New perspectives in monitoring water resources in large tropical transboundary basins based on satellite imagery and radar altimetry

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Abstract The combined use of satellite imagery and radar altimetry offers entirely new perspectives for the monitoring of water resources in large tropical transboundary basins. We illustrate this point of view with results from a study conducted mostly in the region of the Llanos de Mojos, a large complex of wetlands located within the southernmost extension of the Amazon Basin, at the Brazilian border with Bolivia and Peru, and also from previous studies. First, despite the current limitations of the radar altimetry missions, which were designed primarily for ocean level or ice cap studies (essentially the revisit time, the size of the water bodies that can be monitored, and the lack of reliable data in the presence of relief), the data processing and the tools we developed to select the data appropriately, allow us to retrieve quite accurately the seasonal variability of the water elevation within the selected basin. For instance, the common altitudinal reference of the radar altimetry missions is offering new modelling opportunities, as the river slope is a key parameter for hydrodynamic studies. Second, the results emphasize the benefit of coupling these data with remote sensing images, to obtain information on surface water storage in this very complex system. Lastly, the spatial distribution that can be obtained nowadays, and the perspectives offered by future sensors, are moving towards a detailed global capability for monitoring wetlands and flood plains, as well as their relationship with the river flow. The application of these monitoring tools is of primary importance for tropical poorly-gauged basins in terms of infrastructure monitoring and planning, flood and drought monitoring and forecasting, fluvial waterway monitoring and transport planning, and the fluvial dynamics of the riverbed and discharge modelling.

Key words water resources; remote sensing; radar altimetry; transboundary basins; Amazon Basin

INTRODUCTION

Radar altimetry has recently demonstrated a strong potential for hydrological studies. A review of different applications can be found in Calmant *et al.* (2008). We summarize the major ones:

surface water resource monitoring in relation to climate and agriculture. Many studies have been conducted over inland areas, mostly over lakes (see Creteaux & Birkett, 2006, for a review). The previous studies mostly used the water levels derived from the measurements of the 10-day repeat cycle of the CNES/NASA missions: T/P (1992–2005), followed by Jason-1 since 2002, and now Jason-2 since July 2008. Only a few studies were based on water levels derived from ESA altimetry missions (i.e. the ERS series started in 1991, and now ENVISAT, both with a 35-day repeat period) over lakes (Medina *et al.*, 2008) and rivers (Berry *et al.*, 2005; Frappart *et al.*, 2006a,b).

(b) sampling of all kind of water bodies for estimating the spatio-temporal variations of surface water volume over the main stream jointly with the flood plains in the Negro River basin (Frappart *et al.*, 2005, 2008) and the Mekong basin (Frappart *et al.*, 2006b), examining the relationship between river and flood plain through the differences in water levels was conducted by Cauhope (2004), and modelling the transfer of water between river and flood plain partly based on altimetric water levels time series (Bonnet *et al.*, 2008).
(c) Estimates of river slope and implications for hydrodynamics with both T/P and ENVISAT data Leon *et al.* (2006a,b).

The present study presents an application of radar altimetry for estimating slope and bankfull discharge.

DATA AND METHODS

The study area is located at the Brazilian border with Bolivia and Peru. In Brazil, this region is known as the upper Madeira region. The Madeira River has four main tributaries, two flowing through Bolivia: Beni and Mamore rivers; one flowing through Peru and Bolivia: the Madre de Dios River; and one forming the border between Bolivia and Brasil: the Guapore River. The Mamore and Beni are meandering rivers, flowing mostly from south to north, west of an extensive inundation plain, called Llanos de Mojos. The Llanos de Mojos region is a large flood plain of variable extent related to the alternating dry and rainy tropical seasons (Ronchail *et al.*, 2005); it is partly dry during the Austral winter and reaches 150 000 km^2 at the end of the rainy season (Roche & Fernandez, 1988).

Radar altimetry data

The altimetry data used in this study are the along-track measurements from the ENVISAT mission, made available by the CTOH, specifically the range data retracked by the ICE 1 algorithm. In order to extract the value of water surface elevation, we used a manual selection of the altimetry ranges projected in the plane perpendicular to the flow direction (Roux *et al.*, 2009). Virtual gauges are defined at the intersection between a water body and the satellite ground track. Each cycle, the water level is obtained by computing the median of all the data included in the selection window and the associated L1 norm dispersion. This process, repeated each cycle, allows the construction of the time series of water level associated with a virtual station (more details can be found in Frappart *et al.*, 2006a; Santos Da Silva *et al.*, 2008). Water levels are referenced to geoid EIGEN-GRACE02C, complete to order 200 (Tapley *et al.*, 2005).

For the purpose of validation, the data at six virtual stations have been compared with the water levels at six conventional gauges located on the Madeira and the Guapore rivers; gauges Porto Velho, Principe da Beira, Pimenteiras, Abuna, Pedras Negras, Vila Bela de Santissima Trindade, data distributed by ANA, http://www.ana.gov.br. Figure 1 presents the location of the 31 virtual gauges included in this study.

Satellite image data

The satellite images used were the JERS-1 (L Band SAR launched by the National Space Development Agency of Japan, NASDA, in February 1992) images mosaic from the Global Rain Forest Mapping (GRFM) project at 100-m resolution (Siqueira *et al.*, 2000).

Geomorphological parameters and discharge estimation

Three main geomorphological parameters have been estimated at the virtual stations, and are presented in Table 2. Each virtual station is identified by a sequential number, the satellite track number, the river it crosses, and the latitude-longitude of the virtual station's centre given as the mean of the longitude and latitude for the points constituting the station. The width (L) was measured from the JERS-1 images mosaic by the distance measuring tool of ARCGIS, and is

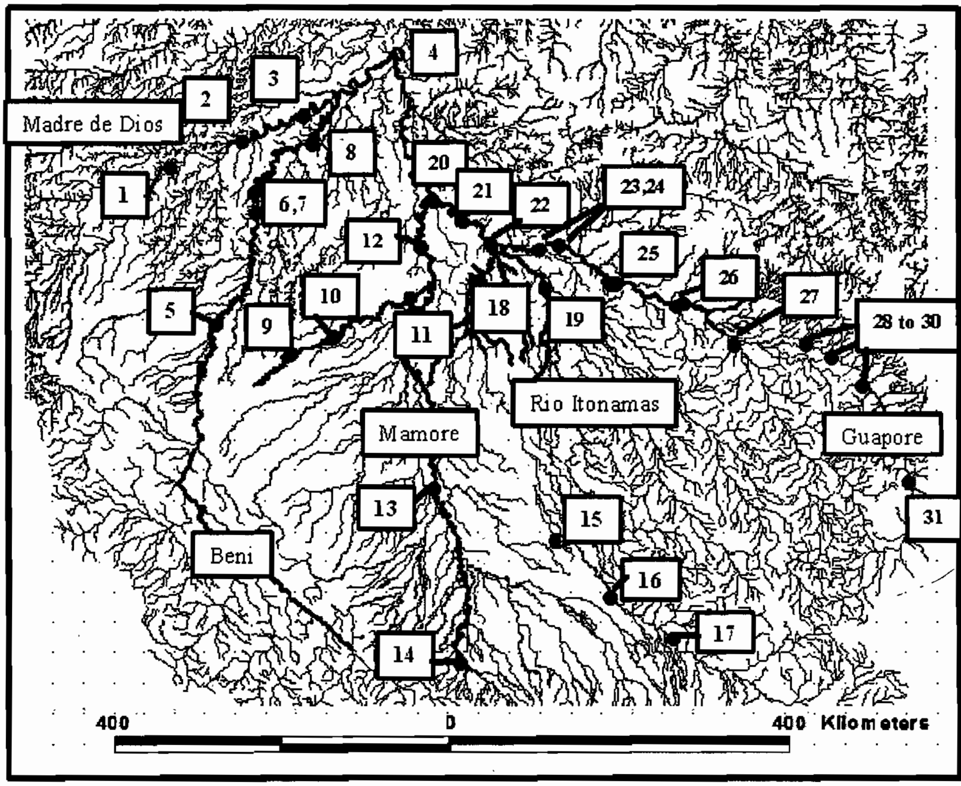

Fig. 1 Location of the virtual gauges.

therefore given with an uncertainty of 100 m, being the resolution of the image. The maximum level difference H (m) has been estimated by the following formula:

$$H = \max(h_i) - \min(h_i) \tag{1}$$

where h_i is the median of the water surface altitude at the virtual station for each ENVISAT cycle (m). Slope (m/m) has been estimated by two methods. The first is given by:

$$S1 = ((\min(h_i) - \min(h_j)) / \mathrm{dist}(SV_i \text{ to } SV_j) \tag{2}$$

SV_j being located downstream of SV_i and dist(SV_i to SV_j) being the distance between SV_i and SV_j in m, and measured by the distance measuring tool of ArcGIS.

$$S2 = 1/2[(\min(h_i) - \min(h_j) / \mathrm{dist}(SV_i \text{ to } SV_j)) + (\min(h_h) - \min(h_i) / \mathrm{dist}(SV_h \text{ to } SV_i))] \tag{3}$$

SV_h being located upstream and SV_j downstream of SV_i.

Bankfull discharge $Q1^*$ (m^3/s) was estimated for each virtual station by:

$$Q^* = 4.00 \times A^{*1.21} \times S^{0.28} \tag{4}$$

given by Williams (1978) where Q^* is the bankfull discharge, A^* cross-sectional area at bankfull and S the slope. A^* has been approximated by:

$$A^* = L \times H \tag{5}$$

Another formula is given by Bjerklie *et al.* (2003):

$$Q2^* = 0.1676 \times L^{*1.86} \tag{6}$$

The estimation of discharge was evaluated by comparing with monthly discharges estimated at two conventional gauges (Table 1).

Table 1 Minimum (Min *Q*), Mean (Mean *Q*), and Maximum (Max *Q*) of monthly discharges (m^3/s) estimated between, respectively, September 1970–November 2007, at Guaraja-Mirim, on Mamore River upstream of the confluence with the Guapore River, and May 1967–June 2008 at Porto Velho, on the Madeira River, 331 km downstream of the Beni-Mamore confluence.

Conventional gauge	Min *Q*	Mean *Q*	Max *Q*
Guaraja-Mirim	1039	7688	21280
Porto Velho	2220	18394	47400

RESULTS AND DISCUSSION

Validation

We can analyse the precision of the altimetric data by estimating the discrepancy between water levels at conventional gauges and at virtual gauges. Table 2 presents the RMS standing for the discrepancy at six couples of conventional gauges/altimetric virtual stations The RMS is calculated with respect to the best fitting regression line, the coefficient of which is provided.

As we have seen, it is difficult to assess the precision of the altimetry-derived water levels by comparison with conventional gauges, as the first is averaging the surface elevation across the channel of the river, and whereas the second is measuring at one single point located on one bank of the river. First, the precision of the conventional gauge with respect to the spatial variability of the river surface is never stated. Koblinsky *et al.* (1993) attributed part of the error in altimetric measurements to the error at *in situ* gauges, having estimated the discrepancy between two conventional gauges located on the opposite banks of the Tapajós River. But most of the time, the *in situ* gauge is given as the absolute reference of the river surface plane. Second, it is very uncommon to have an altimeter track right above the conventional gauge chosen as reference. When located at some distance from each other, the river section can change, or unknown amounts of water can reach the river between the two points from an ungauged tributary, or other unknown amounts can be temporarily lost in a derivation or an inundation plain. Analysing Table 2, we can summarize the validation situation in three categories:

(a) the regression coefficient is very different from 1, which is the case when the river sections (conventional and altimetric) are not similar: Principe da Beira (regression coefficient of 0.75; the track partly crosses over a braided part of the river), Pedras Negras (regression coefficient of 0.74; the track crosses at an angle 30° from the river's longitudinal profile, allowing it to take into account part of the longitudinal slope of the river in the altimetric measurement). The last case is that of Vila Bela de Santissima Trindade. Track 393 of ENVISAT crosses the Guapore River right above the conventional gauge, but is averaging the 100-m wide channel at this point plus the 17-km of flood plain, which gives a regression coefficient of 0.62.

(b) the regression coefficient is near 1, which could indicate a similar river section. It is the case for the comparison made at Porto Velho and Abuna. The Madeira River has an equivalent width at both the conventional and virtual stations, and the track crosses in a near perpendicular direction to the river flow. But the distance between the two measurements points is large, 18 km for Porto Velho and 30 km for Abuna. In both cases, there are some

Table 2 Comparison between *in situ* gauge and virtual gauge.

Conventional gauge	Altimeter track	Distance (km)	Regression coeff. (m/m)	Rms (m)
Porto Velho	951	18	1.06	0.395
Principe da Beira	192	5	0.75	1.349
Pimenteiras	478	0	1.02	0.170
Abuna	278	30	0.99	1.496
Pedras Negras	106	29	0.74	0.689
Vila Bela de Santissima Trindade	392	0	0.62	0.342

derivations by flood plains. For Abuna, the derivations seem very important, as seen on JERS images, and a tributary joins the river between the conventional gauge and the satellite track.

(c) the regression coefficient is near 1, and the distance between the two measurement points is null. This is the case at Pimenteiras. This is the only case where the precision of the altimetric data can be assessed: 17 cm Rms. This is within the range given in Calmant & Seyler (2006) for the ENVISAT data (decimetric accuracy), taking into account the spatial variability of the river across the channel.

Morphological parameters at virtual stations and estimation of discharge

The bankfull discharges estimated from the slope downstream of the virtual station (*S*1) and from the mean slope upstream and downstream of the station (*S*2) are very close to each other. Comparing the bankfull discharge of the Mamore upstream of the confluence with the Guapore (Md), with the maximum discharge at Guajara-Mirim, the closest value is that of D^*1, calculated only with the downstream slope. The value of D^*1 summed for the four tributaries (Sum 4tr, Table 3) is also closest to the values of maximum discharge in Porto Velho. Bankfull discharges calculated with equation (6) (only the width of the river) seem highly overestimated. Retaining the values of D^*1 as the more realistic, it can be assessed that at bankfull, the Madre de Dios contributes 33% of the discharge of the Madeira River, the Beni only 11%, the Mamore before the confluence with the Guapore 21%, the Guapore 20%, and the sum of the two at the confluence with the Beni River contributes 56% of the Madeira discharge (Table 4). These are rough estimates, but it could be useful in an ungauged basin, to have estimates of discharge obtained only from satellite data.

Table 3 Bankfull discharge by rivers, MD: Madre de Dios; B: Beni; M: Mamore; G: Guapore; Sum M-G: sum of value for Mamore and for Guapore; Md: Mamore after the confluence with Guapore; Sum 4tr, sum of the values for the four tributaries; Q^*1 bankfull discharge (m^3/s) estimated by equation (4) with *S*1 (2); Q^*2 bankfull discharge (m^3/s) estimated by equation (4) with *S*2 (3); Q^*3 bankfull discharge (m^3/s) estimated with equation (6).

	MD	B	M	G	Sum M-G	Md	Sum 4tr
Q^*1	12 912	4 161	8 183	7 765	15 918	21 812	38 885
Q^*2	13 355	4 045	7 395	8 695	15 090	19 490	36 890
Q^*3	27 782	11 057	16 270	23 881	40 151	42 075	80 914

Table 4 Contribution (%) of the four tributaries at the bankfull discharge of Madeira River.

	MD	B	M	G	Md
%total Q^*1	33	11	21	20	36
%total Q^*2	36	11	20	24	29
%total Q^*3	34	14	20	30	22

CONCLUSION

Altimetric data, as they are today, are not well adapted to continental hydrology. Nevertheless, we can assess that a radar altimeter can correctly monitor the seasonal fluctuations of water stage in great transboundary basins. From previous studies, we can state that the width of the river is not the only criterion to take into account to predict the reliability of the time series. Rivers less than 100 metres wide can be sampled, provided that they are surrounded by a flood plain, even if covered by flooded forest. Steep relief near the river, steep longitudinal slope, islands, and flow direction along track are major impediments for obtaining a reliable time series. But, in other situations, the time series obtained allow monitoring of the seasonal variation of water stage. Although it is very difficult to assess the precision of the altimetric data by comparison with conventional gauges, in cross-track situations at the exact location of a conventional gauge, discrepancies between virtual and conventional gauges can be analysed, and in all cases, they do not exceed 20 cm. In this study, bankfull discharges have been estimated for the four main tributaries of the Rio Madeira.

Of course, precision, revisit time, size of the water bodies monitored, and conditions of shallow relief impose restrictions on the use of satellite radar altimetry in hydrology. Actually, they limit its use to a range of applications: levelling of conventional unlevelled water gauges; study of the relationship between the river and its flood plain and between the river and the swamps and wetlands within the watershed; study of the elevation profile and river slope. These two last applications have opened up entirely new perspectives in the hydrological field: for example, infrastructure monitoring and planning (in particular monitoring of remote dams for producing hydropower), flood and drought monitoring and forecasting, fluvial waterway monitoring and transport planning, and fluvial dynamics of the riverbed and discharge modelling. All these applications can be conducted with joint spatial and conventional monitoring, but in remote, tropical forested areas, or in vast wetlands, unreachable most of the time, as the region in the present study, or in transboundary basins where conventional data are unevenly distributed, or lastly in a politically troubled region, radar altimetry monitoring is of prime importance. From this perspective, the SWOT mission, which will be launched around 2015, and will provide a global, quasi-continuous measurement of water surface area and elevation, will provide very valuable new data sets. A lot of improvements are yet to be achieved in processing the existing data, and it is necessary to continue other validation works in distinct environments.

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