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Evaluation of multi-mode CryoSat-2 altimetry data over the Po River against in situ data and a hydrodynamic model

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ABSTRACT

Coverage of in situ observations to monitor surface waters is insufficient on the global scale, and decreasing across the globe. Satellite altimetry has become an increasingly important monitoring technology for continental surface waters. The ESA CryoSat-2 altimetry mission, launched in 2010, has two novel features. (i) The radar altimeter instrument on board of CryoSat-2 is operated in three modes; two of them reduce the altimeter footprint by using Delay-Doppler processing. (ii) CryoSat-2 is placed on a distinct orbit with a repeat cycle of 369 days, leading to a drifting ground track pattern. The drifting ground track pattern challenges many common methods of processing satellite altimetry data over rivers. This study evaluates the observation error of CryoSat-2 water level observations over the Po River, Italy, against in situ observations. The average RMSE between CryoSat-2 and in situ observations was found to be 0.38 meters. CryoSat-2 was also shown to be useful for channel roughness calibration in a hydrodynamic model of the Po River. The small across-track distance of CryoSat-2 means that observations are distributed almost continuously along the river. This allowed resolving channel roughness with higher spatial resolution than possible with in situ or virtual station altimetry data. Despite the Po River being extensively monitored, CryoSat-2 still provides added value thanks to its unique spatio-temporal sampling pattern.

1. Introduction and background

Satellite altimetry, initially developed to monitor ocean water levels, also observes water levels of rivers and lakes. It plays an important role in monitoring changes in continental water levels, a crucial parameter to determine surface storage changes, estimating river discharge, deriving hydraulic and hydrologic parameters of poorly gauged river basins, and monitoring climate change impacts on surface waters (Alsdorf et al., 2007). Such remote sensing observations of water level are needed to complement or replace in situ observations, as their coverage on the global scale is insufficient to solve current water resources management challenges, and their availability is decreasing across the globe (Calmant and Seyler, 2006; World Water Assessment Programme, 2009). Increased availability of satellite data thanks to a continuous addition of new altimetry missions, and new methods to combine the altimetry data with hydrologic models have resulted in increased use and significance of the satellite radar altimetry datastream (Berry and Benveniste, 2010; Calmant et al., 2009). These missions have global coverage and deliver point observations along their ground tracks. However, factors such as rugged terrain or the size of the water bodies limit data availability or increase observation error. Currently, a river width of around 200 m has to be considered the minimum to obtain water level observation from satellite altimeters (Biancamaria et al., 2017; Maillard et al., 2015). Common observation errors are in the range of a few centimeters over lakes and a few decimeters over rivers (O'Loughlin et al., 2016; Villadsen et al., 2016).

The ESA satellite altimetry mission CryoSat-2 (European Space Agency and Mullard Space Science Laboratory, 2012) has a distinctive long-repeat ground track pattern. Its primary target is to observe sea ice and continental ice sheets. When used for monitoring of inland water bodies, especially rivers, the particular orbit configuration challenges common ways of processing and using satellite altimetry data: previous satellite altimeters have been on orbits with repeat cycles from 10 to 35 days. This allows to derive time series of water levels at locations where the satellite ground track intersects with the river, the so called virtual stations, with a temporal resolution equal to the orbit repeat period

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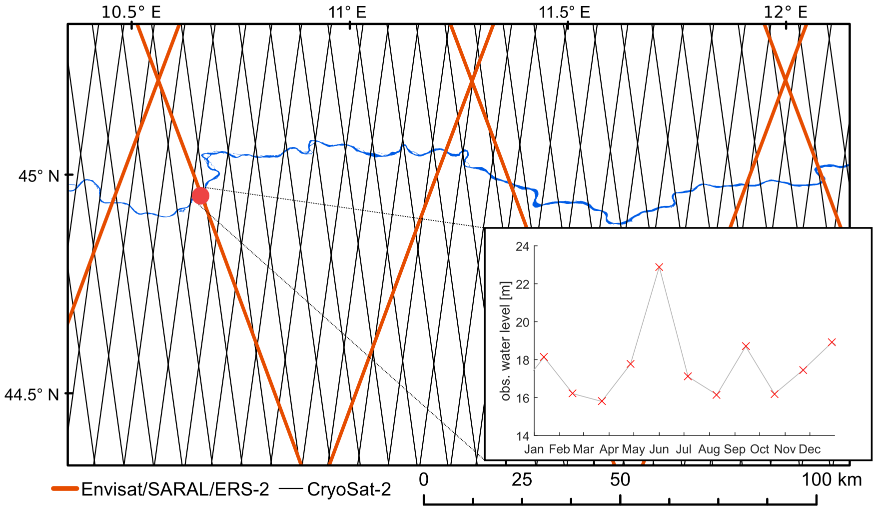

Fig. 1. Comparison of ground tracks over the Po River. Envisat, SARAL, and ERS-2 have identical ground tracks with an equatorial track spacing of 80 km and a repeat cycle of 35 days; they are displayed as an example for short repeat missions. An example virtual station is marked as a dot; with the respective time series of observed water levels in 2008 (data from DAHITI; Schwatke et al., 2015). Due to its orbit configuration, no virtual station time series can be extracted from CryoSat-2.

(Calmant et al., 2016). One example virtual station and its time series of observed water levels over the Po River are displayed in Fig. 1. The orbit repeat period also determines the across-track distance, which conventionally is 80 km to 300 km at the equator. See Jiang et al. (2017) or Calmant et al. (2016) for an overview of past and current satellite altimetry missions. The latter also provides an introduction into technical details of radar satellite altimetry over inland waters.

CryoSat-2, however, has an orbit with a full repeat cycle of 369 days, resulting in a so-called drifting ground track. This has two major consequences for the spatio-temporal sampling pattern: (i) time series of water levels at the same point have insufficient temporal resolution, but (ii) CryoSat-2 offers a very dense spatial sampling pattern with an across-track distance of only 7.5 km at the equator (Wingham et al., 2006). Because of (i) it is not straightforward to construct time series and remove outliers from CryoSat-2 data. As a consequence of (ii), continuous river masks are needed to extract relevant observations over water surfaces. For these reasons, application of CryoSat-2 altimetry over rivers is still limited (Jiang et al., 2017) In addition, no data from CryoSat-2 are yet included in inland altimetry databases such as DAHITI (http://dahiti.dgfi.tum.de/en/), HydroWeb (http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/) and HydroSat (http://hydrosat.gis.uni-stuttgart.de/php/index.php). Only CryoSat-2 data over lakes is readily available, for example provided by AltWater (http://altwater.dtu.space/). However, (ii) also can be seen as one of the main advantages of CryoSat-2, as it provides data with higher spatial resolution than conventional missions on short repeat orbits.

Besides the special orbit configuration, CryoSat-2 also carries a new type of radar altimeter, named Synthetic Aperture Interferometric Radar Altimeter (SIRAL) (Wingham et al., 2006). It is a Ku-band radar and is operated in three distinct modes: in low resolution mode (LRM) it operates like a conventional radar altimeter (e.g. RA-2 on Envisat) with a circular footprint with a diameter of 1.65 km on a smooth surface (European Space Agency and Mullard Space Science Laboratory, 2012). In Synthetic Aperture Radar (SAR) mode, the along-track footprint is reduced to 300 m via Delay-Doppler processing. Finally, the Synthetic Aperture Radar Interferometry (SARIn) mode applies SAR mode processing alongside the use of a second antenna to determine the across-track angle of the main radar return. A geographical mode mask (available at https://earth.esa.int/web/guest/-/geographical-mode-mask-7107) determines where on the globe which mode is used. SARIn mode is mainly used over mountainous regions and margins of ice sheets, SAR mode in many coastal regions, and LRM mode everywhere else.

CryoSat-2 has been validated over lakes (Göttl et al., 2016; Nielsen et al., 2015), but so far only some attempts have been reported to evaluate its accuracy over rivers. For example, Villadsen et al. (2015) compared CryoSat-2 observations over the Ganges and Brahmaputra Rivers against virtual station altimetry data from Envisat. Tourian et al. (2016) used a quantile-based approach to transfer distributed satellite altimetry observations to specified stations (in situ stations). Their method, however, is best suited for virtual station data. Villadsen et al. (2016) evaluated CryoSat-2 accuracy over Lake Vänern, Lake Okeechobee, and over a single in situ station in the Amazon River with daily water level data. Also Bercher et al. (2013) evaluated CryoSat-2 observations over a tributary of the Amazon River against data from a single in situ station. Over these river stations, CryoSat-2 was found to perform similarly to previous missions, with errors in the range of a few decimeters.

CryoSat-2 altimetry is potentially very useful: due to its small across-track distance, practically continuous river water level profiles can be derived. This can normally not be achieved using any other altimetry missions and was exploited to calibrate cross section shapes in a model of the ungauged Brahmaputra River (Schneider et al., 2017). Before that, O'Loughlin et al. (2013) performed a hydraulic characterization of the ungauged Congo River, using water level data from the lidar altimeter ICESat (Schutz et al., 2005). ICESat has an orbit configuration in between all the short repeat missions and the drifting ground track CryoSat-2; hence, it does not provide water level profiles as dense as from CryoSat-2. The usefulness of remotely sensed water level profiles is also acknowledged by Garambois et al. (2016): for a river flowing more or less along the satellite ground track, also repeat orbit missions can observe river water level profiles. They exploit this effect over a tributary of the Amazon River, using Envisat data, and derive different hydraulic information of the river.

In this context, the present study aims to investigate the potential of the Cryosat-2 over rivers, and, specifically, the capabilities of the three operational modes of the SIRAL instrument. For a comprehensive evaluation of the performance, the Po River in Italy is used as a case study because:

i. it is covered by all three modes of CryoSat-2;
ii. it is a relatively narrow river, allowing transferability of the results to many rivers globally;
iii. it has a dense network of in situ gauging stations with high temporal resolution and reliable height reference, allowing evaluation of absolute water levels (and not just water level amplitudes or similar as done in previous studies).

Besides this, we used a hydrodynamic model currently employed in the flood forecasting system by the Interregional Agency for the Po River (AIPo), based on surveyed cross sections. The unique drifting