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Research Article

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River Monitoring Over Amazon and Danube Basin Using Multi-Mission Satellite Radar Altimetry

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Abstract

The "blue marble" planet called Earth is 70% covered by water. Fresh water holds about 2.5% of the Earth's surface water and only 0.26% of the fresh water can be found in rivers and lakes. Rivers are the most important freshwater resource for human so monitoring the quantity and quality of water in rivers requires a reliable system. Water level and discharge are two essential parameters in such a monitoring. Satellite altimetry measurements enable hydrologists to measure basin-wide of discharge and storage, which are much easier than monitoring changes from *in situ* gauge networks. This study was conducted in the Amazon (the largest river basin in the world) and Danube (second largest river basin in Europe) rivers. The altimetric data used for this study are produced by ESA (18 Hz Envisat) and by CNES (40 Hz SARAL). To obtain water level variation, 12 possible scenarios (Ocean, Ice-1, Ice-2 and Sea-Ice retrackers using ALL, MEDIAN and MEAN values) were processed. After removing outliers, water level from each scenario was validated against available *in situ* gauge, to find the most robust water level estimator. Then the discharge of the rivers in different segment has been estimated from the best scenario, i.e. a scenario which leads to minimum RMS for water level. To check the performance of the estimates, we used the root mean square (RMS) and Nash–Sutcliffe coefficient (NS) for water level and discharge. With one exception, the RMS of the water level is between 37 and 72 cm. A good agreement between altimetry and *in situ* data observed for station Jatuarana at the Amazon River. Mainly the water level from MEDIAN values follows the *in situ* gauge water level better than that the MEAN and ALL values. The errors of the derived water level time series yield about 55 cm on average for Amazon and 62 cm for Danube river basin with best results below 40 cm at Jatuarana station using SARAL data. Also best results of discharge were obtained for Budapest (SARAL data) and Baja (Envisat data) stations based on RMS and Jatuarana (SARAL data) based on NS.

Keywords

River Monitoring; freshwater resources; Amazon river basin; Water level; Danube River

Introduction

All organisms, including humans, require water for their survival. Warnings of increasing water scarcity in the world are common while our planet is called the "Blue Plane" [1]. The Earth is 70% covered by water in various forms. Fresh water, which includes ice sheets, glaciers, groundwater, permafrost, river and lake, holds only about 2.5% of the Earth's surface water, compared saline water in the ocean, which accounts for almost 97.5%. Out of this proportion, 0.26% of the fresh water can be found in rivers and lakes [2].

Rivers and lakes are among the most influential sources of water for daily human consumption. There is no doubt that the monitoring of water resources is a crucial issue to date. Monitoring quality and quantity of water require a reliable system to ensure continuous availability [3].

Rivers are the most important freshwater resource for human. Major river water uses can be summarized as follows [4]:

- Sources of drinking water supply,
- Irrigation of agricultural lands,
- Industrial and municipal water supplies,
- Industrial and municipal waste disposal,
- Navigation,
- Fishing, boating and body-contact recreation,
- Aesthetic value.

Stream flow serves human in many ways. It supplies water for domestic, commercial, and industrial use; crops irrigation; dilution and transport for removal of wastes; hydroelectric power energy generation; transport channels; and a medium for recreation. Stream flow records of its availability and its variability in time and space are the basic data used in developing reliable surface-water supplies. Therefore they will use in planning and design of surface-water related projects and in management or operation of such projects [5].

Yet our knowledge of changes in the volume of water stored and flowing in rivers, lakes, and wetlands is poor. Without comprehensive measurements of surface water storage and discharge, the availability of freshwater resources cannot be predicted accurately. Also the performance of climate models with respect to land surface hydrology cannot be evaluated. Water level (also called *stage*) and discharge are essential parameters in monitoring the quantity of fresh water resources. The best way to monitor rivers is through *in situ* measurements [6] while a tremendous number of small to medium-sized rivers around the world are poorly gauged for various reasons [7].

Space geodesy and satellite remote sensing are viable sources of observation to complement *in situ* measured data that are lacking or unavailable [8]. It enables hydrologists to move beyond the point-based observations provided by gauge networks, to basin-wide measurements of discharge and storage. Satellite altimetry has been designed for water level monitoring over open ocean areas [9]. However, for decades, this technology has also been used to retrieve water levels from reservoirs, wetlands and in general any inland water body [10]. Accuracy of radar altimetry reduces to tens of centimeters over inland water bodies by two factors. First, insufficiently large surface area over lakes and rivers for averaging of the multiple radar pulses, which is used in ocean applications. Second, the shape of the returned radar pulse from the water surface deviates from the shape of a typical ocean-like echo [7]. Recent developments in satellite remote sensing can provide more accurate monitoring of freshwater resources [7].

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The application of satellite altimetry to monitor inland waters has several limitations. The low spatial resolution of radar altimeter, as represented by the radar altimeter footprint, limits the measurement only to wide rivers, due to interference of the returned radar signal by non-water features. For Envisat, the resulting footprint varies up to 2 km over the ocean [11]. Even for SARAL/AltiKa, measuring in Ka-band, the footprint size (~ 6 km over land) is still not suitable for inland water monitoring.

The potential of satellite altimetry for the estimation of water level time series and for understanding the terrestrial water cycle was shown by e.g. [12-14]. Scientists have utilized various satellite data sets to derive braided river discharge [15], river and lake water heights [16], and floodplain storage changes [17]. Although none of these approaches is ideal, because they all rely on instruments and platforms designed for other purposes [7]. Bjerklie et al. [18] proposed a method based on remote sensing data only that relies on the measurement of hydraulic data from space and multiple regression analysis of discharge measurements to derive the discharge equations. Leon and Getirana et al. [19-20] developed methods to derive rating curves at virtual stations (VS) locations based on altimetric levels and modeled discharges. Current remote-sensing techniques are not capable of directly measuring discharge. Radar altimeters measure water surface elevation over rivers, which can then be converted to discharge [21].

Earlier studies showed the efficiency of using satellite radar altimetry to monitor large rivers with widths greater than 1 km [16,22]. Also, recent studies demonstrated successful retrieval of water levels of small rivers too (<100 *m* width) [21,23]. Nonetheless, the processing of satellite altimetry measurement for small water bodies remains challenging because of its spatial and temporal limitations [8]. Over Amazon basin, Koblinsky et al. [24] studied using Geosat and found standard deviation between 0.31-1.68 m, Birkett [16] used Topex/Posidon data and found the RMSE of 0.11-0.60 m, Birkett et al. [22] using T/P found RMSE between 0.40 to 0.60 m (over lower width river). Kouraev et al. [25] with T/P data reached 8% accuracy in discharge value over Ob' River. Frappart et al. [26] over Mekong River found RMSE: 0.23 m using Envisat and RMSE: 0.15 m using T/P. Birkinshaw et al. [27] in same river found RMSE: 0.44–1.24 m using multiple mission data ERS-2 and Envisat. Kuo and Kao [23] over Bajhang River reached 0.31 m standard deviation with Jason-2 data. Over Zambezi River, Michailovsky et al. [21] reached RMSE: 0.27–1.07 m by Envisat and Sulistioadi YB [3] using same mission data over Mahakam River reached RMSE: 0.69 m.

Because of the restricted data access and lack of *in situ* data for rivers and lakes, there is a strong need for using satellite altimetry to monitor them. However, because of Satellite radar altimetry measurement geometry, it provides observations along specific ground tracks touching water bodies by chance. Therefore, big water bodies have a higher probability of being crossed than smaller ones. In addition, because of a repeat orbit configuration, the temporal resolution is limited to 35 days (for Envisat and SARAL/AltiKa) when only single altimeter mission is used. Thus, combination of different altimeter systems plays a key role to increase the temporal and spatial resolution as well as the length of time series. A careful data editing and reprocessing is required in order to derive reliable and highly accurate range measurements from the received waveforms, a process called retracking.

Hydrological characteristics of a river are determined by velocity and discharge. The velocity (sometimes referred to as flow) of the river water is the rate of water movement given as m/s or cm/s. The discharge is determined from the velocity multiplied by the cross-sectional area of a river. Cross-sectional area fluctuates with the change in water level or river stage. Similarly, a direct relationship exists between water level and velocity. So measurement of level can be transformed directly into velocity. The discharge of a river is the most important measurement [4] that can be made because:

- A direct measure of water quantity could be obtained accordingly.
- It provides the calculation of loads of specific water quality variables.
- It characterizes the origins of many water quality variables by the relationship between concentrations and discharge.
- It provides the basis for understanding river basin processes and water quality.

In this study, we processed the results of Envisat and SARAL standard waveform retracking procedures (Ocean, Ice-1, Ice-2 and Sea Ice) to monitor the water level and discharge of Amazon and Danube rivers. In addition to the standard waveform retracking procedures, we performed careful spatial selection and outlier detection to screen out low-quality data. We then evaluated the results against *in situ* measured water levels to assess their accuracy.

We investigate the four range products obtained from Ocean, Ice-1, Ice-2, and Sea-Ice retrackers that are available in GDR and SGDR data products. The Ocean retracker is based on the MLE4 retracker and is optimized for open ocean applications and is based on a modification of the Hayne model [28]. Ice-1 is optimized for general continental ice sheets; it is a model-free re-tracker called the "Offset Centre of Gravity Echo Model" and ensures measurement continuity [29]. In this product, a geometrical analysis of the altimeter waveform is used. It was already shown that the Ice-1 product is suitable for hydrological applications over rivers and lakes [26,30]. The third retracker called Ice-2, is optimized for ocean-like echoes from continental ice-sheet interior, it is a Brown-based model re-tracking algorithm [31]. The aim of the Ice-2 retracking algorithm is to make the measured waveform coincide with a return power model, according to Least Square estimators. Finally, Sea-Ice dedicated for specular areas returns from Sea-Ice, it is a threshold re-tracking scheme for peaky waveforms (Laxon) [32], in this retracker, a waveform parameterization based on peak threshold retracking applied [33].

To obtain the Radar Altimetry (RAT) water level, 12 possible scenarios (Ocean, Ice-1, Ice-2 and Sea-Ice retracker using ALL, MEDIAN and MEAN values of water level) in each satellite overpass have been used. Other than fundamental section, i.e. introduction, the paper structured into four main parts: First, the study area is introduced. Methodology presents the strategy for processing observation points. Afterwards, the satellite data over study area are analyzed concerning their capability to measure water level and discharge. Methodology also describes the method used for the performance evaluation of water level time series and discharge. The results are analyzed in results section and were discussed in Discussion and Conclusion.

Satellite radar altimetry

Stream flow is traditionally estimated by measuring the water level and converting it to discharge [7]. At the absence of field gauges to measure the river or lake water level, indirect measurement is an alternative to provide water storage and its dynamics. Remote sensing from space is capable to estimate various hydrological parameters to complement field measured data continuously [34]. Satellite radar altimetry is favorable especially considering its high accuracy on the determination of geocentric water surface changes [3] and is capable of hydrologic monitoring of freshwater resources. These satellite were originally designed to be used over the open ocean or ice sheets (Birkett et al. [22]) and their use are often limited to monitoring large rivers (width>1 km) with longer interval periods (revisit time >1 week) because of its low temporal and spatial [8].

For this study Envisat RA-2 and SARAL/AltiKa data with a good coverage and multiple observations per month are selected to monitor the rivers. An initial evaluation of the suitable observations performed by Prigent C, et al. [35] provides a full description of these data sets. In principle, a combination of different missions ERS-1/-2, Envisat and SARAL is usable to extend the time series [36]. The Envisat and SARAL satellite tracks are illustrated in Figures 1-5 over our study area using QGIS 2.12.3. All investigations are based on high-frequent altimeter waveforms extracted from Geophysical Data Records (GDR) version 2.1 files provided by ESA for Envisat with 18 Hz data rate with ~ 347 m along track distance which are freely available at ftp://ra2-ftp-ds.eo.esa.int/ENVISAT_RA2/ and Sensor Geophysical Data Records (SGDR) altimeter products: SGDR-T (patch 2) for SARAL with 40 Hz rate and ~ 173 m along track distance which are also available at: ftp://avisoftp.cnes.fr/AVISO/pub/saral/sgdr_t/. The dataset time period coverage is mentioned for both missions over different segment of rivers. Both data sets contain additional information such as waveforms, which can be used for retracking. In order to correct the altimeter ranges due to geophysical effects, external models are applied. This holds especially for the atmospheric corrections (dry/wet troposphere delay as well as ionosphere delay) and the geophysical (solid Earth tides), since radiometer and dual-frequency corrections are not reliable over inland water bodies. Usually the corrections need to be added to the measured range are: Ionospheric correction, Polar Tide, Earth Tide, Wet and Dry Tropospheric corrections, which are also summarized in Table 1. Satellite characteristics comparison is also mentioned in Table 2.

Envisat: Envisat was launched on 1 March 2002 and its service stopped on 8 April 2012. We used data for the period of July 2002 to October 2010, corresponding to cycles 6 to 93. Data after 26 October 2010 (cycles 95–113) are not used since for this time period Envisat was on a drifting orbit (Envisat-Extension mission) and its ground track no longer coincides with SARAL. Envisat carried 10 instruments including RA-2 (Advanced Radar Altimetry) and flew in an orbit with 98.6° inclination with 35-day repeat period that covers all of the area between -81.4° to+81.4° latitude. The RA-2 determines the two-way delay of radar echo from the Earth's surface at a very high precision of less than a nanosecond. RA-2 was a high precision nadir radar altimeter that operated at two frequencies 13.575 GHz and 3.200 GHz, corresponding to 2.3 cm and 3.4 cm wavelength in Ku-band and S-band respectively. These data, along with the waveforms, are averaged into the 18 measurements per second (18 Hz). The 18 Hz data correspond to an along track sampling interval of ~ 350 m [37]. The averaged 18 Hz waveforms are arranged into 128 gates with 3.125 nanosecond temporal resolution, and present the default-tracking gate at #46. For this study we used only GDR and Ku-band 18 Hz re-tracked range data to infer the water surface elevation.

Table 1: List of applied models and geographical correction.

Correction	Source/Model
Wet Troposphere	ECMWF (2.5° × 2.0°) for Vienna Mapping Function 1 (VMF1)
Dry Troposphere	ECMWF (2.5° × 2.0°) for Vienna Mapping Function 1 (VMF1)
Ionosphere	NOAA Ionosphere Climatology 2009 (NIC09)
Solid earth tide	IERS Convention 2003
Pole tide	IERS Convention 2003

Table 2: Summary of Envisat and SARAL characteristics.

	RA-2	Alti-Ka
Mission	Envisat	SARAL
Main target application	Ocean+Ice caps	Ocean+Ice caps
Secondary application	Inland water	Inland Waters+Costal zone
Altitude (km)	800	Up to 800
Altimeter band (GHz)	13.575 (Ku)/3.2 (S)	35.75 (Alt), 23.8 and 37 (Rad.)
Tx Bandwidth (MHz)	320-80-20/160	480
Pulse width (µs)	20	105.6
PRF (KHz)	1.8/0.45	4
Best range resolution (cm)	46	30
Tx Power(W)	60 (TWT)/60 (SSPA)	2 (SSPA)
Range noise over ocean (cm) @ SWH=2 m and 1 Hz	<1.8	0.8
Power consumption (W)	114	<80 (including radiometer)
Total mass (kg)	110 (with redundancy)	33 (including radiometer/without redundancy)
Date rate	<65 kb/s nominal operation <100 kb/s individual echoes	38 kb/s
Pulse repetition frequency (kHz)	1.795	3.8
Antenna diameter (mm)	1200	1000
Antenna beam width (˚)	1.29	0.61

SARAL: SARAL, launched on 25 February 2013, has same 35-day repeat period as Envisat. Its orbit constellation should be perfect to extend the long term time series of the ESA satellites. So SARAL can be used to extend inland water bodies level time series. However, Envisat was equipped with a radar altimeter whose main frequency works with Ku-band. In contrast, SARAL/AltiKa is the first altimeter that measures in Ka-band. The Ka-band is more susceptible for atmospheric water such as clouds, rain or snow. It is rarely influenced by ionospheric effects but susceptible for atmospheric water. The SARAL altimeter has a smaller antenna beam width than Envisat which leads to a smaller footprint. The advantage of the smaller footprint of SARAL is demonstrated for land-water transitions where SARAL provides better water level heights. SARAL provides also more reliable water level heights for narrow rivers than Envisat. Furthermore, the hooking effect is decreased for SARAL [33]. The higher measurement frequency of SARAL (40 Hz, ~ 173 m) with respect to Envisat (18 Hz, ~ 347 m) leads to a higher point repetition rate along the altimeter ground track and a resulting increase of measurements over inland waters.

Measurement principles

The ground altitude is obtained by subtracting the range ρ from the altitude of the satellite as and then correcting for the following phenomena that delay the propagation through the atmosphere: ionosphere (iono), pressure (dry troposphere) and humidity (wet troposphere) variations. Solid earth tide (set) and Pole tide (pt) are also taken into account. All these operations are summarized in Eq. (1) [30]:

$$H_w = alt_{sat} - (\rho + (C_{ion} + C_{dry} + C_{wet} + C_{st} + C_{pt}) + h_{geoid}) \quad (1)$$

In this equation H_w stands for water level height alt_{sat} stands for the satellite altitude, ρ stands for the range. C_{ion} stands for the correction due to delay propagation through the ionosphere, C_{dry} and C_{wet} stand for the corrections of dry and wet troposphere. C_{st} and C_{pt} stand for crustal vertical motions respectively due to the solid and polar tides (solid earth tide and pole tide height) and h_{geoid} stands for geoid height [30]. The basic correction parameters are all provided with the data, but are usually applied by the user. These corrections are contained in the Envisat, GDR, and in SARAL, SGDR standard data products.

Study Areas and Dataset

Study area

This study was conducted in the Amazon and Danube rivers. These water bodies represent different geomorphology, climate and anthropogenic situations. To define the study area we used Google Earth to create a polygone for each river segment and extract satellite data in intersection of a water body with the ground track of satellites. Information on the gauge (station name, river, and location) mentioned in Table 3. It shows some specifications (corresponding station, satellite track, coordinates and data periods) of the five satellite water gauging stations (SWG) corresponding to the *in situ* stations. The data for these stations are referenced to an arbitrary reference level. When the *in situ* station is located near the satellite track, the data can serve as validation for the SWG [38].

Amazon river basin: The Amazon Basin is the largest river basin in the world. The drainage basin covers an area of over 6100000 km^2, and covers over one-third of the South American continent. The discharge from the Amazon River is about 220800 m^3/s [39].

Danube river basin: The Danube River Basin (DRB) is the second largest river basin of Europe covering 801463 km^2 and territories of 18 states including Albania, Austria, Bosnia, Bulgaria, Croatia, Czech Republic, Germany, Hungary, Italy, Macedonia, Moldova, Poland, Romania, Serbia, Slovak, Slovenia, Switzerland and Ukraine. In addition to the Danube River Basin, the Danube River Basin District (DRBD) includes a part of the Black Sea coastal catchments. The territory of Hungary is 100% within the basin. Danube flows to the west of the Black Sea in Central and Southeastern Europe. In terms of length, it is listed as 21st biggest river in the world, in terms of drainage area it ranks as 25th with the drainage area of 817000 km^2 [40].

Dataset

The dataset time period coverage of all datasets is mentioned in Table 3. *In situ* time series of five stations were provided by Agência Nacional de Águas (ANA) over Amazon River and Országos Vízjelző Szolgálat (HHFS) over Danube River in Hungary. These data cover the span time from 1968 to August 2017 that overlaps of about 12 years with satellite measurements so they had sufficient temporal resolution to assess the water level precision from satellite altimetry data. These datasets were used for validation of water levels and discharge.

Daily *in situ* data on river water level (cm) measured at 57 stations over Hungarian tributary of Danube River by Hungarian Hydrological Forecasting Service (HHFS). Point data of Amazon river water level (cm) measured at 856 stations and 247 fluviometric stations with water discharge data along different rivers within the Amazon basin. These data is collecting by the Brazilian Government National Water Agency ANA and available *via* their HidroWeb website at http://hidroweb.ana.gov.br. Fluviometric stations are situated to measure both river level and flow. Across our study region, fluviometric stations reference to WGS 1984 with daily data have been monitored for water level and flow between 1968 to 2017 (Table 3).

In situ gauge height is referenced to geoid, EGM96 for Amazon and mBf (*méter Balti felett:* mean sea level above the Baltic Sea) for Danube stations. Due to the lack of infrastructure, direct leveling is not available in the major part of the Amazon basin, therefore geographical information, which mentioned in Table 3 are referenced by satellite altimetry and GPS techniques, which were investigated by Kosuth et al. (2006) [41].

For our study areas over Danube and Amazon basin, numerous gauging stations are available. The time series of these stations are used for comparisons with the nearest satellite altimeter track river upstream and downstream. We selected stations which are close to satellite tracks. As showed in Figure 1 through Figure 5 three stations found in the Amazon and two stations in Danube basin, which are distributed along different regions of the rivers. Figures 1-5 indicate all sub-satellite points over rivers, Envisat data points showed by green and SARAL by red dots. The stations are also showed by yellow square.

Methodology

Water level estimation

To define water level time series derived from satellite data we did the fallowing steps (as described by Roohi, Sh. (2015) [42]):

- Selecting RA2 GDR SARAL to AltiKa data over the rivers closed to *in situ* gauge stations.
- Excluding nonqualified data (preliminary outlier elimination)
- Defining a short water level of the river from all tracks for each satellite pass over the river, called instantaneous water level time series, using ALL, MEDIAN, MEAN, values of

Table 3: Study area and *in situ* and satellite data period.

River	Station (Code)	Lat	Lon	Zero point level	Satellite track	Water level	Discharge	ENVISAT data period	SARAL data period
Amazon	Obidos (17050001)	-1.947	-55.511	2.97	306, 349	1968-2017	1968-2016	2002-2010	2013-2016
	Olivenca (11400000)	-3.45	-68.75	44.47	78, 665	1973-2014	1973-2011	2002-2010	2014-2016
	Jatuarana (15030000)	-3.051	-59.678	2.73	607	1977-2016	1977-2015	2002-2010	2013-2016
Danube	Budapest (001026)	47.494	19.048	94.97	113	2002-2016	2000-2016	2002-2010	2013-2016
	Baja (001344)	46.178	18.925	80.99	616, 657	2002-2016	2000-2016	2002-2010	2013-2016

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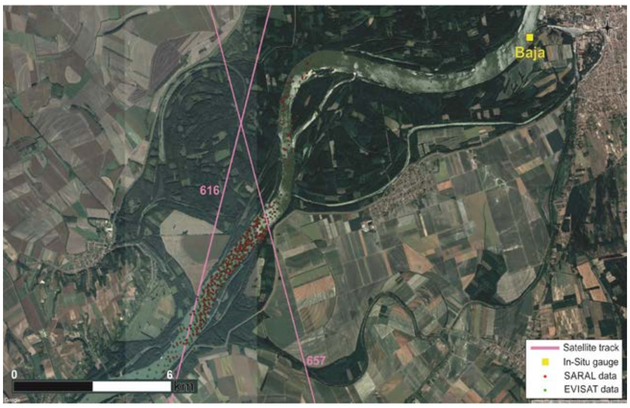

Figure 1: Satellite track over Baja station.

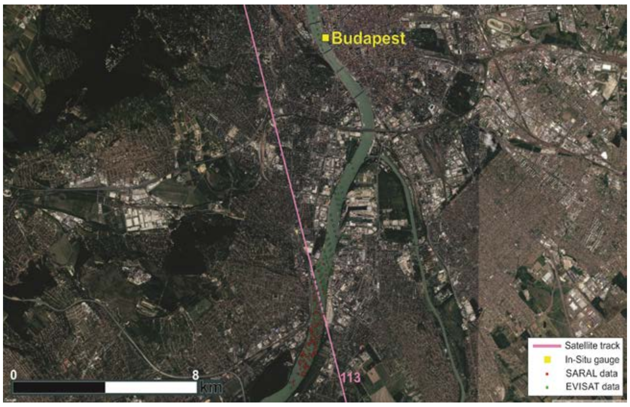

Figure 2: Satellite track over Budapest station.

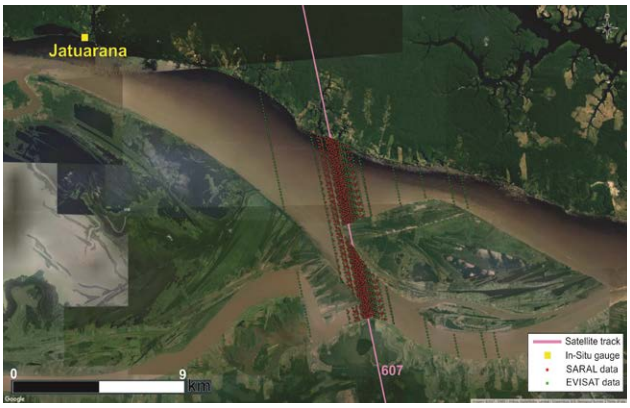

Figure 3: Satellite tack over Jatuarana station.

water level in each pass using Ocean, Ice-1, Ice-2 and Sea-Ice retrackers.

- Merging all single pass water level time series to create a long time series from all pass and all tracks.
- Fitting a model including linear and quadratic trend (Eq. (2)) to delete outliers from time series.
- Comparing combined time series with the *in situ* gauge data to find the most robust water level scenario.

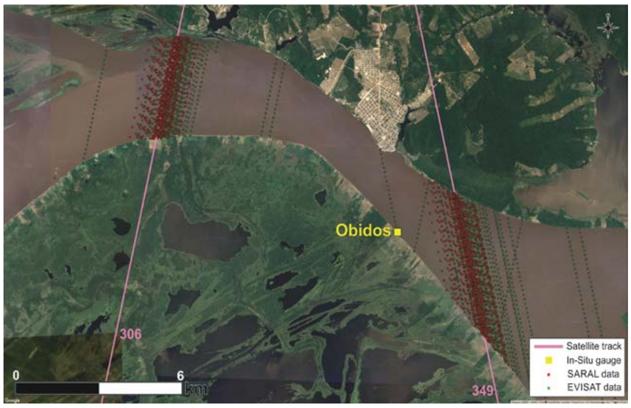

Figure 4: Satellite track over Obidos station.

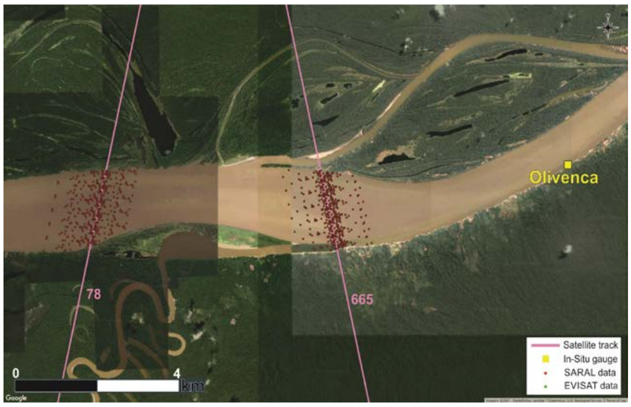

Figure 5: Satellite track over Olivenca station.

- Select the most robust scenario to estimate discharge for each station.

To select data, which covers the regions mention in Table 3, a complete cycle of Envisat and SARAL data was considered. Based on the longitude and latitude of regions only those satellite tracks were selected that pass over the rivers, tracks numbers are also mentioned in Table 3. After preliminary outlier elimination, water level time series are defined for each satellite pass using the Ocean, Ice-1, Ice-2 and Sea-Ice retrackers, separately from ALL, MEDIAN and MEAN values of water level.

Satellite water level obtained from water surface elevation measured by the Ocean, Ice-1, Ice-2 and Sea-Ice retrackers in 3 forms (ALL, MEDIAN, MEAN). To avoid the use of different retrackers and problems with unknown retracker biases [43] only Ice-1 retracker is used in curve fitting to detect and remove outliers. Before computing the water level time series, each retracked range has to be corrected by the ordinary geophysical corrections. Moreover, normal heights refer to ellipsoid are computed using the satellite's height as described in Dataset.

To find outliers we consider a model (trend) which can capture permanent and periodic (seasonal) variations of water level. The model also determines the acceleration of water level variations [42]. This model (Eq.(2)) includes linear and quadratic as well as trigonometric terms and according to linear least squares parametric adjustment method (LLSPA) were estimated and fitted to the time series:

$$h(t_i) = a + b.t_i + c.t_i^2 + d.\sin\left(\frac{2\pi}{T} t_i\right) + e.\cos\left(\frac{2\pi}{T} t_i\right) \quad (2)$$

In which *a*, *b*, *c*, *d* and *e* are unknown parameters that must be estimated. *T* is the annual period and *h* is the observed water height. This trend was removed from the time series. For the residual, a statistical test was performed in an iterative way. After removing the bias between water level from satellite and from *in situ* gauge, retracked water level time series were compared again to the water level time series from the *in situ* gauge data. The result of this comparison, in term of RMS was considered.

The absolute altitude H_{val} has to be known or it needs to be calibrated. The estimated altitudes have been leveled by adding the difference between the mean absolute satellite altimetry data $\bar{H}_w$, the mean relative water level of the station $\bar{H}_{ins}$ and zero gauge point level h_{gauge} to the data (Eq.(3)) [38]. It has been suggested that this calibration is more precise [44] when the signal is less contaminated by the riverbanks or possible sand bars.

$$H_{val} = H_w - \left(\bar{H}_w - \bar{H}_{ins} \mp h_{gauge}\right) \quad (3)$$

Discharge estimation

In next step, acquired river stages are converted to discharge. In traditional *in situ* river discharge monitoring, a rating curve relating water level to discharge is established by simultaneous measurement of flow and discharge at different flow levels [45]. The conversion of altimetry data to discharge could be approached when a rating curve is available at the location of the crossing of the satellite track over the river.

The water discharge is functionally related to the water level at a given location. This relation, called the "stage-discharge rating curve" (or simply "rating curve") is determined from simultaneous measurements of water level and discharge; it can be simple or complex. The simplest forms of the rating curves are observed in the cases of stable channels with steady flow [5]. The rating curve typically follows the power law but a simplified relation between the estimated water level from satellite data (h) and river discharge (Q) can be considered. Therefore, we used polynomial function to fit the curves as below in a least squares sense:

I) $Q_m = a.h^2 + b.h + c$

II) $Q_e = a.h^2 + b.h + c$ (4)

Where a, b and c are unknown parameters that must be estimated, Q_m is the measured discharges from *in situ* gauge data and Q_e is estimated discharge values for RAT data. First the coefficients a, b and c are computed by fitting a polynomial curve then Q_e is evaluated using the same coefficients. To evaluate discharge the best water level estimator of each station for each RAT data has been used.

Validation

For the validation of the estimated water level heights from satellite altimetry, daily *in situ* water level time series are the sole data sets, which enable reliable comparisons. To serve as validation, we established relationships between satellite-derived water level and river discharge measurements at gauging stations. We consider a simplified relation between the water level (h) and river discharge (Q) as described in Measurement principles. The simplification is done in order to estimate the applicability of the approach for conditions when base hydrological information is not available. For comparison, we used part of *in situ* time series, which has overlap with Envisat and SARAL data, i.e. 2002 to August 2013.

For water level root mean square (RMS) were investigated as quality measures for analyzing the performance of retrackers to assess the estimated water level quality. To check the performance of the discharge estimations, we used the RMS and Nash–Sutcliffe coefficient (NS) [46] as the evaluation criteria.

Results

Water level

Satellite altimetry data were processed using on-board retrackers to define water level time series of rivers. We processed these data according to the algorithm, which was described. Since none of retrackers were dedicated to process altimetry data for rivers, we used all of them to define water levels according to our methodology.

The water level at each segment of the rivers is obtained by computing all data (18 Hz for ENVISAT RA-2, and 40 Hz for SARAL/AltiKa) [47,48]. The water level time series derived from the four retrackers are compared with *in situ* gauge stations measurements by calculating. The RMS errors between altimeter-derived and *in situ* water levels are presented in Table 4. Although the altimetry measurements that carry nonqualified data were excluded, some measurements remained far beyond the mean and median values. In order to obtain a data set with minimum influences from outliers, we excluded outliers by fitting a curve (Eq.(2)) using a water level time series obtained from Ice-1 data.

In Figures 6-8 water level time series from ALL, MEAN and MEDIAN values based on Ice-1 retracker curve fitting, respectively corresponding to the *in situ* gauge readings over three stations (Jatuarana by SARAL, Obidos and Baja by Envisat) were shown as samples of six stations. Measurements from *in situ* gauge stations located on Figures 6-8 were used.

Table 4: RMS values (cm) over stations (the smallest RMS value is highlighted in bold, the largest in italic).

Station	Re-tracker	Envisat			SARAL		
		All	Mean	Median	All	Mean	Median
Obidos	H-Ocean	88	91	58	124	*179*	107
	H-Ice1	83	69	**52**	102	90	63
	H-Ice2	104	87	58	101	128	98
	H-Seaice	*109*	102	79	118	110	**56**
Olivenca	H-Ocean	80	*211*	80	No in-suit Data were available during SARAL cycles		
	H-Ice1	81	77	76			
	H-Ice2	79	75	76			
	H-Seaice	75	**72**	74			
Jatuarana	H-Ocean	84	79	64	85	51	**37**
	H-Ice1	*133*	113	131	*133*	116	118
	H-Ice2	92	109	96	83	115	103
	H-Seaice	104	89	**58**	120	84	46
Baja	H-Ocean	103	92	*112*	69	94	*94*
	H-Ice1	97	88	87	60	62	63
	H-Ice2	93	**82**	84	**56**	59	62
	H-Seaice	103	88	87	57	60	63
Budapest	H-Ocean	*95*	78	79	112	*119*	119
	H-Ice1	63	94	95	75	91	80
	H-Ice2	77	74	72	75	89	**55**
	H-Seaice	**58**	65	65	80	89	88

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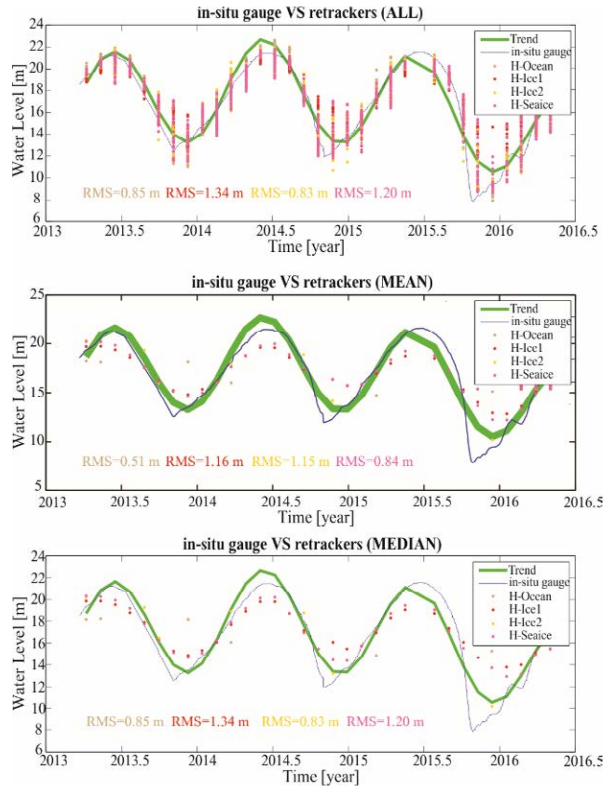

Figure 6: Water level time series over Jatuarana station using SARAL altimeter data.

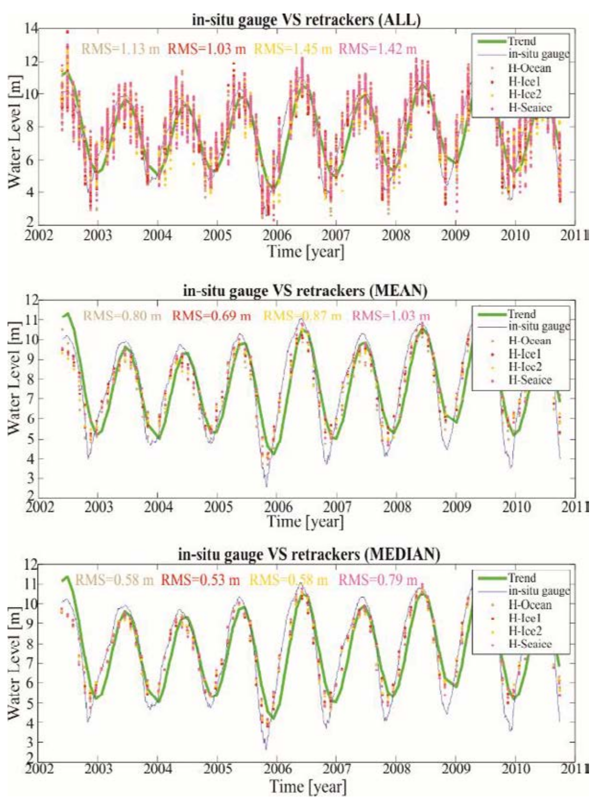

Figure 7: Water level time series over Obidos station using Envisat altimeter data.

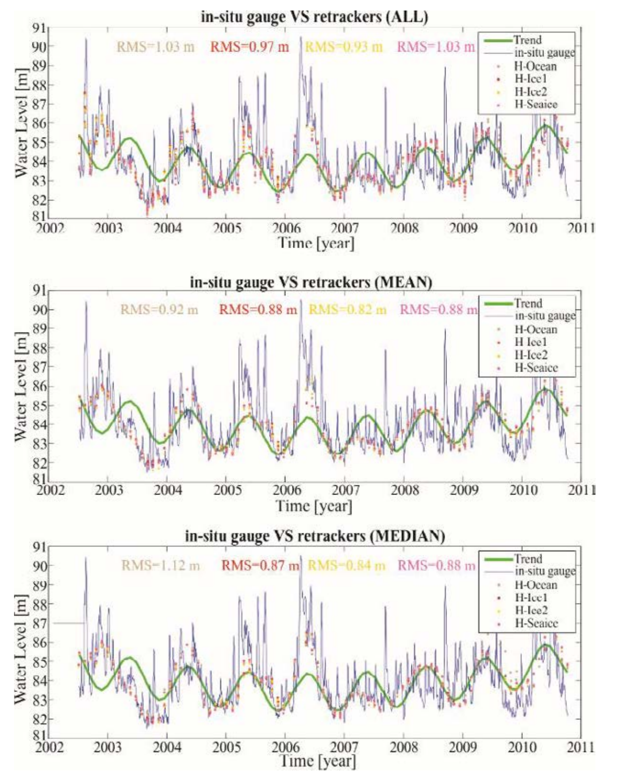

Figure 8: Water level time series over Baja station using Envisat altimeter data.

Table 4 shows the results in terms of the RMS between what was achieved with the Envisat and SARAL data and the corresponding *in situ* ANA and HHFS stations for the same date. The lowest RMS values were showed by bold numbers and the highest by italic numbers. Six columns of the table show statistics from the time series comparisons (RMS) for both Envisat and SARAL data, for each retracker and three sets of data (all data, average of data and median). With one exception, the RMS differences are between 37 and 72 cm. A good agreement between altimetry and *in situ* data is observed for station Jatuarana at the Amazon River. The absolute difference considering all methods for all records varies from 0.38 to 0.82 m. These results are illustrated per station in Figure 6 through Figure 8.

Finally, water level time series were derived and plotted. Plots are an essential part of this study since the understanding of the behavior of the point measurements is still mostly done by visual analysis and interpretation. The water levels ascertained from the satellite altimetry are plotted over *in situ* data to give an overall comparison of the two kinds of data. Figures 6-8 show the time series for 3 selected stations with the best results in which the satellite-based altimetry measurements (dots) are displayed over the *in situ* gauge measurements (continuous blue line) to give a better idea of the kind of accuracy that was achieved and the range of behavior that was observed.

Discharge

The calculated discharges (as described in Measurement principles) are compared with *in situ* measurements and an assessment of the accuracy of the altimeter discharge estimates are performed as described in Measurement principles. The results are mentioned in terms of RMS and NS and the best results in each river basin are highlighted by bold numbers. Figures 9 and 10 illustrated

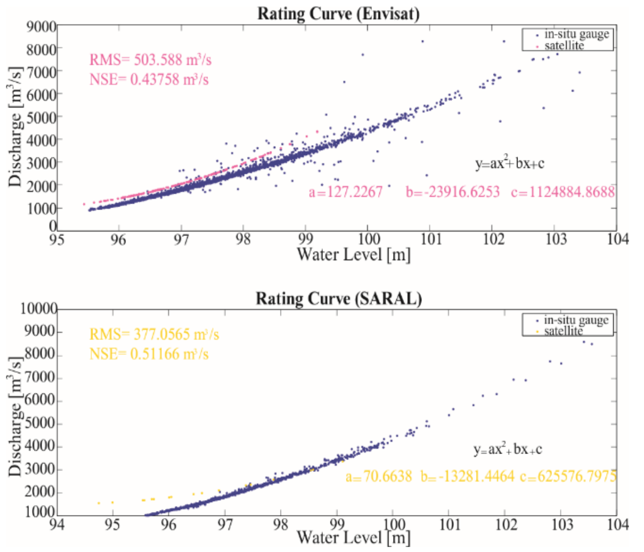

Figure 9: Rating curve over Budapest station.

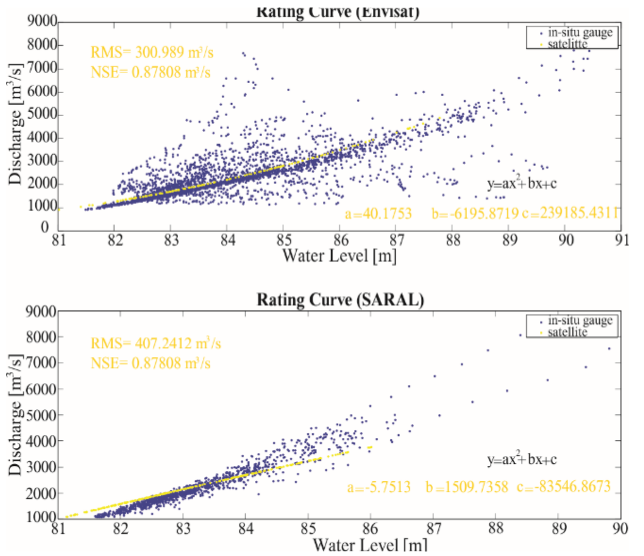

Figure 10: Rating curve over Baja station.

the rating curve of 2 stations (Budapest and Baja by Envisat and SARAL data as example) as a polynomial function from satellite derived discharge estimation and the accuracy were compared by *in situ* gauge data for all stations.

Discussion and Conclusion

This study demonstrates the ability of radar altimetry for monitoring water levels and discharge over Danube River and Amazon River basin. Within the test regions, the formal errors of the derived water level time series obtained about 55 cm on average for Amazon and 62 cm for Danube river basin. For discharge the best results yield at Baja station using Envisat data over Danube River basin and at Jatuarana station using SARAL data over Amazon River. The best results below 40 cm at Jatuarana station using SARAL RAT data were obtained. Due to the different temporal resolutions, the *in situ* data were interpolated at the altimeter epochs. Keeping this in mind, an accuracy of ~ 40 cm is good [49-54].

The quality of water level time series depends on the retracking algorithm used to process the waveforms. Due to environmental effects on the waveforms, it is too difficult to define a standard waveform retracker for all inland water bodies. We employed different retracker algorithms to find the most qualified water level and discharge accordingly.

Based on Satellite Radar Altimetry data, river water level confirmed by *in situ* gauge reading, i.e. there is the same behavior for *in situ* gauge time series during this time. Comparing the result of our data analyzing from the ALL, MEDIAN and MEAN values of water level based on the tracker and different retrackers, confirms that mostly using the MEDIAN values of water level for each satellite overpass provides the minimum values of standard deviation and RMS in the water level determination. Figures and numerical results clearly speak that mainly the water level from MEDIAN values follows the *in situ* gauge water level better than that the MEAN and ALL values would do. Also comparing numerical results from external validation in Table 4 shows that the MEDIAN values outperforms the ALL and MEAN value for all retrackers except than ocean tracker. The ocean is not reliable tracker for inland water bodies and this exception cannot be a negative point against the performance of the MEDIAN values. Therefore, using the MEDIAN operator and mostly retracker sea-ice algorithm would be the most robust estimator to determine water level in the case of study areas. A general comparison of water level from tracks shows that they are consistent and there is not unusual change in terms of bias and systematic error in the time series. From the figures, one can apparently see the annual periodic term of water level from the *in situ* reading gauge. The annual cycle behavior also can be seen from the altimetry time series with maximum and minimum water levels especially for the water level from the MEDIAN values.

The relative regularity of the wet and dry season cycle is clearly apparent in all-time series displayed except Budapest station for SARAL data. The stations Jatuarana, Obidos, Olivenca and Baja clearly show a fine match between the satellite measurements and the *in situ* levels behavior. We argue that these stations have the right combination of environmental factors that make them good candidates. Since the accuracy of inland altimetry strongly depends on the characteristics of the reflecting surface, varying conditions such as ground level elevations and vegetation cover, may lead to different accuracies and thus limit the applicability of satellite altimetry for the monitoring of rivers. Due to satellite ground tracks geometry along river, satellite altimetry is not able to provide a complete data coverage of the area. Even though high along-track resolution of a few km is possible, the cross-track resolution depends on the orbit geometry of the mission(s). In another hand this study is limited to ENVISAT and SARAL data. So the use of additional missions such as Jason-2 or Sentinel-3 and other missions improve the spatial (and temporal) data coverage.

Table 5: Statistical characteristics ($m^3.s^{-1}$) for discharge computation using altimeter data.

Station	Mission	RMS	NS
Obidos	Envisat	15215	0.915
	SARAL	12458	0.938
Olivenca	Envisat	3734.5	0.939
Jatuarana	Envisat	6513	0.958
	SARAL	**450.31**	**0.999**
Budapest	Envisat	503.588	0.438
	SARAL	377.056	0.512
Baja	Envisat	**300.989**	**0.878**
	SARAL	407.241	0.609

We have confirmed that satellite altimetry can be used for measuring the water levels of rivers with acceptable precision provided that appropriate processing methods are applied [38]. For the river morphology to estimate water level from RAT data, the important characteristic is not only width but also is its sinuosity. Sinuosity may cause the satellite track to cross path of the river more than once within a short distance in each satellite ground path. Our results also confirmed that SARAL can fulfill the role of being a substitute for the Envisat mission, as produces somehow similar results. Although SARAL is thought of as an improvement over Envisat, these improvements (mainly the smaller footprint and the higher rate of measurements) were clearly observable in the particular context analyzed here.

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