A REVIEW OF CRYOSAT-2/SIRAL APPLICATIONS FOR THE MONITORING OF RIVER WATER LEVELS

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ABSTRACT

Regarding hydrology applications and particularly the monitoring of river water levels from space, the CryoSat-2 ice mission has two main valuable characteristics: (1) its geodetic orbit and (2) the altimeter's SAR and SARin modes.

The benefits of the geodetic orbit of the satellite have been illustrated in the frame of the ”20 years of progress in radar altimetry” symposium (Venice, 2012) [2]. It has been shown that, with such an orbit, the way river water level was monitored using conventional altimeters had to be revisited. In particular, using LRM mode only, CryoSat-2 allowed us to build spatio-temporal time series of the river water level, to map river's topography and eventually derive pseudo-time series and pseudo-profiles of the river.

This paper focuses on the new ways to use altimetry for the monitoring of river water levels. SIRAL's (CryoSat-2 altimeter) SAR and SARin modes have the ability to deliver surface heights with an unprecedented along-track resolution of about 300 m. Moreover, using the SARin mode (involving the satellite's two antennas), the cross-track angle of the retracked echo is also available in routine. These two aspects of the SARin mode (high resolution and cross-track angle) make it a new tool to distinguish whether the retracked echo came from the surface of interest (e.g., a river) or any other reflective object nearby the surface of interest (e.g., another river section, lakes or temporary lake after flooding events or any other specular surfaces).

We introduce the multiple benefits of using the intermediate multi-look matrix (also known as stack matrix), among them: (1) to refine and select among the multiple Doppler-beam waveforms before averaging and retracking them, and (2) to be able to study the surfaces response according to their view angle.

Custom products processed at ESA (ESRIN) by Dinardo et al. [7], in the perspective of Sentinel-3, as well as official CryoSat-2 L1b and L2 products were used to illustrate these perspectives.

The paper mainly introduces the potential new applications brought by SIRAL's SAR and SARin modes. Finally, combined with its really dense geodetic orbit, CryoSat-2 can be seen as a topography mission that paves the way toward the SWOT mission.

Key words: satellite altimetry, CryoSat-2, SAR, SARin, hydrology, river water level.

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1. INTRODUCTION & CONTEXT

In this paper, we focus on the new applications of CryoSat-2 SAR & SARin modes to monitor the river water levels. This work is under heavy development and is still in its early days at Legos. Therefore, this paper is more about perspective discussions than results.

1.1. Repetitive orbits: time series

Usual altimetry data processing is done under the strong assumption of collecting data on repetitive orbits of shorter repeat periods (10 to 35 days) than CryoSat-2 geodetic orbit (369 days). In this section, we briefly introduce an example over the Solimões river using Topex/Poseidon data.

Data are collected within geographical windows in order to build time series : after geo-extraction, we apply custom editing (based on product parameters such as flags, etc.), filtering (usually along the “time” or “calendar time” dimension) in order to remove outsider measurements and finish by performing the selection of an unique measurement per overflight measurements group. For that matter, the median measurement along the vertical axis is usually the best choice. This latest processing step aims at suppressing the very high frequencies inherent to 20 Hz measurement groups, usually characterised by important discrepencies. Finally, time series are validated against in situ data using a standardised method [1, 4, 3]). See figure 1 for illustrations.

They may later be distributed, for example, via the LEGOS/HydroWeb web portal[1].

1.2. Geodetic orbits: spatio-temporal time series

Note: The example presented in this section is based on CryoSat-2 LRM mode measurements (and not SAR or SARin modes) for the only reason that in situ limnimetric data from gauging stations and CryoSat-2 Baseline B products do not overlap yet.

During the 20 past years in radar altimetry, geodetic orbit phases were relatively rare and relatively short. CryoSat-2 is the very first altimetry mission to permanently occupy a geodetic orbit.

Concerning "alti-hydrology", the assumption of collecting data on fixed locations (i.e., at the crossings between rivers and tracks from orbits of shorter repeat periods) vanishes. This leads us to rethink the way CryoSat-2 altimetry data can be used to monitor river water levels. Hence, due to the very tight spatial coverage (7 km is the inter-track distance at equator), we are considering spatio-temporal time series, acquired through time (t) and space, that is, along the river pathes (x).

Altimetry measurements (fig. 2) are geographically collected within polygons that delineate the river bed (isolated Madeira river from the hydrographic network polygons, cf. fig. 3). The polygons come from the SRTM WaterBody Data (SWBD) ShapeFiles [10]. At this stage, extracted data need editing, filtering and "unique measurement per overflight" selection to obtain clean spatio-temporal time series of the river water level.

Spatio-temporal time series can be decomposed into two main signals: the temporal time series (fig. 4) and the river profile (fig. 5).

Please, refer to [2] (poster & paper) presented in the frame of the symposium on "20 years of progress in radar altimetry" for more details about such spatio-temporal data processing.

1.3. CryoSat-2 data products

This section briefly lists the various CryoSat-2 products used at LEGOS and the associated on-going studies.

- **ESA Official L2 products**

[1] http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/

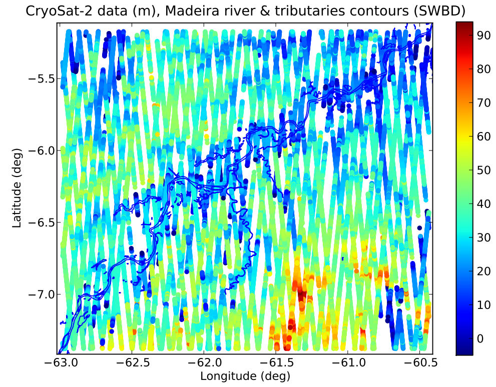

Figure 2. CryoSat-2 LRM measurements collected around the Madeira river (Amazon basin) plus polygons delineating various rivers around the Madeira river.

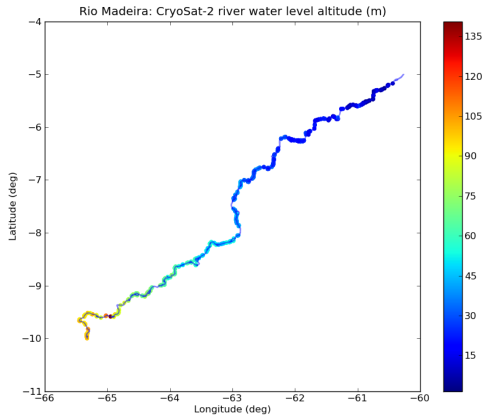

Figure 3. CryoSat-2 LRM measurements extracted within polygons delineating the Madeira river only.

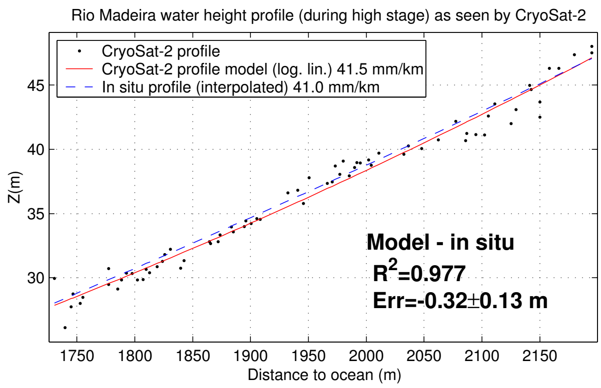

Figure 5. CryoSat-2 LRM pseudo-profile of the Madeira water level around Manicore. The spatial signal is isolated by removing an estimate of the river water level time series derived from in situ data.

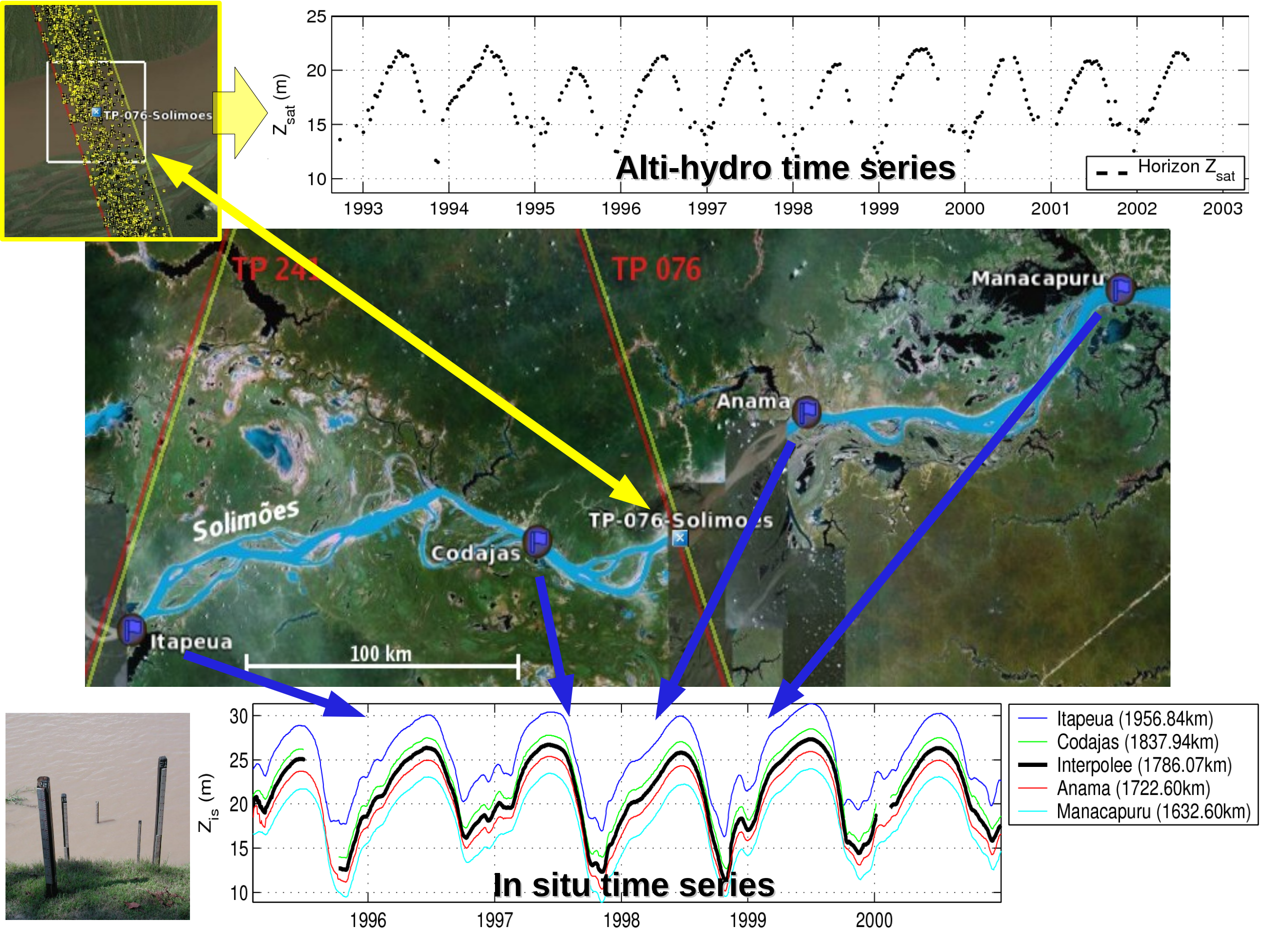

Figure 1. Example of river water level time series generation based on Topex/Poseidon data (AVISO M-GDR). Altimetry measurements are collected within a rectangular window (middle), edited and filtered to derive the most meaningful time series (top). It is later compared to river water levels reconstitued from upstream and downstream in situ data [1, 4, 3] (bottom, in situ data from ORE-Hybam/ANA, Brazil).

   - Product files for LRM, SAR & SARin modes (Baseline B, since Feb. 2012)
   - Use: river water level spatio-temporal time series extraction and validation, analysis of longitudinal & transversal instantaneous river profiles, (SAR:) benefits of the along-track resolution, (SARin:) benefits of the cross-track angle

- **ESA/ESRIN EOP/SER L1b/L2 prototype**
   - Data samples: stack matrices, L1B (waveforms), L2 (Samosa retracker outputs)
   - Use: exploring SAR stack matrices applications (surface roughness & classification), assessment of along-track resampling (spotlight) performed by Dinardo et al.

- **CNES CPP (CryoSat Processing Prototype)**
   - Data samples: SAR / Reduced-SAR (aka pseudo-LRM)
   - Use: SAR / Reduced-SAR comparison and assessment

2. WHAT'S NEW WITH SAR & SARIN MODES ?

2.1. Better along-track resolution

The SAR Doppler processing, compared to conventional Ku-band LRM altimetry, reduces along-track resolution from approximately 20 km to 300 m (1/64 exactly). This is of major interest for hydrology applications where, unlike ocean surfaces, LRM waveforms never really conform to a specific waveform model because of too much land contamination. Using SAR altimetry, two main aspects can be envisioned:

(1) Higher along-track resolution means less land contamination within waveform echoes acquired over rivers. But since SAR ground resolution cells are not isotopic (they extend along the cross-track direction), their benefit directly depends on the relative orientation of the rivers to the satellite tracks.

Figure 8 illustrates three waveforms acquired over the

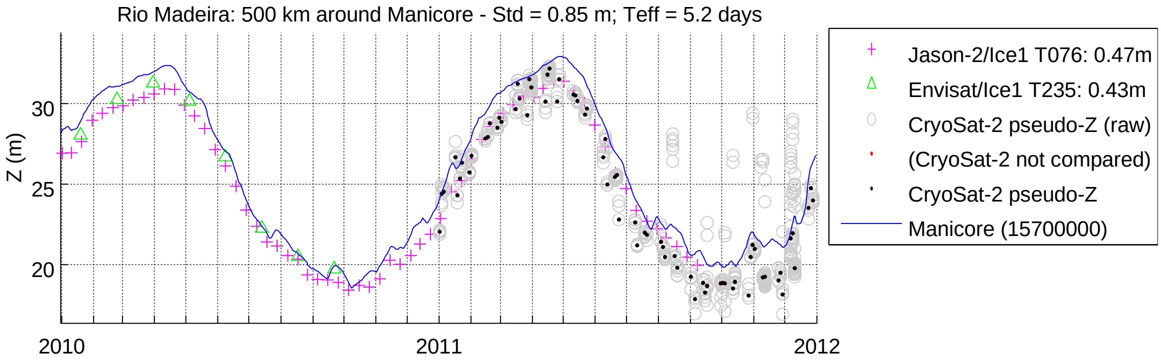

Figure 4. CryoSat-2 LRM pseudo-time series of the Madeira water level around Manicore. The temporal signal is isolated by removing an estimate of the river water level profile during high water stage, derived from in situ data.

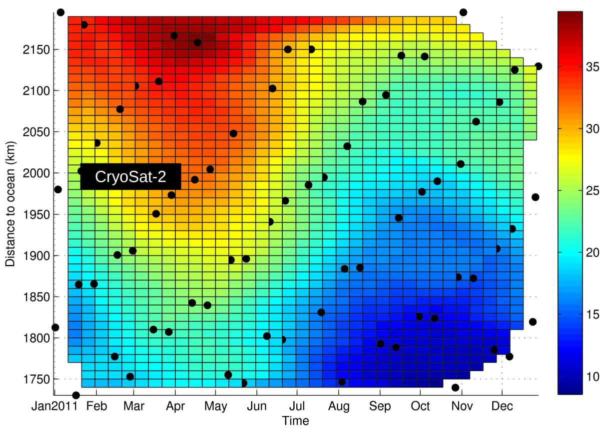

Figure 6. Water level of the Madeira around Manicore. 2D view of spatio-temporal distribution of CryoSat-2 LRM river water level measurements $Z(x,t)$. CryoSat-2 measurements (●) were interpolated to estimate river water level $Z(x,t)$ "anywhere along the river path and at any time" (colored surface).

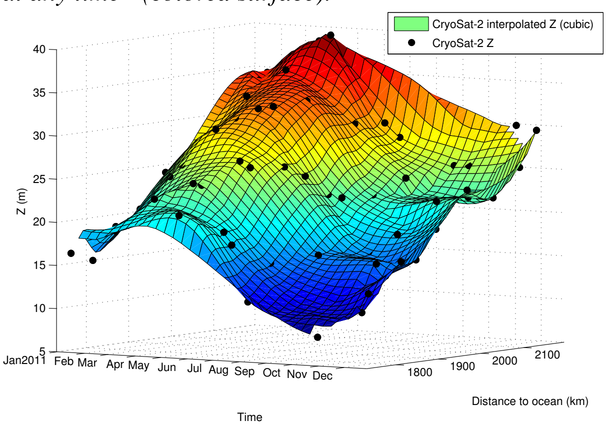

Figure 7. Water level of the Madeira around Manicore. 3D view of data from figure 6.

Mekong river using SAR mode: two were acquired halfway on the river's banks and one centered on the river bed.

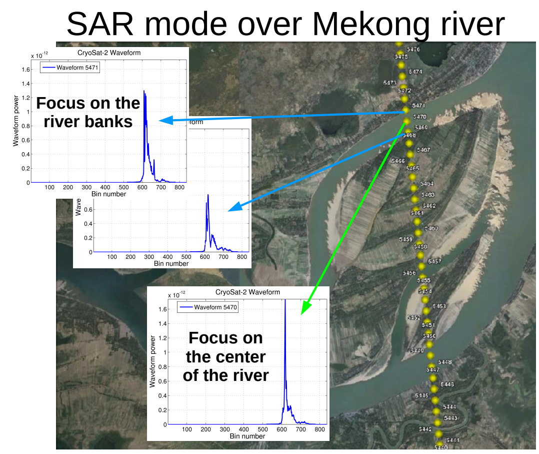

Figure 8. Illustration of SAR waveforms over the Mekong river: the higher resolution provided by SAR mode (300 m along-track) allows to acquire waveforms on illuminated surfaces that are 64 times smaller than LRM ones. As a result, waveforms built from stacks of ground point centered on river beds should often be less affected by land contamination. This assumption is true for this example but might be wrong for others, depending on the river's orientation relative to the satellite ground track. (Data from ESA/ESRIN EOP/SER prototype.)

(2) The location of SAR ground resolution cells are determined at the level of SAR Doppler processing. This operation is called "spotlighting" and was introduced by Dinardo et al. [7] during this workshop. Regarding hydrology, there are two major applications of spotlighting that we actually forsee: focusing SAR beams (a) on a specific point where land contamination should be minimum (e.g., centered onto the river beds or onto the gravity center of the surface intersecting the river bed and track footprint) ; (b) on a grid of higher resolution by implementing synthetic beams super-sampling along the along-track direction, between the river banks. After spotlighting, we would then obtain SAR stack matrices over custom lo-

cations. Several scenarios could then be envisioned to derive a custom SAR waveform to be retracked (for example, the mean waveform derived from sliced consecutive stacks or the waveform that get the highest correlation score with the retracker's fitted model, etc. Cf. next section 2.2).

2.2. SAR/SARin stacks

Among the available products derived from CryoSat-2 (official ESA/L2, NOAA/RADS, CNES/CPP), none of them prodive SAR stack matrices because they are usually considered as an intermediate step toward the production of L1B and L2 products. Nevertheless, there are numerous applications that could be derived from the use of SAR stack matrices.

SAR stack matrices are attached to a single ground resolution cell. Their columns contain waveforms seen from a range of different look angles[2]. On the other hand, rows contain power response of the surface observed according to the look angles. Figure 9 illustrates stack matrices as colored images for ocean-like (rough) and river-like (specular) surfaces.

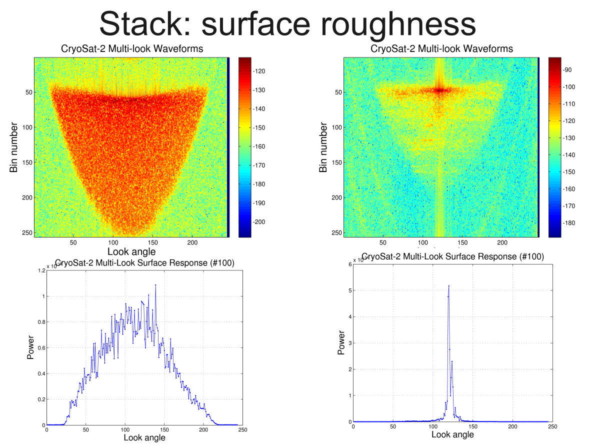

Figure 9. Illustration of SAR stack matrices as colored images. (Left column, top) Rough ocean-like surface response, (Right column, top) specular river-like surface response and (Both columns, bottom) respective power response according to the (along-track) surface look angles. Looking at the surface roughness responses (bottom images), we can note the typical differences between rough and specular surface responses, the later responding only within a tight range of the look-angle. (Data from ESA/ESRIN EOP/SER prototype.)

Actually, both stack dimensions (range bins and look angles) are interesting. For instance, focusing only on a few waveforms around the central part of the matrix would certainly result in a valuable reduction of the land contamination induced by synthetic beams side lobes. This looks like the Hamming filtering that is applied on stack matrices (along the look angle dimension only), in routine, by the CryoSat-2 ground segment.

Another interesting application would consist in the study of surface response according to their look angle. This could help, for example, to perform surface classification and improve water detection from the altimeter measurements only. Figure 10 illustrates the evolution of the roughness and mean power response derived from 120 consecutive ground resolution cells. The satellite was overflying a small lake at measurement #5539, in the middle part of the Mekong basin. On this example, gaussian functions were fitted on the angular power response (illustrative examples are given as bottom images of figure 9) derived from each one of the 120 stacks attached to the ground resolution cells. Roughness is computed as the standard deviation of the fitted gaussian curves while the mean power is taken within their mean $\pm$ Std Dev. In this figure, we can note the very specular (small roughness value) and strong power response of the ground resolution cell that is over the small lake.

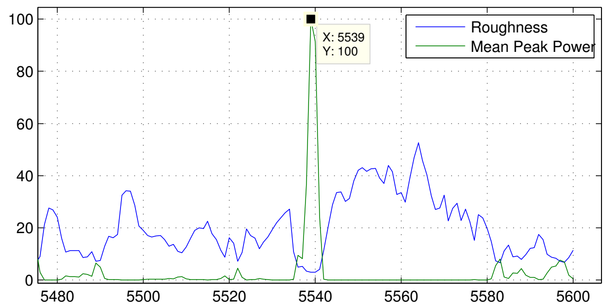

Figure 10. Evolution of the roughness and mean power response derived from 120 consecutive SAR ground resolution cells while the satellite was overflying a small lake at measurement #5539 (middle part of the Mekong basin). We can note the very specular (small roughness value) and strong power response of the ground resolution cell that is over the small lake. (Data from ESA/ESRIN EOP/SER prototype.)

2.3. SARin: "the magic of two antennas"

CryoSat-2 SARin implements the two satellites' antennas. The phase difference between the echoes received on each antenna is used to derive the cross-track angle of every waveform bin (available from L1b products). Within official CryoSat-2 Level 2 Product Files, only the waveform's retracked point is considered and its ground coordinates (lon,lat) are provided as additional parameters (as well as usual satellite nadir coordinates). It becomes straightfoward to extract SARin measurements that were acquired while the SIRAL altimeter was focused on some water surface, within the river bed polygon boundaries. Because LRM and SAR modes can not solve cross-track ambiguity, measurements location are always artificially localised at the satellite's nadir and water surface eleva-

[2] There are 256 waveforms / "different look angle values" for SAR mode and 64 for SARin mode in each single stack matrix.

tion underestimated (i.e., range values are not migrated to the real, off-nadir, echo provenance).

In figure 11, we can see maps of the SARin measurement coordinates extracted over the rivers of the Amazon basin. This kind of plot usually results in a map of the satellite ground tracks. But in the case of SARin measurement coordinates, we no longer observe these ground tracks anymore. Instead, it is remarkable to note that, while SIRAL is tracking as much water surfaces as it is possible within the antenna's aperture footprint, we actually obtain a map of significant parts of the hydrographic network. Based on simple observations, we can observe that off-nadir tracking of water surfaces can extend to up to 7 km across-track. Given the inter-track distance of CryoSat-2 orbit which is also 7 km, the neighbour parallel tracks overlap at least halfway.

We can state that CryoSat-2 orbit and SARin mode certainly constitute the most valuable altimeter configuration we have ever used to monitor river water level.

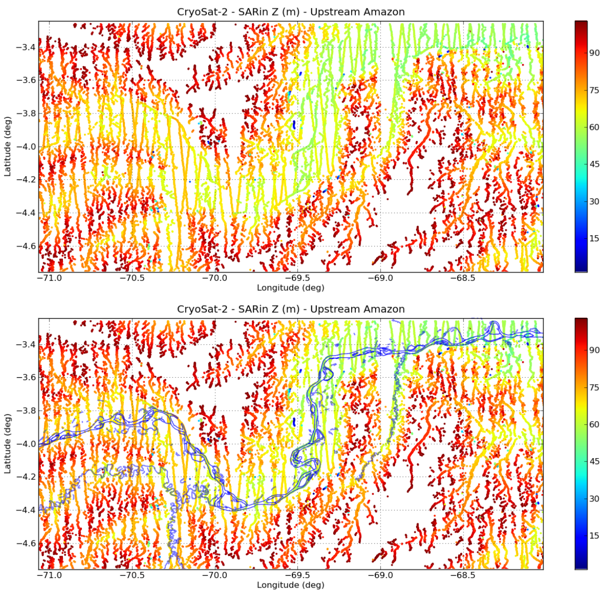

Figure 11. (Top) Map of Cryosat-2 SARin mode measurement points on the Solimões river (Amazon) in the West-South part of the current SARin mode mask. (Bottom) Same map with superimposed SWBD river bed boundaries (non-exhaustive hydrographic network). It is remarkable to note that, while SIRAL is tracking as much water surfaces as it is possible within the antenna's aperture footprint, we actually observe a map of significant parts of the hydrographic network. (Data from official ESA L2 products files, Baseline B.)

The smallest rivers tracked by SIRAL in SARin mode have a width of about 30 m. Ironically, such rivers are quite hard to see using satellite imagery (from Google Earth for example).

3. CONCLUSION & PERSPECTIVES

After an introduction to standard altimetry data processing for hydrology purposes, this paper gave an overview of the on-going and envisioned applications of SAR and SARin modes for the monitoring of river water level. (For more examples of on-going study areas, please refer to Calmant et al. [6].) SAR and SARin modes bring an unprecedented along-track resolution that is 64 times finer than conventionnal Ku-band LRM modes of the Jason, ERS and Envisat satellites series.

SAR Doppler processing leads to an intermediate step of data that consist in the stack matrices. Despite their unavailability as publicly released products, stack matrices are of major interest for the monitoring of land waters and more specifically for smaller targets such as rivers.

We gave an overview of possible uses of the stack matrices, including surface classification and computation of a custom SAR waveform prior retracking.

One of the major perspectives regarding SAR mode, compared to LRM mode, will be to quantify the improvement brought by its higher along-track resolution for the monitoring of river water level, as it is excepted by Jensen et al. [9]. This must be done on a significant set of SAR measurements of river water levels. Since LRM mode can be approximated by degrading SAR mode[3], we can compare, in perfect synchronism, SAR and LRM modes over the same surfaces, at the same time[4]. Work has already been initiated in collaboration with CNES in order to assess the performance of the CNES/CPP SAR processing chain [5] and its SAR analytical retracking model [8].

Using SARin mode phase difference information, the location of off-nadir water surface elevation measurements can be derived, up to 7 km far from the nadir satellite track. Early analysis shows that SARin mode helps to track the rivers in a way that we can map a significant part of the hydrographic network.

Finally, the assessment of RSAR, SAR and SARin measurements of river water levels will be performed as soon as possible and results will be compared to past and present LRM mission performances [1, 4, 3].

4. ACKNOWLEDGEMENT

This study was developed in frame of the EVALEC project funded by CNES.

[3]Degraded SAR mode is also known as Reduced-SAR (RSAR) or Pseudo-LRM (PLRM). RSAR processing involves no SAR processing at all: the SAR burst waveforms are just processed using standard LRM routines on decorrelated waveforms (that is usually one in nine).

[4]Note that the higher range noise of RSAR mode, compared to conventional LRM mode, is really low in comparision to the usual error bugdet in “alti-hydrology” and can be neglected as a first approximation.

Topex/Poseidon M-GDR data come from CNES/AVISO. In situ water level measurements of the Amazon basin rivers are provided by ORE-Hybam project, using data from ANA (Agência Nacional de Águas, Brazil). CryoSat-2 data come from ESA Official L2 product files. Stack matrices and SAR/SARin waveforms were outputted from ESA/ESRIN EOP/SER L1b/L2 prototype. Polygons of river bed contours come from SRTM/SWBD.

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