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)"

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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 repeat-orbit 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.

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.

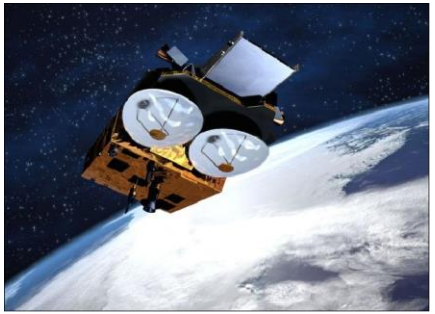
- **CryoSat-2** FBR data were used as inputs for preliminary analyses over:

- Amazon & Danube rivers: 2015-03→2016-02

- Brahmaputra river: 2014-10 → 2015-09

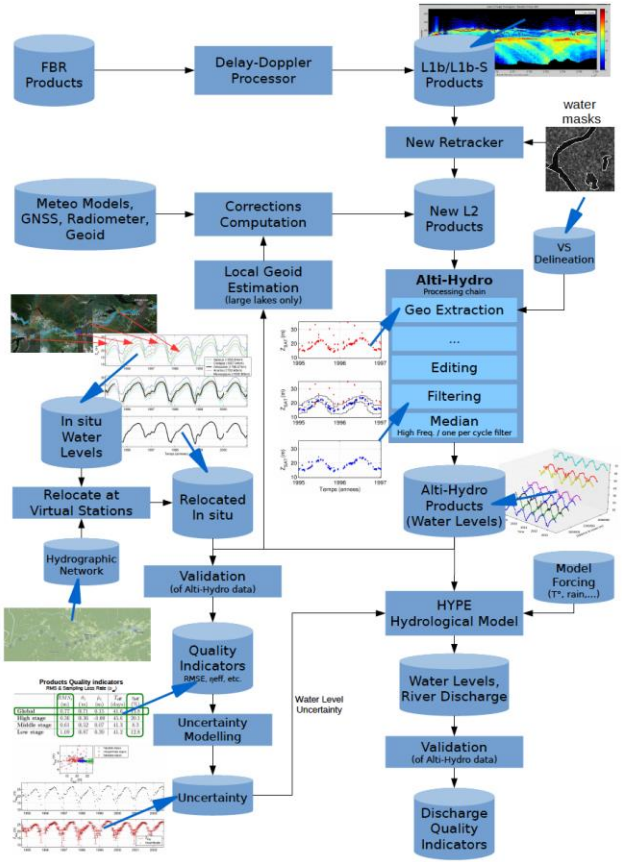
- Vänern & Titicaca lakes: 2015-03 → 2016-02

- **Sentinel-3** data will be used in the near future (early 2017).



The SHAPE Processor

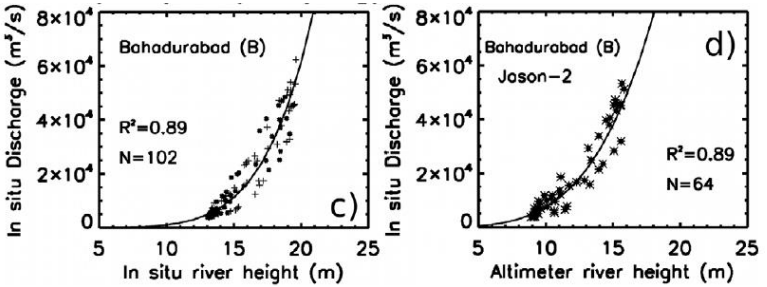
- The SHAPE Processor derives **rivers and lakes water levels and discharge** performing **validation against in situ data (river gauges).**
- CryoSat-2/FBR (or Sentinel-3/L1A) data plus various ancillary data (processing parameters, water masks, L2 corrections, etc.) are given as input to produce surface 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 satellite altimetry data for transformation into lake level and river stage and discharge, avoiding the need for co-located in-situ data and rating curves, and frequent revisits at fixed locations (**Virtual Stations**)

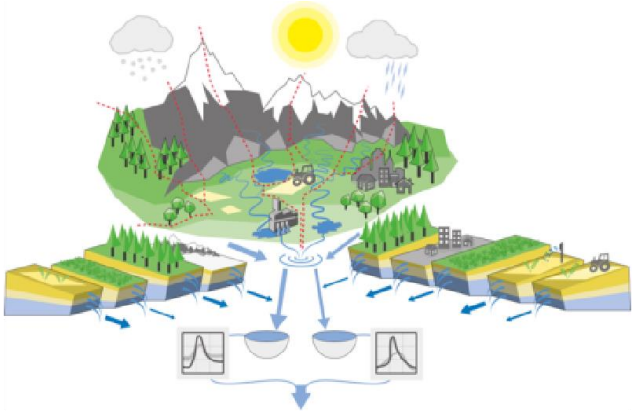


Hydrological model and Alti-hydro data assimilation

HYPE Model

- **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** (m^3/s) by water level-discharge relationships (rating curves).
- **River discharge** (m^3/s) is based on **River stage** (m^3), 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.



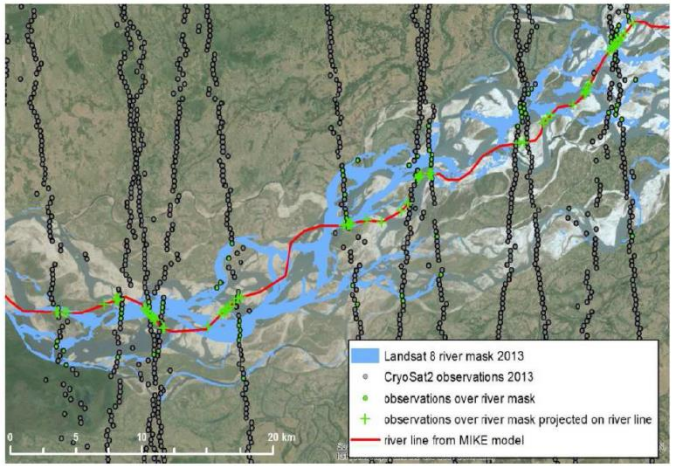


Visit http://hypeweb.smhi.se for more details.

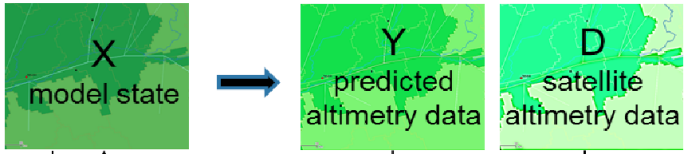
Assimilation of Altimetry data (1)

- 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 sub-basin outlets of the hydrological model is the crucial step in bridging the gap between model and satellite data.



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



2. Analysed model state X based on innovation (Y-D)

3. River discharge after model state update.

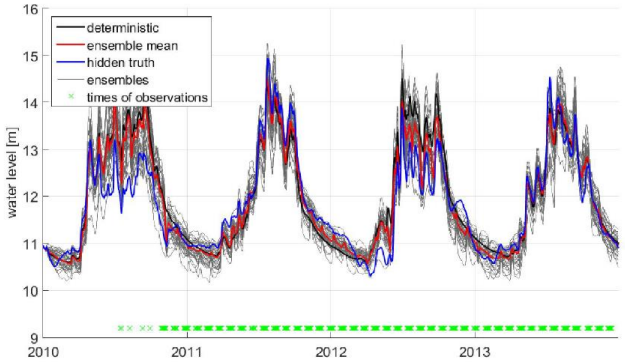


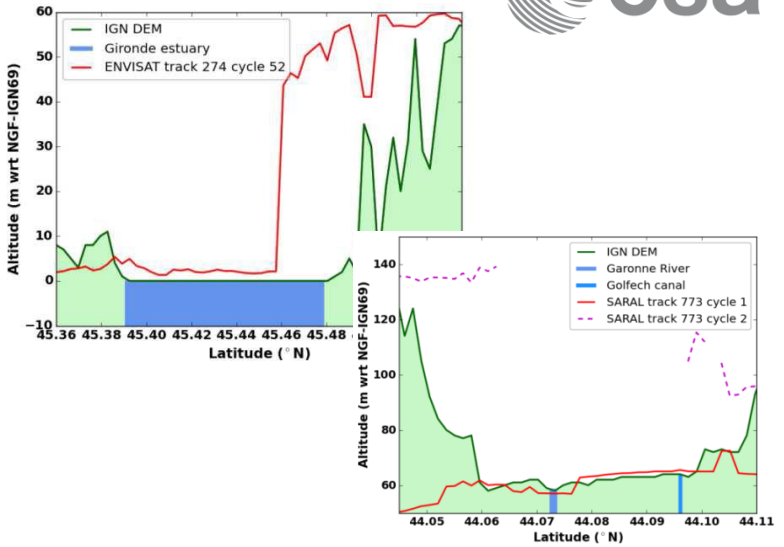
Figure 59: Results of the DA of *synthetic* Cryosat-2 data in terms of water level at Bahadurabad station. The times of synthetic observations are marked with green dots on the x-axis.

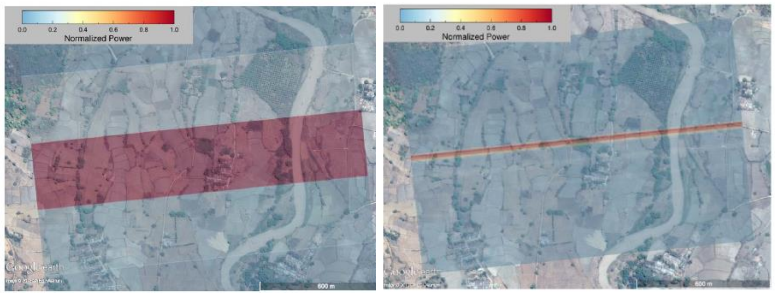
Inland Water Altimetry - Limitations

- 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 inland water domain.
- The recently developed Fully Focused SAR Processing, pushing the spatial resolution up to 0.5 m.





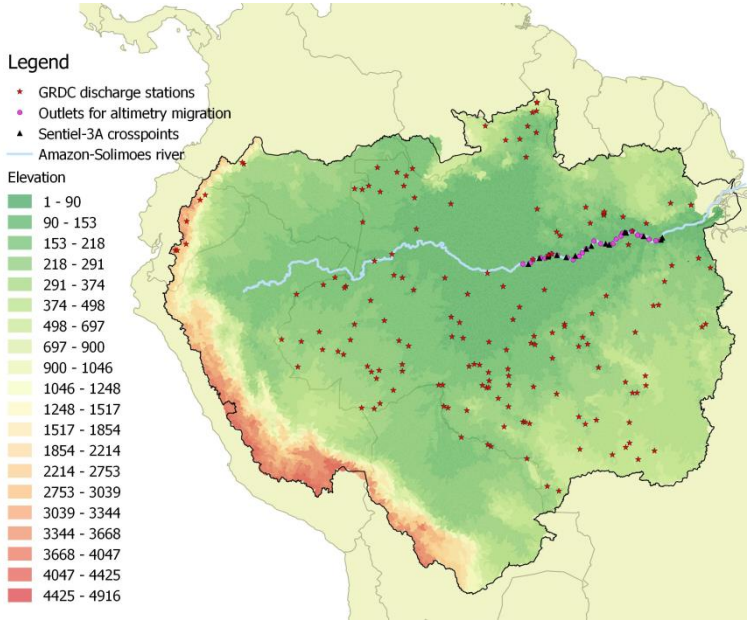
(b)

Case Study – Amazon River (1)

Amazon-HYPE model application

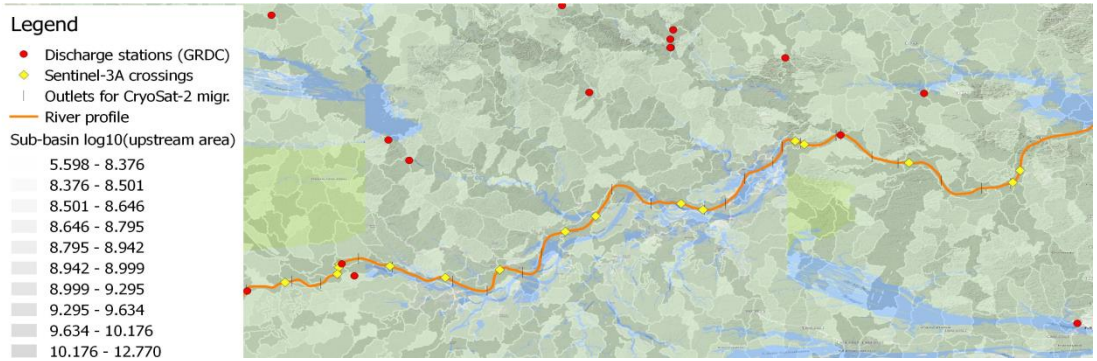
- A HYPE model application was developed for the 5.9 Million km^2 Amazon River basin including **~11000 sub-basins** with an average size of 530 km^2.

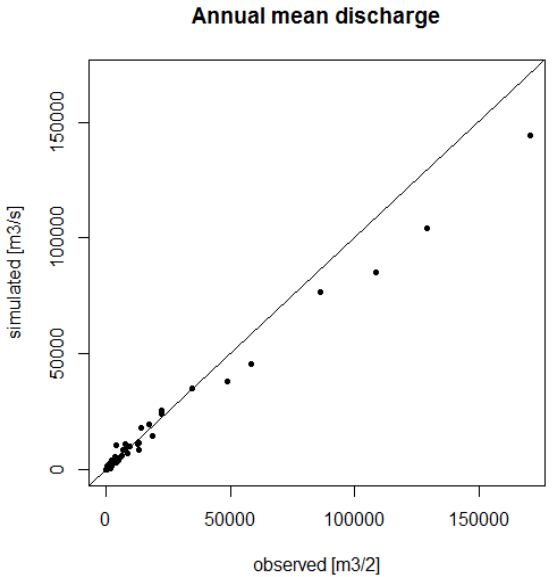
- The model is based on open data sets for hydrography (USGS HydroSHEDS), land cover (ESA CCI), soil (HWSD), lakes (GLWD), river width (GWD-LR) and discharge (GRDC).



Case Study – Amazon River (2)

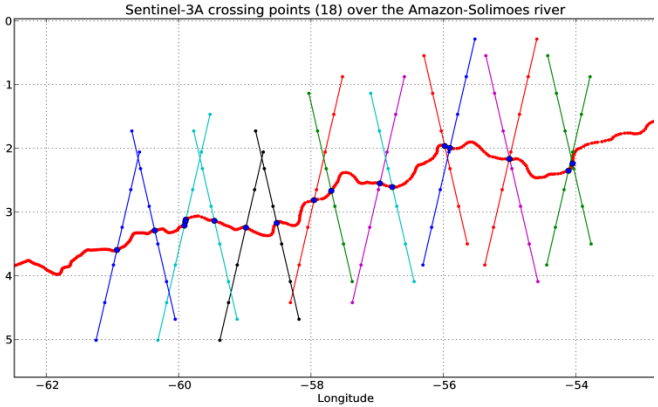
- The river routing was especially adopted for the case study area covering about 1000 km of the lower Amazon-Solimoes river using the same river profile as used for the Alti-hydro data processing.

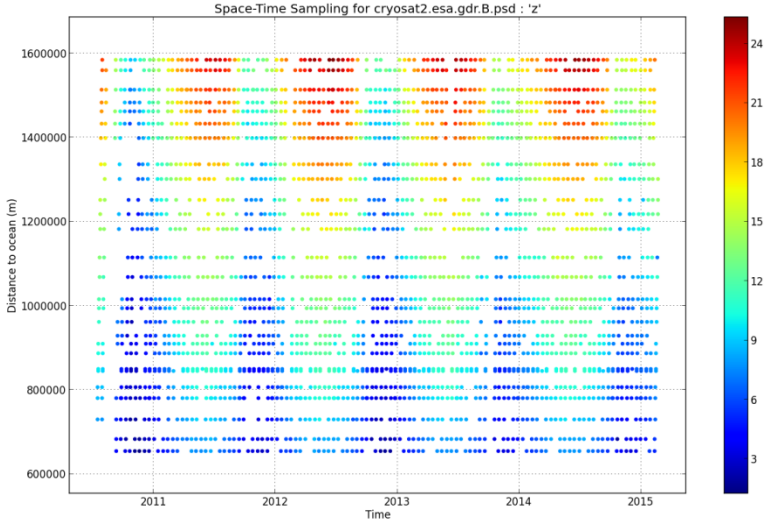




Alti-Hydro Processing

- 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 sub-basin river outlets.



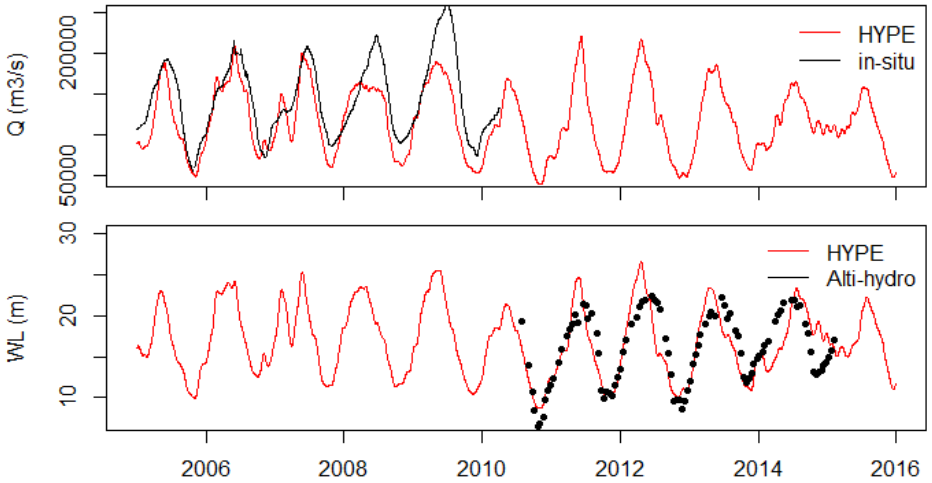


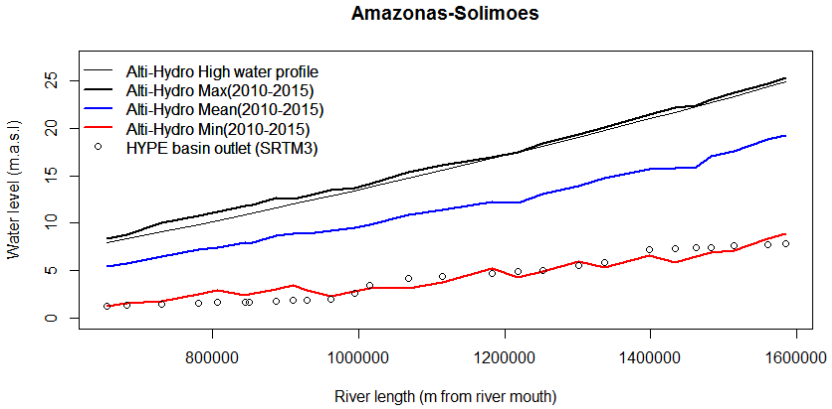
- Space-Time migrated Alti-hydro data, that can be used for:

1) model calibration/evaluation
2) assimilation for improved modeled discharge, or
3) direct discharge estimation (empirical rating curves or hydraulic modelling).

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 and high flow situations by projecting the minimum and maximum levels in the Alti-hydro time series on the underlying DEM





- 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 altimetry data will be evaluated.

The Nash–Sutcliffe index as a performance indicator

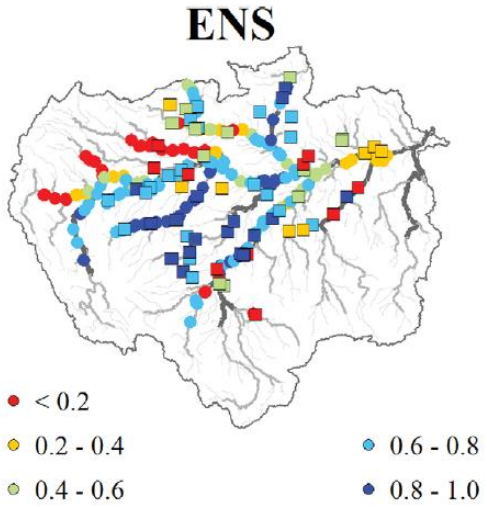
Validation of hydrological models

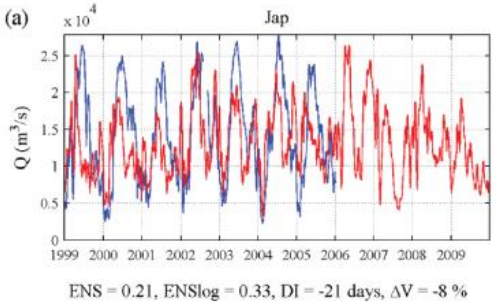
- The closer to 1 the ENS coefficient is, the closest to the in situ time series the altimetry-based water elevations are. NS above 0.5 can be considered satisfactory.

Performance degradation (ENS <0.5) due to:

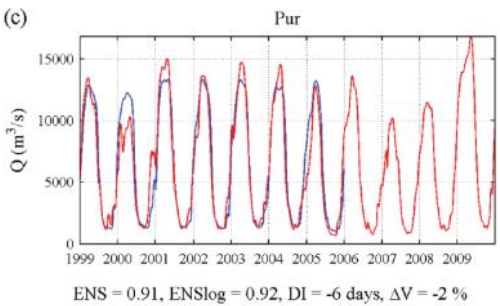
- The uncertainty of both river and floodplain geometry and digital elevation model.
- Poor quality of rainfall data sets (e.g. TRMM), especially in areas which are mountainous and/or poorly monitored.

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





ENS = 0.21, ENSlog = 0.33, DI = -21 days, ΔV = -8 %



ENS = 0.91, ENSlog = 0.92, DI = -6 days, ΔV = -2 %

“Sentinel-3 Hydrologic Altimetry Processor prototypE”

- More information about the SHAPE Project can be found at

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

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