospheric correction.

2.1. Evolution in processing

From the technological point of view the breakthrough initiated by CryoSat and continuing with the other two missions is the SAR mode, which offers intrinsic higher along–track resolution (of the order of 300m) and therefore is sometimes referred to as the High–Resolution Mode (HRM). CryoSat's SIRAL, Sentinel–3's SRAL and Sentinel–6's POSEIDON4 altimeters are all operating in HRM but in a different manner. While SIRAL and SRAL transmit and ensemble of pulses and turn into listening mode until all pulses bounce back to the altimeter (closed burst mode), Sentinel–6's POSEIDON4 will be the first to operate in the so called interleaved mode which allows for a continuous transmission/reception as is done in conventional altimetry but at a higher pulse repetition frequency (open burst mode). Furthermore, this last includes several design upgrades that should enable further advances in the retrieval of the geophysical quantities. The changes in design imply changes in the processors. Figure 1 shows the block diagrams of the Sentinel–3 and Sentinel–6 processors; the differences are highlighted.

2.2. Evolution in products

The technical evolution brings about an evolution in the products that are generated and distributed. CryoSat started with no dedicated ocean products, but user demand has resulted in the availability of FDM (Fast Delivery Marine) products delivered within ~3 hours from acquisition; and then since Apr 2014, Interim Ocean Product (IOP, delivered within 3 days) and Geophysical Ocean Product (GOP, delivered within 30 days) from a dedicated ocean processor. GOP and IOP however do not yet take advantage of the improved SAR mode performance, as over SAR mode areas those products are still generated by 'reducing' the waveforms to conventional pulse–limited waveforms, the so–called pseudo–LRM.

With Sentinel–3 SRAL, three consolidated levels of latency appear:

- Near–Real–Time or NRT (3 h) for meteorology and operational oceanography, corresponding to Jason–2 OGDRs
- STC (short time critical, 48 h) for operational oceanography and numerical ocean prediction (corresponding to Jason–2 IGDRs)
- NTC (non–time critical, 30 days) for ocean and climate studies (akin to Jason–2 GDRs)

and three levels of complexities:

- 1–Hz data,
- 1–Hz and 20–Hz data
- 1–Hz and 20–Hz data and waveforms.

Moreover data will be available for R&D by expert users as L1A, i.e. all the individual echoes in the time domain; L1B, i.e. the I/Q (complex) waveforms; and as L1B–S '('Stack') product, with the individual waveforms stacked and geo–located.

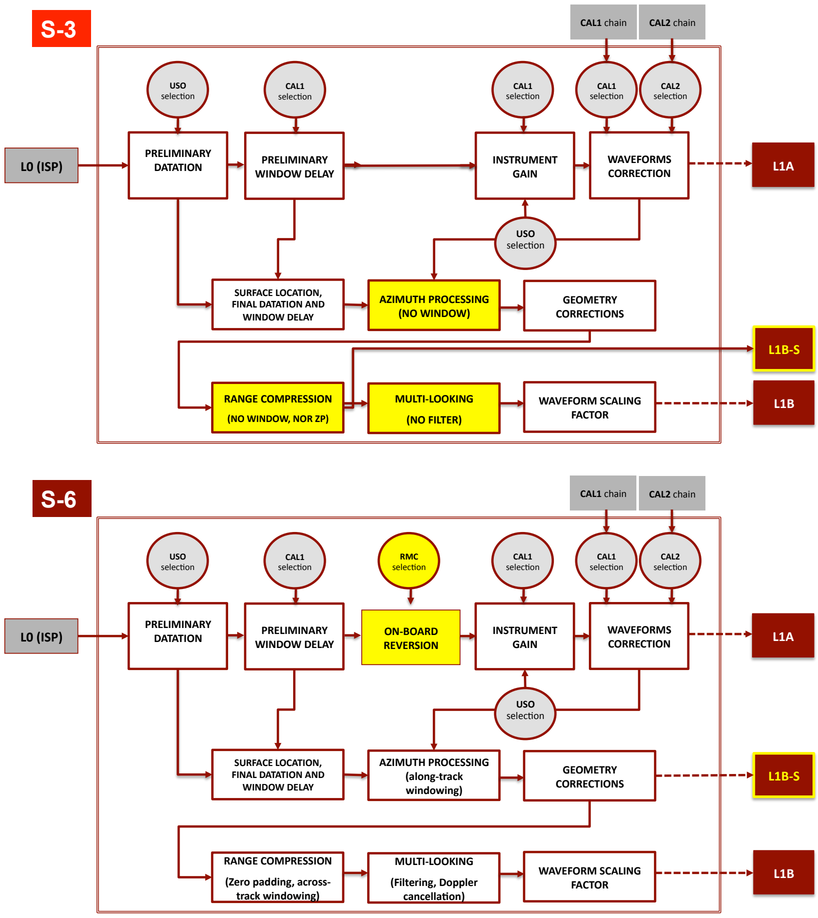

Figure 1 Ground processor high level block diagrams of the Sentinel–3 (upper panel) and Sentinel–6 (lower panel). Differences are highlighted in yellow

Similarly, with Sentinel–6, there will be the three consolidated levels of latency:

- NRT (3 h) for meteorology and operational oceanography
- STC (short time critical, 36h) for operational oceanography and numerical ocean prediction
- NTC (non–time critical, 60 days) for ocean and climate studies

but only two levels of complexities

- 1–Hz data (for NRT data only),
- 1–Hz and 20–Hz data (all latencies)

This because the waveforms will only be disseminated as part of the 'expert' L1B data. All data will be in netCDF format and nowadays users are expected to be capable of readily combining fields from different netCDF files. The data levels for the expert users will be L1A, i.e. all the individual echoes in the time domain and L1B, i.e. the I/Q (complex) waveform, while a L1B–S product is not part of the plan, but software will be provided allowing users to generate it from L1A. Two higher–level products for Sentinel–6 (L2P and L3 products) will be produced in STC only, for the specific purpose of assimilation in oceanographic models.

2.3. Evolution in ocean sampling capability

CryoSat is already demonstrating that SAR altimetry is capable of better sampling of shorter scales in the ocean when compared to LRM altimetry. Spectra of along–track SSH from SAR mode acquisitions conform to theoretical expectations (see S. Labroue et al's presentation in this workshop) and do not show the spectral 'bump' seen in spectra from conventional LRM altimetry between 5 and 50 km, i.e. at the shorter end of the oceanic mesoscale and at the sub–mesoscales. There is not yet complete consensus on the causes of the spectral bump seen in LRM data, despite it having been the subject of some dedicated investigations (Dibarboure et al., 2014). However there is consensus that its presence reduces the value of altimeter data for assimilation at those scales. With SAR altimetry this problem is overcome and the surface height signature of short mesoscale and submesoscale features can be fully characterized. Much of the energy dissipation in the ocean and of air–sea interaction happens at those scales, so they are important both for operational models and for climate models, Moreover, their signature has been recorded routinely for years in surface temperature, ocean colour and surface roughness (from SAR) so the availability of SAR altimetry globally from Sentinel–3 opens up many opportunities for synergies with those observations to investigate the underlying processes, such as for instance the local transport of nutrients that modulates phytoplankton growth.

3. COASTAL INCURSIONS WITH SAR ALTIMETRY

SAR altimetry is particularly suited to mitigate some of the issues that have so far prevented a full utilization of altimetry in the coastal zone. The higher along–track resolution w.r.t. LRM altimetry can be directly exploited to better resolve coastal currents, eddies and filaments. It is also expected to ease the screening of waveforms affected by land returns or bright targets at the coast, especially when the satellite track approaches the coastline at normal incidence (when the angle of approach is oblique this advantage is lower as the SAR footprint is still pulse–limited in the across–track direction). But what makes SAR altimetry so appealing is not just its resolution but also its excellent performance as far as measurement precision is concerned, and this is once again being demonstrated by CryoSat. Figure 2, a result from the CryoSat Plus for Ocean (CP4O) Project (Cotton et al, 2015) shows a proxy for 20–Hz noise in CryoSat data from a number of tracks around the coast of the United Kingdom (which, especially in its northern part, has a very complex coastline configuration), as a function of distance from the coast. The median 20–hz noise stays flat up to 5 km from the coast at a value lower than 5 cm, and is still <6cm at 3 km.

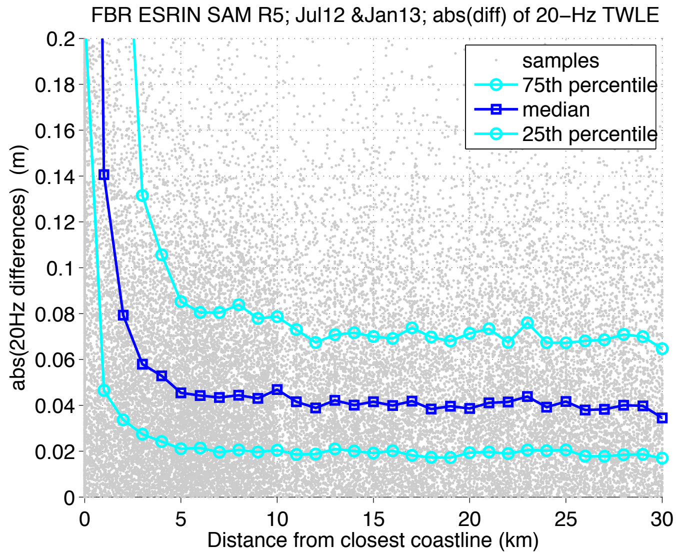

Figure 2: absolute value of the differences between adjacent 20–Hz values of total water level envelope (TWLE), a proxy for noise, for all the CryoSat tracks around the coast of the UK in July 2012 and January 2013, as function of distance from coast. The lines are 25th, 50th (median) and 75th percentile and show that the noise remains flat (with a median of about 4.5 cm) up to 5 km from the coast. Figure from the CP4O Project (Cotton et al., 2015)

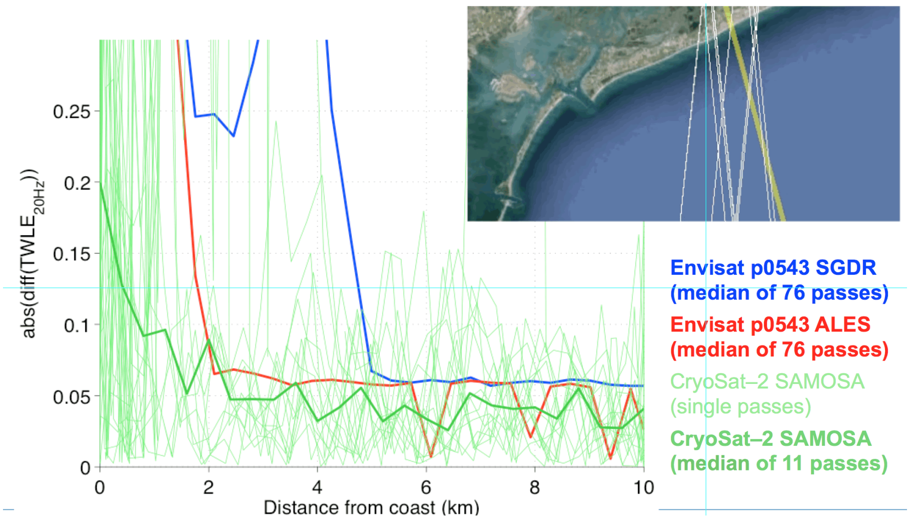

Figure 3. Coastal performance, in terms of absolute value of the 20–Hz TWLE differences for Envisat pass 0543 (shown in yellow in the inset map) and a number of nearby CryoSat passes (in white) crossing the coastline in the vicinity of Venice. (from Cipollini, Passaro and Vignudelli, manuscript in prep.)

Data in figure 2 have not been screened based on the angle of approach. An example near Venice, where the tracks are nearly orthogonal to the coastline (figure 3) shows that CryoSat data degrade on average at ~1 km from the coastal, a clear improvement over Envisat where good measurements are limited to ~5 km in the official SGDR, and can be retrieved up to 2 km from the coast when a dedicated coastal retracker (Passaro et al., 2014) is employed.

Customized processing can improve the quality of coastal SAR altimetry data further, as demonstrated for instance by Thibaut et al (2014) and Egido et al (2014). The data can then be averaged with a tradeoff between precision and resolution according to the desired application. Figure 4 shows a very valuable application of the coastal data – i.e. the observation of the raised water level profile during surge events. The example shown is a CryoSat overpass during the surge caused by the Xaver/Bodil storm in the Danish Straits in December 2013, and has been processed within the ESA DUE eSurge Project for the provision of Earth Observation data for storm surge modeling and forecasting (http://www.storm–surge.info). The surge profile is a quantity that no other observational technique can provide at the moment, and SAR altimetry can provide observations of this quantity with greater accuracy and more detail than conventional altimetry.

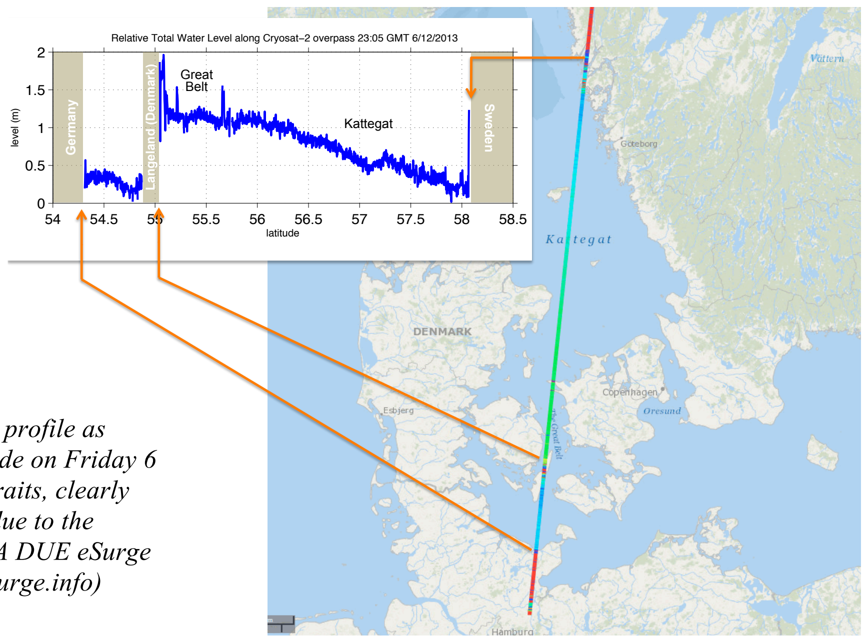

Figure 4 – total waver level profile as measured by CryoSat in SAR mode on Friday 6 Dec 23:05 over the Danish Straits, clearly showing the raised levels due to the Xaver/Bodil storm (from the ESA DUE eSurge project http://www.storm–surge.info)

4. CONCLUSIONS

CryoSat has sparked a formidable evolution in altimetry: processing, products, applications, as we have illustrated in this short review. There is obviously still much work to do, including much necessary validation, which several researchers will carry out within the framework of the Sentinel–3 Validation Team. However from the work already shown we can make two very encouraging conclusions: 1) we seem to be ready to capture the dynamic signature of the meso– and sub–mesoscales, and we will do this globally with Sentinel–3; and 2) good coastal altimetry from SAR up to 1km from the coast is now a realistic prospect based on what we see with CryoSat data.

References

Cipollini, P., Benveniste, J., and Vignudelli, S., "Coastal Altimetry Benefits from CryoSat Synthetic Aperture Measurements", *EOS*, v. 94, n. 8, 19 February 2013. doi:10.1002/2013EO080010

Cotton, D. et al., CryoSat Plus for Oceans (CP4O) Final Report, Executive Summary and Abstract, Version 1.0m 23rd February 2015, *ESA Contract 4000106169/12/I–N*, available from http://www.satoc.eu/projects/CP4O/

Dibarboure, G., Boy, F., Desjonqueres, J. D., Labroue, S., Lasne, Y., Picot, N., Poisson, J. C., and Thibaut, P. "Investigating Short–Wavelength Correlated Errors on Low–Resolution Mode Altimetry". *J. Atmos. Oceanic Technol*., 31, 1337–1362, 2014

Egido, A., "Geo–referencing of the Delay/Doppler Level–1 Stack with Application on Coastal Altimetry", *8th Coastal Altimetry Workshop, Konstanz, Germany*, 23–24 October 2014, available from http://www.coastalt.eu/konstanzworkshop14

Fenoglio–Marc, L., Dinardo, S., Scharroo, R., Roland, A., Dutour Sikiric, M., Lucas, B., Becker, M., Benveniste, J. and Weiss, R., "The German Bight: a validation of CryoSat altimeter data in SAR mode", *Advances in Space Research* (2015), doi: 10.1016/j.asr.2015.02.014

Gommenginger, C., Martin–Puig, C., Dinardo, S., Raney, R. K., Cipollini, P., Cotton, C. and Benveniste, J., "On the performance of CryoSat SAR mode over water surfaces", *Proc. CryoSat Validation Workshop 2011*, Frascati, Italy (ESA SP–693), June 2011.

Passaro, M., Cipollini, P., Vignudelli, S., Quartly, G. D., and Snaith. H. M., "ALES: A multi–mission subwaveform retracker for coastal and open ocean altimetry", *Remote Sens. Environ*., 145, 173–189, 2014. doi:10.1016/j.rse.2014.02.008

Thibaut, P., Aublanc, J., Moreau, T., Boy, F., Picot, N., "Delay/Doppler Waveform Processing in Coastal Zones", *8th Coastal Altimetry Workshop, Konstanz, Germany, 23–24 October 2014*, available from http://www.coastalt.eu/konstanzworkshop14