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New processing approaches on the retrieval of water levels in Envisat and SARAL radar altimetry over rivers: A case study of the *São Francisco* River, Brazil

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ABSTRACT

Radar-based satellite altimetry is well recognized for oceanographic applications. For continental hydrology, its use is complicated by a number of environmental factors such as river width and shape, land cover type in the vicinity of the river banks, and the topography of the relief. These factors make precision vary significantly. Locations where the satellites cross the river can be used as "virtual gauging stations" that can complement the existing network of *in situ* stations. This article describes processing techniques that take some of these environmental factors (river shape and width) into account to improve the precision of altimetry measurements of the water level. These techniques are based on some *a priori* information about the river banks and on modeling a phenomenon called "off-nadir hooking". This approach is tested on the *São Francisco* River in Brazil, which for most of its path is considered narrow for satellite altimetry applied to hydrology. Data from Envisat cover the period 2002–2010 while the recently launched SARAL satellite provided data for 2013. The results show that the accuracy varies significantly depending on a number of environmental factors some of which are discussed in depth. In about one-half of the 16 satellite water gauging stations, the RMS errors are lower than 60 cm and in some cases better than 30 cm. These variations could not be directly related to the river width, but appear to be mostly related to the land cover and to the processing chain that often extracts altimetry points from an off-nadir location. All processing is fully described and the results are presented for both the Envisat/RA-2 and SARAL/Altika altimeters.

1. Introduction

Satellite altimetry was originally developed mostly for the study of ocean levels and phenomena like "El Niño" and "La Ninã" but is being increasingly used for applications to coastal and inland waters (Silva et al., 2012). Satellite altimetry has the advantage of enabling repeated systematic global measurements with a unique reference frame of worldwide continental water resources (Rosmorduc, Benveniste, Lauret, Milagro, & Picot, 2006). Although the frequency of measurements is often insufficient for monitoring specific locations (10 days in the case of Jason, 35 days in the case of Envisat and SARAL), this is likely to improve with the launching of other altimetry satellites planned in the near future (2015 for Sentinel 3, http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-3) and the medium-term future (2020 for SWOT, http://smsc.cnes.fr/SWOT/index.htm). Radar altimeters onboard satellites can be used to create what will be here called "Satellite Water Gauging" (SWG) which can be produced by anyone at no cost other than acquisition and processing time.

Numerous studies have been published in recent years to show the application of satellite altimetry to fluvial hydrology. It has been shown that there is a good potential for wide rivers (usually >1 km) especially in remote regions like the Amazon Basin. Monitoring the water level through satellite altimetry really started during the 1990s with the TOPEX/Poseidon satellite and studies from Koblinsky, Clarke, Brenner, and Frey (1993), Birkett (1995, 1998), Ponchaut and Cazenave (1998) and others. Calmant and Seyler (2006) made a review of satellite altimetry for continental waters, outlining the major advantages, such as the monitoring of inaccessible areas and near-real time availability of measurements worldwide, but also its limitations, such as the temporal sampling (10 days at best with Jason) and the measurement uncertainty with accuracies varying from a few centimeters to over a meter (typically between 30 cm and 1 m). For smaller rivers (narrower than 1 km) a number of problems have been identified that can seriously restrict the application of satellite altimetry to water level monitoring. It has been suggested, however, that improved processing might provide acceptable solutions to these problems and offer acceptable levels of precision. With upcoming missions, the satellite monitoring of water levels of rivers is

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likely to get more attention with the increase in coverage and accuracy. To be even more efficient, water level data based on satellite altimetry can be coupled with a calibration curve that establishes the relation between the water level and water discharge (Arora, Chiew, & Grayson, 1999).

The object of study of this article is the stretch of the *São Francisco* River between *Vargem Bonita*, about 50 km from its source, and *Penedo*, near its mouth. The lower section of the Velhas River, an important tributary of the *São Francisco*, was also included due to its relative importance for the State of Minas Gerais. The *São Francisco* is a strategic river both as a water resource and a waterway. Despite strong opposition from environmental groups, in 2007 a colossal project took place for the transposition of part of its water to the dry regions of Northeast Brazil. This brought a lot of attention to the *São Francisco* River and brought about increased interest in satellite monitoring technologies. Because about one-half of the course of the *São Francisco* River runs through semi-arid land, it is considered an essential factor affecting human survival in the region. Climatic changes have also increased concerns and reinforced the need for better management of the river (Galvíncio & de Moura, 2010).

The objective of this article is to describe the different processing methods that take river width and shape into account to improve the accuracy of water level measurements in relatively narrow rivers (roughly between 100 m and 1 km) using satellite altimetry. Secondly, it aims to compare the Envisat/RA-2 altimeter data (which was deactivated in 2012) and the recently launched SARAL satellite carrying the Altika altimeter which follows the exact same orbit pattern as Envisat. The usefulness of the approaches is demonstrated through testing on the *São Francisco* River and a section of the *Velhas* River in Brazil. Finally, a preliminary study of the effects of the land cover near the river banks on the altimetry measurements gives some insight on how it may affect the accuracy of water level measurements obtained from satellite radar altimeters.

2. Background

The principle of satellite altimetry is rather simple. The satellite antenna emits microwave impulses that travel through the atmosphere at a speed near that of light, and are reflected and scattered by the surface of the Earth. The time taken for the impulse to return to the antenna can be transformed in distance so that one-half of this distance corresponds to the satellite above ground level (AGL) altitude. Since the above mean sea level (AMSL) altitude of the satellite is known, the difference between the two yields the elevation of the surface. Over the ocean, these measurements give an excellent estimate of the ocean's topography and its evolution (Cabane, Cazenave, & Le Provost, 2001). Over continental surfaces, however, the irregularity of the relief sometime causes the first return to come from an off-nadir direction, especially if the path to that point is shorter. Considering that the propagation cone of the microwave impulses can have a radius of several kilometers (Chelton, Ries, Haines, Fu, & Callahan, 2001), the effect of the surrounding relief can "contaminate" the return echoes (Berry, Garlick, Freeman, & Mathers, 2005; Siddique-E-Akbor, Hossain, Lee, & Shum, 2011). This is especially true for rivers in deep valleys surrounded by higher ground. The radar altimeter receives a series of echoes during a short time lag, based on the expected range (an operation carried out by the on-board "tracker") known as a "waveform". Then, special processing functions known as "retrackers" included in the ground processing chain reprocess the data of the impulse backscatter to detect the most likely target within the waveform (Berry et al., 2005; Zhang et al., 2010). The retracker selects the target based on the range and on the strength of the echo. This implies that environmental factors such as the nature of the surface can have a significant effect on the target selected by the retracker. Additionally, when the topography abruptly changes (steep slopes), the onboard tracker can miss the echoes, creating gaps in the data. Fig. 1 illustrates some problems of off-nadir contamination that can affect the retracker. In the first case (impulse at time 1), the path to the left bank is shorter than the path to the water so that the sensor is likely to record the distance to the ground even though the water is at nadir. In the second case (impulse at time 2), the width of the river (a few kilometers) is such that there is no contamination by the banks and the waveform is characterized by a single strong peak. In the last case (impulse at time 3), the trees produce the first return but somewhat weaker than the water, which is no longer at nadir. This latter situation is somewhat common, given the large footprint of the sensors (four to eight kilometers in most cases for the low resolution mode sensors found onboard most satellite altimeters) and has been recognized by other authors and has been given the name "hooking" by Silva et al. (2010).

3. Method

3.1. River section studied

Fig. 2 shows the area of study of the river, superimposing a representation of the topography and the location of the 16 Satellite Water Gauging (SWG) stations selected for being relatively close to their real *in situ* counterparts. The Envisat/SARAL orbital tracks are also represented.

3.2. Data

3.2.1. Altimetric data

The altimetric data were obtained from two satellite altimeters: Envisat/RA-2 and SARAL/Altika (RA-2 and Altika being the name of the altimeters). These two satellites have the advantage of sharing the same orbit paths and same return cycle for two different periods, Envisat from March 2002 to October 2010 (after which it was moved to another orbit until April 2012 when it finally stopped sending data) and SARAL from March 2013 to the present day. Envisat data can be downloaded from the CTOH (Center for Topographic studies of the Ocean and Hydrosphere) database (http://ctoh.legos.obs-mip.fr/) whereas SARAL data is available from the Aviso (Archiving, Validation and Interpretation of Satellite Oceanographic data) web site (http://www.aviso.oceanobs.com/). Envisat altimetric data was acquired by the RA-2 altimeter operating in dual-frequency microwave bands (Ku at 13.575 GHz and S at 3.2 GHz) and at 18 measurements per second for a distance of approximately 365 m between measurements. The Ku band is used for precise altimetry measurements. SARAL/Altika uses the Ka band (hence its name at 35.75 GHz) with 40 measurements per second for a distance of about 165 m between measurements. The shared orbit has a repeat period of 35 days. Table 1 gives a list of the parameters for Envisat and SARAL and their use.

3.2.2. Validation using in situ gauging station data

One reason for using satellite altimetry to create satellite water gauging stations is to complement the existing network of *in situ* stations, but until a reliable method with predictable precision has been developed and thoroughly tested, it is necessary to use a validation scheme using the *in situ* data for comparison. It is in that spirit that all the SWG data shown in this article were selected: because of their proximity with the existing physical stations. The Brazilian water agency (ANA) collects daily *in situ* data from a large number of stations spread along the most important rivers of Brazil and makes the data publicly available from its website hidroweb.ana.gov.br. When the *in situ* station is located near the satellite path, the data can serve as validation for the SWG. Most of these stations are simple graduated poles read by a local inhabitant twice a day (at 7 h00 and 17 h00) and their precise absolute altitudes (base level) are usually unknown. Because the slope of the São Francisco River can be relatively large, it was preferred to not rely on interpolated water level values but simply to use directly the data of the nearest station. Thirteen gauging stations located on the São Francisco River and three on the Velhas River were chosen to validate