→ 10th COASTAL ALTIMETRY WORKSHOP

SAR Altimetry Training Course

ESA Projects on Radar Altimetry

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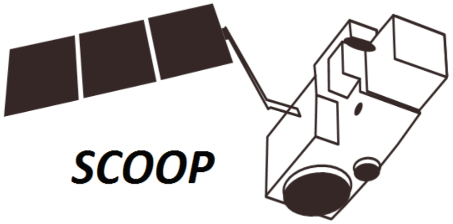
21–24 February 2017 | Florence, Italy

Radar Altimetry in SEOM

Under the **Scientific Exploitation of Operational Missions** **(SEOM)** Programme, 3 Projects are currently underway to accurately **characterise and improve the performance** of the **Sentinel-3 SRAL SAR mode altimeter** in the following scenarios of interest:

- Coastal and Open Ocean

SCOOP: **S**AR Altimetry **C**oastal & **O**pen **O**cean **P**erformance Exploitation and Roadmap Study



- Inland Water

SHAPE: **S**entinel-3 **H**ydrologic **A**ltimetry **P**rototyp**E**

Sentinel-3 Hydrologic Altimetry Processor prototypE

- Ice Sheets

SPICE: **S**entinel-3 **P**erformance improvement for **ICE** sheets

Credits: ESA/SLCCI (left), ESA/CS-2 (right: top), JPL/NASA (right: bottom)

Radar Altimetry in SEOM

- Open source SAR processor

DeDop: Delay-Doppler Altimetry Studio (http://dedop.org/)

The project aims to provide a Fully Adaptable and Configurable Delay Doppler Processor.

DAY 3	Friday 24 February 2017	SAR ALTIMETRY TRAINING COURSE
13:30–14:30	SARvatore Demo and Hands-On	S. Dinardo and M. Restano
14:30–15:30	DeDop Demo and Hands-On	M. Roca
15:30–16:00	Coffee Break	
16:00–16:45	BRAT Demo	R. Capote
16:45–17:15	GUT Demo	A. Ambrózio
17:15–17:45	Future Missions: Sentinel-6, SWOT, CryoSat Follow On	M. Roca and J. Benveniste
17:45–18:45	Wine & Cheese	

Common Shared Objectives

- The **SCOOP**, **SHAPE** & **SPICE** Projects **share the following overall objectives**:

- **Accurately characterise** the expected performance of Sentinel-3 SRAL SAR mode altimeter products in the respective area of study.

As Projects started before the launch of Sentinel-3, Cryosat-2 data have been processed according to the Sentinel-3 processing baseline.

- **Develop and evaluate** enhancements to the current baseline Sentinel-3 data processing schemes, in order to provide improved performance.

- **Support the correct interpretation and application** of SRAL SAR L1 products by providing clear technical information on these products and their processing to the user community.

- **Produce** new datasets, including updated tropospheric corrections (only for SCOOP & SHAPE).

- Provide recommendations for further developments and implementations through a scientific roadmap.

Troposheric Corrections in Brief

Dry Troposphere

$$DTC(\mathrm{h_S}) = -\frac{0.0022768 p_s}{1 - 0.00266\cos 2\varphi - 0.28 \cdot 10^{-6} h_s}$$

- DTC has a relatively well-known height dependence. However, for very high targets (hs>2000m), the commonly used expressions for the height dependence of atmospheric pressure may cause additional errors.

Wet Troposphere

$$WTC = -\left\{1.116454 \times 10^{-3} \int_{P_{sat}}^{P_{surf}} q dp + 17.66543928 \int_{P_{sat}}^{P_{surf}} \frac{q}{T} dp\right\} \times [1 + 0.0026\cos(2\varphi)]$$

- Unlike the DTC, which has a relatively well-known height dependence, the height dependence of water vapour is not easy to model, due to its large variability. Therefore, the associated delay is one of the major error sources

- The computation of the WTC requires a value of the surface pressure at the terrain surface altitude (Psurf=hs), a value of the gravity at the altitude and latitude (φ) of the measurement point and a value of specific humidity (q) and temperature (T) given by the 3D ECMWF meteo fields.

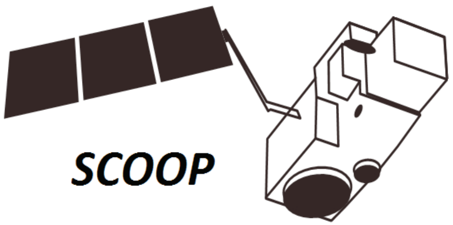
- But Large MWR footprints (30-40km) lead to unusable measurements in coastal regions.

- GPD+ model: WTC has been developed using data combination (DComb) from external data sources: Global Navigation Satellite Systems (GNSS) derived wet path delays from coastal and island stations, water vapour products from scanning imaging MWR (SI-MWR) on board various remote sensing missions.

The SCOOP Project

SAR Altimetry **C**oastal & **O**pen **O**cean **P**erformance Exploitation and Roadmap Study

National Oceanography Centre NATURAL ENVIRONMENT RESEARCH COUNCIL	SATOC Satellite Oceanographic Consultants	CLS Collecte Localisation Satellites
isardSAT	Starlab Living Science	TU Delft Delft University of Technology
NOVELTIS	Technische Universität Darmstadt	U.Porto FC Faculdade de Ciências Universidade do Porto



Kick-off: October 9, 2015

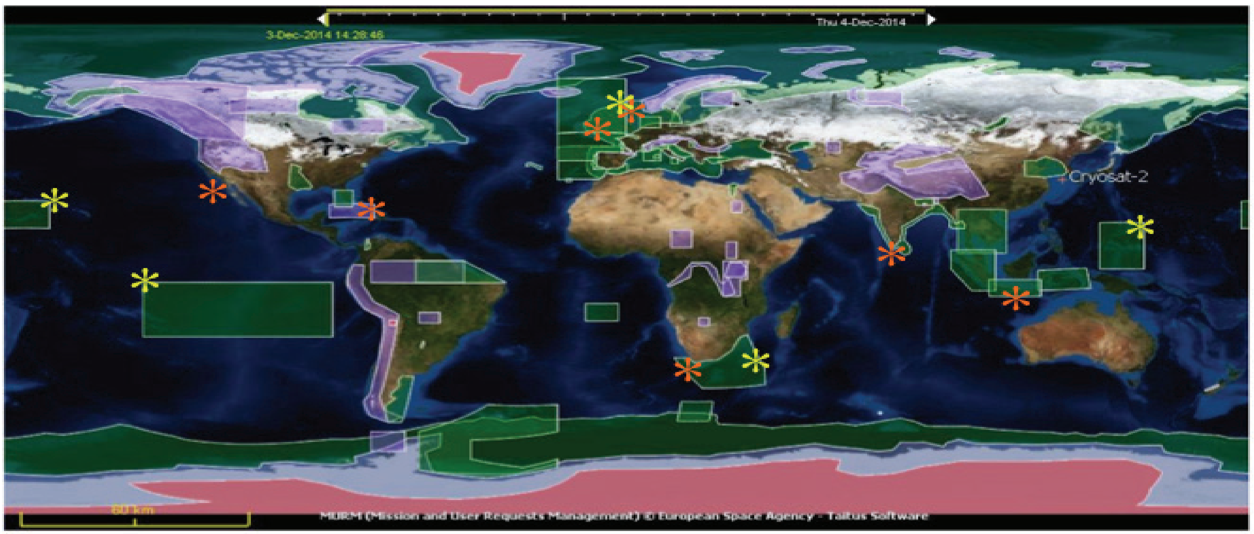
website: http://www.satoc.eu/projects/SCOOP/

The SCOOP Project – Objectives

- To **characterize** the performance of Cryosat-2 SAR mode data in the open ocean using the Sentinel-3 processing baseline applied to Cryosat-2 FBR Baseline C data.
- To **develop, test and implement** modifications in the processing of the L1B-S to the L1B product not currently implemented in the Sentinel-3 ground segment.
- To **develop** an improved SAMOSA retracker.
- **Open Ocean specific objectives**
- To **carry out a study** into the dependency of SAR altimeter data on **swell**.
- To **propose a solution** for a SAR mode **Sea State Bias correction** for the open ocean build on findings from a parallel study being funded by EUMETSAT.
- **Coastal Zone specific objectives**
- Investigate techniques to **improve performance close to the coastline** by developing techniques to **identify and discriminate** against the **impact of land contamination** of the nadir ocean echo.
- Investigate how the **orientation of the ground track with respect to the coastline**, and the proximity of the land affect the performance of Sentinel-3 SRAL data.

Regions of interest

- Selected Regions of Interest: **5 Open Ocean**, **7 Coastal Zone**.

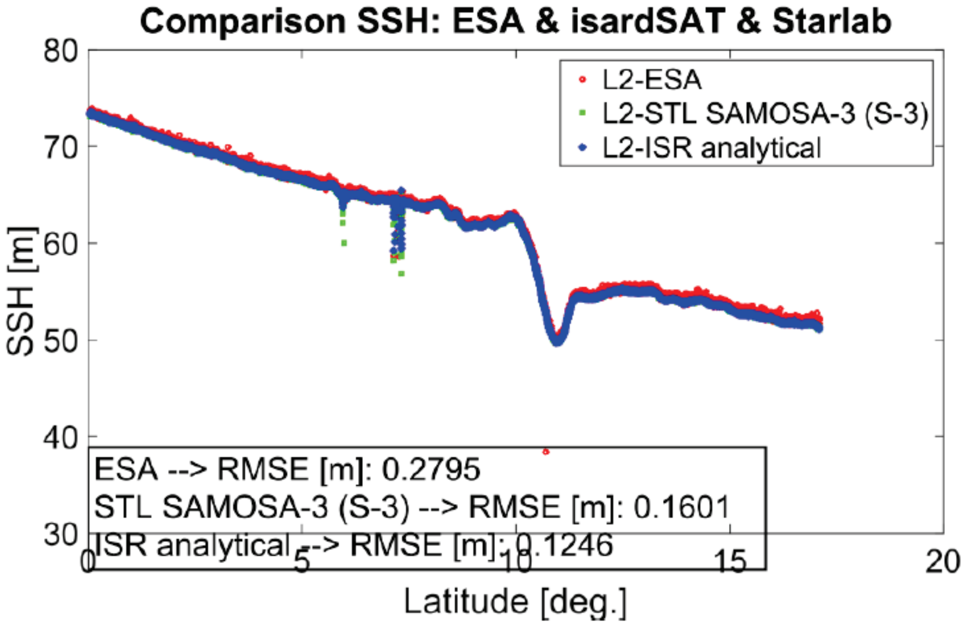


- Starting Processing Baselines & Retrackers adopted
    - FBR to L1b: Sentinel-3 baseline using Cryosat-2 Baseline C calibrated data as input.
    - L1b to L2: SAMOSA retracker.

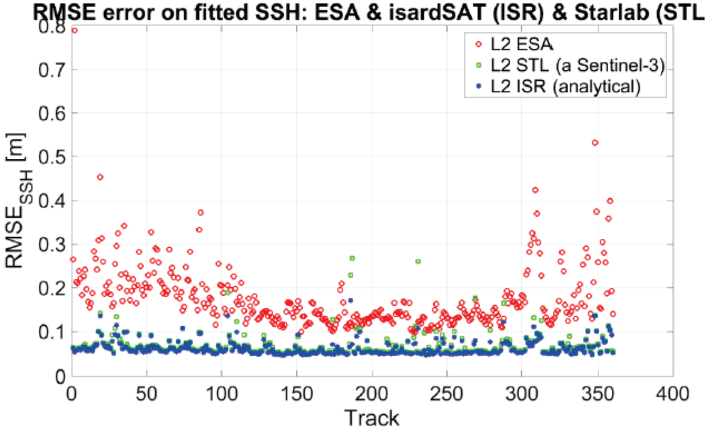
L1b & L2 data data processing

- Data processed according to the **Sentinel-3 baseline**: the first **SCOOP L1B & L2 dataset, including WTC,** has been produced for all **ROIs** (**2012-2013**) and made available to end-users (http://www.satoc.eu/projects/SCOOP/data.html).

- L1B validation against ESA and isardSAT L1B & L2 data over West/East/**Central Pacific** + Agulhas open ocean regions indicated a very good agreement.



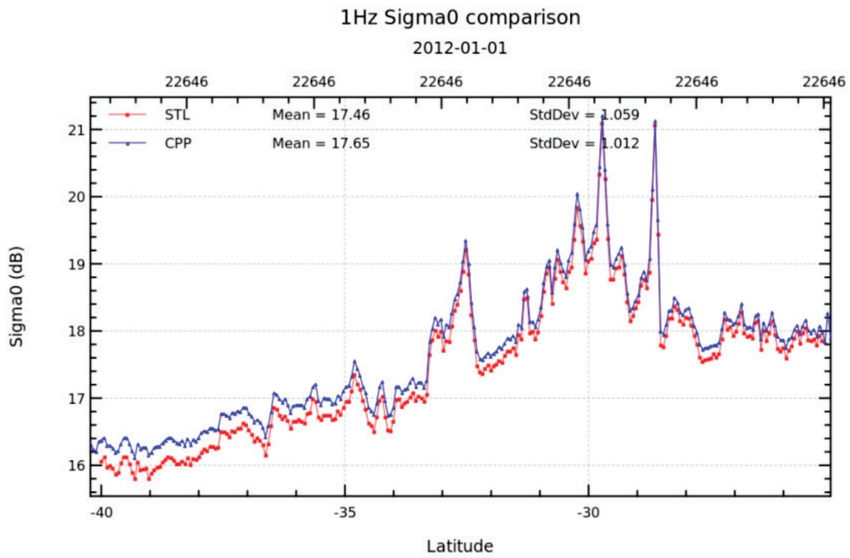
SSH noise-performance

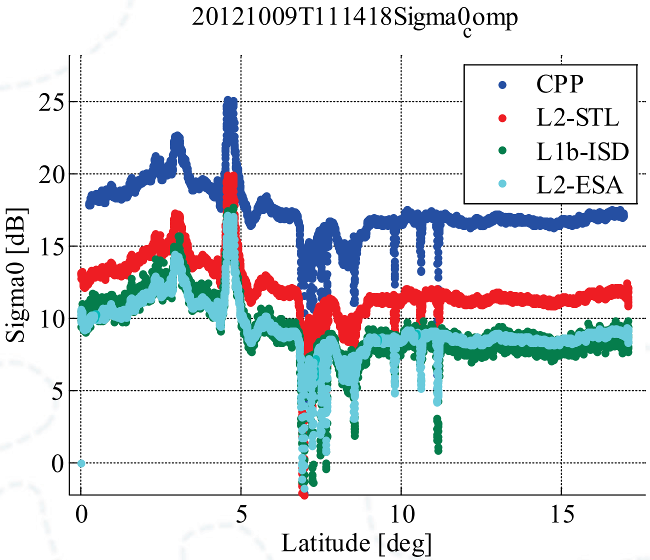


Source	μ_{RMSE} [m]	σ_{RMSE} [m]
ESA	0.1760	0.0714
STL a la S-3	0.0672	0.0259
ISR a la S-3	0.0619	0.0168

L1b & L2 data data processing (2)

- L2 validation against CLS CPP data is also very good.

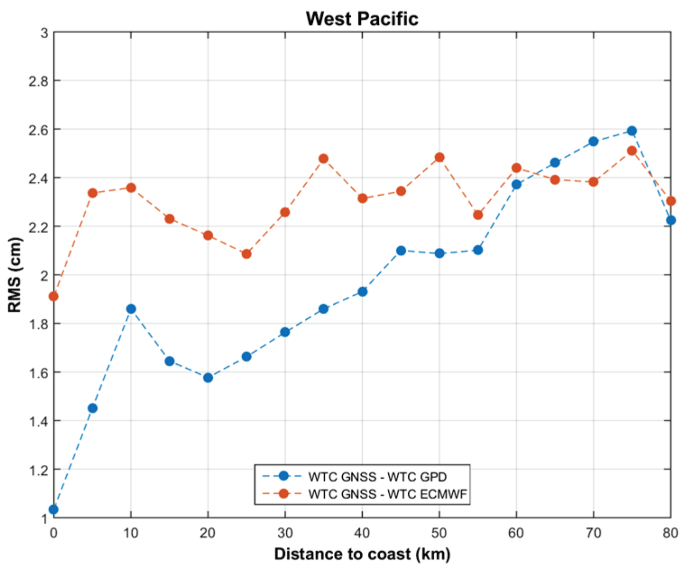


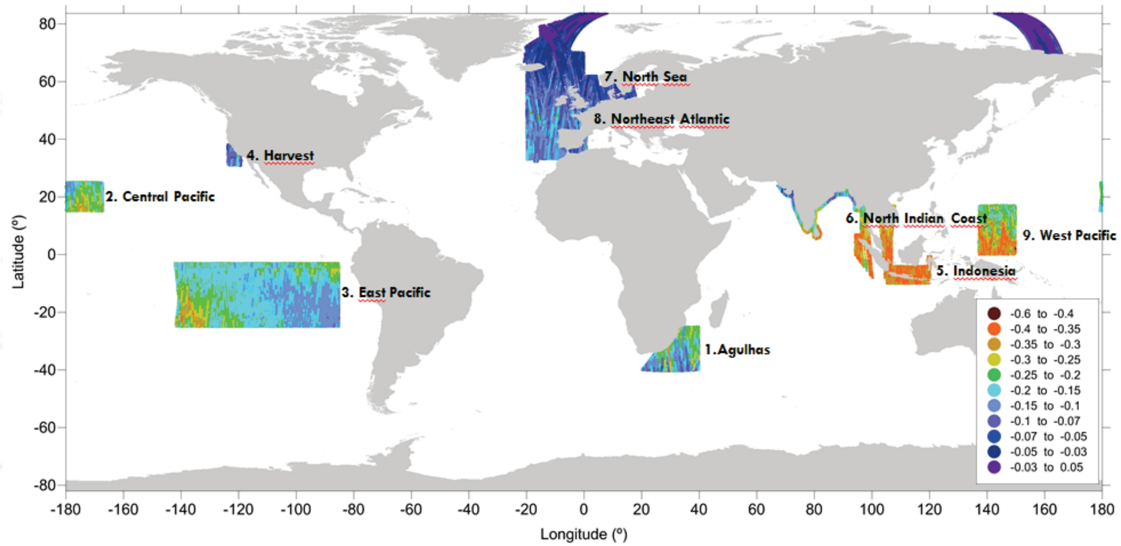


- There is a sigma0 bias between all solutions. Further investigations are currently underway.

Wet Tropospheric Corrections

- Statistical analyses of SLA, from RADS, derived with *i)* the GPD+ WTC, *ii)* the ECMWF-Op WTC.
- Diagnostics (WTC difference w.r.t. J2 and difference w.r.t. to GNSS) confirm that GPD+ is better than the ECMWF model in all SCOOP ROIs.
- Next efforts will be focused on computation of GPD+ WTC for Sentinel-3.





GPD wet tropospheric correction (m) for CryoSat-2, for the various ROI, for the year 2012.

The SHAPE Project

Sentinel-3 Hydrologic Altimetry PrototypE

Kick-off: September 14, 2015

website: http://projects.alongtrack.com/shape/

The SHAPE Project – Objectives

- **Prepare** for the operational exploitation of Sentinel-3 over the inland water domain. **Design and assess** the impact of alternative and innovative techniques not implemented in the Sentinel-3 ground segment (no Inland Water dedicated processing).

- **Transpose results** obtained by using Cryosat-2 data processed according to the Sentinel-3 baseline **to the Sentinel-3 framework** (repeat versus geodesic orbit, differences in the geoid and tropospheric corrections, etc.) and provide a first insight on the effective capabilities of Sentinel-3 in terms of precision and accuracy.

- **Migrate** results into an **hydrological model** evaluating the potential of the Sentinel-3 data to improve hydrological catchment modelling and the estimation of rivers' discharge,

- Provide customized SAR and RDSAR waveforms over selected river and lakes to improve the estimation of river stage and lake level.

Regions of interest

- Selected Regions of Interest:

Rivers:

Amazon downstream (SAR, Baseline C)

Danube (SARIn, Baseline C)

Brahmaputra (SAR, SARIn, LRM in Baseline C)

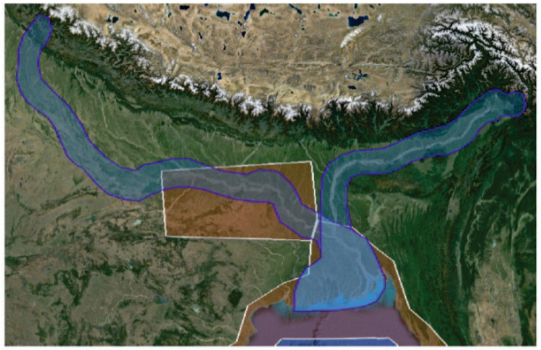


Figure 2 : CryoSat-2 SAR mode mask (brown areas with white contours) over the Ganges and Bragmaputra ROI (blue areas with purple contours).

Lakes:

Titicaca (SARIn, Baseline C): the main scientific objective is to assess DTC & WTC.

Vanern (SAR, Baseline C): to perform a joint exercise (models, altimetry and imagery).

- Starting Processing Baselines & Retrackers adopted:

- **FBR to L1b**: S3 baseline using Cryosat-2 Baseline C calibrated data as input.
- **L1b to L2**: 4 retrackers: “**Threshold**” & “**Ice1**” retrackers + 2 **analytical** retrackers (Type “**A**”: estimated MSS / fixed SWH; Type “**B**”: estimated SWH / fixed MSS).

- Auxiliary data:
  - Sentinel-1 (SAR imaging) products for the production of water masks.

L1b & L2 data data processing

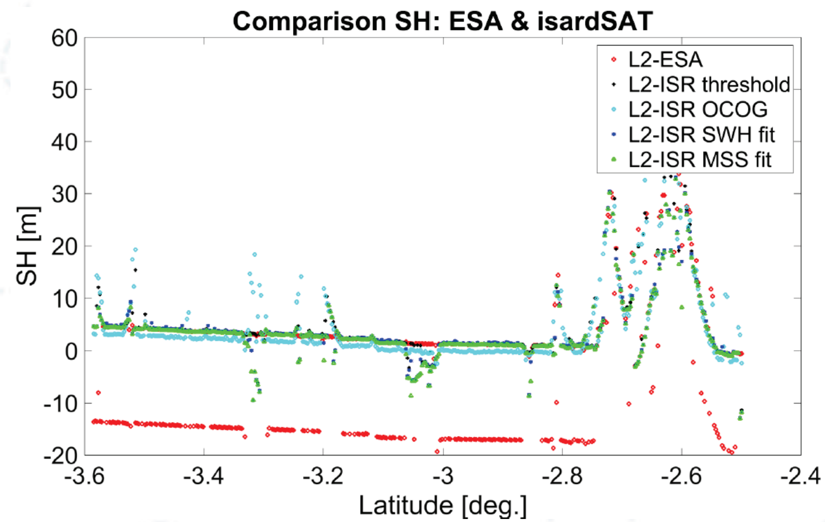
- L1B processor replicating the Sentinel-3 baseline.

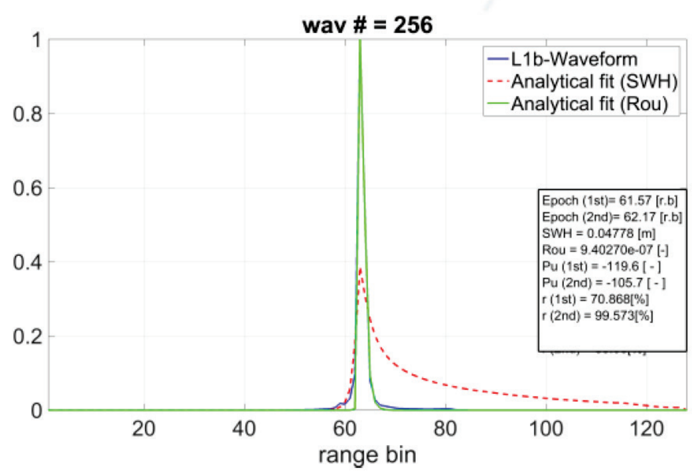
- Retrackers:
- A: Analytical (**Adapted SAMOSA**), estimated MSS / fixed SWH.
- B: Analytical (**Adapted SAMOSA**), estimated SWH / fixed MSS.
- Threshold-based (50% of the Peak).
- Threshold OCOG.

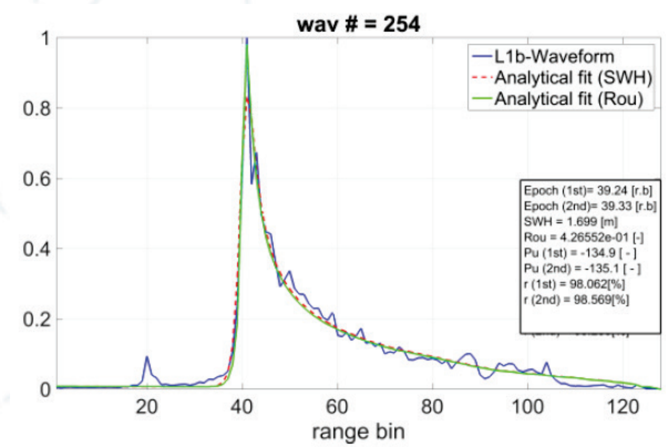
- Comparison against L2 ESA CryoSat-2 products.

- The Analytical SAR ocean retracker has been adapted for inland water.

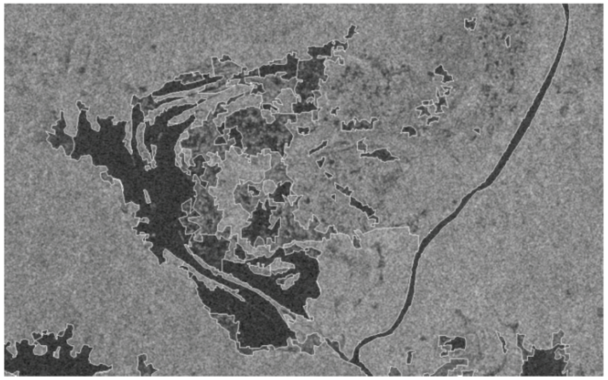
- Demonstrated capability to fit both types of waveforms: specular-like and Ocean-like.







L1b & L2 data data processing (2)



- 1) Water masks needed to select data over rivers & lakes generated through SAR Image Segmentation (Sentinel-1 in VH & VV) by means of a **Minimum Description Length Automated Segmentation Grid** (MDLSAG) algorithm.

- 2) Assuming **Zsat = alt - (range + L2 corrs + geoid),** with **Z: water levels,** the <u>Median Absolute Deviation (MAD) operator</u> has been **<u>defined to measure the dispersion</u>**:

MAD(Zsat) = MAD(alt - (range + L2 corrs + geoid))

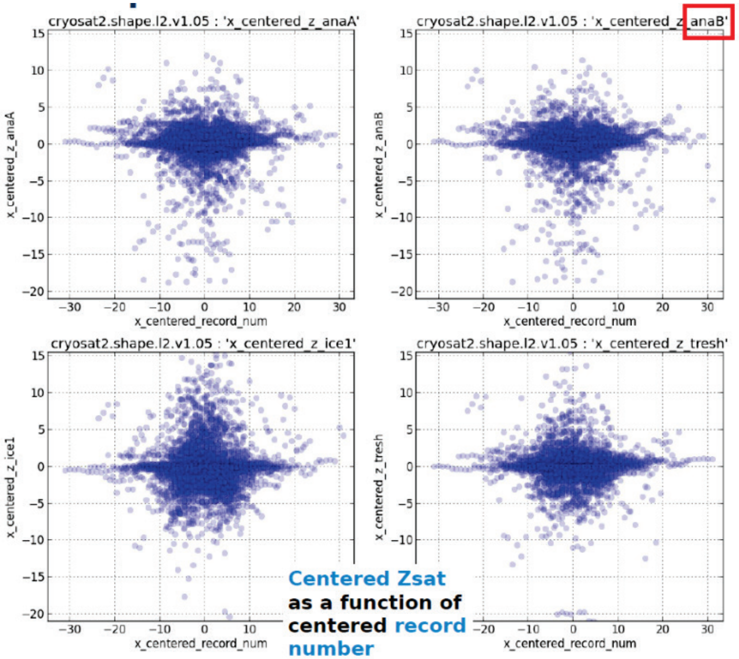
- Done locally, i.e., on short track segments, so that L2 corrections & geoid can be approximated as constants (no dispersion): **MAD(Zsat) ~= MAD(alt – range) ->** focuses on dispersion due to altimetric components.

- 3) For each river/lake crossing: **compute mean and STD of the group's MAD values** for <u>each of the four retrackers</u>.

- Analytical **retracker type B (**estimated SWH / fixed MSS**)** performed better in this analysis on the Amazon ROI.

MAD(Zsat):

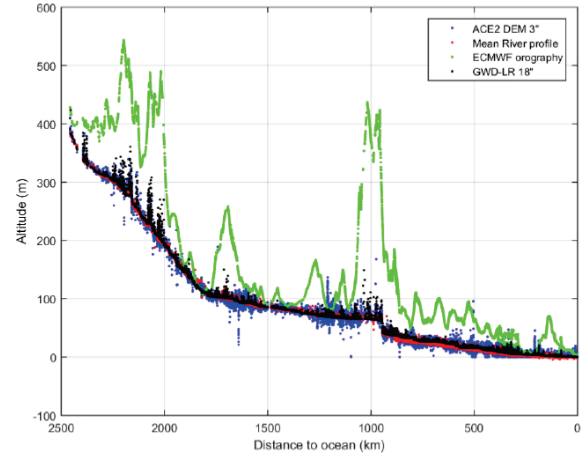
384 crossings / 4292 samples	min	max	mean	std
x_disp_mad_z_anaA	0,0000	5,6927	0,4018	0,6567
x_disp_mad_z_anaB	0,0000	4,9207	0,3785	0,5662
x_disp_mad_z_ice1	0,0000	7,7274	0,9168	1,3576
x_disp_mad_z_tresh	0,0000	8,8917	0,4372	0,8167



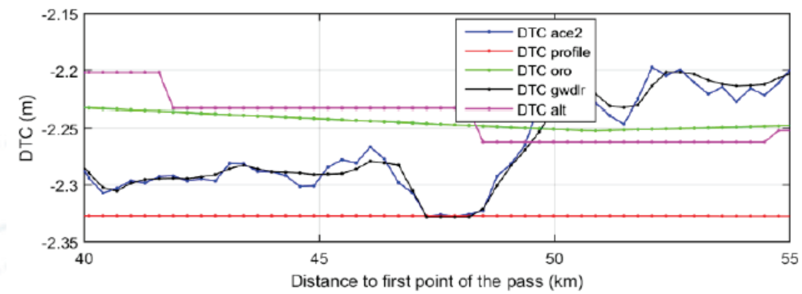
Centered Zsat as a function of centered record number

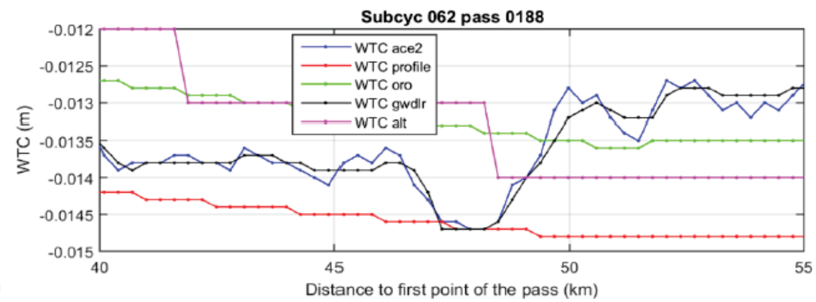
Wet Tropospheric Corrections

- Main L2 errors are in the dry and wet tropospheric corrections.
- Inland water: due to the height dependence of each correction, it is important to analyse the height variations within each SHAPE ROI.
- For each measurement point, **4 different altitudes** have been analysed: the Mean water level profile (***hprofile***) and Interpolated altitudes from ACE2 DEM (***hdem*** or ***hace2***), GWD-LR DEM (***hgwdlr***) and ECMWF orography (***horo***).
- For the **Danube ROI**, some specific zones have high errors due to narrow zones and surrounding areas with high altitude variation.
- **All SHAPE ROIs** have been investigated using **CryoSat-2** tracks. Where possible, results have been validated with independent evaluations based on GNSS data from surrounding stations.



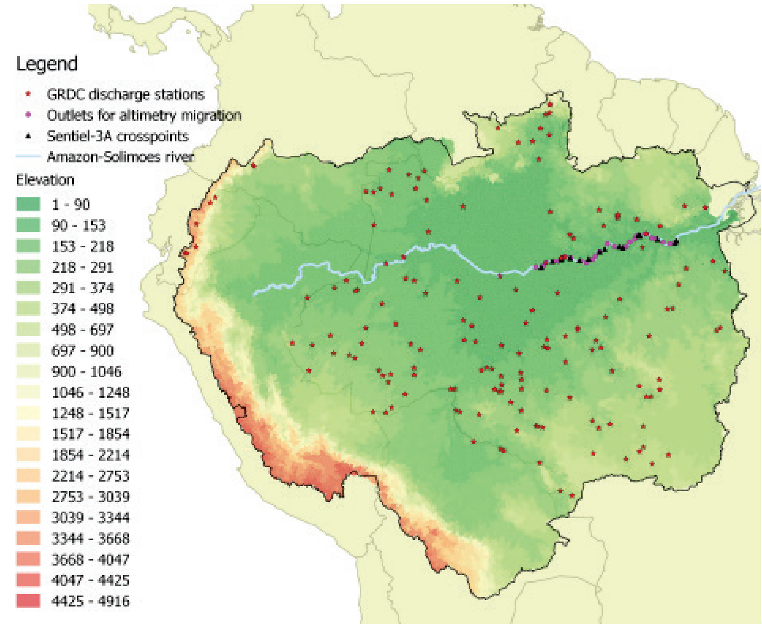
Altitudes above geoid along the Danube river mean profile – ACE2, Mean profile, ECMWF, GWD-LR



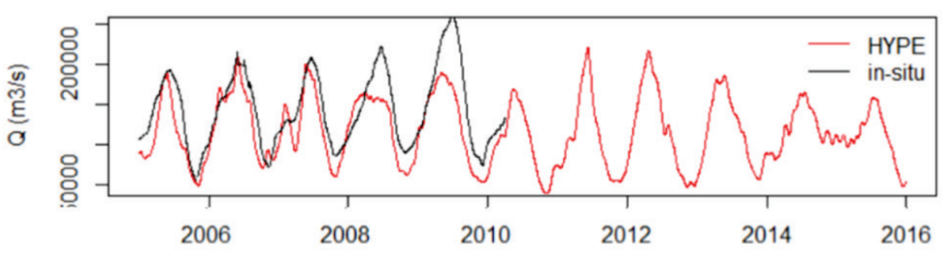


Hydrology in SHAPE

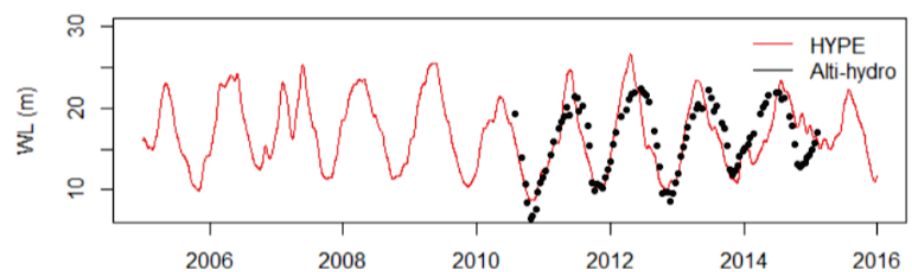
- 1) Provide modelled discharge (m^3/s) and water level data.
- 2) Assess benefits of assimilating Alti-Hydro Products in hydrological models.
- HYPE hydrological model from SMHI will be used for SHAPE ROI's.
- Analysis performed over the Amazon:



River discharge (model and in-situ)



River water level (model and altimetry from CryoSat-2)



- Next efforts will be focused on evaluating the benefit from the assimilation of altimetry water level for the Amazon and for all other SHAPE ROIs.

The SPICE Project

Sentinel-3 Performance improvement for ICE sheets

Kick-off: September 9, 2015

website: https://www.seom-spice.org/

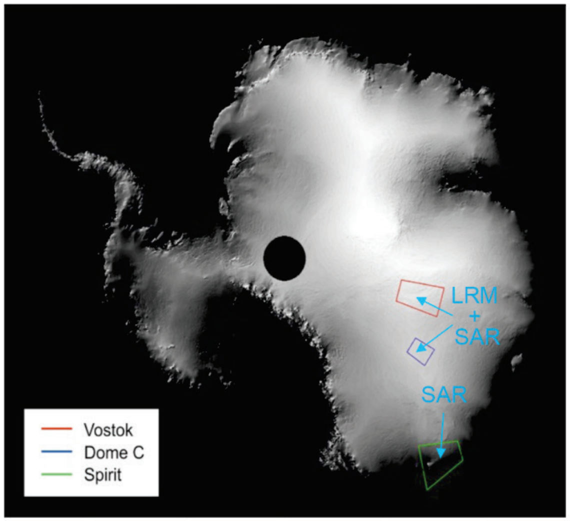
The SPICE Project – Objectives

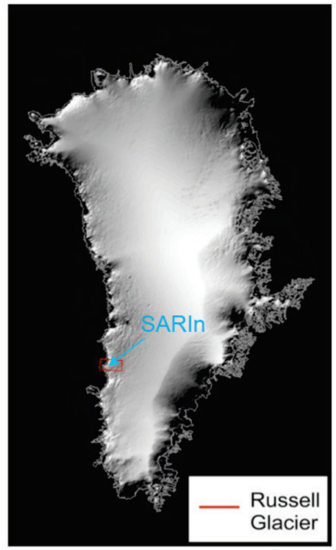
SPICE will **develop and test** novel algorithms with the purpose of addressing four high level objectives:

- **Assess and improve** the Delay-Doppler altimeter processing for ice sheets.
- **Assess and develop SAR** waveform **retrackers** for **ice sheets.**
- **Evaluate the performance** of SAR altimetry relative to conventional pulse limited altimetry.
- Assess the impact on SAR altimeter measurements of radar wave **interaction with the snowpack**.
- This will be achieved by analysis of CryoSat data, emulating Sentinel-3 processing.

Regions of Interest, input data and processors

- Selected regions of interest





WP 2				
Product	Level	Mode	AOI	Time Period
CryoSat-2 Baseline C	FBR	SAR	Dome C	Dec. 2014
			Spirit Sector	Nov. 2014
			Lake Vostok	Nov. 2014
		SARin	Russell Glacier	Apr. 2011
	L1B (for comparison)	SAR	Dome C	Dec. 2014
			Spirit Sector	Nov. 2014
			Lake Vostok	Nov. 2014
		SARin	Russell Glacier	Apr. 2011
	CAL	All	All	Average (Mar. 2011 - Nov. 2015)

WP 3				
Product	Level	Mode	AOI	Time Period
CryoSat-2 Baseline C	L2 (for comparison)	SAR	Dome C	Dec. 2014
			Spirit Sector	Nov. 2014
			Lake Vostok	Nov. 2014
		SARin	Russell Glacier	Apr. 2011
isardSAT	L1B (from WP2)	SAR	Dome C	Dec. 2014
			Spirit Sector	Nov. 2014
			Lake Vostok	Nov. 2014
		SARin	Russell Glacier	Apr. 2011
		pLRM	Spirit Sector	Nov. 2014
			Russell Glacier	Apr. 2011

- Processing Baselines & Retrackers

  FBR to L1B: Sentinel-3 baseline.

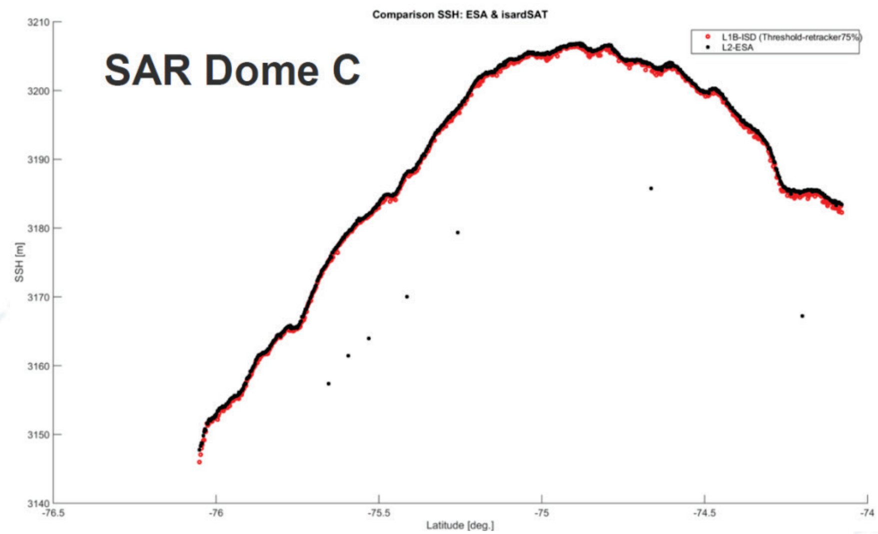
  Retrackers: OCOG and a Threshold peak retrackers.

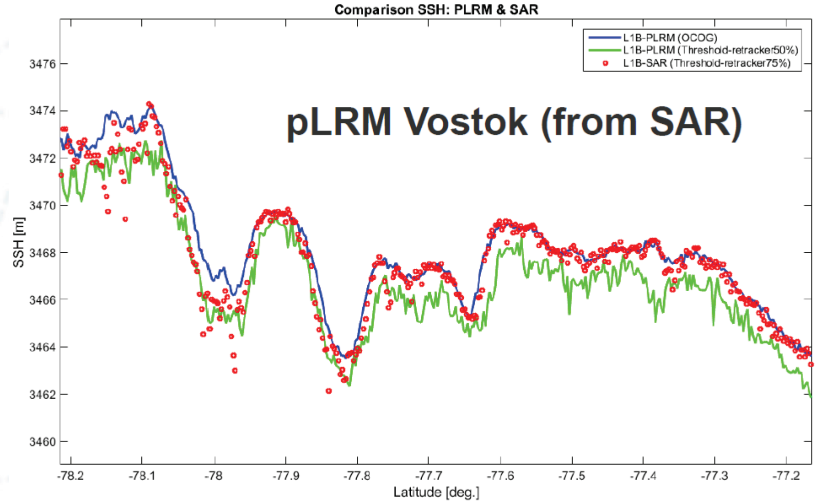
- SARin/SAR data will be also converted to SAR and pLRM.

- Dataset for validation: ESA Products, ICESat, IceBridge

L1b & L2 data data processing

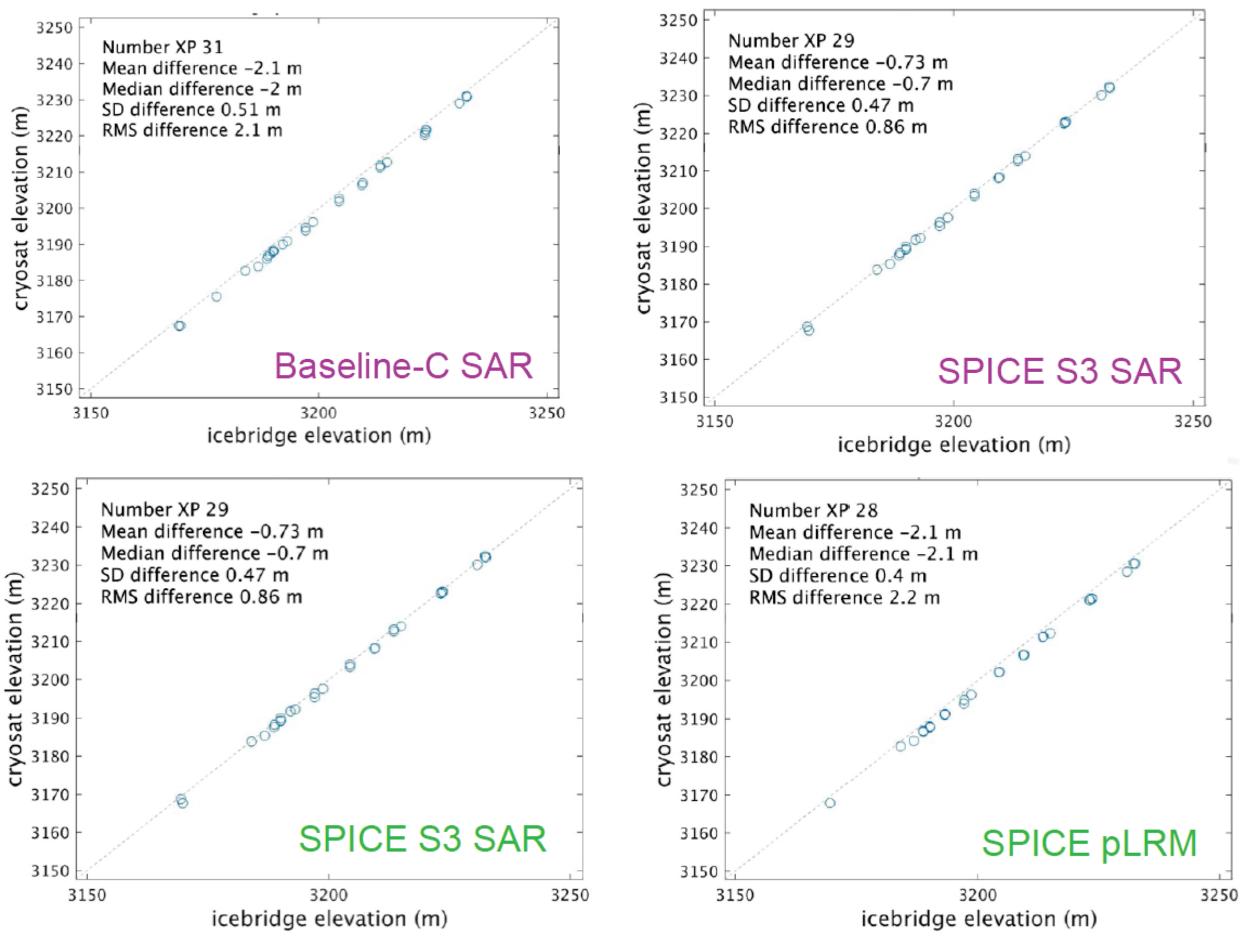
- L1B processor replicating the Sentinel-3 baseline
- Assessment of existing retrackers:
  - OCOG and Threshold peak retracker.
  - Comparison against L2 ESA CryoSat-2 products:
- **Output products available (second test dataset):**
  - SAR: L1B (all areas) & L2A (all areas)
  - pLRM from SAR: L1B & L2A (all areas)
  - SARin (Russell Glacier): available very soon.
- The implementation of both a new DDP and a new retracker based on SAMOSA & isardSAT C. Ray's formulations is currently underway.
- Retrackers assessed so far will be improved. OCOG/leading edge threshold retrackers performing better than physical model based retrackers





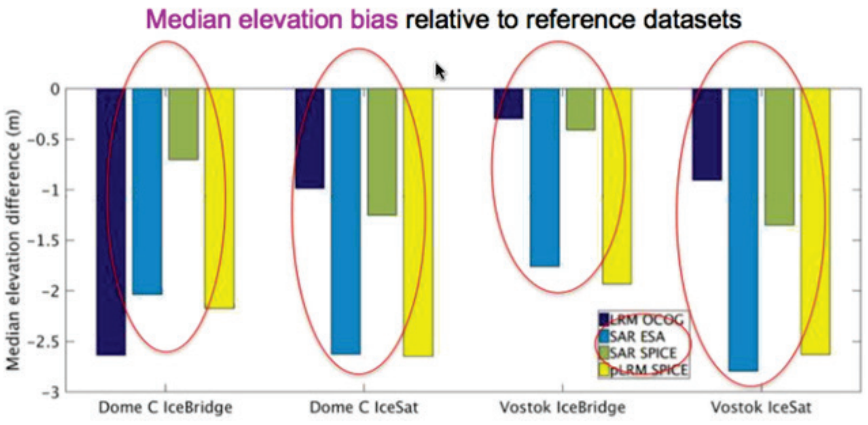
Validation

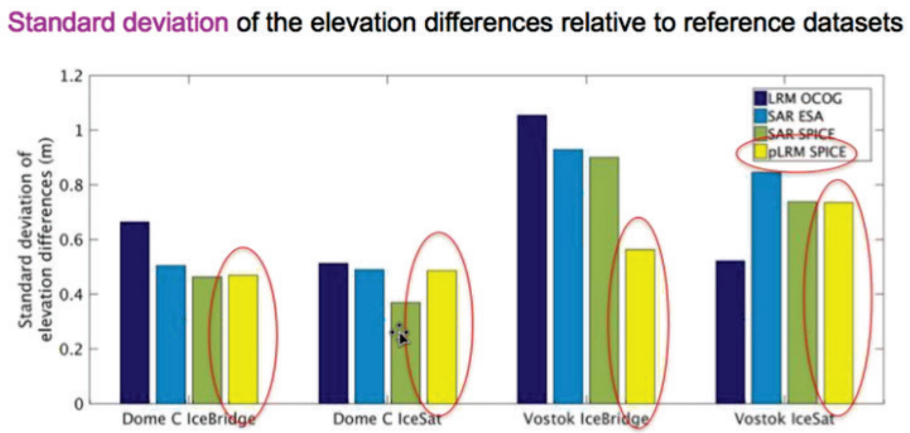
- SPICE SAR/pLRM vs ICEBridge over Dome C:



Validation (2)

- Median elevation bias/STD against reference datasets for 2 ROIs:





- SPICE SAR lower bias than ESA SAR – tracking closer to the snow-air interface.
- pLRM performing consistently well relative to other datasets.

- Preliminary analyses of both SAR and pLRM data indicate an improvement of results with respect to official ESA CryoSat-2 products.

The CRUCIAL Project in the frame of the STSE Programme

- Cryosat-2 Success over Inland Water and Land

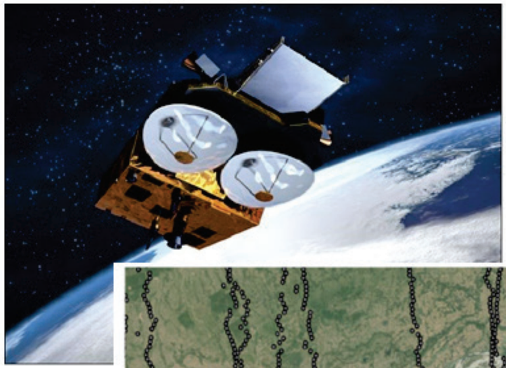
Newcastle University   DTU

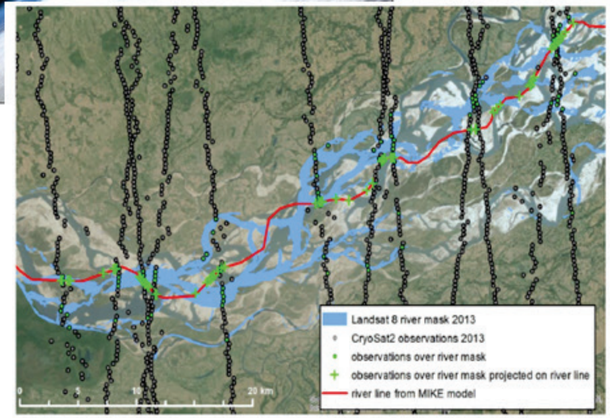
Current state: near completion.

website: http://research.ncl.ac.uk/crucial/

The CRUCIAL Project – Objectives

- **CRUCIAL** is funded by the **ESA's Support To Science Element (STSE)** Programme.
- Goal: investigate the application of CryoSat-2 data over inland water with a forward-look component to the Sentinel-3 mission.
- The high along-track sampling of Cryosat-2 altimeter in SAR/SARin modes offers the opportunity to recover high frequency signals.





Part 1: Process bursts (Q, I data)

SAR $\sim 80\ Hz, 80\ m\ along\ track$

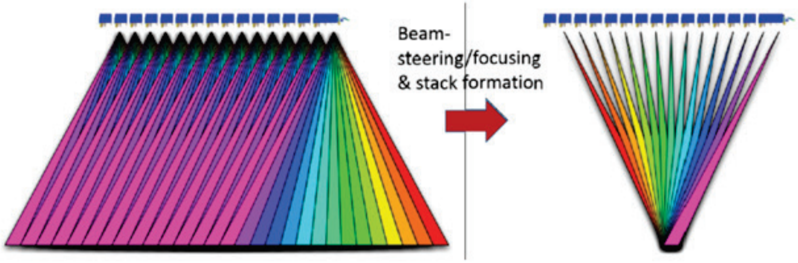
SARin $\sim 20\ Hz, 320\ m\ along\ track$

- Range FFT over 64 pulses in burst
- Beam formation and steered to nadir direction
- Heights from OCOG/Threshold retracker
- Orthometric heights using EGM08
- Coarse orthometric surface recovered from polynomial fit to ocean/inland water heights
- Improved ellipsoidal surface height by reinstating geoid

Part 2: Multi-look

$(\sim 300\ m\ along\ track)$

- Form sequence of ground points at beam angle using coarse approximate steering
- Beam formation and steered to ground points
- Stack beams pointing at ground points
  - max 240 beams in SAR mode and 60 for SARin in stack for multi-look
- Apply slant range correction, tracker range correction, Doppler range correction
- Heights from empirical and OCOG/Threshold retrackers



Regions of interest, input data and processors

- Selected regions of interest (Rivers)

- Tonlé Sap river, Cambodia (SAR)
- Mekong River (SAR)
- Amazon (SAR)
- Ocean off Amazon estuary (SARin)
- Amazon (SARin)
- Brahmaputra (SARin)

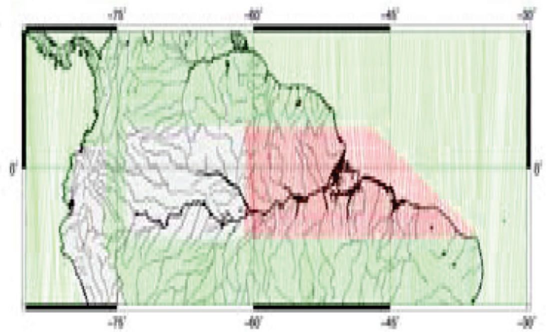


Figure 1. Amazon Basin: LRM (green), SAR (red) and SARIN(blank) tracks. Blank area is SARIN.

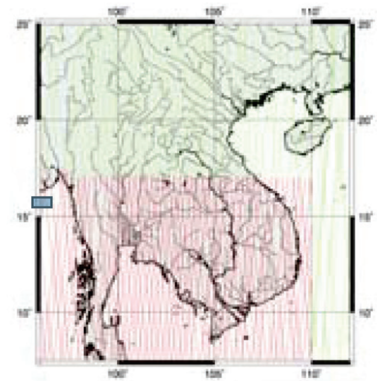


Figure 2. As Fig. 1 for Mekong

- Processing Baselines & Retrackers

- FBR to L1B: Innovative processing optimizing the number of beams in the stack for ML.
- CS-2 Baseline B SAR & SARin data as input.

- Retrackers: OCOG/Threshold retrackers, re-adapted within the project, and SAMOSA2.

- ESA G-POD SARvatore & SARinvatore service data.

Date: Friday, 24/Feb/2017

13:30 - 14:30	**SARvatore Demo and Hands-On** Salvatore Dinardo and Marco Restano

- Auxiliary dataset for validation: a) River Gauges data, b) Jason-2, Envisat and SARal-AltiKa data, c) LANDSAT data for river masks computation. D) ACE2 and other GDEM data to estimate river slope.

Project results (1) – SAR

- The speckle in the burst echoes affects the recovered heights from the 80 Hz SAR data and multi-look waveforms are essential for precise heights.

- A reduction from the maximum possible number in the stack of approximately 240 to 81 waveforms centred on the beam directed closest to nadir reduced the variability in derived heights across Tonlé Sap.

- **N=40 (2N+1=81 beams) was selected for all ROI in SAR mode**.

- The reduction of stacked waveforms sharpens the leading edge of the multi-looked SAR waveform.

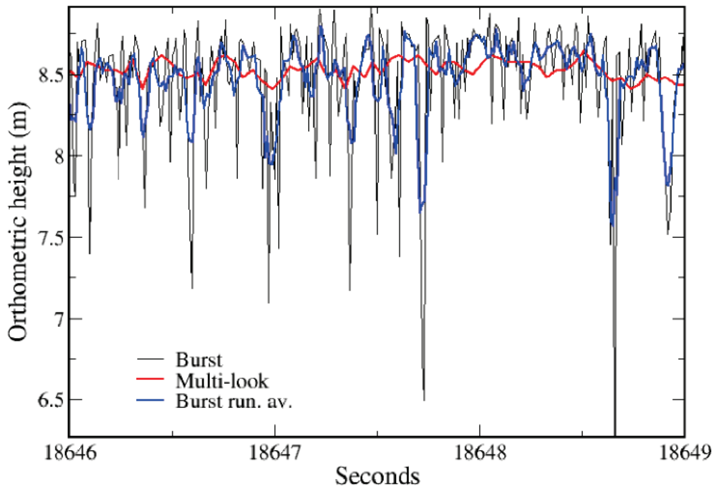
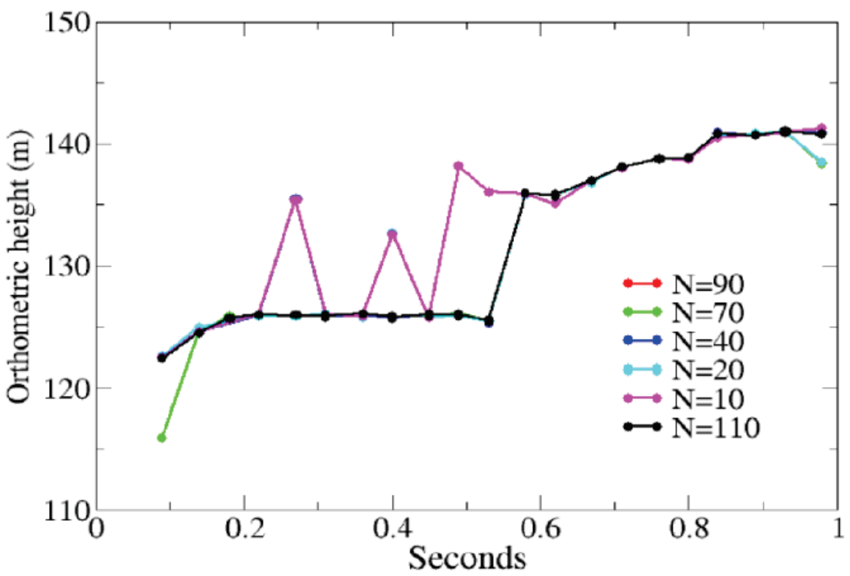
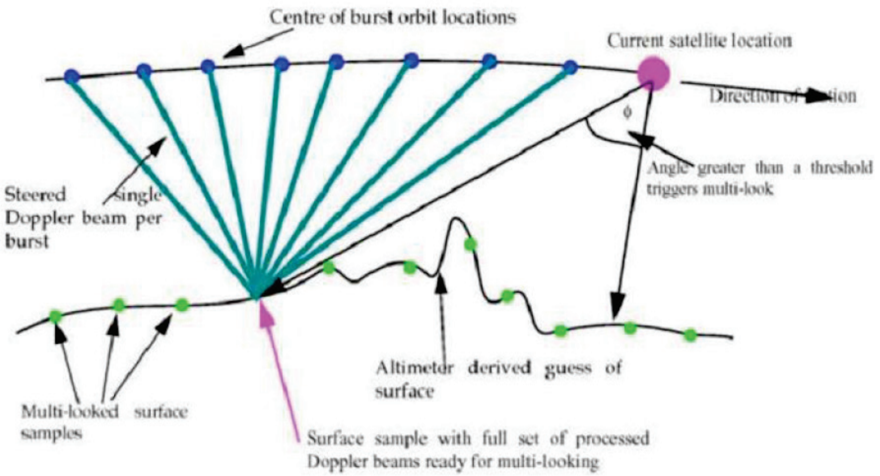


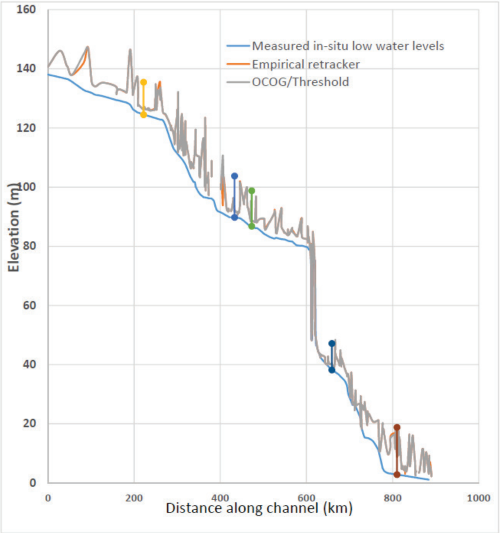
Figure 1: Pass across Tonlé Sap of 3 Dec 2011. 80 Hz burst data (black); running average over 4 points of burst data (blue) and multi-look with N=40 (red). The orthometric height is the height on the surface above the EGM96 geoid.





Validation for the Mekong ROI (SAR)

- SAR FBR heights along the Mekong (N=40). Gauges and range identified by lines/circles. Circles at gauge show low water level (Dec-Apr) and high water level (Aug-Sep).
- Validation of Cryosat-2 inland water heights along the Mekong are severely affected by the non-repeating orbit.
- **RMS errors at the Kratie gauge are equal to 67 cm (N=40) and 94 cm (N=110), respectively**. T
- These differences are comparable to those of Birkinshaw et al (2010, doi:10.1002/hyp.7811) where an RMS of 76 cm was seen for ERS-2 for the years 1995-2003 and 57 cm for Envisat for the years 2002-2008.



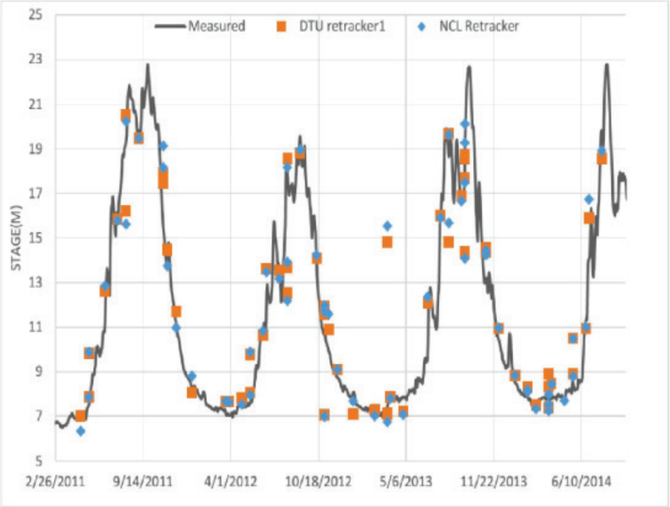
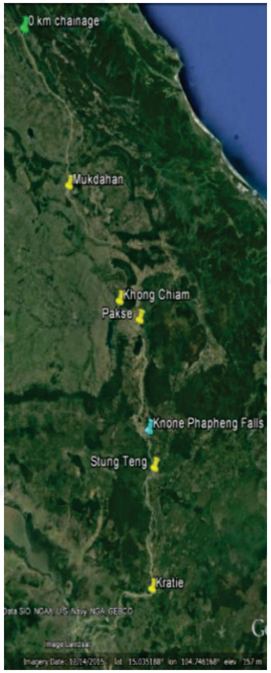


Figure 19: Comparison of Kratie gauge data with heights from near-by altimetric points from NCL (this study; N=110) and DTU. RMS 91.9 cm (NCL, empirical retrackers) and 96.8 cm (DTU).



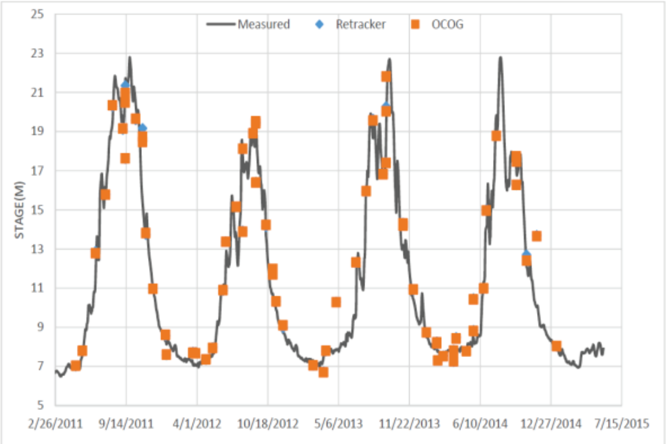


Figure 20: Comparison of Kratie gauge data with heights from near-by altimetric points from NCL (this study) waveforms using N=40. RMS 67.8 cm (empirical retrackers) and 66.9 cm (OCOG/Threshold) using 3σ rejection level.

Report of Project results – Hydrology & Data Assimilation

- Cryosat-2 altimetry data for one of the first times was used in combination with river models.
- The distributed nature of Cryosat-2 data, did not allow for the creation of Virtual Stations but provided a continuous river water level profile (higher spatial resolution).
- A procedure of cross section calibration based on Cryosat-2 altimetry data in combination with virtual station type altimetry data from Envisat was developed. This allows to accurately reproduce water levels across the entire model in space and time.

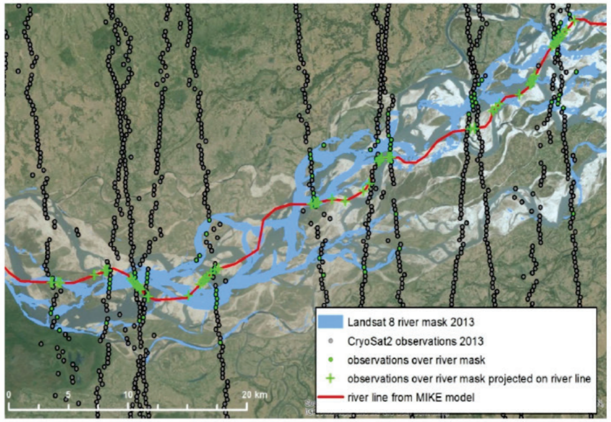


Figure 22: Section of the Brahmaputra in the Assam valley showing the Landsat river mask, the CryoSat-2 observations and their mapping to the 1D river model, all for 2013.

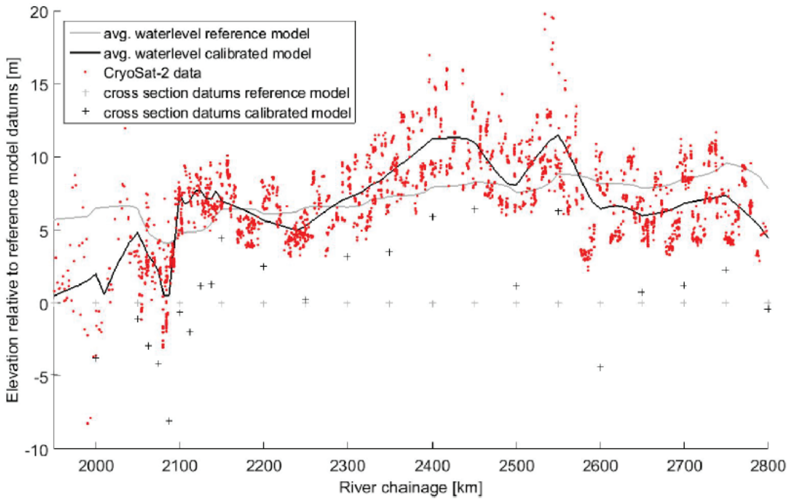


Figure 24: Result of the river bottom elevation calibration for the Assam Valley for the period 2010 to 2013. All levels are shown relative to the reference model's cross section datums based on SRTM DEM.

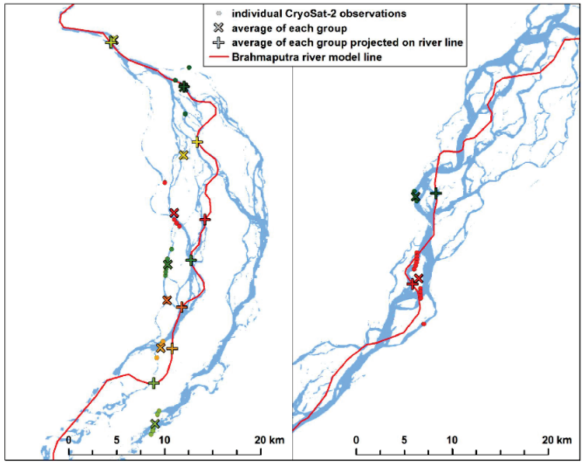


Figure 23: Clustering of individual CryoSat-2 data points from one river crossing based on k-means clustering. The left panel shows a crossing from 09-04-2011, and the right panel from 30-10-2010. Note that the panels are showing different parts of the river, with the 2010 and 2011 river mask respectively.

Report of Project results – Hydrology & Data Assimilation

- The **data assimilation (DA) of real Cryosat-2** data did improve the model prediction of in situ discharge at Bahadurabad station.

Table 8: Results of DA experiments using real CryoSat-2 data. Performance is expressed in terms of discharge at Bahadurabad station. Sharpness is given as the width of the 90% confidence intervals

		CRPS [m^3/s]	sharpness [m^3/s]
synthetic data	open loop run	3688	15647
	DA, 0.2m obs. error	2778	11500
	DA, 0.4m obs. error	2757	11336
real data	open loop run	4198	14893
	DA	3557	10957

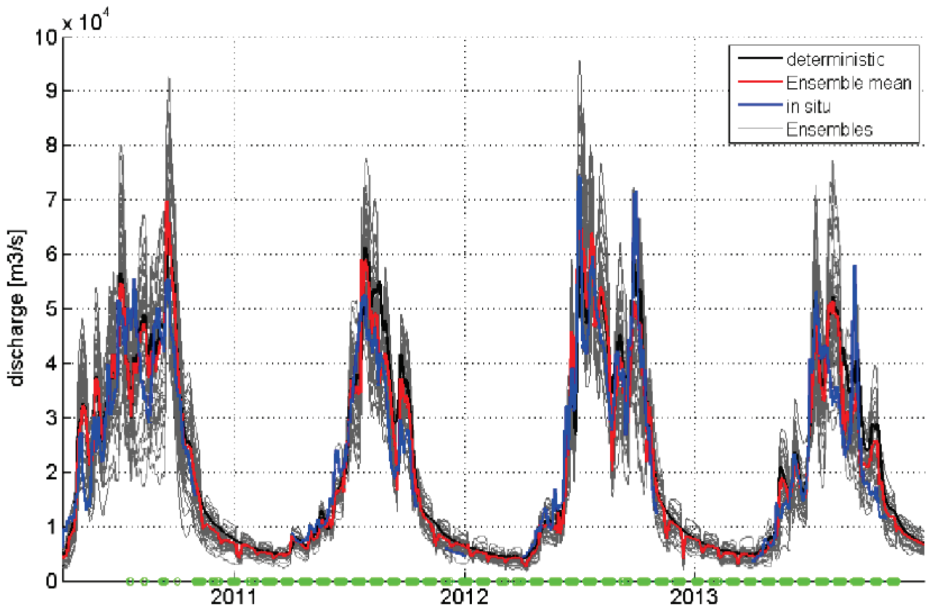


Figure 28: Results of the DA of *real* CryoSat-2 data in terms of *discharge* at Bahadurabad station. The times of observations are marked with green dots on the x-axis.