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CryoSat-2 altimetry for river level monitoring — Evaluation in the Ganges–Brahmaputra River basin

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ABSTRACT

The performance of CryoSat-2/SIRAL altimetry for river level monitoring is investigated by using river levels retrieved from Ganges and Brahmaputra. A key concern for the CryoSat-2 orbit has been its long repeat period of 369 days, which is usually undesirable for river and lake monitoring. However, the results from the method developed in this study involving virtual stations show that the CryoSat-2 data can indeed be used for such monitoring by utilizing the high spatial coverage and the sub-cycle period of 30 days. The results show that it is possible to capture the peak flow occurring during late summer due to monsoonal precipitation and the melting of snow in the Himalayas. The evaluation of CryoSat-2 river levels is performed by comparing with Envisat data in terms of annual signals and amplitudes. The obtained annual amplitudes agree well with the Envisat data, although CryoSat-2 exhibit larger differences. For five virtual stations in the Brahmaputra River, the mean difference between the obtained amplitudes is ~10 cm, whereas the mean phase difference is less than 2.7 days. A virtual station in the Ganges River shows a phase difference of around 5 days and a difference in amplitude of 2 cm.

1. Introduction

Satellite radar altimetry was mainly developed with the purpose of monitoring the oceans, but is now also used for monitoring other surfaces such as inland water. Fresh water is a very valuable resource, and a lot of effort is going into monitoring of lakes and rivers to get accurate estimates of the available water resources. Obtaining in-situ data can be difficult due to lack of infrastructure, inaccessibility of remote rivers and lakes, and undisclosed data, especially in a transboundary context. Satellite altimetry can be used to improve hydrological models by either complementing existing in-situ data or by offering elevation estimates in un-gauged rivers and lakes while staying within the same height reference system.

In one of the first studies on the potential of radar altimetry over rivers (Koblinsky, Clarke, Brenner, & Frey, 1993), the study focused on the Amazon Basin using Geosat-derived elevation estimates, which were found to have a root-mean-square error (RMSE) of 70 cm relative to in-situ measurements. Birkett (1998) showed that the NASA radar altimeter carried by the TOPEX/Poseidon satellite was able to track rivers and wetlands with widths >1 km with a RMSE sometimes as low as ~11 cm. A more recent study by Berry, Garlick, Freeman, and Mathers (2005) demonstrated the value of satellite radar altimetry in the field of measuring and monitoring land hydrology using multi-mission altimetry data over the Amazon Basin. In general, satellite altimetry has been accepted as an important provider of global inland water heights with a unique monitoring capability (Berry, 2006).

The usefulness of satellite radar altimetry data both in near real-time and long-term applications has been demonstrated in several studies, with purposes such as discharge modelling and flood warning (Biancamaria, Hossain, & Lettenmaier, 2011; Michailovsky, Milzow, & Bauer-Gottwein, 2013; Neal et al., 2009). In addition to the scientific and practical advantages, satellite altimetry also provides a way of overcoming the difficulty of transboundary river management, which is often hindered by local governments considering their hydrological measurements as sensitive.

Several projects already provide historical inland water levels from altimetry through web databases, such as the ESA River&Lake project (http://earth.esa.int/riverandlake, Berry et al., 2005), the Global Reservoir and Lake Monitor (http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/, Birkett, Reynolds, Beckley, & Doorn, 2011) and the HYDROWEB database (http://www.LEGOS.obs-mip.fr/soa/hydrologie/HYDROWEB, Crétaux et al., 2011). However, none of these data archives have included CryoSat-2 data.

In this study the potential of CryoSat-2 for river level monitoring is evaluated by comparing the annual signals obtained from CryoSat-2 and Envisat. CryoSat-2 offers altimetry in three modes, particularly the SAR mode reducing the along track resolution to 300 m is very interesting for hydrology, but it has a very special orbit. Envisat has a repeat orbit period of 35 days, whereas the repeat orbit of CryoSat-2 is 369 days with sub-cycles of 30 days. Usually, a shorter repeat period, such as that for Envisat, is preferred by hydrologists in order to

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obtain time series that are easily comparable to river gauge data and readily applicable to river modelling. However, with this study we want to show that CryoSat-2 river retrievals can be just as valuable for hydrologist, even if not sampled from a repeat orbit, by applying only few adjustments.

2. The Ganges–Brahmaputra River basin

For this study the Ganges and Brahmaputra Rivers were chosen due to their decent sizes, which act as a good base for conducting an initial validation of CryoSat-2 altimetry data. Choosing this river basin also has the benefit that the area is covered by all three CryoSat-2 SIRAL modes (LRM, SAR and SARIn; see Section 3.1) making an intercomparison possible. The Ganges and Brahmaputra Rivers constitute one of the largest river basins in the world, and is home to around 600 million people across five Asian countries: India, Bangladesh, Nepal, China and Bhutan, which makes exchange of river gauge information complicated. The drainage basin includes some of the highest mountains in the world, the Himalayas, and is plagued by floods and droughts as well as sedimentation in the rivers and flood plains due to erosion of the steep topography surrounding the river (Babel & Wahid, 2011). The high rate of erosion and subsequent deposition of sediments in the river basin leads to constant changes in channel pattern and shifting of bank lines (Sarkar, 2012). The Ganges–Brahmaputra delta is one of the most densely populated areas in the world, and the people living here depend heavily on the state of the rivers and their tributaries. 89% of the extracted water is used for agricultural purposes, corresponding to an annual demand of around 230 billion m^3 (Babel & Wahid, 2011). The strong seasonal signal caused by the summer monsoon and the melting of glaciers in the Himalayas gives rise to flooding from June to October, which is followed by a much drier period in the winter months.

3. Data sets

3.1. CryoSat-2

CryoSat-2 was launched by the European Space Agency (ESA) on the 8th of April 2010 to monitor variations in the cryosphere, i.e. the marine ice cover and continental ice sheets. The primary payload on-board CryoSat-2 is the altimeter, SIRAL (SAR Interferometric Radar Altimeter), which is a state of the art altimeter working in three different measurement modes depending on a geographical mode mask (Wingham et al., 2006). Besides the conventional low resolution mode CryoSat-2 operates in high resolution modes which are very valuable for hydrology. The three modes are:

LRM: Over the oceans and ice sheet interiors, CryoSat-2 operates like a conventional radar altimeter in Low Resolution Mode (LRM).

SAR: Designed for observing sea ice with an increased resolution and precision, coherently transmitted echoes are focused via Synthetic Aperture Radar (SAR) processing (also known as Delay–Doppler processing), to reduce the along-track surface footprint to 300 m. It can also be used more successfully over difficult surfaces such as coastal zone and inland water.

SARIn: The most advanced mode of SIRAL is used in areas with high surface slopes, and is as such used mostly over mountainous regions and the margins of the ice sheets. Here, the altimeter performs synthetic aperture processing along-track, has an extended range sampling window, and uses a second antenna as an interferometer to determine the across-track angle to the earliest radar returns with the interferometry technique.

Since the launch of CryoSat-2 the mode mask have changed several times over the river basins. The previous as well as the current mode masks can be seen in Fig. 1. The current mode mask was implemented in October 2012 and introduced a region where the altimeter operates in SAR mode instead of LRM mode along the coast of Bangladesh.

All data were taken from the ESA baseline-b L1b 20 Hz data product. The waveforms retrieved from CryoSat-2 since July 2010 over the chosen region were retracked using a primary peak threshold retracker (Bao, Lu, & Wang, 2009; Fenoglio-Marc et al., 2010; Jain, Andersen, Dall, & Stenseng, 2015; Vignudelli, Kostianoy, Cipollini, & Benveniste, 2011), which was found to give the most stable results over land and inland water. The retracker first identifies the leading and trailing edge of the primary peak, and then uses the OCOG method (Wingham, Rapley, & Griffiths, 1986) around the start and end gates to compute the amplitude of the extracted sub-waveform. For the retracking a threshold of 80% for SAR and SARIn waveforms and 31% for LRM waveforms was used. These threshold levels were chosen in order to obtain continuity in the retracked heights above inland water when the altimeter switches from one mode to another.

For SARIn data the range error due to off-nadir ranging was determined according to Armitage and Davidson (2014). Furthermore, the phase difference waveforms were used to determine the off-nadir coordinates corresponding to the retracked waveform bins.

Hence, since no available in-situ measurements were found to coincide with the CryoSat-2 mission, Envisat data were chosen as the basis for our evaluation.

3.2. Envisat

Previous studies using Envisat data over large rivers have shown that the altimetric data is a powerful tool for obtaining river levels for hydrological purposes (da Silva et al., 2010; Frappart, Calmant, Cauhopé, Seyler, & Cazenave, 2006; Michailovsky, McEnnis, Berry, Smith, & Bauer-Gottwein, 2012; Papa, Durand, Rossow, Rahman, & Bala, 2010).

Envisat was launched in 2002 by ESA with a conventional LRM radar altimeter, RA-2, which delivered altimetry data until April 8th 2012 when all contact with the satellite was lost. Envisat had a 35-day repeat period from 82.48°N to 82.48°S until October 2010. In November 2010 the so-called “Envisat extension orbit” was implemented, which introduced a minor drift in the orbit and a new repeat cycle of 30 days. The Envisat data used for this study was processed using the ICE-1 retracker. The ICE-1 retracker has previously been found to be the Envisat retracker that compares best to in situ measurements over inland water (Cheng et al., 2009; da Silva et al., 2010; Frappart et al., 2006).

3.3. Water mask

The MODIS (or Moderate Resolution Imaging Spectroradiometer) land-water mask was used to identify water. MOD44W is an improvement of the previous MODIS Nadir Bidirectional Reflectance Distribution Function (BRDF)-Adjusted Reflectance (NBAR) and MODIS land cover-based global land-water mask (Salomon et al., 2004). The binary

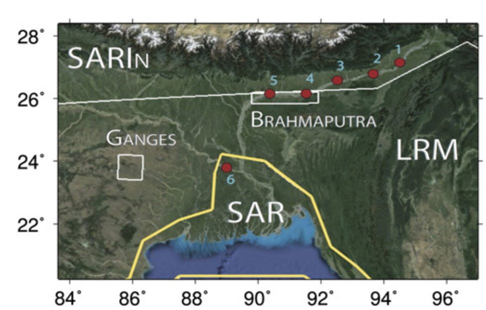

Fig. 1. Original CryoSat-2 mode mask (white polygons) and the SAR mask which was implemented in October 2012 (yellow). The red markers indicate the locations of the virtual stations (VS1–VS6).