COMPARISON OF THE ENVISAT WAVEFORM RETRACKERS OVER INLAND WATERS

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ABSTRACT

Since the launch of ENVISAT satellite in 2002, the Radar Altimetry Mission provides systematic altimeter observations of the Earth surface. The ENVISAT Geophysical Data Records products contain, over all type of surfaces, altimeter ranges derived from four specialized retrackers: Ocean, Ice-1, Ice-2 and Sea-Ice retracker. Among the different goals of the ENVISAT Mission, one directly concerns land hydrology : the monitoring of water levels of the lakes, wetlands and rivers. In the present study, we compare the performances of these retracking algorithms for hydrology, in particular the ability to provide reliable water levels during high-water as well as low-water season.

1. INTRODUCTION

In the framework of its Earth observation programme, ESA launched ENVISAT satellite in 2002. It has been designed to help the scientific community to better understand the Earth environment and the processes which are responsible for climatic changes. Two main objectives were identified for the ENVISAT mission [1]:
- to collect measurements of the Earth environment at global scale and in long time series in order to highlight trends,
- to improve the capabilities of monitoring and managing the Earth's resources and to contribute to a better understanding of the solid Earth processes.

To complete these goals, it carries ten scientific instruments which provide atmosphere, ocean, land and ice measurements over five years planned life-time [2]. Its payload is mainly composed of :
- a high resolution SAR (ASAR - Advanced Synthetic Aperture Radar) to image Earth day or night under all weather conditions,
- a medium resolution spectrometer (GOMOS – Global Ozone Monitoring by Occultation of Stars) to measure atmospheric trace gases concentrations,
- the imaging spectrometer MERIS (MEdium Resolution Imaging Spectrometer) observing Earth surface in 15 VIS-NIR spectral bands with a ground resolution of 300/1200 m,
- an IR spectrometer (MIPAS – Michelson Interferometer for passive Atmospheric Sounding) to analyse the gases present in the atmosphere,
- a radar altimeter (RA-2 or Advanced Radar Altimeter) whose function will be detailed in section 2.

Our goal in this study is to assess the performances of ENVISAT RA-2 altimeter for continental hydrology purposes.

2. ENVISAT RA-2

Since its launch in 2002, the ENVISAT RA-2 35-day repeat cycle provides observations of the whole Earth surface (ocean and land) from 82.4° latitude North to 82.4° latitude South. RA-2 equatorial ground track spacing is about 85 km and and its beam footprint width is about 3.4 km. RA-2 is a nadir looking pulse limited radar altimeter operating with two frequencies: 13.575 GHz (or 2.3 cm of wavelength) in Ku-band and 3.2 GHz (or 9.3 cm) in S-band [3]. The radar altimeter emits a radar pulse and measures the two way travel-time from the satellite to the surface (ocean, ice or land). The distance between the satellite and the Earth surface – the altimeter height or range - is thus derived with a precision of a few centimeters. The altitude of the measurement to a reference ellipsoid is given by the difference between the satellite orbit information and the range. A very precise orbit determination is the result of the use of DORIS (Doppler Orbitography and Radiolocation Integrated by Satellite) system : an accuracy of around 5 cm is obtained in the radial direction [4]. The goal of RA-2 sensor is to provide a global scale collection of radar echoes over ocean, land and ice to measure ocean topography, water level variations in the great river basins, land surface elevation, to monitor sea ice, polar ice caps [2]. Processing of radar echoes or altimeter waveforms is performed on ground to obtain accurate range values [3].

3. RETRACKING

To improve the accuracy of range estimates, refined procedures known as waveform retracking are performed. Waveform retracking consists in ground-processing waveform altimeter to obtain better range

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estimates than what can be done by on-board tracking algorithms. Over non-ocean surfaces, the on-board tracking system is unable to place correctly (at the nominal tracking position) the waveform in the reception window due to fast variations of range values.

Radar altimetry has many limitations over land due to the complexity of returned waveforms. Many radar echoes are multipeaked revealing the presence in the altimeter footprint of several reflectors such as water, vegetation canopy, rough topography or ground vegetation. For the ENVISAT mission, four different retrackers are operationnally applied to RA-2 raw-data to provide accurate height estimates. Each of them was developped for a specific surface response : ocean, ice sheets and sea ice. Two of the retracking schemes (Ocean and Ice-2) applied on RA-2 measurements are based on the Brown model [5]. According to this theoretical model, the waveform (Eq. 1) can be described as the double convolution of the radar pulse, the radar point target response and the probability density of the specular points on the surface [6].

$$P_r(t)=P_e(t)*f_{ptr}(t)*g_{pdf}(z) \quad (1)$$

where $P_r(t)$: return power

$P_e(t)$: power emitted

$f_{ptr}(t)$: radar point target function (including the antenna gain of the sensor)

$g_{pdf}(z)$: probability density function of the specular points on the surface.

The parameters of the theoretical waveform are fitted to minimize the distance between the observed and the theoretical waveforms. The width of the radar echo leading edge is comptuted and thus the tracking point can be inferred.

Ice-1 retracker is intended to ice caps and more generally topographic surface height estimation. From the waveform parametrization using the Offset Centre Of Gravity (OCOG) scheme, a tracker offset is estimated and a corrected height value can be derived.

The Sea Ice retracker principle is based on a parametrization of the waveform and the use of a threshold to calculate the tracker offset and as a consequence of the corrected height.

For details on the retracking algorithms, see [7] for Ocean tracker, [8] for Ice-1, [9] for Ice-2 and [10] for Sea-Ice. Unfortunately, none of them is intended to hydrological purposes. In section 7, the consistency of the water level measurements is examined for each retracker. The results given by each retracker are then compared to in-situ gauge station records in section 8. Section 9 is devoted to the multi-satellite validation of ENVISAT data.

4. THE STUDY ZONES

We have particularly focused our attention on four zones of the Amazon basin: the area surounding Tabatinga, the Negro River sub-basin, the confluence between Negro and Solimões Rivers and the lower part of the Tapajos River. Their location are summarized in "Table 1". This choice allows us to have a thematic (related to the nature of water) and a geographical (upper, mid and lower part) overview of the Amazon basin. Tabatinga represents the entry of the Amazon river in Brazil. Until recently, only few data from the Brazil neighbour countries were available. Discharge estimations and sediment loads of the “white waters” of the Andean tributaries were derived from the gauge station records. The monitoring of the Negro river sub-basin and the confluence between Solimões and Negro rivers is necessary to quantify the dissolved fluxes of organic matters contained in the “black waters” of Negro River. The lower part of Tapajos river represents the third type of waters that can be encountered in the Amazon river: the “clear water” characterized by their absence of sediments. Besides, near the confluence between Amazon and Tapajos, a complex system of lakes - or várzeas - of great importance in hydrological processes between the river main stream and floodplains is studied by the HYBAM project.

Table 1 : Geographical extension of the sudy zones.

Zone	Longitude (°)		Latitude (°)	
	min	max	min	max
Negro River sub-basin	-73.25	-59.35	-3.35	5.4
Tabatinga	-70.69	-69.59	-4.85	-3.67
Tapajos	-56.1	-54.43	-3.82	-1.54
Solimões-Negro conf.	-62.47	-58.01	-4.22	-1.05

5. DATASETS

5.1 ENVISAT radar altimetry data

We used here the first available ENVISAT RA-2 20Hz range measurements contained in the Geophysical Data Records (GDRs) [11] from cycle 14 to cycle 25 of ENVISAT RA-2 mission (February, 2003 to March, 2004).

5.2 TOPEX/POSEIDON radar altimetry data

The measurements used in this study are the 10Hz Ku-range estimates contained in the GDRs from cycle 369 to cycle 421 of Topex/Poseidon (T/P) mission (September 20, 2003 to February 2, 2004) corresponding to the new orbit of the satellite. The GDRs are made available by the Archiving, Validation and Interpretation of Satellite Data in Oceanography (AVISO) data centre at the Centre National d'Etudes Spatiales (CNES) [12].

5.3 ERS-1&2 radar altimetry data

The data used are the 20 Hz range estimates of ERS-1&2 from 1991-2003 retracked with Ice-2 algorithm and made available by OSCAR (Observations des Surfaces Continentales par Altimétrie Radar or Land Observations by Radar Altimetry) project at LEGOS in Toulouse (France).

5.4 GFO radar altimetry data

Geosat Follow-On is a U.S. Navy altimeter mission launched in 1998. Since November 9, 2000, the data has been delivered to the scientific community. We used the 10 Hz range estimates made available by the NOAA from cycle 55 to 124 (November 9, 2000 to February 16, 2004).

5.5 ICESat laser altimetry data

The Ice, Cloud and Land Elevation Satellite is a part of NASA's Earth Observation System (EOS), the goal of which is to measure changes in elevation of the Earth surface and mainly the Greenland and Antarctic Ice sheets. ICESat is censed to provide independant high-accuracy data to calibrate and validate topographic products [13]. In this study, we use the 14 orbits of GLA16 ICESat/GLAS (Geoscience Laser Altimeter System) product recommended for land scientists and topographic mapping to level in-situ gauge stations in the Amazon basin.

5.6 In-situ gauge stations

The Brazilian Water Agency (Agencia Nacional de Aguas or ANA) has the responsability to manage a network of 571 gauging stations in the Brazilian part of the Amazon basin. At each station, daily measurements of water stage are collected, and daily estimates of discharge are produced using rating curves obtained from periodical (sometimes several times a year) simultaneous measures of stage and discharge . In the selected zones, 7 gauging stations are leveled [14] using GPS measurements or high accuracy ICESat laser altimetry data [13] and combine availability of data for 2003 and the begining of 2004 with proximity to RA-2 groundtracks (see "Table 2").

Table 2 : Location and altitude of the in-situ gauge stations.

Station	Basin	Long (°)	Lat (°)	Stage-0 altitude (m wrt GRACE)
Tabatinga	Solimões-Amazon	-69.933	-4.25	55.98
Manacapuru	Solimões-Amazon	-60.609	-3.308	3.87
Obidos	Solimões-Amazon	-55.511	-1.947	2.41
Curuai	Solimões-Amazon	-55.476	-2.267	-1.04
Curicuriari	Negro	-66.812	-0.192	32.46
Tapuracuara	Negro	-65.015	-0.42	25.45
Manaus	Negro	-60.035	-3.149	-7.5

6. ALTIMETRY DATA ANALYSIS

Water levels are obtained as the difference between the values of the satellite orbit and the range values, taking into account different instrumental and geophysical corrections to the range (Eq. 2).

$$R = \hat{R} - \sum_j \Delta R_j \quad (2)$$

where $\hat{R} = \frac{ct}{2}$ is the range computed neglecting refraction based on the free-space speed of light c and ΔR_j are corrections for instrumental, environmental and geophysical effects.
The corrections applied to the different sensors, contained in the ENVISAT and T/P GDRs and in ICESAT/GLAS standard data products are mentionned in "Table 3".

Table 3 : Corrections used for each altimeter.

Type of correction	ENVISAT, ERS, GFO	Topex/ Poseidon	ICESat
Onboard instrumental drifts and biases	Yes	Yes	Yes
Ionospheric	Yes	Yes (DORIS)	No interaction
dry troposphere	Yes	Yes	Yes
wet troposphere	Yes	No	Yes
solid Earth tide	Yes	Yes	Yes
pole tide	Yes	Yes	Yes

The first step is to identify intersections between the satellite tracks with the rivers using the mosaic of JERS-1 SAR images acquired from september to december 1995 [15]. Then the validation of water levels from ENVISAT measurements can be decomposed in two different stages :

- the study of the consistency of water levels derived from each ENVISAT retracker,
- the estimation of the accuracy of water levels derived from each ENVISAT retracker by comparison with in-situ measurements at different gauging sites.

7. RIVER PROFILES FROM RA-2 DATA

In this part, the consistency of the water levels derived from each RA-2 retracker is examined. To assess the performances of the algorithms, river profiles estimated by the four methods are compared. Two typical cases are presented (see “Fig.1”): the satellite is along strike the river (ENVISAT track 764) and the satellite is crossing the river (ENVISAT track 349).

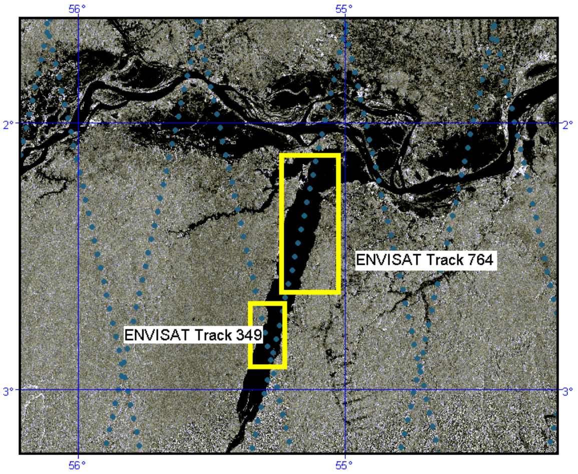


Fig. 1. Location of ENVISAT tracks on lower Tapajos.

On the lower Tapajos, all run along-strike the river measure water level along 80 km long profiles. To quantify the noise on these profiles, 4th order polynoms are fitted. For each cycle, the noise is defined as the rms error between water level measurements and the corresponding estimates of the 4th order polynom previously determined. One example of these profiles is presented on “Fig. 2”. For a better viewing, profiles for “Ice-1”, “Ice-2” and “Sea Ice” are artificially shifted downward of respectively 1, 2 and 3 m of their real level.

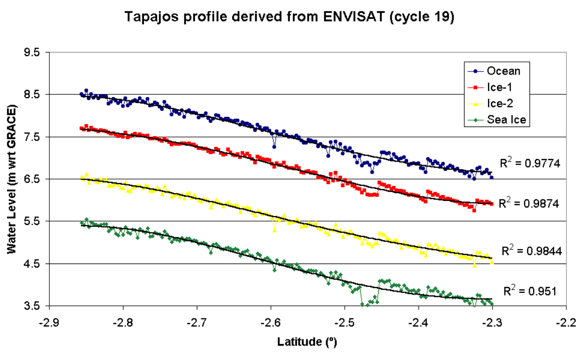


Fig.2. Tapajos profiles along strike the river derived from each ENVISAT tracker for cycle 18.

Whatever the considered retracker, the results (mean values of number of valid points, RMSE and determination coefficient are presented in “Table 4”) obtained are very good: a great number of valid data, weak rms error (<0.15 m) and a high value for the determination coefficient of the least square error estimator (>0.95). However, this example can be considered as idealistic. In most of the cases, the satellite ground track only intersects the river on a few kilometers, the width of the river evolving from a cycle to another. This type of situation is illustrated by “Fig. 3” for ENVISAT track 349 on the lower Tapajos.

Table 4: Results for along strike the river measurements.

	Number Of data	RMSE (m)	R^2
Ocean	157	0.1	0.98
Ice-1	165	0.09	0.98
Ice-2	161	0.11	0.97
Sea Ice	151	0.13	0.95

As it is obvious on “Fig. 3”, the four retrackers are able to restitute a good estimation of the river level for each cycle. Nevertheless, some height measurements derived from “Ocean”, “Ice-2” and “Sea Ice” are eroneous.

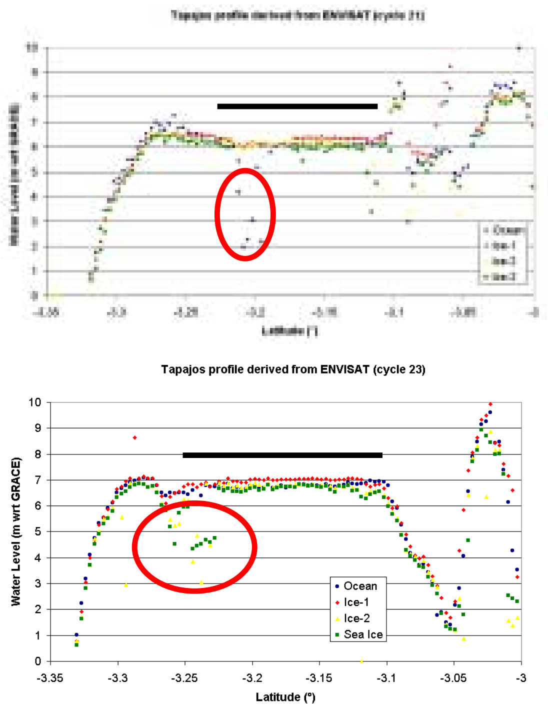


Fig.3. Tapajos profile derived from each ENVISAT tracker for cycles 21 et 23. Black lines represent the river width. Red circles bring to the fore eroneous height measurements.

The Ice-1 retracking algorithm gives the better results for water level estimation in terms of number of available valid data and minimization of the RMSE.

8. CROSS-COMPARISON WITH IN-SITU GAUGE STATIONS

8.1 Water level time series construction

Once the identification of intersections of satellite groundtracks with rivers is done, time series of water level can be built. For each cycle, the median of the hi-rate data (20Hz for RA-2, ERS-1&2 and 10Hz for T/P, GFO) present on the intersection is computed. The dispersion is given by the estimator known as median absolute deviation (Eq. 3):

$$MAD(x)=\frac{1}{N}\sum_{i=1}^{N}\left|x_i-x_{med}\right| \quad (3)$$

where MAD(x): mean absolute deviation of the observations

N: number of observations

x_i: i^{th} observation

x_{med}: median of the observations

The spatially “averaged” of hi-rate measurements represent the basis a given altimeter-river intersection. Water levels are expressed in reference to the GRACE geoid.

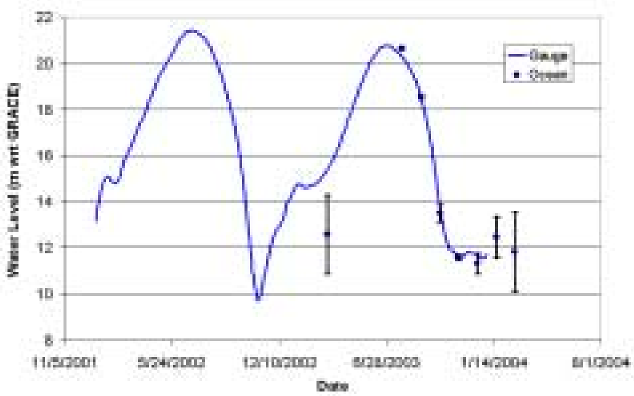
8.2 Water level time series validation

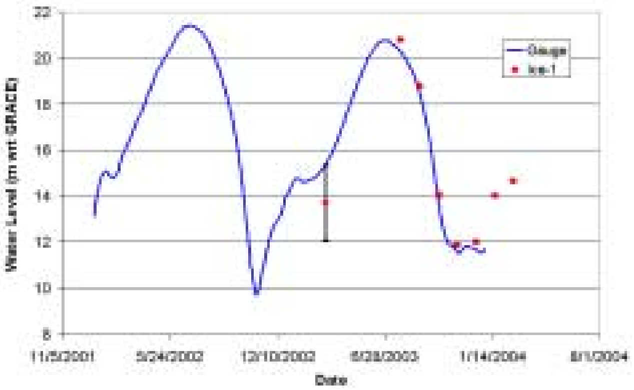
With its relatively few important equatorial groundtrack spacing, RA-2 allows to identify intersections with rivers at less than 85 km to the location of the gauge stations. The water level time series derived from the four retrackers are compared with gauge stations measurements (see “Fig. 4”). In “Table 5” are presented the rms error between the altimeter and the gauge water levels.

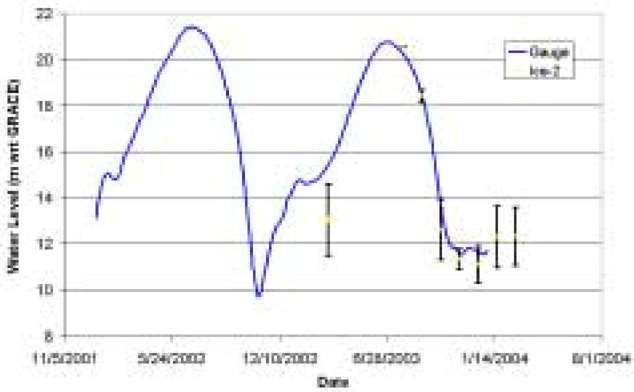
Table 5: RMSE between water levels derived from ENVISAT for each retracker and water levels measured at in-situ stations.

Reference station	ENVISAT track Position (km)	RMS Error (m)			
		Ocean	Ice-1	Ice-2	Sea Ice
Tabatinga	20 lower	0.27	0.40	0.32	1.37
Manacapuru	43.5 upper	0.27	0.20	0.86	0.69
Manacapuru	43.5 lower	0.31	0.27	0.29	0.21
Obidos	5.25 lower	0.26	0.26	0.58	0.4
Curuai	Lake 1	0.99	0.44	0.97	1.15
Curuai	Lake 2	0.85	0.27	1.21	3.28
Curuai	Lake 3	0.55	0.53	1.35	0.99
Curicuriari	29 upper	0.12	0.07	0.10	0.13
Tapuruquara	15.5 upper	0.50	0.35	0.42	0.33
Tapuruquara	47.5 lower	0.42	0.12	0.23	0.14
Manaus	29 upper	0.31	0.11	0.56	0.32

In most of the cases, Ice-1 exhibits the lowest rms. Nevertheless, even if Ice-1 retracker seems to be the most suited for hydrologic appliances, some problems go on existing, mainly complete lack of data at an intersection for a given cycle creating gaps in the time series.







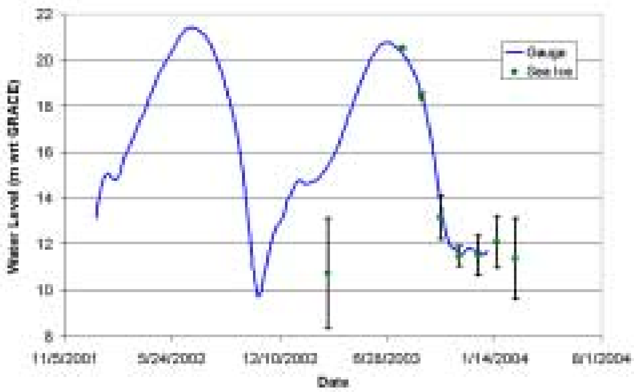


Fig. 4. Time series of water level derived from each ENVISAT retracker 29 km upper Manaus and compared with Manaus gauge measurements. The blue lines represent in-situ water level measurements, blue, red, yellow and green dots stand for respectively water levels derived from Ocean, Ice-1, Ice-2 and Sea Ice retrackers. Black lines are the uncertainties on ENVISAT measurements.

9. MULTI-SATELLITE VALIDATION

In this part, we propose to compare river slopes obtained with different sensors and to combine these data to obtain water level time series with a maximal number of data. For ENVISAT, the water levels are derived from Ice-1 retracking algorithm.

9.1 Tapajos river slope from ENVISAT, ERS and ICESat

ENVISAT track 349 (and formely ERS) runs along the lower Tapajos, recording more than 50 km of water level and highlighting the curvature of the water surface. A comparison of slopes measured by ENVISAT (for five different dates), ERS (for two cycles) and ICESat is presented on Fig. 5. Profiles derived from ICESat and RA-2 with a time-lag of 15 days are very similar bringing to the fore the consistency of ENVISAT data.

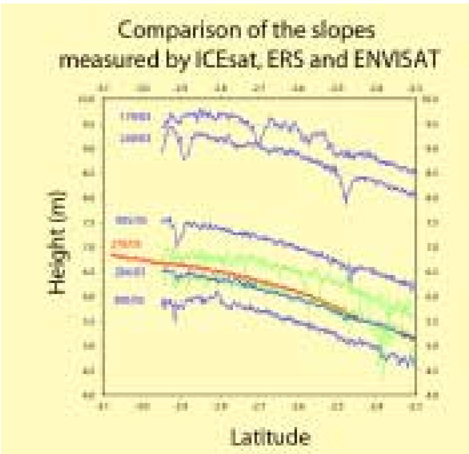


Fig. 5. Lowest Tapajos river profiles from ICESat (red), ENVISAT (blue), ERS-2 (green).

9.2 Multi-mission water level time series

Two zones were identified on the lower Tapajos where ENVISAT tracks are crossing other altimeter tracks. ENVISAT track 349 intersects T/P track 50 in box A and ENVISAT 764 and GFO 063 tracks in box B on Fig. 6. The combined water level time series are respectively presented on Fig. 7 and Fig. 8 and compared to the records of Itaituba on the upper Tapajos and Santarem on Amazon main stream.

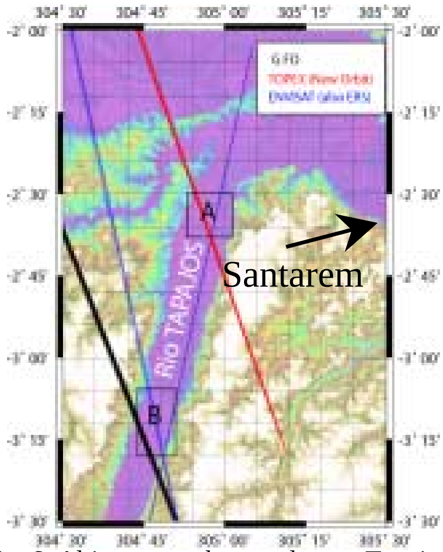


Fig. 6. Altimeter tracks over lowest Tapajos.

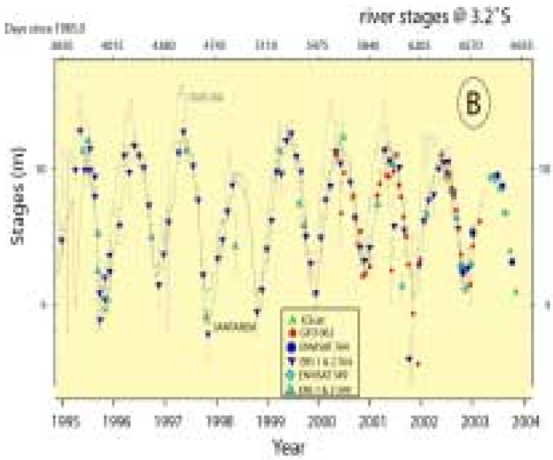


Fig. 7. Multi-satellite water level time serie in box B at 3.2° S.

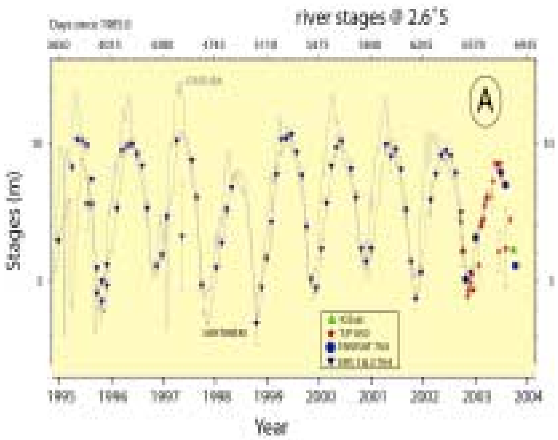


Fig. 8. Multi-satellite water level time serie in box A at 2.6° S.

The multi-satellite time series show that all along the lower Tapajos (from 3.2° S to 2.6° S), the river stages are controled by the Amazon main stream, as recorded at Santarem, and not by the upper Tapajos fluctuations, recorded at Itaituba.

10. MIGRATION OF ALTIMETER DATA

Over lakes, rivers and wetlands, water level profiles derived from altimeter measurements are supposed to be flat or slightly inclinated due to the slope of the water body. As we can notice on Fig. 5, downward turning parabolic features are observed on altimeter profiles corresponding to the water bodies.

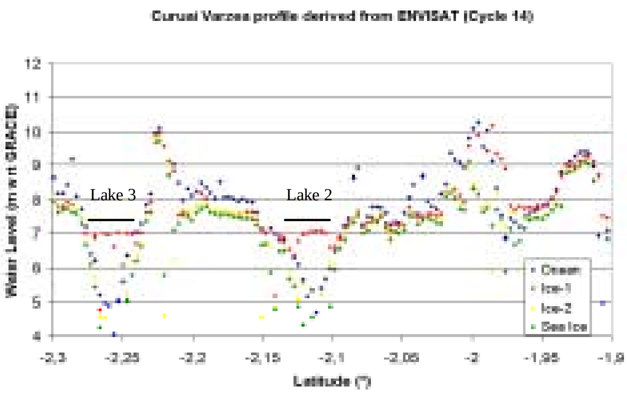


Fig. 5. Water level profile derived from ENVISAT 20-Hz measurements over Curuai Várzea.

This problem occurs wen the altimeter tracker remains locked on the brighter target present on the reception window and does not estimate the distance between the satellite on its orbit and the Earth surface in the nadir direction. The round-trip travel time between the altimeter and the surface (and the range as a consequence) is thus over estimated. As it is presented on Fig. 6, an height estimation error can inferred (Eq. 4):

$$\Delta h = h' - h \sim \frac{d^2}{2h} \quad ; \quad d << h \quad (4)$$

where Δh is the height error,

h the range of the water body,

h' the over estimated height,

d the distance between two altimeter acquisitions.

The method which consists in integrating energy over parabolic features and focusing the resultant sum at the apex of the curve is known as migration and is commonly used by seismologists. It was already used in altimetry over ice caps to improve the resolution of topographic features [16].

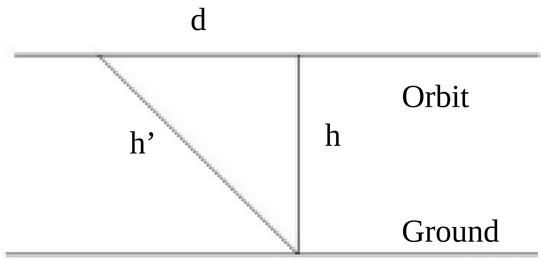


Fig. 6. Travel-time diagram.

We do not apply the migration technique to the altimeter waveform data but to the ICE-1 ranges over lake 2 of Curuai Várzea. For each cycle, we have compared the results obtained with migration to water level derived from mean and median estimators. We can thus estimate the error commited without migrating altimeter data. For the whole cycle, the water level error is 0.44 m and 0.27 m respectively to mean and median estimator. We have then computed the RMSE between Curuai in-situ gauge and ENVISAT derived water levels. Compared to the previous result given by the median estimator (0.27 m), the RMSE is now reduced of 0.08 m (new RMSE of 0.19 cm). This simple example illustrates the importance of radar altimetry data migration for hydrological studies.

11. CONCLUSION

ENVISAT RA-2 exhibits a strong capability for the monitoring of inland waters. It is, at the moment, the only radar altimeter in function able to provide high quality repetitive measurements for continental hydrology due to the quality loss of T/P measurements for hydrology and the lack of Jason-1 data over rivers. Among the four retracking algorithms applied on ENVISAT waveforms, Ice-1 provides the most suited ranges for continental hydrology studies in terms of number of valid data and minimization of the RMSE. Nevertheless, an important number of data are lacking in the GDRs. This fact reminds us that the problem of the retracking over inland waters is still open. To improve the accuracy of the water level series, some tests can be envisaged on the ENVISAT 20Hz measurements to eliminate invalid data thanks to parameters from other retrackers. For instance, values of the sea wave height or of the leading edge slope (outputs of respectively Ocean and Ice-2) can be used to discriminate between valid and invalid data. To obtain a better accuracy of the altimeter derived hydrological datasets, it is necessary to perform migration process. To assess the accuracy of RA-2 for land (water) studies, absolute range calibration should be performed using the the same type of experiments as for ocean [17].
Different hydrological appliances of RA-2 data can be envisaged. As RA-2 efficiently completes the present

network of "virtual" or altimeter gauge stations on rivers and wetlands, a better understanding of the hydrological processes at basin scale is forecome. Besides, the combination of RA-2 raw-data with simultaneously acquired MERIS or ASAR images is very useful to estimate water volume variations in the river basins.

The assimilation of RA-2 data in hydrological models can increase the quality of outputs and predictions and become the first step toward operational hydrology.

12. AKNOWLEDGEMENT

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