Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 26, e28, 2021
Scientific/Technical Article

https://doi.org/10.1590/2318-0331.262120210069

Análise da qualidade de séries de nível d'água obtidas por satélite radar altimétrico ao longo do Rio São Francisco

Quality analysis of water level series obtained by altimetric radar satellite along the São Francisco River

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Received: May 17, 2021 - Revised: July 07, 2021 - Accepted: July 08, 2021

ABSTRACT

Radar altimeters are instruments carried on space missions and allow for determination of heights, particularly in oceans and ice sheets. The use of altimetry data on continental waters involves several challenges, such as the revisit frequency (typically 27 to 35 days), an accuracy of decimeters, data handling and processing, particularly for narrow rivers such as the São Francisco River (width<1km). Radar satellite altimetry has advantages over the conventional *in situ* monitoring network, including in terms of spatial coverage and global altimetric reference of data. Thus, altimetry data should be used as a complementary and/or alternative source to *in situ* data. In this context, this study consolidates and evaluates the altimetric series of five different altimetry missions: Envisat in two orbits, Saral, Sentinel 3-A, and Sentinel 3-B. The altimetry water level time series of 17 Virtual stations were compared with leveled gauging stations series to calculate absolute and relative errors. Ultimately, the errors varied from 0.13 m to 0.36 m in the best cases (41%), in line with recent literature. Sentinel-3 satellites showed the best RMSE absolute/relative results: 0.95/0.49 m (S-3A) and 0.96/0.52 m (S-3B). The second best RMSEs was Envisat-X (1.39/0.50 m), then Envisat (1.87/0.56 m) and Saral (1.74/0.60 m).

Keywords: Satellite altimetry; Absolute error; Water level time series; São Francisco river; Sentinel-3.

RESUMO

Radares altimétricos são equipamentos que permitem a obtenção da elevação da superfície, especialmente nos oceanos ou geleiras. O uso de dados de altimetria em cursos d'água continentais envolve desafios metodológicos, como a frequência de passagem do satélite (27 a 35 dias tipicamente), acurácia de decímetros, manipulação e processamento dos dados, especialmente para rios mais estreitos (largura < 1 km) como o Rio São Francisco. A altimetria por satélite radar propicia ganhos como a cobertura espacial e referência altimétrica global dos dados, que seriam impensáveis para a rede de monitoramento fluviométrico *in situ* convencional. Assim, os dados altimétricos deveriam ser usados como uma fonte complementar e/ou alternativa aos dados *in situ*. Neste contexto, este trabalho se propõe a consolidar e avaliar séries altimétricas de cinco diferentes missões: Envisat nas duas órbitas, Saral, Sentinel 3-A e Sentinel 3-B. Para análise do desempenho dos altímetros, 17 séries de nível d'água foram comparadas aos dados de estações fluviométricas niveladas viabilizando o cálculo do erro absoluto e relativo. Os erros encontrados são compatíveis aos encontrados na literatura, variando entre 0.13 m a 0.36 m nos melhores casos (41%). Os satélites Sentinel-3 apresentaram os melhores resultados de RMSE absoluto/relativo: 0.95/0.49 m (S-3A) e 0.96/0.52 m (S-3B). Na sequência, Envisat-X (1.39/0.50 m), Envisat (1.87/0.56 m) e Saral (1.74/0.60 m).

Palavras-chave: Altimetria por satélite; Erro absoluto; Séries de nível d'água; Rio São Francisco; Sentinel-3.

INTRODUCTION

The generation of basic hydrological data, such as the time series of water levels and rainfall and measurements of waterway flow and slope, is essential for monitoring and characterizing hydrographic basins. The installation and maintenance of systems for monitoring water resources is complex and expensive, requiring specialized teams, calibrated equipment, and uninterrupted data collection to ensure high-quality data.

In Brazil, the National Water Agency (*Agência Nacional das Águas - ANA*) manages the National Hydrometeorological Network (*Rede Hidrometeorológica Nacional - RHN*), which includes private and public entities such as the Mineral Resources Research Company (*Companhia de Pesquisa de Recursos Minerais - CPRM*) that manages most stations across the country. Maintaining and operating a network with several actors in a large country such as Brazil is challenging. The number of stations is low in some regions such as the Amazon, where hydrological data collection can take up to one year.

Given the challenges of generating conventional hydrological data, remote sensing data are a complementary and/or an alternative source of information in hydrology (Lettenmaier et al., 2015). Earth observation satellite data allow for the consistent, continuous, and repeated visualization of the continental surface, and the spatial coverage in this case is higher than that in the case of conventional monitoring networks (McCabe et al., 2017).

Satellite radar altimetry can provide valuable data for hydrological and hydraulic studies (Domeneghetti et al., 2021). Although space missions involving radar altimetry aim to obtain data on ocean levels, polar caps, and sea ice, studies conducted for approximately three decades have demonstrated the feasibility of using altimetry in continental waters, particularly in large lakes and rivers (Chen at al., 2021). The Amazon Basin is a reference for the validation of altimetry data owing to its worldwide importance, difficult access, large extension and large width of watercourses, in which case a high volume of hydrological data can be obtained through remote sensing (Nielsen et al., 2020; Moreira, 2016).

The use of satellite data can reduce the costs of purchasing and installing new equipment, the operational costs of performing daily readings, and the costs involved in transportation of crews conducting measurements in various locations, including in complex and dangerous places or areas with limited access. Furthermore, satellite altimetry data uses a global datum such as WGS84, as reference, directly providing absolute water levels. (Sichangi et al., 2018; Calmant et al., 2013).

Altimetry satellites commonly use repeat orbit, meaning they overfly the same ground position at fixed time intervals, known as revisit times, which vary from 10 to 35 days. The frequency of collection of altimetry data is lower than that of automatic data collection equipments (usually collection time intervals of a minute) and the daily readings conducted by RHN observers (collection at 07h00min and 17h00min). Such a limitation can be reduced using a multi-mission approach when constructing time series with data obtained from several altimetry missions, with tracks covering the same cross-sections or surroundings. (Jarihani et al., 2013; Tourian et al., 2016). Especially in large rivers, with widths of kilometers, the extensive areas of water surface provide a large amount of satellite altimetry data. In medium and small rivers this approach can be more limited, depending on the number of missions used and the availability of data close enough to be considered as having the same cross-section. Furthermore, depending on the angle at which the satellite track crosses the river, a greater or lesser number of altimetry measurements can be achieved. Rivers parallel to the equator are more favorable, since the direction of the tracks is grossly SSE -NNW and NNE -SSW.

Ground tracks over river sections are known as virtual stations (VSs). VS data are compared with data from nearby gauging stations (GSs) to estimate the accuracy of altimetry time series and reduce errors resulting from the slope of waterways. Despite of the recent evolution of altimeters the accuracy of its measurements is in the decimeter range (Normandin et al., 2018).

The datum of the gauges stations, usually are arbitrary chosen for convenience, consequently gauging time series values are referenced to this local datum, also called the gauge zero. Most studies on the quality of satellite time series compare altimetry data (global datum) with data from GSs (arbitrary datum plane), so both data are adjusted using measures of central tendency of the series (usually mean). This results is an optimistic errors values because with the adjustment only the fluctuations or anomalies are compared, not the absolute errors. (Bercher, 2008; Jarihani et al., 2013). A VS rarely coincides with the location of a GS, and consequently there is a difference in level between them. Ideally, leveling to obtain absolute altitudes (global datum) should be performed at VSs. Moreover, factors such as alterations of the morphodynamics of the cross-section and the existence of tributaries between the VSs and GSs should be considered.

Another limiting factor to be considered when using satellite altimetry data is the width of watercourses. Most radar altimetry studies have focused on large water bodies. The use of altimetry in narrower rivers is limited by the along track resolution (typically 300 m). This topic is best discussed in the results section of this paper.

Under this context, this study assesses the quality of satellite altimetry time series along the São Francisco River, with an average width <1 km in most of its course. For this purpose, 12 leveled GSs along the river were selected to compare with VSs and calculate absolute errors in time series, discussing the possible causes of these errors. The altimetry time series of past missions (Envisat in two orbits and Saral) and current missions (Sentinel-3A [S-3A] and Sentinel-3B [S-3B]) were evaluated.

STUDY AREA

The São Francisco River basin occupies 7.5% of Brazil and has several physiographic and climatic characteristics, carrying an average water volume of 2180 m^3/s (minimum of 1543 and maximum of 3000 m^3/s) to the semi-arid region of the country. Despite its importance, the width of most of the river's course is small-to-medium (<1 km). The selected river stretch begins downstream of the Três Marias dam and extends to Santa Maria da Boa Vista GS, located approximately 170 km downstream of the Sobradinho reservoir. The GSs and VSs of the selected river stretch are shown in Figure 1. Fifteen RHN GSs are in operation in this section and radar altimetry missions generated several VSs.

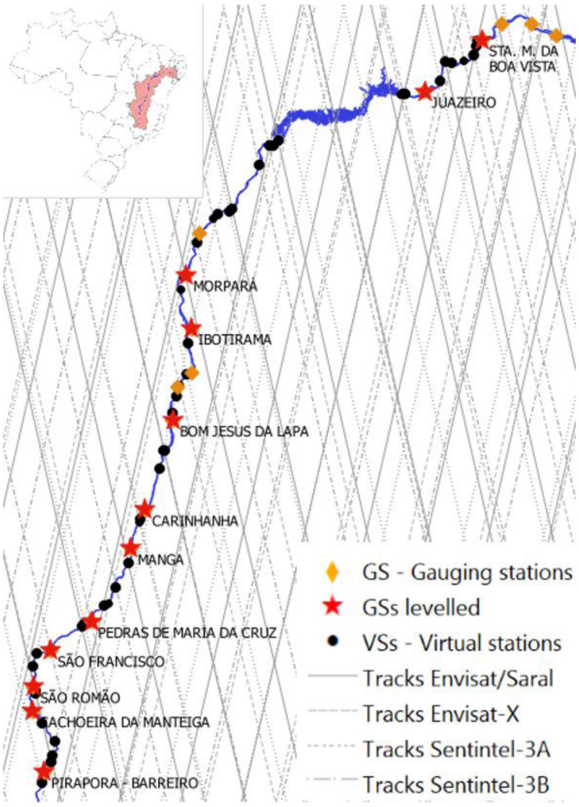


Figure 1. Location of *in situ* gauging stations (GSs) and virtual stations (VSs) along São Francisco River.

MATERIAL AND METHODS

Satellite altimetry radar technique

Satellites equipped with radar altimeters fly in predefined orbit according to the objectives of their mission: the nominal orbit. The projection of the orbits on the ground constitutes the tracks, which goes from one pole to the other. The distance between the measurement points on the ground is called the along track resolution, it varies from one mission to another and is typically in the order of 300 m. Figure 2a and Equation 1 show the principle of altimetric measurement and how water level is obtained. The altimeters emit microwave pulses towards the nadir and capture the echo reflected by the surface (soil, ice caps, and water bodies). The recording of these echoes, with a duration of a few micro-second for each point, over time is the waveform. The satellite altitude (a_s in Figure 2a) above the reference ellipsoid is calculated from precise instruments and systems of positioning and orbit determination. The distance between the satellite and the surface, called 'Range', is calculated by determining the time taken by the return trip and the propagation speed of the electromagnetic waves. The range value is corrected (R in Equation 1) for delays in the propagation speed of electromagnetic waves in the atmosphere: ionosphere (iono), pressure (dry troposphere: dry) and humidity (wet troposphere: wet). Geophysical corrections referring to crust movements due to polar (pt) and terrestrial (set) tides are also applied. Then, the water level (H in Figure 2a and Equation 1) is obtained by subtracting the range from the satellite altitude and corresponds to the distance from the water surface to the reference ellipsoid (Archivage, Validation et Interprétation des données des Satellites Océanographiques, 2020).

$$H = a_S - \left(R + iono + dry + wet + pt + set\right) \quad (1)$$

Variations in the topography along the altimeter's track (Figure 2b) causes oscillation in the return time of the echoes. The tracker is the algorithm that will define the altimeter's recording windows so that all returns can be properly collected in the waveform. The propagation of radar impulses from the satellite spread in a cone shape and can reach diameters in the order of kilometers on land, producing a footprint typically from 4 to 16 km, varying from one satellite to another. Large footprints can contain returns from different surfaces which add complexity to the waveforms (Figure 2b).

Due to the phenomena affecting the echo recorded by the altimeter, all data, especially for heterogeneous surfaces, must be post-processed to generate more accurate measurements of water level. This post-processing activity is called retracking and, in a simplified way, it is about defining which point on the waveform corresponds more closely to the target surface. The retracker computes a point in the waveform corresponding to the target surface based on the analysis of the waveform. The power of the returned echoes and the environmental factors, such as the nature of the surface (Figure 2b), can have significant effects on the choice made by the retracker (Rosmorduc et al., 2016; Archivage, Validation et Interprétation des données des Satellites Océanographiques, 2020; Maillard et al., 2015).

Satellite altimetry data acquisition and processing

Altimetry data are available free of charge from websites, FTPs, or platforms of space agencies and organizations involved. Raw data are usually available a few hours after the satellite passes by, and processed corrected data are available a few days to three months after acquisition. Envisat and Saral data were downloaded from the European Space Agency FTP (European Space Agency, 2021) and the Center for Topographic Studies of the Ocean and Hydrosphere (2020), a french organization that provides altimetry products. Sentinel-3 data were obtained through the Copernicus "Open Hub" platform, a European Union Earth Observation Program. The data are available in Network Common Data Form (NetCDF) format, which is widely used in climatological studies and altimetry missions.

The data were processed using the Satellite Water Gauging (SWG) tool, available for download on the website of the UFMG Remote Sensing Research Laboratory (UFMG/IGC/Geografia/Remote Sensing). This open-source tool processes data from satellite altimetry files, which contains all information needed (including all the corrections) to obtain water level time series as in Equation 1. This application was developed in Python and has a user-friendly graphical interface (Figure 3). The main submenu, "Prepare Data," allows for creating VSs along a watercourse. Final processing to obtain satellite time series is performed on the main screen. The output file includes dates, coordinates and average water levels for each satellite passage (Maillard et al., 2015).

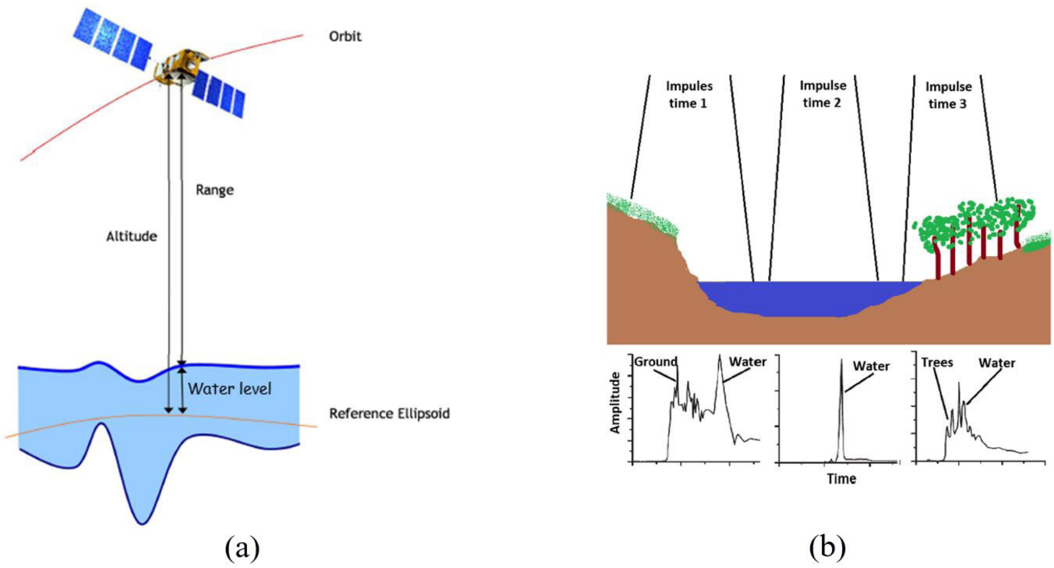


Figure 2. Altimetric radar operation: (a) Principle of altimetric measurement and how water level is obtained. Source: Adapted from SARAL/AltiKa Products Handbook - Centre National d'Études Spatiale, 2013); (b) Variation of waveforms according the footprint context. Source: Maillard et al. (2015).

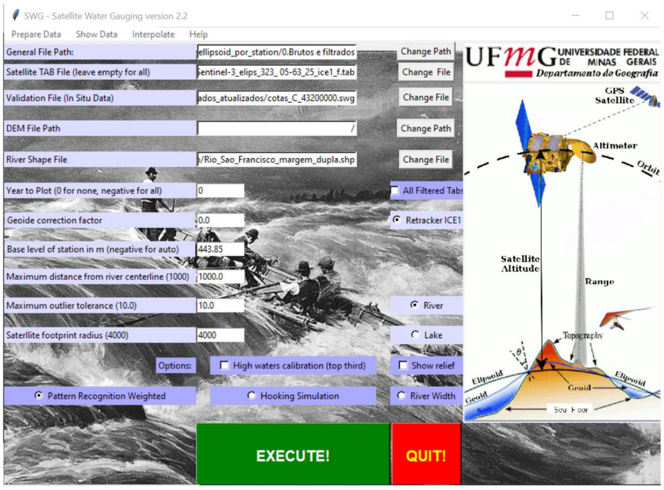


Figure 3. Main screen of Satellite Water Gauging tool.

Altimetry missions

The Envisat European Space Agency (ESA) satellite with the RA-2 altimeter was launched in March 2002, providing approximately eight years worth of data obtained during its original orbit, with a revisit time of 35 days and 80 km of inter-track distance in Equator. The satellite was moved to a lower orbit (revisit time of 30 days, 94 km of inter-track distance in Equator) in October 2010 to extend the mission for a few years, and its name was changed to Envisat-X. The mission ended in May 2012 owing to a loss of communication with the satellite.

The Saral satellite with an Altika altimeter is a joint initiative of the French Centre National d'Études Spatiale (CNES) and the Indian Space Research Organisation (ISRO) and was launched in February 2013 in the same orbit and with the same revisit time as those of Envisat. Saral entered a drift phase in July 2016 because of technical problems. In this study we use data only from the original orbit, that like Envisat, had 80 km of inter-track distance in Equator.

The Sentinel-3A and Sentinel-3B satellites are a joint initiative of the ESA and the European Union and part of a family of satellites that observe and monitor different aspects of the Earth. Sentinels 3A and 3B were launched in February 2016 and April 2018, respectively. These satellites are in operation as of the publication of this study, have a revisit time of 27 days, and make complementary orbits. Satellites 3C and 3D are expected to be launched in the coming years. Each satellite S-3 alone has 104 km of inter-track distance in Equator.

This group of satellites generated altimetric time series from 2002 to 2020 in a multi-mission approach (Figure 4).

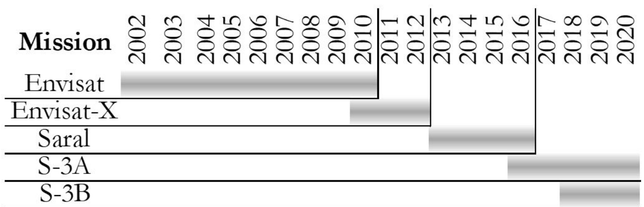


Figure 4. Dates of altimetric missions.

GPS leveling

The GPS leveling of GSs was performed by technicians and engineers from CPRM. TECGEO GTR-2 dual-frequency GNSS (Global Navigation Satellite System) receivers with 702

GG antennas were used to obtain the absolute altitudes (global datum) of the GSs reference marks.

The data obtained by GNSS receivers were processed on the Brazilian Institute of Geography and Statistics (IBGE) website using the Positioning by Precise Point (IBGE-PPP) mode. This is a free online service for post-processing GNSS data based on the Canadian Spatial Reference System (CSRS-PPP) developed by the Geodetic Survey Division of Natural Resources of Canada (NRCan). The PPP processing followed the recommendations of the International Earth Rotation and Reference Systems Service (IERS) (Petit & Luzum, 2010).

The field procedure was to place the antenna's reference point on the local reference mark of the GS to estimate its absolute altitude (global datum level). Then the GNSS receivers collected more than 2 h of satellite observations without signal obstructions to obtain highly accurate data. The estimated vertical accuracy of the data was 2-3 cm, with established standards and processes being followed. After processing with IBGE-PPP mode we obtain the absolute altitude for the reference mark. The local value of reference mark was subtracted from absolute one to obtain the absolute altitude of the gauge zero, wich is the ellipsoidal height that corresponds to the zero reading of the vertical-staff gauge. Then, the absolute altitude of gauge zero was used to adjust gauging station data. Output coordinates (latitude, longitude, and ellipsoidal height) were used in the SIRGAS2000 geodetic system in PPP-IBGE, compatible with the WGS84 at the centimeter level for adjustment of gauging series to satellite data.

Analysis of errors in time series

The following analytical methods were used to measure errors in time series.

a) The mean error (ME) is the mean of all deviations $\hat{Y}_t - Y_t$ (where $\hat{Y}$ is satellite data and Y is the GS) for each date *t* available for VSs, resulting in a series of size N. The ME indicates the direction of the discrepancy in the series and whether satellite data ($\hat{Y}$) tend to over or underestimate water levels when compared to gauge data (Y). The ME also estimates systematic errors, or mean biases, which are used as a correction factor to generate adjusted time series. However, it is limited because negative errors cancel out positive errors.

$$\boldsymbol{ME} = \frac{\sum_{t=1}^{n} \left(\hat{Y}_t - Y_t\right)}{N} \tag{2}$$

b) The absolute mean error (AME) is determined using the absolute value ($\left|\hat{Y}_t - Y_t\right|$) of individual errors, such that positive errors do not cancel out negative errors. However, the AME does not indicate the general trend of errors (positive or negative).

$$AME = \frac{\sum_{t=1}^{n} \left(\left|\hat{Y}_t - Y_t\right|\right)}{N} \tag{3}$$

c) The root mean square error (RMSE) provides average errors and is more sensitive to large deviations by squaring individual differences. It is commonly used to express the accuracy of quantitative data.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n} \left(\hat{Y}_t - Y_t\right)^2}{N}} \tag{4}$$

d) The adjusted RMSE is obtained in the same way as the RMSE, but adjusts satellite time series ($\hat{Y}_t$ values) by subtracting the mean bias (ME) from the original series.

e) The sample efficiency rate, η_{eff}, of satellite series was proposed by Bercher (2008), where N_{eff} is the number of data points obtained via altimetry, and N_{sat} represents the number of data points expected for a given period (total number of passages during a time interval).

$$\eta_{eff} = \left(\frac{N_{eff}}{N_{sat}}\right).100\% \tag{5}$$

The η_{eff} of each mission is important because several factors can cause loss of radar altimetry data. For this reason, obtaining accurate data at a low frequency may not be useful. The temporal resolution of satellite data is lower than that of gauge data and can decrease in the presence of a low η_{eff}.

Notably, in some graphics (presented in the results section) is possible to identify very significant errors in some water level time series. In these cases, the results before and after outliers removal are shown.

RESULTS AND DISCUSSION

Water level data from the GSs are presented in Table 1. The water levels and river widths were obtained from Hidroweb (Agência Nacional de Águas, 2020) and adjusted with the staff-gauge zero level.

Table 1. Levelled gauging stations in São Francisco River.

Station Code	Name	Latitude	Longitude	Staff-gauge zero level (m)	Measured average width (m)
41135000	Pirapora Barreiro	-17.3693	-44.9431	469.38	379
42210000	Cachoeira da Manteiga	-16.6575	-45.0811	447.49	388
43200000	São Romão	-16.3718	-45.0664	443.85	386
44200000	São Francisco	-15.9498	-44.8682	437.90	541
44290002	Pedras de Maria da Cruz	-15.6004	-44.3954	432.06	528
44500000	Manga	-14.7593	-43.9330	420.70	487
45298000	Carinhanha	-14.3059	-43.7654	416.91	603
45480000	Bom Jesus da Lapa	-43.4362	-13.2566	403.30	799
46150000	Ibotirama	-43.2230	-12.1840	392.19	561
46360000	Morpará	-43.2840	-11.5533	384.19	680
48020000	Juazeiro	-9.4062	-40.5042	344.81	924
48290000	Santa Maria da Boa Vista	-8.8098	-39.8240	332.15	814

Water level data at the VSs located between the Três Marias reservoir and Santa Maria da Boa Vista station obtained from these five altimetry missions were processed using the SWG tool. The amount of altimetry information acquired using radar satellites provides knowledge on a continental scale to the detriment of information at the local level provided by staff gauges.

For the satellite data analysis, a selection criteria for VSs located close to the GSs (up to 15km distance) was established to assure that the satellite was observing approximately the same cross section as the staff gauges. For some GSs there was no VS close enough, for others there was a single VS and in some interesting cases, more than one VSs from different missions were in the vicinity of the same GS. The latter scenario enabled construction of multi-mission satellite series. These cases are presented in detail, facilitating a broader discussion of the relevant aspects and limitations in the case of using spatial altimetry data in hydrology.

Satellite water level time-series are presented in Table 2 and Figures 5 to 8 show:

a) *In situ station - daily*: daily average water level series adjusted with staff-gauge zero level

b) *In situ station*: a marker indicating the GS-based average water levels on the day of passage of the satellite.

c) Satellite altimetry series, with raw data named '*Satellite*' and after bias (mean error) removal '*Satellite (adjusted)*'

Altimetry time series: Single VS versus GS

Sentinel-3A has a VS located 13 km upstream of the **BJLapa** GS and other VS located 15 km downstream of **Carinhanha**. Both VSs had a high η_{eff} (98%) and AME <1.0 m. For BJLapa, the RMSE and adjusted RMSE were 0.85 m and 0.13 m, respectively. For Carinhanha, the RMSE and adjusted RMSE were 1.14 and 0.64 m, respectively.

The Envisat and Saral missions provided data from 2002 to 2015 for a VS located approximately 6 km upstream of the **Santa Maria da Boa Vista** station (Figure 5). After Envisat changed orbit, the VS ran out of data as of October 2010, and time series acquisition was resumed by Saral in April 2013. The absolute RMSE of the original series for Envisat and Saral exceeded 2.5 m (Table 2). The linear distances from ground tracks to GSs accounted for the observed systematic errors. The adjusted RMSE was 0.34 m for Envisat and 0.16 m for Saral and the η_{eff} was 95% for Envisat and 63% for Saral.

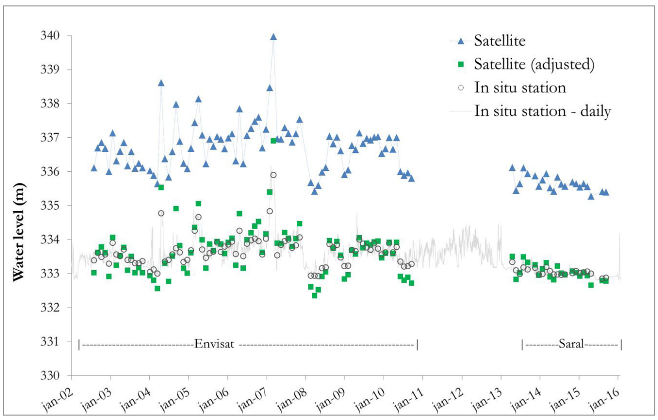


Figure 5. Water level time series obtained by Envisat and Saral 6 km upstream of Santa Maria de Boa Vista.

Sentinel-3A has provided data within the vicinity of the **Ibotirama** station since September 2016; these data exhibit a good fit to gauging station data (Figure 6a). The RMSE and AME were 0.86 m and 0.52 m, respectively, and the adjusted RMSE was 0.69 m. Errors were below 0.5 m in most of the time series and approximately 1.0 m in a few time series (Figure 6b). There were two outliers at approximately 3.0 m The adjusted RMSE was 0.36 m, and the ME was 0.10 m.

Figure 6a shows that the frequency of the Sentinel-3A data varied, with some missing data, resulting in a η_{eff} of 66%. For **Ibotirama**, Sentinel-3A data were limited because the track intercepted a curve of the river. Some river sections were not covered because the satellite could drift up to 1 km from each side of the nominal track during each cycle (Figure 6c). Data acquired near the margins provided little data on water levels and generated outliers (Figure 6b).

The Sentinel-3B mission has a VS near the São Francisco station. Although this satellite was launched in April 2018, data were available in November 2018 after several tests were conducted to assess the performance of the instruments (Collecte Localisation Satellites, 2019). Thus, data on 21 cycles from 25 passages are available (η_{eff} = 84%). The absolute RMSE was 0.80 m, and the average error was 0.58 m.

Multi-mission series

VSs from more than one satellite were available for Morpará, São Romão, and Pedras de Maria da Cruz gauging stations.

In **Morpará**, a VS from Envisat and Saral was located less than 1 km from the GS, and a VS from Envisat-X was located approximately 5 km upstream of the GS. The combined data from these missions produced a time series from July 2002 to February 2014 (Figure 7a). Data acquisition thereof was interrupted for approximately 16 months (January 2012 to April 2013), corresponding to the period in which the Envisat-X mission ended and the Saral mission commenced. Although the Saral mission ended in July 2016, data on this VS were available until March 2014. Sometimes, data were not provided by the responsible agencies for some cycles because of the need for corrections or reprocessing or failure to maintain the nominal orbit.

The best result for **Morpará** was obtained during the Envisat mission (Figure 7b), with the lowest absolute RMSE (0.95 m), lowest adjusted RMSE (0.29 m), and highest η_{eff} (93%). The performance of the Envisat-X mission was similar to that of its predecessor regarding the adjusted RMSE (0.33 m); however, η_{eff} was 71% after exclusion of two outliers. The η_{eff} and adjusted RMSE in this region during the Saral mission were 26% and 0.87 m, respectively.

The VSs from the Envisat, Envisat-X, and Saral missions were located less than 1 km from **São Romão** station. Similarly, data collection by Envisat-X and Saral at Morpará was interrupted from April 2012 to April 2013 (Figure 8a). The average error was positive, varying from 0.83 to 1.16 m, indicating a tendency to overestimate the water levels relative to gauging station data (Figure 8b). The value of η_{eff} was higher for Envisat (94%) and lower for Envisat-X (71%) and Saral (69%). The adjusted RMSE of Envisat-X was 0.22 m.

VSs for **Pedras de Maria da Cruz** were available from Envisat/Saral, Sentinel-3A, and Sentinel-3B, located 11, 9, and 13 km from this GS, respectively. For the Envisat-X mission, the VS coincided with the GS, but the real track could be located 1 km from each side of the original track. The η_{eff} was low, except for the case of Sentinel 3-B (92%) (Table 2). The RMSE, average error and absolute error were greater than 1 m for all missions, except for Sentinel 3-B (with an adjusted RMSE of 0.48 m).

The poor results of Pedras de Maria da Cruz for all missions except Sentinel-3B are attributed to the steep topography of the right side of the river (Figure 9). Under this condition, the altimeter does not capture the water level because the tracker predicts returns from a higher surface and does not have sufficient time to readjust when crossing the river. Therefore, the nadir altimeter tends to get locked on the top of hilly areas and miss steep-sided valleys.

The performance of Sentinel 3-B was higher because its altimeter uses previous information of the expected altitude for the target in open-loop tracking mode (OLTM). These auxiliary data are extracted from two sources: 1) a digital terrain elevation model and 2) a water mask. In the traditional operating mode (closed-loop), the altimeter collects data considering the last waveforms received, which limits its ability to adjust to sudden changes in relief, as is the case in rivers located in embedded valleys. The other operational Sentinel 3 mission, Sentinel 3-A, also has the OLTM available on its altimeter, but until March 2019 it only operated in some regions of the globe that did not cover the São Francisco River (European Space Agency, 2021).

Comparison of missions

In VSs more than 3-5 km from GSs, positive MEs are expected for the upstream cases and negative for the downstream ones, due to the slope of the waterline. At coinciding VSs the ME should be close to zero or at least positive in some cases and negative in others. However, all nine VSs coinciding with GSs (distances of ±1 km and 3 km) had a positive ME (Table 2), indicating a possible tendency of these missions to overestimate water levels. A probable cause of the positive errors for different missions was the use of underestimate corrections in Equation 1, consequently the water level of VSs is systematically higher than that of the GSs, leading to a positive ME. This hypothesis is supported by Calmant et al. (2013), who found a positive bias (1.044 ± 0.212 m) in the Amazon Basin for the Envisat mission with the Ice-1 retracker, which was used in this research.

Table 2. Satellite water level series statistics.

Station code	Gauging Station	Satellite	Track number	RMSE (m)	RMSE adjusted (m)	ME (m)	AME (m)	η_{eff} (%)	Distance* (km)
45480000	BJLapa	S-3A	380	0.85	0.13	-0.84	0.84	98%	+13
45298000	Carinhanha	S-3A	173	1.14	0.64	0.95	0.95	98%	-15
48290000	SMBVista	Envisat	276	3.09	0.34	3.08	3.08	95%	-6
	SMBVista	Saral	276	2.62	0.16	2.61	2.61	63%	-6
46150000	Ibotirama	S3A	380	0.86	0.69	0.52	0.52	66%	-1
	Ibotirama	S3A**	380	0.42	0.36	0.1	0.36	63%	-1
44200000	SFrancisco	S3B	116	0.80	0.56	0.58	0.69	84%	+3
46360000	Morpará	Envisat	749	0.95	0.29	0.9	0.9	93%	±1
	Morpará	Saral	749	1.46	0.87	1.16	1.16	26%	±1
	Morpará	Env-X	306	1.92	0.78	1.76	1.76	82%	-5
	Morpará	Env-X**	306	1.50	0.33	1.47	1.47	71%	-5
43200000	SRomão	Envisat	921	1.56	1.05	1.16	1.16	94%	±1
	SRomão	Saral	921	1.15	0.77	0.85	0.98	69%	±1
	SRomão	Env-X	321	0.86	0.22	0.83	0.83	71%	±1
44290002	PMCRuz	S3B	377	1.11	0.48	1.00	1.00	92%	-13
	PMCRuz	Env-X	377	5.91	4.85	3.37	5.62	35%	±1
	PMCRuz	S3A	637	6.11	5.08	3.39	3.4	63%	-7
	PMCRuz	S3A**	116	1.53	2.31	1.15	1.16	53%	-7
	PMCRuz	Envisat	116	4.01	1.13	3.84	3.89	70%	-13
	PMCRuz	Saral	380	49.72	45.91	49.32	49.32	11%	-13

*VS is upstream of GS and + VS is downstream of GS; **Series after removing outliers.

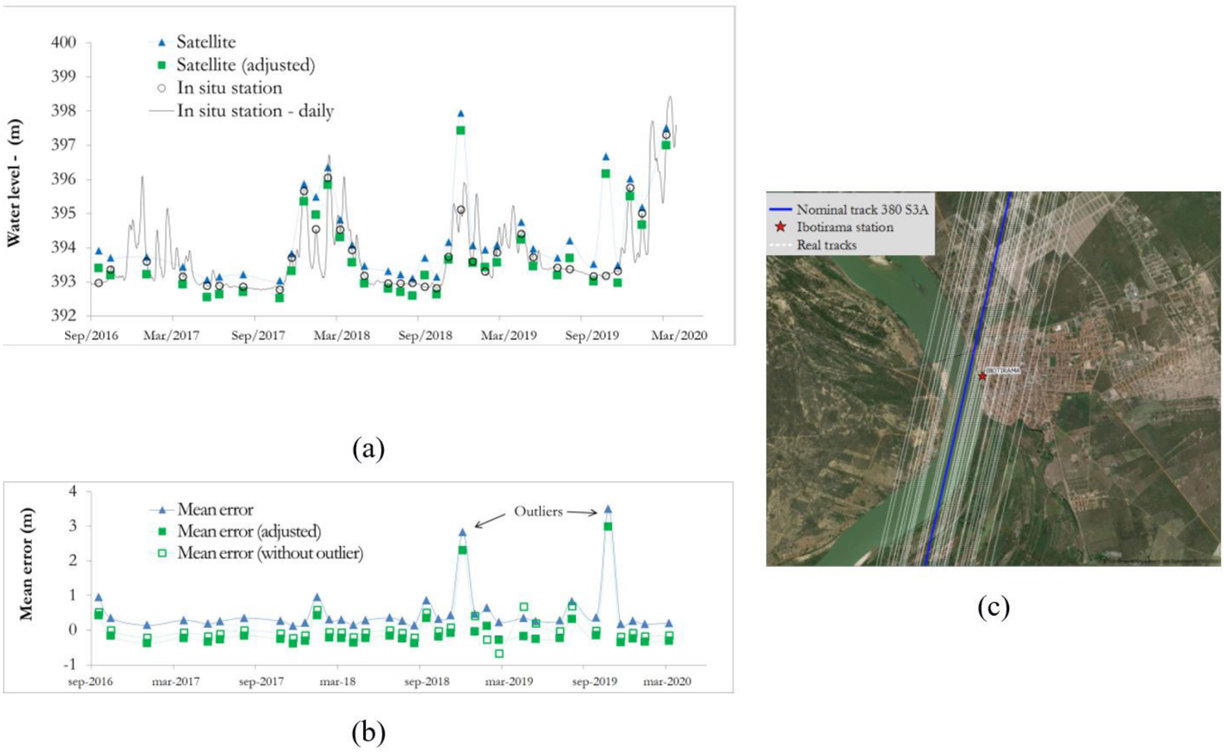


Figure 6. Ibotirama Station - Sentinel 3A: (a) series of water level (b) deviations before and after removal of bias and outliers, and (c) nominal and real tracks

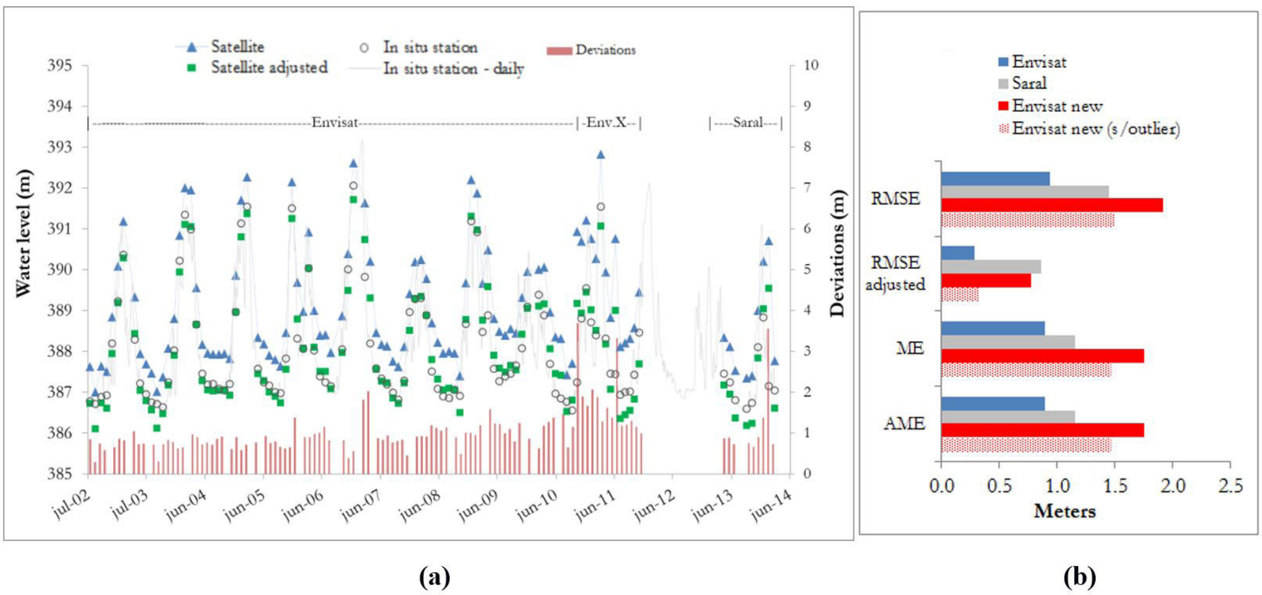
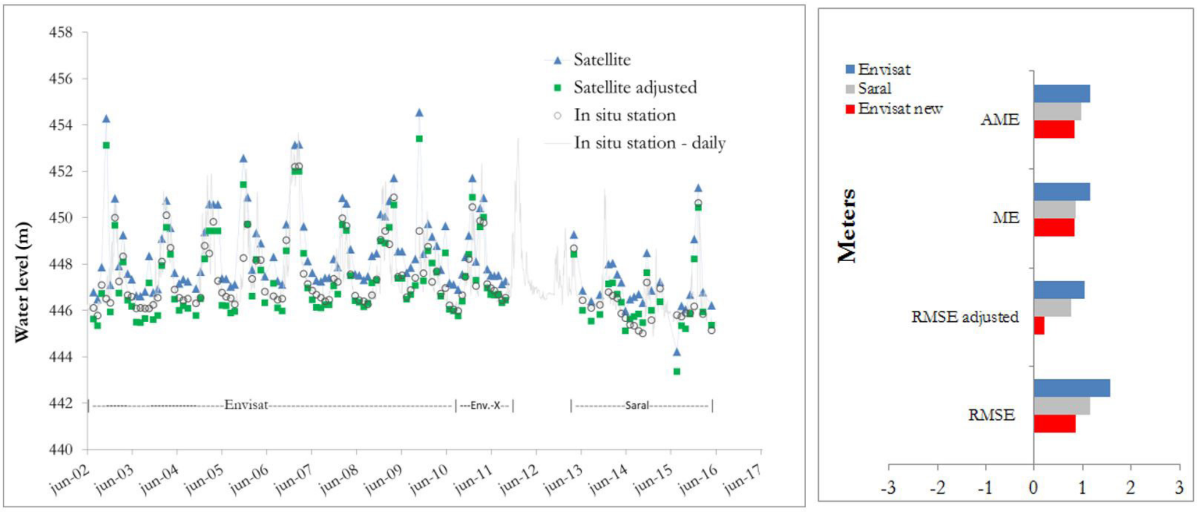


Figure 7. Morpará hydrological station: (a) Multi-mission time series of water levels; (b) Absolute and adjusted root mean square error, mean error, and absolute mean error.

Average statistics by satellite, considering the original series (before removing outliers), are shown in Table 3. Data from the Pedras de Maria da Cruz station were not used because this limited the operation of altimeters until the development of OLTM. Only the PMCruz time series obtained by S-3B was used because the results of this mission were significant and to prevent the S-3B from having only one VS analyzed. The missions are presented in chronological order.

Envisat is the oldest and longest mission used in this study and had the highest η_{eff} (94%) during its eight-year operation. Errors were slightly higher during this mission, but not very significant. Envisat mission was successful and continuously provided altimetry data with a quality close to that of recent missions with superior technology.

The performance of Envisat-X was lower than that of its predecessor regarding η_{eff} (77%); nonetheless, RMSE, adjusted



(a) **(b)**

Figure 8. São Romão hydrological station: (a) Multi-mission time series of water levels; (b) Absolute and adjusted root mean square error, mean error, and absolute mean error.

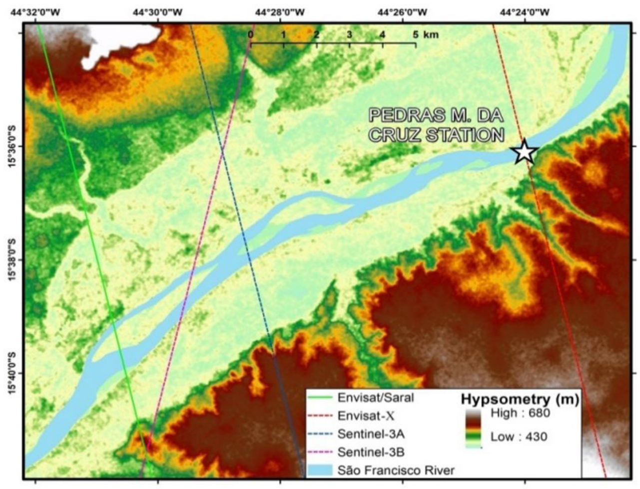


Figure 9. Region of Pedras de Maria da Cruz station.

Table 3. Average statistics of altimetric missions.

Satellite	Number of VS*	Average of analyzed stations			
		RMSE (m)	RMSE adjusted (m)	AME (m)	ηeff
Envisat	3	1.87	0.56	1.71	94%
Envisat-X	2	1.39	0.50	1.30	77%
Saral	3	1.74	0.60	1.58	53%
S-3A	3	0.95	0.49	0.77	87%
S-3B**	2	0.96	0.52	0.85	88%

*PMCuz EVs are not included; **The only satellite that includes PMCruz data.

RMSE and AME were better. Despite the change in orbit, the use of data from this phase of Envisat is interesting to obtain altimetric data from other river sections, providing a spatial and temporal complement to the original phase of the mission.

The Saral mission showed good results regarding the RMSE and average bias, compatible with recent missions. In its 35 cycles, this mission had the lowest η_{eff} (53%). Maillard et al. (2015) reported a low η_{eff} but used only the first six or seven cycles. In the present study, η_{eff} was low at several VSs, even when considering all cycles, which confirms this limitation. The reasons for data loss are not fully understood but may be because, in narrow rivers and steep banks, the altimeter tracker remains locked in higher neighboring areas and does not reach the water surface (Biancamaria et al., 2017).

The Sentinel-3A mission achieved the best performance, with higher η_{eff} (87%) and better results for RMSE, adjusted RMSE and AME. The Sentinel-3B mission (the most recent) had higher errors than those of S-3A, but the best η_{eff} (88%) after Envisat. However, the adopted selection criteria allowed for analysis of only two VSs from S-3B. Therefore, additional VSs should be evaluated to better assess the performance of S-3B.

The success of the Sentinel mission is attributed to the OLTM, synthetic aperture radar (SAR) and other altimeter configurations resulting from recent technological improvements in remote sensing instruments. Our results agree with those of recent studies that point out the improvements in Sentinel-3 configurations (Jiang et al., 2020; Kittel et al., 2021).

Limitations of altimetry radar data in medium and small rivers

The influence of the width of the watercourse on the use of spatial altimetry data has been frequently mentioned over the last two decades (Calmant and Seyler, 2006; Maillard et al., 2015; Biancamaria et al., 2018; Coss et al., 2020). The limitations are inherent to the footprint size of the altimeters in low-resolution mode (LRM), reducing the potential to obtain accurate data for small rivers (below 1 km). The satellite footprint can reach 8 km for Envisat and 4 km for Saral. For Sentinel-3A and 3B operating in SAR mode, the footprint is small (300 m by a 1.6 km ellipse).

Thus, in rivers that are much smaller than the footprint, the altimeter "sees" an adjacent area beyond the river surface. In this area, other types of land cover may emit signals similar to those of water producing a complex waveform with multiple peaks, like the first graph in Figure 1b. In these cases, the retracking may not define appropriately which peak corresponds to the water surface and compromise water level measurements. Altimeters may lose lock over areas with abrupt changes in relief, leading to data loss along extensive sections, particularly in rivers that are smaller than the satellite footprint. The hooking effect can also reduce accuracy. This effect occurs when the altimeter measures the height of a reflective surface (water) outside its nadir (off-nadir), forming a hydrological profile in parabolic format, overestimating the distance between the satellite and water, and, consequently generating a water level lower than the river level.

The altimetry results of Birkett et al. (2002) for the Topex/Poseidon satellite in the Amazon Basin suggest that the river width should be greater than 1 km in floodplain areas for the atimeter capture the water level correctly. Getirana et al. (2009) reported gaps in altimetric series for river sections less than 200 m wide and attributed them to the Envisat along track resolution of 350 m. Conversely, Silva et al. (2013) found that the river width was not the most significant contributor to the quality of satellite altimetry time series because water level variations were detected by Envisat in rivers and wetlands 50 m wide. Maillard et al. (2015) observed that environmental factors such as wind, soil type and topography of river margins could compromise altimetry data acquisition and are more important than river width.

Biancamaria et al. (2017) and Normandin et al. (2018) found that inadequate coverage in narrow watercourses could be circumvented by OLTM. Jiang et al. (2020) evaluated 50 VSs from S-3A in various rivers in China and demonstrated that the results were satisfactory in medium rivers (300 m wide) and large rivers (more than 500 m wide), and the terrain surrounding the VS strongly affected the results.

It is expected that the challenges of working with narrower watercourses will be overcome in the coming years, as missions are planned for observation of continental watercourses. In this context, Sentinel-6 (Jason-CS) was launched in November 2020, and the Surface Water and Ocean Topography (SWOT) satellite will be launched in 2022. The altimeter configurations of these satellites and operating parameters will improve altimetry data accuracy in narrower watercourses.

CONCLUSIONS

The results demonstrate the potential of using spatial altimetry data in medium-sized continental waterways. However, data validation is essential because several factors can affect the quality of measurements, particularly in narrow rivers, such as the São Francisco River. The main obstacles are the large footprints of altimeters (in the order of kilometers), loss of lock in steep sided valleys, the off-nadir "hooking" pattern, and the resolution along the track (typically of 300 m).

The validation activity is common in satellite altimetry studies, but usually it is done in relative terms due to the lack of levelled gauge stations in rivers. The present study analyzed VSs in close proximity (<15 km) to GSs to enable a direct and fair comparison with leveled gauge station data. This approach made possible to calculate absolute errors in satellite altimetry time series with less interference from other factors such as river slope. The absolute RMSE obtained in satellite series was higher than the adjusted RMSE, which is usually presented in the literature, given that these studies do not have the absolute altitudes of the gauge stations. This finding indicates that the statistical data presented in studies applying relative adjustments to a series can show an optimistic view of the accuracy of the satellite data, reinforcing the importance of leveling to obtain the absolute altitude (global datum) of the gauge stations.

The analysis of time series at VSs very close to leveled GSs (distance of up to 3 km) showed a tendency to overestimate the water levels along the São Francisco River, with positive errors for different missions. The adjusted errors (optimal values between 0.13 and 0.36 m in the best cases [41%]) are similar to those presented in the literature and are in the order of decimeters even in recent missions from S-3A and S-3B. It is expected that the limitations will be leveraged in future missions by using new approaches and technologies, increasing data accuracy.

ACKNOWLEDGEMENTS

To technicians and engineers from CPRM who performed GPS leveling of the gauging stations. To the institutional support of CPRM. ESA and CTOH for making altimetric data available.

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