CryoSat-2 sUCcess over Inland water And Land (CRUCIAL)
ESA/ESRIN Contract 1/6287/11/I-NB

Final Presentation Meeting, ESRIN-ESA, Frascati, Italy
6 June 2017

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CRUCIAL: Overview

- CRUCIAL is funded by ESA's **Support To Science Element** (STSE), a programmatic component of the Earth Observation Envelope Programme, to investigate the application of CryoSat-2 data over inland water with a forward-look to the Sentinel-3 mission.
- CryoSat-2's primary instrument is SIRAL (SAR Interferometric Radar Altimeter). SIRAL operates in one of three modes; Low Resolution Mode (LRM), Synthetic Aperture Radar (SAR) and Interferometric Synthetic Aperture Radar (SARin).
- Previous satellite radar altimeters lost significant amounts of information due to onboard echo averaging. The high along-track sampling of CryoSat-2 altimeter in SAR/SARin modes offers the opportunity to recover high frequency signals over certain regions of the Earth's surface.
- CRUCIAL investigated processing of SAR and SARin Full Bit Rate (FBR) data to construct multi-looked waveforms and comparison against in situ water heights and contemporaneous satellite altimetric missions.
- CRUCIAL assessed CryoSat-2 radar altimetry data for river analysis and modeling. Due to the drifting ground-track, processing is more complicated for CryoSat-2 than for classical repeat-orbit missions. CRUCIAL developed methods for filtering, processing and aggregation of CryoSat-2 data over rivers and implemented a data assimilation system consisting of a one-dimensional hydrodynamic model and an ensemble filter.

CRUCIAL Work Packages and Deliverables:

email: philip.moore@ncl.ac.uk: website: http://research.ncl.ac.uk/crucial/

WP #	Work Package Title	Deliverable #	Deliverable Title
WP 1000	Scientific Requirement Consolidation	D1100	Requirement Baseline (RB)
WP 2000	Preliminary Analysis of the State-of-the-Art	D2100	Preliminary Analysis Report (PAR)
		D2200	Development and Validation Plan (DVP)
WP 3000	Data Set Collection	D3100	Data Set
		D3200	Data Set User Manual
WP 4000	Product Development and Validation	D4050	Algorithm Interim Report
		D4100	Algorithm Theoretical basis Documents (ATBD)
		D4200	Product Validation Report (PVR)
		D4300	Experimental Data Set (prototype products)
		D4400	Updated Data Set User Manual
WP 5000	Impact Assessment	D5000	Impact Assessment Report (IAR)
WP 6000	Scientific Roadmap	D6000	Scientific Roadmap (SR)
WP 7000	Outreach, Promotion and Publication	D7100	Project web site
		D7200	Publications
		D7300	Presentations
		D7400	Brochure
WP 100	Project Management and Reporting	D130	Final Report
		D140	Executive Summary

WP1000: Scientific Requirement Consolidation

ESA's R&L project pioneered near real-time inland water heights. A questionnaire in **WP1000** solicited responses for future products including

- Higher spatial and temporal resolution of flooded areas
- Water extent and discharge.
- Continuous long-term time series for large ephemeral rivers and lakes, e.g. Okavango, Lake Eyre
- Greater density of data points
- Reliability and sustainability
- The R&L data for the largest rivers should be extended to a greater number narrower river channels
- A clean filtered height data set, not containing false values as outliers.
- Uncertainty estimation of the data.
- Explanation on the data referencing, datum used and how it relates to measured data.
- Multi-location merging to create a set of high quality long-term and updated time series.
- Emulation of the USA Department of Agriculture (and DAHITI) in presenting water levels as a single file per site with each new acquisition appended in a user friendly way.

WP2100: Preliminary Analysis Report

- summary of the state of the art in waveform analysis and retracking, including results from the SAMOSA project showcasing the technical state of the art and requirements over both inland water and land surfaces. A discussion of constraints is included.
- state of the art - land.
- state of the art -inland water including both rivers and lakes.
    - Review of in-situ measurement techniques
    - Critical issues for inland water application of satellite altimetry
    - Most promising user cases for satellite altimetry

WP2200: Development and Validation Plan

- A detailed review, assessment and cross-comparison of existing products, datasets, methods, models and algorithms, as well as related range of validity limitations, drawbacks and challenges.
- A detailed analysis of the suitable models and data integration approaches as well as their related limitations, drawbacks and challenges.
- A survey of all accessible associated data sets (space, airborne and in situ) of use for development and validation activities (problems such as the lack of sufficient data sets will be investigated and practical solutions identified).
- An analysis and identification of the best candidate test areas including analysis and description of the available data over those test areas.
- Review of scientific publications in conjunction with drawing on the expertise of the consortium in related ESA projects, and other relevant research activities.

WP3000: Data Set Collection

- Cryosat -2 LRM data
- Cryostat-2 SAR L1B data
- Cryostat-2 SAR L1A data
- Cryostat-2 SARin L1A data
- Geophysical correction data
- ACE2 and other GDEM data
- Jason-2 validation data
- River mask data
- In-situ river and lake data

Milestone 2: Review of CRUCIAL Objectives

Initial analysis concentrated on

- CryoSat-2 LRM land and inland water
- L1B waveforms
- Hydrological modelling

Change of direction with emphasis on

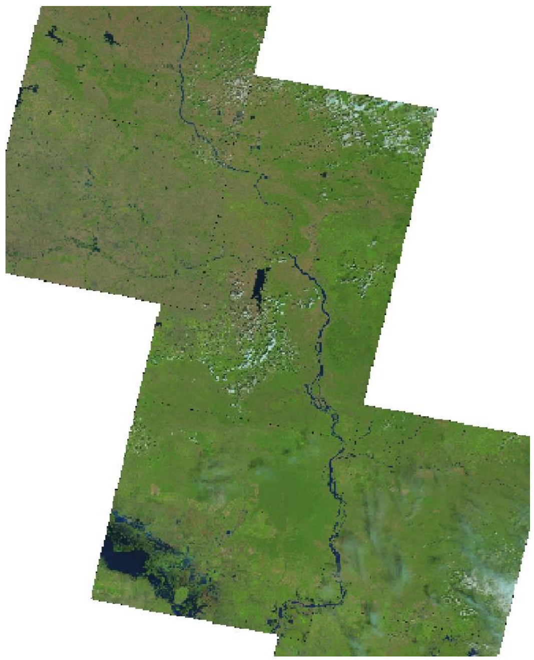
- Processing FBR L1A SAR/SARin data over inland waters
- SAR/SARin FBR L1A Product and Validation
- Hydrological modelling

WP4000/5000: Product Development and Validation and Impact

- **River Masks**
- **SAR/SARin waveforms from L1A data**
    - Multi-look Analysis from I and Q SAR/SARin telemetered data
        - Ground points
        - Zero padding doubles samples in waveforms
        - Beam steerage
        - Beam Formation
        - Retracking of waveforms over inland water
    - SARin analyses
        - Heights from two antennae
        - Coherence and cross angle
- **SAR FBR Product and Validation**
    - Tonlé Sap
    - Mekong
    - Amazon
- **SARin FBR Product and Validation**
    - Amazon
    - Brahmaputra
- **Informing regional-scale hydrodynamic models**
    - Implications of the orbit configuration for hydrologic analysis
    - Preprocessing of CryoSat-2 altimetry
    - Calibration of river morphology parameters
    - Synthetic assimilation experiments
    - Assimilation of real CryoSat-2 altimetry

River Mask: Use of Normalised Difference Water Index (I)

- Use of Normalized Difference Water Index (NDWI) (McFeeters, 1996) or NDVI (Normalized difference vegetation index)
- Uses reflectance of green band 3 and near-infrared band 5 of Landsat NDWI=(Green-NIR)/(Green+NIR).
- Mosaic of Landsat images merged
- NDWI identifies water
- Extract approximate mask to eliminate off river reflectance
- Convolve approximate mask and water for final river mask



Six Landsat images of the Mekong River between 12°N and 18°N

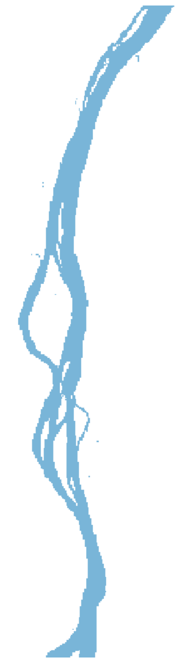
Water
12°N -18°N

Water mask
14.2°N -14.8°N

River Mask: Use of Normalised Difference Water Index (II)

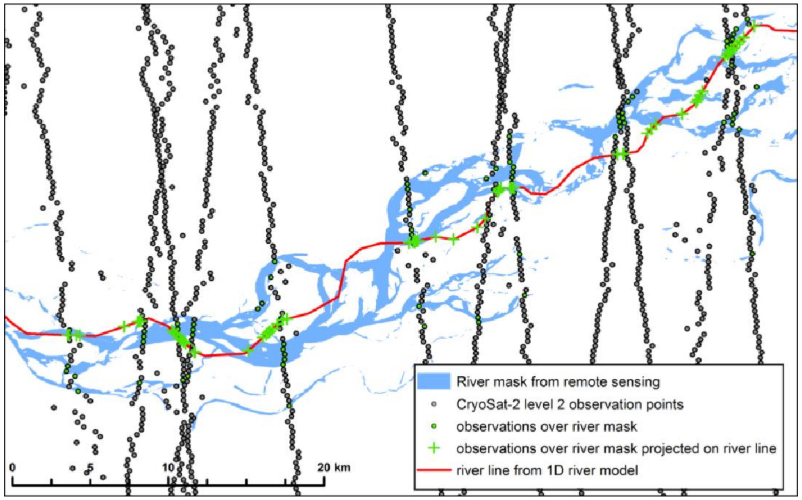
Approximate mask
12°N -18°N

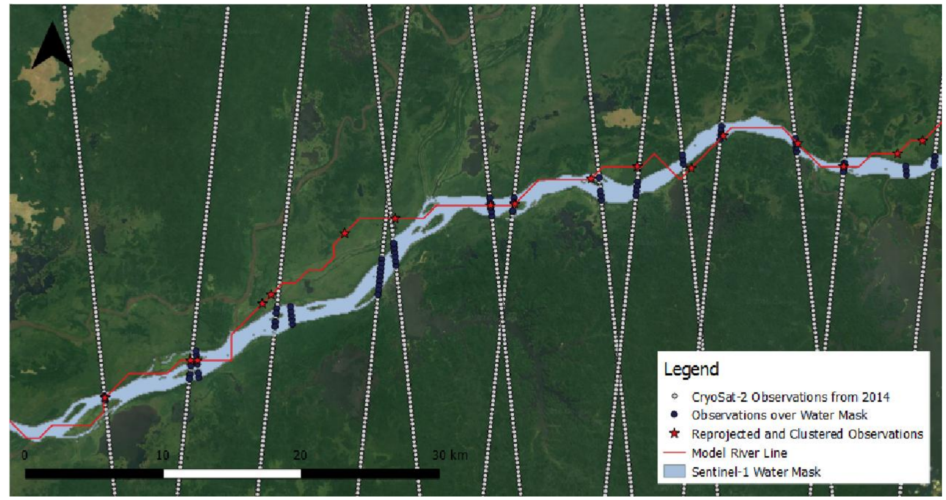
Final mask
12°N -18°N



Final mask
14.2°N -14.8°N

River Mask from NDVI and Sentinel-1 SAR





Brahmaputra water mask (NDVI<0)

Ogooué water mask from SAR

River Mask: Use of Normalised Difference Water Index (III)

- Landsat imagery is straightforward to use but may not be applicable in all locations due to cloud cover. For such areas SAR imagery can be used.
- The mask for the Mekong is not time dependent but can be temporal if imagery is used in near real-time.
- River masks over areas with large inland water distributions need to be cleared to remove spurious off-river points.
- Time-variable masks could improve coverage of satellite altimetry data
- Newcastle/DTU adopted similar approaches.

SAR and SARin FBR Parameters

Baseline B, except for data in March 2015.

SAR (Baseline B)

Burst repetition interval = 11.7 ms
Echoes per burst = 64
Tracking Samples per echo = 128
Measurement range window = 30 m
Range bin samples ~ 0.23 m
Pulse Repetition Frequency (PRF) = 18181.82 Hz
Speed of light (c) = 299792458 m/s
Carrier Frequency (CF) = 13.575e9 Hz
Wavelength: $\lambda = c/CF$
Carrier wave-number: $k_0 = 2\pi/\lambda$
Along-track antennae 3 dB width 1.0766˚ (full beam width)
Cross-track antennae 3 dB width 1.2016˚ (full beam width)
Antenna: Left of the flight direction

SARin (Baseline B)

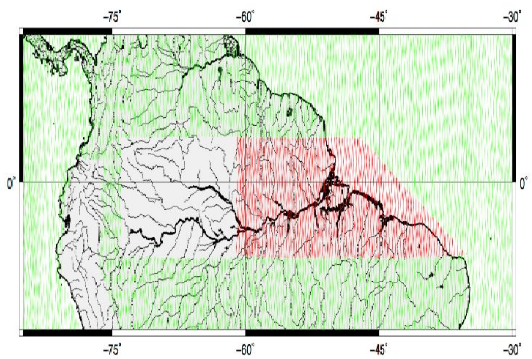
As for SAR with the exceptions
Burst repetition interval = 46.7 ms
Measurement range window = 120 m
Interferometer baseline: 1.172 m
Tracking Samples per echo = 512
Antennae: Left and right of the flight direction

Baseline configuration differences (Baseline B to Baseline C)

https://wiki.services. eoportal.org/ tiki-index.php?page=CryoSat+Technical+Notes.
Baseline C Level-1B products distributed in updated format, including attitude information (roll, pitch, yaw) and, for SAR/SARin, the waveform length doubled with respect to Baseline B.

Description	Baseline B	Baseline C	Comments
Range window samples	SAR 128 SARin 512	SAR 256 SARin 1024	Loss of trailing edge in Baseline B. No impact on quasi-specular waveforms
Range window size	SAR~ 30m SARin ~ 120m	SAR~ 60m SARin ~ 240m	As above
Window delay reference sample (range bin starting from zero)	SAR 64 SARin 256	SAR 128 SARin 512	
Attitude bias	Pitch = 0. 0˚ Roll = 0.0˚	Pitch = 0.0550˚ Roll = 0.1062˚	
Datation bias	SAR/SARin = -0.5195 ms	SAR/SARin = 0	
Range bias	SAR/SARin = 0.673 m	SAR/SARin = 0	
External phase correction	SARin = -0.612 rad	SARin = 0	

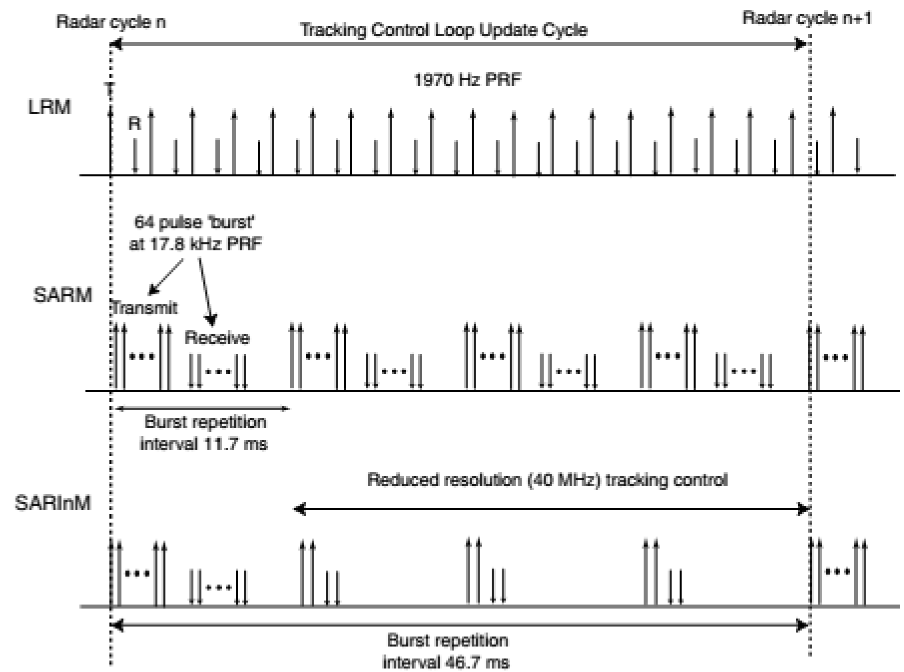
CryoSat-2 modes



Amazon Basin: LRM (green), SAR (red) and SARIN (blank) tracking.

Calibration applied to all heights

Instrument range bias
USO correction
Datation correction
Range Bias
Roll correction



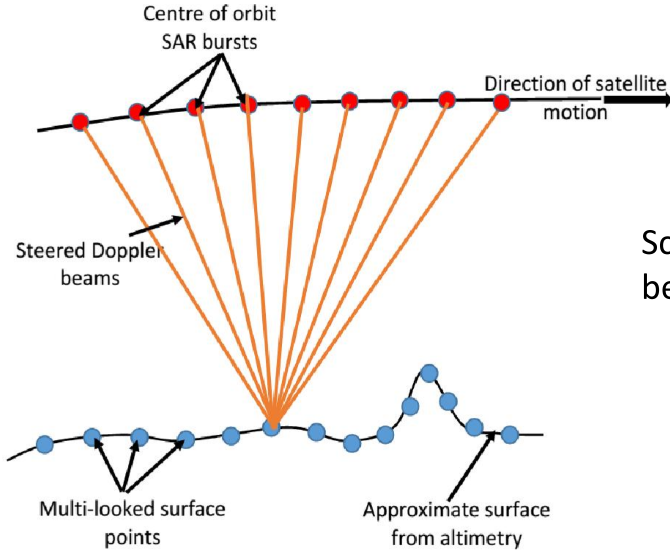
SIRAL transmission and reception timing in the LRM, SAR, and SARIn modes with transmission timing and changes in the sampling of the received echo (Wingham et al., 2006).

Multi-look Analysis

SAR/SARin multi-look waveforms ≈ 320 m along ground track; i.e. factor four reduction compared to burst echoes.

SAR (SARin) burst echoes at 80 (20) Hz processed through the following steps.

- Range FFT over 64 pulses in burst
- Beam formation and steering to nadir direction
- Form burst centre ground points from OCOG/Threshold retracker applied to nadir beam
- Form a sequence of ground points at beam angle using a coarse approximate steering
- Beam formation and steering to ground points
- Stack beams pointing at ground points
- Apply slant range correction, tracker range correction and Doppler range correction
- Height retrieval from empirical and OCOG/Threshold retrackers.
- **Details in D4100 Algorithm Theoretical Basis Document**



Schematic of bursts, the fan of Doppler beams, ground points and multi-looks

Steering to nadir/ground point directions

Use of rock angle

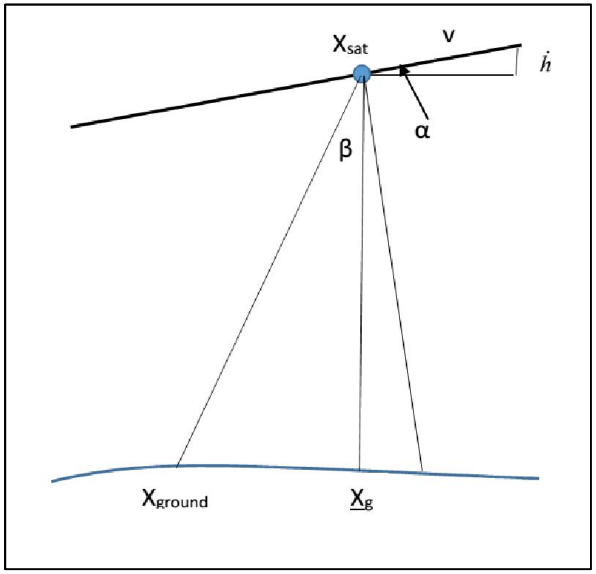
$$\alpha = -\arcsin(\dot{h} / \mathrm{v})$$

$$\beta = -\arccos\left(\frac{(\underline{X}_{ground} - \underline{X}_{sat}).(\underline{X}_{g} - \underline{X}_{sat})}{\left|\underline{X}_{ground} - \underline{X}_{sat}\right|.\left|\underline{X}_{g} - \underline{X}_{sat}\right|}\right)$$

whence

$$\theta_R^b = \begin{cases} \alpha \\ \alpha + \beta \end{cases}$$

Upper definition for nadir direction;
Lower for ground point



Inland water Empirical Retrackers

e.g. Type 1 (Specular):

Waveform given by positive and negative exponential branches with continuity at branch $t{=}t_0$ intended to capture quasi-specular waveforms

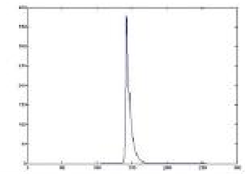
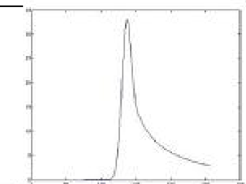
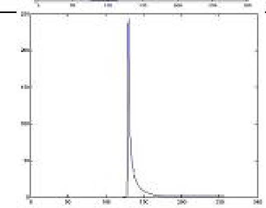
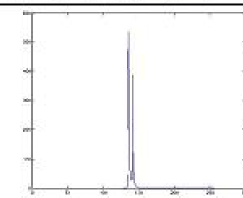
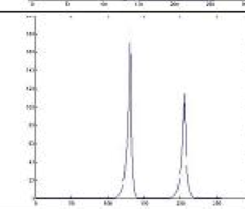
Parameters: $a,\ t_0,\ k_1,\ k_2$

$$f = \begin{cases} \left(-k_1(t-t_0)\right)^{1/2} & t \le t_0 \\ \left(k_2(t-t_0)\right)^{1/2} & t \ge t_0 \end{cases}$$

$$P = a\,e^{-f^2}$$

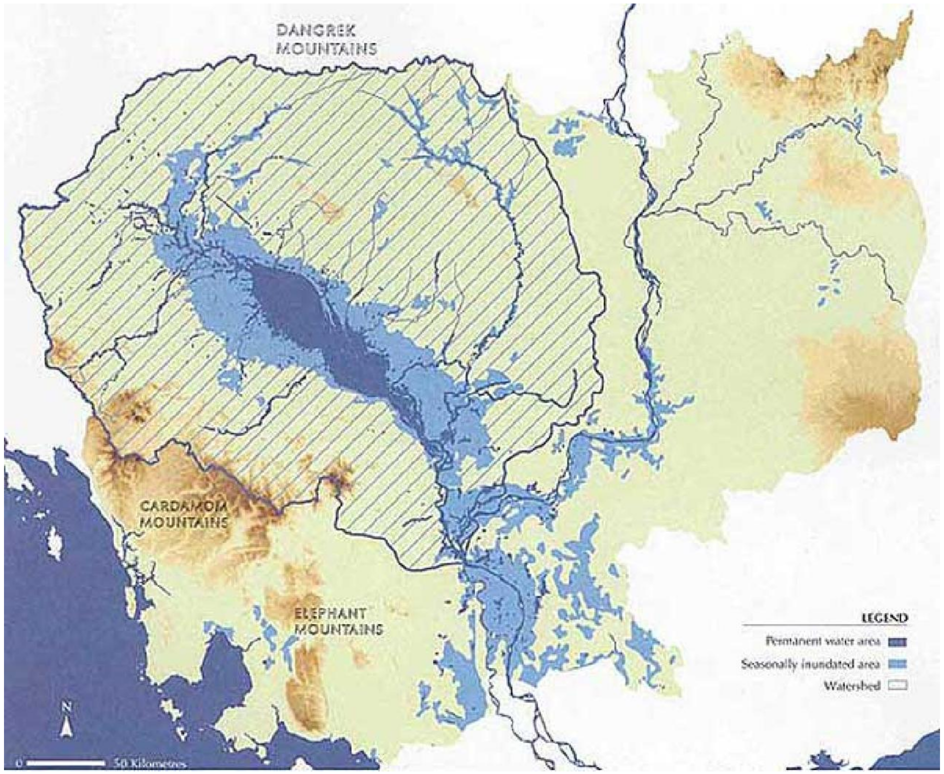
Each waveform was fitted with best fitted waveform of lowest Normalized Residual Error

$$NRE = \sum_{i=1}^{N_{pad}} (P_i^{obs} - P_i^{\mathrm{mod}})^2 \Big/ \sum_{i=1}^{N_{pad}} (P_i^{obs})^2$$

Retracker #	**Description**	**Waveform Shape**
1	Specular (still water)	
2	Ocean like (ruffled water)	
3	Ocean like with fall away at high # bins (ruffled waters)	
4	Two specular peaks (strong returns off two patches of still water)	
5	Retracker Type 2 with additional specular peak (ruffled and still water)	

FBR SAR Analysis: Tonlé Sap, Cambodia

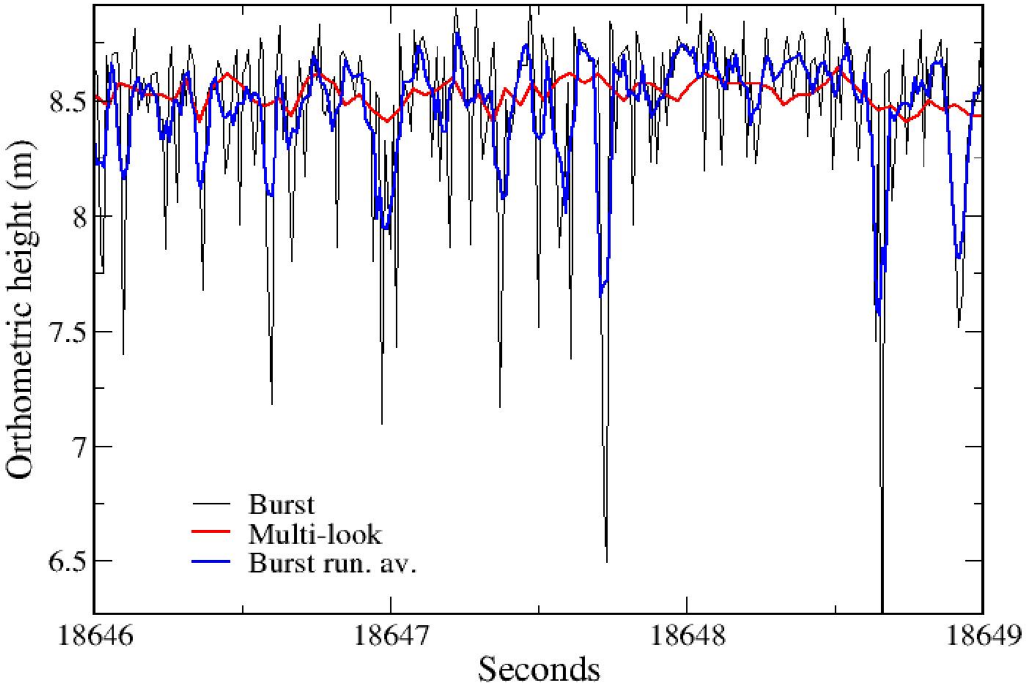
- primary validation site for FBR SAR data.
- A combined lake and river, flow changes direction twice a year; lake expanding/shrinking with the seasons. Nov to May (dry season) drains into Mekong; after heavy rains (start June) backs up to form a lake.



Seasonal variation in extent of Tonle Sap

FBR SAR Analysis: Tonlé Sap, Cambodia (3 Dec2011 Pass)

Cryosat-2 ground points across Tonlé Sap North to South pass



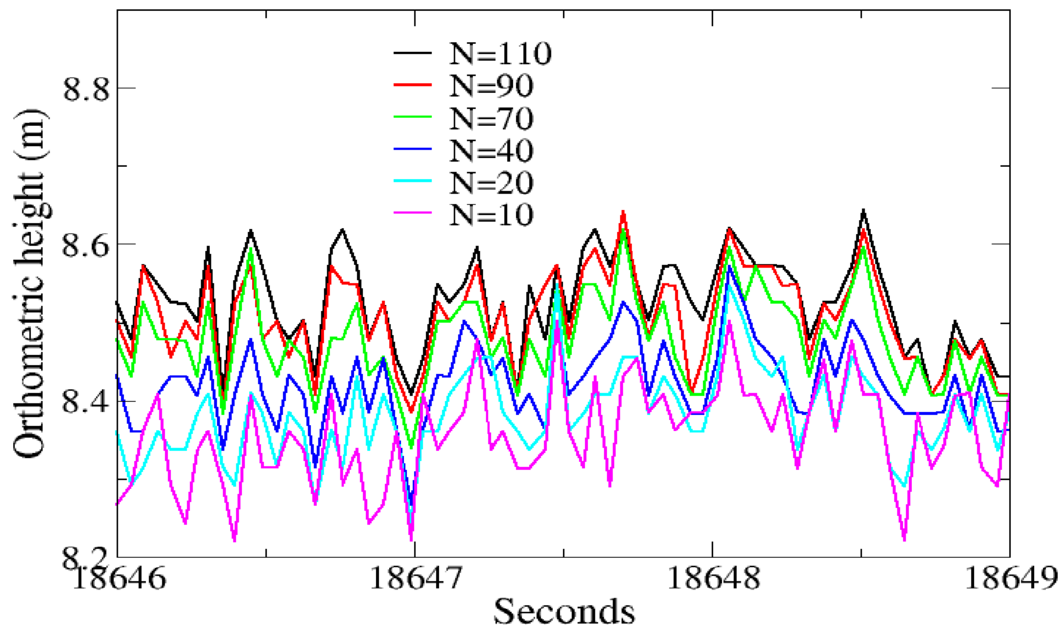
Orthometric height above EGM96 geoid. 80 Hz burst data (black); running average over 4 points of burst data (blue) and multi-look with N=40 (red).

Conclusion: Multi-looking is essential due to radar speckle in the burst echoes.

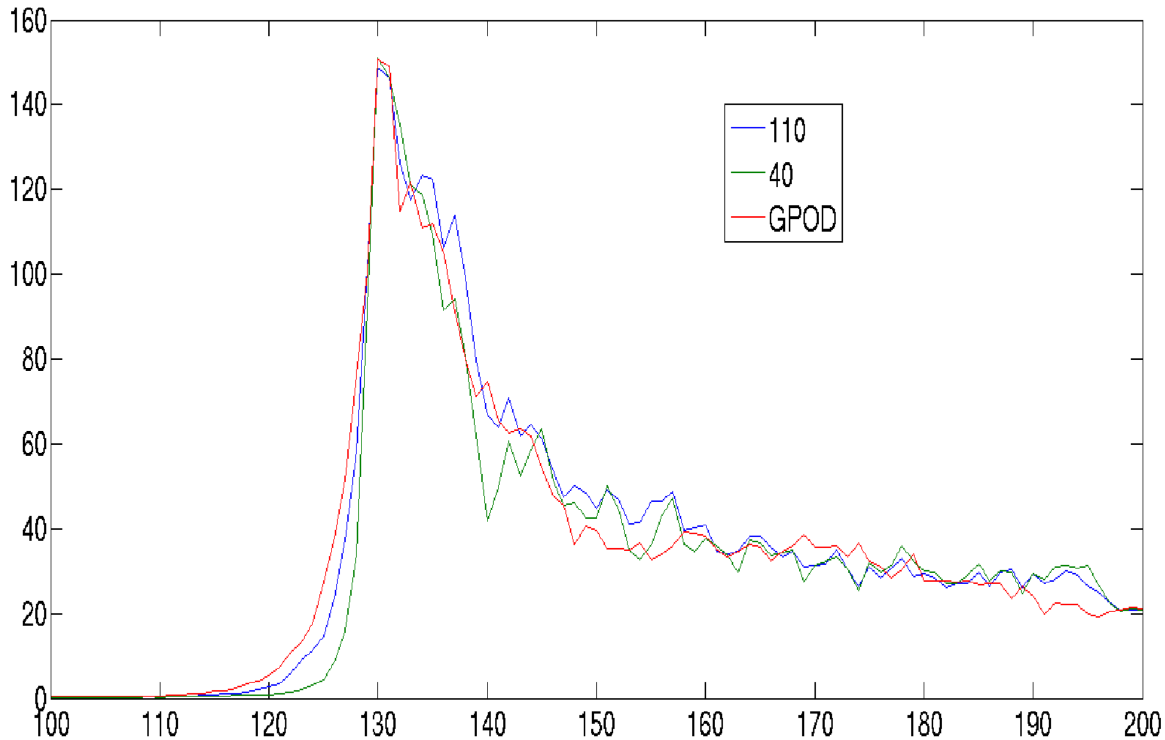
Tonlé Sap, Cambodia: Multi-looking

Multi-looking over a moderate number 2N+1 of waveforms in the stack is preferable (D4200)

- N, number of waveforms either side of burst closest to nadir with the ground point.
- Preference for N≈40, rather than maximum possible (N≈120).
- The lower N gives a steeper leading edge to waveform facilitating retracking.
- Change in N causes offset between the derived heights, indistinguishable from other contributions to altimeter bias, a fixed value for N must be applied to all analyses.
- Hamming window for weighting the waveforms outperformed a unit weight



Tonlé Sap: Waveform Comparison



WF across Tonlé Sap on 3 Dec 2011. Waveforms from G-POD and N=110 and 40 aligned at peak (amplitude and bin). X-axis bin number. The earlier bin retracked point for large N causes the range to surface to decrease, i.e. the land/water height above reference ellipsoid (and hence orthometric height) to increase. Lower N increases the noise on the waveform tail.

Tonlé Sap, Cambodia: Multi-looking

Multi-look N	Sigma Empirical retrackers (cm)	Sigma OCOG/Threshold (cm)
G-POD: SAMOSA2	7.30	
G-POD: retracked	5.63	6.60
140	5.69	6.14
	6.01	6.23
110	5.72	6.08
	6.01	6.23
90	5.75	6.01
	6.01	6.23
70	5.58	5.81
	5.89	6.35
40	5.01	5.38
	5.87	5.88
20	5.20	5.09
	5.88	5.67
10	5.94	5.35
	5.74	5.03
5	9.20	7.66
	7.59	6.92

Statistics of fit for pass across Tonlé Sap 3 Dec 2011. G-POD: value from closest fit to CRUCIAL ground points in time. CRUCIAL values: top cosine weighting; lower unit weight.

Conclusion: For SAR mode, a reduction in the number of waveforms in the stack to about 81 (N=40) centred on the near nadir burst is preferred.

Conclusion: A weighting system based on the Hamming window is strongly recommended.

Tonlé Sap, Cambodia: Height Validation

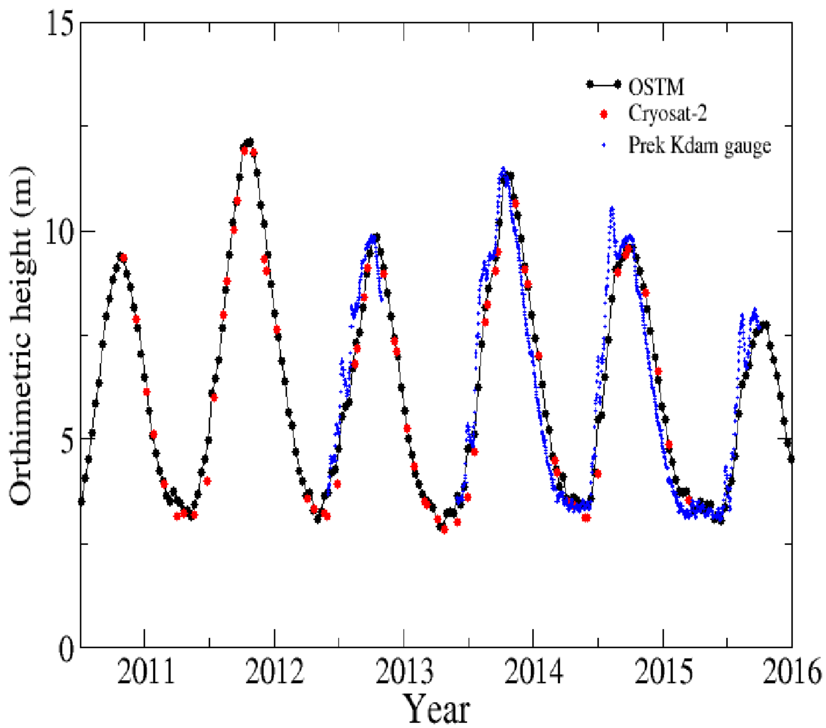
Google earth image of Tonlé Sap showing locations of

- 62 CryoSat-2 passes.
- 2 gauges (turquoise markers).
- S-N OSTM altimetric pass (red marker).

Internal consistency of pass provides measure of the scatter in the data. Points either side of Tonlé Sap midline accepted until multi-look waveform best retracked by double peak empirical retracker identifying reflectance off two water surfaces. Maximum of 10 data points either side of midpoint imposed in the first instance. Passes with 5 or less accepted points rejected. A total of 34 passes gave RMS 2.44 - 6.54 cm, with mean 4.35±0.10 cm. Increasing points either side of Tonlé Sap centre from 10 to 20 gave RMS 1.2 - 18.7 cm with mean 6.0±3.4 cm. Risk in low flow regimes some points could be overland.

Conclusion: Crysosat-2 SAR heights have precision of 4-6 cm on average.

Tonlé Sap, Cambodia: Height Validation



Time series of aligned heights across Tonlé Sap.

Prek Kdam days advanced	Correlation OSTM	Correlation Kumong Luong
0	0.962826	0.934639
6	0.982969	0.961042
11	0.988296	0.978429
12	0.988325	0.980823
13	0.987864	0.982860
17		0.987490
18		0.987807
19		0.987806
20		0.987491

Time difference and auto-correlations between gauge data at Prek Kdam against the Kumong Luong gauge data and OSTM altimetric heights.

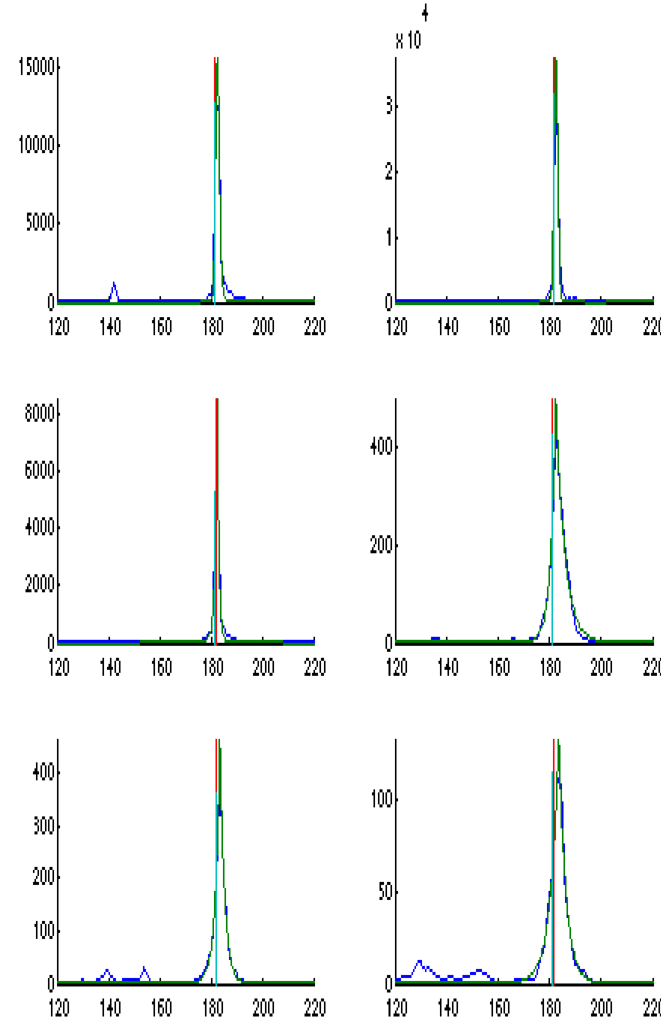
Satellite	#	RMS v Prek Kdam(t+12) (cm)
OSTM	99	42.6
CryoSat-2	26	42.1

RMS differences between Prek Kdam gauge advanced 12 days and OSTM and CryoSat-2 altimetric heights

Conclusion: We cautiously infer that CryoSat-2 is performing better than OSTM across Tonlé Sap.

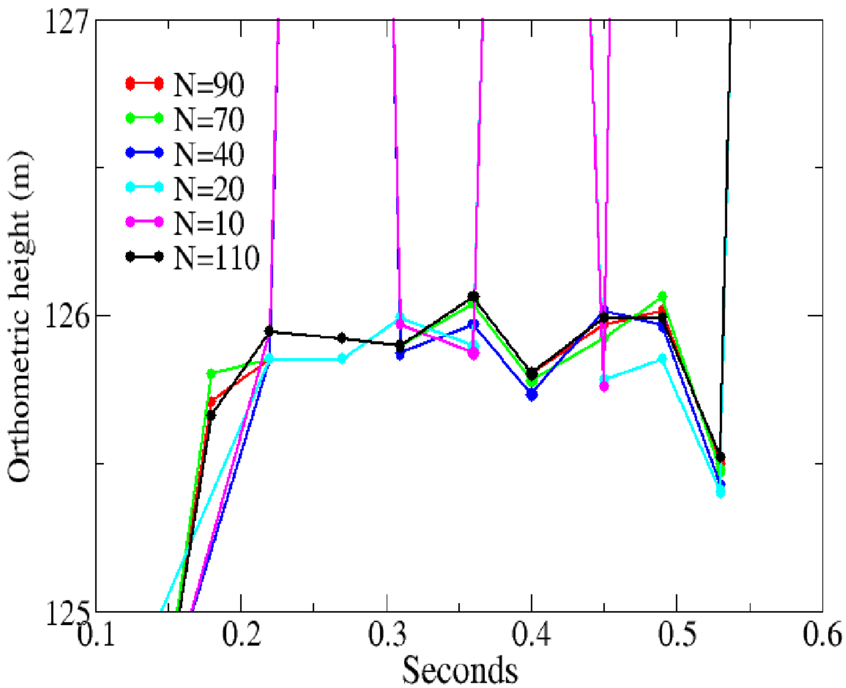
Mekong: Waveforms

Google Earth image of 19 Apr 2011 Mekong crossing. Satellite ground track N-S

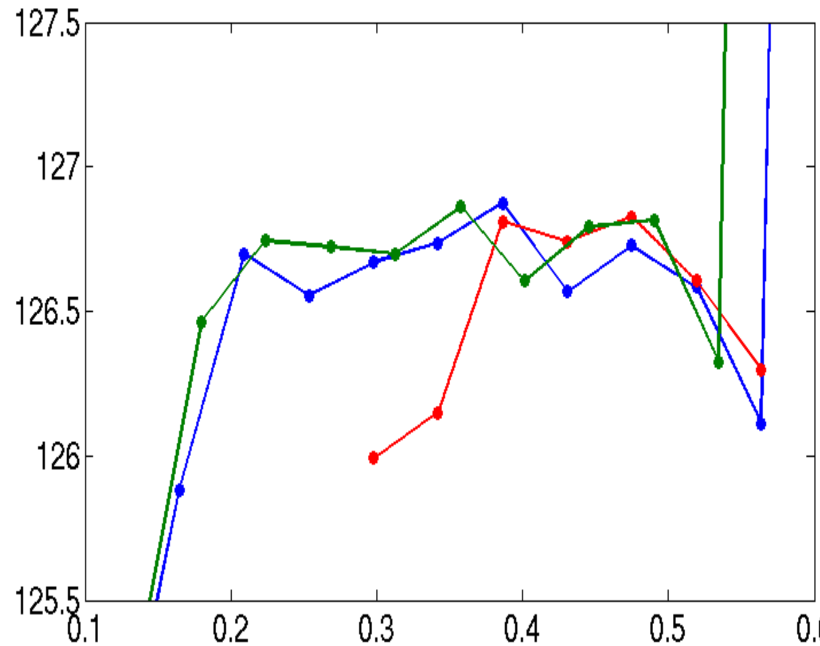


Waveforms (blue curve) across the Mekong (N=110) with empirical retracker (green curve) with retracked bin given by red line; cyan line shows OCOG/Threshold retracked bin

Mekong: Heights from Multi-look Waveforms



Orthometric heights from empirical retrackers across the Mekong for 19 Apr 2011 (seconds after 59084) for various number of echoes in multi-look.



Orthometric heights. G-POD heights (red), retracked G-POD waveforms (blue) and cosine weighted waves (green) using N=110.

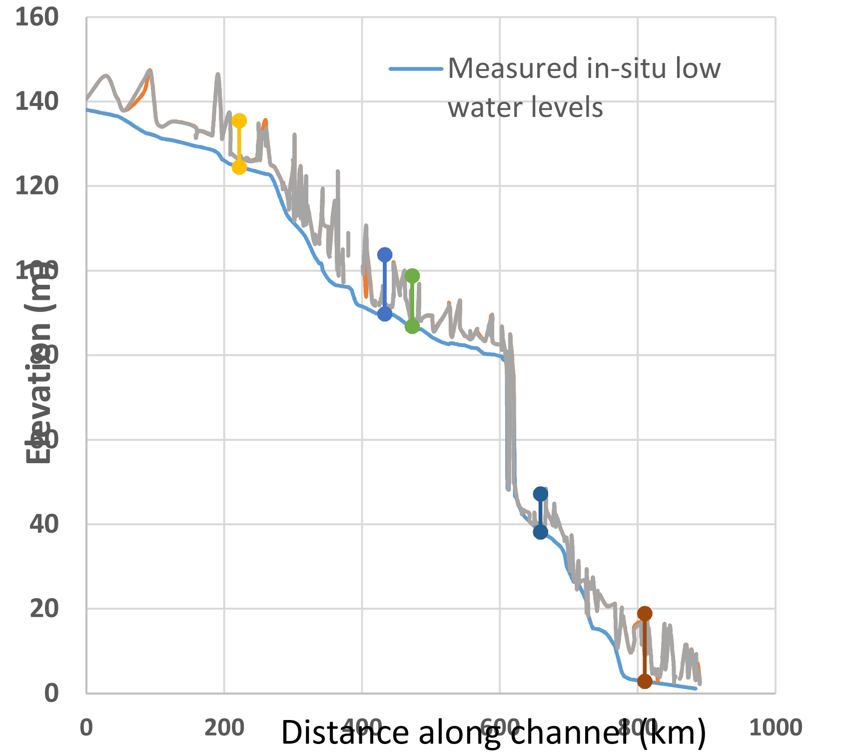
Conclusion: The SAMOSA2 retracking in G-POD is inappropriate for inland waters. Retracking G-POD waveforms using the empirical trackers developed in CRUCIAL or with the OCOG/Threshold retracker yields enhanced results.

Mekong: Height Validation

Location of 5 gauges along Mekong, the Khone Phapheng Falls and the 0 km chainage point.

CryoSat-2 heights assigned to nearest gauge and corrected to gauge location using low water level slope. Correction less accurate at high water levels as range not consistent along the Mekong. DTU supplied retracked heights based on L1B waveforms. RMS between DTU and NCL heights is 9.1 cm including values that are clearly off the Mekong.

Conclusion: Heights from CRUCIAL and independent retracking of SAR L1B waveforms is 9 cm RMS for the Mekong.



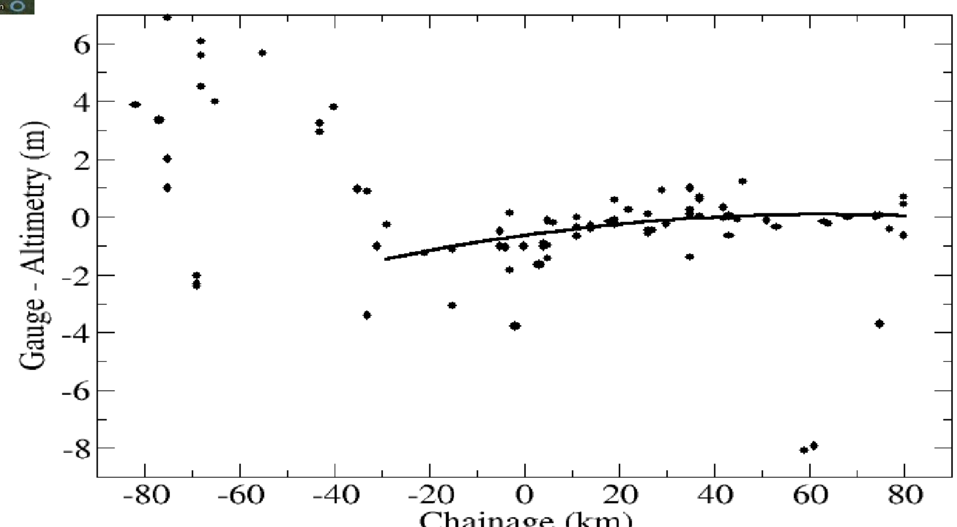
SAR FBR heights (N=40). Gauges and range identified by lines/circles. Circles at gauge show low water level (Dec-Apr) and high water level (Aug-Sep). Waterfall located at chainage 620km. The 0 km chainage location corresponds to (18.23536°N, 104.0412°E).

Mekong: Height Validation near Kratie

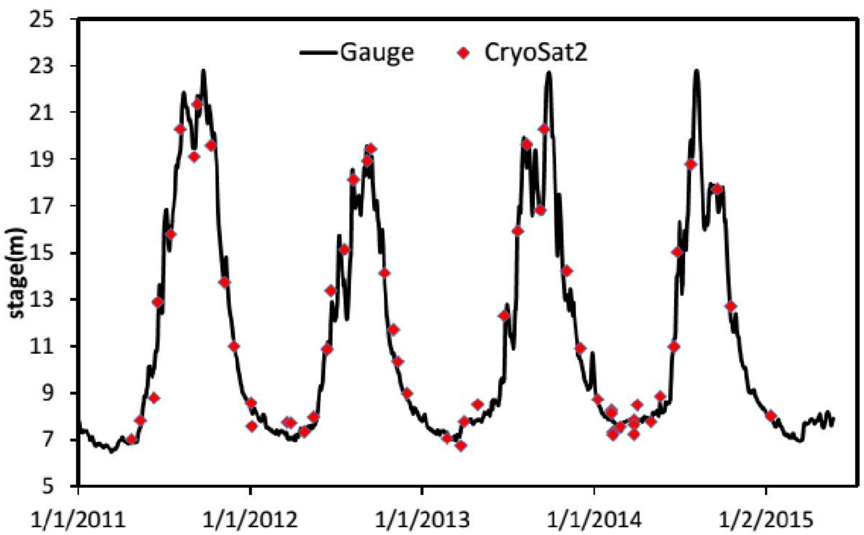
Of 5 gauges only Kratie permitted detailed investigation

Google earth image overlaid by CryoSat-2 passes across the Mekong near the Kratie gauge (red circle) and the two ENVISAT/Altika crossing points. The river width is about 1900 m. DAHITI (Schwatke et al., 2015a) altimetric heights from the near identical ground tracks of ERS-2, Envisat and Alitka are available for two crossings 7 km and 43 km downstream from Kratie.

Differences between gauge heights at Kratie and the CryoSat-2 heights modified for river slope (courtesy of Mekong River Commission).



Mekong: Height Validation near Kratie



FBR SAR heights (N=40, empirical retrackers) near Kratie (RMS 59.9 cm). CryoSat-2 data taken within range 5 km upstream to 80 km downstream of gauge.

Data Provider	Satellite	Period	RMS (cm)
CRUCIAL	Cryosat-2	Jan 2011 - Mar 2015	54.0
DAHITI	Envisat	Jul 2002 – Nov 2010	62.0
DAHITI	Altika	Jun 2013 – Nov 2014	47.2
River&Lakes	ERS-2	Apr 1995 – Jun 2003	70
River&Lakes	Envisat	Jul 2002 – Mar 2006	65

Mekong near Kratie: Comparisons of altimetric and gauge data. Cryosat-2 data corrected for quadratic slope

Conclusion: Comparison against gauge date is dependent on distance from gauge for a non-repeating orbit even if correction is made for river slope.

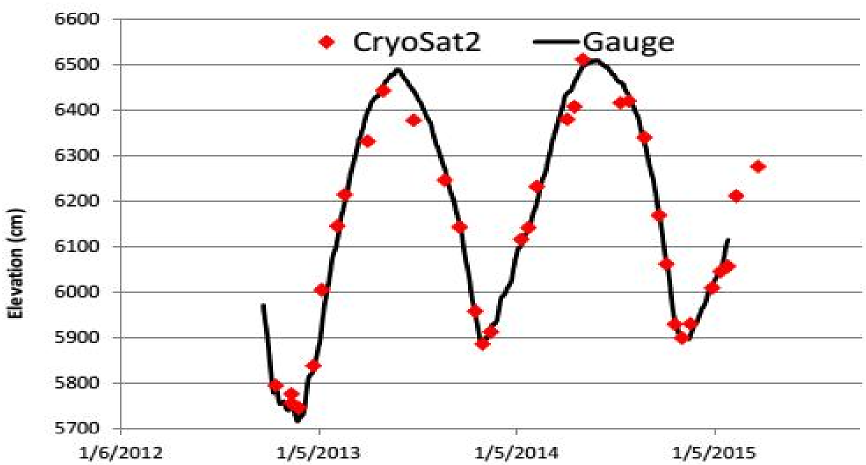
Conclusion: Given the conclusion about distance from gauge the CryoSat-2 comparisons are comparable to ENVISAT at Kratie on the Mekong but less accurate than SARAL/Altika.

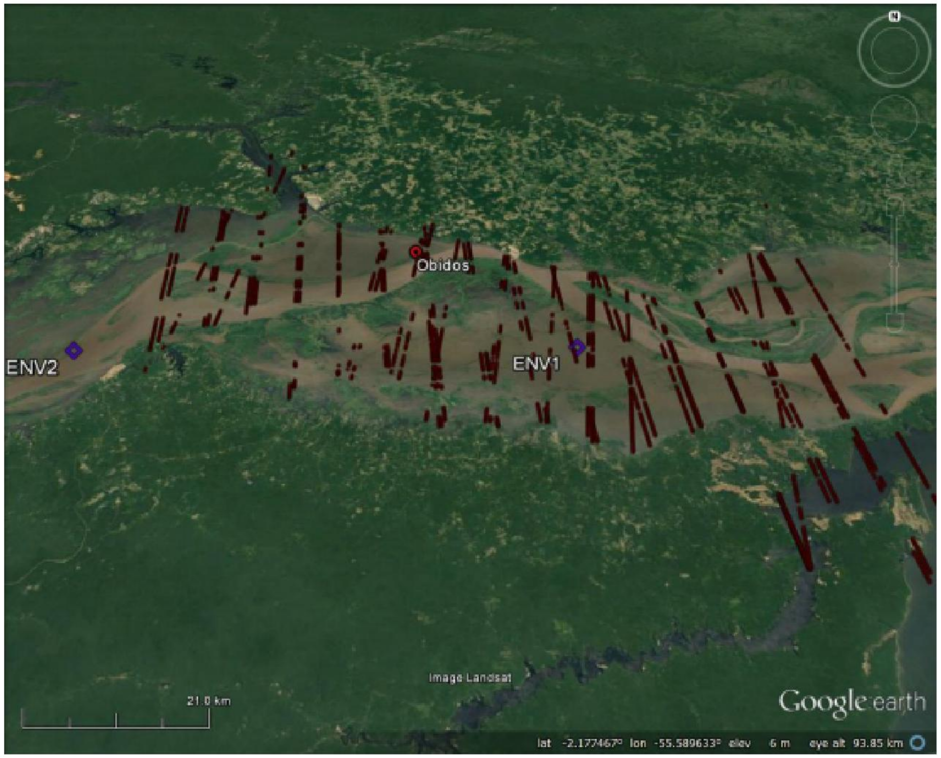
Ka band altimeter (35.75 GHz) of SARAL/AltiKa insensitive to ionosphere. The high frequency has advantages over Ku band altimeters: (1) reduced antenna beam width; (2) reduced radar footprint; (3) increased Pulse Repetition Frequency; (4) better range resolution (0.47 m Envisat/CryoSat-2 etc, 0.3 m SARAL/AltiKa). The disadvantage is its sensitivity to rain and clouds reducing the operational window

SAR FBR Analysis: Amazon Gauge Comparison near Obidos

Gauge at Obidos (1.9225°S, 55.6753°W).

- mean height over 11 points centred on mid crossing point; heights in excess of 1 m from from median rejected (sd 5-20 cm).
- data over long stretch approximately ± 45 km from gauge





Source	Satellite	Crossing	Date	Sigma (cm)	#
DAHITI	ENV+AltiKa	ENV1	May 2002 - Jun2016	37.4	92(2)
	ENV		May 2002 – Oct 2010	40.2	77(0)
	AltiKa		May 2013 – Jun 2016	17.4	15(2)
	ENV+AltiKa	ENV2	May 2002 – Jun 2016	56.4	103(2)
	ENV		May 2002 – Oct 2010	57.7	78(0)
	AltiKa		May 2013 – Jun 2016	26.3	25(2)
CRUCIAL	CryoSat-2	Various	Oct 2012 – Apr 2015	36.1	34(0)
	CryoSat-2		Oct 2012 – Apr 2015	34.9	34(0) slope adj
	CryoSat-2		Oct 2012 – Apr 2015	27.3	32(2) slope adj + 2.5σ

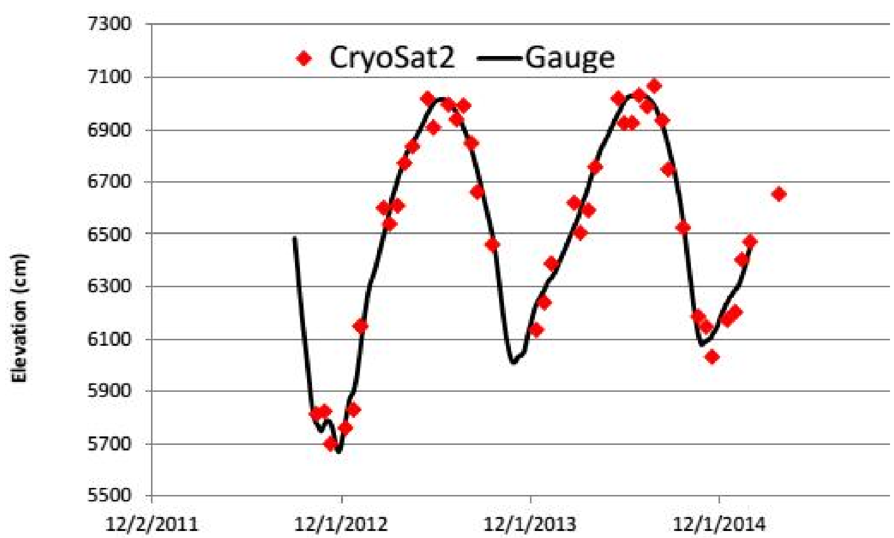
Google earth image overlaid by CryoSat-2 passes across the Amazon near the Obidos gauge (red circle) and the two ENVISAT/AltiKa crossing points.

Comparison of altimetry against the Obidos gauge on the Amazon. Final column gives number of accepted measurements with rejected points in parenthesis.

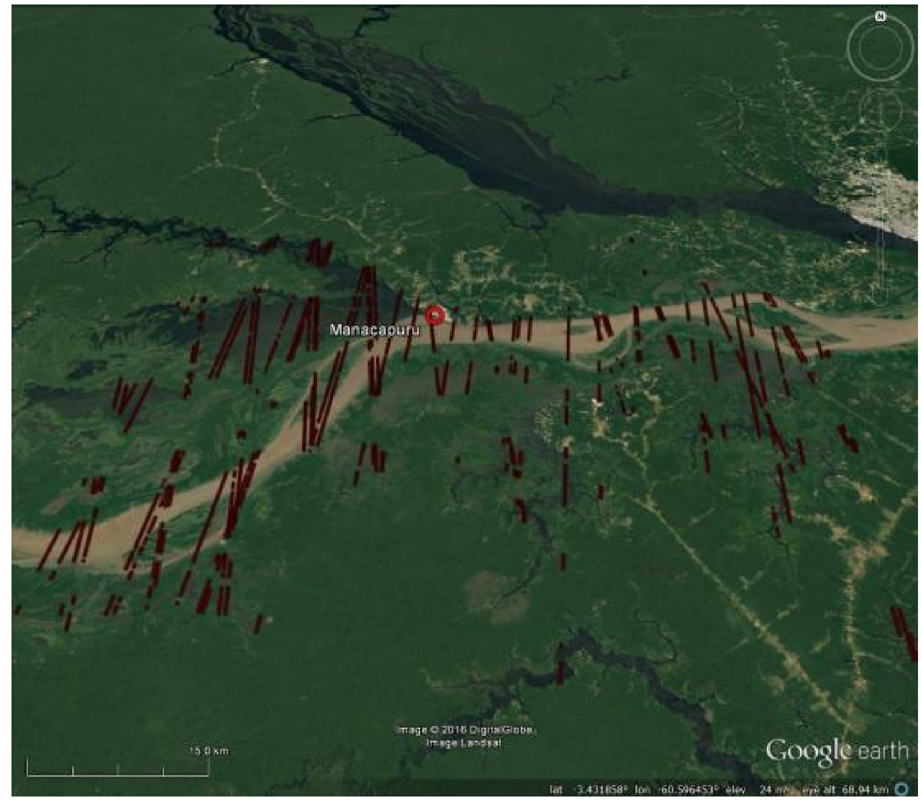
SAR FBR Analysis: Amazon Gauge Comparison near Manacapuru

Gauge at Manacapuru (3.3122°S, 60.6303°W) 650 km upstream of Obidos

- mean height over 11 points centred on mid crossing point; heights in excess of 1 m from from median rejected (sd 5-20 cm).
- data over long stretch approximately ± 45 km from gauge



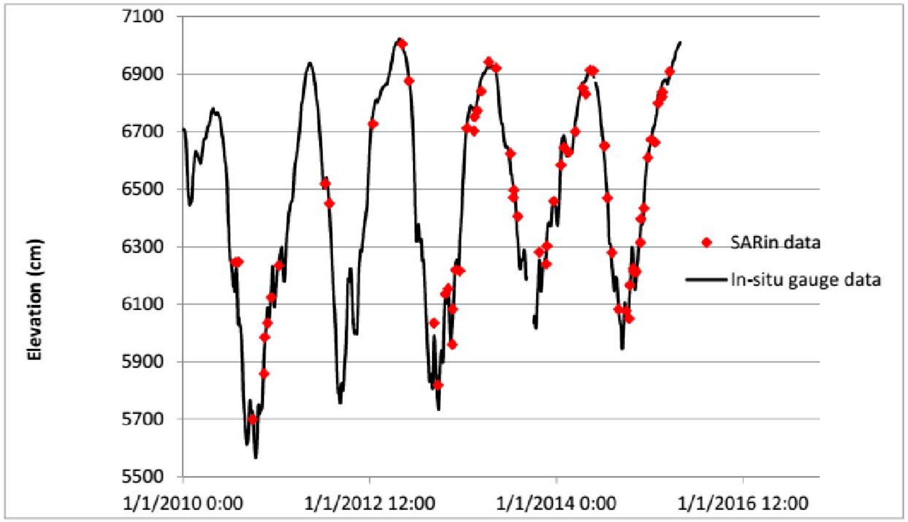
FBR SAR heights (N=40, empirical retrackers) near Manacapuru (RMS 53.6 cm)

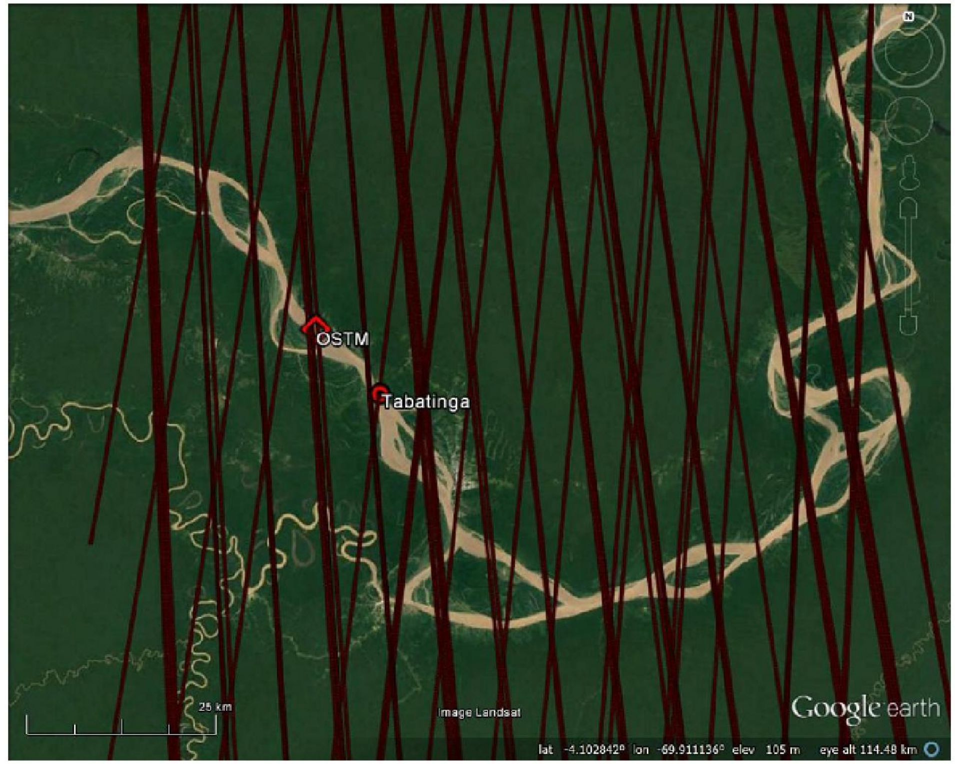


Google earth image overlaid by CryoSat-2 passes across the Amazon near the Manacapuru gauge (red circle).

SARin FBR Analysis: Amazon Gauge Comparison near Tabatinga

Google earth image of Amazon near Tabatinga; gauge marked as red circle with Jason-2/OSTM crossing denoted by red diamond.





Tabatinga gauge heights and CryoSat-2 SARin (N=60, OCOG/Threshold) heights corrected for river slope. With some SARin mode passes ≈ 2 days apart, but differ in longitude by 1.2˚ the difference between heights gave slope of the river. RMS difference 29.9 cm.

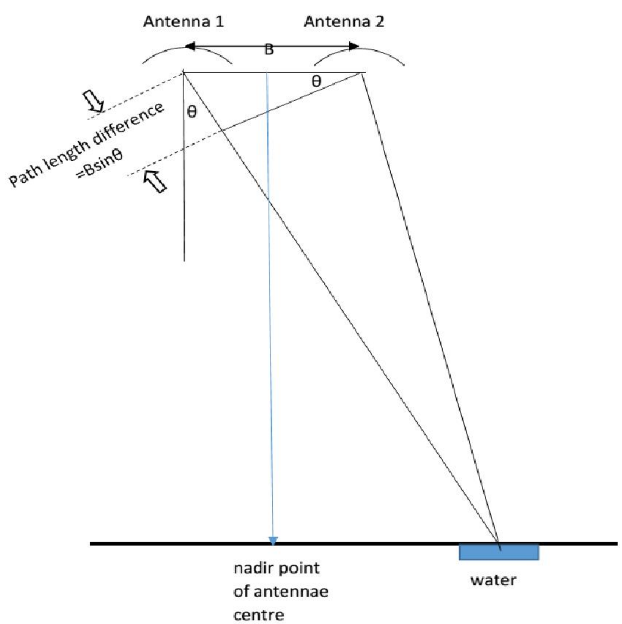
The CryoSat-2 value is comparable to the RMS of 29.1 cm from 445 points of a Jason-2/OSTM crossing about 8 km from the gauge.

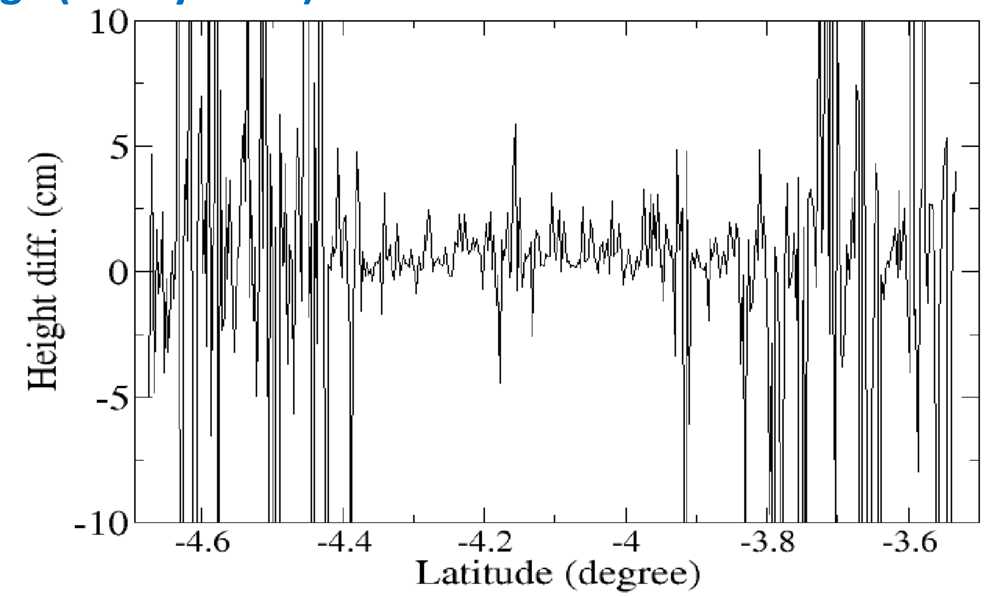
Conclusion: Despite utilizing crossings over a 150km stretch the CryoSat-2 agreement with the Tabatinga gauge data is comparable to the Jason-2/OSTM DAHITI gauge data for a crossing just 8 km from the gauge.

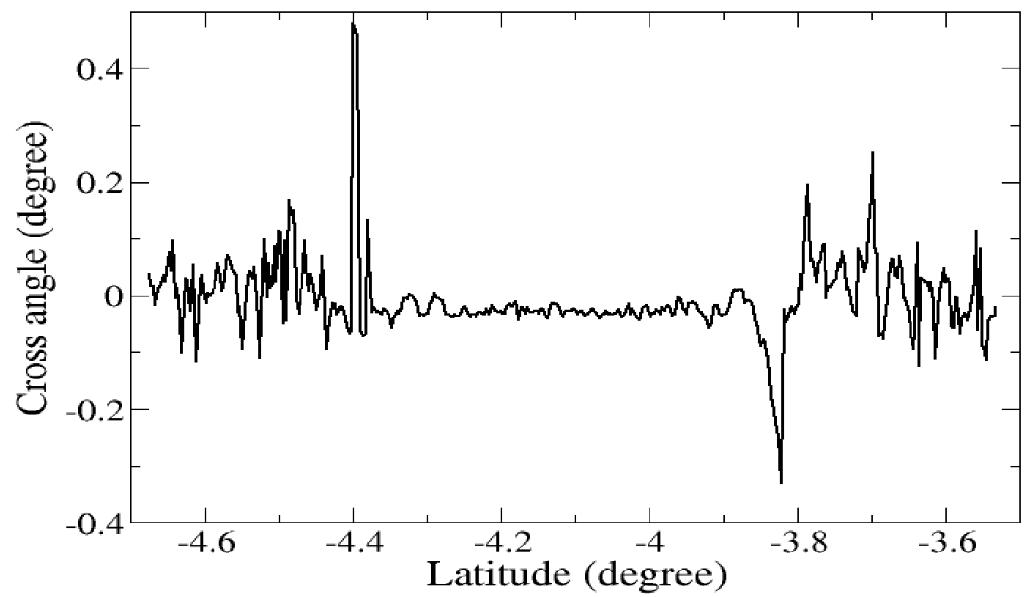
SARin FBR Analysis. Amazon near Tabatinga (5 May 2012).

OCOG/Threshold based difference between heights from the two SARin antennae.

Conclusion: The two antennae provide height measurements to within 1 cm (standard deviation) over flat areas.



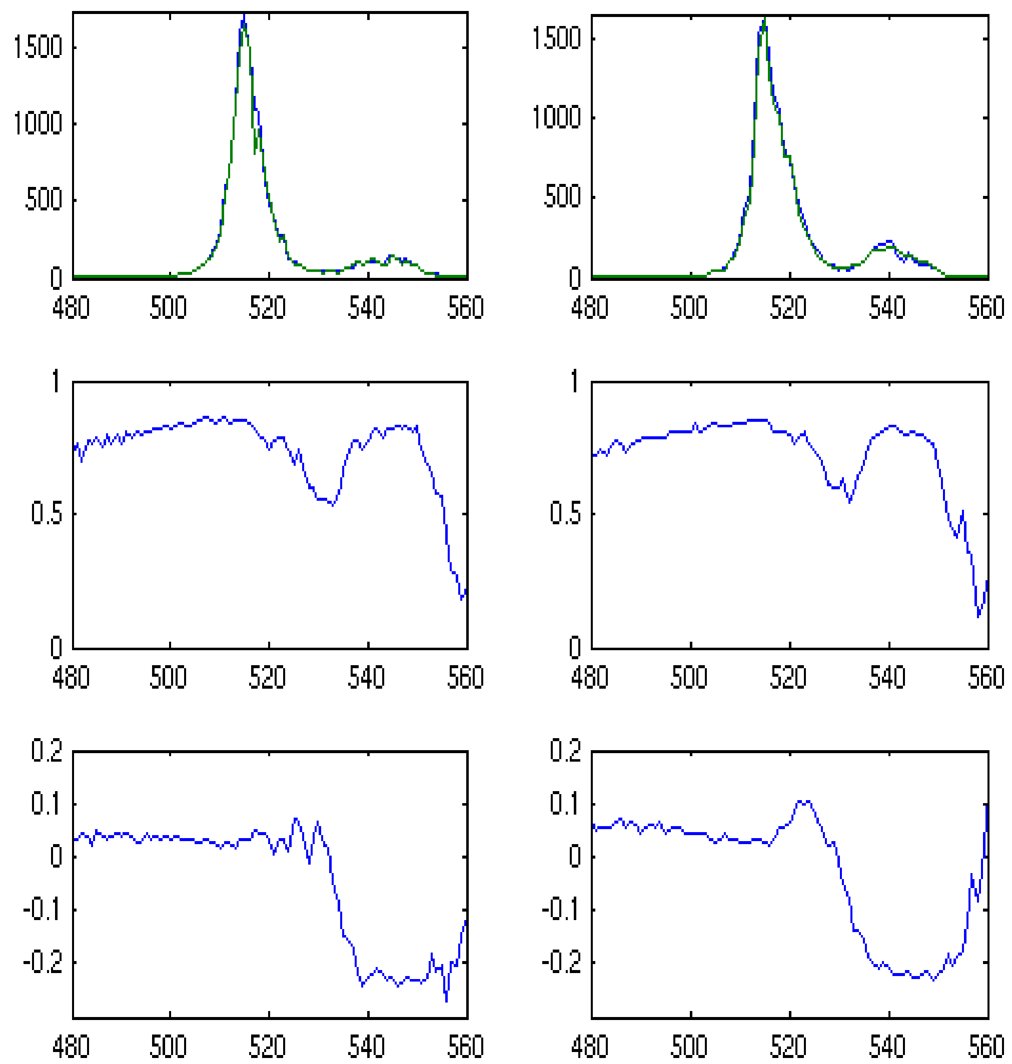




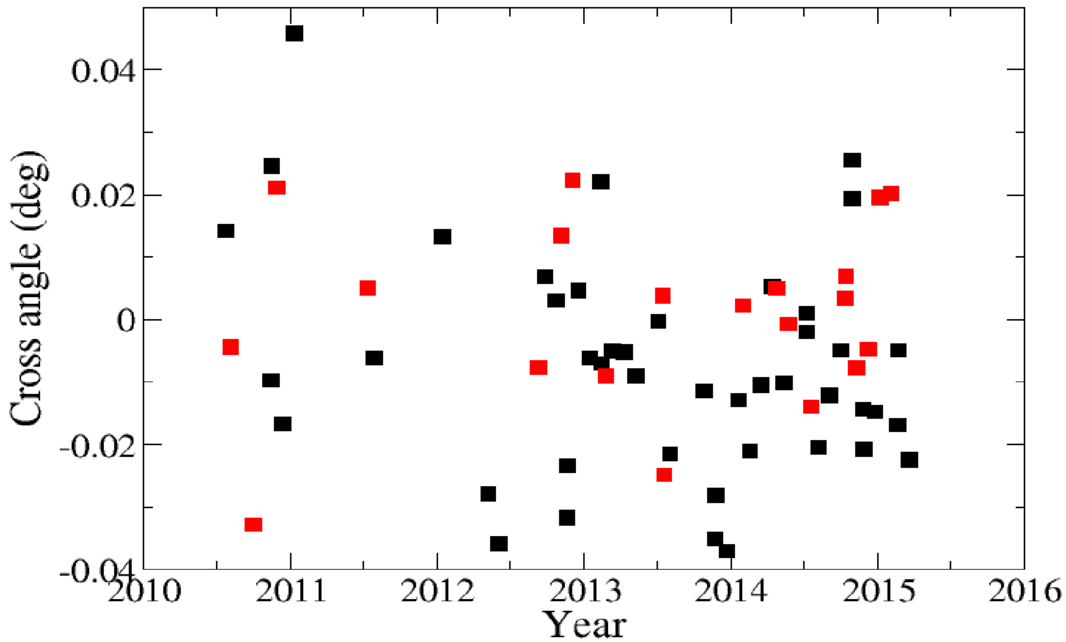
Mathematical expressions for cross angle in D4100 and D4200

SARin FBR Analysis. Amazon near Tabatinga (5 May 2012).

SARin waveforms (upper), coherence between phases (middle) and cross angle in degrees (lower). In the upper plot the right antennae is coloured blue and the left antennae is green. X-axis is bin number; Y axis is power (upper), coherence (middle) and degree (lower). Left hand column location #274 (3.930 ˚S 70.207 ˚W); right hand column location #275 (3.927 ˚S 70.207 ˚W).



SARin FBR Analysis. Amazon near Tabatinga.



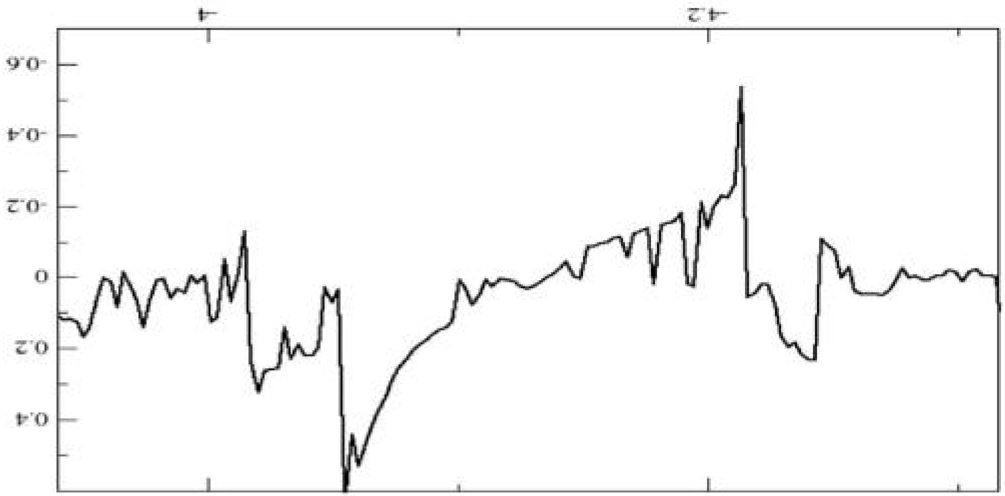
Plot of the 64 accepted cross angles comprising 44 ascending passes (black squares) and 20 descending passes (red squares).

SARin FBR Analysis. Amazon near Tabatinga.

Google earth plot of descending pass on 8 September 2012 across Amazon near Tabatinga (upper).

Cross angles from SARin mode (lower). The blue arrow points along direction of flight.

Conclusion: In general the cross track angle is relatively noisy due to the complex nature of saturated ground and inland water. However, the plots generally show the expected behaviour of the cross angle particularly for large excursions of the river to left or right of the flight path.

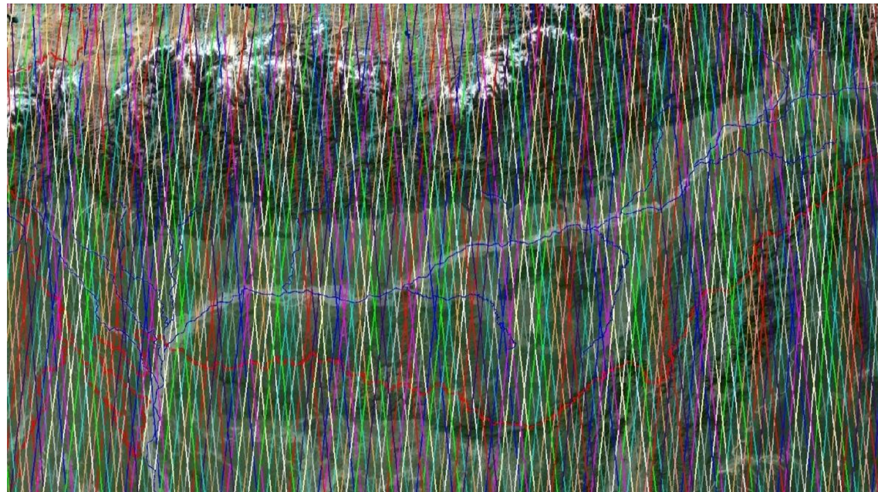


Use of CryoSat-2 data in combination with hydrological models:

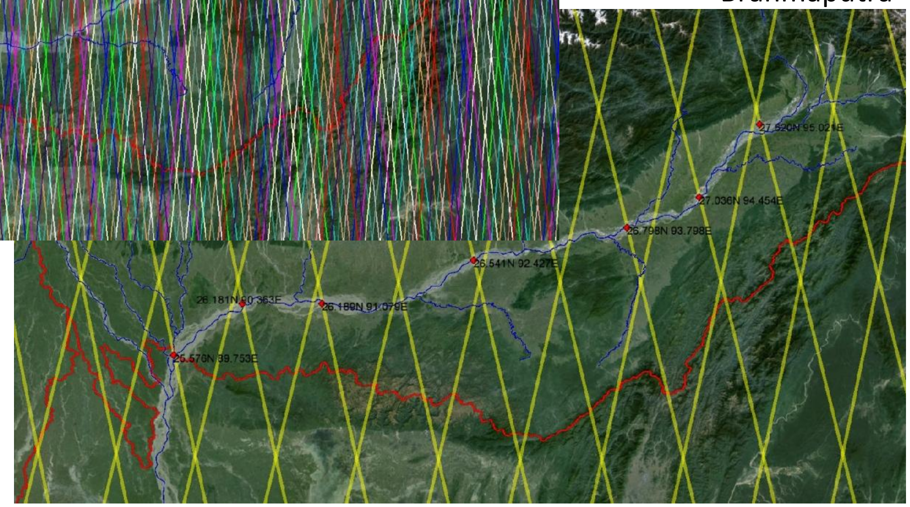
Drifting ground track

Drifting ground track challenges conventional ways of using satellite altimetry data for hydrological modelling, which are all based on repeat orbits:

- Continous river masking necessary
- No direct construction of virtual station water level time series possible



CryoSat-2 ground tracks for one 369-day cycle over the Assam Valley, India

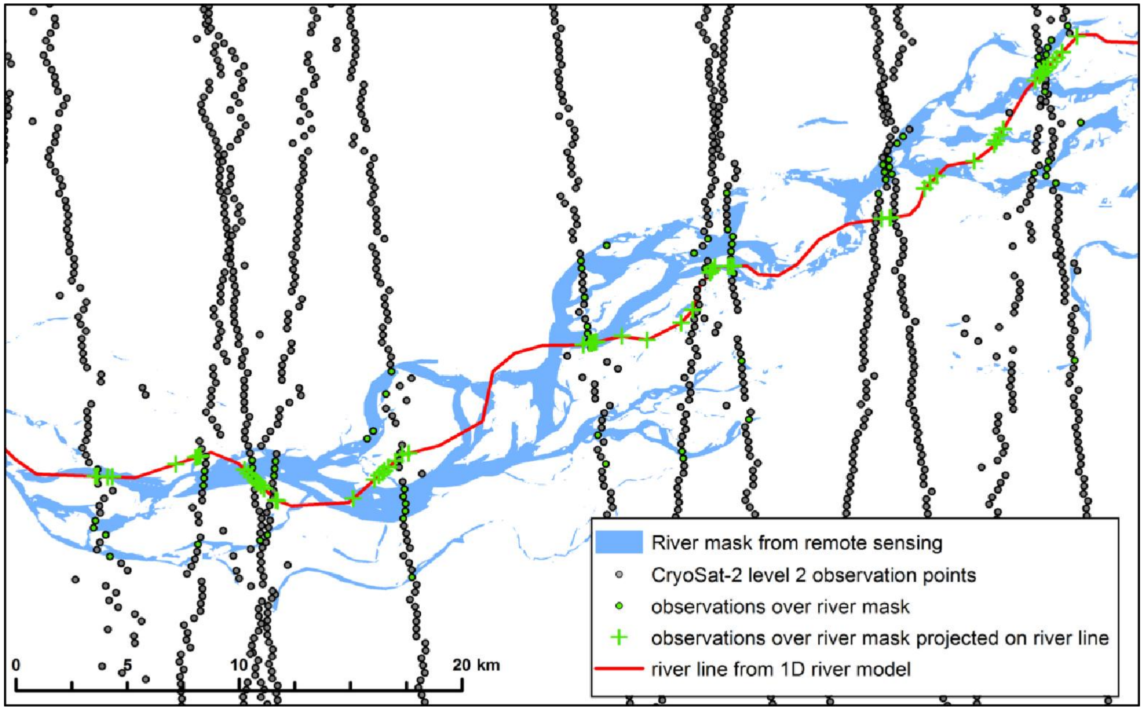


Envisat 35-day repeat tracks over the Assam Valley, India, with virtual stations along Brahmaputra

- Arbitrary spatio-temporal resolution can cause challenges for combination of data with hydrological models

But: CryoSat-2 also offers unique advantages over other missions, for example contionous river water level profiles.

Data processing for uptake into hydrological model



1.) Filtering with water mask
2.) Projection on the 1D river line
3.) Clustering

Calibration of river morphology parameters

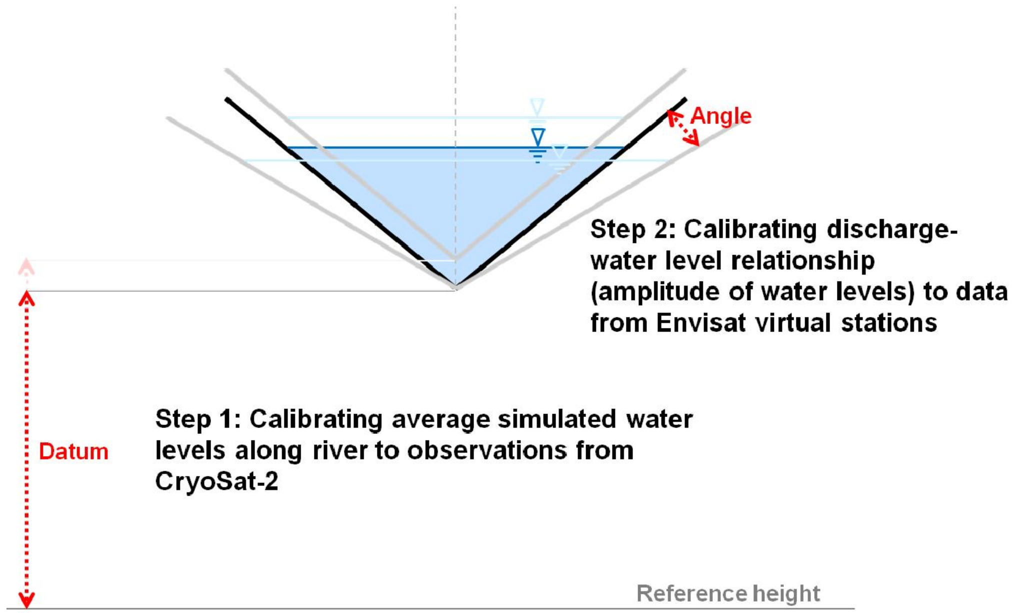
WITHOUT INFORMATION ABOUT RIVER BED GEOMETRY

(after calibration of discharge)

Calibration of synthetic cross sections to make model accurately reproduce water levels

- Step 1: **CryoSat-2 data** to calibrate average simulated **water level profiles** along the river
- Step 2: **Envisat virtual station data** to calibrate **water level-discharge relationships**

(virtual station data is not needed; both steps can also be performed with CryoSat-2 data only)



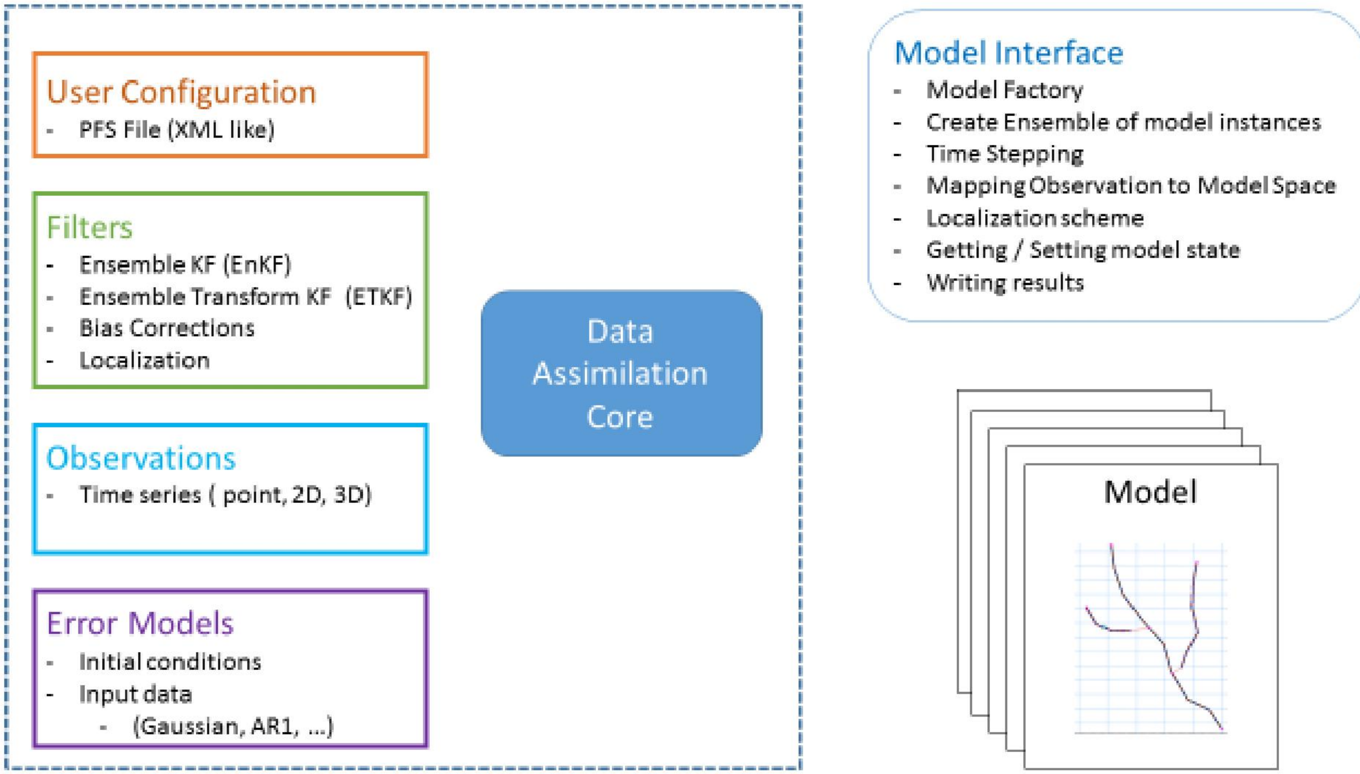
from Schneider et al. (2017)

Result:

A **1D hydrodynamic model**, utilizing synthetic cross sections that still is able to **accurately reproduce water levels** across the entire model

(despite the lack of an accurate DEM or bathymetry)

Assimilation of CryoSat-2 data with DHI Data Assimilation framework



in this case:

MIKE HYDRO River (MIKE 11) modelling system

- Sub-catchment rainfall-runoff modelling
- 1D hydrodynamic river modelling

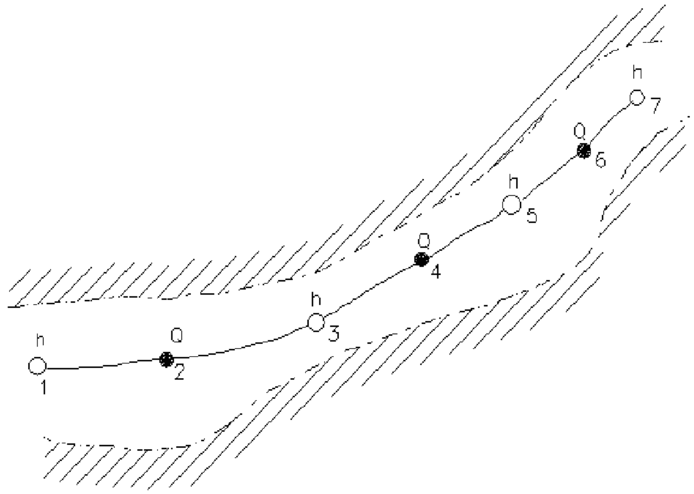
Data assimilation setup

DA algorithm

Ensemble Transform Kalman Filter implemented after Sakov & Oke (2008)

State vector

- Water levels at all grid points of the hydrodynamic model
- Model error via state augmentation



Sketch of the MIKE 11 model computation grid

Data assimilation setup

Model error description

Temporally and spatially correlated perturbation of forcing (runoff from subcatchments)

Observation error

Clustering individual CryoSat-2 data points from one transect into one or more groups, based on their location along the river:

Standard deviations of elevations derived from each cluster group

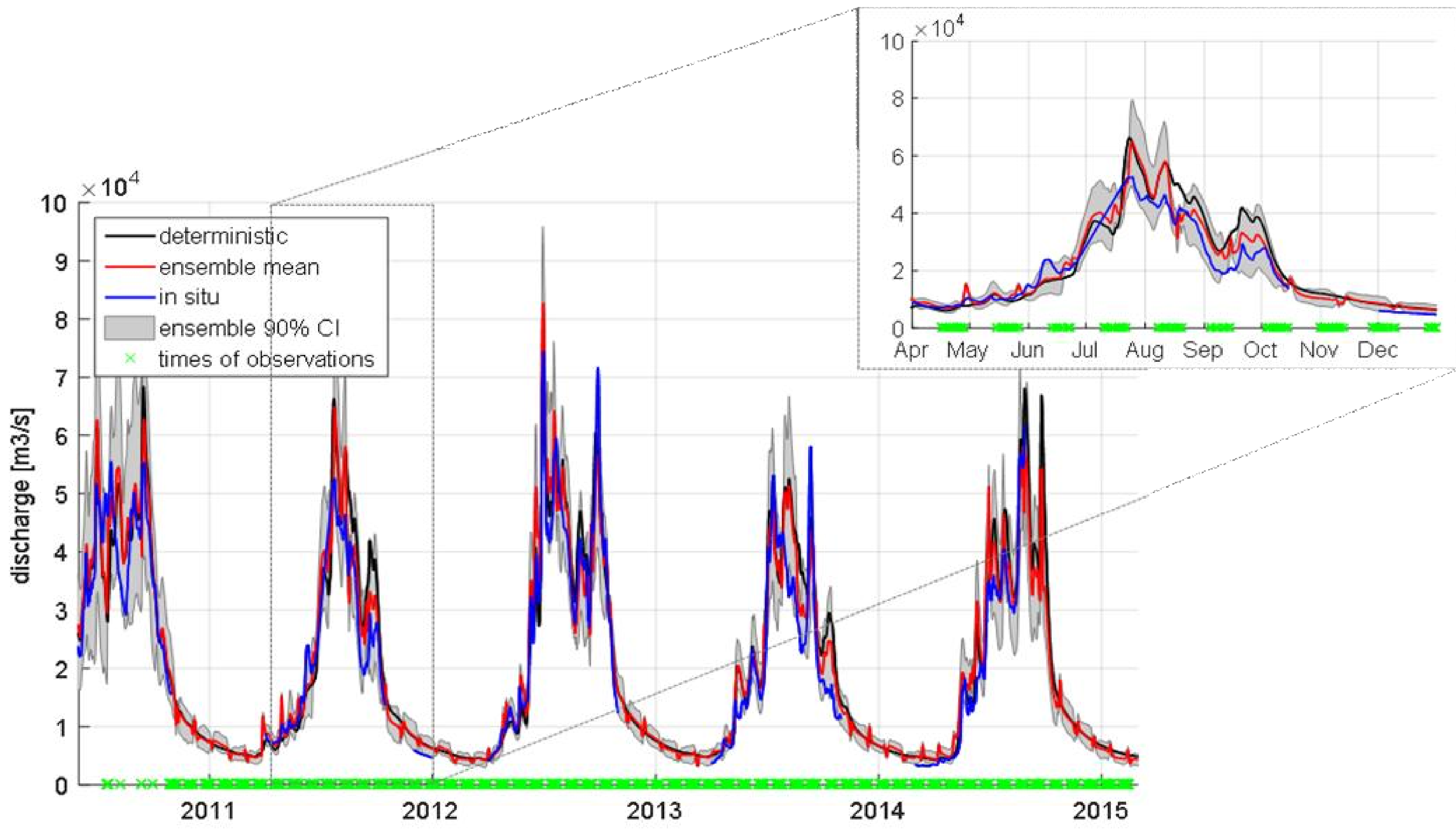
Localization

Distance-based localization needed as otherwise spurious correlations across the river network give unreasonable updates

Virtual observation window

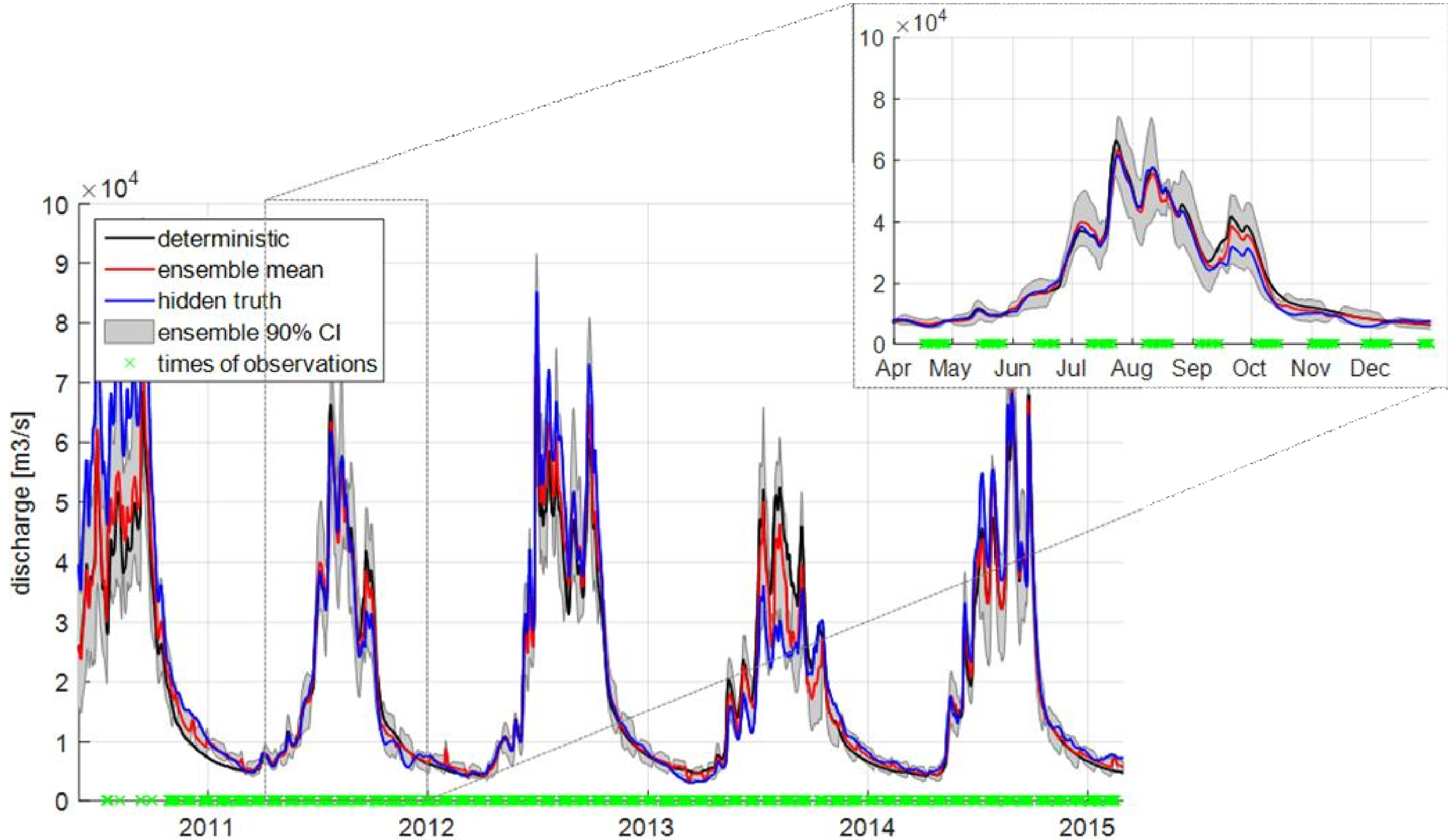
To extend measurement info over several simulation time steps

Results of DA of real CryoSat-2 data, discharge at Bahadurabad station



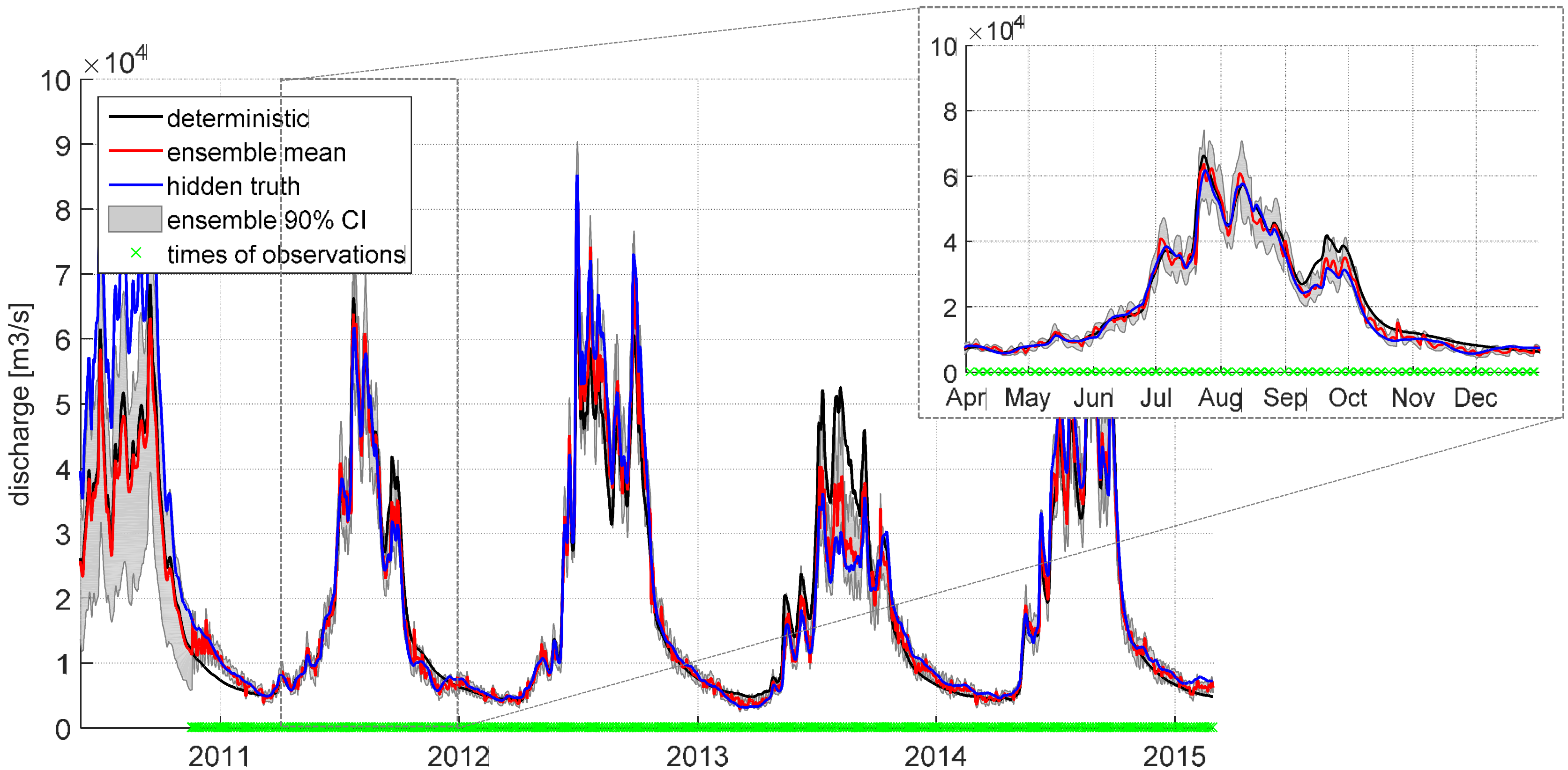
→ Improvement of CRPS of ~10%

Results of DA of synthetic CryoSat-2 data, discharge at Bahadurabad station



→ Improvement of CRPS of ~26% - 32%

Results of DA of synthetic Sentinel-3 data, discharge at Bahadurabad station



→ Improvement of CRPS of ~28% - 34%, i.e. slightly better than with CryoSat-2 (despite the number of river crosssings in this period: 754 with Sentinel-3A, 973 with CryoSat-2)

CRUCIAL Dataset (WP4000)

Online key data sets:

- CryoSat-2 SAR FBR L1A data
- CryoSat-2 SARin FBR L1A data
- Geophysical correction data
- ACE2 and other GDEM data
- Jason-2 validation data
- Envisat validation data
- SARAL/Altika validation data
- River mask data
- In-situ river (gauge) data
- Data Assimilation for hydrology

CRUCIAL Dataset (WP4000)

Theme	Product	Input (i) or Output (o)	Area	Time Period	Time Frame
River Masks		I & O	Mekong Brahmaputra Selected Locations	N/A	N/A
Waveform Data	SAR FBR Multi-look	I O	Amazon, Tonlé Sap Mekong	CS2 mission	2010-2015
	SARin FBR Multi-look	I O	Amazon, & Brahmaputra	CS2 mission	2010-2015
Inland water heights	Multi-look waveforms	O	Amazon	CS2 mission	2010-2015
Hydrological data assimilation	Heights Meteorological data Discharge	I I O	Brahmaputra	CS2 mission	2010-2013

CRUCIAL Summary (WP4000/5000) and Scientific Roadmap (WP6000) I

- Landsat seems to be the way forward to produce the most reliable river masks. SAR delineation of water is more fuzzy than optical sensors although has the advantage of an all-weather/time system. Dynamic river masks may be needed for changing river morphology (particularly for braided rivers) where the flow can be affected by flooding and the seasons. An operational product would need to produce a global river mask product starting with the major rivers/lakes and downscaling to other water bodies.
- Speckle in burst echoes affects the 80 Hz SAR data and multi-looks essential for precise heights.
- The number of stacked waveforms used in the multi-look waveform is important for SAR altimetry. A reduction from the maximum possible number ≈ 240 (N=120) to say 81 (N=40) waveforms centred on beam closest to nadir has been seen to reduce the variability in derived heights across Tonlé Sap.
- The reduction from N=120 to N=40 in the waveform stack sharpens the leading edge of the multi-look waveform.
- The change in N causes an offset between the derived heights which is indistinguishable from other contributions to the altimeter bias. In consequence, a fixed value for N must be applied to all analyses to avoid bias.
- The G-POD SARvatore and SARinvatore waveforms are almost identical to those derived within CRUCIAL on using N=120 or N=123.
- The use of a Hamming window (cosine weighting) is recommended.
- Difference between empirical and OCOG/Threshold retrackers is not significant. More advanced retrackers or the use of auto-correlation between consecutive waveforms across large lakes might change this conclusion. Variability in height recovery has been shown to be 5 cm across Tonlé Sap for multi-look SAR data at about 20 Hz. This is equivalent to a precision of 1-2 cm in 1 Hz data.
- Validation across Tonlé Sap affected by distance from gauge. For OSTM a 12 day lag inferred to Prek Kdam gauge. Lag increases with distance of pass from Prek Kdam. Agreement between Prek Kdam and OSTM of 42.6 cm is slightly reduced to 42.1 cm between Prek Kdam and CryoSat-2 assuming 12 dy time lag for all CryoSat-2 non-repeating passes. Since this is incorrect there is evidence that CryoSat-2 is performing better than OSTM across Tonlé Sap.

CRUCIAL Summary (WP4000/5000) and Scientific Roadmap (WP6000) II

- Validation of CryoSat-2 along the Mekong severely affected by the non-repeating orbit. Correction based on low flow river slope is not exact as the gauges show a difference in range and hence a change in slope at high flow.
- A comparison of the OCOG/Threshold (RMS 66.9 cm) and empirical retrackers (67.8 cm) for N=40 shows a slight preference for the OCOG/Threshold retracker.
- Above differences are comparable to those of Birkinshaw et al (2010) 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.
- FBR SAR data close to the Obidos gauge on the Amazon allowed the river slope to be computed from the gauge/altimetery residuals and chainage. On correcting for the slope gave RMS 27.3 cm applying a 2.5σ rejection criterion . The slope with R^2 = 0.07 was just positive.
- At Manacapuru, 650 km upstream from Obidos, the RMS, was 53.6 cm. Here the slope was well determined with R^2 = 0.89. These RMS values can be compared against Birkett et al. (2002), where best results from Topex/Poseidon for 1992-1999 were in the range 0.4–0.6 m RMS. Thus, the Manacapuru RMS falls within the Birkett et al. (2002) best results while the CryoSat-2 result at Obidos is superior by a factor of two.
- Over the inland waters utilised in this study CryoSat-2 is comparable or slightly more accurate than ENVISAT and Jason-2/OSTM but probably less accurate than SARAL/Altika. Although only a small number of SARAL/Altika measurements are available to date a few epochs are classified as outliers. This may reflect the susceptibility of the Ka altimeter to cloud and rain.
- Altimetric heights for Cryosat-2 can be obtained from ESA's Ground-Processing on demand (G-POD) services **SAR**vatore (**SAR** **V**ersatile **A**ltimetric **T**oolkit for **O**cean **R**esearch & **E**xploitation) and **SARin**vatore (**SARin** **V**ersatile **A**ltimetric **T**oolkit for **O**cean **R**esearch & **E**xploitation). The SAMOSA2 retracker is inappropriate for inland waters. Retracking the G-POD waveforms yields enhanced results. Since CRUCIAL analyses the SAMOSA+ retracker has become available on SARvatore. SAMOSA+ is the SAMOSA2 model tailored for inland water, sea ice and coastal zone domain.

CRUCIAL Summary (WP4000/5000) and Scientific Roadmap (WP6000) III

- Heights from SARin FBR data in the vicinity of the gauge at Tabatinga yielded an RMS of 29.9 cm. Again this is an improvement on the best results of Birkett et al. (2002) for the Amazon.
- The SARin cross angle is dominated by the location of the dominant water surface reflectors in the cross-track footprint slice.
- In general the cross track angle recovered from SARin FBR data is relatively noisy due to the complex nature of saturated ground and inland water. However, the results generally show the expected behaviour of the cross angle particularly for large excursions of the river to left or right of the flight path.
- Heights for the Lower Brahmaputra derived by DTU from SARin L1B waveforms retracked using a primary peak threshold retracker were consistent with results obtained within CRUCIAL from L1A data. A 12 cm offset is due to the different procedures including the waveform construction and threshold for retracking. More important is the scatter in the data of standard deviation just 16 cm. We are confident that the DTU data used in the Data Assimilation work is of high accuracy.
- Satellite altimetry can provide near real time water heights over a large geographical distribution. Not all time series need to be continuous as Arctic rivers, for example, are ice bound for winter months. There is scope for an additional on-line near real time product for rivers as epitomized by R&L but with assured reliability, sustainability and user friendliness.
- Progressing from water levels to lake volumes and discharge is a major advance. Discharge either requires extensive modelling or can be based on statistical methods using water height, width and slope. All are available from remote sensing although altimetry gives the height above a datum and not true depth. There are methods to derive depth at minimum flow or a rating curves can be used.

CRUCIAL Summary (WP4000/5000) and Scientific Roadmap (WP6000) IV

- CryoSat data is useful for river analysis and modeling. In an inverse river modeling framework, it can constrain river geometry (datum, cross-section shape) and/or river hydraulic parameters (Manning numbers). This is not possible with classical short-repeat data. In this context, CryoSat data has a role to play even for rivers with comprehensive in-situ monitoring systems.
- Dynamic water masks could increase CryoSat data availability over rivers, especially for highly seasonal rivers with low bank slopes. SAR imagery has a key role to play here as an all-weather water masking tool.
- In an updating/data assimilation framework, CryoSat2 data can be used to increase predictive performance of models. The drifting ground track sampling pattern appears to have a lower data value than classical short-repeat in this case. Data value also depends on the magnitude and direction of the wave speed in the river relative to the ground track drift speed.
- Synthetic data assimilation experiments provide an opportunity to systematically assess data value for different missions / orbit configurations and combinations of missions.
- Comparisons between CryoSat-2 water heights and in-situ data for the Po and several Chinese rivers generally indicated a standard error of 0.5 m or better. In synthetic DA experiments, a standard error of 0.4 m resulted in a 27% improvement of CRPS while a standard error of 0.2 m resulted in a 32% improvement of CRPS. Higher accuracy of the data increases data value, but not proportionally.
- The best way of disseminating satellite radar altimetry to hydrologists is as spatio-temporal height point clouds, not as time series. The ideal inland water altimetry toolbox would integrate the height database with water masking tools (multispectral data, SAR) and allow the user to flexibly extract data points falling on water.

CRUCIAL Outreach: Posters/Oral Presentations (WP7000)

- Benveniste, J., Moore, P., Berry, P.A.M., Balmbra, R., Birkinshaw, S., Bauer-Gottwein, P., Dinardo, S. and Lucas, B., (2014), CRUCIAL: CryoSat-2 Success over Inland Water and Land: Preliminary Inland Water Heights and Validation, AGU Fall Meeting Abstracts, http://adsabs.harvard.edu/abs/2014AGUFM.H33P..04B}
- Moore, P., Birkinshaw, S., Restano, M., Ambrozio, A. and Benveniste, J., (2016), Methodology and Validation of SAR and SARin Full Bit Rate Altimetric Waveforms and Heights from the CRUCIAL Project, 2016 SAR altimetry Workshop, La Rochelle, France, http://www.ostst-altimetry-2016.com/wp-content/uploads/abstracts_books_SAR_161017. pdf
- Moore, P., Birkinshaw, S., Restano, M., Ambrozio, A. and Benveniste, J., (2016), Methodology and Validation of SAR and SARin Full Bit Rate Altimetric Waveforms and Heights from the CRUCIAL Project, AGU Fall Meeting
- Moore, P., Birkinshaw, S., Restano, M., Ambrozio, A. and Benveniste, J., (2016), CRUCIAL: CryoSat-2 Success over Inland Water and Land: SAR and SARin Full Bit Rate Altimetric Heights and Validation, EGU General Assembly Conference Abstracts, 18, 6200, http://adsabs.harvard.edu/abs/2016EGUGA..18.6200M
- Moore, P., Berry, P.A.M., Birkinshaw, S., Balmbra, R., Dinardo, S., Lucas, B. and Benveniste, J., (2015), CRUCIAL: CryoSat-2 Success over Inland Water and Land: Full Bit Rate Altimetric Heights and Validation, Geophysical Research Abstracts. Vol. 17, EGU2015-4687-1.
- Moore, P. , Balmbra, r., Birkinshaw S., Dinardo, S, Benveniste, J., (2015), CRUCIAL: CryoSat-2 Success over Inland Water and Land: Full Bit Rate Altimetric Heights and Validation, IUGG, 26th IUGG General Assembly, Prague
- Moore P, Berry P.A.M, Birkinshaw S, Balmbra R, Bauer-Gottwein P, Benveniste J, Dinardo S and Lucas B. (2014) CRUCIAL: CryoSat-2 Success over Inland Water and Land. 40th COSPAR Scientific Assembly, Moscow.
- Moore, P, Berry, P, Balmbra, R, Birkinshaw, S, Kilsby, C, Bauer-Gottwein, P, Benveniste, J, Dinardo, S & Lucas, B (2014), CRUCIAL: CryoSat-2 Success over Inland Water and Land, Geophys. Res. Abstr., 16, EGU2014-7390-1.
- Moore P, Berry P.A.M, Birkinshaw S, Balmbra R, Kilsby C, O'Donnell G.M, Bauer-Gottwein P, Benveniste J, Dinardo S and Lucas B., (2013), CRUCIAL: CryoSat-2 Success over Inland Water and Land, AGU Fall Meeting Abs, http://adsabs.harvard.edu/abs/2013AGUFM .H51E1234M
- Schneider, R., P. N. Godiksen, H. Villadsen, H. Madsen, and P. Bauer-Gottwein (2015), Combining Envisat type and CryoSat-2 altimetry to inform hydrodynamic models, Geophys. Res. Abstr., 17, 9372.
- Schneider, R., P. N. Godiksen, M.-E. Ridler, H. Madsen, and P. Bauer-Gottwein (2016), Assimilation of CryoSat-2 altimetry to a hydrodynamic model of the Brahmaputra river, Geophys. Res. Abstr., 18, 12534.
- Schneider, R., P. N. Godiksen, M.-E. Ridler, H. Villadsen, H. Madsen, and P. Bauer-Gottwein (2016), Combining Envisat type and CryoSat-2 altimetry to inform hydrodynamic models, in Proceedings Living Planet Symposium 2016, vol. SP-740, edited by L. Ouwehand, ESA.

CRUCIAL Outreach: Journal Publications (WP7000)

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CRUCIAL Outreach: Website (WP7000)

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

Thankyou for listening

Final Presentation Meeting, ESRIN-ESA, Frascati, Italy
6 June 2017

CRUCIAL was funded by ESA's Support To Science Element (STSE), a programmatic component of the Earth Observation Envelope Programme, to investigate the application of CryoSat-2 data over inland water with a forward-look to Sentinel-3.

CryoSat-2's primary instrument is SIRAL (SAR Interferometric Radar Altimeter). SIRAL operates in one of three modes: Low Resolution Mode (LRM), Synthetic Aperture Radar (SAR) and Interferometric Synthetic Aperture Radar (SARin) as illustrated in Fig. 1 for the Amazon Basin.

CryoSat-2 FBR Level 1A complex valued quadrature data for the burst echoes have been processed over inland waters to derive altimetric virtual stage inland water heights. The processing chain uses an azimuth Fast Fourier Transform for beam formation and steerage towards a set of spatially equiangular ground track points every 300m along the ground track. By consideration of all burst echoes a stack of waveforms at each ground point (Fig. 2) was derived. High resolution river masks identified the inland water targets.

Utilising slant range multi-look waveforms were retracked using empirical waveforms designed for inland waters and the OCOG/Threshold retracker (Fig. 3).

Methodology validated against in situ data for the Mekong including Tonlé Sap, the Amazon (Fig. 4) and the Brahmaputra.

SAR virtual inland water heights near Óbidos show excellent agreement to gauge data (Fig. 5) with RMS 27.3 cm. This compares to 40.2 (57.7) cm for ENVISAT, for May 2002 – Oct 2010, and 17.4 (26.3) cm for AltiKa, May 2013 – Jun 2016, at ENV1 (ENV2).

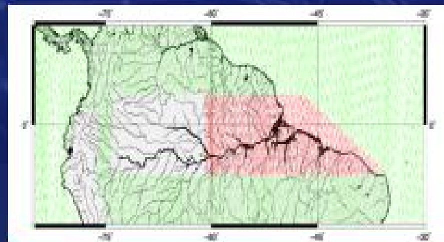

Figure 1. Amazon Basin: LRM (green), SAR (red) and SARin (blank) tracking.

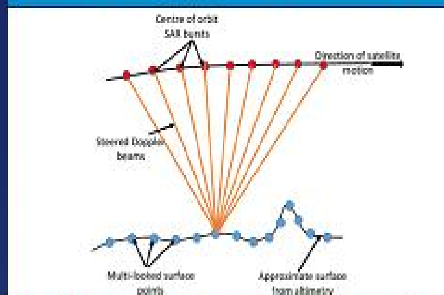

Figure 2. Schematic of bursts, the fan of Doppler beams, ground points and multi-looks.

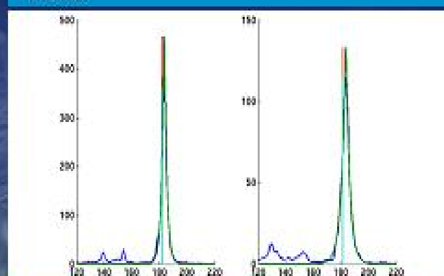

Figure 3. Waveforms (blue curve) across the Mekong with empirical retracker (green curve), the retracked bin given by red line. Cyan line shows OCOG/Threshold retracked bin. X axis bin number, Y axis power.

Amazon and Mekong comparisons show that river heights from CryoSat-2 are more accurate than TOPEX/Poseidon and Envisat heights but less accurate than SARAL/AltiKa. The CryoSat-2 SAR altimeter performs better than conventional Ku band altimeters, due to the drastically increased resolution of the footprint in the along-track direction. The Ka band SARAL altimeter onboard AltiKa is the most accurate satellite data, due to the reduced footprint size, although a number of heights are outliers which probably reflects the susceptibility of the Ka altimeter to rain and clouds.

CRUCIAL has assessed the value of CryoSat-2 radar altimetry data for river analysis and modelling with application to the Brahmaputra River. With a sliding ground-track in the 12 monthly sub-cycles, processing, outlier removal and quality control of river levels are more complicated than for classical short repeat-orbit missions (10 or 35 days).
Ingestion of CryoSat-2 data into hydrodynamic models required a novel approach. CRUCIAL developed methods for filtering, processing and aggregating CryoSat-2 data over rivers and implemented a data assimilation (DA) system consisting of a one-dimensional hydrodynamic model and an ensemble transform Kalman filter.

The Continuous Ranked Probability Score (CRPS) is improved by approximately 15% in the DA run over the open loop run (Fig. 6). The data assimilation system developed in CRUCIAL is generic and can be applied to any river system using data from any mission or combination of missions. It is a useful tool to compare data value across missions and river systems and a significant step towards a global real-time inland water forecasting system.

Figure 4. Google Earth image overlaid by CryoSat-2 passes across the Amazon near the Óbidos gauge (red circle) with two Envisat/AltiKa crossing points (ENV1 and ENV2).

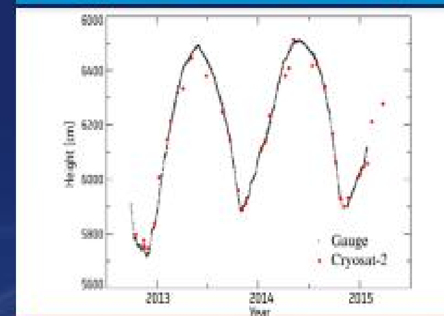

Figure 5. Comparison of gauge and CryoSat-2 heights in vicinity of Óbidos gauge.

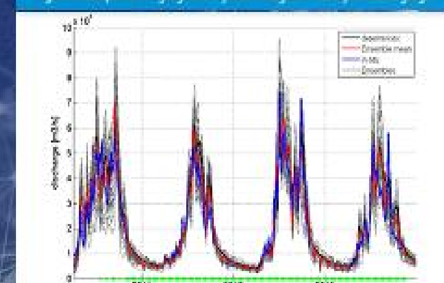

Figure 6. Results of DA of CryoSat-2 data in terms of discharge at Bahadurabad on the Brahmaputra River. Times of observations are marked with green dots on the x-axis.