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MONITORING OF WATER RESOURCES BY SPATIAL ALTIMETRY

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ABSTRACT
Although most of the space missions discussed here have not been primarily dedicated to hydrology, 31 years of spatial altimetry have provided complementary data that can be used to create hydrological products for watersheds, such as time series water levels, estimates of river flows, longitudinal riverbed altitude profiles, minimum and maximum elevations, or leveling of stations in situ. The raw data still suffer from uncertainties of several decimeters. Today, altimetry techniques are evolving rapidly. One direction is the change of the radar band, from Ku to Ka. Another change is the replacement of the current LR Mode with SAR or Interferometry modes. Both evolutions tend to drastically decrease the imaged range, reducing both the contamination of the echo by the environment of the water body, and improving the vertical accuracy. Finally, as of 2015, the research missions were replaced by operational ones, making the longevity of the sampling sites more certain. All the aforementioned technical evolutions have been grouped together in the SWOT mission, a Ka-band interferometric altimeter, the first satellite mission actually dedicated to providing full coverage of continental waters, launched in December 2022.

Keywords: Spatial Altimetry. Hydrometry. River Monitoring.

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INTRODUCTION

Water is the basis of life and the most precious natural resource on Earth [1-3]. The river level is one of the hydrological quantities that are routinely considered when assessing the basic needs of societies for fresh water. The monitoring of this variable is carried out through networks of hydrometric stations organized at the national level. This monitoring requires that an extensive network be maintained for very long periods, with high installation and maintenance costs [4]. The HidroWeb Portal, part of the National Water Resources Information System (SNIRH), maintained by the National Water and Basic Sanitation Agency of Brazil (ANA), offers access to the database that contains all the information collected by the National Hydrometeorological Network (RHN), gathering data on river levels, flows, rainfall, climatology, water quality and sediments [5]. Despite this huge hydrometheological network, spatial resolution is limited and updating information can take 6 to 12 months. In addition, the Amazon basin is a transboundary basin. Consequently, Brazil cannot decide on the basin-wide sampling scheme whatever its need for hydrological information, in particular in the Andean parts of the basin that belong to other countries.

Several initiatives have been carried out in search of advances to provide hydrological information in basins without fluviometric monitoring or little monitored, such as the intensification of the use of hydrological data estimated from remote sensors, embedded in satellites, since they provide an acceptable spatial and temporal resolution, providing a synoptic and multitemporal view of extensive areas with complex seasonal variability, difficult to access and limited infrastructure [6,7], being used in various studies of hydrological processes, such as: mapping the extent and elevation of water bodies and their changes over time [8,9], surface water storage [10-12], groundwater [13-17], precipitation [18,19], evapotranspiration [20] and ice and snow [21-23].

Table 1 - Altimetric missions.

Mission	Launch	Temporal resolution	Application
GEOS-3	1975-1979	37 days	Ocean
SEASAT	1978-1978	17 days	Ocean
GEOSAT	1985-1990	17 days	Ocean
ERS-1	1991-2000	35 days	Earth Observation
Topex/Poséidon	1992-2006	10 days	Ocean
ERS-2	1995-2011	35 days	Earth Observation
GFO	1998-2008	17 days	Ocean
Jason-1	2001-2013	10 days	Ocean
ENVISAT	2002-2012	35 days	Earth Observation
Jason-2	2008-2019	10 days	Ocean
Cryosat-2	2010-present	369 d (30d cs)	Polar Observation

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HY-2A	2011-2020	14 days	Ocean
SARAL	2013-2016	35 days	Ocean
Jason-3	2016-present	10 days	Ocean
Sentinel-3A	2016-present	27 days	Ocean
Sentinel-3B	2018-present	27 days	Ocean
HY-2B	2018-present	14 days	Ocean
HY-2C	2020-current	14 days	Ocean
HY-2D	2021-current	14 days	Ocean
Jason-CS/Sentinel-6A	2020-current	10 days	Ocean
SWOT	2022-current	21 days	Inland waters
Jason-CS/Sentinel-6B	(2026)	10 days	Ocean

Of particular note here is the satellite radar altimetry or space altimetry, as will be discussed in this article, which provides water levels measured by satellites. Spatial altimetry is a remote sensing technique whose purpose is to obtain the surface level of the water depth (SLA) of a water body. Radars on board satellites emit an electromagnetic wave at the nadir of these satellites, estimating the instantaneous height of the water body [24]. Spatial altimetry was conceived and developed in the 1970s to study the spatiotemporal variability of ocean levels (Table 1) and is already a robust technique in this domain, collecting with centimeter precision the instantaneous height of the surface of the seas [25]. Since the late 1990s, data from altimetric missions have been demonstrating a great contribution to the monitoring of continental water levels [26-29].

Today, spatial altimetry provides long-term monitoring of continental waters, presenting time series with three decades of data, in thousands of Virtual Stations (EV) [30]. Laser equipment (LIDAR) and synthetic aperture radars (SAR) have been deployed on aerial platforms and altimetric satellites [31]. In parallel, many studies, applying satellite observations, obtained in a wide range of the electromagnetic spectrum (visible, infrared, and microwave), have been developed to monitor the extent and dynamics of continental water bodies, with varying degrees of success [32–35]. In addition, the technology involving multi-satellite altimetry has the advantage of allowing global monitoring providing important information on the temporal variations of terrestrial continental waters on a meso and large scale [36-38].

This work presents the main contributions of spatial altimetry to the monitoring of water resources, as well as future opportunities, currently fostered in the *Surface Water and Ocean Topography* (SWOT) mission dedicated to surface hydrology [39]. One of the new capabilities of SWOT, along with monitoring surface water levels, extent and flow, will be to provide variations of the SLA on a global scale with an unprecedented horizontal resolution (~100 m). In this work, we will not address the monitoring of water in artificial reservoirs, this

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specific and very important topic can be found in other publications and reviews [40-43]. Here, the monitoring of SLA in rivers, floodplains and wetlands stands out.

ALTIMETRY CUSTOM

ALTIMETRY RADAR

The altimetric radars installed on board different altimetric missions emit a wave in the direction of the nadir, defined by the vertical in relation to the ground. On return, the radar receives the echo reflected by the SLA. Echo analysis allows extracting a measure of the travel time between the satellite and the water surface (Figure 1). In the course of its round trip that separates the satellite from the Earth's surface, the radioelectric radiation emitted by the altimeter, then reflected by the SLA, crosses the Earth's atmosphere and is slowed down by the gaseous or electronic content of the different atmospheric layers encountered. For a good accuracy of the altimetric measurement, it is necessary to correct the errors introduced by these effects, which can translate into an elongation of the ground clearance of several meters [24]. The radar altimeter satellites are ERS (1 and 2), Topex/Poseidon, GFO, Jason-1, ENVISAT, Jason-2, Saral, HY-2 (B, C and D) and Jason-3 (as well as their successors).

The time of emission and return of the wave is transformed into distance considering the speed of propagation, in a vacuum, of the emitted electromagnetic waves. The SLA level, *h*, deducted from the altimetric measurement, is obtained by the difference between the satellite's orbit, *H*, relative to a reference ellipsoid and the distance between the satellite and the SLA $(c\Delta t/2 - \Sigma cor)$ (Equation 1).

$$H = H - (c\ \Delta t/2 - \sum cor) - N \qquad (1)$$

where *c is* the speed of light in a vacuum, Δt is the time of emission and return of the electromagnetic wave, Σcor is the instrumental, environmental and geophysical corrections and *N*, the geoidal undulation that converts ellipsoidal heights into geoid heights, called altimetric elevations [29].

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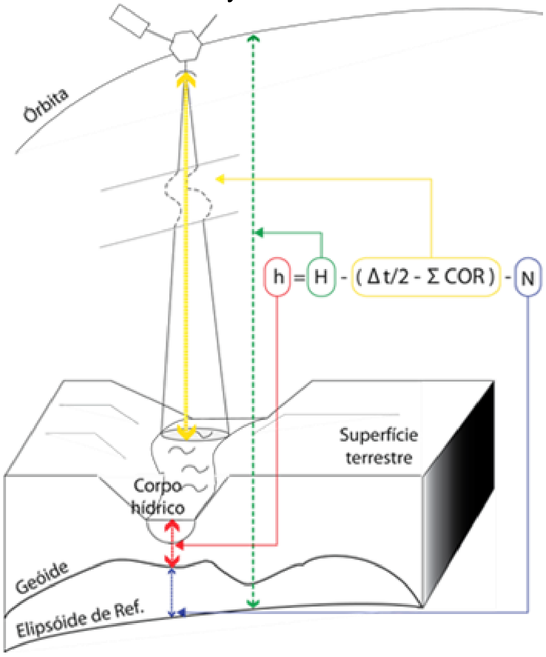
Figure 1 - Principle of measurement by altimetric radar in continental hydrosystems.



SAR/DOPPLER ALTIMETRY

SAR altimetry, an acronym for *Synthetic Aperture Radar*, which are synthetic aperture radars, uses the Doppler effect with a higher pulse emission rate. The same band along the satellite's trace will reflect the pulses at different frequencies as the satellite moves, to distinguish the reflections coming from the back or the front of the reflected echo, if they come from the back, it is as if the satellite moves away, if they come from the front, it is as if the satellite approaches. Consequently, a higher spatial resolution is obtained, at least in the direction of the satellite's motion, allowing a more precise determination of its position [44]. The satellites that fall into this category are Cryosat-2, Sentinel-3 (A and B), Jason-CS/Sentinel-6A and in the future Sentinel-3 (C and D) and Jason-CS/Sentinel-6B.

The emission and reflection of a pulse for the ideal case of an ocean surface for radar and SAR altimeters are outlined in Figure 2. The surface imaged by the reflected wave is represented by the intersection of the Earth's surface and the spherical shell. The vertical axis is positioned at the moment of the altimeter pulse emission. The representation of the power received by the altimeter (echo) as a function of time is usually called waveform (FO). Radar altimetry shows a near-plateau of energy after ascent because the surface of each of the rings represented is equal, whereas SAR altimetry decreases dramatically [45].

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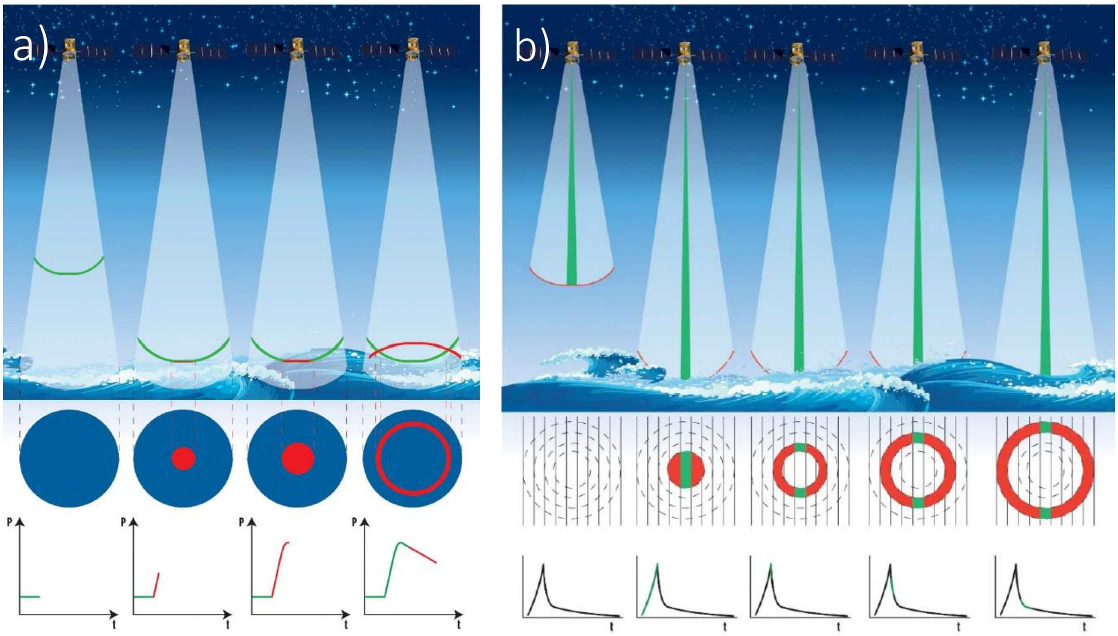
Figure 2 – Formation of the echo reflected by the altimeter in the ocean environment by radar altimetry (a) and SAR (b) (Source: CNES/CLS/Mira Production).



VIRTUAL STATION

Rivers are generally not monitored by altimetric satellites along their course. Instead, they are crossed at certain points. Thus, each intersection of a trace of the altimetric satellite with the reflective surface of the water plane consists of a virtual station (EV), and it is potentially possible to obtain a time series of the SLA [46,47]. It is as if there were a hydrographic station at the point where, on average, the satellite crosses the watercourse. These measurements can then be used in hydrological studies in a similar way to *in situ observations*, except that the depth of the watercourse is not precisely known at this point, so more work is done on the basis of variations in SLA than on depth.

As they resemble oceanic conditions, large lakes and inland seas present analogous conditions for the acquisition of altimetric measurements, with extensive SLAs, considering points sufficiently distant from the margins and surrounding reliefs. In rivers, floodplains and wetlands, the signal is more complex due to the heterogeneity of the observed surfaces, being reflected by a mixture of surfaces of different types and with discrepant reflectivities, such as watercourses, forests, swamps, among others. This significantly affects the shape of the reflected echo, and, consequently, the ability to extract the intended information, in particular the distance measurement, resulting in less accurate measurements, requiring a more improved treatment in the selection of altimetric data in these areas [26,28].

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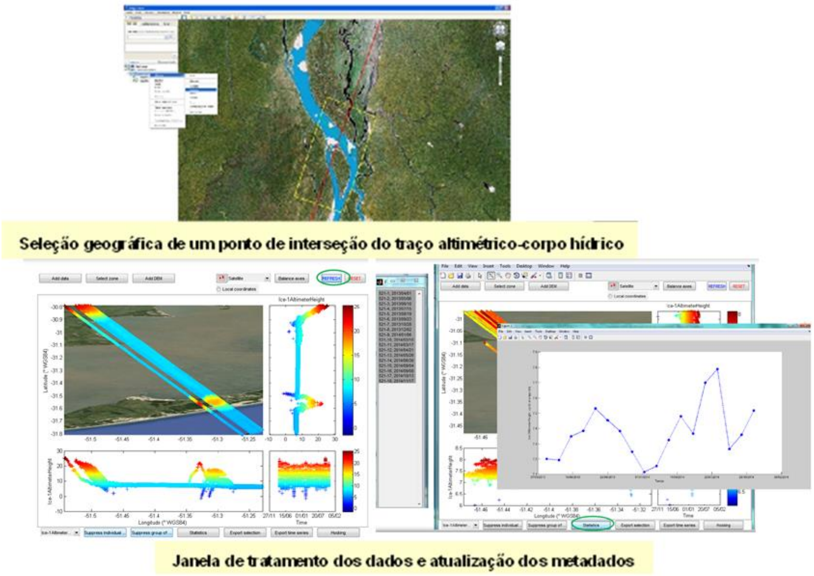
Figure 3 – Example of the elaboration of a virtual station.



Seeking an alternative to solve such problems, a manual methodology was developed and tested for the creation of EVs [46,47], by selecting the data corresponding to the crossing of the SLA plane, adapted to variations in time and space, allowing a three-dimensional selection of data in a surface-depth space (Figure 3) using the programs *Google Earth* [48] and *Multi-mission Altimetry Processing Software* (MAPS) [49].

The Hydroweb-Theia (https://www.theia-land.fr/en/product/water-levels-of-rivers-and-lakes-hydroweb/) website is the result of a cooperation between several French research institutions, including the *Centre National d'Études Spatiales* (CNES) and the *Institut de Recherche pour le Développement* (IRD). The University of the State of Amazonas (UEA), through the Laboratory of Water Resources and Spatial Altimetry of the Amazon (RHASA) collaborates with this platform through several research projects. In Hydroweb-Theia, continuous and long-duration time series from EVs in large lakes with surface areas above 100 km², reservoirs and the 20 largest rivers in the world are available (Figure 4). The information on the *website* is constantly updated no later than a day and a half after a new altimetric measurement is available.

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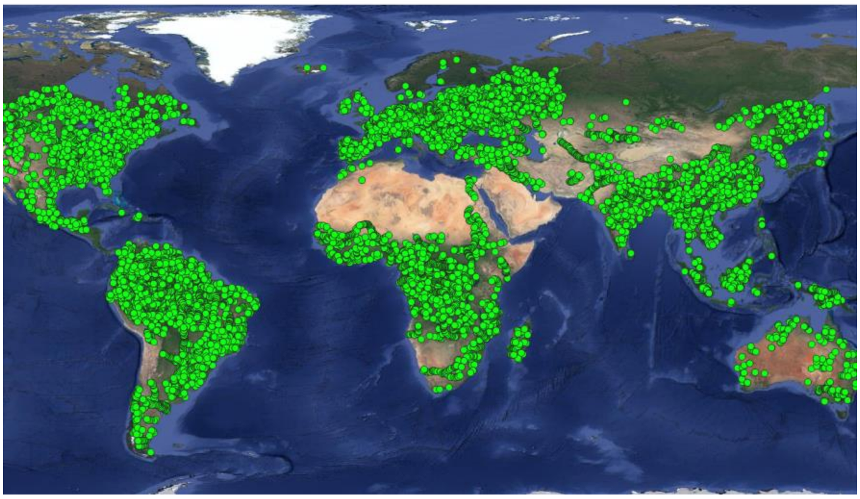
Figure 4 – Altimetric series available on Hydroweb (Source: https://www.theia-land.fr/en/product/water-levels-of-rivers-and-lakes-hydroweb/, accessed on: 01 Nov 2024)



ACCURACY OF THE ALTIMETRIC MEASUREMENT

The need to couple the measurements of current space missions with future ones, through their comparability, homogeneity and reliability, has led the scientific community and agencies to develop mechanisms that ensure the realization of some quality indicators, such as calibration and validation studies (CAL/NPV analyses). CAL/NPV activities are also required prior to data dissemination. On the one hand, it is essential to estimate the performance of the altimeter, consolidate the reliability of the data and allow the evolution and improvement of the measurements. On the other hand, the data from the altimetric radars show the inconsistencies in *the in situ* measurements [50], as well as make it possible to overcome such inconsistencies [51].

Satellite altimetric CAL/NPV activities in the ocean domain have a long history and the protocols are well known, with several studies published. However, some methodologies do not apply to continental hydrosystems, for example, the corrections associated with dynamic topography and tides. In continental hydrosystems the tides and waves are generally low and the dynamic variability is much lower than in the oceanic domain. AFOs are not optimized for continental hydrosystems. The width of the imaged range of the altimeter, adapted to the ocean surface, presents, in the case of continental hydrosystems, a contamination of the signal by "parasitic echoes" coming from the banks of rivers, islands and riparian vegetation, the reflected FOs have particularities to be integrated for the determination of height and consequently in the activities of CAL/VAL. However, the results from the pioneering study dedicated to the validation with the altimetric data of the GEOSAT satellite in rivers demonstrate the interest of using altimetric data for SLA monitoring in continental hydrosystems, at least in the Amazon basin [52]. Unfortunately, despite its promising results, GEOSAT data has never been reprocessed globally to be usable in inland waters.

Given the extension of its rivers and the existence of an *in situ* hydrometeorological monitoring network , the Amazon basin is the great laboratory for validation activities of altimetric satellites in continental hydrosystems, where several studies are continuously developed. In the Amazon River, the RMS ranged from 25 to 60 cm [53] as well as from 45 to 80 cm [54]. RMS variations between 38 and 246 cm are shown in studies carried out in rivers, with widths between 0.58 and 1.16 km and in floodplains [55]. In a study in the Tapajós River, the RMS presented was of the order of 35 cm [56]. The results described above used the standard AFO for the Topex/Poseidon mission.

Altimetric products have evolved significantly since the 1990s when data from the Topex/Poseidon missions were reprocessed. The data reprocessing routines of the ENVISAT satellite, using four AFO *Ocean*, *Ice-1*, *Ice-2* and *Sea Ice*, are more efficient in continental hydrosystems. A validation study relating the four AFOs shows RMS ranging from 26 to 140 cm, 7 to 40 cm, 10 to 110 cm and 14 to 324 cm for, respectively, in Amazonian rivers and floodplains [57] and correlations of Topex/Poseidon, ERS and ENVISAT data with the Careiro fluviometric station, on the Amazon River, denoted values of 0.91, 0.93 and 0.98 for Pearson's coefficient [58]. Another validation study of altimetric data with *in situ* data in several rivers of the Amazon basin, presented 70% of the time series of estimated water levels, with uncertainties of less than 40 cm, using the AFOs *Ice-1 and Ice-2* of the ENVISAT satellite and 80 cm with data from the ERS-2 satellite (using the AFO *Ice-2*), for rivers up to 20 m wide [46], while the study with AFO *Ocean* of the Topex/Poseidon satellite expressed uncertainties of up to 110 cm for 70% of the series analyzed, with good results only in rivers with a width greater than 1 km [55].

Projects such as *Observation de Surface Continental Altimetrie Radar* (OSCAR) [59] or *Contribution de l'Altimetrie Spatiale pour l'Hydrologie* (CASH) [60] reprocessed previous data from the ERS and Topex/Poséidon missions with the same AFOs as the ENVISAT satellite, making better products available in the continental domain. An altimeter using the Ka-band is less affected by ionospheric disturbances than an altimeter in the Ku-band, and is more efficient in terms of vertical and spatial resolutions, echo handling and signal noise. With the help of an adapted AFO, this type of altimeter is more efficient over any type of surface, especially in coastal and continental areas. A Ka-band altimeter, called AltiKa, on board the Franco-Indian satellite SARAL (*Satellite with ARgos and ALtika*), was launched in 2013, positioned under the same orbit as the ENVISAT satellite, ensuring the continuity of observations started with ESA's ERS-1/ERS-2/ENVISAT running until 2016 [61]. Validation studies in the Amazon basin using altimetric data from the SARAL satellite, with the AFO *Ice-1*, denoted minimal variations in the standard deviation of 8 cm, especially in narrow rivers, with a width of 40 m [62].

At present, several scientific studies are focused on understanding the risks associated with global warming of the Earth due to changes and increase in the average temperature of the oceans, but another equally important challenge is to better understand the circulation of the oceans on a large scale (including the coastal zone). All these studies need long and homogeneous altimetric time series from different missions and resulting from the various compartments that make up the hydrological cycle, especially the terrestrial system, such as continental freshwater reservoirs, stored or flowing in lakes and rivers. In this context, the validation of data from the JASON 1, 2 and 3 satellites, with the AFO *Ice-1*, during the period between 2002 and 2018, showed RMS lower than 40 cm [63]. Recently, the validation of the altimetric data of the SENTINEL 3A and 3B satellites indicated RMS ranging between 12 and 32 cm [64]. These results are promising for the use of long and homogeneous altimetric time series resulting from different missions.

BRIEF HISTORY OF THE MAIN APPLICATIONS OF SPATIAL ALTIMETRY IN HYDROLOGY

In the early 1970s, satellites began to regularly transmit data on the physics, chemistry, and dynamics of continental lands, the atmosphere, and the biosphere. GEOS-3 (*Geodynamics Experimental Ocean Satellite*) was the first satellite dedicated to ocean mapping, but still, some authors used its altimetric radar for territorial mapping and monitoring of continental waters. Miller [65] shows that GEOS-3 data could be used to monitor the SLA of lakes. From these pioneering studies, three main axes stand out:

The first axis of applications concerns the monitoring of water resources in relation to climate and agriculture. Studies along these lines are numerous [66-72]. Most of these studies were conducted in large lakes, with extensive review of spatial altimetry on the topic [27, 40-43]. The first study on a river system was carried out with GEOSAT's waveform algorithms (AFO*) (GEOdetic SATellite),* whose discrepancy between satellite and *in situ data* resulted in RMS variations of the order of 19 and 109 cm, at four sites in the Amazon

[52]. The uncertainties were partially attributed to the determination of the orbit, but also to the records of the in *situ* rulers, this subject will be addressed in the next axis of studies. Altimetric data from the Topex/Poséidon satellite [73], launched in 1992 with a 10-day revisit period, have been used in several river studies [55,74-77] and are currently part of long time series together with the Jason 1, 2 and 3 satellites launched later under its orbit [78]. ENVISAT *(ENVIronmental SATellite)* positioned under the same orbit as the satellites of the ERS missions, which began in 1991, with a revisit period of 35 days, was the mission most used in studies with the purpose of validating altimetric data in rivers, floodplains and wetlands, where time series of water levels with decimetric precision were obtained [46,47,51,58,79].

The second major axis of application of spatial altimetry for hydrology comes from the fact that the traces of the satellites cross the water bodies in their entire extension in the various hydrological contexts. The hydrological monitoring networks, consisting of *in situ* stations, are located on the banks and in narrow and straight stretches of the river, as it is necessary to carry out frequent measurements, whether the SLA levels or the flows. For this reason, the variability of SLA in wetlands is globally unknown. In the first application of spatial altimetry for wetland monitoring [80] it was difficult to distinguish river and floodplain with the Topex/Poseidon satellite data. However, success was achieved by considering a lag of a few days in SLA variations between the river and the adjacent floodplain [55]. The spatiotemporal variation of the volume of water in the Rio Negro basin, considering the main channel together with the floodplain, was determined using mosaics of images captured by the SAR radar, from the *Japanese Earth Resources Satellite* (JERS-1), to estimate the variation of the flooded area for a seasonal cycle, together with the changes of the SLA with altimetric data from the Topex/Poséidon satellite, in 88 EVs combined with 8 liminimetric stations [81]. A volume variation of 331 km3 was estimated for the entire Rio Negro basin, highlighting the complex relationship between the volume potentially stored in the flooded area of the basin and the volume of river runoff during the same period. Similarly, the spread of flooding along the Mekong River was monitored by combining spatial altimetry data with SPOT4 satellite imagery [82]. The same methodology was used to reestimate the volume of water stored in the floodplains of the Negro basin and that of the Amazon basin using images with better temporal resolution [83,84]. The first study using ENVISAT data to examine the relationship between river and floodplain was conducted in the Curuaí floodplain, located in the Amazon basin [85]. In the same floodplain, the transfer of water between the river and the plain was estimated using hydrological modeling and altimetric time series of ENVISAT water levels [86], as well as other studies were developed on the same theme [87,88].

The third axis of application consists of the use of the unique geodetic reference system of altimetric data to study the slope of rivers and thus be able to model the hydrodynamics of the runoff. Among several applications, the pioneering works were carried out in the main channel of the Amazon River with data from the SEASAT satellite [89-91] followed by data from the Topex/Poséidon satellite [55]. With mixed data from the Topex/Poséidon and ENVISAT satellites [92] or only from ENVISAT [87] a different methodology was proposed for determining river height and slope profiles derived from altimetric data, employing key curves from the EVs and hydrodynamic modeling. Some studies cover EV flow estimation using empirical regressions with *in situ stations* [93-95] or hydrological and hydrodynamic modeling [96-99]. On this same axis, key curves were developed in more than 1000 Evs with altimetric data from ENVISAT and flow resulting from hydrological modeling [100].

CURRENT MISSIONS AND PLANNED IMPROVEMENTS

New horizons are opening up beyond what is offered by current operational missions. Future satellites should provide better spatial and temporal coverage, as well as improve measurements in continental and coastal areas and observations of phenomena at the meso-scale. In the medium term, the projects are oriented towards missions capable of detailing the ocean surface, improving spatial resolution, with a scale of approximately tens of kilometers, and temporal resolution, returning to the same terrestrial points in a few days.

To ensure the continuity of the series of measurements carried out since 1992 by the Topex/Poséidon, Jason-1, Jason-2 satellites within the framework of a cooperation between CNES, EUMETSAT (*Organisation Européenne pour l'Exploitation des Satellites Météorologiques*), NASA and NOAA (*National Oceanic and Atmospheric Administration*), at the beginning of 2016 the Jason-3 mission was launched, which carried out a 6-month calibration period with the Jason-2 satellite [101].

SAR/Doppler *altimetry* differs from classical radar altimetry in that it treats the various groups of transmitted pulses in a coherent way. The *Doppler* bandwidth is entirely used to exploit, in the best possible way, the signal reflected by the target. The SENTINEL-3A and 3B satellites, dedicated to operational oceanography, launched in 2016 and 2018

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[102], respectively, as well as the Jason-CS/Sentinel-6A satellite, launched in 2016 [103], carry a *SAR/Dopple altimeter* reusing the technique tested on the Cryosat-2 satellite, launched in 2010, an optical imager in the visible and infrared channels, and a precise orbitographic system Doris [104].

An interferometric altimeter may include several altimeters mounted on arms, allowing several measurements to be obtained simultaneously which, single or combined, provide a wider and more continuous spatial coverage. The *WideSwath Ocean Altimer* (WSOA) interferometric altimeter was initially proposed to board the Jason-2 satellite, but this offer was abandoned: a new project embarked such a system aboard the SWOT (*Surface Water Ocean Topography*) mission, launched in December 2022 [105]. The SWOT mission brings together the needs of oceanographers and hydrologists in a single satellite, as it performs a complete mapping of ocean and continental surfaces, as well as water levels in lakes, wetlands and reservoirs [28], using the KaRIN (*Ka-band radar interferometer*) band, a technology called interferometric altimetry [106,107], with a revisit time of 21 days. The total imaged range for SSH (*Sea Surface Heights*) and continental water levels is 120 km wide [108]. In the oceans, the SSH is every 1 km2 and, in the continental domain, it has a horizontal resolution of 100 m for rivers and 250 m2 for lakes, wetlands and reservoirs, with an accuracy of 10 cm for water levels and 1.7 cm/km for slope [108].

CONCLUSION

In this work, the main applications of spatial altimetry for the monitoring of water resources and how these applications contribute to improve the hydrological knowledge of large river basins were addressed. It focused on SLA monitoring in rivers, floodplains, and wetlands, a key component for understanding the hydrologic cycle, surface hydrology, and water resources management, for which the impacts of current climate change on the hydrologic cycle remain uncertain.

Spatial altimetry is currently a remote sensing technique with several studies in continental waters, allowing the study of the hydrographic basin at all scales, from a single and small tributary, to the entire basin. The Amazon basin is probably the hydrographic basin with the most studies and applications with data from altimetric satellites. In fact, it has been the site where many advances in spatial altimetry in rivers, floodplains, and wetlands have been achieved over the past three decades. Today, time series extend for at least 20 years, in some favorable places, although most present a decade of data. However, many more series with larger time windows could be obtained if the raw data from previous altimetric missions were reprocessed with the various existing AFOs.

In the current decade, there has been a significant improvement in the vertical accuracy and spatial resolution of altimetric data with the launch of SWOT in December 2022, with an altimeter that ensures full coverage of water bodies twice every 21-day cycle, in addition to satellites with altimetric radar and SAR/Doppler altimeter. These changes in the spatial and temporal resolutions of data collection must be accompanied by changes in the way hydrological monitoring is carried out, making the most of this technique of SLA measurements in rivers, floodplains and wetlands, as a result of the development of the concept of EVs, which can be defined in places never monitored, expanding and complementing *in situ monitoring networks*.

Finally, the Amazon basin remains one of the very few river basins that has a monitoring network with a low density of stations in operation, particularly in small tributaries and wetlands that are monitored only by spatial altimetry. Therefore, it will still be, for a long time, the right place for applications of spatial altimetry to study the impacts of climate change on the hydrological cycle.

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