		ESA Contract:	1/6287/11/I-NB
		Doc. Title Doc. No	D6000 Scientific Roadmap NCL_CRUCIAL_D6000
		Version No Date	2 4.4.17

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

D6000 Scientific Roadmap

Document No: **NCL_CRUCIAL_D6000**

Issue: **2**

Issue Date: **4 April 2017**

Newcastle University School of Civil Engineering & Geosciences	DTU	ESA Contract:	1/6287/11/I-NB
		Doc. Title Doc. No	D6000 Scientific Roadmap NCL_CRUCIAL_D6000
		Version No Date	2 4.4.17

Author (Chapters 1-2): Philip Moore

Signature:

Author (Chapters 1-2): Steve Birkinshaw

Signature:

Author (Chapter 3): Peter Bauer-Gottwein

Signature:

Author (Chapter 3): Raphael Schneider

Signature:

Authorised by: Philip Moore

Signature:

Document Change Record

Version	**Date**	**Modified by**	**Description**
1	13.12.16	PM, PB-G	Created
2	4.4 2017	PM	Corrected as recommended by ESA

Abstract

The objective of the Scientific Roadmap (D6000) is to look to the future use of SAR altimeters over Inland Water, with particular emphasis on the forthcoming Sentinel-3 mission. In addition focus will be paid to areas of scientific priority for future CryoSat-2 data exploitation and plans to aid the transition activities from research to operational systems.

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 (http://research.ncl.ac.uk/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 Scientific Roadmap reports the output of the investigated issues during the CRUCIAL project and defines future strategic actions for fostering a transition from research to operational activities of the target methods and models developed within the project. This document thus considers the feedback from the user community to identify areas of strength and potential for improvement of any new products to be generated. Potential strategies are also identified for integrating the development methods and models into existing scientific initiatives and operational institutions. Similarly, recommendations are presented for maximization of benefit to be gained from the Sentinel-3 mission.

1.2 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
FF	Fully Focussed
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
MODIS	Moderate Resolution Imaging Spectroradiometer
JASON	US/French Altimeter Satellite
NCL	Newcastle University
OCOG	Offset Centre of Gravity
OSTM	Ocean Surface Topography Mission (JASON-2)
PRF	Pulse Repetition Frequency

R&L	River and Lake
RA	Radar Altimeter
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-1(3)	ESA Earth Observation Satellite Missions
SIRAL	SAR Interferometric Radar Altimeter
USDA	United States Department of Agriculture
VNIR	Very Near Infra-red
WP	Work Package

2 SAR waveforms from 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. Baseline B data have been used in CRUCIAL. For future projects, baselines C & D (from Q3 2017) data will be available.

2.1 Multi-look 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 earlier assumption, the Cryosat-2 individual bursts have limited hydrological usage.

2.2 G-POD SARvatore (SARinvatore)

Altimetric heights for Cryosat-2 can be obtained from ESA's Ground-Processing on demand (G-POD) services SARvatore (**SAR** **V**ersatile **A**ltimetric **T**oolkit for **O**cean **R**esearch & **E**xploitation) and SARinvatore (**SARin** **V**ersatile **A**ltimetric **T**oolkit for **O**cean **R**esearch & **E**xploitation). The SARvatore service can be accessed by using the link http://wiki.services. eoportal.org/tiki-index.php?page=GPOD+CryoSat-2+SARvatore+ Software + Prototype+ User+ Manual. Both SAR and SARIN multi-look waveforms and heights are derived by retracking with the SAMOSA2 retracker (Gommenginger et al., 2010). Analyses of SARin FBR data for an ocean pass shows slightly less accurate results with the CRUCIAL retrackers compared to the G-POD SARinvatore heights. This is as expected as G-POD uses the SAMOSA2 retracker designed for ocean applications.

Results showed that the SAMOSA2 retracker is inappropriate for inland waters. For future operational products the SAMOSA2 retracker must be replaced by either empirical retrackers developed for inland waters or, given the quasi-specular waveform, an OCOG/Threshold retracker. It is noted that since the analyses were performed the SAMOSA+ retracker has become available on SARvatore. SAMOSA+ is the SAMOSA2 model tailored for inland water, sea ice and coastal zone domain. This retracker needs consideration in future projects.

The recommendation is that CryoSat-2 waveforms across inland waters within services such as SARvatore (SARinvatore) should utilise retrackers specifically designed for that the application.

2.3 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 for SAR mode. This is not applicable to SARin as the number of waveforms is far less (maximum 60). 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.

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. As an example, 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 (see D5000 for further analyses).

2.4 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. It is noted that 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.

2.5 Near Real Time Product

The R&L project pioneered the concept of a near real-time inland water height product. A questionnaire in WP1100 solicited a number of responses with recommendations for future products including

- Higher spatial and temporal resolution of flooded areas
- Water level, water extent
- Discharge.

- Continuous long-term time series where possible, and water level data for large ephemeral rivers and lakes, e.g. Okavango, Lake Eyre, etc.
- Greater density of data points
- Reliability and sustainability
- Narrower river channels

Users also stated desirability for

- A global comprehensive and consistent database of all satellite altimetry over inland waters.
- The R&L online data for the largest rivers should be extended to a greater number of rivers.
- 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.

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). An alternative is the use of rating curves (e.g. Kennedy 1984) if available. A rating curve is a graph typically at a river gauge of discharge versus stage. If the ricer overflows its banks then the use of MODIS or SAR onboard satellites such as Sentinel-1 (Clement et al, 2017) can be used for near-real time monitoring.

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

With reference to the greater density of data points a new technique of Fully Focused (FF) SAR altimetry has been proposed by Egido and Smith (2017). In FF-SAR the waveform "is obtained by performing a coherent integration of the altimeter echoes along the entire illumination time of a scatterer on the surface after SAR focusing". Thus the methodology requires compensation for range and phase migrations with respect to the scatterer's position. In this approach along-track resolution that can be obtained is equivalent to the theoretical limit of the SAR altimeter, that is equal to half the antenna length. For typical SAR altimeters, this corresponds to about 0.5 m, in contrast to the approximately 300-m resolution of the unfocused delay/Doppler processing.

2.6 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.

2.7 SARin analyses of cross angle

SARin is unique to CryoSAT-2 and hence recommendations are limited to the scientific priority for future exploitation. In our analyses, the number of SARin waveforms used in the multi-looking is different (N=60 giving 2N+1=121 waveforms) to SAR (N=40 and 2N+1=81 waveforms) as reported in section 2.3. 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

(Peter Bauer-Gottwein and Raphael Schneider)

The results obtained in the CRUCIAL project show that river heights from SAR altimeters can improve the sharpness and reliability of hydrological model predictions. This has been demonstrated in synthetic data assimilation experiments for both CryoSat-2 and Sentinel-3 and in data assimilation experiments using real CryoSat-2 data. The following three main issues require further research and investigation: 1) Preprocessing of SAR altimetry for uptake into hydrodynamic models; 2) Impact of spatio-temporal sampling pattern; 3) Uncertainty of river heights derived from SAR altimetry.

3.1 Preprocessing of SAR altimetry for uptake into hydrodynamic models

Accurate water masks are required to filter out altimetry data points representing inland water heights. Ideally, water masks should be dynamic because many rivers have unstable morphology and the location of open water surfaces changes in time. In CRUCIAL, we have successfully used Landsat VNIR imagery to derive water masks. However, VNIR imagery can only be used under cloud-free conditions. SAR imagery is a promising all-weather alternative. Sentinel-1 provides free SAR imagery at high spatio-temporal resolution. Combination of Sentinel-1 SAR imagery and Sentinel-3/CryoSat-2 altimetry is a promising avenue for further research and operational application of the river modeling tools developed in CRUCIAL. Instead of filtering Level 2 altimetry data points over river masks, information from these masks also could be used in an earlier processing step to inform waveform analysis and retracking algorithms.

3.2 Impact of spatio-temporal sampling pattern

Location and orientation of the river system relative to the ground-tracks of the satellite orbit are key factors determining the value of altimetry data for a specific river. They control the spatio-temporal sampling pattern of the different altimetry missions. A powerful tool to investigate data value for a specific river is a synthetic data assimilation experiment. Such an experiment quantifies the performance improvement that can be achieved by assimilating altimetry data from a specific mission, under the assumption that the model is unbiased and both model and data uncertainties are perfectly described. Because these assumptions are never met in reality, the synthetic DA experiment provides an upper bound on the performance improvement. Synthetic DA experiments enable direct comparison of different altimetry missions in terms of their value for hydrologic modeling and forecasting. In CRUCIAL, we have compared CryoSat-2 and Sentinel-3 for the Brahmaputra river system; it would be interesting to extend this analysis to other river systems, with different characteristics and other satellite altimetry missions.

3.3 Uncertainty of river heights derived from SAR altimetry

A key factor determining the value of altimetry data is their uncertainty, and – maybe even more importantly – whether their uncertainty can be reliably characterized and quantified. Many of the large and remote river systems, where satellite radar altimetry provides the largest added value, are poorly gauged or ungauged. One possibility is to evaluate SAR altimetry data over well-gauged rivers and transfer these results. Besides that, innovative solutions are required to provide independent ground truth to validate altimetry data against. Apart from classical in-situ monitoring, unmanned autonomous airborne platforms can be used to access remote virtual stations and collect calibration and validation datasets. Potentially, such systems can also be used to establish rating curves at virtual stations, which would enable direct estimation of river discharge from altimetry. Developing innovative ground-based instrumentation that complements Copernicus satellite missions is a promising and high-impact direction for future research, which is also highlighted e.g. in the European Union's Horizon2020 program (https://ec.europa.eu/programmes/horizon2020).

4 References

Birkinshaw, S.J., Moore, P., Kilsby, C.G., O'Donnell, G.M., Hardy, A.J., Berry, P.A.M., 2014. Daily discharge estimation at ungauged river sites using remote sensing. Hydrol. Process. 28, 1043–1054. doi:10.1002/hyp.9647

Clements, K., Kilsby, C.J, and Mppre, P. 2017. Multi-Temporal SAR Flood Mapping using Change Detection, J. Flood Risk Man., doi:10.1111/jfr3.12303

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

EU Horizon2020 program (https://ec.europa.eu/programmes/horizon2020).

Egido, A and Smith, W.H.F., 2027,Fully Focused SAR Altimetry; Theory and Applications, IEEE Trans. Geo. Remote Sens. 55, 1, 392-406, doi:10.1109/TGRS.2016.2607122

Gommenginger, C., Martin-Puig, C., Cotton, P.D., Dinardo, S., and Benveniste, J., 2010, A prototype SAR altimeter retracker to assess the precision of SAR altimetry over the ocean. ESA SeaSAR Workshop 25-29 January 2010

Kennedy, E.J. (1984). Discharge ratings at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3 (PDF). US Government Printing Office. p. 5.