Satellite Altimetry for Hydrology – A review

Joecila Santos da Silva [1]
Stéphane Calmant [2]
Frédérique Seyler [3]

[1] Universidade do Estado do Amazonas – UEA
Centro de Estudos do Trópico Úmido – CESTU
Av. Djalma Batista 3578, Flores, 69050-010, Manaus-AM, Brasil
jsdsilva@uea.edu.br

[2] Institut de Recherche pour le Développement – IRD
UMR 5566 LEGOS (CNES/CNRS/IRD/UT3)
14 av. Edouard Belin, 31400, Toulouse, France
stephane.calmant@ird.fr

[3] Institut de Recherche pour le Développement – IRD
UMR 228 ESPACE-DEV (IRD,UM2,UR,UAG)
0,275 km Route de Montabo, BP 165 97323, Cayenne, Guyane Française
frederique.seyler@ird.fr

Abstract. Water is a critical natural resource upon which all social and economic activities and ecosystem functions depend. However, regular gauging networks fail to provide the information needed for spatial coverage and timely delivery. Although the space missions discussed here were not primarily dedicated to hydrology, 20 years of satellite altimetry have furnished complementary data that can be used to create hydrological products for river basin, such as time series of stages spread throughout the basins, estimated discharges of rivers, derive longitudinal altitude profiles of river bed, lowest and highest stages, or leveling of *in situ* stations. Raw data still suffer uncertainties of several decimeters. These require specific reprocessing such as waveform retracking or geophysical correction editing; much work still remains to be done. Inundated surfaces, and the time variations of their extent, are currently almost routinely computed using satellite imagery. Today, the altimetry techniques are evolving rapidly. One direction is the change of the radar band, from Ku to Ka. Other change is the replacement of today LR Mode to SAR or Interferometry modes. Both evolutions tend to diminish dramatically the ground footprint, reducing as much the contamination of the echo by the environment of the water body, and improving as much the vertical accuracy. Last, from 2015, the research class missions will be replaced by operational ones, making the long living of the sampling locations more certain. All the aforementioned technical evolutions will be grouped in the SWOT mission, a Ka band interferometric swath altimeter, the first satellite mission actually dedicated to provide full coverage of the continental waters, to be launched in the early 2020's. Besides its intrinsic improvement in the high resolution of height, slope and width of the reaches, SWOT will be an invaluable tool to put altogether in an inter-calibrated dataset all the nadir missions' part of the aforementioned constellation.

Palavras-chave: Satellite Altimetry, River Monitoring, Remote Sensing

1. Introduction

Level is one of the hydrological quantities that are considered routinely when evaluating societies' basic need for fresh waters. The monitoring of this variable is accomplished through nets of hydrometric stations organized at the national level. This monitoring requires that an extended net is maintained over very long time periods, with high cost of installation and maintenance (Alsdorf *et al*., 2001). The system of hydrological information HidroWeb, maintained by the National Water Agency (ANA) of Brazil contains numerous gauging stations. In spite of this huge hydrological network, the spatial resolution is limited and the update of the information can take 6 to 12 months. Besides, the Amazon basin is a transboundary basin. Consequently, Brazil cannot decide on the sampling scheme in the entire basin, in particular in the Andean parts of the basin that belong to other countries, whatever its need for the hydrological information. Remote sensors, embarked in satellites, provide an acceptable space and time resolution, providing a synoptic and multi-temporal vision of such extensive areas with complex seasonal variability, difficult access and, limited infrastructure (Florenzano, 2002). Satellite altimetry is already a robust technique in the oceanic domain. Altimetric satellites collect with a centimetric precision the instantaneous height of the oceanic surface. For 2 decades, several groups have worked to develop this technique for the continental waters (Birkett, 2002, Calmant and Seyler, 2006; Creteaux and Birkett ,2006; Asdorf et al., 2007, Calmant et al., 2008; Silva et al., 2012). This paper presents the major advantages and drawbacks of radar altimetric data used in hydrology today, either *in situ* or space borne.

2. Measurement Principles

Altimeters installed onboard various satellite missions emit a pulse towards the nadir and receive the echo reflected by the water surface level. The half time span for the pulse to be reflected back to the altimeter corresponds to the distance ρ run by the electromagnetic pulse between the satellite and the Earth's surface, assuming that the pulse is propagating at the speed of light. The satellite altitude a_s with respect to a reference ellipsoid is known accurately by orbitography modelling. Therefore, the height H of the reflector with respect to the geodetic reference is given at each pass of the satellite. Corrections relating to the delayed propagation through the atmosphere, the interaction with the ionosphere, and the solid Earth tides are taken into account:

$$H = a_s - \rho + C_{iono} + C_{dry} + C_{wst} + C_{st} + C_{pt} \quad (1)$$

where C_{iono} is the correction for delayed propagation through the ionosphere, C_{dry} and C_{wet} are corrections for delayed propagation in the atmosphere, accounting respectively for pressure and humidity variations, and C_{st} and C_{pt} are the corrections for crustal vertical motions, respectively, due to the solid and polar tides. Errors in all these corrections were not evaluated in this study. A full discussion of the derivation of altimetric heights and their associated errors can be found in Fu and Cazenave (2001).

3. Brief history of satellite altimetry applications to hydrology

GEOS3 was the first altimeter to be dedicated to ocean mapping, but yet, some authors sought to use these new sensors to land mapping and continental water monitoring. Miller (1979) shown that GEOS3 data could be used to monitor lakes water level. From these pioneer studies, three main applications have been drawn. A review of the application of radar altimetry to hydrology can be found in Calmant and Seyler (2006) and Calmant *et al*. (2008). We will only give here some salient points:

a) The first line of applications concerns water resource monitoring in relation with climate and agriculture. The studies in this line are numerous. We can cite Mason *et al*. (1985), Morris and Gill (1994), Birkett (1995), Ponchaut and Cazenave (1998), Birkett *et al*. (1999), Birkett (2000), de Oliveira Campos *et al*. (2001), Mercier *et al*. (2002), YI *et al*. (2012). Most of these studies were conducted over great lakes. A review of radar altimetry over lakes can be found in Creteaux and Birkett (2006). The first study on a river system was conducted by Koblinsky *et al*. (1993) from GEOSAT waveforms. They estimated to 70-cm rms the discrepancy between satellite and *in situ* measurements at four sites on the Amazon.

They attributed partly the uncertainties to the orbit determination, but partly to the *in situ* record, and we will comment that in the next paragraph. The altimetric data that have been most used in river studies have been those of T/P (10-day repeat period, between 1992 and 2002 (Birkett, 2002, Leon, 2006, Zhang, 2010). ENVISAT (following the ERS series started in 1991 with a 35-day repeat period) mission has been used afterward in many studies (Berry *et al*.,2005; Frappart *et al*. 2006; Silva *et al*. 2010 with a purpose of validation on rivers. Water level time series with decimeter accuracy were obtained for wetland in Silva (2010) and Silva *et al*. (2012).

b) The second great application of satellite altimetry for hydrology is coming from the fact that altimeters paths are crossing water bodies at all types of hydrological situations. Hydrologic networks *in situ* stations are located in narrow, straight sections of the river, as they are to be gauged from time to time, to estimate discharge and be able to relate river stage and discharge, in linear stage-discharge relationship known as rating curve. For this reason the status of wetlands water level is largely unknown globally. The first application of satellite altimetry for monitoring wetlands has been by Cudlip *et al*., (1992). But it is difficult to distinguish river and floodplain with T/P data. Birkett *et al*. (2002) have succeeded in a number of cases as a phase offset of a few days in stage variations between river and nearby floodplain has occasionally been observed. Frappart *et al*. (2005) have determined spatiotemporal variations of water volume over the main stream jointly with the floodplain in the Negro River basin, using area variation estimates for a seasonal cycle captured by the Synthetic Aperture Radar (SAR) onboard the Japanese Earth Resources Satellite (JERS-1), and changes in water level from the T/P altimetry at 88 altimetric stations, combined with 8 *in situ* liminigraphic stations. A volume variation of 331 km^3 was estimated for the whole Negro basin, enhancing the complex relationship between the volume potentially stored in the inundated area and the volume flow during the same period. Similarly, Frappart *et al*. (2006) monitored the flood propagation along the Mekong River by combining satellite altimetry data and SPOT4 vegetation imagery. Recently Frappart *et al*., (2008 and 2012) have used combined satellite imagery to re-estimate the volume of water stored in the inundation plains of the Negro basin and the over the Amazon basin with a better temporal resolution. The first study using ENVISAT data to examine the relationship between river and floodplain through the differences in water levels was conducted by Cauhope, (2004). On the same floodplain located in the Amazon basin, Bonnet *et al*. (2008) have modelled the transfer of water between river and floodplain partly based on altimetric water levels time series.

c) The third application is using the unique reference system of the altimetric data for studying the slope of the rivers and therefore be able to model the hydrodynamics. As for the other applications the pioneer works were conducted on the Amazon main stem with SEASAT data (Guskowska *et al*., 1990; Cudlip *et al*.,1992; Mertes *et al*., 1996 and Dunne *et al*. (1998) and T/P data (Birkett *et al*., 2002). With mixed T/P and ENVISAT data, Leon *et al*. (2006a and 2006b) and Getirana *et al*. (2009) with ENVISAT data have proposed different methodology to derive stream profiles from the river bed height and slope derived from altimetry, through the estimation of rating curves at the altimetric virtual stations. Some works have estimated discharge at altimetric stations using empirical regressions from *in situ* gauging stations (Coe and Birkett , 2004; Kouraev *et al*., 2004; Zakharova *et al*., 2006).

4. Drawbacks of current missions

The major drawbacks in using satellite altimetry for hydrology are often reported as being the precision of the measurements and the revisit time of the altimeters (10 days for T/P and Jason and 35 days for ERS/ENVISAT). We can add the lack of reliable data in case of steep relief close to the margin and before the river in the flight direction (Seyler *et al*., 2008). Also, Birkett *et al*., (2002) stated that for T/P, the river reach had to be larger than 1 km. Seyler *et al*., (2009), Silva *et al*., (2010) and Silva *et al*., (2012) have shown that the width of the river reach does not appear as a factor strongly affecting the quality of the series for all the missions. Using ENVISAT, seasonal fluctuation of river stage can be captured for wetlands and rivers as narrow as 50 m wide. (see example of Rio Pardo in Silva *et al*., 2010)

As for precision and revisit time, most of the studies attempting to validate altimetric data have used comparison with *in situ* data. Bercher *et al*. (2006) evaluated the amount of information lost due to the revisit time of the currently used radar altimeters under-sampling, compared with daily measurements at *in situ* stations. Roux *et al*. (2008) have proposed a methodology for reconstructing daily time series at the location of an altimetry track by combining its spectral information with that of gauges in the vicinity. The method is based on a linear model exploiting data at a limited number of *in situ* data. But for some hydrologic applications, as monitoring fast flood events, hourly or even more frequent measurements are needed. Nevertheless, basin wide daily *in situ* water stage measurements have never been questioned for most hydrological application, neither.

5. Future missions and improvements foreseen

Altimetry over rivers evolved rapidly during the past decade and will evolve even more in the coming years. As aforementioned, the quality of the time series improved significantly from ERS2 to ENVISAT in the one hand (Silva *et al*., 2010) and from T/P to J2 in the other hand (Seyler *et al*., 2012). An interesting point to be highlighted is the evolution in the capability of radar altimetry to sample narrow reaches (see introduction). All the existing missions were operating radar pulses in Ku band radar pulses in Low Resolution Mode (LRM). The two major evolutions to arrive in the coming years are the change from Ku to Ka band and the change from LR Mode to Synthetic Aperture Radar mode. In Ka band, the ground footprint is about ten times smaller than it is in Ku band. Consequently, the possible pollution of the radar echo from the ground environment of the water body to be monitored is reduced and “purer” echoes are expected, making the range evaluation from the two-way travel time of the pulse is more precise. Another advantage of the Ka band vs the Ku band is that the reduced interaction of the electromagnetic wave with the ionosphere. In Ku band, this interaction requires that the altimeter be dual-frequency. In Ka band, the altimeter can be lighter, single frequency. The first Ka band mission to be launched is the joint India-France mission AltiKa. It is scheduled to be launched in early 2013. It will re-use the same sun-synchronous orbit as ERS1, ERS2 and ENVISAT used, permitting the extension of the time series of water level interrupted by the orbit change of ENVISAT in 2010.

The LR mode was based on a low rate of emission of the pulse (typically ~2 kHz) in order that the echoes received are uncorrelated and can be added to significantly remove the random noise. Conversely, in SAR mode, a high rate of emission is performed (over 15 kHz) in order that the correlation between the echoes can be used to slice the footprint bouncing back the energy to the satellite antenna by differentiating the successive echoes, reducing the footprint to being a small band of a few hundreds of meter in the along track direction. This new technology has been successfully used in the Cryosat-2 satellite, launched in 2008. Given the difficulties encountered in the processing of this new types of measurements, few results are been published yet but pioneer study by Bercher *et al*. (2012) showed very promising capabilities. Yet, such a mission is mostly important by the demonstrating the performance of the technology, in order that operational satellites based on this knowledge be funded. Europe decided to launch a series of Earth Observation satellites in the frame of the GMES project.

Among these, the SENTINEL-3 satellites will embark Ku band SAR altimeters. Although these were not primarily dedicated to the continental waters, we know, owing to Cryosat-2, that these altimeters will also produces highly valuable measurements over the continental water bodies. Hopefully, in the light of the aforementioned Cryosat-2 results, the SAR mode of the SENTINEl-3 altimeters will be switched on over the continents. The first satellite of the SENTINEL-3 series, SENTINEL 3A should be launched in mid-2014. The second one should follow it 2 years later on an interleaved orbit. According to funds, these satellites should be followed by two other ones, respectively SENTINEL 3C and SENTINEL 3D to guarantee a 25 year duration of uninterrupted survey of the Earth Environment. Therefore uninterrupted series of water level at the crossings of their orbit with the river systems can be expected.

Similarly, the research class JASON-2 satellite, last satellite of the renowned NASA/CNES altimetric missions started in the 90's with TOPEX/Poseidon, will be followed by an operational version, JASON/CS, to be launched in 2017. As it is an operational mission, JASON/CS will no more be operated by the French CNES and US NASA space agencies but by the operational European EUMETSAT and US NOAA agencies. Taking advantage of the aforementioned technology advance, JASON/CS will not work in LR mode as JASON-2 does today but in SAR mode. Hopefully, it will fly the same orbit as JASON-2 does, enabling the highly expected continuity in the 10 day series at the crossing of this orbit ground track with the river reaches over most large basins of the world.

Taking all these evolutions together, one can say that at the end of the decade, 3 operational missions working in SAR mode should be flying together with one research mission in the Ka band and possibly a last one in LRM Ku band, JASON-3. Not to mention, a laser mission, ICESat-2 should also collect altimetric measurements over the rivers from 2016. With a 70 cm along-track resolution and expected 10 cm accuracy in the range determination, this mission will clearly provide additional high valuable measurements. The major limitation of this mission will be that it will fly a 91 day repeat orbit, with very little time sampling at a given place. However, as it has been shown by Bercher *et al*. (2012) with Cryosat which is flying a 369 day repeat orbit, such a sampling scheme can also be quite useful. First, the low time sampling is compensated by a high spatial sampling, ~10 km on the Madeira River for example. Yet, ICESat-1, which flew 7 years from 2003 to 2009, has been little used for studies in hydrology and most remains to be done to take the full advantage of the high quality measurements collected by the GLAS instrument born by ICESat.

At the very beginning of the 2020s, all the aforementioned missions will be over stridden by the SWOT mission. SWOT will be the first satellite mission actually dedicated to the measurement of river levels, among other goals. SWOT will embark KARIN, a wide swath Ka band interferometer. Owing to this instrument, SWOT will provide a full coverage of all the continental domain, but the polar most area of the Antarctic, since orbit inclination should be around 78°. Orbit repeat period is planned at 22 days. These characteristics mean that SWOT will sample the stage, slope and width of all the river reaches wider than 100m, twice every 22 days. The expected vertical accuracy should be at the centrimetric level at the km^2 scale of river surface. Intrinsically, this mission will clearly bring a complete revolution in the way the hydrology data are collected since it will be close to some continuous spatial monitoring, well far from the today very sparse gauge networks in most of the great basins of the world. But, it must be considered also as a companion of the aforementioned constellation of nadir satellites. With respect to this constellation, SWOT will bring temporal densification of their long living series since it will sample all the ground tracks at each cycle, it will be a powerful inter-calibration tool since it will make consistent measurements in the series of the various missions, and it will be a unique tool to tune the hydrological/hydrodynamical models between the locations of the gauges, when exist, and the nadir constellations crossings with the river network.

6. Conclusion

Satellite altimetry is now a mature technique over large rivers. Within the current decade, it will evolve towards a dramatic improvement in vertical accuracy and target resolution. In the early 2020, with the launch of SWOT, we should have a swath altimeter insuring full coverage of the water bodies twice every 22-day cycle, besides the pre-existing constellation of 2 to 5 nadir pointing satellites. These changes in the spatial and temporal rates of data collection must be accompanied with changes in the way we think river monitoring if we want to fully take advantage of this new way of collecting height measurements over rivers.

Acknowledgements

The authors thank the students of the UEA (Universidade do Estado do Amazonas, Brazil) involved in the Research Initiation Program of the RHASA Research Team, who processed the satellite altimetry data. Their work is part of the CASAM, IHESA, DS BIODIVA and CLIVAR projects, respectively funded by CNPq, FINEP and by FAPEAM. CPRM and IRD participated to funding the study in the frame of the Project *Hidrodinâmica Fluvial*, and CNES participated with the project *TOSCA/FOAM*.

References

ALSDORF, D.E., BIRKETT, C.M., DUNNE, T., MELACK, J., HESS, L., 2001, Water level changes in a large Amazon lake measured with spaceborne radar interferometry and altimetry, ***Geophysical Research Letters***, 28(14):2671-2674. doi: 0094-8276/01/2001GL012962

ALSDORF, D.E., RODRIGUEZ, E., LETTENMAIER, D.P., 2007, Measuring surface water from space. ***Reviews of Geophysics***, 45(2), RG2002, doi:10.1029/2006RG000197

BERCHER, N., KOSUTH, P., BRUNIQUEL, J., 2006, Quality of river water level time series issued from satellite radar altimetry: influence of river hydrology and satellite measurement accuracy & frequency. ***Presented at EGU, General Assembly 2006 Vienna***, AUT, 02-07 April 2006.

BERCHER, N., CALMANT, S., PICOT, N., SEYLER, F., SANTOS da SILVA, J., FLEURY, S., 2012, In symposium "20 years of progress in radar altimetry", 24-29 september, Venise, Italy.

BERRY, P.A.M., GARLICK, J.D., FREEMAN, J.A., MATHERS, E.L., 2005, Global inland water monitoring from multi-mission altimetry. ***Geophysical Research Letters***, 32, L16401, doi:10.1029/2005GL022814

BIRKETT, C.M., 1995, The contribution of TOPEX/POSEIDON to the global monitoring of climatically sensitive lakes. ***J. Geophys. Res***., 100 (C12), 25, 179–25,204.

BIRKETT, C.M. and MASON, I.M., 1995. A new Global Lakes Database for a remote sensing programme studying climatically sensitive large lakes. ***J. Great Lakes Research***, 21 (3), 307–318.

BIRKETT, C.M., MURTUGUDDE, R., ALLAN, T., 1999, Indian Ocean climate event brings floods to East Africa's lakes and the Sudd Marsh, ***Geophys. Res. Lett***. 26 1031–1034.

BIRKETT, C. M., 2000, Synergistic Remote Sensing of Lake Chad: variability of Basin inundation, ***Remote Sens. of Environ***., 72, 218-236.

BONNET, M.P, BARROUX, G., MARTINEZ, J.M., SEYLER, F., MOREIRA-TURCQ, P., COCHONNEAU, G., MELACK, J.M., BOAVENTURA, G. MAURICE-BOURGOIN, L., LEÓN, J.G., ROUX, E., CALMANT, S., KOSUTH, P., GUYOT, J.L., SEYLER, P., 2008, Floodplain hydrology in an Amazon floodplain lake (Lago Grande de Curuaí), ***Journal of Hydrology***, 349 (1- 2): 18-30.

CALMANT, S. and SEYLER, F., 2006, Continental surface water from satellite altimetry, ***Comptes Rendus Geosciences***, 338(14-15):1113-1122. doi: 10.1029/2001JD000609

CALMANT, S., SEYLER, F., CRETAUX, J-F., 2008, Monitoring Continental Surface Waters by Satellite Altimetry, ***Survey in Geophysics***, 29(4-5):1573-0956. doi: 10.1007/10712-008-9051-1

CALMANT, S., SILVA, J, MEDEIROS MOREIRA, D. SEYLER,, F. SHUM, CK.CRETAUX, J-F.,GABALDA, G.,2012. Detection of Envisat RA2 / ICE-1 retracked Radar Altimetry Bias

Over the Amazon Basin Rivers using GPS, ***Advances in Space Research***, doi: 10.1016/j.asr.2012.07.033CAUHOPÉ, M., 2004, ***Hauteurs d'eau d'une plaine d'inondation amazonienne par altimétrie spatiale***, rapport de stage de DEA 'Sciences de la Terre et l'Environnement', 30 p., in French).

COE, M.T., BIRKETT, C.M., 2004, Calculation of river discharge and prediction of lake height from satellite radar altimetry: Example for the Lake Chad basin. ***Water Resources Research,*** 40: W10205, doi:10.1029/2003WR002543.

CRÉTAUX, J. F., BIRKETT, C., 2006, Lake studies from satellite radar altimetry. ***Comptes Rendus Geoscience***. 338(14-15):1098-1112. doi: 10.1016/j.crte.2006.08.002

CUDLIP, W., RIDLEY, J.K., RAPLEY, C.G., 1992, The use of satellite radar altimetry for monitoring wetlands, in: ***Remote Sensing and Global Change, Proc. 16th Annu. Conf. Remote Sensing Society***, London, pp. 207–216.

DE OLIVEIRA CAMPOS, I., MERCIER, F., MAHEU, C., COCHONNEAU, G., KOSUTH, P., BLITZKOW, D., CAZENAVE, A., 2001, Temporal variations of river basin waters from Topex/Poseidon satellite altimetry. Application to the Amazon Basin, ***C. R. Acad. Sci. Paris***, Ser.IIa 333 (2001) 633–643.

DUNNE, T., MERTES, L.A.K., MEADE, R.H., RICHEY, J.E., FORSBERG, B.R., 1998, Exchanges of sediment between the floodplain and channel of the Amazon river in Brazil, ***GSA Bull***., 110(4), 450-467.

FLORENZANO, T.G., 2002, ***Imagens de Satélite para Estudos Ambientais,*** São Paulo: Oficina de Textos.

FRAPPART F., SEYLER, F., MARTINEZ J.-M., LEÓN J. G. AND CAZENAVE A., 2005, Floodplain Water Storage in the Negro River Basin Estimated from Microwave Remote Sensing of Inundation Area and Water Levels. ***Remote Sensing of Environment***, 99: 387 – 399.

FRAPPART, F., CALMANT, S., CAUHOPE, M., SEYLER, F. AND CAZENAVE, A., 2006, Preliminary results of envisat ra-2-derived water levels validation over the amazon basin. ***Remote Sensing of Environment***, 100 (2): 252-264.

FRAPPART, F., PAPA, F., FAMIGLIETTI, J.S., PRIGENT, C., ROSSOW, W.B., SEYLER, F., 2008, Interannual variations of river water storage from a multiple satellite approach: A case study for the Rio Negro River basin, ***J. Geophys. Res***., 113, D21104, doi:10.1029/2007JD009438.

FRAPPART, F., PAPA, F., SILVA, J.S., GUILLAUME RAMILLIEN, G., PRIGENT, C., SEYLER, F., CALMANT, S., 2012, Surface freshwater storage and dynamics in the Amazon basin during the 2005 exceptional drought, ***Environ. Res. Lett., 7:*** 044010, doi:10.1088/1748-9326/7/4/044010

FU, L., CAZENAVE, A., 2001, ***Satellite altimetry and earth sciences: a handbook of techniques and applications***. Academic Press, London (UK), 464 p.

GETIRANA, A.C.V., BONNET, M.-P., CALMANT, S., ROUX, E., ROTUNNO FILHO, O.C., MANSUR, W.J., 2009, Hydrological monitoring of poorly gauged basins based on rainfall-runoff modeling and spatial altimetry, ***Journal of Hydrology***, 379, 205-219, doi:10.1016/j.jhydrol.2009.09.049.

HALL, A., SCHUMANN, G J-P, BAMBER J.L., BATES, P., TRIGG, M. A., 2012, geodetic corrections to Amazon River water level gauges using ICESat altimetry, Water Resources Res, 48, W06602, doi:10.1029/2011WR010895.

GUZKOWSKA, M.A.J., RAPLEY, C.G., RIDDLEY, J. K., CUDLIP, W., BIRKETT, C.M., SCOTT, R.F., 1990, Developments in inland water and land altimetry. ***ESA contract report 78391881FIFL***.

KOBLINSKY, C.J., CLARKE, R.T., BRENNER, A.C., FREY, H., 1993, Measurements of river level variations with satellite altimetry, ***Water Resour. Res.,*** 29 (6) 1839–1848.

KOURAEV, A., ZAKHAROVA, E., SAMAIN, O., MOGNARD, N., CAZENAVE, A. 2004, Ob' river discharge from TOPEX/Poseidon satellite altimetry (1992–2002), ***Remote Sensing of Environment***, 93, 238– 245.

LEON J.G., CALMANT S, SEYLER, F., BONNET M.P., CAUHOPÉ M., 2006a, Rating curves and average water depth estimation at the upper Rio Negro from altimetric spatial data and calculated remote discharges. ***Journal of Hydrology***, 328, 481-496.

LEON J.G., SEYLER, F., CALMANT S., BONNET M., CAUHOPE M., 2006b, Hydrological parameter estimation for ungauged basin based on satellite altimeter data and discharge modeling. A simulation for the Caqueta River (Amazonian Basin, Colombia). ***Hydrology and Earth System Sciences***. SRef-ID: 1812-2116/hessd/2006-3-3023

MASON, I.M., RAPLEY, C.G., STREET-PERROTT, F.A., GUZKOWSKA, M., 1985, ERS-1 observations of lakes for climate research, in: ***Proc. EARSeL/ESA Symposium 'European Remote Sensing Opportunities'***, Strasbourg, France, 31 March–3 April 1985.

MERCIER, F., CAZENAVE, A., MAHEU, C., 2002, Interannual lake level fluctuations (1993–1999) in Africa from TOPEX/Poseidon: Connections with ocean–atmosphere interactions over the Indian ocean, ***Global Planet. Changes,*** 32 (2002) 141–163.

MERTES, L.A.K., DUNNE, T., MARTINELLI, L.A., 1996, Channel-floodplain geomorphology along the Solimões-Amazon river, Brazil, ***GSA Bull***., 108(9), 1089-1107.

MILLER, L.S., 1979, Topographic and backscatter characteristics of GEOS 3 overland data, ***J. Geophys. Res***. 84 (B8), 4045–4054.

MORRIS, C.S., GILL, S.K., 1994, Variation of Great Lakes waters from Geosat altimetry, ***Water Resour. Res***. 30, 1009–1017.

M. ZHANG, M., LEE, H., SHUM, CK, SCHWARTZ, F., ALSDORF, D., TSENG, S.,, YI, Y, CHUNG-YEN , K., TSENG H-Z, BRAUN, A., CALMANT, S., FILIZOLA, N., and SEYLER, F. 2010. Application of Retracked Satellite Altimetry for Hydraulic Studies; ***Int. J. Of Remote Sensing***,31-14, 3913-3929, doi : 10.1080/01431161.2010.483495

PONCHAUT, F., CAZENAVE, A., 1998, Continental lake level variations from TOPEX/Poseidon (1993–1996), C. R. ***Acad. Sci. Paris***, Ser.IIa 326 13–20.

ROUX, E., CAUHOPÉ, M., BONNET, M.-P., CALMANT, S., VAUCHEL, P. and SEYLER, F., 2008, Daily water stage estimated from satellite altimetric data for large river basin monitoring. ***Hydrological Sciences Journal***, 53: 81–99.

SEYLER, F., CALMANT, S., SILVA, J.S., FILIZOLA, N., ROUX, E., COCHONNEAU, G., VAUCHEL, P., BONNET,M-P., 2008, Monitoring water level in large trans-boundary ungauged basins with altimetry: the example of ENVISAT over the Amazon basin**. *Journal of Applied Remote Sensing,*** 7150, 715017, doi:10.1117/12.813258.

SEYLER, F., CALMANT, S., SANTOS DA SILVA, J., FILIZOLA, N., COCHONNEAU, G., BONNET, M.-P. and ZOPPAS COSTI, A.C., 2009, Inundation risk in large tropical basins and potential survey from radar altimetry: example in the Amazon basin. ***Marine Geodesy,*** 32: 303–319.

SEYLER, F., CALMANT, S., SANTOS da SILVA, J., MEDEIROS MOREIRA, D., MERCIER, F., SHUM, CK, from TOPEX/Poseidon to JASOn-2/OSTM in the Amazon basin, 2012. ***Advances in Space Research***, doi: 10.1016/j.asr.2012.11.002

SILVA, J.S., 2010, ***Altimetria Espacial em Zonas Úmidas da Bacia Amazônica - Aplicações Hidrologicas***. Saarbrücken (GE), Édition Universitaires Européennes. ISBN: 978-613-1-52979-5

SILVA, J.S., CALMANT, S., ROTUNO FILHO, O.C., SEYLER, F., COCHONNEAU, G., ROUX, E., MANSOUR, J.W., 2010, Water Levels in the Amazon Basin derived from the ERS-2 and Envisat Radar Altimetry Missions, ***Remote Sensing of Environment***, 114, 2160-2181, doi:10.1016/j.rse.2010.04.020,.

SILVA, J.S., ROTUNO FILHO, O.C., SEYLER, F., CALMANT, S., ROUX, E., ARAUJO, A. M., GUYOT, J-L., 2012, Water level dynamics of Amazon wetlands at the Watershed Scale by satellite altimetry, ***International Journal of Remote Sensing***, 33(11), 3323-3353, doi:10.1080/01431161.2010.531914

YI, Y, KOURAEV, A. V., SHUM, CK., VUGLINSKY, V. S., CRETAUX, J-F., CALMANT, S., 2012, Performance of altimeter waveform retrackers in Lake Baikal, *Terr. Atmos. Ocean Sci.*, in press.

ZAKHAROVA, E.A, KOURAEV, A.V, CAZENAVE, A, SEYLER, F., 2006. Amazon River discharge estimated from TOPEX/Poseidon altimetry. ***Geosciences Comptes Rendus (French Academy of sciences)***. 338 (3): 188-196.