Sentinel-3 Performance improvement for ICE sheets

Scientific Roadmap

Scientific Exploitation of Operational Missions (SEOM)

Sentinel-3 SAR Altimetry

Study 4: Ice Sheets

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Acronyms and Abbreviations

AD	Applicable Documents
CLS	Collecte Localisation Satellites
CryoSat-2	CryoSat-2 satellite
DEM	Digital Elevation Model
ESA	European Space Agency
FF SAR	Fully Focused Synthetic Aperture Radar
ITT	Invitation To Tender
LRM	Low Resolution Mode
pLRM	Pseudo-LRM
POCA	Point Of Closest Approach
SAR	Synthetic Aperture Radar
SRM	Scientific Roadmap
SPICE	Sentinel-3 Performance improvement for Ice sheets
UL	University of Leeds
WP	Work Package

Applicable Documents

AD1	Scientific Exploitation of Operational Missions (SEOM). Sentinel-3 SAR Altimetry Statement of Work (SEOM S3-4SCI SAR Altimetry). Issue 1, 27/09/2014.
AD2	Special Conditions of Tender. Appendix 4 to AO/1-8080/14/I-BG.
AD3	SPICE Technical Proposal.

1. Introduction

Purpose

This document is the Scientific Roadmap (SRM) for the Sentinel-3 Performance improvement for ICE sheets (SPICE) proposal (AD3), which is a response to the European Space Agencies (ESA's) Sentinel 3 For Science – SAR Altimetry Studies (S3 4 SCI – SAR Altimetry Studies) Invitation To Tender (ITT), Ref. AO/1-8080/I-BG (AD1 and AD2). SPICE addresses the Study 4 theme related to Ice Sheets. The Scientific Roadmap has been written by the University of Leeds (UL), with contributions from isardSAT and CLS. UL as the prime contractor is the contact point for all communications regarding this document.

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Scientific Roadmap structure

The aim of the Scientific Roadmap is to identify and discuss options for future work, which build upon the achievements and knowledge gained during the SPICE study. Specifically, we map out what we believe to be the principal and highest priority areas for future study, which have the potential to deliver further advances in scientific and technical understanding. Within the document, we have categorised items according to those with a 'Data' focus, and those with a 'Methodological' focus. After this section, the SRM is therefore ordered as follows:

- **Section 2 – Priorities for Future Activities: Data.** For each identified item, we provide a brief description of the proposed activity. We then outline the scientific importance, technical justification, main objectives, and possible risk associated with the proposed study.
- **Section 3 – Priorities for Future Activities: Methodological Advances.** For each identified item, we provide a brief description of the proposed activity. We then outline the scientific importance, technical justification, main objectives, and possible risk associated with the proposed study.
- **Section 4 –** Summary.

In Section 2, we describe proposed activities that are targeted at exploiting new data streams, to advance the scope and domain of the SPICE study. Within the context of the SPICE study, these are particularly important because of the limited duration of CryoSat-2 SAR ice sheet acquisitions, and the clear potential for expansion now that the Sentinel-3A and -3B satellites are operational.

In Section 3, we outline activities that focus on methodological advances, that have the potential to further improve the accuracy and coverage of SAR retrievals over ice sheets, and associated estimates of ice sheet volume change, mass loss and sea level rise. Within the context of SPICE, the new processing methods developed during the study were novel and, as such, much of the work represented initial proof-of-concept and validation activities. Given the positive results achieved, for example with the implementation of pre-retracking modules, it is important that these methods and the technical lessons learned during SPICE are built upon in subsequent studies, to ensure that (1) these new techniques are further refined and optimised, and (2) they are embedded within future routine processing activities.

2. Priorities for Future Activities: Data

In Section 2.1, we firstly summarise the priorities identified for future work related to data evolution. Then in Section 2.2 we take each activity in turn, and discuss in further detail the proposed work, objectives and justification of the activity.

2.1. Summary of Priorities for Data Focussed Activities

ID	Roadmap Item Name	Origin WP	Description	Innovation Type	Effort	Risk
SRM01	Comparison of Sentinel-3 ESA Level-2 and SPICE Level-2 elevation measurements.	4	Validate ESA Sentinel-3 Level-2 product at SPICE study sites and compare to SPICE data emulated from CryoSat-2.	Data	Low	Low
SRM02	Analysis of Sentinel-3 ESA Level-2 elevation measurements at the ice sheet scale.	4	Use ice sheet wide coverage provided by Sentinel-3 to validate Sentinel-3 SAR altimetry at the ice sheet scale, relative to airborne reference datasets.	Data	Medium	Low
SRM03	Analysis of Sentinel-3 waveform morphology	2,3	Assess the distribution of single- and multi-peaked waveforms for conventional SAR, FF SAR and pLRM over the ice sheets.	Data	Medium	Low
SRM04	Analysis of Sentinel-3 ESA Level-2 derived elevation rates.	4	Compute and validate rates of ice sheet elevation change from the existing record of ESA L2 Sentinel-3 elevation measurements.	Data	Medium	Low
SRM05	Analysis of Sentinel-3 elevation rates derived using SPICE pre-retracking modules.	3,4	Assess the extent to which the SPICE pre-retracking modules can improve the accuracy of measurements of	Data + Methodological	Medium	Low

			surface elevation change derived from Sentinel-3.			
SRM06	Temporal evolution of Ku and Ka band measurements.	5	Extend the Ku/Ka SAR/LRM analysis to assess the temporal stability of both backscattered power and elevation retrievals from each mode.	Data	Medium	Low
SRM07	Comparison of coincident Sentinel-3 SAR, LRM and pLRM elevations.	4	Utilise the unique Sentinel-3A/B tandem phase to assess the difference between SAR, LRM and pLRM accuracy and precision.	Data	Medium	High

Table 1. Summary of priorities for future activities related to data innovation.

2.2. Detailed Description of Data Focussed Activities

2.2.1 SRM01 – Comparison of Sentinel-3 ESA Level-2 and SPICE Level-2 elevation measurements

Summary Description

Validate the ESA Sentinel-3 Level-2 product at SPICE study sites using independent, high-quality airborne reference datasets and compare to the performance of the SPICE emulated data.

Scientific and technical value

- Estimates of the accuracy and precision of SAR altimetry elevation measurements are important for establishing the scientific basis for a new era of operational SAR altimetry over ice sheets.
- SPICE activities focused on emulating Sentinel-3 data from CryoSat-2 SAR acquisitions, in advance of the operational phase of Sentinel-3.
- It is therefore important to perform the same analysis with actual Sentinel-3 Level-2 data produced by the operational ground segment, in order to confirm whether the same conclusions reached by SPICE hold.

Objectives

- Perform validation of Sentinel-3 L2 SAR at Dome C, Vostok, Spirit and Russell Glacier study sites.
- Perform validation of Sentinel-3 L2 pLRM at Dome C, Vostok, Spirit and Russell Glacier study sites.
- Compare validation statistics of Sentinel-3 SAR and SPICE emulated Sentinel-3 SAR and analyse any differences.
- Compare validation statistics of Sentinel-3 pLRM and SPICE emulated Sentinel-3 pLRM and analyse any differences.

Risk

Low – sufficient Sentinel-3 data to complete this task has already been acquired.

2.2.2 SRM02 – Analysis of Sentinel-3 ESA Level-2 elevation measurements at the ice sheet scale

Summary Description

Utilise the ice sheet wide coverage provided by Sentinel-3 to validate ESA Level-2 Sentinel-3 SAR altimetry at the ice sheet scale.

Scientific and technical value

- Due to the dedicated nature of CryoSat-2 SAR model acquisitions, SPICE study sites were limited in their spatial extent, meaning that (1) performance over all types of ice sheet topography could not be evaluated, and (2) not all of the available airborne validation data were utilised.
- With the complete ice sheet coverage up to ~81.5° in SAR mode provided by Sentinel-3, there is now the opportunity to extend the analysis methods developed in SPICE, and apply them to the whole ice sheet.
- This activity would allow a comprehensive assessment of SAR altimetry performance, for example to evaluate the sensitivity of SAR measurements to the full range of along- and across-track surface slopes, which is important for understanding the benefits and limitations of SAR mode altimetry over ice sheets.

Objectives

- Perform Antarctic-wide validation of Sentinel-3 ESA L2 SAR using all available airborne validation data.
- Produce comprehensive accuracy statistics for ESA L2 Sentinel-3 altimetry elevations.
- Investigate bias and precision as a function of the magnitude and orientation of the surface slope.

Risk

Low – sufficient Sentinel-3 data to complete this task has already been acquired.

2.2.3 SRM03 – Analysis of Sentinel-3 waveform morphology.

Summary Description

Use Sentinel-3 data to determine the distribution and prevalence of single- and multi-peaked waveforms across the ice sheets for conventional SAR, FF SAR and pLRM modes of acquisition.

Scientific and technical value

- SPICE analysis has shown the challenges associated with retrieving reliable elevations in regions where complex topography produces multi-peaked waveforms.
- Because of the different along-track beam-width of the SAR and pLRM measurements, we expect that each mode will vary in the extent to which multi-peaked waveforms will be produced.
- A comparison of the extent of this differing sensitivity will inform understanding of the relative performance of SAR and pLRM, and the need to employ more complex processing strategies to each mode, such as the pre-retracking modules developed during the SPICE study.
- Additionally, the recent development and application of Fully Focused SAR methods (see SRM12) allows the possibility to extend this analysis further, to consider waveform morphology for along-track resolutions up to the theoretical 0.5 metre limit of the antenna.

Objectives

- Develop a classification tool to identify different types of waveform.
- Classify Sentinel-3 SAR, FF SAR (see SRM12) and pLRM waveforms across the whole ice sheet.
- Compare SAR, FF SAR and pLRM statistics, and investigate relationship to topographic complexity, and magnitude and orientation of surface slope.
- Assess the extent of any correlation between waveform type and accuracy of elevation measurements.

Risk

Low – sufficient Sentinel-3 data to complete this task has already been acquired. A tool to classify waveforms would need to be developed but this is not expected to be an activity with a high failure risk.

2.2.4 SRM04 – Analysis of Sentinel-3 ESA Level-2 derived elevation rates.

Summary Description

Utilise the multi-year record of Sentinel-3 data to map ice sheet wide rates of surface elevation change, and evaluate Sentinel-3 performance using airborne measurements of surface elevation change.

Scientific and technical value

- Rates of ice sheet elevation change are critical for determining ice sheet evolution and the associated contribution to sea level rise.
- During the SPICE study, due to the short duration of the SAR acquisition period operated by CryoSat-2, we focused only on the validation of ice sheet surface elevation measurements, and not elevation change.
- The longer Sentinel-3 record now offers the opportunity to perform a further analysis, focussed on the ability of SAR altimetry to accurately determine rates of surface elevation change.

Objectives

- Determine rates of surface elevation change from Sentinel-3 data, spanning the whole of Antarctica.
- Investigate coverage and precision of Sentinel-3 SAR elevation rates.
- Determine the accuracy of Sentinel-3 SAR elevation rates using independent airborne reference datasets.
- Determine equivalent accuracy of pLRM, LRM and SARIn elevation rates from Sentinel-3 and CryoSat-2.
- Compare relative accuracies of different modes of operation over various topographic regimes.

Risk

Low – sufficient Sentinel-3 data to complete this task has already been acquired.

2.2.5 SRM05 – Analysis of Sentinel-3 elevation rates derived using SPICE pre-retracking modules

Summary Description

Assess the extent to which the implementation of the SPICE pre-retracking modules for Sentinel-3 data (SRM08) can improve the accuracy of Sentinel-3 measurements of surface elevation change.

Scientific and technical value

- The SPICE analysis has demonstrated that the introduction of novel pre-retracking modules can improve the accuracy of SAR elevation retrievals, particularly in regions of complex coastal terrain.
- These results are particularly encouraging, although they now need to be extended to analyses of rates of surface elevation through time, to determine the extent to which these methodological innovations can benefit estimates of ice sheet mass balance and sea level contribution.
- The multi-year record of Sentinel-3 data now offers the opportunity to do this.

Objectives

- Use reprocessed elevations (see SRM08) to determine rates of ice sheet surface elevation change and validate these using airborne reference datasets.
- Inter-compare accuracies with and without pre-retracking modules to reach conclusions about their ability to improve the accuracy of elevation rate estimates.
- Evaluate the sensitivity of any performance differences to factors such as surface slope.

Risk

Low – data and methodologies are already established.

2.2.6 SRM06 – Temporal evolution of Ku and Ka band measurements.

Summary Description

Extend the SPICE Ku/Ka SAR/LRM analysis to look at the temporal stability of both backscattered power and elevation retrievals made by each mode.

Scientific and technical value

- The SPICE analysis compared waveform characteristics and elevation measurements derived by Ku/Ka SAR/LRM instruments.
- Due to the limited CryoSat-2 SAR acquisitions, these analyses were focused on a week-long period in 2014.
- For the purposes of future mission concepts, it is important not only to understand the instantaneous differences, but also to establish how stable each frequency and mode is through time.
- This is now possible given the growing period of Sentinel-3 acquisitions, in combination with the existing AltiKa Ka-band record.

Objectives

- Assess and inter-compare temporal changes in waveform shape of Ku/Ka SAR/LRM at the Lake Vostok validation site.
- Investigate the link between any differences and meteorologically-driven changes in snowpack characteristics.
- Repeat the same analysis for a site within the Greenland interior, where changes in melt and snowpack characteristics may be more pronounced.
- Assess changes in backscattered power and retrieved elevations through time for Ku/Ka SAR/LRM at the Lake Vostok and Greenland study sites, in order to investigate the relative stability of each mode of operation.

Risk

Low – data and methods already exist.

2.2.7 SRM07 – Comparison of coincident Sentinel-3 SAR, LRM and pLRM elevations.

Summary Description

Utilise the unique Sentinel-3A/B tandem phase to assess the difference between SAR, LRM and pLRM accuracy and precision, using coincident and co-orientated acquisitions.

Scientific and technical value

- To ensure a consistent long-term record of ice sheet evolution, it is necessary to inter-calibrate new SAR measurements with the historical LRM record.
- The most effective way to achieve this is through the use of coincident, co-located and co-orientated acquisitions, in order to minimise the impact of other factors, which may introduce additional sources of elevation change.
- The cycle of the Sentinel-3A/B tandem phase where the satellites operate in a dual SAR/LRM configuration provides a unique opportunity to perform such an analysis.

Objectives

- Assess differences in SAR/LRM/pLRM waveforms, both at inland sites with simple topography, and at coastal sites with more complex topography.
- Compare SAR/LRM/pLRM elevation measurement precision, by investigating shot-to-shot variations above the Lake Vostok validation site.
- Assess SAR/LRM/pLRM accuracy, using airborne reference datasets.

Risk

High – tandem phase data has not been analysed yet and so its quality is unknown.

3. Priorities for Future Activities: Methodological Advances

In Section 3.1, we firstly summarise the priorities identified for future work related to further advancing the SPICE methods. Then in Section 3.2 we take each activity in turn, and discuss in further detail the proposed work, objectives and justification of the activity.

3.1. Summary of Priorities for Methodological Focussed Activities

ID	Roadmap Item Name	Origin WP	Description	Innovation Type	Effort	Risk
SRM08	Application of SPICE pre-retracking modules to Sentinel-3 data.	3	Assess the extent to which the SPICE pre-retracking modules can improve the accuracy of Sentinel-3 elevation measurements.	Methodological	Medium	Low
SRM09	Pre-retracking module evolution.	3	Develop more advanced pre-retracking methodologies through integration of DEM and Batch pre-retracking modules.	Methodological	High	Medium
SRM10	Algorithm evolution for the DEM pre-retracking method	4	Further develop the current DEM pre-retracking method to include a fine-scale sub-peak slope correction.	Methodological	Medium	Medium
SRM11	Analytical retracker development	3	Incorporate topographic information and a snowpack backscattering model into analytical retracker formulation.	Methodological	High	High
SRM12	Assessment of Fully Focused SAR over ice sheets	2	Assess the capability of Fully Focused SAR to improve the resolution and accuracy of ice sheet elevation measurements.	Methodological	Medium	Low

Table 2. Summary of priorities for future activities related to methodological innovation.

3.2. Detailed Description of Methodological Focussed Activities

3.2.1 SRM08 – Application of SPICE pre-retracking modules to Sentinel-3 data.

Summary Description

Implement and assess the extent to which the novel DEM and Batch pre-retracking modules developed during the SPICE study can improve the accuracy of Sentinel-3 elevation measurements.

Scientific and technical value

- The SPICE analysis demonstrated that the introduction of novel pre-retracking modules can improve the accuracy of SAR elevation retrievals, particularly in regions of complex coastal terrain.
- Introduction of these additional processing methods therefore has the potential to greatly improve the accuracy of Sentinel-3 ice sheet elevation measurements.
- To further establish the evidence base supporting the wider implementation of these types of modules, it is important that the improvements can be convincingly demonstrated for actual Sentinel-3 data, in additional to the emulated data used in SPICE.

Objectives

- Adapt SPICE WP2 and WP3 processors for Sentinel-3 data.
- Perform DEM and Batch processing of Sentinel-3 data at SPICE study sites.
- Evaluate relative performance of elevation data derived with and without pre-retracking modules.

Risk

Low – data and methodologies have already been established during the SPICE activities.

3.2.2 SRM09 – Pre-retracking module evolution.

Summary Description

Develop more advanced pre-retracking methodologies through integration of DEM and Batch pre-retracking modules.

Scientific and technical value

- The SPICE analysis has demonstrated that the introduction of novel pre-retracking modules can improve the accuracy of SAR elevation retrievals, particularly in regions of complex coastal terrain.
- During the study, the initial basis and proof-of-concept of these approaches was convincingly demonstrated, which now presents the opportunity for further methodological refinements.
- One specific issue that was identified during the project was that although Batch worked to ensure consistency in the peak that was retracked, it did not necessarily mean that the peak corresponding to the Point Of Closest Approach (POCA) was selected. Hence it may not always be appropriate to apply the subsequent POCA relocation that is a common step in all conventional Level-2 processing chains.
- A further refinement is therefore proposed for future work, whereby through integration of Batch and DEM processing, it could be ensured that the nadir peak was selected (DEM) and that consistency was maintained throughout a sequence of echoes (Batch).
- This approach has the potential to further improve the accuracy of elevation measurements in regions of complex coastal terrain.

Objectives

- Develop methodological refinements within the SPICE code to integrate the DEM and Batch pre-retracking modules.
- Compute ice sheet surface elevation measurements using refined processing and validate using airborne reference dataset.
- Inter-compare the accuracy of elevation measurements derived with both the original and integrated pre-retracking modules and assess any improvements in accuracy.

Risk

Medium – methodological innovation may not ultimately be successful or deliver improved results.

3.2.3 SRM10 – Algorithm evolution for the DEM pre-retracking method.

Summary Description

Further develop the current DEM pre-retracking method to include a fine-scale sub-waveform-peak slope correction.

Scientific and technical value

- The novel SPICE DEM pre-retracking module was designed to overcome the first-order problem of multi-peak waveforms by ensuring the selection of the peak closest to nadir.
- In theory, it would be possible to further refine this approach to account for the fact that the peak closest to nadir may not necessarily be exactly at nadir.
- The proposed methodology would be to introduce a fine scale slope correction that would be applied after the DEM peak selection and retracking, which would have the potential to further improve the performance of the DEM-based method.

Objectives

- Introduce a fine scale slope correction into the DEM-based pre-retracking method.
- Process data to Level-2 using this approach.
- Inter-compare the existing and refined DEM-based approaches using independent airborne validation data, to reach conclusions about relative performance, both at topographically simple, and complex, sites.

Risk

Medium – involves methodological innovation that may not necessarily deliver successful or improved results.

3.2.4 SRM11 – Analytical retracker development.

Summary Description

Incorporate topographic information and a snowpack backscattering model into the analytical retracker formulation.

Scientific and technical value

- Analytical retrackers have proved to be very effective over water surfaces.
- Over ice surfaces, however, the added complexity resulting from surface topography and radar wave penetration into the snowpack means that the distribution of elemental scatterers as a function of range is poorly resolved, and not currently included within any analytical model.
- Indeed SPICE analysis found that analytical retrackers do not currently perform as well as their empirical counterparts, particularly over regions with complex topography.
- This presents the challenge of incorporating topography and sub-surface scattering into the analytical model, which if successful has the potential to greatly improve the process of waveform retracking over ice sheet surfaces.

Objectives

- Develop a physically-based sub-surface backscattering model suitable for incorporating into an analytical retracker.
- Develop a method for incorporating topographic information into the analytical formulation.
- Produce a new analytical retracker that includes sub-surface backscattering and topographic components.
- Test, validate and inter-compare the new retracker, relative to baseline results developed during the SPICE project.

Risk

High – technically challenging and exploratory work, but with the potential for high rewards.

3.2.4 SRM12 – Assessment of Fully Focused SAR over ice sheets.

Summary Description

Assess the capability of Fully Focused SAR to improve the resolution and accuracy of Sentinel-3 ice sheet elevation measurements.

Scientific and technical value

- Recent proof of concept studies have demonstrated that Fully Focused SAR (FF SAR) processing can successfully be applied to both Cryosat-2 and Sentinel-3 closed burst SAR data.
- Demonstrations of the technique to date have been limited to ocean, inland water and sea ice surfaces.
- FF SAR is of interest over land ice because it has the potential to (1) improve the along track resolution towards the theoretical 0.5 metre limit defined by the antenna, and (2) improve the noise statistics by allowing averaging of a greater number of independent looks.
- It is therefore of scientific interest to investigate and quantify the capabilities of FF SAR over ice sheets, and this activity will also serve to inform decisions relating to future mission design, for example in selecting between an open burst and closed burst configuration.

Objectives

- Implement FF SAR at several test sites, including those with a range of topographic complexity.
- Assess FF SAR shot-to-shot precision.
- Investigate the extent to which FF SAR is able to resolve finer scale ice sheet surface features, such as short wavelength topography or supraglacial lakes and streams.
- Compare accuracy of FF SAR and conventional unfocused SAR, through comparison to independent airborne measurements.

Risk

Low – the technique has already been demonstrated, so the assessment itself – irrespective of what the results show – represents a low risk activity.

6. Summary

This Scientific Roadmap serves to outline the scientific and technical priorities for future work, building upon the achievements and lessons learned from the SPICE study. In the document we have described a range of potential activities, which are focussed on (1) expanding the work of SPICE to new domains and sources of data, and (2) building upon the methodological innovation of SPICE to further advance the processing techniques used for SAR altimetry over ice sheets. All of the proposed activities have been designed so as to directly contribute to the future scientific exploitation of the Sentinel-3 programme over ice sheets, with a view to improving the accuracy and coverage of these geophysical measurements over polar regions. Importantly, these activities will also benefit our technical understanding of how SAR altimetry senses the ice sheets, which is essential for fostering the sustainable community, and evidence base, required for the future exploitation of these operational data. All of the activities identified within this document are achievable, we believe, given the legacy and knowledge established during the SPICE study.