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

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Executive Summary

CRUCIAL is one of a few projects to process CryoSat-2 altimetric records from FBR Level 1A complex valued quadrature data for the burst echoes over inland waters to a final altimeter virtual stage inland water height with validation against in situ data. The processing chain used 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 was derived. Utilising slant range and bin corrections for beams in the stack a multi-look waveform was constructed. These waveforms were subsequently retracked using either a set of empirical waveforms designed for inland water application or by an OCOG/Threshold retracker. The methodology was applied to FBR SAR and SARin data across the Mekong including Tonlé Sap, the Amazon and the Brahmaputra. Analysis across Tonlé Sap based on variability in the height time series established a preference for a multi-look waveform derived from a reduced number of say 81 waveforms from the stack. Data across Tonlé Sap was compared against heights derived from OSTM (Jason-2) and to data from a gauge downstream. Results showed that CryoSat-2 was as accurate as OSTM despite the drifting ground track. Along the Mekong itself, the reduction in waveform numbers from the stack was seen to provide additional height values compared to usage of all beams in the stack close to the river bank. Comparisons against Envisat and SARAL/Altika at near the gauge at Kratie showed comparable accuracy between CryoSat-2 and Envisat although SARAL/Altika was generally the most accurate. Similar results were seen along the Amazon where CryoSat-2 was in SAR and SARin mode. Analysis of the two antennae in SARin mode established negligible difference in height from the two antennae. Use of coherence between the waveforms from the antennae provides the cross-angle providing insight into the location of the reflectance within the footprint. The procedure developed within CRUCIAL for CryoSat-2 is generic in the sense that the methodology can be applied to other SAR altimeter satellites such as Sentinel-3.

CRUCIAL was also one of the first projects to systematically assess the value of CryoSat-2 radar altimetry data for river analysis and modeling. Due to the drifting ground-track of the CryoSat-2 orbit, processing, outlier removal and quality control of river levels are more complicated for the CryoSat-2 mission than for classical repeat-orbit missions. Also, ingestion of CryoSat-2 data into hydrodynamic models requires new approaches. 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. Processing and data assimilation techniques were demonstrated for the Brahmaputra river system in South Asia. Data value was assessed and compared to other missions and orbit configurations using synthetic data assimilation experiments. Synthetic data assimilation experiments showed significant performance improvements due to the assimilation of CryoSat-2 data. Assimilation of

real-world CryoSat-2 data resulted in more moderate but still significant performance improvements. The modeling and data assimilation system developed in CRUCIAL is generic and can be applied for any river system with any satellite altimetry mission / any combination of satellite altimetry missions.

Contents

1 Introduction

1.1 Purpose and Scope

CryoSat-2 was launched on 8 April 2010 following on from previous ESA Earth orbiting satellite radar altimeters (e.g. ERS-1, ERS-2 and Envisat) that have been used for land surface applications including mapping and measurement of river and lake systems. CryoSat-2's primary instrument is SIRAL (SAR Interferometric Radar Altimeter), which uses radar pulses to determine and monitor the spacecraft's altitude. Although the CryoSat-2 primary aim is to measure sea ice and ice sheets it can provide valuable data over the rest of the Earth surface. SIRAL operates in one of three modes, depending on where (above the Earth's surface) CryoSat-2 is flying. The three modes are: the conventional altimeter mode or Low resolution Mode (LRM), the Synthetic Aperture Radar (SAR) mode and Interferometric Synthetic Aperture Radar (SARin) mode. CryoSat-2 is in a low non Sun-synchronous Earth orbit of period of 100 minutes. The orbit of CryoSat-2 drifts across the Earth's surface with a repeat cycle of 369 days.

CRUCIAL is investigating innovative inland water applications from CryoSat-2 with a forward-look component to the future Sentinel-3 mission. All previous altimetric missions utilized standard nadir pointing altimetry while CryoSat-2 and now Sentinel-3 operate a SAR mode altimeter. With the exception of ERS-1 in its geodetic phase and now CryoSat-2 all previous altimeter missions have a repeat orbit in which the satellite follows the same ground-track after a number of days; 35 days for ERS-2 and Envisat and 10 days for Topex/Posiedon, Jason-1, Jason-2 (OSTM) and the recently launched Jason-3 (OSTM2). This presents an added difficulty for hydrological modelling, as well as for the validation, as the crossing points of inland waters migrate with the ground track.

The Final Report summarises the studies initiated during the CRUCIAL project and defines future strategic actions for developing the studies within the project.

1.1 Abbreviations and Acronyms

Abbreviation	**Meaning**
CRUCIAL	CryoSat-2sUCcess over Inland water And Land
DA	Data Assimilation
DAHITI	Database for Hydrological Time Series of Inland Waters
DEM	Digital Elevation Model
DTU	Danish Technical University
ERS-1/2	European Remote Sensing satellite 1 (2)
Envisat	Environmental Satellite
ESA	European Space Agency
FBR	Full Bit Rate
G-POD	ESA's Ground-Processing On Demand service
G-REALM	Global Reservoirs/Lakes
IE	Individual Echoes
L1A	Level 1A
L1B	Level 1B
LRM	Low Resolution Mode
JASON	US/French Altimeter Satellite
NCL	Newcastle University
OCOG	Offset Centre of Gravity
OSTM	Ocean Surface Topography Mission (JASON-2)
R&L	River and Lake
SAMOSA	SAR Altimetry MOde Studies and Applications

SAR	Synthetic Aperture Radar mode of CryoSat-2 SIRAL
SARAL	Satellite with ARgos and ALtiKa
SARin	Interferometric Synthetic Aperture Radar mode of CryoSat-2 SIRAL
SARvatore	SARin Versatile Altimetric Toolkit for Ocean Research & Exploitation
SARinvatore	SARin Versatile Altimetric Toolkit for Ocean Research & Exploitation
Sentinel-3	ESA Earth Observation Satellite Mission
SIRAL	SAR Interferometric Radar Altimeter
USDA	United States Department of Agriculture

2 SAR waveforms from FBR L1A data

This section reports on the issues associated with Full Bit Rate (FBR) L1A data analyses and future considerations for operational products. SARin is unique to CryoSat-2 and will be considered in a separate section.

2.1 FBR L1A data Analysis

In the CRUCIAL proposal it was stated that Envisat individual echoes (IE) analysis had shown that inland water targets too small to generate even one uncontaminated echo at 18Hz can be monitored successfully with the higher PRF of the RA-2 1800Hz data. This gave the impression that the high PRF of CryoSat-2 will allow detailed measurements to be made of small inland water targets. The pertinent question is whether the burst echoes can supply useful heights at the higher spatial and temporal resolution as required for inland water studies. Investigations in CRUCIAL showed that the burst echo heights are considerably noisier than the multi-look data. Due to speckle in the burst echo data, sensible and accurate recovered heights are obtained only through stacking and forming multi-look waveforms. For hydrological purposes the noise in the burst echoes contaminates the recovered heights. Thus, as for nadir pointing altimetry at 18 Hz, the requirement to generate multi-look waveforms at ground points about 320 m along track does limit the size of the targets. However, the cross-track slicing of the altimetric footprint in SAR mode does reduce noise in the resultant waveform. In summary, converse to the earlier assumption, CryoSat-2 individual bursts have limited hydrological usage.

2.2 Multi-look waveforms for inland waters

The SARvatore (SARinvatore) services for CryoSat-2 utilise all available waveforms in the stack to form the multi-look waveform product. This has been shown to be sub-optimal and a reduced number of say 81 (instead of the maximum 240) has been shown desirable. This is, however, not a major consideration over large water bodies giving an RMS difference decrease of say 5 cm from 6-7 cm. Over rivers, the reduction from 240 to 81 can give an additional height value across the river due to less contamination by the river banks. The Sentinel-3 service analogous to CryoSat-2 SARvatore should consider an additional waveform height for inland water targets. A consistent approach by users over inland waters is essential to avoid introduction of an offset or altimeter bias in the time series.

Application of a Hamming window weighting scheme for the waveforms in the stack was shown to be advantageous over a unit weight strategy.

Use of G-POD SARvatore and SARinvatore inland water heights showed that heights derived using the SAR retracker SAMOSA designed for ocean applications is not advised over inland waters. Rather, retrackers specific to inland waters or the OCOG/Threshold retracker should be used. The difference between the empirical retrackers formulated in CRUCIAL and OCOG/Threshold 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.

2.3 River Masks

River masks are required to identify ground points over inland waters to avoid off pointing issues. The river masks used in the earlier ESA River and Lakes (R&L) project are fairly rudimentary and produce altimetric heights from points off river. Rivers with braiding and changing morphology are a particular problem. Both Newcastle (NCL) and Danish Technology University (DTU) derived river masks from Landsat data as part of CRUCIAL. This does seem to be the way forward to produce the most reliable river masks. SAR data from satellites such as Sentinel-1 can be used but SAR delineation of water is more fuzzy than optical sensors although has the advantage of an all-weather/time system. An operational product would need to produce a global river mask product starting with the major rivers/lakes and downscaling to other water bodies.

2.4 Near Real Time Product

The best on-line site for inland water heights is DAHITI (http://dahiti.dgfi.tum.de/en/) providing 419 time series (Africa 68 time series, Asia 75, Australia/New Zealand 6, Europe 10, North America 54, South America 206). Some of the DAHITI targets are near real time products.

Satellite altimetry has the ability to provide near real time water heights over a greater geographical distribution and hence a greater number of sites as shown in R&L. Not all time series need to be continuous as Arctic rivers, for example, are ice bound for winter months. Only the Ob and Volga, and then at a single location for each, are available in DAHITI. The USDA Global Reservoirs/Lakes (G-REALM) is entirely a lake level data set while DAHITI is dominated by lake data and major river basins such as the Amazon. Thus, 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. The simplest product is lake volume above minimum level based on either lake extent assuming vertical sides or, more accurately, a DEM of the near lake terrain. Bathymetry is needed for true lake volume. Discharge either requires extensive modelling, as for the Brahmaputra, 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 (e.g. Birkinshaw et al., 2014 Daily discharge estimation at ungauged river sites using remote sensing. Hydrol. Process. 28, 1043–1054. doi:10.1002/hyp.9647)

A near real time product with discharge would have a major impact in ungauged basins.

2.5 CryoSat-2 for inland water heights

The major difficulty with CryoSat-2 is the non-repeating orbit which limits or complicates its usage in hydrology. Even validation of CryoSat-2 heights against in situ gauge data is hampered by varying distance from the gauge particularly where the river morphology is changing. Our conclusion is that CryoSat-2 heights are comparable or slightly superior to Jason-2 (OSTM) and Envisat. However, all are inferior to the Ka band altimetry of SARAL/Altika. Although only a small number of SARAL/Altika measurements are available to date a few epochs some are classified as outliers. This may reflect the susceptibility of the Ka altimeter to cloud and rain.

2.6 SARin analyses of cross angle

SARin is unique to CryoSat-2 and hence recommendations are limited to the scientific priority for future exploitation. The SARin cross angle over inland waters is dominated by the location of the dominant water surface reflectors in the cross-track footprint slice. Even over the Amazon SARin cannot provide a meaningful measure of the cross-angle for say river slope studies. Rather, SARin provides a measure of the predominance of water reflectors from either side of the ground track. A dominating nadir water body target should give a zero cross-angle. Conversely, a positive or negative cross angle indicates that the waveform is dominated by reflectance to the right or left of the satellite ground track. The computations in CRUCIAL with the cross angle used the convention of left antennae minus right antennae. Thus, the phase difference will be positive if the target range using the left antennae exceeds that of the right antennae. Thus, conceptually for the satellite flying into the page, a positive cross track angle denotes a target to the right of the nadir point of the antennae center. In essence SARin over water bodies can be used as a proxy to determine off ranging.

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. There is scope to utilize this data in either excluding off nadir ranging or to correct the range measurement to the nadir for additional height data.

3 Informing regional-scale hydrodynamic models with CryoSat-2 Altimetry

This section summarizes the application of CryoSat-2 data for river analysis and modeling. The work consisted of the following main steps:

- Filtering and pre-processing of CryoSat-2 data
- Hydrologic and hydrodynamic modeling
- Data assimilation

These steps were demonstrated for the Brahmaputra case study located in South Asia.

3.1 Filtering and pre-processing of CryoSat-2 data

To separate water echoes from land returns, accurate open water masks are required. We used Landsat multi-spectral imagery to generate dynamic open water masks, which were subsequently used to filter the CryoSat-2 returns. Multi-spectral water mapping is severely restricted by cloud cover. Experimental analysis with Sentinel-1 SAR imagery yielded promising results and will likely be the method of choice in future applications. Outliers have to be removed from the filtered dataset. However, contrary to lake targets, constant water level along one overflight cannot be assumed. We used the hydrodynamic model as an approximation of the truth and removed heights that were too different from the assumed truth. Next, observations need to be projected on the model space, which in our case is one-dimensional. Subsequently, individual heights representing the same model state need to be aggregated. This is necessary to avoid conflicting updates in the data assimilation step and provides error statistics for the aggregated observations. We used a k-means clustering approach to aggregate the data. This sequence of steps resulted in a rich, spatio-temporally resolved dataset of river heights, which was consistent with the hydrodynamic model and ready for uptake via calibration/data assimilation.

3.2 Hydrologic and hydrodynamic modeling

The hydrologic-hydrodynamic modeling system consists of a lumped-conceptual rainfall-runoff model and a one-dimensional hydrodynamic model solving the cross-section averaged dynamic wave equations of open channel flow. Both models are dynamically linked and implemented in the proprietary software DHI Mike Hydro. This modeling approach is appropriate to predict river height and discharge at regional scales. It does not produce flood extent maps and cannot predict surface water extent. However, contrary to popular 1D-2D hydrodynamic models (LISFLOOD-FP, DHI Mike Flood, SOBEK 3 etc.), the models are computationally efficient and lend themselves to ensemble-based uncertainty analysis, calibration and data assimilation. For the Brahmaputra case, the rainfall-runoff models were first calibrated using in-situ tributary discharge data. Subsequently, river morphology parameters in the hydrodynamic model were calibrated using the CryoSat-2 dataset. The model showed excellent predictive performance for river discharge and was consistent with the CryoSat-2 dataset.

3.3 Data Assimilation

The hydrologic-hydrodynamic model was combined with a generic ensemble-based data assimilation (DA) system. The DA system provides a number of different filtering algorithms and allows for flexible model and data uncertainty specifications. The data assimilation system was used to perform several synthetic DA experiments in order to quantify the value of CryoSat-2 data for hydrologic forecasting and compare CryoSat-2 data value to repeat orbit missions such as Sentinel-3. Synthetic DA experiments resulted in significant improvements of predictive model performance. For the Brahmaputra case, assimilation of synthetic Sentinel-3 data resulted in larger performance improvements than assimilation of synthetic CryoSat-2 data. Assimilation of real-world CryoSat-2 data improved predictive model performance, but improvements were smaller than for the assimilation of synthetic data. This may indicate that model and/or data uncertainties are not sufficiently characterized yet. 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.

4 Outreach: Publications and access to project outputs.

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