QUANTIFYING ACCURACY & UNCERTAINTY AND MODELLING NOISE & ERROR OF SATELLITE RADAR ALTIMETRY MEASUREMENT OF INLAND WATER LEVELS

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ABSTRACT

Satellite radar altimetry, originally designed and developed for the monitoring of ocean surface topography, has shown a promising potential for the monitoring of water levels of inland water bodies such as inner seas, great lakes and large rivers.

However, the operational use of satellite derived water levels for hydrological applications remains very limited, partly due to the lack of qualification of their accuracy and to their low temporal sampling frequency.

Developing standardized methods to (1) quantify the quality (accuracy, uncertainty and effective sampling frequency) of satellite radar altimetry water levels, (2) model the noise that affects these measurements due to interactions between the radar signal and the morphology of water bodies and surrounding environment and (3) over-sample satellite measurements to provide daily time series required for hydrological applications, are key issues for further development of this technique.

1. INTRODUCTION

Satellite radar altimetry was initially designed for the monitoring of ocean surface topography. Numerous works during the last fifteen years have shown its potential contribution to the monitoring of water levels of inland water bodies (inner seas, lakes, floodplains and large rivers) [1], [3], [5]. Over this period, a significant number of satellites have provided radar altimetry information (Topex Poseidon, ERS, Envisat, Jason) and could ensure the continuity of operational monitoring of continental water levels.

Recently, various research groups have dedicated large efforts in multiple complementary directions : (1) comparing waveform retracking algorithms [2] and improving them in order to increase the accuracy of radar altimetry measurement of inland water levels; (2) building databases of rivers and lakes water levels derived from satellite radar altimeters ("Global reservoir and lake monitor" Project, "River and Lake" Project, "CASH" Project, MSSL Global Lakes Database); (3) developing new measurement concepts for the monitoring of inland water levels from space (satellite radar interferometry, LiDAR altimetry).

The objective of this paper is to present a standardized methodology for the characterization of the quality (accuracy, uncertainty, effective sampling frequency) of inland water levels measured from satellite radar altimetry. Its results will be illustrated on various stations of the Amazon Basin. Further on it will be applied to the analysis and modelling of the measurement noise in relation with river morphology.

1.1 Altimetry satellite characteristics

Radar altimetry satellites use heliosynchronous orbits that permit a global and repetitive coverage of the Earth. Such orbits imply a compromise between spatial et temporal sampling.

Each satellite is characterized by its spatio-temporal parameters : the orbital frequency or period (T_{SAT}=10, 17 or 35 days), the altitude (ex 1400 km), the equatorial distance between ground tracks (d_{eq}=300 or

70km), the measurement frequency along the track (f_{track}=10Hz, 20Hz, etc.), the associated distance between measurements (d_{track}), the track enveloppe width (W_{track}~1km). The figure 1 below illustrates theses characteristics for the Topex/Poseidon satellite(1992-2006).

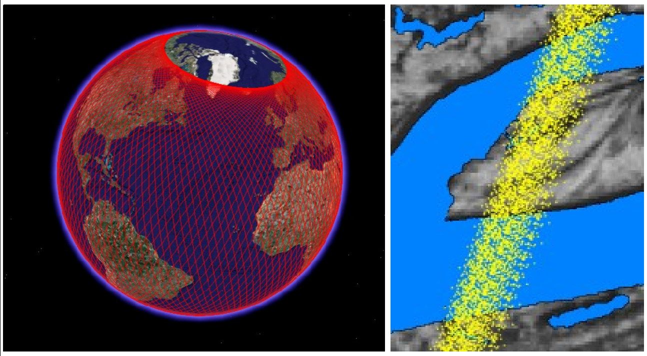

Figure 1: (left) Topex/Poseidon coverage ; (right) ground track 63 variation over the Solimões river, Brazil along ten years (1992-2002).

[T_{SAT}=10days ; d_{eq}=300km ; f_{track}=10Hz ; d_{track}=560m ; W_{track}=1.5km].

All of these parameters affect the ability of the satellite to monitor river water levels around the world. The spatial coverage by ground tracks directly defines the potential sites of interest while the effective sampling period over a given site will impact the ability to characterize the hydrological signal (aliasing phenomenon [6]).

The morphology of the water body affects the echo signal and the methods used for the backscatter signal processing strongly influence the quality of the resulting time series.

2. BUILDING TIME SERIES OF SATELLITE RADAR ALTIMETRY WATER LEVELS

Building water level time series from satellite radar altimetry measurements involves four steps : (1) delineating a geographic window around the intersection of the satellite ground track and the water body, (2) extracting all satellite measurements (waveforms) over the selected window and processing them with retracking algorithms to quantify corresponding water levels, (3) determining a unique value of water level for each satellite overflight over the water body, (4) filtering the resulting radar altimetry water level time series to remove unrealistic values.

2.1. Satellite data windowing

As heliosynchronous orbits of altimetry satellites are relatively stable and satellite positioning highly accurate (~3cm), it is possible to time monitor a given water body under one (or more) satellite track .

For that purpose it is necessary to define the geographic coordinates of the extraction window. The choice of the window size is a result of a compromise between:

(a) large window to get a large number of measurements and a high effective sampling frequency. However a large window will include land surface around the water body thus increasing the measurement noise and dispersion.

(b) small window to get "pure" water body echo, but will result in fewer measurements, thus reducing the effective sampling frequency.

Favoring smaller windows is an efficient way to limit data dispersion: when the water body is large enough, the extraction window results in time series where multiples measurements are available for a single satellite overflight (fig. 2, top: raw data extraction).

2.2. Waveform retracking

The analysis of backscatter waveforms recorded by the satellite is performed by a retracking algorithm whose objective is to determine the distance between the satellite and the ground target (water body). Such algorithms were originally optimized for ocean type surfaces (i.e. large surfaces) or ice surfaces. It is important to keep in mind that the radar echo footprint on Earth is about 2~5km wide (depending on both the altimeter specifications and the satellite altitude). New retracking algorithms, optimized for inland applications are currently developed by various research teams and should be characterized and compared in terms of performances in a near future.

Analysing and processing radar waveforms is an intensive process that requires the original waveforms records (~15 Tbytes for Topex/Poseidon) and a dedicated powerful computing platform. In this paper, in order to illustrate the methodology, we used GDR (Geophysical Data Records) products from AVISO (Archivage, Validation et Interprétation des données des Satellites Océanographiques) that integrate waveform retracking results (Topex/Poseidon on-board "Ocean tracker") as well as many other physical variables measured by the satellite (instrumental and atmospheric corrections, instruments states, statistics, etc.).

2.3. Satellite time series

In order to derive time series from satellite measurements, it is necessary to select one value for each satellite overpass, from the various measurements realized on the extraction window during the satellite overflight. One possibility, adopted here, is to apply a median filter that will remove unrealistic values as it is well known for noise removing.

2.4. Time series filtering

Filtering the resulting time series is a necessary step of the process to remove remaining unrealistic values. A possibility, adopted here, is to apply a simple $\mu \pm 3\sigma$ filter to the whole time series (fig. 2, bottom). This is a quite limited way to clean the time series and future investigations will take into account the main seasonal fluctuations that are characteristics of large and non regulated rivers.

2.5. Measurements dispersion

For each satellite overflight over the extraction window, the dispersion of the set of measurements is computed and characterized by a couple $(\mu;\sigma)$ (fig. 2, bottom). This dispersion is not an estimate of the measurement error but indicates the variability of instantaneous measurements.

2.6. Geoid undulation

Finally, the resulting satellite time series is transferred to the standard reference ellipsoid WGS-84 and translated in orthometric heights using a given geoid model (in this paper we use the EGM96 geoid model).

3. METHOD FOR QUANTIFICATION OF SATELLITE MEASUREMENTS ACCURACY

In order to quantify the accuracy of river water levels time series derived from satellite radar altimetry we need to compare them to the real river water levels. Such *in situ* measurements can be obtained from Water Agencies in various countries. In the present paper, the method was illustrated over the Amazon basin . The Amazon basin is a valuable experimental site as there are many rivers from extremely large to small, many satellite track crossings can be analysed.

Satellite altimetry data from the Topex Poseidon Satellite (CNES/NASA) are provided thanks to AVISO, the method is illustrated with measurements on track n°76 (61.686W ; 3.863S) and have been compared to in situ water levels provided thanks to ANA (Agencia Nacional das Aguas), and reconstructed (see 3.1) from 4 gauging stations: Itapeua, Codajas, Anama and Manacapuru.

3.1. Virtual gauging station

We here call a virtual station the place where the satellite ground track crosses a river and can potentially deliver water levels. The ability to quantify the accuracy of satellite data at a virtual station depends on the availability of in situ data on this location.

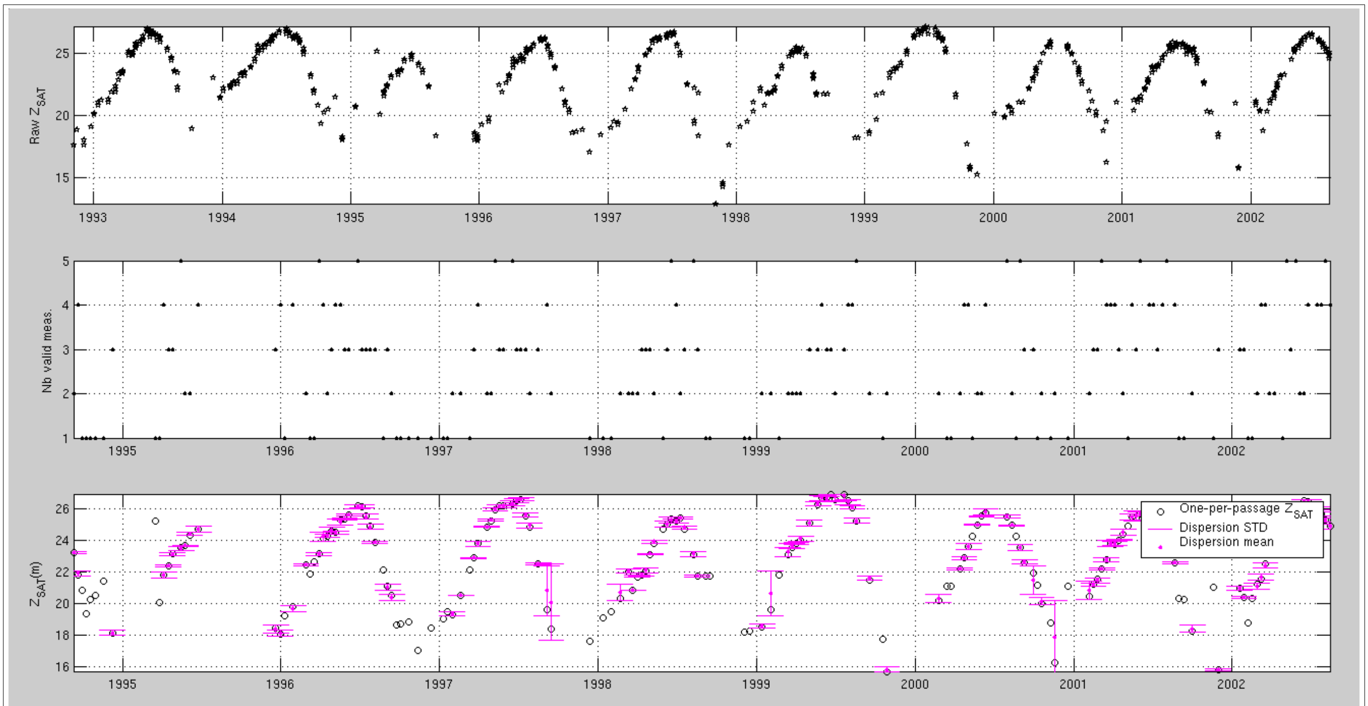

Figure 2: Generation of a water level time serie derived from satellite altimetry. Topex Poseidon track 76 (61.686W ; 3.863S).

Figure 3: Illustration of 4 gauging stations on the Solimões river (Itapeua, Codajas, Anama, Manacapuru) and Topex/Poseidon virtual station on track 76.

In many cases for a given virtual station, the closest gauging station is at least at a few tens kilometers (upstream or downstream) but this distance can be extended to a few hundreds kilometers in the worst cases.

In such cases (i.e. in most cases) it is necessary to use a spatial interpolation method to approximate the in situ water level time series at the virtual station. We developed such a method that calculates "reconstructed *in situ* time series" of water levels at the virtual station, based on 1 to 4 gauging stations (upstream and downstream when possible).

The method is based on a N^{th} degree polynomial interpolation using N stations (N=2, 3 or 4) with a constraint on minimizing the second derivative of the polynomial $p_N(x)$ which is equivalent to minimize the energy of the river longitudinal profile:

$$J(t) = \int_{x_{min}}^{x_{max}} [\frac{\partial^2 p_N(x,t)}{\partial x^2}]^2 .dx = 0$$

where x is the curvilinear abscissa along the river ($x=0$ at the ocean); x_{min} and x_{max} are curvilinear abscissas of the reach where the energy of the longitudinal profile is minimized; t is the date of interpolation (see fig. 4 below).

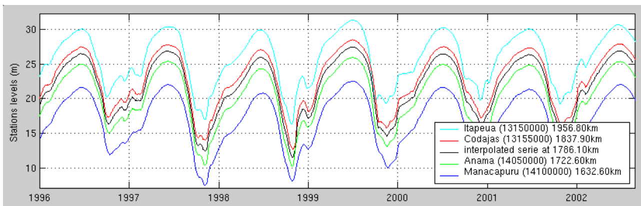

Figure 4: Interpolation of the river water level time series at a virtual station based on 4 real gauging stations (Itapeua, Codajas, Anama, Manacapuru).

This method is efficient for large and quiet rivers, as it does not take into account wave delay or damping. For other rivers propagation models (such as delayed second order) can be used.

3.2. Measurements error

Once the virtual station's time series is reconstructed, it is simple to compute the difference between radar altimetry water level measurements and in situ (or "reconstructed" in situ) measurements. A few time related corrections must preliminary be applied : translation from local time (in situ) to UTC time (satellite), interpolation of the in situ time series to match the exact satellite dates of measurements.

The resulting error time series is illustrated in figure 5. (Topex Poseidon measurements on track n°76 (61.686W ; 3.863S) compared to in situ water levels reconstructed from Itapeua, Codajas, Anama and Manacapuru gauging stations). The error appears to be structured according to the river level (Fig. 5 bottom right). By classifying the river level (Z_{IS}) into 3 water flow stages (low, medium and high), we can figure out the structure of the error (see table 1).

It should be noted that, even if the satellite time series are referenced to the geoid, systematic bias appear in the error. This can be induced by 2 main factors: (a) the Amazon gauging stations are not referenced to the geoid (for this study we used Kosuth & al. [4] results on establishing an altimetric reference network derived from Topex/Poseidon measurements), (b) Satellite measurements are still perfectible and could have a systematic bias : the data shown in this paper integrate multiple instrumental and geophysical corrections (for instance the wet tropospheric correction is still an investigation issue for inland applications [7] and is not available for this study: it is estimated as a systematic bias of 31cm but not applied here). As a general rule we consider here that the bias should be zero for high river stage and we correct "reconstructed in situ" Amazon data to remove this bias.

Error (m)	**RMS**	**Mean**	**STD**
GLOBAL	**1.145**	**0.353**	**1.093**
23.7 < Z_{IS} < 26.8	**0.233**	**0.000**	**0.235**
19.4 < Z_{IS} < 23.7	**0.516**	**-0.020**	**0.520**
10.8 < Z_{IS} < 19.4	**2.307**	**1.596**	**1.687**

Table 1: Global error and stage by stage (according to the river level Z_{IS}) error.

As table 1 shows, accuracy of the satellite measurement strongly decreases while the river levels decreases : high flow stage show a relatively good accuracy 0±0.23m while flow stage water levels are strongly overestimated 1.6±1.7m. This shows the difficulty to get

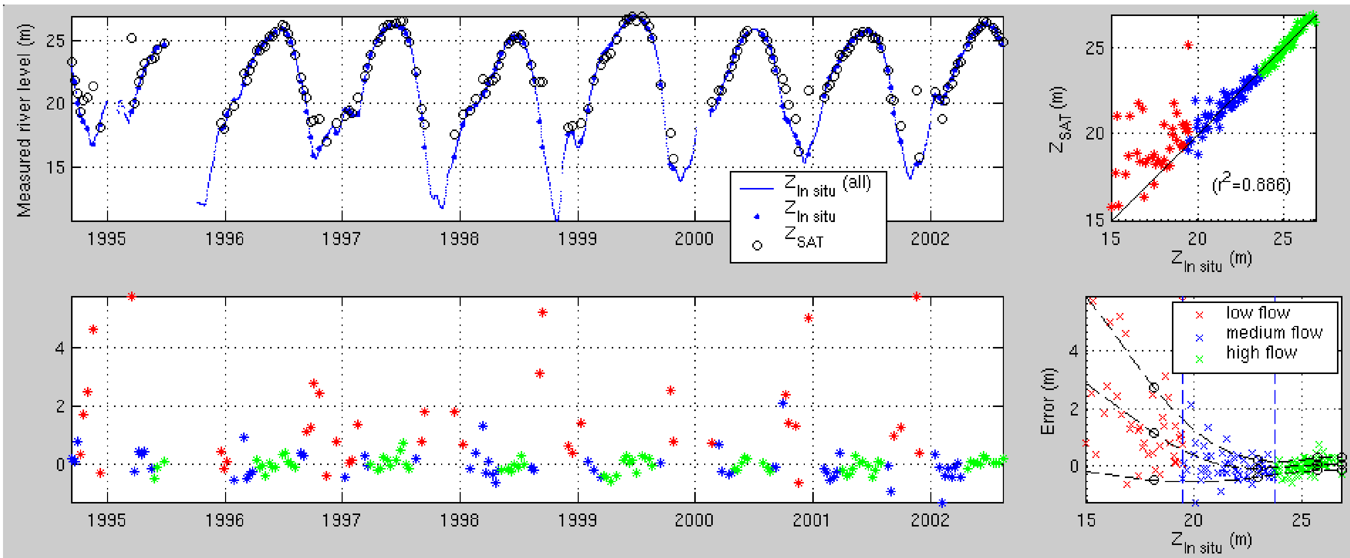

Figure 5: In situ & satellite measurements for matching dates (top). Error time series (bottom). Satellite measurements correlation to in situ ones (top/right). Error structure according to the in situ measurements (bottom/right).

correct satellite measurements during the dry season period (Figure 6). The overall satellite radar altimetry (Topex Poseidon, ocean retracker) accuracy on track n°76 crossing with the Solimões river can be synthesised by the RMS value of 1.15m.

Figure 5 illustrates the satellite effective sampling period for each water flow stage: 15.8 days for high flow stage, 21.3 days for medium flow stage and up to 31.2 days for low flow stage, while the theoretical sampling frequency of the satellite (Topex/Poseidon) is 10 days. Therefore, not only the accuracy but also the effective sampling frequency decrease when the river level decreases.

Figure 6 illustrates the satellite effective sampling period for each water flow stage: 12.1 days for high flow stage, 14 days for medium flow stage and up to 25.3 days for low flow stage. Once the accuracy is decreasing with the river as the river level, but moreover the effective sampling period for during low stage is really poor and fixes the limit of monitoring rivers with this satellite altimetry GDR product (other optimized products will be processed with this method in a near future).

Finally, this method allows both (1) to quantify the accuracy in a wide range of locations along rivers where we have at least 1 gauging station close to satellite ground track or 2 or more gauging stations upstream and downstream, (2) to compare different retracking algorithms, GDR products, and satellite missions.

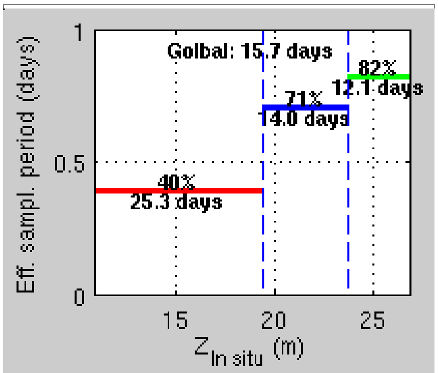

Figure 6: Satellite effective sampling period for each river flow stage.

4. METHOD FOR QUANTIFICATION OF SATELLITE MEASUREMENTS UNCERTAINTY

One of the advantage of satellites compared to gauging networks is the potentially short delay of availability of the data (from a few hours to a few days depending on the processing) and the homogeneous measurement over large regions. It can therefore bring valuable information for flood forecasting, water resource management, etc.

The reluctance of hydrologists to use satellite monitoring of river water levels is partly due to the lack of a standardized way to assess the accuracy (a posteriori: historical analysis, etc.) and uncertainty (a priori: near real time, etc.) of these data. Being able to compute uncertainty values associated to a satellite measurement is an important issue for satellite radar altimetry applications on inland waters.

4.1. Uncertainty modeling

When analyzing the accuracy, we relate the satellite measurement error to the river water level (Fig. 5). In the case where we have no information on the real river water level, the error can be estimated only from the satellite measurement. This is the uncertainty of the measurement.

We will focus here on relating the error to the satellite measured river level. Figure 7 shows the error structure according to the satellite measurements. The colors of the previous classification have been kept : for instance a red cross indicates that the river was at low stage at the time of the measurement. Figure 7 illustrates how low flow stage measurements are often overestimated.

The measurements have been classified in 3 classes according to the satellite measurements (***Z**$_{SAT}$*) : high ***Z**$_{SAT}$* measurements, for example, have a higher dispersion 0.17±0.78m (table 2) compared to hight ***Z**$_{IS}$* 0±0.23m. Cross confusion (a high satellite measurement can have a high error due to the fact that the real river level was low) induces a redistribution of the error through classes, averaging the global error structure. One can check that the global uncertainty (RMS) 1.15 m is equal to the global accuracy (table 1) but class uncertainties are distributed in a different way than class accuracies.

Black dashed lines on figure 7 are interpolated curves that fit the control points defined by each class of ***Z**$_{SAT}$* (mean error and "mean error +standard deviation"). This model can be used to estimate the uncertainty for each satellite measurement. Figure 8 shows the application of this uncertainty model. The result is a first response to hydrologist requirements in terms of quantification of the uncertainty of radar altimetry data. This uncertainty if far higher than the dispersion provided by figure 2 (bottom).

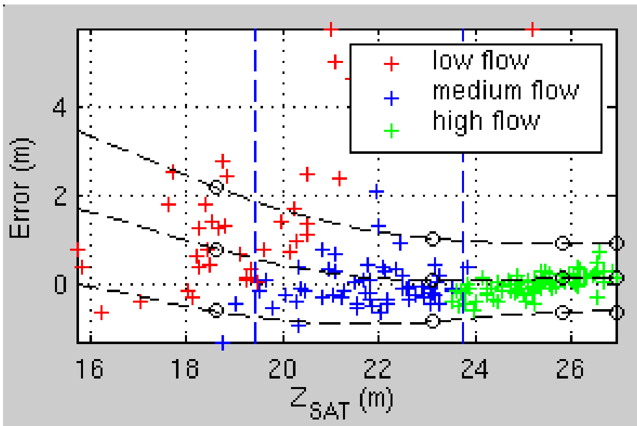

Figure 7: Error according to the satellite measurements.

Error (m)	RMS	Mean	STD
GLOBAL	**1.145**	**0.353**	**1.093**
24.7 < *Z*$_{SAT}$ < 26.9	**0.785**	**0.171**	**0.773**
21.6 < *Z*$_{SAT}$ < 24.7	**0.912**	**0.100**	**0.915**
15.7 < *Z*$_{SAT}$ < 21.6	**1.583**	**0.797**	**1.380**

Table 2: Global and stage by stage error according to the satellite measurements ***Z**$_{SAT}$*.

However, this kind of approach remains limited to the very same extraction window where the model has been calibrated and cannot be transferred to measurements on other satellite tracks and other rivers. Still this method is relevant to characterize near real time data uncertainty, once the uncertainty model has been calibrated on a few years of data.

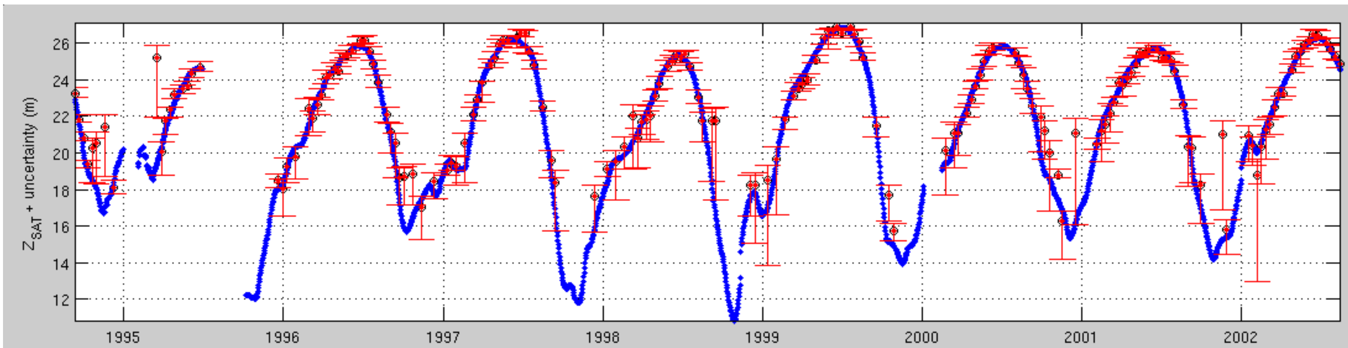

Figure 8: Satellite time series (red dots) with associated uncertainty (red bars).

5. ANALYSIS OF SATELLITE MEASUREMENT ACCURACY: APPLICATION TO 12 STUDY SITES OVER THE AMAZON BASIN

The above presented method for quantification of satellite measurement accuracy and uncertainty has been applied to 12 virtual stations over 3 Amazonian rivers: the Amazon river (3 virtual stations), the Solimões (4 virtual stations) and the Madeira (5 virtual stations) river. Results are presented in table 3.

Table 3 shows that satellite altimetry provides promising results for high flow stages with RMS values from 0.21m to 0.93m (mean RMS is 0.37m) and a good effective sampling period whose average is 17.1 days. Measurements during medium flow stages present an RMS from 0.36m to 1.51m (mean RMS is 0.67m) and an average effective sampling period of 45.9 days. Problems remain really critical for low flow stages with a mean RMS of 2.85m and an average sampling period of 70.9 days. Optimized retracking algorithms should be able to strongly improve these results, but this still has to be verified.

Figure 9 illustrates both the structure of the global RMS error and effective sampling period according to the river width. River width were extracted from geographical shapes (SRTM Water Body Data) that do not take into account seasonal fluctuations and therefore are not highly accurate. Nevertheless, they show a global trend : both the RMS error and the effective sampling period decrease when river width increases. This confirms the fact that the global quality of satellite measurements should increase while the river width increases, presenting a larger reflective area to the radar echo. However, the number of data used for this illustration is not sufficient to generalize results and will be further completed with more virtual stations.

CONCLUSION & PERSPECTIVES

The method presented here aims to provide a standardized way for quantification of the accuracy and uncertainty of satellite radar altimetry measurements, thus allowing qualification and comparison of various data products, satellite missions and retracking methods.

The quantification of the accuracy of satellite data (Topex Poseidon; ocean retracker) for 12 virtual stations showed a global RMS error ranging from 0.7m to 3.6m (to 2.0m for stations with river width larger than 1000m), and a high river stage RMS error ranging from 0.2m to 0.9m. It is important to note that while AVISO products we used result from retracking algorithms optimized for ocean surfaces, new retracking algorithms for inland water should result in increased accuracy.

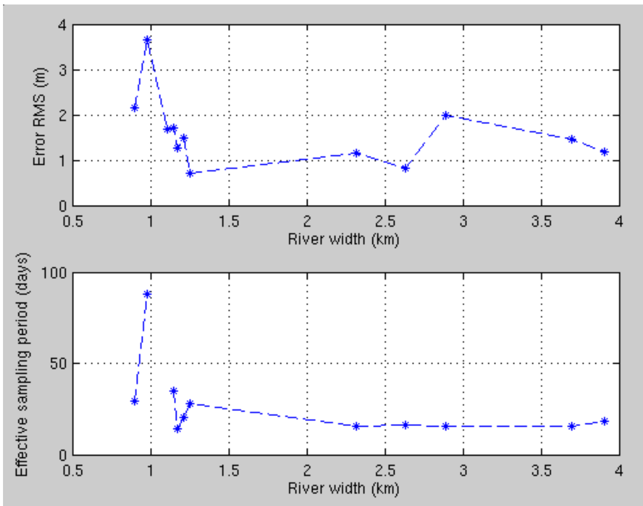

Figure 9: Error RMS according to the river width (top), Effective sampling period according to the river width (bottom).

This framework fetches up to an automated software chain (C++/Matlab) that allows to compute all of the presented results in a few minutes (including window data extraction from 75GByte of Topex/Poseidon GDR).

Future works will focus on: (1) characterizing radar altimetry data quality for large rivers all around the world (Senegal, Niger, Volga, Rhône, ...) ; (2) quantifying the quality of Topex/Poseidon retracked products with 4

ACCURACY OF 12 VIRTUAL STATIONS OVER THE AMAZON BASIN

	Curv. Abscissa from ocean (km)	Coordinates lon, lat (°)	River width (km)	RMS (m)				Teff (days)			
				GLOBAL	High	Medium	Low	GLOBAL	High	Medium	Low
Amazon river	1058.5 (TP228)	-56.500, -2.500	3.7	1.46	0.26	0.77	2.54	15.4	13.7	17.2	16.5
	1106.9 (TP139)	-56.900, -2.570	3.91	1.18	0.34	0.43	2.35	18.3	15.4	17.5	25.1
	1438.6 (TP152)	-59.060, -3.260	2.63	0.81	0.65	0.59	1.23	16.2	14.8	13.9	22
Solimões river	1561.2 (TP063N)	-59.970, -3.229	1.17	1.26	0.25	0.36	2.56	14.3	11.8	11.9	22.3
	1564.4 (TP063S)	-59.986, -3.281	2.89	1.99	0.23	0.64	4.41	15.8	11.7	13.6	29.3
	1786.1 (TP076)	-61.686, -3.863	2.32	1.15	0.23	0.52	2.31	15.7	12.1	14	25.3
	1967.7 (TP241)	-63.099, -4.052	1.21	1.49	0.93	1.51	2.13	20.4	14.7	25.8	26.3
Madeira river	1754.4 (TP063)	-60.720 -5.308	0.9	2.15	0.21	0.71	3.69	29.4	16.9	34.2	108
	1764.7 (TP063)	-60.750 -5.389	1.11	1.67	0.25	0.47	2.85	-	-	-	-
	1779.0 (TP063)	-60.783 -5.482	1.25	0.7	0.28	0.43	1.1	27.8	14.5	35.1	252
	1815.9 (TP076)	-61.075 -5.577	0.98	3.64	0.4	0.9	6.33	88.1	43.4	266	189.2
	2297.8 (TP254)	-62.976 -8.145	1.15	1.71	0.5	0.81	2.8	34.5	19.3	55.8	64

Table 3: Satellite measurements accuracy for 12 virtual stations over the Amazon, Solimões an Madeira rivers.

different retracking algorithms and possibly other satellites (ERS1/2, ENVISAT) ; (3) improving the filtering method and removing the bias linked to the interpolation between gauging stations.

Alternate approach for uncertainty calculation

Another way to develop a generalized approach for uncertainty quantification could be to relate the error structure to the backscatter coefficient which is the ratio between the energy received from the radar echo and the energy sent by the altimeter. As this parameter is independent of the river level dynamics, it could allows us to build a model by integrating data from multiple virtual stations. This model could then be used for any virtual station.

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