

Assimilation of satellite altimetry data in hydrological models for improved inland surface water information:

Case studies from the "Sentinel-3 Hydrologic Altimetry Processor prototypE" project (SHAPE)"

David Gustafsson(1), Berit Arheimer(1), Pierre Fabry(2), Nicolas Bercher(2), Mònica Roca(3), Bernat Martinez(3), Joana Fernandes(4), Clara Lázaro(4), Américo Ambrózio(5), Marco Restano(6), Jérôme Benveniste(7).

> (1) SMHI - (2) ALONG-TRACK - (3) IsardSAT UK - (4) Univ. Porto -(5) Deimos/ESRIN - (6) Serco/ESRIN - (7) ESA-ESRIN.

Issue/Revision: Corresponding authors: david.gustafsson@smhi.se and pfabry@along-track.com

Reference:





The SHAPE Project



 The SHAPE project is funded by ESA through the Scientific Exploitation of Operational Missions (SEOM) Programme to prepare exploitation of Sentinel-3 data over the inland water domain (water heights and discharge).

Objectives

- Characterize CryoSat-2 SAR data for inland water.
- Assess the performances, in Hydrology, of applying Sentinel-3 IPF to CryoSat-2 data and emulating repeatorbit Alti-Hydro Products (AHP).
- Analyze weaknesses of Sentinel-3 IPF at all levels and design innovative SAR processing and re-tracking algorithms to improve data exploitation over river and lakes.
- Assess the benefits of assimilating SAR/RDSAR derived AHP into hydrological models.
- Provide improved L2 Corrections (tropospheric, geoid) for Sentinel-3 over land and inland water.
- Specify, prototype, test and validate the Sentinel-3 Innovative SAR Processing Chain for Inland Water.

ESA UNCLASSIFIED - For Official Use

= II 🛏 :: = + II = 🔚 = 1 II II = = :: :: 🖬 🖬 🚺 💥 🙌

The SHAPE Project: Regions of Interest



- Regions of interest have been selected considering both previous studies as well as the need of developing innovative algorithms and corrections for challenging areas.
- **CryoSat-2** FBR data were used as inputs for preliminary analyses over:
- Amazon & Danube rivers: 2015-03→2016-02
- Brahmaputra river: $2014-10 \rightarrow 2015-09$
- Vänern & Titicaca lakes: $2015-03 \rightarrow 2016-02$
- **Sentinel-3** data will be used in the near future.





ESA UNCLASSIFIED - For Official Use

European Space Agency

The SHAPE Processor

- The SHAPE Processor derives rivers and lakes water levels and discharge performing validation against in situ data (river gauges).
- CryoSat-2/FBR (or Sentinel-3/L1A) data plus various ancillary data (processing parameters, water masks, L2 corrections, etc.) are given as input to produce surface water levels.
- At a later stage, water level data are assimilated into hydrological models to derive **river discharge**.
- Assimilation into hydrological models provides a way of utilizing the full potential of the satellite altimetry data for transformation into lakes and rivers discharge, avoiding the need for co-located in-situ data and rating curve establishment and frequent revisits at fixed locations (Virtual Stations)







ESA UNCLASSIFIED - For Official Use

= II 🛏 ## II = 🚝 = II II = = ## 🖬 🚺 📰 💥 🙌

Hydrological model and Alti-hydro data assimilation

HYPE Model

ESA UNCLASSIFIED - For Official Use

- **The HYdrological Predictions for the Environment** model (HYPE) is developed and used for research and operational purposes:
- **HYPE is a semi-distributed multi-basin** hydrological model, simulating water balance and runoff from land, lakes, and rivers.
- **Runoff** (mm/day) from land/soil sub-classes is **Routed** through the lake and river network as defined by the sub-basin delineation and links:
- Lake water level (m) is *directly* related to lake outflow (m³/s) by water level-discharge relationships (rating curves).
- **River discharge** (m³/s) is based on **River stage** (m³), and velocity dependent delay and damping of inflow and is only *in-directly* related to **River water level** (m) through a non-linear inflow-velocity response-function and river width.



Visit http://hypeweb.smhi.se for more details.

visit http://iypeweo.shihi.se



Assimilation of Altimetry data (1)

- Ensemble Kalman filters and/or Particle filters are implemented in data assimilation.
- The Migration of the Altimetry water levels along the river, from the crossing of the satellite track to the subbasin outlets of the hydrological model is the crucial step in bridging the gap between model and satellite data.



ESA UNCLASSIFIED - For Official Use



1. Predicted model state X is transformed to predicted observation Y



3. River discharge after model state update.



Figure 59: Results of the DA of *synthetic* Cryosat-2 data in terms of water level at Bahadurabad station. The times of synthetic observations are marked with green dots on the x-axis.

Inland Water Altimetry - Limitations

- Low spatial resolution in along track (LRM: 5-7 km, SAR: 300 m).
- Low temporal resolution (repeat cycle of 27 days for Sentinel-3, 369 days for CryoSat-2).
- Altimeters miss most high and low flows periods and flash floods.
- Altimeter performances are not only dependent on the water body size but also on the surrounding topography.

Improvements are expected from

- Open loop trackers (DIODE/DEM): including onboard DEM. Useful to support the acquisition phase in the inald water domain.
- The recently developed Fully Focused SAR Processing, pushing the a spatial resolution up to 0.5 m.

ESA UNCLASSIFIED - For Official Use





= II 🕨 == + II = 🔚 = 🗄 = II II = = = H 🖬 🖬 💶 💥 🙌

Latitude (°N)

Case Study – Amazon River (1)



Amazon-HYPE model application

- A HYPE model application was developed for the 5.9 Million km² Amazon River basin including ~11000 sub-basins with an average size of 530 km².
- The model is based on open data sets for hydrography (USGS HydroSHEDS), land cover (ESA CCI), soil (HWSD), lakes (GLWD), river width (GWD-LR) and discharge (GRDC).



ESA UNCLASSIFIED - For Official Use

Case Study – Amazon River (2)

• The river routing was especially adopted for the case study area covering about 1000 km of the lower Amazon-Solimoes river using the same river profile as used for the Alti-hydro data processing.







ESA UNCLASSIFIED - For Official Use

_ II ⊾ II ➡ + II ■ ≝ _ II II = _ II = Ø . _ II II . .

Alti-Hydro Processing

- esa
- To mimic the use of Sentinel-3A data, CryoSat-2 water level measurements 2010-2015 where first migrated along the river path to Sentinel-3A tracks crossing, and secondly migrated to the selected Amazon-HYPE subbasin river outlets.



- Space-Time migrated Alti-hydro data, that can be used for:
- 1) model calibration/evaluation
- 2) assimilation for improved modeled discharge, or
- 3) direct discharge estimation (empirical rating curves or hydraulic modelling).

ESA UNCLASSIFIED - For Official Use



_ 11 b_ :: = + 11 = [_ 11 11 _ 2 : : :: b [_ 2 : : : : : [_ 2 : : : : : ! ! ! ! ! ! !

Model results and evaluation



 The assimilation of Alit-hydro water levels is dependent on a correct relation between River stage and Water level in the model. This relation was much improved by estimating the river area at low flow and high flow situations by projecting the minimum and maximum levels in the Alti-hydro data time series on the underlying DEM data:



- The overall water balance and river velocity response was roughly calibrated with discharge data in upstream areas.
- Systematic deviations from observations of discharge (in-situ) and water level (Alti-hydro) is still seen in the lower Amazon, most likely due to missing floodplain dynamics and overestimated river velocity.
- The improvement of further model development versus assimilation of the altimetry data will be evaluated in the next phase of the project.

ESA UNCLASSIFIED - For Official Use

· = ■ ► = = + ■ + ■ = ≔ = ■ ■ ■ = = = ■ ■ ■ = = ■ ₩ |•|

+

European Space Agency

ESA UNCLASSIFIED - For Official Use

 $Q(m^3/s)$

(c) (a) x 1015000

1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

ENS = 0.21, ENSlog = 0.33, DI = -21 days, $\Delta V = -8\%$

Moreover, in situ measurements might be considered sensitive information and are not always freely available to the research community

The Nash–Sutcliffe index as a performance indicator

Validation of hydrological models

• The closer to 1 the ENS coefficient is, the closest to the in situ time series the altimetry-based water elevations are. NS above 0.5 can be considered satisfactory.

Performance degradation (ENS < 0.5) due to:

- The uncertainty of both river and floodplain geometry and digital elevation model.
- Poor guality of rainfall data sets (e.g. TRMM), especially in areas which are mountainous and/or poorly monitored.











• More information about the SHAPE Project can be found at

http://projects.along-track.com/shape/

ESA UNCLASSIFIED - For Official Use

