Polar Monitoring Mission, Assessment and Consolidation of Requirements and Analysis of Campaign Data

Technical Note 1:

Task 1 Report

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Acronyms and Abbreviations

AD: Applicable Document

CLS: Collecte Localisation Satellite

CMEMS: Copernicus Marine Environment Monitoring Service

CRISTAL: Copernicus polar Ice and Snow Topography ALtimeter

DEM: Digital Elevation Model

FF-SAR: Fully Focused Synthetic Aperture Radar

GMSL: Global Mean Sea Level

LRM: Low Resolution Mode

MSL: Mean Sea Level

MSS: Mean Sea Surface

NRT: Near Real Time

POD: Precise Orbit Definition

SAR: Synthetic Aperture Radar

SARIn: Synthetic Aperture Radar Interferometer

SIT: Sea Ice Thickness

SSH: Sea Surface Height

SWH: Significant Wave Height

Applicable Documents

AD1	Copernicus Polar and Snow Cover Applications User Requirements Workshop, http://www.copernicus.eu/polar-snow-workshop
AD2	PEG-1 Report, User Requirements for a Copernicus Polar Mission, Step 1 Report, Polar Expert Group, Issue: 12th June 2017
AD3	PEG-2 Report, Polar Expert Group, Phase 2 Report on Users Requirements, Issue: 31st July 2017
AD4	2015 Update of Actions in The Response of the Committee on Earth Observation Satellites (CEOS) to the Global Climate Observing System Implementation Plan 2010 (GCOS IP-10), 10th May 2015, http://ceos.org/document_management/Working_Groups/WGClimate/WGClimate_The-CEOS-CGMS-Response-to-the-GCOS-2010-IP_Jun2015.pdf
AD5	CMEMS requirements for the evolution of the Copernicus Satellite Component, Mercator Ocean and CMEMS partners, February 21, 2017, http://marine.copernicus.eu/wp-content/uploads/2019/01/CMEMS-requirements-satellites.pdf

1. Introduction

1.1 Purpose

This document is the Technical Note summarising Task 1: *Review of the state of the art and analysis of user requirements and potential applications*, which forms part of the *Polar Monitoring Mission, Assessment and Consolidation of Requirements and Analysis of Campaign Data* study, Ref AO/1-9539/18/NL/NA.

The Technical Note has been written by Lancaster University, CLS, the Finish Meteorological Institute and LEGOS. CLS is the prime contractor is the contact point for all communications regarding this document.

1.2 Document Structure

The aim of this Technical Note is to summarise Task 1 activities, which have been to document a snapshot of the User Requirements and Earth Observing System context, including gap analysis, for a future Polar Monitoring Mission. Following Section 1, the remainder of the document is structured into three thematic themes:

- Sea Ice.
- Ice Sheets.
- Ocean.

2. Sea Ice

2.1 Review of state-of-the-art Ku and Ka band altimetry over sea ice.

This subsection briefly describes the results and lessons learned from previous missions as well as presents the scientific applications of CRISTAL from the viewpoint of sea ice. For the technical details of sea ice thickness processing, please see for example the Sea Ice CCI ATDV document. Furthermore, for a detailed review on altimeter remote sensing of polar oceans the reader is suggested to familiarise with the current review paper “Retrieving Sea Level and Freeboard in the Arctic: A Review of Current Radar Altimetry Methodologies and Future Perspectives” by Quartly et al., 2019.

2.1.1 Progress to the current state-of-the-art

The European Space Agency has a strong background in altimetry. During the past 30 years, ESA has launched a series of altimeter satellites, represented in Figure 1. After the launch of ERS-1 in July 1991, at least one new satellite altimeter has been launched each decade, ensuring timewise consistent time series of measurements. In addition to the European altimetry, NASA has had a few early radar altimeters and the more recent laser altimeters ICESat-1 and ICESat-2.

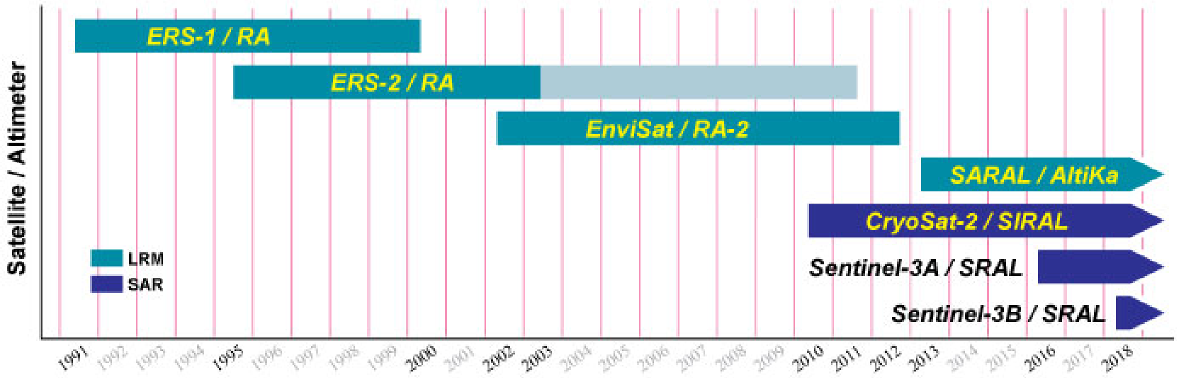

Figure 1***: The past and current radar altimeter missions with an orbit poleward of 72° N and separated into traditional low-resolution measurement (LRM) and synthetic aperture radar (SAR): Years of mission launch and end are highlighted; ERS-2 only provided limited data after June 2003. (Figure from Quartly et al., 2019)***

The majority of the European radar altimeters used for sea ice have worked on a Ku-band, which has resulted in decades of knowledge and greatly improved acquisition resolution and reduced uncertainties. With the improved understanding, scientist have been able to improve the earlier records, e.g. Paul et al. (2018) who have used the understanding gained with CryoSat-2 to produce a consistent time series for CryoSat-2 and Envisat. An exception to the

European Ku-band altimeters was introduced by SARAL, carrying an AltiKa instrument working on a Ka-band. Armitage and Ridout (2015) demonstrated retrieval of sea ice freeboard with the AltiKa instrument, but a record of sea ice thickness did not come across in that study.

The series of satellites have provided almost continuous records of sea ice freeboard and thickness (see examples of several data sets in Figure 3.2, Laxon et al., 2003; Giles et al., 2008, Laxon et al., 2013; Kurtz et al., 2014; Ricker et al., 2014; Price et al., 2015; Tilling et al., 2018; Hendricks et al., 2018), and efforts have been made to get these records consistent in the sea ice variables converted from the direct measurements (Guerreiro et al., 2017; Paul et al. 2018). Having a continuous record with consistent measurements enables understanding the ongoing changes, their speed and magnitude.

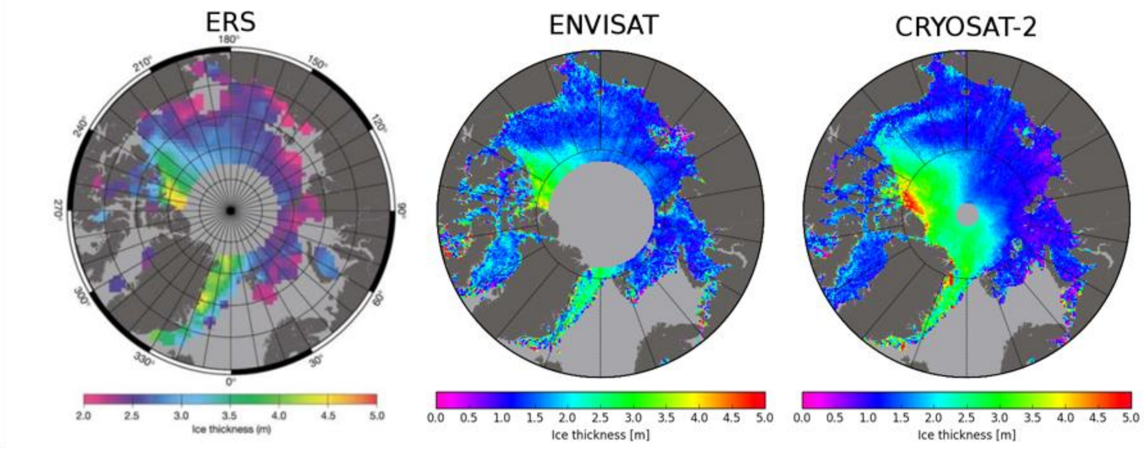

Figure 2*: Examples of average winter (October to March) Arctic sea ice thickness. Left is the combination of ERS-1 and ERS-2 from October 1993 to March 2001 (Figure from Laxon et al., 2003), middle Envisat from October 2004 to March 2005 and right CryoSat-2 from October 2014 to March 2015. Data for the Envisat and CryoSat-2 plots is from the Climate Data Record made for the ESA Climate Change Initiative (Paul et al., 2017, Hendricks et al., 2018)*

The satellite orbits have had a typical inclination of approximately 98.5°, enabling geographical coverage up to 81.5°N/S. The first three of the altimeter-carrying satellites (ERS-1, ERS-2 and Envisat) operated at Ku-band (13.6 GHz) and had a 35-day repeat period, and a large footprint. Ku-band altimetry was used for first time to map Arctic-wide sea ice thickness by Laxon et al. (2003), who provided the first map of sea ice thickness from radar altimeter measurements with the data from ERS-1.

The next radar altimeter to adopt the 35-day orbit was SARAL/AltiKa, which operates at Ka-band (35 GHz) instead of Ku-band. All of the mentioned Ku-band satellites operated low-resolution measurement (LRM) sensors, and a major technological change was introduced by instruments with a delay-Doppler or SAR Measurement (SARM) processing capability. The new technology enabled a finer along-track resolution and lower noise levels. CryoSat-2 was the first satellite operating with this new technology, accompanied by the more recently-launched Sentinel-3A (2016) and Sentinel-3B (2018). Besides the new technology, CryoSat-2 extended the capabilities of measuring elevation changes from 81.5°N/S to 88°N/S, meaning almost full coverage of the Arctic sea ice. However, the Sentinel-3 pair did not continue on the track of CryoSat-2, rather continued on the more common orbit reaching only 81.5°N/S, leaving a bigger uncovered area in the poles. Also, in comparison with CryoSat-2, Sentinel-3 pair has no interferometer, making the interpretation of the return echo less accurate. We were not successful in finding a Sentinel-3 data record of sea ice thickness or any related parameter, which could imply it is not favourable for this polar mission task.

SARAL/AltiKa introduced for the first time spaceborne measurements with Ka-band. Compared to Ku-band instruments, the signal penetrates differently to the snow on top of the sea ice. Armitage and Ridout (2015), Maheswari (2015) and Guerreiro et al. (2016) have studied the penetration depths and concluded the reflection for Ka-band originates from a region close to the snow-ice interface, whereas for Ku-band the main echo comes closer to the snow-ice interface (see Figure 3a). As the uncertainty of the snow depth over sea ice is considered the biggest contributor to the uncertainty of sea ice thickness estimation, a combination of both Ka- and Ku-bands could help to enlighten the closer truth of the actual snow depths, which is exactly what Guerreiro et al. (2016, see Figure 3b-d) and Lawrence et al. (2018) demonstrated.

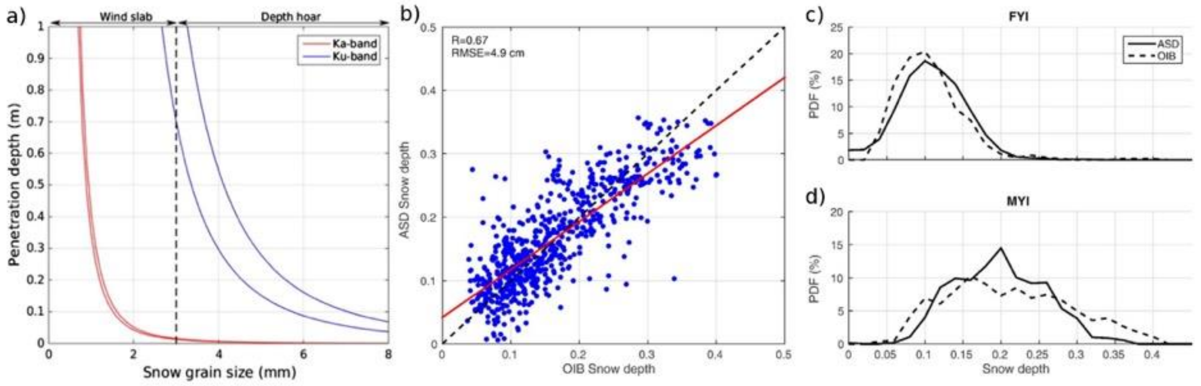

Figure 3 ***a) Penetration depth as a function of grain size for Ka- (red) and Ku-band (blue) frequencies. b) Comparison of combined Altimetric Snow Depth (ASD) from SARAL/AltiKa (Ka-band) and CryoSat-2 (Ku-band) to Operation IceBridge (OIB) snow depths, and probability distribution functions of snow depth for ASD and OIB over first year ice c) and multi year ice d). (Figure combined from Guerreiro et al. 2016).***

<u>Note on the Warren climatology</u>

Warren et al. (1999) provide snow climatology data set of snow depth and density for each month of the year. The averages are based on measurements from usually only two stations, and the high spatial and temporal variability of snow depth makes it difficult to estimate the errors of these Warren climatology means (Shalina et al., 2018). Another known limitation of Warren climatology is that the measurements are made mainly on multiyear ice, making it heavily biased towards multiyear ice. This is well apparent when comparing the more recent measurements, involving large areas of first-year ice, which shows that the average snow depths are smaller than in the Warren climatology (Kurtz and Farrell 2011, Shalina et al., 2018).

In summary:
- Outdated over first-year ice, could be improved over multiyear ice
- Monthly climatological means, do not represent the current conditions, especially not in NRT

2.1.2 Summary of current applications

2.1.2.1 Sea ice freeboard and thickness

Laxon et al. (2003) produced the first Arctic-wide sea ice thickness estimates from radar altimetry. Since then various methods for converting the received signal to physical variables have been established (Giles et al., 2008, Laxon et al., 2013; Kurtz et al., 2014; Ricker et al., 2014; Price et al., 2015; Tilling et al., 2018; Hendricks et al., 2018). The capability to get an estimate of thickness, and converting this to volume, enabled the scientist to better understand the changing Arctic. Before, satellite observations had mainly covered ice extent. Sea ice freeboard can be calculated for both Ka- and Ku-band measurements (Armitage and Ridout, 2015). Comparison of several current CryoSat-2 sea ice thickness products can be found in Sallila et al., 2019.

Sea ice thickness products are currently provided on a 25 km grid, which corresponds to the GCOS user requirements (GCOS, 2011), but do not meet the accuracy requirements of 0.1 m. It is estimated the systematic uncertainty in sea ice thickness is 0.6 m for first year ice and 1.2 m for multi-year ice, caused mainly by the unknown penetration of the radar pulse into the snow layer, as well as the choice of the retracker (Ricker et al., 2014).

2.1.2.2 Snow depth over sea ice

An estimate of snow depth over sea ice is needed when converting the altimeter measurements into sea ice thickness. The snow climatology of Warren (Warren et al., 1999) is still to this date the single most used estimate of snow depth in sea ice thickness processing (Sallila et al., 2019). With more recent knowledge, the original Warren snow depth estimates are halved over first year ice (Kurtz and Farrell, 2011), but snow represents still the single most important contribution to estimation of sea ice thickness and volume (Tilling et al., 2018).

A key driver for launching a dual-frequency altimeter is retrieval of snow load on sea ice. As suggested by Guerreiro et al. (2016) and further demonstrated by Lawrence et al. (2018), snow depth has been retrieved based on dual-frequency method to create snow depth products. Due to the novelty of the method, not many applications are yet in use, but for example the ESA Support To Science Element Arctic+ Snow Thickness on Sea Ice project (Tsamados 2017, Tsamados et al. 2017, Sallila and Rinne 2018, Bulczak 2018) resulted in several novel snow products, aiming to bridge the observational gaps and reduce the uncertainty related to snow. In addition to a model based snow product, a Dual-altimeter Snow Thickness (DuST) snow product, utilizing data from multiple contemporary satellite altimeters, was created during the project. The project assessed the impact of these new snow products on both modelling and satellite sea ice thickness processing. When using the CryoSat-2 - AltiKa dual-altimeter snow depth product both the model sea ice volume, and processed CryoSat-2 sea ice thickness appeared lower than reference. Without a comprehensive validation data set it is hard to state the absolute truth, but these results would imply a possibility of overestimated sea ice thickness and volume in both modelling and sea ice thickness processing, due to inadequate knowledge of snow on sea ice. It was also apparent in this study that the lack of measurements closer to pole resulted in lower coverage of the snow products.

2.1.3 Potential CRISTAL products already used in services

Copernicus Marine Environment Monitoring Service (CMEMS)

SEA ICE Satellite product variables:

- sea ice concentration
- sea ice thickness
- sea ice drift
- sea ice edge
- sea ice type (first year / multi year)
- iceberg density
- sea ice temperature

Real time products: a new product update every day, a few hours after sensing

Reprocessed products: a new products every 1 to 2 years with optimal accuracy and homogenous time series

The Copernicus Climate Change Service (C3S)

1) C3S Climate Data Store

Parameters: sea-ice concentration, edge, type, thickness

https://climate.copernicus.eu/ocean

2) Global Shipping Project, to aid decision-making process and support medium to long-term planning in the global shipping sector

Parameters: ice thickness and concentration from historical data and climate projections

https://climate.copernicus.eu/global-shipping-project

2.2 Gap analysis relative to the 2025 observing system

2.2.1 User Requirements

This review shall take stock of all user requirements obtained through release of outputs from the Commission User Requirements Study and Workshop [RD-1] and the Polar Expert Group (PEG) reports (Duchossois et al., 2018a, 2018b) as well as those resulting from similar initiatives.

2.2.1.1 Modelling community user needs

Several of the floating ice parameters and snow listed in Section 2.2.1.1, identified by the PEG, are relevant for climate modelling (Duchossois et al., 2018a). Out of these, sea-ice modellers constantly rank improved measurements of sea ice thickness distributions as a top priority, and already satellite-based sea ice thickness estimates are successfully assimilated into dynamic sea-ice models, resulting in more accurate forecasts (Yang et al., 2014; Allard et al., 2018; Blockley and Peterson, 2018; Stroeve et al., 2018; Xie et al., 2018). Better accuracy and knowledge of the estimate uncertainties are necessary for a better understanding of the impact of climate change in the Arctic and Antarctic, as well as for the areas impacted by these. For icebergs, it was mentioned that the volume is needed typically on 50 km resolution, even 15 km to match the latest air-sea flux resolutions (Duchossois et al., 2018b).

2.2.1.2 Climate research user needs

The highlighted parameters essential to climate research are those needed for assimilation in operational products, such as sea-ice ocean reanalyses. Among these are sea ice thickness (freeboard, including summer ice and thin ice), ice type, icebergs (detection, volume change and drift) and snow (depth and density). For sea ice thickness the requirements correspond to those that CryoSat-2 fulfils, except that extended temporal coverage and reduced uncertainties due to snow loading should be added, and for snow parameters the requirements follow those for sea ice thickness. Similar to modelling, uncertainties are expected to be delivered with the data, as they are needed in the assimilation system setup and when assessing the quality of the prediction (Duchossois et al., 2018a).

Requirements for sea ice thickness products for climate research have been documented more in detail in user requirements survey by the ESA Climate Change Initiative Phase 1 (Sandven, 2012) and Phase 2 (Sandven, 2018). In Phase 1 the users requested sea ice thickness from radar altimeter data for all seasons, spatial resolution of 10-50 km and error of maximum 5-20 cm (error being separated to precision 5-10 cm accuracy and to bias and long-term stability with 10-20 cm accuracy). Although this survey focused on sea ice concentration and sea ice thickness, users were asked to name other important sea ice parameters. These included sea ice drift, snow depth on sea ice, sea ice type, sea ice volume, lead fraction, ridge fraction, sea ice freeboard, floe size, melt parameters, polynyas and surface roughness. The temporal resolution requirements for these additional variables varied between daily and monthly, and the resolution requirements in the 10-50 km range (Sandven, 2012). In Phase 2 a spatial resolution better than 50 km and measurement precision better than 20 cm for the sea ice thickness product was something the data users requested. Temporal resolution of a month appeared to be sufficient and in addition there was a requirement of long-term stability of 5 cm per decade for sea ice thickness. (Sandven, 2018).

2.2.1.3 Winter navigation user needs

WMO (2006) has identified four sea ice features that have the biggest impact on marine operations:

1. Sea ice thickness (stage of development)
2. Sea ice concentration
3. Form of the ice, meaning distinguishing between fast and drift ice, and the size of the constituent floes
4. Any movement of the ice

However, spaceborne measurements of sea ice thickness are not used in operational ice charting. Most ice services use imaging radar data, where sea ice stage of development is deducted from backscattering coefficient and ice development history. Often in-situ observations from ships or coastal stations as well as different models are also used. There are two major user needs for altimeter measurements used in operational ice charting (example of need 2. In Figure 4):

1. Timeliness requirement close to that of imaging SAR, so that both are available at the same time when ice analysis is made.
2. Requirement for the SAR and altimeter acquisitions to be as coincident as possible due to ice drift.

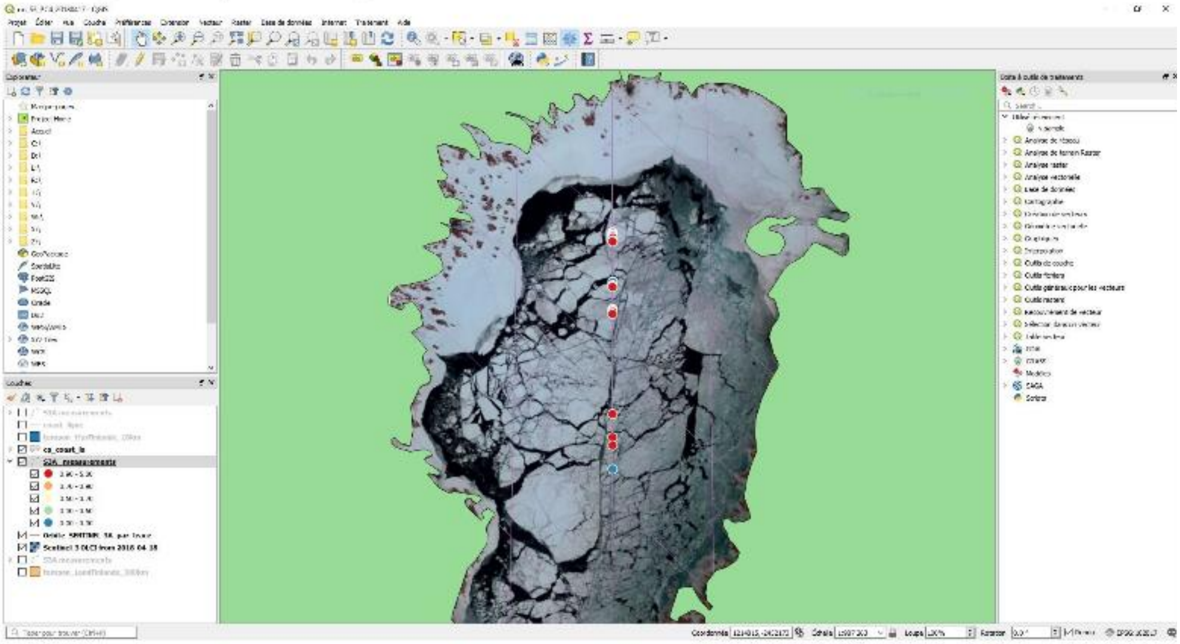

Figure 4. *Sentinel-3 SRAL measurements overlaid on an OLCI frame on a Finnish Ice Service workstation showing the ice conditions in Northern Bay of Bothnia on April 17th 2018.*

One of the contacted potential users was Aker Arctic ship design company based in Helsinki, Finland. They recognised altimeter based SIT estimates potentially valuable for ship transit modelling. Currently their system only ingests climatological sea ice extent. They see that any global sea ice thickness estimates - including altimeter based ones - would improve their transit time estimates. However, the data to quantify the effect is already available since CryoSat-2 thickness estimates from several ESA projects are publicly available.

2.2.1.4 Floating-ice parameters

Floating-ice parameters have been listed as the top priority for the polar mission user requirements by a collective of polar experts (Duchossois et al., 2018a). These parameters include sea ice extent/concentration/thickness/type/drift/velocity, thin sea-ice distribution, iceberg detection/drift and volume change as well as ice shelf thickness and extent. These parameters are given a top priority due to their key position in operational services such as navigation and marine operations, and in climate modelling. The user requirement study emphasized the importance of operational use for the future mission concept.

Furthermore, the Global Climate Observing System (GCOS, 2011) pointed out that actions should be taken to ensure continuation of altimeter missions over sea ice, as part of the assessment of the adequacy of observations for meeting requirements for monitoring climate and global change in support of the UN Framework Convention on Climate Change (UNFCCC) [RD-1]. They suggested continuation of satellite SAR altimeter missions, with enhanced techniques for monitoring sea ice thickness, to achieve capabilities to produce time series of monthly, 25 km sea ice thickness with 0.1 m accuracy for north and south polar regions. It was mentioned near-coincident data, achieved for example through close coordination between radar and laser altimeter missions, would help resolve uncertainties in sea ice thickness retrieval. In addition to sea ice thickness, other sea-ice parameters retrievable from SAR, such as ice drift, shear and deformation, leads and ice ridging, were pointed as variables under focus for future improvement.

Almost ten years have passed since the GCOS user requirements were stated, during which CryoSat-2 and Sentinel-3 satellites have started their operations. Still many of the requirements, for example the 0.1 m accuracy for sea ice thickness monthly fields, or adequate uncertainty and bias estimate, or improvement in the handling of snow on sea ice has not been achieved.

2.2.1.5 Snow

Knowledge of snow depth is essential for several users and applications. It is used in climate modelling, navigation and it has a key role in sea ice thickness processing. Snow depth is an essential variable when estimating sea ice thickness with satellite altimetry. Snow is used together with ice freeboard, snow and ice density to calculate sea ice thickness, and further, with estimates of sea ice concentration, sea ice volume. The snow on top of sea ice has an impact on the instrument signal, and there are uncertainties related with this. It is often assumed that radar instrument penetrates to the snow/ice interface, but there are known faults to this assumption (Willatt et al., 2011). An error of 0.1 m in snow depth will lead to 0.5 m error in sea ice thickness (Tilling et al. 2015). The role of snow in climate models is not less meaningful, as it greatly controls the energy balance and fluxes between the ocean and atmosphere. For navigation, snow on sea ice slows the speed and increases the effort the ship needs to go through the ice. Snow was also listed as a key parameter for future polar missions in the PEG report (Duchossois et al., 2018a).

Currently users lack a snow depth product and related uncertainties that they could trust, although recent research has shown ability to retrieve snow depth when using dual-frequency measurements Guerreiro et al. (2016). Besides the importance of knowledge snow depth in climate modelling, this would be a great step towards more trustworthy sea ice thickness measurements.

The recently launched ICESat-2 could be used together with CryoSat-2 for estimating snow depth. However there are several problems with this approach. First of all, CryoSat-2 is already living past is designed lifetime, and as there is no guarantee of continuation, a great area north of 81.5°N/S might be left uncovered by radar altimeters. Secondly, having separately flying satellites with different mission parameters, collocating the measurements would be hard. It might take weeks before the other satellite would revisit the same location as the previous one, during which the sea ice has moved possibly hundreds of kilometres.

2.2.1.6 Uncertainty information

The study of Lawrence et al. (2018) shows the possibility of using Ku- and Ka-bands in mitigating the snow uncertainty. Dual-frequency methods would improve our abilities to reduce and estimate the uncertainties related to snow depth and sea ice thickness retrieval. The modelling community is in particular interested in the uncertainty information, which according to a user requirement study (Duchossois et al., 2018a/PEG-1) is required together with the parameters and is critical when designing and setting up assimilation systems. Better abilities to estimate the related uncertainties will improve prediction quality assessment.

2.2.1.7 Co-located measurements

Issues with co-locating the measurements from multiple instruments speaks in favour of deploying a satellite with more than one instrument. It is noted that observations should be made within an hour to account for the sea ice motion when correcting the observations to the same time frame (e.g. Passaro et al., 2017), which is not achieved by the current systems. Winds are a primary driver of sea-ice motion and can cause drift speeds of up to 40 km/day (Hakkinen et al., 2008; Johannessen et al., 2013), meaning within an hour the ice can move several kilometres.

NRT altimeter SIT estimates combined with satellite imagery - most importantly imaging SAR - would be of interest to operational ice services. However, the 1 h time difference requirement is rarely met with current systems. In clear sky conditions, OLCI and SRAL instruments onboard Sentinel-3A and Sentinel-3B provide coincident image and SIT measurements. Example of these is shown in Figure 5 below. When contacted, both Finnish and Norwegian ice services agreed that altimeter measurements co-located with S1 frames would bring added value to the ice charting process.

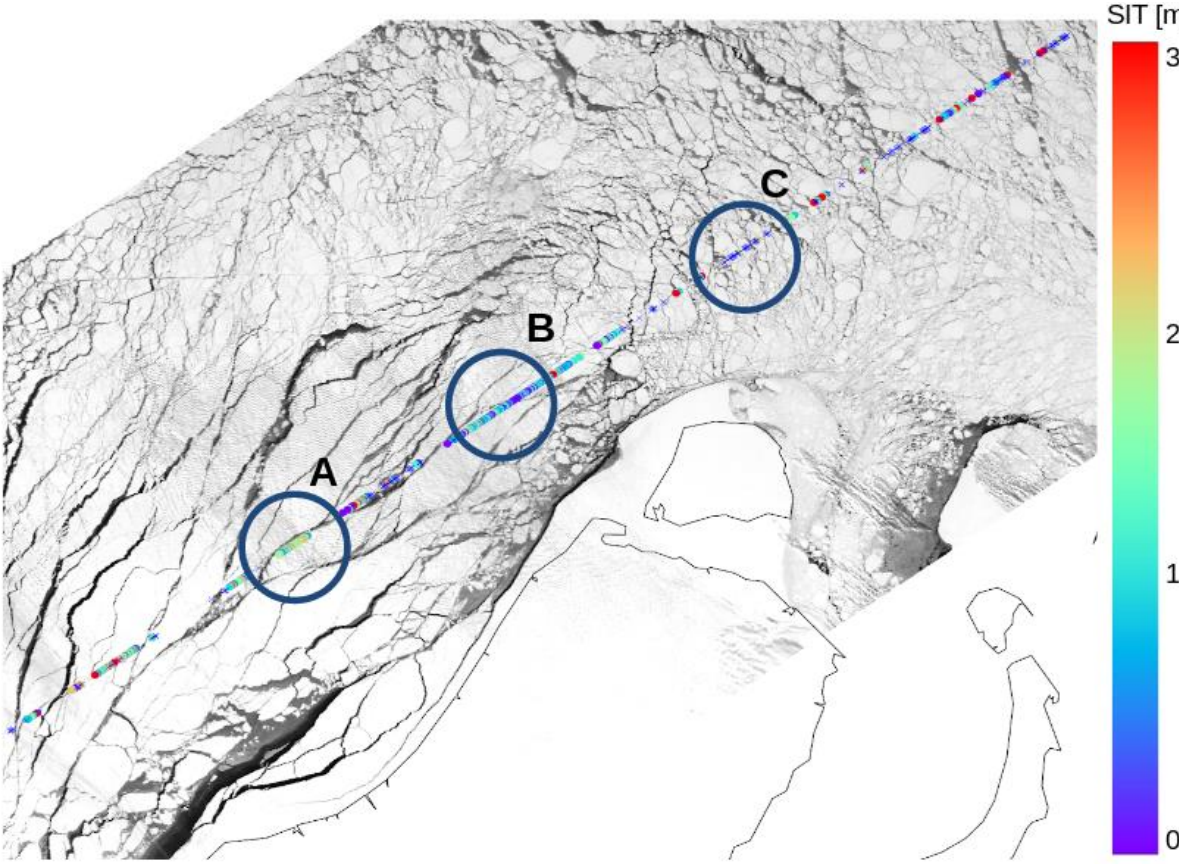

Figure 5. *Combined Sentinel-3 OLCI and SRAL over ice covered Kara Sea, April 9:th 2018.Blue crosses are SRAL measurements filtered out due to anomalous high freeboard. Areas of thick ice (A), relatively thin ice (B) as well filtered out estimates (C) are marked on the image.*

2.2.1.8 Complementing in-situ measurements

Polar expert group pointed out in their user requirements study (Duchossois et al., 2018a/PEG-1) that planning future polar missions should be planned in parallel with the intended in-situ measurements. In addition to the buoy observations and flight campaigns, there is a planned research cruise MOSAiC taking place for one year starting fall 2019 studying mainly the first-year ice. There will be a dedicated group studying the Ku- and Ka-band backscattering horizon over snow on sea ice (NERC grant NE/S002499/1). Although not overlapping with the future polar satellite missions, this provides invaluable possibilities to study and polish the methods of estimating snow with dual-frequency method, ensuring capabilities to do so efficiently with a future polar satellite mission.

It was highlighted by GCOS that special care should be taken in the sea ice product calibration and validation. Currently there is a lack of in situ observations to do this. It is costly to collect in-situ data, and it was suggested some satellite data could be used to replace this as validation data. However, first a better inter- and cross-sensor calibration should be developed so that robust uncertainty and bias estimates could be provided.

2.2.1.9 Icebergs

Iceberg detection, volume change and drift have been listed as a priority user requirement (Duchossois et al., 2018a, 2018b. Tournadre et al. (2018) have demonstrated detection of icebergs from CryoSat-2 altimeter data using several modes, and mention results with Sentinel-3 seem promising, which would result into a comprehensive dataset, already built under ALTIBERG project (Tournadre et al., 2016). The volume of an iceberg is valuable information for operational services and climate monitoring. For climate studies, the freshwater flux from the volume of ice transported by icebergs is a key parameter, with large uncertainties related to the volume of the icebergs. Measuring volume is currently possible only with altimetry, as that is the only means of providing the elevation from the ocean surface. Iceberg volume has been calculated with altimetry for example by Tournadre et al. (2015) with Envisat, Jason-1 and Jason-2.

2.2.2 Gap analysis

In the 2025 observing system, four main gaps remain for the sea ice thickness retrieval:

(1) Lack of measurements beyond 81.5°N/S, resulting in no data over most of the Arctic September sea ice pack

(2) Remaining uncertainty in Sentinel-3 based SIT estimates due to uncertainty in snow load and ice type estimates

(3) Limitation of SIT retrieval to winter months only

(4) Antarctic SIT retrieval

The first gap will be present after CryoSat-2 has finished its already well extended intended lifetime. The second one can be substantially mitigated with a dual-frequency altimeter instrument.

Alas, at the time of writing, due to temporal differences between the Ku and Ka -band measurements, it is only possible to give statistical snow depth estimates for a large area. There can be several days between the two instruments visit the same moving sea ice floe, during which there might have been snowfall, melt events or winds blowing snow. Thus an airborne dual frequency altimeter, in the style of ASIRAS, would be beneficial in increasing the scientific maturity of dual frequency snow retrieval.

Currently altimeter SIT retrieval is limited to winter months. During summer melt liquid water on ice, so called melt ponds, distort the waveforms so that the surface type classification does not work. In other words, waveforms from ice floes become more like lead waveforms. Even before melt pond formation, wet snow makes radar penetration into the snow pack ambiguous (Willatt et al., 2011; Quartly et al., 2019). Prior to 2025, significant research efforts should be made to develop SIT retrieval in wet snow conditions.

In 2018 ESA Sea Ice CCI produced a prototype SIT product for Antarctic waters, which shall be developed further in the CCI+ programme. However, due to heavy snow load and ambiguous radar penetration (Willatt et al., 2011) as well as lack of reliable snow estimates, freeboard to SIT conversion includes significant uncertainties. Thus the SRL of Antarctic SIT retrieval is lower than that for Arctic SIT and more research efforts are required.

2.3 Review and prioritisation of potential scientific applications of dual-frequency interferometric SAR altimetry over sea ice.

Within Section 2.2.1, we summarised the principle current applications of the state-of-the-art altimeter systems. A dual frequency interferometric SAR altimeter would, however, open up important new scientific applications. The purpose of this section is to outline these new potential applications. The principal scientific value and opportunities that would be realised by a dual frequency polar SAR interferometric altimeter over sea ice, within the reference frame of the 2025-2030 observing system, are therefore summarised as follows:

(1) Resolving accurately the penetration of Ka- and Ku-band into the snow on top of sea ice. Co-located measurements would not only enable the most accurate snow depth measurements from satellites, it would also mean the increased accuracy in every measured variable. This would lead to better estimates of sea ice thickness and volume, surface roughness, sea ice type and leads. It could also enable the reconstruction of old time series with the new knowledge gained from the new physical understanding. However, research work will be necessary to improve the SRL of the Ku- Ka-band altimeter acquisitions.

(2) Altimeter measurements above 81.5°N are crucial to Arctic-wide sea ice thickness and volume estimates. Knowledge of sea ice above 81.5°N is needed in modelling and forecasting, as well as in shipping and when executing other activities. When CryoSat-2 mission will eventually come to its end, it will leave a large area of unknown in our knowledge that Sentinel-3 satellites will not be able to measure. To ensure that the gap is filled, a new polar topography mission must fly in a near polar orbit.

(3) Continuity of Ku-band measurements would be ensured with a CryoSat-2 style successor. Almost 30 years of altimeter sea ice thickness records should be continued as smoothly as possible to extend the time series with improved estimates. Pairing the Ku instrument with a Ka-band interferometer would bring added value to the continuation, and possibly in the past measurements as well.

A future polar topography mission with dual-frequency Ku- and Ka-band SAR interferometric altimeter would deliver the following scientific geophysical parameters over sea ice:

- sea ice freeboard
- sea ice thickness
- sea ice volume
- snow on sea ice
- sea ice deformation
- lead distribution
- iceberg detection

Higher level products can be derived from sea ice freeboard and thickness distribution. Most important of these is a dedicated winter navigation product, that would complement imaging radar data with coincident sea ice thickness estimates. Also, multiple geophysical parameters can and should be processed into risk estimates for ships.

With more accurate estimates, and improved NRT capabilities that the dual-frequency system provides, these could easily be implemented as operational products, further improving the capability to serve the users.

2.4 Summary of the added value offered by the proposed system and mission characteristics

A future polar topography mission with dual-frequency Ku- and Ka-band SAR interferometric altimeter would greatly improve the current sea ice records and our understanding of the Arctic and Antarctic systems. It will provide estimates of sea ice thickness with a pole hole much smaller than that of the S3 mission. The dual frequency system will provide better snow estimates than current systems, which shall help lower the uncertainty of the SIT product. However, the uncertainty of the snow retrieval itself still remains to be studied. On a larger scale, the sea ice and the changes in it shall be better understood.

The two most important characteristics for the mission from the viewpoint of sea ice applications are:

- Dual-frequency Ku- and Ka-band SAR interferometric altimeter capable to provide snow thickness on sea ice in addition to sea ice freeboard.
- Orbit inclination between 88° and 92°, allowing reasonable coverage of the Arctic ocean to 88°N.

Summary table

Variable	Detail	PEG UR	Current state	Achievable/value added by CRISTAL
Sea ice thickness	General	Accurate sea ice thickness measurements (climate research) Better short-range forecasts (ship routing)	Spatial and temporal resolution requirements of navigational purposes not fulfilled by CS2 and SMOS combination	Improvement of sea ice thickness measurements. For short-range forecasts the revisit time might be a limitation
Sea ice thickness	Thin ice (<0.5m)	Daily coverage (operational use) NRT availability (operational use)	There is a daily and NRT sea ice thickness product from SMOS	Uncertain improvement over thin ice
Sea ice thickness	Thick ice (>0.5m)	Continuity of altimeter-derived thickness estimates. Improved accuracy on the freeboard measurements	Continuity not guaranteed above 81.5 N/S after CryoSat-2Not much more improvement to be seen with current methods available	Would ensure continuity of radar altimeter thickness measurements. Improved freeboard measurements
Sea ice thickness	Distribution	Improved measurements(models and operational)	Not much more improvement to be seen with current methods available	Improved sea ice thickness distribution
Snow on sea ice		Needed for accurate determination of sea ice freeboard. Resolution and sampling requirements follow SIT	Currently used (modified) Warren snow climatologies not following SIT requirements ICESat-2 could provide insight, but temporal sampling discrepancies remain	Dual-frequency method has a great capacity to improve snow depth estimates. Resolution and sampling would be consistent with SIT
Icebergs		Automatic detection (navigation safety and icecharts)	Large icebergs (>100 m) detected with SAR and scatterometers, smaller challenging. CMEMS catalogue provides iceberg concentration at 10 km	Would bring added value to current methods, e.g. with more accurate detection capabilities, but not to be used independent of other means

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3 Ice Sheets

3.1 Review of state-of-the-art Ku and Ka band altimetry over ice sheets.

This subsection briefly describes the achievements of previous missions Ku and Ka band altimetry missions, as well as the range of scientific applications relevant to the CRISTAL mission from the viewpoint of ice sheets.

3.1.1 Progress to the current state-of-the-art

It is fifty years since the concept of mapping ice sheet topography using satellite altimetry was first proposed (Robin, 1966). Since then, this vision has become a reality, as a succession of satellite radar altimeters have acquired measurements across Earth's polar regions, and resolved the ice sheets of Greenland and Antarctica at the continental scale (Figure 6 and Figure 7). During this time, measurement accuracy has improved by orders of magnitude, and satellites have been launched into orbits with higher inclinations, providing greater coverage of Earth's ice sheets. From the first glimpse of the southern tip of the Greenland Ice Sheet offered by GEOS-3 during the 1970's, satellite observations have progressed to increasingly higher latitudes, notably with Seasat (72.2°), ERS-1/2 & Envisat (81.5°), and CryoSat-2 (88°). Most recently, the launch of the Sentinel-3A & B satellites has introduced a new era of operational radar altimetry, capable of making measurements up to ~81.5° (McMillan et al., 2019).

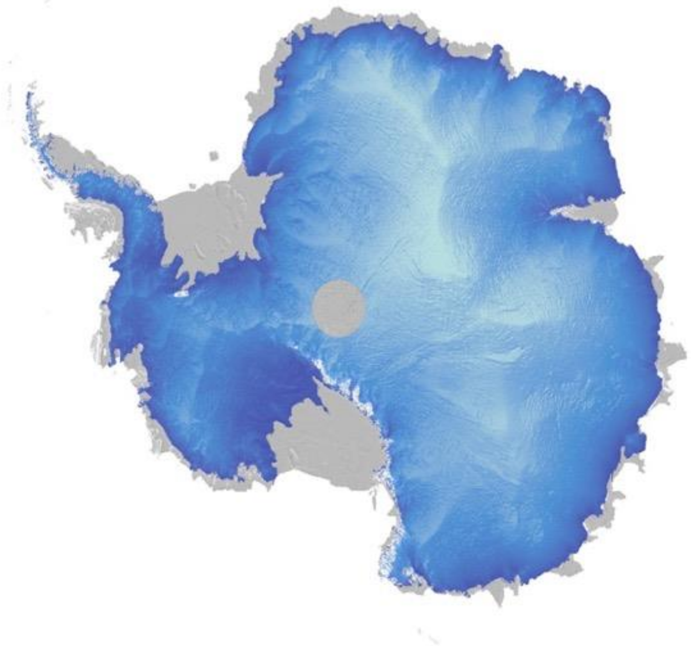

Figure 6. Shaded relief of Antarctic Ice Sheet surface topography, derived from CryoSat-2 observations.

These measurements have, over the last quarter of a century, provided a near-continuous record of ice sheet elevation and elevation change (Davis et al., 2005; Flament & Rémy, 2012; McMillan et al., 2014; Shepherd & Wingham, 2007; Wingham et al., 1998; Zwally et al., 2011) (Figure 7). In doing so, they have transformed our ability to monitor Earth's ice sheets, and fostered a new understanding of both the speed and manner in which they change.

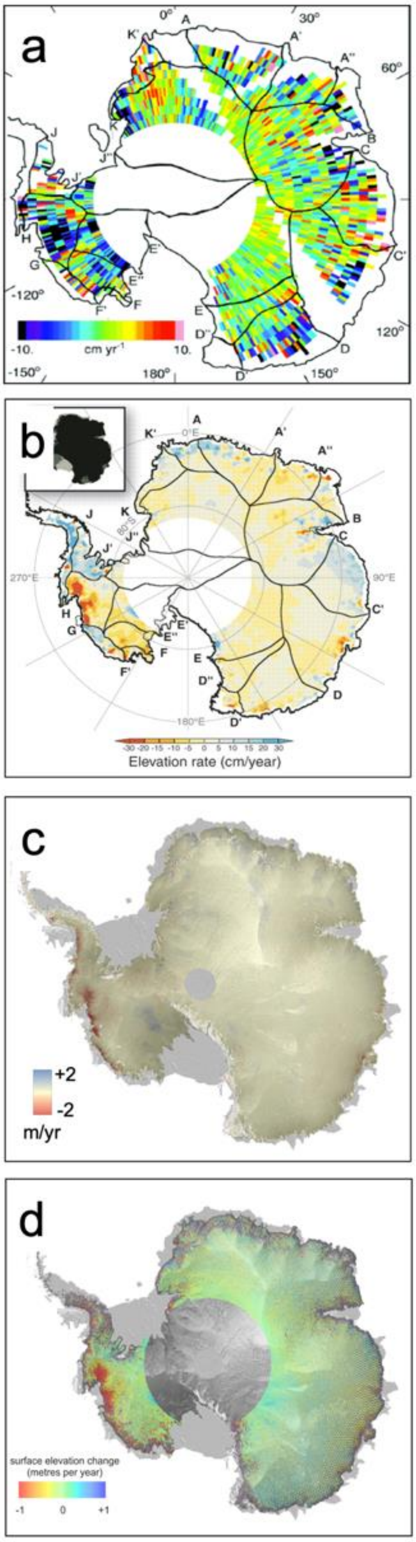

Figure 7. Evolution in altimeter observational capability over Antarctica. Rates of Antarctic surface elevation change are determined from (a) ERS-1 (Wingham et al., 1998), (b) ERS-1 & ER-2 (Shepherd & Wingham, 2007), (c) CryoSat-2 (McMillan et al., 2014), and (d) Sentinel-3A (McMillan et al., 2019).

During the earlier part of this 25-year polar record, radar altimeter missions carried conventional low resolution, or pulse-limited, instruments, including those flown onboard the ERS-1, ERS-2, Envisat and SARAL satellites. These systems, which were originally developed to measure the ocean surface topography, flew to a latitude of ~ 81.5°, and provided a ground footprint of approximately 2 km^2 (when considering only the leading edge of the waveform acquired by a Ku-band pulse-limited instrument over a flat, orthogonal surface). The size of this footprint, together with the large area illuminated by the radar antenna beam (~200 km^2), meant that correctly locating the origin of the surface reflection over ice sheet regions with complex terrain was challenging.

To address this, in 2010 the first dedicated ice radar altimetry mission, CryoSat-2, was launched, with two improvements in system design that were specifically aimed at enhancing altimeter performance in areas of steep and complex ice margin terrain. Synthetic Aperture Radar (SAR), or Delay-Doppler, processing delivered a four-fold improvement in along-track resolution, to 300-400 m, and interferometric techniques were used to locate the origin of the surface reflection in the across-track plane (Raney, 1998; Wingham et al., 2006). These developments, in conjunction with the unique long-period, high-inclination orbit (Figure 8), have delivered improved coverage of Earth's ice sheets (McMillan et al., 2017; McMillan et al., 2014), and yielded greater confidence in determining their ongoing evolution (Figure 9).

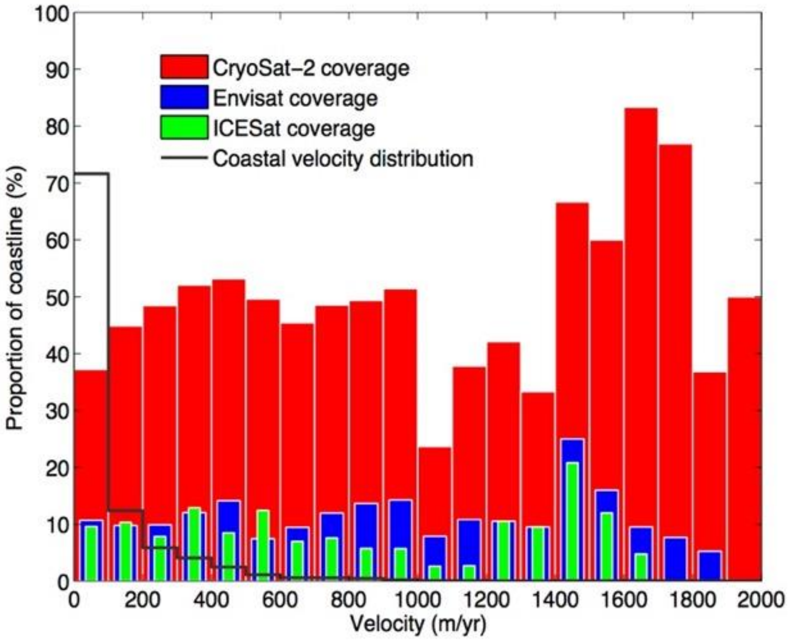

Figure 8. Comparison of the spatial sampling of coastal regions of the Antarctica Ice Sheet as measured by recent satellite altimeter missions (McMillan et al., 2014).

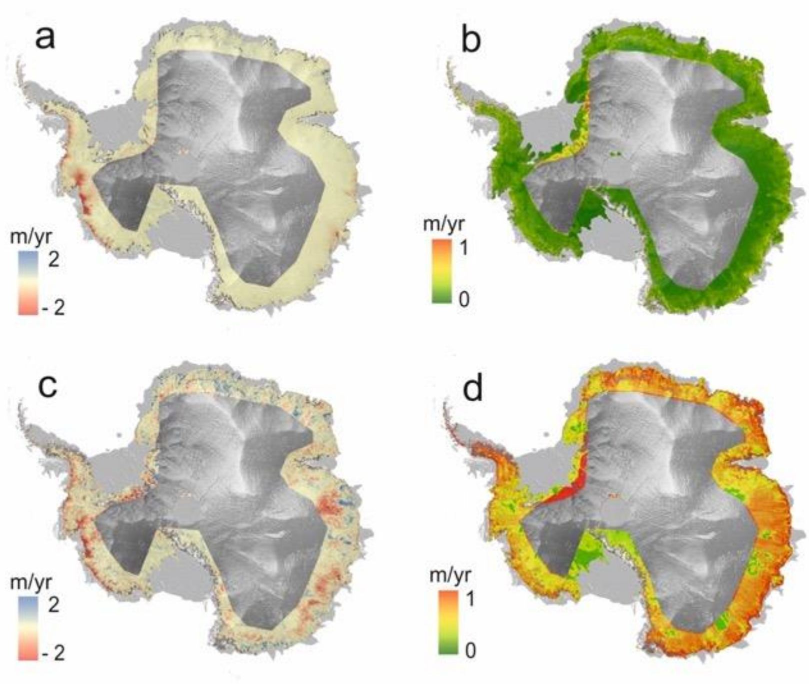

Figure 9. A comparison of rates of Antarctic elevation change for interferometric (a) and non-interferometric (c) CryoSat-2 SAR altimeter measurements, showing the improved coverage and precision achieved by the interferometric mode of operation. Panels (b) and (d) show the uncertainties on the respective interferometric and non-interferometric elevation change estimates (McMillan et al., 2018).

The launch of Sentinel-3A in 2016, followed by Sentinel-3B in 2018, represented a further addition to polar monitoring capability. Given that CryoSat-2 is now far beyond its original 3.5 year design lifetime, it is important, however, to note the several key differences that Sentinel-3 has relative to the CryoSat-2 mission, that will impact upon observational capability after CryoSat-2 operations end:

(1) In terms of measurement configuration, the Sentinel-3 satellites represent the first operational polar radar altimeter missions, and the first to operate globally in SAR mode.

(2) Regarding orbital configuration, Sentinel-3 reaches only to 81.5°N/S, compared to the more comprehensive 88°N/S coverage of CryoSat-2. Furthermore, Sentinel-3 operates with a repeat period an order of magnitude smaller than CryoSat-2 (27 days for Sentinel-3 compared to 369 days for CryoSat-2), therefore delivering more frequent temporal sampling but less complete spatial coverage.

(3) In terms of the main altimeter payload, unlike CryoSat-2, Sentinel-3 does not carry an interferometer, meaning that the precise location of the return echo within the

Doppler beam footprint cannot be directly determined, and instead auxiliary information has to be utilised for this purpose.

Although Sentinel-3 is still in its infancy, early studies of these data have provided encouraging results over both inland and ice sheet margin regions (McMillan et al., 2019), albeit subject to the differences outlined above.

In addition to the 25-year Ku-band record, the launch of the French-Indian SARAL/AltiKa satellite in 2013 into the historical Envisat orbit presented a new capability, with the first spaceborne Ka-band (~36 GHz) measurements of ice sheets, up to a latitude of ~ 81 °N/S. The differing wavelengths of the Ku and Ka band instruments (2.21cm and 0.84cm, respectively) interact differently with – and penetrate differently into – the ice sheet snowpack. Whilst Ku-band may typically penetrate 10 metres into a dry snowpack, Ka-band is expected – from theoretical considerations - to penetrate only several tens of centimetres [Vincent *et al.*, 2006]. Furthermore, AltiKa also operates with both a smaller beamwidth and wider bandwidth than past Ku-band instruments, meaning a smaller area of illumination on the ground, and a more densely sampled waveform return.

Comparisons to date between Ka-band (AltiKa) and Ku-band (Envisat, CryoSat-2) measurements suggest that (1) over the interior of the Antarctic Ice Sheet, Envisat Ku-band retrieves an elevation on average several tens of centimetres lower than Ka-band (Michel *et al.*, 2014), (2) that Ka-band elevations may exhibit less sensitivity to changes in backscattered power (Remy *et al.*, 2015), (3) that Ku SAR and Ka LRM waveforms have similar leading edges which are less modified by the volume echo than Ku LRM, albeit Ku SAR has greater sensitivity to volume scatter in the trailing edge than Ka LRM (results from the *Sentinel-3 Performance Improvement for Ice Sheet* study, WP5), and (4) both Ku-band (CryoSat-2) and Ka-band (AltiKa) missions are capable of monitoring regions of rapid surface elevation change in West Antarctica (Otosaka *et al.*, 2017). These initial comparisons point to the future value of both Ku- and Ka-band measurement systems.

3.1.2 Summary of current applications

Having reviewed progress to the current state-of-the-art, this section summarises the range of applications for which altimetry data are now currently used over ice sheets. As such, it serves to establish what is currently possible with the state of the art, and the basis for the following gap analysis.

3.1.2.1 Digital elevation models

Digital Elevation Models (DEM's) provide information about the topography of the ice sheets, and important geophysical parameters such as elevation and surface slope. DEM's have a range of applications, encompassing fieldwork planning, modelling and satellite Earth Observation. Topographic information forms an important boundary condition for both regional climate models (Noël et al., 2018), and dynamical ice sheet models, which in turn are an essential component of climate projections of future sea level rise (Cornford et al., 2015;

Price et al., 2011). It can also be used to derive information about subglacial conditions at the ice sheet base (Remy & Legresy, 2004); an important boundary conditions for physical models, but one that is difficult to measure. Within the field of Earth Observation, DEM's can be used to delineate drainage basins and to calculate ice thickness, which are necessary steps for computing an ice sheet's mass balance via the Input-Output method (Rignot, 2006; Rignot et al., 2008; Shepherd et al., 2012, 2018). They are also commonly used as an auxiliary input when defining the Open Loop Tracking Command for radar altimeters, and during the processing of non-interferometric radar altimetry (McMillan et al., 2019; Roemer et al., 2007) and interferometric imaging Synthetic Aperture Radar (McMillan et al., 2012; Rignot, 1996) data.

One of the principle sources for contemporary ice sheets DEM's is radar altimetry data (Bamber et al., 2009; Helm et al., 2014; Slater et al., 2017). The launch of CryoSat-2, with its high-resolution coverage of the coastal margins, fine track spacing, and coverage up to a latitude of 88 N/S, heralded a particular step forward in our ability to determine surface topography. The resulting DEM products (Helm et al., 2014; Slater et al., 2017) are typically posted at km-scale resolution, cover more than 95% of the ice sheet's surface, and provide, on average, an accuracy in the range of 0.1-10 m.

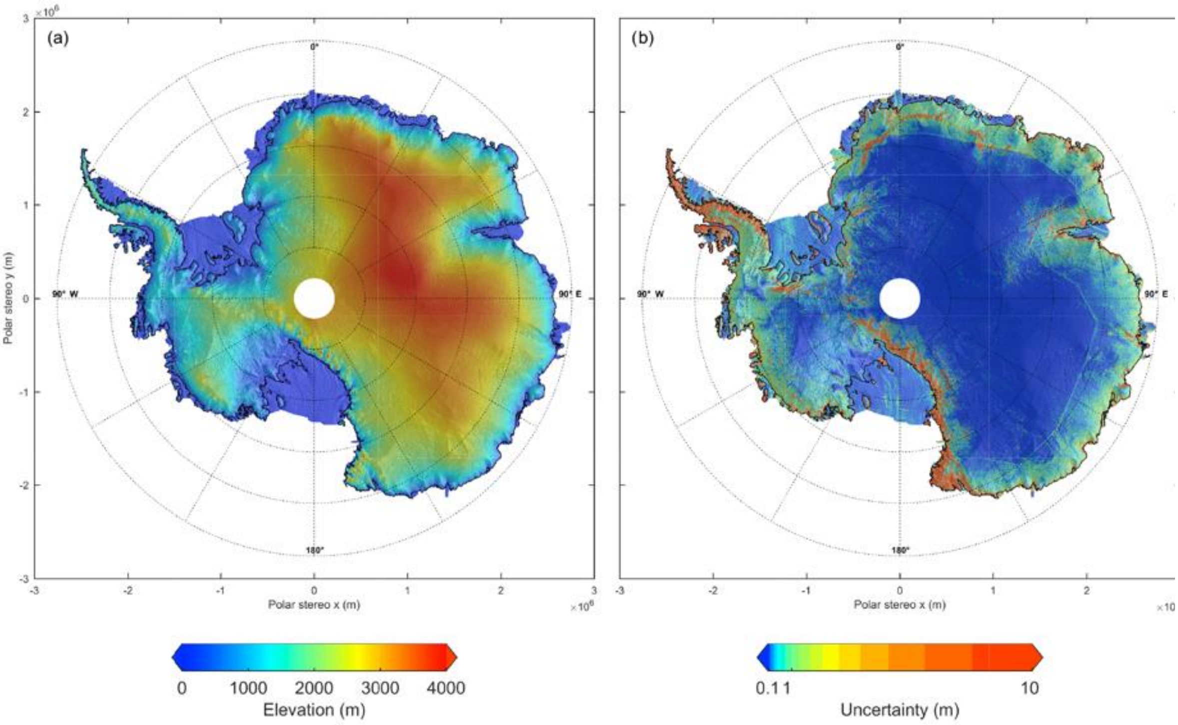

Figure 10. A Digital Elevation Model (a) and associated uncertainty (b) derived from 6 years of CryoSat-2 radar altimetry data (Slater et al., 2017).

3.1.2.2 Surface elevation change & mass balance

Estimates of ice sheet surface elevation change provide a wealth of geophysical information. They are used as the basis for computing the mass balance and sea level contribution of both Greenland and Antarctica (McMillan et al., 2014, 2016; Shepherd et al., 2012), for identifying emerging signals of mass imbalance (Flament & Rémy, 2012; Wingham et al., 2009) and for determining the loci of rapid ice loss (Hurkmans et al., 2014; Sørensen et al., 2015). Through combination with Regional Climate and firn modelling of surface processes, surface elevation change can be used to isolate ice dynamical changes, at the scale of individual glacier catchments (McMillan et al., 2016).

The continuous record of elevation measurements provided by radar altimeters, dating back to 1992, provides a unique long-term record of surface elevation change and mass balance. Rates of surface elevation change and timeseries of cumulative changes in elevation are usually derived using one of two methods; a cross-over or plane fit technique. These typically deliver (1) high-resolution (5-10 km) rates of surface elevation change (for single or multiple missions, typically computed as a linear rate of change over a period of several years to decades), and (2) frequently (monthly-quarterly) sampled time series of the cumulative change, averaged across individual glacier basins. In addition to being used to quantify rates of mass balance and sea level rise, they also have a range of other applications, such as investigations of the initiation and speed of inland propagation of dynamic imbalance (Konrad et al., 2017), which in turn provides valuable information relating to the underlying physical processes that drive ice loss.

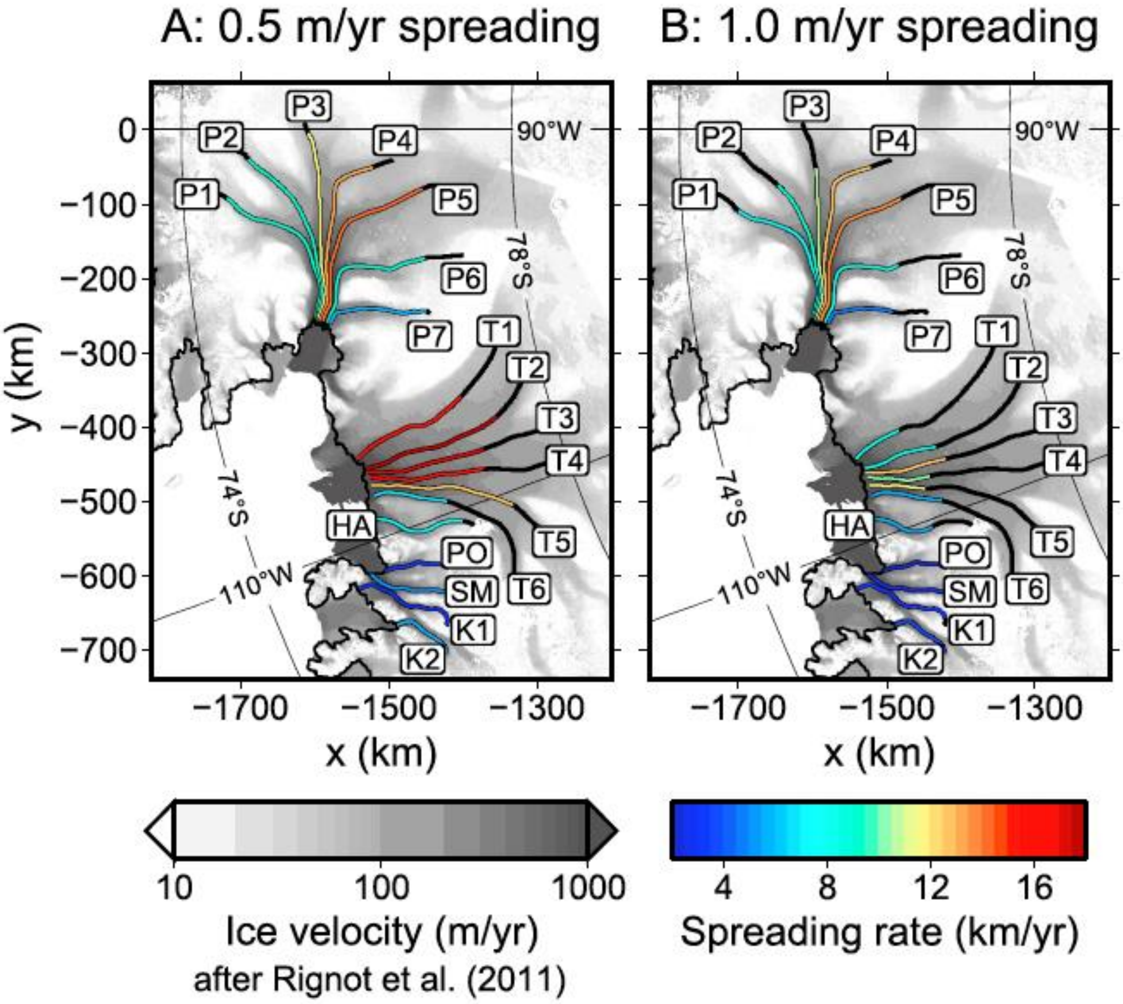

Figure 11. The rate of inland propagation of surface lowering, in response to enhanced ice flow in the Amundsen Sea Sector of West Antarctica, as derived from radar and laser altimetry data acquired between 1992 and 2015 (Konrad et al., 2017).

3.1.2.3 Ice shelf thickness change & basal melt

Approximately three quarters of the Antarctic coastline is comprised of ice shelves. These floating portions of ice are particularly sensitive to changes in their surrounding oceanic and atmospheric conditions, and are therefore a crucial part of the cryosphere to monitor in order to track the effect of climate change on the polar regions. These floating portions of ice form the interface through which ice is lost to the ocean (either through iceberg calving of basal melting) and are therefore critical to regulating the ice sheet's sea level contribution. Where ice shelves have thinned or disintegrated, the associated reduction in resistive stresses causes an acceleration of the upstream ice, leading to dynamical glacier thinning and increasing rates of ice discharge and sea level contribution (Mouginot et al., 2014; Rignot et al., 2005; Shepherd et al., 2001). Quantifying the rate of thinning of ice shelves, together with understanding the basal melting processes that control much of the current deficit, is therefore key to understanding the wider ice sheets' current and future evolution.

Radar altimeters provide one of the principle sources of measurements for quantifying ice sheet change; providing estimates of time-varying elevation, which can be used to determine ice thickness change (Paolo et al., 2015; Shepherd et al., 2010). Typically, the same techniques employed to measure grounded ice elevation change are used (see previous section), in conjunction with information relating to the density structure of the ice shelf (typically from firn models) and an assumption that the ice is floating in hydrostatic equilibrium. Other factors, such as tidal and atmospheric pressure-induced motion must also be accounted for (typically using ocean and atmospheric models). As with estimates over grounded ice, the typical spatial resolution is km to 10's of km, and the temporal sampling varies from monthly timeseries to longer-term linear rates of change. Once ice shelf thickness change has been determined, this information can be combined with knowledge of the ice velocity, density and topography, and surface mass balance, to calculate the rate of ice shelf basal melting (Adusumilli et al., 2018; Gourmelen et al., 2017). This provides critical insight into the nature of ocean properties beneath the ice shelf, and the ice-ocean interactions which control much of the current Antarctic ice imbalance.

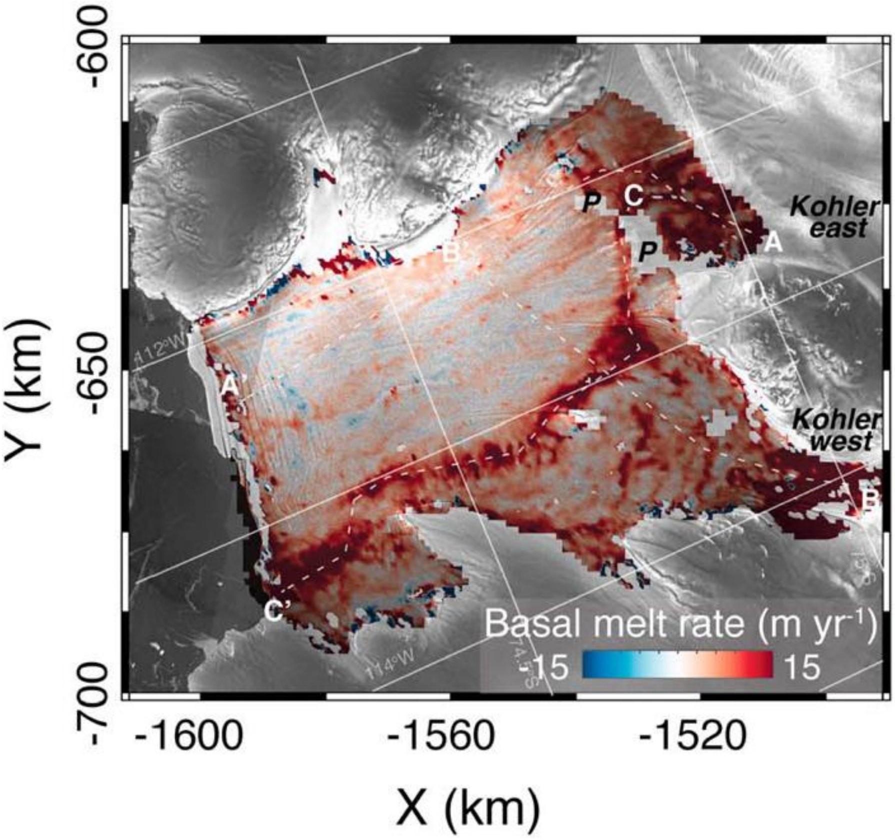

Figure 12. Example of basal melt rates of the Dotson Ice Shelf determined from swath processing of CryoSat-2 interferometric altimetry (Gourmelen et al., 2017).

3.1.2.4 Subglacial lake drainage

Beneath the Antarctic ice sheet is a complex hydrological network, made up in part by several hundred subglacial lakes (Smith et al., 2009; Wright & Siegert, 2012), fed by water from frictional and geothermal heating of the ice sheet base. For many years following their initial discovery, lakes were believed to be largely stable features of the hydrological system; however, we know now that this is not the case. Indirect observations suggest that many lakes fill and drain episodically, discharging large (up to several billion tonnes) volumes of stored water into the subglacial system over a period of months to years (Fricker et al., 2007; McMillan et al., 2013; Siegfried et al., 2014; Smith et al., 2009). Understanding the characteristics of these drainage events has far reaching consequences, because of the impacts it may have upon the persistence of stable subglacial ecosystems, freshwater discharge into sub-ice shelf cavities, ice dynamics, and ice sheet mass balance estimates.

Observations from radar altimetry have provided crucial insight into subglacial lake dynamics, by detecting localised (of the order of 10’s km), transient (of the order of years) changes in the ice surface elevation (McMillan et al., 2013; Siegfried et al., 2014; Wingham et al., 2006). Although subglacial lakes have been monitored using conventional pulse limited radar altimetry (Wingham et al., 2006), the improved resolution offered by both interferometric (McMillan et al., 2013) and non-interferometric (McMillan et al., 2019) SAR altimetry offers a far more detailed view of subglacial lake activity, allowing much more precise quantification of the associated water fluxes.

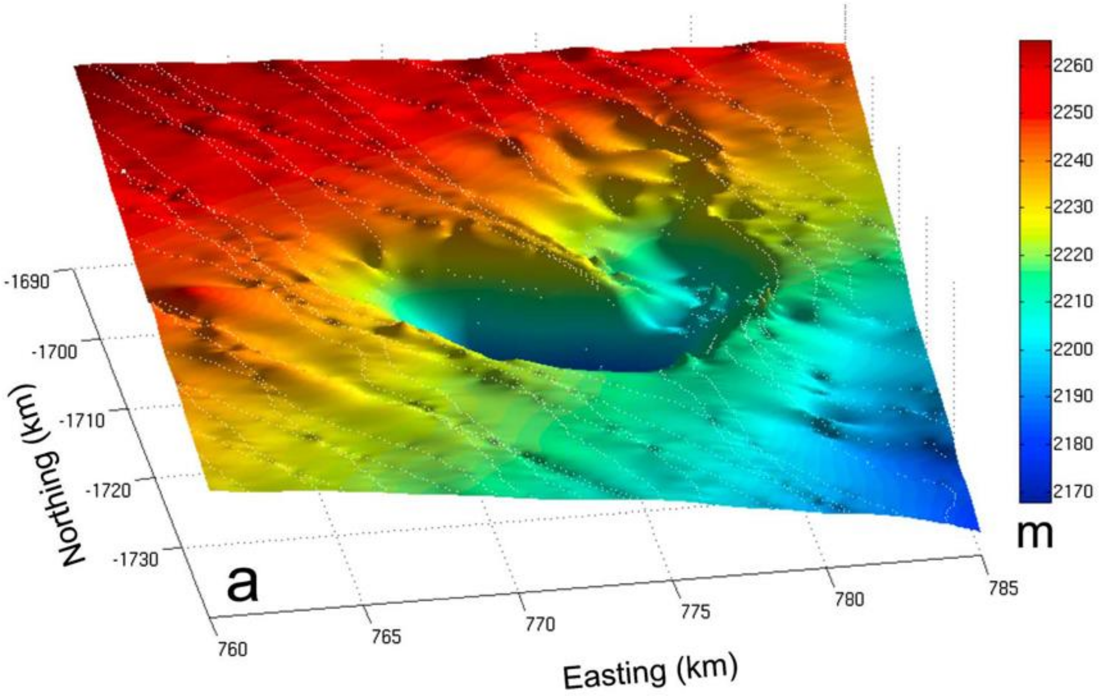

Figure 13. A 260 km^2 depression in the surface of the East Antarctic Ice Sheet caused by the draining of an estimated 6 billion tonnes of water from the Cook E2 subglacial lake, mapped by CryoSat-2 interferometric altimetry (McMillan et al., 2013).

3.1.2.5 Grounding Line Location

The grounding line of marine terminating ice sheets is the intersection between the ice sheet, the bedrock and the ocean and marks the outer boundary of the grounded ice sheet, before it transitions to a floating ice shelf. Locating and monitoring the temporal evolution of the grounding line is critical both as a boundary condition for numerical models and projections (Cornford et al., 2015), for establishing the stability of the current configuration of the Antarctic Ice Sheet (Joughin et al., 2014; Rignot, 1998; Rignot et al., 2014) and for monitoring ice discharge (Rignot et al., 2008). Although the most precise method for locating the hinge line (the inward limit of tidal flexure; a surface proxy for the grounding line) is Interferometric Synthetic Aperture Radar (InSAR), SAR imagery coverage is often based upon targeted acquisitions, meaning that coverage is not continuous in space or time. Furthermore, the InSAR technique requires that the microwave backscattering properties of the near surface snowpack remain stable through time (i.e. that coherence is maintained) which can limit data retrieval, particularly in regions of fast, rapidly-deforming ice flow.

Alternatively altimeters can be used to map the grounding line, either by measuring the characteristic patterns in the ice surface topography (the so-called break in ice slope (Hogg et al., 2018)) or through the detection of the inland limit of the non-linear surface elevation changes associated with ice shelf tidal motion (Dawson & Bamber, 2017). These techniques have both been successfully applied to CryoSat-2 SAR interferometric data to provide spatially continuous maps of the grounding line location for many Antarctic Ice Shelves (Figure 14). These datasets provide an important complement to the spatially and temporally dispersed measurements made by SAR imaging radar.

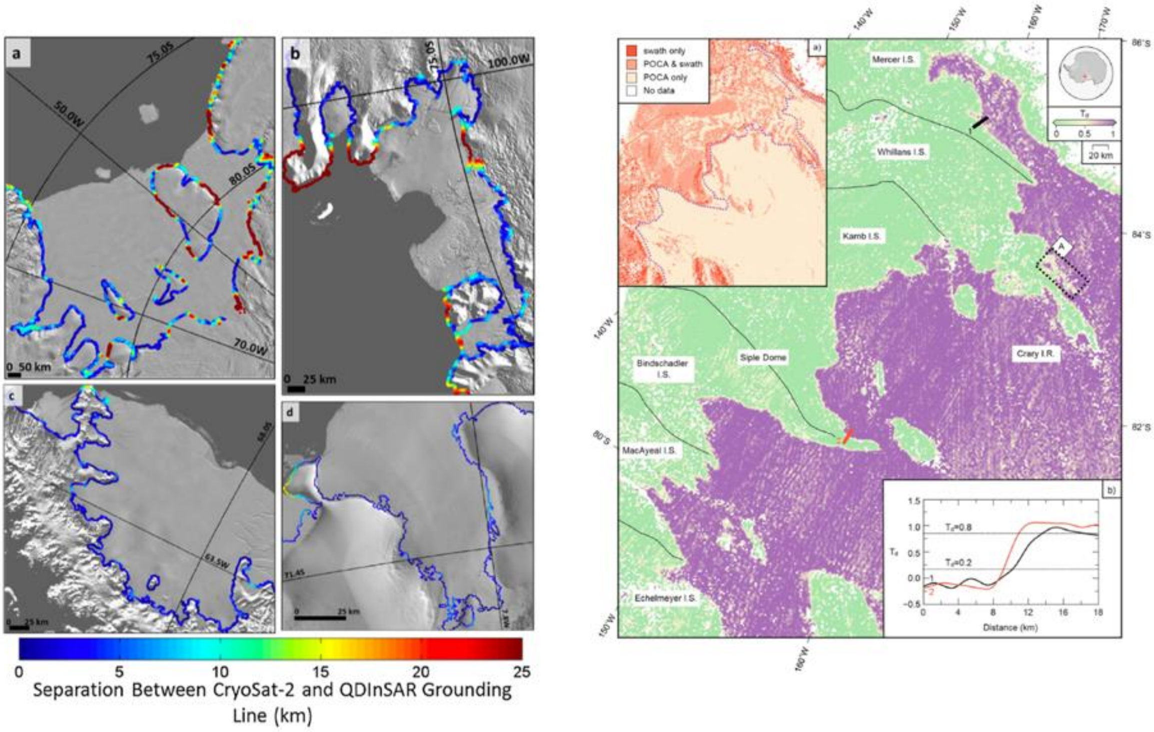

Figure 14. Estimates of grounding line location from CryoSat-2 determined (left panel) by identifying the break in slope of the ice surface (Hogg et al., 2018), and (right panel) based upon the correlation with the modelled tidal amplitude (Dawson & Bamber, 2017).

3.1.2.6 Grounding Line Migration

In addition to mapping the instantaneous location of marine terminating ice sheets' grounding line (see previous section), it is also important to understand the rate at which grounding lines migrate. This provides important information relating to the stability of certain sectors of the ice sheet, and in particular serves to identify regions of rapid grounding line migration, which may suggest a state of rapid mass loss or ice sheet collapse (Joughin et al., 2014; Rignot et al., 2014).

Although mapping grounding line migration is possible using repeated measurements of grounding line position (see previous section), these approaches can often be hampered by limited temporal sampling or precision. An alternative technique is to combine altimeter measurements of surface elevation change, with knowledge about the ice sheet's surface and basal topography (Konrad et al., 2018). In essence, this approach calculates the propensity for retreat at each point around the ice sheet's margin, based upon its geometry, and uses this to project altimeter-derived changes in surface elevation into an equivalent lateral grounding line migration rate (Figure 15). The key advantage of this altimetry-based technique is that it is able to provide continental scale estimates of grounding migration, thereby providing a synoptic view of how the areal extent of the ice sheet is changing (Konrad et al., 2018).

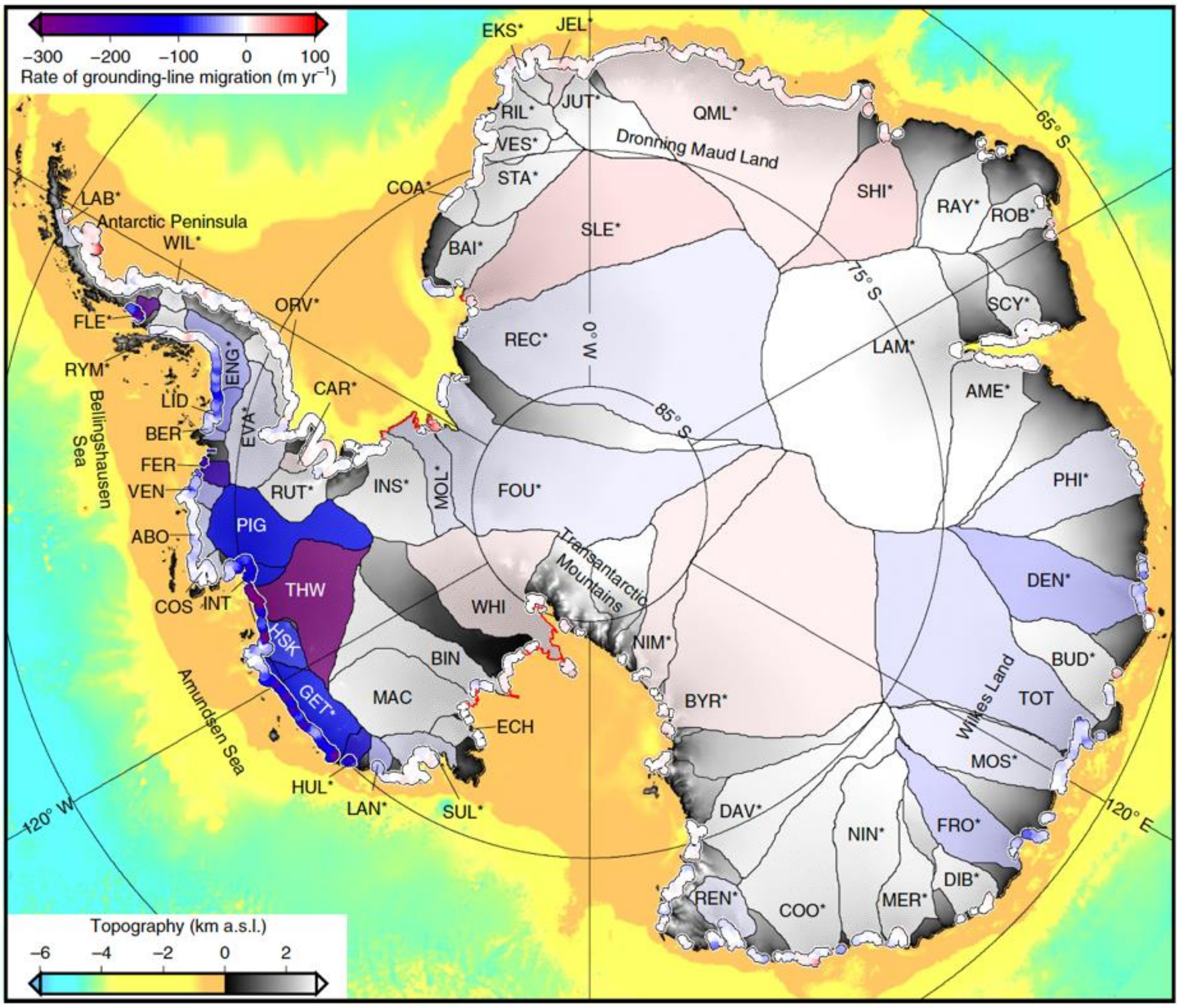

Figure 15. Estimates of grounding line migration determined from CryoSat-2 (Konrad et al., 2018).

3.1.3 Potential CRISTAL products already used in services

To conclude this section we summarise the usage of ice sheet altimetry products within existing and planned User Services. These are, namely, observations of ice sheet and ice shelf surface elevation change. At present provision of ice sheet products for downstream services is still very much in its infancy, although it is an area that is anticipated to grow, as user demand and product maturity develops. Currently, Copernicus Climate Change Services (C3S) provides authoritative information to support EU adaption and mitigation strategies to climate change. To achieve this, C3S delivers key indicators of climate change, including consistent records of Essential Climate Variables (ECVs) through their Climate Data Store (CDS). As part of these activities, the C3S Ice Sheets & Ice Shelves Service is currently under development, with the objective of delivering consistent estimates of ice sheet elevation change to inform scientists, planners and policy makers.

The Copernicus Marine Environment Monitoring Service (CMEMS) provides core reference information relating to the state of the global ocean, supporting downstream services in the fields of Maritime Safety, Coastal and Marine Environment, Marine Resources, and Weather, Seasonal Forecasting and Climate activities. Looking to the future, CMEMS Evolution is being driven by future Service User Requirements, which in turn places requirements upon the upstream satellite measurement platforms. One of the three main areas identified for future improvements is better monitoring of the polar regions, and in particular the monitoring of continental ice shelf elevation change by a dual frequency interferometric altimeter mission [AD5].

3.2 Gap analysis relative to the 2025 observing system

This review shall take stock of the key user requirements obtained through release of outputs from activities such as the Polar Expert Group (PEG) reports [AD-2 and AD-3], and use these as a basis for identifying the gaps in observational capability that will exist at 2025.

3.2.1 User Requirements

The capability to make long-term, systematic measurements of land ice topography, elevation and mass change constitutes a key requirement for a broad user community. The extensive range of applications for which these data are used has been reviewed in Section 3.1.2. More specifically, there is an increasing demand for spatially comprehensive coverage of the polar regions, seamlessly spanning multi-decadal periods and longer, with sufficient resolution to determine the dominant signals of ice sheet change, and error sources that are well characterised. To formalise and prioritise the user needs, several community and expert activities have taken place in recent years [AD1; AD2; AD3].

In 2016, the European Commission (EC) initiated a workshop (Copernicus Polar and Snow Cover Applications User Requirements Workshop 23 June 2016, Brussels; AD1) to gather the user requirements for the Next Generation of the Copernicus Space Component (CSC). The workshop was attended by a broad spectrum of relevant parties, including users, service providers, representatives from the scientific community, the European Commission, ESA and EUMETSAT. Within the context of the current study, and focusing on land ice, key outputs from this workshop were that (1) Polar regions have not been given the right level of attention to date within the Copernicus framework, (2) there was a clear and identified need for an enhanced, operational continuity to CryoSat-2, and (3) that this could not be delivered by satellites such as Sentinel-3, who's orbit coverage up to ~81.5 degrees latitude omits large parts of the polar zones (about 70%) and several critical elements of the cryosphere [AD1].

Following the strong interest displayed at this workshop, a Polar Experts Group (PEG) was established in 2017, to consolidate and update the user requirements for a Copernicus Expansion Mission dedicated to Polar and Snow Monitoring. Two workshops were held, in

April and May 2017, to facilitate these activities. During these workshops, user requirements were further consolidated, both in terms of the application domain (e.g. ice sheets) and in terms of the parameters and products (e.g. elevation, elevation change), with particular attention given to prioritisation. In this regard, ice sheet surface elevation and elevation change were both identified to sit within the two highest-priority categories for user requirements. These conclusions complement other community assessments; most notably the periodic assessment of the adequacy of observations for meeting requirements for monitoring climate and global change in support of the UN Framework Convention on Climate Change (UNFCCC). In this report [AD-4], the Global Climate Observing System (GCOS) noted that action was required to ensure the continuity of altimetry missions to adequately monitor ice masses over decadal periods.

In addition to prioritization, these community activities have dedicated considerable effort to defining the detailed specifications required by the user community for each parameter, such as accuracy, resolution and sampling frequency. This has led to the following User Requirements, with respect to monitoring ice sheet elevation and elevation change, for any future observing system. Note that, as they have already been presented in detail in previous documents [AD1-AD4], our objective here is to summarise the most pertinent points, together with their traceability and how they would be addressed by the CRISTAL mission; we refer the reader to the full documentation for further details.

Requirement	Value	Source	Impact on CRISTAL design specification
Absolute accuracy of surface elevation measurement	Goal: 0.5 metres absolute; 0.2 metres relative.	AD2; Table 8.	SAR interferometer achieves higher accuracy than SAR in coastal regions (McMillan et al., 2018); SAR achieves high accuracy at interior sites of Dome C and Lake Vostok (>97% measurements within 50 cm (McMillan et al., 2019)).
Accuracy & stability of surface elevation change measurement	Goal: 0.1 m/yr	GCOS/CEOS Action T20 [AD4].	SAR interferometer achieves higher accuracy than SAR in coastal regions (McMillan et al., 2018).
Latitudinal coverage	To within 2° latitude of the poles.	AD3; Section 4.3; Annex 4.	CRISTAL will operate on a high inclination orbit to ~88° N/S.
Temporal sampling frequency	Goal: Monthly-seasonal (ice margin); annual (interior).	AD2; Table 8.	A long-period orbit of ~370 days has been shown to be capable of delivering monthly-seasonal sampling over Greenland (McMillan et al., 2016) and Antarctica (Shepherd et al., 2018).
Spatial resolution	Goal: 1000 m (interior) and 50-100 m (ice margin).	AD2; Table 8.	SAR achieves kilometre-scale resolution (footprint of ~ 0.3 x 2 km, depending upon surface roughness). Techniques such as fully-focused SAR have the potential to improve along-track resolution by several orders of magnitude; swath processing can improve across-track resolution by up to an order of magnitude.

Table 1. Summary of User Requirements over ice sheets. With respect to the accuracy of elevation and elevation change measurements, determining whether a single value is met cannot be done without considering the metric it relates to (e.g. RMS, median absolute difference) and also the domain of measurements (performance varies greatly between interior and ice margin regions).

3.2.2 Gap Analysis

Within the context of the 2025-2030 observing system, it is therefore possible to identify the gaps in requirements that will exist, and that need to be addressed by a future dedicated polar altimeter topography mission. With respect to ice sheet monitoring, the principle gaps at 2025 will be as follows:

(1) A lack of measurements beyond 81.5°N/S.

Beyond 2025, altimeter coverage of ice sheets will be dependent upon Sentinel-3, which is limited by its orbital inclination of 98.65°. This will mean that the User Requirement *Coverage of measurements to within 2° latitude of the poles* will not be met.

(2) A lack of continuous coverage of ice sheet margins.

Beyond 2025, altimeter coverage of ice sheets will be dependent upon Sentinel-3. Sentinel-3 has a relatively short repeat period of 27 days, meaning that, even with the combined Sentinel-3A/B constellation, the ground tracks will still be somewhat spaced at the ice sheet margin. For example, at a latitude of 75°S (corresponding to the margin of the Amundsen Sea Sector of West Antarctica), a ground track spacing of the order of ~10 km can be expected. Analysis of past missions with a configuration similar to a single Sentinel-3 satellite (e.g. Envisat) have shown that this achieves only around 8% coverage of the Antarctic ice sheet margin, as compared to 49% for a satellite in a CryoSat-2 orbit (McMillan et al., 2014). This will limit the capability to meet the User Requirement *Kilometre-scale spatial resolution* around the entirety of the ice sheet margin.

(3) A lack of certainty in coastal regions with complex topography, due to the absence of interferometric SAR altimeter measurements.

Beyond 2025, coverage in the complex ice sheet margin regions will be limited to the non-interferometric SAR mode acquisitions of Sentinel-3. Analysis of interferometric and non-interferometric SAR altimetry (McMillan et al., 2018) has shown that this is likely to reduce the accuracy and precision of estimates of surface elevation and elevation change. This, in turn, can be expected to degrade the certainty of estimates of ice sheet mass balance and sea level rise, compared to what is currently possible using the state-of-the-art. This will hamper efforts to meet the User Requirements of an *absolute accuracy of approximately 0.5 metres* and *an accuracy and stability of 0.1 m/yr* in ice sheet margin regions.

(4) A demand for greater certainty in resolving small elevation changes across large inland areas of the ice sheet due to the poorly understood changes in Ku-band penetration and subsurface scattering within the snowpack. Such knowledge would also serve to improve efforts to retrieve surface elevation (defined as the air-snow interface), and to accurately inter-compare and harmonise other satellite missions (for example, ICESat and ICESat-2 laser altimetry) for the purpose of long-term seamless climate datasets.

To date, CryoSat-2 has convincingly demonstrated the ability of a SAR interferometric mission operating in a long-period, high inclination orbit to address the first three gaps. Concerning the final point, the comparisons of AltiKa, Envisat and CryoSat-2 outlined above have provided some progress in understanding. However, they are limited by the constraints of the current observing system and as such serve to highlight several fundamental gaps that could, in the future, be addressed by a dual frequency system.

The first issue is that current Ku-Ka comparisons can only be made by comparing measurements from different satellite platforms, and therefore the measurements do not identically image the same point in space and time. This means that a direct assessment of the differing Ku-Ka snowpack backscattering properties is difficult, because (1) measurements that are acquired simultaneously are lacking, and so temporal changes in the snowpack, for example due to snowfall, wind or surface melt, may alter its scattering properties between acquisitions, (2) differences in the viewing geometry and polarisation configuration of the two antennas, namely the orientation of the antenna polarisation vector relative to the prevailing direction of surface roughness, may affect the backscattering signal (Remy et al., 2012; Armitage et al., 2014), and complicate the separation of effects due to differing frequency from those due to backscattering anisotropy, and (3) the only satellite Ka-band record to date was acquired in Low Resolution Mode, and so no analysis of the performance of Ka-band SAR altimetry, nor Ka-band SAR interferometric altimetry has been possible.

3.3 Review and prioritisation of potential scientific applications of dual-frequency interferometric SAR altimetry over ice sheets.

Within Section 3.1.2, we summarised the principle current applications of the state-of-the-art altimeter systems. A dual frequency interferometric SAR altimeter would, however, open up important new scientific applications. The purpose of this section is to outline these new potential applications. The principal scientific value and opportunities that would be realised by a dual frequency polar SAR interferometric altimeter over ice sheets, within the reference frame of the 2025-2030 observing system, are therefore summarised as follows:

(1) Accurate determination for the first time of Ku- and Ka-band penetration into the ice sheet snowpack; providing simultaneous, co-located measurements of elevation and penetration over all ice sheet surface types. This would provide the capability to

systematically correct for changes in penetration (i.e. the depth distribution of scattering elements) caused by changing surface conditions (e.g. wind, melt, snowfall) which would address one of the main uncertainties associated with current radar altimeter estimates of ice sheet mass change and sea level rise. This could be expected to provide a major step towards achieving the GCOS requirements on observational accuracy and stability. Importantly, this new information would additionally deliver a new physically-based understanding of the radar scattering properties of the ice sheets, which would aid the retrospective interpretation of the entire existing 25-year Ku-band altimeter record.

(2) Once CryoSat-2 ceases to operate, there will be an absence of radar altimeter measurements at latitudes higher than ~81.5°N/S. Over Antarctica, this will lead to a reduction in coverage of ~25%, which diminishes the certainty of comprehensive continental-scale assessments of ice mass change. A new high-inclination polar topography mission, operating within the 2025-2030 reference frame, would address this shortfall in coverage, to provide comprehensive monitoring capability for Earth's polar regions.

(3) A Ku-band interferometer onboard a future polar mission would provide continuity with CryoSat-2, delivering both higher accuracy, particularly in complex ice margin regions, and higher resolution, for example using novel swath processing techniques. If the mission were to operate in interferometric mode over the entire ice sheet region, then the benefits of swath mode could be extended to inland sectors of the ice sheet for the first time, for example providing far more detailed observations of subglacial lake evolution. The further addition of Ka-band interferometer would potentially open up further novel applications, based upon the differing frequencies, beamwidths and bandwidths of the two instruments.

In an applied sense, and given the proposed concept of a future polar topography mission, a dual frequency Ku- and Ka-band SAR interferometric altimeter would deliver numerous important scientific parameters over ice sheets. With time, it is expected that many of these parameters have the potential to become operational products and services, and to be used routinely by numerical ice sheet projections that assimilate such operational data. A summary of the principle parameters, and their potential User Services are given in the table below.

Parameter	Priority	Existing or Future Services	Potential Users
Ice Sheet elevation.	Primary	Boundary conditions for operational climate forecasting.	Climate modellers.
Ice sheet elevation change and mass balance.	Primary	Validation datasets for operational climate forecasting; ECV's contributing to sea level rise estimates.	Climate modellers; policy makers; planners.
Snowpack penetration and backscattering properties.	Secondary	-	-
Subglacial lake evolution.	Secondary	-	-
Grounding line location.	Primary	Boundary conditions for operational climate forecasting; validation datasets for operational climate forecasting; ECV – indicator of ice sheet stability.	Climate modellers; policy makers; planners.
Grounding line migration rate.	Secondary	-	-
Surface ablation and mass balance.	Primary	Validation datasets for regional and global climate models; ECV – indicator of atmospheric warming in polar regions, and freshwater input into the polar oceans.	Climate modellers; policy makers; planners.

Table 2. Scientific Parameters and potential Users and Services supported by a Dual Frequency Altimeter.

3.4 Summary of the added value offered by the proposed system and mission characteristics.

A future polar topography mission with dual-frequency Ku- and Ka-band SAR interferometric capability would greatly improve current ice sheet records, leading to improved certainty in estimates of sea level rise, and enhanced capability to make accurate future climate projections. The principle added value that such a mission would provide can be summarised as (1) the capability to systematically monitor nearly all (>95%) of both ice sheets (due to the long-period, high-inclination orbit improving coverage in both the coastal and pole-hole regions), (2) the improved accuracy and precision of elevation change measurements in coastal regions of the ice sheet (due to the SAR interferometer), and (3) the improved accuracy of elevation change measurements across the vast interior regions of the ice sheet (due to the dual Ku and Ka band system).

3.5 Chapter 3 References

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4 Ocean

4.1 Review of state-of-the-art Ku and Ka band altimetry over ocean.

This subsection briefly describes the achievements of previous missions Ku and Ka band altimetry missions, as well as the range of scientific applications relevant to the CRISTAL mission from the viewpoint of the oceans.

4.1.1 Progress to the current state-of-the-art

4.1.1.1 Conventional altimetry in LRM, Ku band

Before the emergence of space technologies, our knowledge of the Earth shape and ocean dynamics was poor due to the sparsity of the available in-situ data available, and the huge areas to cover. Very early in the development of space remote sensing, radar altimetry was identified as a key technique to fill this knowledge gap [Kaula, 1969]. The 1970-1990 period has seen the appearance and the developments of the first altimeter instruments, leading to the technology advent made by the NASA/CNES Topex-Poseidon mission in the 1990's.

Skylab (1973–1974) was the first satellite ever launched carrying an altimeter. It produced the first measurements of undulations in the marine geoid due to seafloor features. The Geodynamic Experimental Ocean Satellite (GEOS 3, 1975–1979) inherited radar technology from Skylab and provided more accurate altimetry measurements, mainly thanks to a laser retroreflector array improving the orbit accuracy. Seasat (1978) took a major step forward by upgrading and bringing valuable technologies. In particular, the full deramp technique was first employed to improve the altimeter signal resolution, and a dedicated on-board radiometer was used to estimate more accurately the tropospheric water content correction. Seasat gave us a first global view of ocean circulation, waves and winds, providing new insights into the links between ocean and atmosphere that drive our climate.

From these experiences, a new mission was designed and developed: TOPEX/Poseidon (T/P; 1992–2006). A specific effort was made to significantly enhance the Precise Orbit Determination (POD) techniques. This included the development of a new tracking system named, DORIS (Doppler Orbitography and Radio positioning Integrated by Satellite), with precise range rate measurements. T/P used a specific non-sun-synchronous orbit, which was designed to allow good aliasing and restitution of tide signals, and was on a higher orbit than usual to minimize the impact of errors in Earth gravity and drag modelling on the POD accuracy. In this way, the T/P mission was able to provide high-precision for mesoscale and largescale monitoring [Fu and Lefebvre 1989]. Thanks to its long life and its accuracy, Topex-Poseidon marked a major turning point in the study of oceanic dynamics and oceanic response to climate change. This mission was concurrent with the European Remote Sensing (ERS-1; 1991–2000) satellite, which flew on a sun-synchronous orbit that provided high latitude information, up to 81.5°.

T/P was then followed by the Jason series (Jason-1, 2001–2013; Jason-2, 2008– ; and Jason-3, 2016–), which maintained and even improved T/P accuracy thanks to successive upgrades on the Poseidon altimeter. In particular a C-band was added to derive more precisely the ionospheric correction. Other improvements were also set up to improve orbit determination and signal tracking. In parallel, ERS-1 was followed by ERS-2 and then Envisat (2000–2012) [Benveniste et al. 2001]. Envisat's radar altimeter (RA-2) was inherited from ERS RA-1 with the addition of a second frequency measurement, a S-band dedicated to estimate ionospheric correction. The S-band also brings improvements to study complex vegetated or snow-covered areas, as the emitted signal penetrates these structures. [Legresy, 2005].

All these historical missions employ a radar signal in Ku-band frequency (13.575GHz). They operate in the conventional Low Resolution Mode (LRM), corresponding to a specific time sequence of emitted pulses (chronogram). In this mode, radar pulses are emitted/received continuously at ~2kHz by the altimeter. Around 90 individual and uncorrelated pulses are summed on-board to create 20Hz rate waveforms from which geophysical parameters are retrieved by level-2 retracking algorithms. In LRM, these four parameters are: the altimeter range, from which the Sea Surface Height is retrieved (SSH), the Significant Wave Height (SWH), the Backscattering coefficient (Sigma0) and potentially the antenna mispointing.

4.1.1.2 Recent advances in Ka band altimetry

Conventional radar altimeters previously presented emit radar signals at a dedicated Ku-band frequency: 13.575GHz. Such frequency is a good trade-off accounting for technological and geophysical observation constraints: gain of the antenna, the relative low signal sensitivity to atmospheric and ionospheric perturbations, and the available bandwidth (determined by international regulations). Radar altimeters operating in Ku band have an averaged antenna aperture of ~1.3° (at -3dB). The surface sampled on-ground by such antenna characteristics corresponds to a disk-shaped surface of about 15km diameter (Cryosat-2, 725km nominal altitude) to 20km (Jason series, 1300km nominal altitude).

SARAL, which stands for "Satellite with Argos and AltiKa", was launched in February 2013 and is the first mission carrying a Ka-band altimeter (AltiKa). The 0.84 cm signal wavelength in Ka band is much shorter compared to the 2.21cm in Ku band. Given the direct link between a circular antenna dimension and the signal wavelength [Ulaby et al., 1981], the SARAL antenna is smaller and its aperture is narrower compared to Ku-band altimeters. The radar footprint size is consequently smaller, around 11km diameter. Another specificity of the AltiKa altimeter is its 480MHz bandwidth, wider than the 320MHz of Ku-band missions. Consequently, the vertical resolution is improved: 0.33cm for SARAL compared to 0.47cm for other regular altimeters. This means the on-ground surface is more finely sampled. Finally, the shorter decorrelation time of sea echoes at Ka-Band allows to implement a higher Pulse Repetition Frequency (4KHz instead of 2KHz in Ku-band) leading to a better along track sampling (40Hz instead of 20Hz).

SARAL flies on the same orbit of ERS and ENVISAT to continue the time series and to benefit from the existing mean sea surface model computed with those missions. The SARAL/AltiKa mission was considered as a "gap filler" between Envisat (lost in April 2012) and Sentinel-3A (launched in February 2016). While there were historically some serious concerns about the performances of a Ka-band altimeter, notably linked to its sensitivity to the rain events, all the results collected demonstrate the success of AltiKa, especially with regards to its capacity to monitor sea level and study the ice-covered surfaces [Bonnefond et al., 2018].

The main advantages/drawbacks of the Ka-band **over the oceanic surface** are summarized as follows [Bonnefond et al., 2018]:

- Ka-band is much less affected by the ionosphere than Ku-band. This low ionospheric attenuation can even be considered as negligible, except for some exceptional ionospheric situations. It discards the need for a C-band dual-frequency altimeter.

- On the other hand, water or water vapour in the troposphere theoretically affects Ka-band measurements in case of rain, and can increase significantly the rate of missing data for strong rain rates. Nonetheless, this was not found to be true in practice (thanks to margins taken for the emitted power) and rain cells had finally little influence on data availability and quality.

- Ka-band provides a better estimation of sea surface roughness than Ku-band. The 8 mm wavelength of Ka-band is better suited for describing the slopes of small facets on the sea surface (capillary waves, etc.), and gives a more accurate measurement of the backscatter coefficient over calm or moderate seas. Consequently, the backscatter coefficient noise is reduced by a factor of two compared to Jason-series altimeters for wave heights greater than 1 m.

- SARAL/AltiKa also provides an improved resolution of the oceanic signals in particular at mesoscales. Based on spectral analysis, AltiKa has the ability to sample oceanic signals down to 40–50 km wavelengths, where Jason and Envisat altimeters are constrained to 70–80 km. This is mainly due to the higher bandwidth in Ka band, leading to a smaller range resolution.

- The reduced footprints of both radiometer and altimeter instruments provide more valid data in coastal zones, which are key areas for a wide range of applications.

4.1.1.3 Delay-Doppler altimetry

The 2010's have seen the emergence of new radar altimeter technologies, based on the exploitation of the Delay Doppler effect. The technique itself is inspired by the Synthetic Aperture Radar imagery, allowing a dramatic reduction of the radar footprint. CryoSat-2 is the first satellite ever launched using this new concept. Designed primarily for the cryosphere study, its on-board altimeter SIRAL (Synthetic Interferometer Radar ALtimeter) has the capacity to operate in the conventional LRM, and also in the innovative delay-Doppler mode (or SAR mode). While the LRM footprint has a circular shape with 15km diameter, SAR mode processing reduces the footprint to strips of only ~300m width in along-track, with same resolution as LRM in across-track (15km). Last but not the least, SIRAL is even capable to operate in the SAR Interferometric (SARIn) mode by exploiting the phase difference of the signal received on two distinct antennas. In this way, it is theoretically possible to precisely determine the across-track location of the surface sampled by the radar within the SAR footprint. Nevertheless, several constraints exist, notably due to surface ambiguities on the received signal [Gray et al, 2013]. The satellite operates sequentially in LRM, SAR and SARIn based on a geographical mask. To provide coverage of the polar ice zone, the satellite is flying on a nonsynchronous 92-degrees inclination orbit. The repetition cycle is long (369 days) to provide dense space sampling of the cryosphere [Wingham et al., 2006].

SAR altimetry technique was chosen to be the operational mode of the Sentinel-3 altimeters series, decided in the frame of the European Commission's Copernicus programme [Donlon et al.,2012]. In contrast of CryoSat-2 which employs SAR mode only in dedicated and sparse areas, Sentinel-3A is continuously operating in SAR mode. With its high orbit inclination (98.65°), it ensures continuity with the ERS / Envisat satellites (even if not exactly on the same orbit). Sentinel-3A was launched at the beginning of 2016 and is the first of the four satellites of the Sentinel-3 series.

Overall, results from Cryosat-2 and first analyses from Sentinel-3A demonstrate that SAR altimetry measure is highly valuable for the study of the oceanic surface. Firstly, the SSH and SWH estimations in LRM and SAR mode are in excellent agreement, except for a small centimetric bias in SWH, currently under investigations. Secondly, spectral analysis show that SAR altimetry has the ability to resolve oceanic mesoscales down to about 30km, compared to 70-80km in Ku-band LRM. [Heslop et al., 2017 ; Boy et al., 2016 ; Raynal et al., 2018]. With its finer along-track footprint, SAR altimetry is also capable to observe finer topographic scales, such as those created by submarine mounts. The current main drawback of SAR altimetry is its sensitivity to long-wavelength oceanic signals, acting mainly on the SWH retrieval [Moreau et al., 2018].

Besides, progresses are on-going on the exploitation of the delay-Doppler processing to diminish even more the SAR footprint. The Fully-Focused SAR (FF-SAR) takes advantage of the phase stability along the entire surface illumination time, approximately 2.5 seconds, to reduce the along-track footprint down to 0.5 meters [Egido et al, 2017 ; Guccione et al., 2018]. The Sentinel-6A/B satellites will continue the Jason series with the exact same orbit and a new altimeter: Poseidon-4. The altimeter major innovation is the interleaved chronogram, enabling constant emission/reception of pulses at high frequency (~9kHz). It will provide a simultaneous SAR mode and LRM data processing. Sentinel-6A is planned to be launched for late 2020, and Sentinel-6B in 2026. Finally, developments of new altimeters dedicated to the observations of the oceanic waves and currents are in progress: CFOSAT (2018), COMPIRA (planned for 2020), SKIM (feasibility phase), together with inland waters (SWOT planned for 2021).

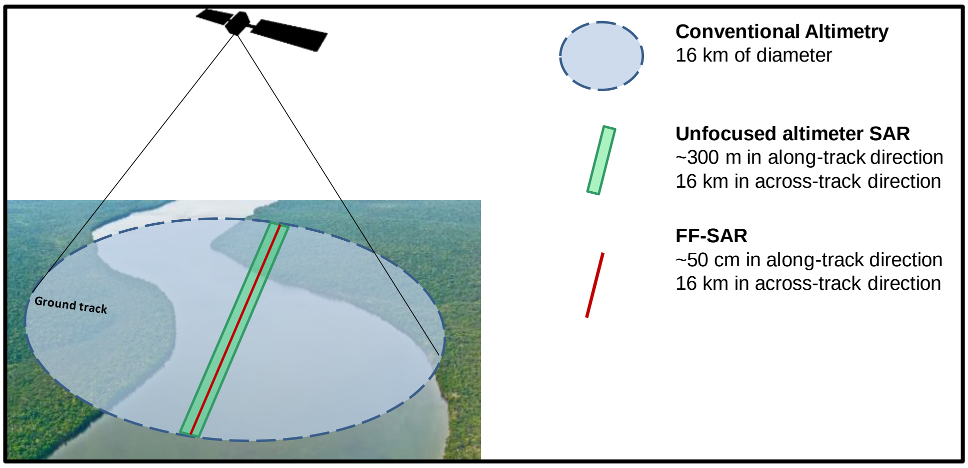

Figure 16. Illustration of radar footprints in LRM (blue), SAR (green) mode and FF-SAR mode (red). Footprints orders of magnitude are given for CryoSat-2 / Sentinel-3A mission.

4.1.2 Summary of current applications

Over the years and through constant improvement of the data quality, satellite altimetry has been used in a growing number of applications in Earth sciences. The altimeter measure is helping us understanding and monitoring the ocean: its topography, dynamics and variability at different scales, as described and sorted below by scientific themes:

- **Climate change studies:** A main application of altimetry with regards to climate change is the monitoring of the Global Mean Sea Level (GMSL). GMSL is defined as the height of the oceans averaged over the globe, and is a key indicator of climate change. It reflects both the amount of heat being added to the oceans and the mass loss of global ice reservoirs. Since the launch of Topex/Poseidon in 1992, GMSL rise is estimated at an average rate of approximately 3 mm/year with a trend uncertainty estimated at -0.4mm/year over the whole period [Ablain et al., under review]. Another application is the monitoring of intraseasonal oceanic cycles such as El Niño Southern Oscillation (ENSO).

- **Geodesy:** 99% of the SSH measurement is correlated to the geoid, the remaining 1% is comprised of oceanic dynamic signals or other geophysical signals. Before the launch of dedicated gravity satellite missions, our knowledge of the global geoid was poor, and satellite altimetry has played an important role in mapping it from space. The altimetry marine gravity fields insight has led directly to a greatly improved understanding of global bathymetry and marine tectonics.

- **Oceanic tides:** Ocean tides represent more than 80% of the variability of the surface in the open ocean. Altimetry has been a powerful tool to improve our knowledge of the phenomena. The primary motivation of the work has also been the source of its advances, as it is crucial to use accurate tide models to correct the altimeter data from tide signals.

- **Oceanic circulation:**
    - **Ocean eddies and mesoscale variability:** Mesoscale variability generally refers to ocean signals with spatial scales of 30 to 1000 km and timescales of one to several months [Wunsch and Stammer 1998]. The oceanic circulation is dominated by mesoscale variability, due to ocean eddies or isolated vortices, meandering currents or fronts.

    - **Mean Dynamic Topography (MDT) & large scale circulation**: The Mean Dynamic Topography (MDT) is the quantity that bridges the geoid and the mean sea surface, constraining large-scale ocean circulation. The oceanic dynamic topography shows all the features of the general circulation with geostrophic currents, gyres and associated western boundary currents (e.g. Gulf Stream, Kuroshi…).

    - **Tropical Ocean Variability:** The tropical oceans, which are responsible for meridional and zonal heat transports have significant influence on the Earth's climate. The interactions between the tropical oceans and the atmosphere, and their impact on intraseasonal to multidecadal timescales result in climate variability. A very well-known example is the El Niño-Southern Oscillation (ENSO) phenomenon.

- **Operational oceanography:** Operational oceanography can be defined by the development and implementation of scientific algorithms, analysis tools and information systems that routinely produce and deliver observation data and model-based information. These materials are used for near-real time monitoring, state assessment/reanalyses, ocean forecasts and for scientific research. In the past few years, ocean forecasting has matured to a stage where many nations have implemented global and basin-scale ocean analyses and short-term forecast systems that provide routine products that serve the oceanographic community, and a variety of applications. Important parameters that needs to be forecast are the waves and surface wind, used for different purposes such as offshore industries or navigation. Satellite altimetry is a critical observing system required for operational oceanography [Le Traon 2013; Le Traon et al. 2015]. Global ocean forecasting is not possible without it, and no other observing system can enable global ocean forecasting in the absence of altimetry.

The following figure, from Chelton et al. [2001] (after Dicket et al. [1991]), summarizes all the major processes occurring in the oceans, as function of their spatial and temporal scales. The box in dotted line displays the altimetry observation domain:

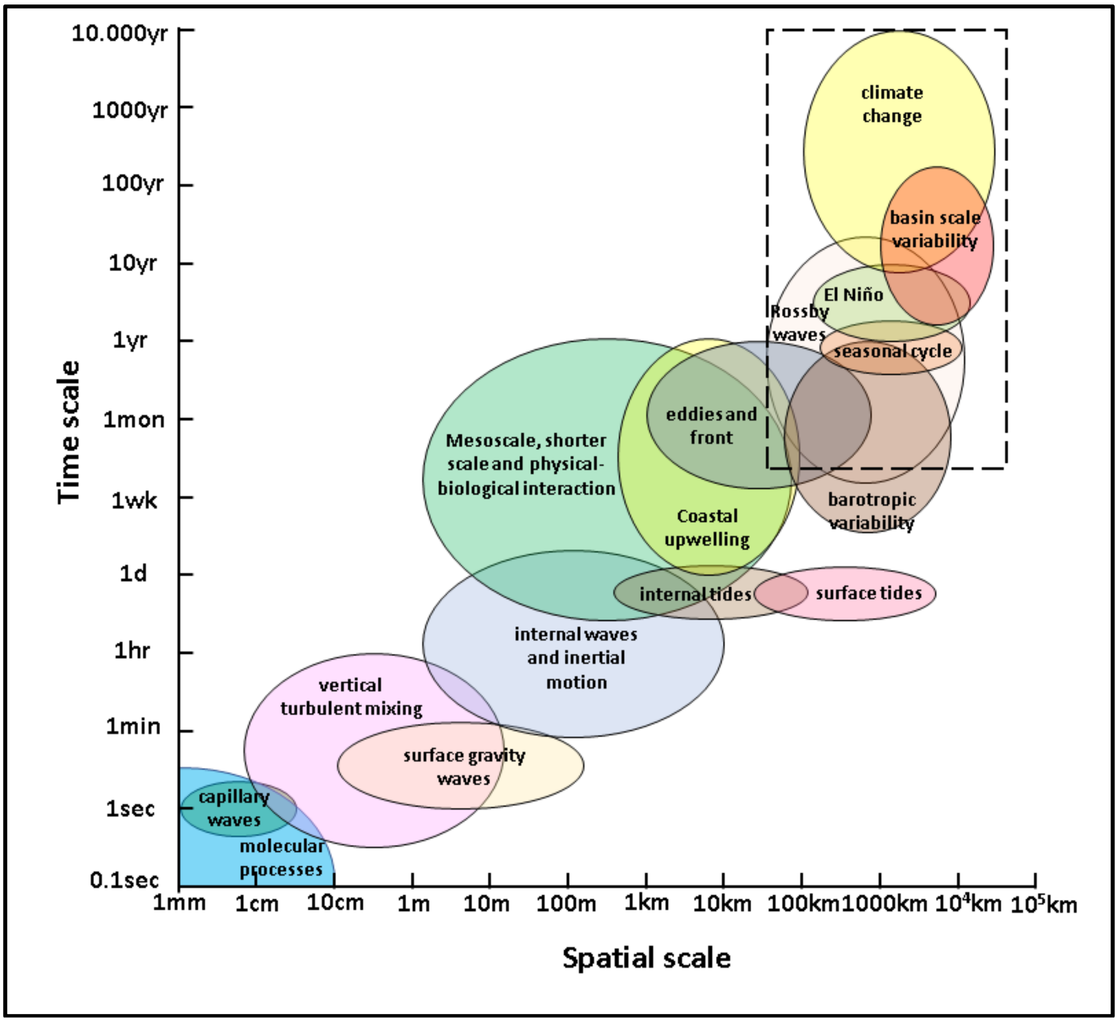

Figure 17: Temporal and spatial scales of ocean variability processes, from Chelton et al. [2001].

Downstream applications

Altimetry provides global, real time, all-weather sea level measurements with high space and time resolution. Over the past decade, there has been increased attention to the development of products and downstream services. For instance, the Copernicus Marine Environment Monitoring Service (CMEMS) provides regular and systematic reference information on the physical and biogeochemical ocean and sea ice state for the global ocean and the European regional seas. CMEMS serves a wide range of users and applications and more than 15 000 users are now registered to the service [Le Traon et al, 2019].
Below are listed main downstream activities requesting oceanic analyses and forecasts:

- **Fishery and sustainable management of living marine resources:** Oceanic circulation is one of the main factors influencing the ocean productivity, in both the coastal areas and high seas. Satellite altimetry has the ability to detect and monitor the areas of high dynamic biological activity (oceanic currents, fronts mesoscale features, eddies…) [Bakun, 2006]. With the use of other satellite sensors (measuring sea surface temperature and chlorophyll content), altimetry data are used to model the distributions of fish populations, optimise fishing effort, and identify vulnerable zones.

- **Offshore industry:** The offshore industry covers activities mainly from oil platforms and power generation (from winds, currents and waves). Many offshore operations are critically dependent on the prevailing meteorological and oceanographic conditions. Important parameters are winds, waves, and currents. To ensure that such operations are performed safely and efficiently, real time oceanic forecasts are required. For example, offshore platform operators rely on ocean circulation models to avoid accidents when raising or lowering drill strings. Seasonal statistics on wind and wave help to plan the best times for marine activities such as surveying, dredging, and salvage.

- **Marine safety:** Oceanic forecasts are critical to ensure the safety of the maritime community, promoting the economic health of maritime transportation, and protecting the environment. The observation of waves is essential for ship operations and ship planning. Additionally, tracking surface currents is a necessity for search and rescue, port and harbour operations, and recreational boating. Furthermore, sea-ice concentration monitoring and iceberg drifts forecasting also helps to minimise boat damages over the polar oceans.

- **Maritime transport and ship routing:** Maritime transport accounts for more than 80% of international freight transport. Ship weather routing is widely used. But routing by the current remains recent and innovative. The emergence of new operational ocean forecasts makes it possible to better understand the mesoscale dynamics of the upper ocean and to provide optimized and qualified forecasts. Using surface current for ship routing in areas where the weather conditions do not prevail may allow to save about 1% of the fuel consumption [from CMEMS website].

- **Pollution forecasting:** The monitoring and forecasting of marine pollution is one of the main uses of operational ocean numerical modelling. In order to deal with oil spill accidents, the marine security and safety agencies must have real time accurate ocean observations and forecast of oil trajectories for the next few days. The increase of accuracy of short term ocean projections constitutes a great advantage and may allow a faster response in case of accident. In addition to oil spill accidents, monitoring sargassum invasion in the Caribbean is another application of pollution forecasting.

- **Coastal management:** Coastal regions represent only 5% of Earth's land area, yet their societal and economical importance are larger than their surface area suggests. The land area within 100 km from the coast accommodates about 39% of the global population according to the CIESIN (Center for International Earth Science Information Network). Coastal systems are experiencing high pressures due to population growth and the overexploitation of their resources [Salameh et al., 2018]. In the need for a better understanding of the costal ocean dynamics, satellite radar altimetry measuring the variation of the surface elevation is a very useful tool providing key information, especially for non-monitored areas.

4.1.3 Focus on polar oceans

The Arctic environment has been warming more than twice as rapidly as the rest of the world for the past 50 years [AMAP, 2017]. Despite strong interannual variability, sea-ice extent clearly continues a long-term downward trend. By extrapolating the recent observations, an ice-free Arctic Ocean is predicted by the late 2030's [Screen and Williamson, 2017 ; Jahn, 2018]. On the other hand, the Antarctic sea ice cover has experienced a small increase in extent in the past decades, as a result of much stronger but opposing regional trends, that are in turn linked to a variety of mechanisms involving changes in atmospheric and oceanic forcing and feedbacks [Hobbs et al., 2016]. Observations of decadal trends in Antarctic ice thickness, and hence ice volume, do not currently exist and our knowledge is limited to model estimates [Holland et al, 2014], sparse in-situ [Kern et al, 2016] , airborne campaigns [Petty et al, 2017] and uncertain satellite measurements [Pope et al, 2017].

The need of satellite observations to study, understand and monitor climate change is more than essential over polar areas, where in-situ data networks are very sparse, and where profound and dramatic changes occur. Currently, a number of different datasets are used and brought together: sea-ice area, concentration, drift, thickness, as well as the topography of the ocean at global and regional scales. It is a major challenge to construct homogeneous time series from consecutive satellite sensors, and they are required for the detection of changes over several decades. This is one of the main objectives of the Climate Change Initiative from ESA, with projects both on Sea Level and Sea Ice [Ablain et al., 2015 ; Legeais et al., 2018]. On this section we will focus on the sea level parameter, as freeboard and sea-ice concentration & thickness are discussed in a previous chapter.

Although satellite altimetry is a very precise technique for monitoring global mean sea level over open ocean, it suffers from several uncertainties at disparate spatial and temporal scales. As GMSL is a crucial indicator for the Intergovernmental Panel on Climate Change (IPCC) experts, it is imperative to estimate the uncertainty magnitude from all error sources. It is only during the past years that these uncertainties have been quantified in different studies. Below the major sources of error are listed, the numbers specified relate to uncertainty on the global GMSL trend [Ablain et al, *under review*]:

- The largest error comes from the wet troposphere correction, bringing an uncertainty from 0.2 to 0.3 mm/yr, over a 5 years period [Legeais et al. 2014]

- Error in the satellite orbit characterization generates an uncertainty in the magnitude of 0.05 mm/yr, over a 10 year period [Couhert et al., 2015 ; Ablain et al., 2012].
- Drifts in the International Terrestrial Reference Frame (ITRF) realization, in which altimeter orbits are determined, cause an uncertainty of 0.1 mm/yr [Couhert et al., 2015].
- Furthermore, imperfect links between consecutive missions also create artificial drift in the GMSL, especially when the inter-calibration phase is not performed, such as the switch between TOPEX-A and TOPEX-B [Zawadzki et al., 2018].

Overall, the GMSL uncertainty over the 1993-2017 period is estimated at 0.4mm/yr [Ablain et al., *under review*]. Nonetheless, sea level estimation from altimetry also experiences other source of errors, with shorter time scale correlation, such as ones on geophysical corrections (dry tropospheric content, mean sea surface…), instrumental corrections, and retracking errors on the range retrieval. These errors have a weak impact on the GMSL trend computed over the whole open ocean (+/- 66°), and over the 25 years time series. However, specific problems arise at regional scales, and especially considering the polar oceans [Prandi et al., 2012]:

- **Altimeter range:** The first one is the degradation of the altimeter range accuracy derived from level-2 retrackers. Firstly, altimeter waveforms acquired over sea-ice leads are very specular. Consequently, the physical Brown model used by the level-2 retrackers is not valid any more and empirical retrackers are employed, less accurate and precise. Nonetheless, progress have been made during the past years to develop physical models of the backscattered echoes accounting for the Mean Square Slope [Poisson et al., 2018] and results show very promising outcomes [Carret et al., 2017]. For sure, they will be extensively used in the future to derive sea surface heights in the leads. They will also ensure a good continuity of measurements with the free open ocean. Secondly, the presence of floes within the radar footprint pollutes the measured waveform and may create errors on the estimated range. Currently, the adopted approach to deal with the problem consists to discard the measurements, based on the waveform shape, with the drawback of creating missing data.

- **Wet tropospheric correction:** Radiometer measurements are also contaminated in both ice-covered and coastal regions due to the large footprint. Scientists usually use the operational ECMWF model to derive the wet troposphere correction, which is equally accurate than the on-board radiometer correction over polar areas but increase the number of available measurements [Cheng et al., 2015].

- **The Dynamic Atmospheric Correction (DAC)** is a modelling of the sea surface response to the preceding time series of pressure and wind. The correction is a sum of two terms: the first corresponds to the static inverted barometer effect (low frequency time signals) and the second to the dynamic response of the ocean to wind and pressure (high frequency time signals). The correction content is determined from meteorological models [Carrère and Lyard, 2003]. There are some doubts regarding the correction accuracy over oceans, Ricker et al. [2016] suggest this correction is one of the major errors when estimating the freeboard.

The lack of accuracy of altimetry over polar areas acts retroactively on several geophysical corrections, themselves derived from altimetry data. Specifically:

- **Oceanic tides correction**: For more than two decades altimetry has been providing critical information to improve tide models. In a virtuous loop, enhancement of tide models improved the accuracy of the sea level anomaly. However, the principal limitations of modern tide models in polar regions arise from combination of poor bathymetry and relatively sparse and poor quality of altimetry data for model validation and assimilation [Stammer, 2014].

- **Mean Sea Surface (MSS):** Corresponding to the sum of the geoid and the mean ocean circulation, it is considered as a correction that is applied to the sea surface height to derive Sea Level Anomalies (SLA). The MSS is the largest correction, as it ranges over more than 40 metres across the Arctic Ocean, but is missing precise altimetry data, and an adequate model of the tide, to be accurate.

Overall, the regional mean sea level trend estimated for the Arctic Ocean for latitudes from 66°N to 82°N, and during the 1993-2009 period, is 3.6 mm/yr with an uncertainty of 1.3 mm/yr [Prandi et al., 2012]. Another study from Cheng et al. [2015] shows a mean sea level trend of 2.1 ± 1.3 mm/year over the 1992-2012 period and same area. It is worth noticing that the uncertainty over the Arctic ocean is three times greater than the global GMSL one. From our knowledge, there is no extensive study assessing uncertainty and errors of the Antarctic ocean mean sea level. Errors are expected to be in the same magnitude than those computed for the Arctic ocean, but there is no certainty about this.

From now, mean sea level computation is derived from LRM altimetry. By dramatically reducing the along-track footprint, SAR mode altimetry provides a new alternative to better discriminate surface type over ice-covered ocean compared to LRM. Consequently, the measure brings promising expectations to estimate more accurately sea level in sea-ice leads and polynyas. The Fully-Focused SAR processing, by providing an even stronger reduction of the along-track resolution, is also a data processing that should be taken into account [Egido et al, 2017]. The potential assets brought by a dual frequency Ku/Ka bands, combined with the delay-Doppler processing, are discussed later in the document.

4.1.4 Potential CRISTAL products already used in services

Copernicus Marine Environment Monitoring Service (CMEMS)

Oceanic satellite product variables are available in the website in Near Real Time (NRT) & delayed time (reprocessing), except for the SWH only available at NRT. Level-3 refers to mono-sensor, along-track products & level-4 to multi-sensors, gridded products.

- *Sea Level Anomaly (SLA)*

A sea-level anomaly is the difference between a punctual measured Sea Surface Height (SSH) and an averaged sea-level (retrieved from the 25 years time-series of altimetry). Products are available at level-3 & level-4.

- *Absolute Dynamic Topography (ADT)*

The absolute dynamic topography is obtained by estimating the ocean Mean Dynamic Topography and adding it to the altimetric sea level anomalies. Products are available at level-4 (multi-missions gridded products).

- *Surface Geostrophic Current Velocity*

The geostrophic current products disseminated to users are computed by geostrophy using the ADT estimations. More details are available in Arbic et al. [2012] & Pujol et al. [2016]. Products are available at level-4.

- *Significant Wave Height (SWH)*

SWH is commonly used as a measure of the height of ocean waves. Products are available at level-3, and a level-4 product will be available soon.

More informations available here regarding sea level parameters:
http://resources.marine.copernicus.eu/documents/QUID/CMEMS-SL-QUID-008-032-062.pdf

Copernicus Climate Change Service (C3S):
From the C3S website : https://climate.copernicus.eu/ocean

- Sea level & surface current velocities

The C3S sea-level products aim at answering the users' needs regarding the monitoring of the long-term evolution of the sea level for climate applications and the analysis of ocean/climate indicators. Within the C3S service, CLS provides the sea-level ECV based on Earth observations. The along-track measurements are used to produce the merged gridded sea-level products. The delayed-time daily products are delivered in three regions of interest: the Global Ocean, the Mediterranean Sea and the Black Sea covering the period from January 1993 until a few months delay versus present time. Within the products, the users have access to the observed sea surface heights and the associated surface current velocities. A typical use case of the sea-level products is the computation of global and regional Mean Sea Level evolution and trends.

Level-2 Plus (L2P) products:
Finally, sea level anomaly & geophysical standards used to calculate it (i.e. instrumental, geophysical, environmental corrections; Mean Sea Surface…) are also available at level-2 for all the current and historical altimetry missions. They can be downloaded from the aviso website. EUMETCAST is also distributing them for the Sentinel-3 missions.

More informations below:
https://duacs.cls.fr/duacs-system-description/l2p-upstream-data/

4.2 Gap analysis relative to the 2025 observing system

4.2.1 User requirements

From CMEMS:

- ***"Ensuring continuity (with improvements) of the Cryosat-2 mission** for […] sea level monitoring in polar regions*" is one of the CMEMS recommendations/priorities for the evolution of the Copernicus satellite component. In addition, "***Reliable retrieval of sea level in the leads to reach the retrieval accuracy required to monitor Climate Change***" is another CMEMS recommendation for polar and sea ice monitoring. [RD-1].

From the Polar Expert Group (PEG) reports (Duchossois et al., 2018a, 2018b):

- ***"The altimeter sea-level anomaly (SLA) is an essential variable** for oceanic operational system as it gives outstanding information both on the small-scale dynamics (if sufficient resolution is available which, currently, is not the case) and climate change. A continuity is at least required with however a coverage closer to the North Pole with measurements in the leads. Global ocean along-track sea-surface height is a CMEMS product given in NRT. **No data is however available within the leads, nor is the spatial resolution high enough to retrieve meaningful statistics on mesoscale currents**. Actual data from the CMEMS catalogue does not allow a satisfactory sampling north of 82° N. **It is of prime importance that the orbit configuration allows covering the central Arctic Ocean."***

- *"Desirable improvements with regards to CryoSat-2, would be to improve lead detection capabilities further (resulting in more measurements over sea ice) and to **observe sea surface topography at the scale of eddy fields** (1-5 km)."*
  - ⇨ *Note that the 1-5 km spatial scale looks currently unreachable by altimetry technology. [Dufau et al., 2016]*

The table below reports goals expected for the oceanic parameters, from the PEG report [RD-1], table 3:

Parameter	Spatial Resolution	Frequency	Accuracy
Sea level anomaly ***Climate (along-track & gridded products)***	**Minimum goal is 10km** **Optimum is 1km for climate application**	**Goal: daily sampling**	**2 to 3cm specified**
Sea-level anomaly in leads ***Ocean (along-track products)***	**Minimum goal: 10km**	**Minimum goal: 10day sampling** **Optimum goal: Daily sampling**	**2 to 3cm specified**
Mean dynamic topography ***Climate (along-track & gridded products)***	**Minimum goal: 10km** **Optimum is 1km only for climate gridded products**	**Goal: 10days sampling**	**/**
Mean dynamic topography ***Ocean (along-track products)***	**Minimum goal: 10km**	**Goal: 10days sampling**	**/**

Table 3: Goals expected for the oceanic parameters, from the PEG report

Comments regarding the table above:

- We believe that terminology used in table 3 for “Mean Dynamic Topography” (MDT) is wrong, and that PEG refer to “Absolute Dynamic Topography” (ADT), at least for along-track products. In fact, MDT corresponds to an average of the difference between the mean sea surface and the geoid, estimated over a long period. Therefore, the MDT cannot be available as an along-track product.
- Gridded products must be discussed in the context of a multi-mission constellation. For instance, the altimetric gridded-products generated by CMEMS exploit mainly a constellation of 3 to 5 satellites (depending on altimetry satellites available).
- Requirements between along-track & gridded products should be discriminated, as they are completely different products.

- In addition, all the parameters & products should be discriminated between open-ocean / polar ocean. As presented before (section 4.1.3), the performances achieved by radar altimetry are not comparable between both oceans.
- A temporal sampling specification does not make sense for an along-track product. Unless PEG refers to the revisit rate (orbit cycle), but in this case a daily sampling is completely unrealistic.
- Current topographic gridded products (SLA, ADT) in CMES are usually available at **0.25° (~28km) spatial resolution,** with a **daily temporal sampling**. Therefore, reaching a 10km spatial resolution with a daily sampling (optimum goal) appears complicated. A 10km spatial resolution (minimum goal) might be reachable at regional scales, or by releasing temporal sampling. A complete study should be performed to answer this problematic, as spatial/temporal resolutions are constrained by the altimeter constellation sampling capabilities. The 2025 constellation will be relativity different to the current one (see next section), and it is not straightforward to anticipate optimal resolutions of future gridded products.
- The 2-3 cm accuracy required for the open-ocean SLA is in line with the SSH accuracy of most of the current altimeters (source : 2018 OSTST report, table 4.7-1) *https://www.aviso.altimetry.fr/fileadmin/documents/OSTST/2018/OSTST_2018_Meeting_Report_Final.pdf*
- Nonetheless, from our knowledge, no calibration study has been performed over sea-ice leads. But, we know that the accuracy is degraded with the current empirical level-2 retrackers employed for sea-ice waveforms [Crétaux et al., 2018], along with the precision. The 500MHz bandwidth of CRISTAL will reduce the vertical resolution (~30cm) and will help improving accuracy & precision. But it is doubtable that it will entirely allow to reach the 2-3cm accuracy. Note that a physical retracker, such as the “adaptive retracking“ [Poisson et al.,2018], or GPOD SAMOSA+, fitting SAR/SARIn waveforms will help improving even more the performances over the ice-covered ocean.

4.2.2 Gap analysis

The launch date of the Copernicus polar Ice and Snow Topography ALtimeter (CRISTAL) is planned in 2025. To assess the performances of the future constellation, it is of major importance to identify all the altimetry mission components, along with their characteristics. This is mandatory to conceive the most relevant satellite payload and define an adequate orbit to address efficiently the user requirements. The following figure displays a view of the current and future altimetry constellations:

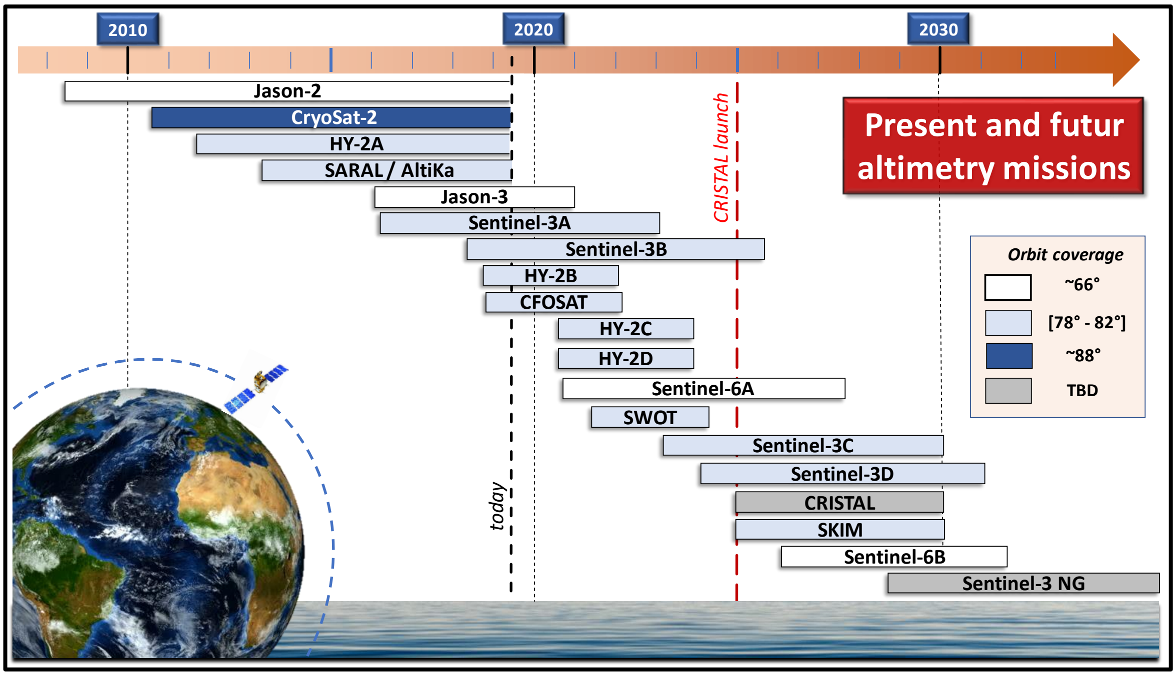

Figure 18: Diagram of the current and future altimetry constellation

The following table shows the main missions characteristics for those that are expected to be in operation during the 2025-2030 period:

Mission	Agency	Planned life	Orbit inclination	Orbit revisit	Operation mode	Frequency band
Sentinel-6A	CNES/NASA/EUMETSAT/NOAA	2020 - 2027	66°	10 days	SAR + LRM	Ku
*SWOT***	*CNES/NASA/ACS/UKSA*	*2021 - 2024*	*77.5°*	*21 days*	*LRM + swath*	*Ku (LRM)*
HY-2C*	NSOAS / CNSA	2021 - 2024	99.3° (80.7°)	14 days	LRM	Ku
HY-2D*	NSOAS /CNSA	2021 - 2024	99.3° (80.7°)	14 days	LRM	Ku
Sentinel-3C	ESA	2021 - 2028	98.6° (81.4°)	27 days	SAR + P-LRM	Ku
Sentinel-3D	ESA	2021 - 2028	98.6° (81.4°)	27 days	SAR + P-LRM	Ku
*SKIM****	*ESA*	*2025 - 2030*	*82°*	*TBD*	*connical scanning*	*Ka*

Table 1: Table summarizing the main characteristics of the altimetry missions planned to be in operation during the 2025-2030 period

** HY2 missions are planned for 3 years, but they will probably exceed their lifespan. For example, HY-2A launched in 2011 is still in operation.*
*** SWOT expected lifetime is 3 years and will probably not be anymore in operation during the 2025-2030 period*
**** As SKIM is still in phase 1 and is not yet confirmed, we will not include it in the discussion. Moreover, SKIM will not embark any classical altimeter, but a specific instrument dedicated to the observation of the currents*

In the above table, the significant statistics are summarized regarding the altimetry constellation predicted for 2025:

- All in all: at least 5 altimeters are expected to be in operation.
- 3 missions in SAR mode (Sentinel-6A + Sentinel-3C/D); 3 missions in LRM (Sentinel-6A, HY2 C/D). All missions in Ku band.
- 1 mission on the reference Jason orbit (Sentinel-6A); 2 Sentinel-3 missions on the 35-days orbit cycle of ERS/Envisat/ALtiKa; 2 HY missions on a 14-days orbit cycle.
- The maximum geographical coverage will be up to +/- 82° only, leaving a big gap of observation up to the pole.

The following figures show the geographical coverages of the current (top) and probable future (2025-2030 period, bottom) missions over polar areas:

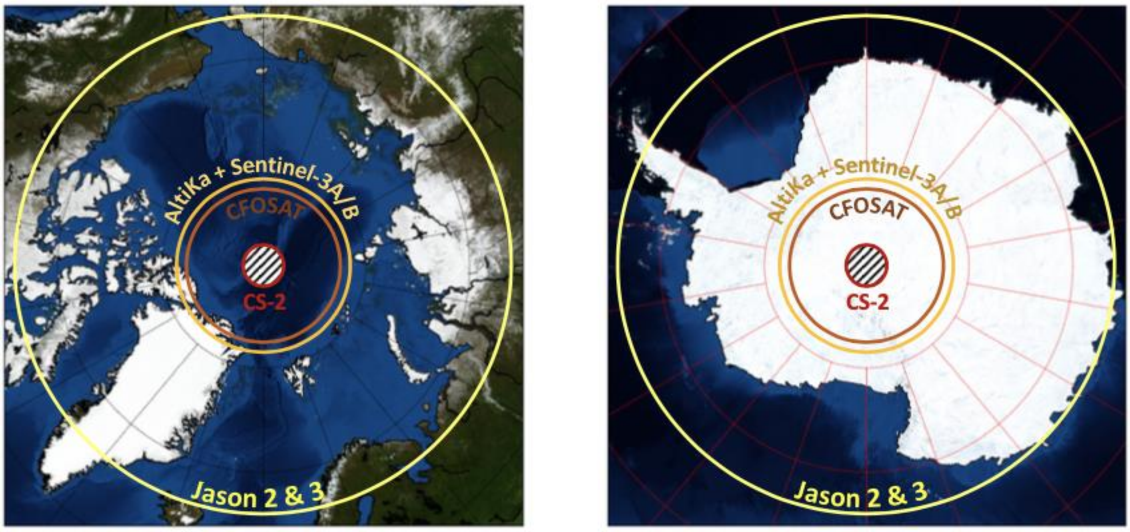

Figure 19: Geographical coverage of the current altimetry missions (mid 2019) over north (left) and south (right) poles

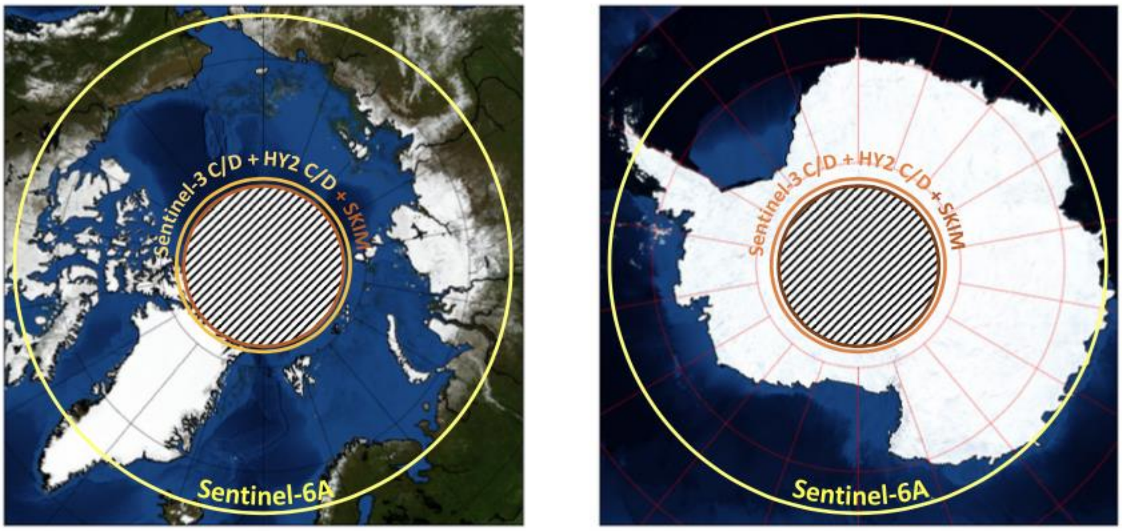

Figure 20: Geographical coverage of the probable altimetry missions that will be in operational concurrently with CRISTAL, over north (left) and south (right) poles.

The two primary objectives of CRISTAL are (1) to measure and monitor variability of Arctic and Southern Ocean sea-ice thickness and its snow depth and (2) to quantify and monitor the surface elevation and changes of glaciers, ice caps and the Antarctic and Greenland ice sheet. Even if the observation of the ocean is not a primary objective of the CRISTAL mission, it seems mandatory to guarantee as well the measurement of the sea level because of its strong correlation with sea ice and ice sheet behaviour and height trends. Therefore, among secondary mission objectives there is the observation of the ocean topography as a continuum up to the poles, and support applications related to coastal and inland waters [RD-2].

From all the elements provided before, the main gaps of the future 2025 altimetry constellation with regards to the ocean monitoring are listed here:

- CryoSat-2, launched in 2010, was initially planned for 3.5 years lifetime, hence the mission has already exceeded its objectives and will be most probably over before 2025. As explained before, it is crucial to cover the Arctic Ocean for scientific purposes, as well with operational applications such as ship routing and offshore industry. Ideally, the optimal orbit should cover polar areas up to 90°, while CryoSat-2 orbit goes up to 88°.

- Following the success of CryoSat-2, covering the polar areas must be achieved with a mission carrying a SAR altimeter. As described before, one of the main weaknesses of conventional altimetry over sea-ice relies on the large radar footprint, preventing it from discriminating different surface types (leads/floe). Delay-Doppler altimetry allows to dramatically reduce the along-track footprint, from several kilometres down to 300 meters. In addition, a one-meter along-track resolution is even possible when exploiting the FF-SAR processing. Nonetheless, to optimally exploit the FF-SAR processing, an interleaved chronogram is required as it will be the case for the Sentinel-6 mission [Egido et al., 2017].

- It is of major priority to improve tide models accuracy over the polar areas with regards to their importance on the sea level estimation accuracy. Therefore, in addition to sea-ice and land ice requirements, the orbit selection should also be driven to achieve this goal.

- The same remark applies for the capability to derive the Mean Sea Surface at high latitudes

Regarding the orbit definition, there is a difficult trade-off to make, depending on the area of priority (open oceans VS polar oceans) and the targeted purposes (mesoscale signals, MSS, tides, GMSL, wave assimilation…). Below are listed several aspects that need to be taken into account regarding the orbit of CRISTAL, with regard of the future 2025-2030 constellation.

- **Open Ocean:** The future constellation would be composed of 5 altimeter satellites. Adding a new orbit would be beneficial for better sampling mesoscale signals, especially for operational systems running numerical models that assimilate real time altimetric data [Pascual et al., 2015]
- **Open Ocean:** The addition of CryoSat-2, AltiKa in its drifting phase, and the future SWOT measurements will significantly improve the MSS accuracy between Jason tracks. Therefore, estimating an accurate sea level anomaly between +/- 66° latitude from a geodetic mission would be possible.
- **Open Ocean:** The sub-cycles choice is extremely important and drives the oceanic signals/processes that can be measured. For instance, the current CryoSat-2 orbit is not well suited for measuring mesoscale signals, as large oceanic areas remain unsampled after two weeks of acquisition (areas located at +/- 15° and +/-70° latitude). To do so, a sub-cycle of about 15 to 17 days is required.
- **Open Ocean:** For the observations of waves, a sub-cycle of 2 to 3 days is required.
- **Polar Ocean:** To improve tide models over polar areas, orbit definition should take into account tidal aliasing properties. For example, a sun-synchronous orbit is not desired.
- **Polar Ocean:** A repetitive orbit would be profitable for the polar GMSL to derive the sea level anomaly accurately over well-known along-track profiles.
- **Polar Ocean:** An orbit with cycle / sub-cycles of 90 days helps removing seasonal biases in the polar MSL

4.3 Review and prioritisation of potential scientific applications of dual-frequency interferometric SAR altimetry over ocean.

Context

The new perspectives brought by a SAR Interferometric (SARIn) altimeter operating with a dual-frequency in Ku/Ka bands are discussed in this section. Given that SAR Interferometry and dual Ku/Ka bands are two distinct technologies, they are discussed separately:

- The advantage of the SARIn mode is to precisely locate the Point Of Closest Approach (POCA) within the SAR footprint. Besides, it provides an estimation of the cross-track slope [Gray et al, 2013].

- The main interest of a dual Ku/Ka bands altimeter is to study surfaces where the signals behave differently due to inequivalent microwave properties (surfaces covered by snow).

SAR Interferometric processing over Ocean

Up to now, CryoSat-2 is the unique mission to have operated in SARIn mode over the open and polar oceans, nonetheless on limited geographical areas. The interest of SARIn mode over open ocean to improve the resolution of mesoscale fields has been discussed by Dibarboure et al. [2013]. Their conclusions, based on a limited theoretical analysis, state that the precision of the estimated cross-track slope would not be satisfactory to resolve small features (radius <100km). However, a preliminary study performed at CLS showed the capacity of the SARIn mode to capture the relative strong cross-track slopes induced by the Mean Sea Surface. But the cross-track slope noise is currently large as it stands, and probably prevents from reaching signals linked to oceanic dynamics. Dedicated processing strategies and efficient noise filtering are perspectives that might improve the estimation.

Over the ice-covered ocean, SARIn mode is valuable to improve our knowledge of the lead location within the SAR footprint. In fact, in LRM or SAR altimetry the estimated range associated to a lead is computed considering a nadir reflection. Off-nadir lead create therefore a positive bias in the altimeter range and consequently tend to underestimate the sea level heights (which has also consequences in the estimation of ice freeboard and thickness). A dedicated study led by Armitage et al. [2014] quantified the ability of the SARIn to deal with this issue. They concluded that the benefit exits, even if relatively limited, as most of the waveforms classified as “lead measurement” correspond to nadir reflection. Nevertheless, the study also showed that the knowledge of the lead across-track location allows to be less restrictive in the waveform classification, and enables to recover more data to compute the sea level or the freeboard. A study conducted at CLS reached exactly the same conclusions, with very similar statistics.

Finally, SAR Interferometry has also proved to be more efficient than conventional altimetry over coastal areas. Firstly, improvements are due to the SAR smaller footprint, enabling observations closer to the coast than conventional altimeters, as demonstrated by Dinardo et al., [2018]. The gain being dependant on the track orientation with regard to the coastline. Secondly, using interferometric information (phase difference along with the coherence vector) helps removing outliers and provides better precisions and accuracies on the estimated sea level close to the coasts [Garcia et al., 2018].

Dual Ku/Ka bands altimeter

There is no direct gain to simultaneously exploit Ku and Ka bands observations over the ocean surface, as the Ku/Ka signals don't penetrate the oceanic surface and are backscattered by the top of the water column. Things are different over snow- or ice-covered surfaces where the Ku-band signal penetrates the medium, while Ka-band does not (or barely) [Vincent et al., 2016].

AltiKa and the Ka band assets over ocean were already discussed in a previous section. Among advantages brought by the Ka band, one of the most relevant is its capacity to resolve finer oceanic mesoscales compared to LRM Ku band. This gain is due to a 40Hz sampling and a reduced footprint, itself brought by the Ka-band antenna's narrower aperture and the 480MHz bandwidth. With its Ka-band frequency and equivalent bandwidth, CRISTAL should benefit from the same advantages as AltiKa in LRM. In addition, by using delay-Doppler altimetry, CRISTAL could theoretically exploit both the advantages of the Ka-band and the reduced SAR footprint.

Discussions about the configuration currently retained for Open-Ocean: <u>SAR closed-burst with the on-board RMC processing</u>

From the lessons learned from CryoSat-2 & Sentinel-3A/B, we draw below a list of conclusions

- **SAR mode is suitable for sea level measurement**, bringing improvement with regards to LRM. But there is still some issues to solve regarding wave estimation (swell sensitivity & decimeter bias in SWH by comparison with LRM => on-going studies at CNES/CLS)

- On-board RMC is valuable to reduce telemetry data without impacting SAR mode and FF-SAR mode performances, as already demonstrated for Sentinel-6 studies conducted by CNES/CLS.

- But, **is there a necessity of a dual frequency Ku/Ka altimeter over ocean**? If there was a choice to made, a study should be conducted regarding both frequency bands capabilities to reduce oceanic speckle noise and resolve small spatial scales (depending on the planned altimeter chronogram).

- Interleaved chronogram is always preferable as closed-burst to keep the possibility to process LRM / SAR simultaneously & perform FF-SAR processing without ambiguities, with particular benefits expected over heterogeneous area such as inland waters and sea-ice leads [Egido et al. 2017].

Note on the ionospheric correction

This correction takes into account the path delay in the radar return signal due to electron content in the atmosphere. Calculated by combining radar altimeter measurements acquired at two separate frequencies (C-band and Ku-band for Topex and Jason-1, Ku-band and S-band for Envisat). Its order of magnitude can reach 0 to 5 cm in Ku band & 0 to 0.5cm in Ka band.

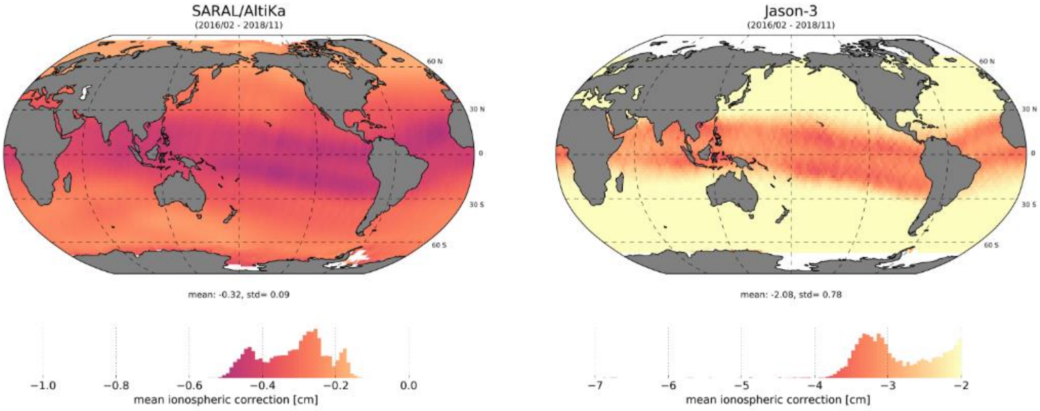

Figure 21: *From AVISO website: "SARAL/Altika validation and crosscalibration activities, annual report 2018":* Average map of ionospheric correction for SARAL/AltiKa (GIM, left) and Jason-3 (filtered dual-frequency ionosphere correction, right).

For the CRISTAL mission there is discussions about the C band need to derive precisely the ionospheric correction, considering the altimeter will already possess two frequency bands (Ku & Ka). This subject has been studied at CLS, in the frame of the Polar-Ice project. Below is a summary of the assessment:

The noise on the estimated ionospheric correction can be computed as follow:

$$\sigma_{Iono\_Corr\_Freq1} = \frac{1}{Freq1^2}\left|\frac{Freq1^2 * Freq2^2}{Freq1^2 - Freq2^2}\right| \sqrt{\sigma^2_{Range\_Freq1} + \sigma^2_{Range\_Freq2}}$$

The range noise is estimated based on a closed-burst chronogram, allowing to produce SAR waveforms similarly to Sentinel-3 configuration. Only difference is the 500Mhz, leading to a noise reduction by a 0.64 factor (320Mhz/500Mhz). Therefore, the range noise levels used to resolve the equation above are:

- **SAR Ku band => 5.5cm** *(From the 5.5cm of Sentinel-3A)*
- **SAR Ka band => 5.5cm** *(From the 5.5cm of Sentinel-3A)*
- **C band =>** 18cm *(from Jason-3)*

The 5.5cm range noise in Ku & Ka is taken from Sentinel-3A as a conservative approach. Nevertheless, we expect a lower range noise level with CRISTAL, in particular due to the 500MHz bandwidth (more details in the TN2).

The following table shows the expected noise level on the ionospheric correction for the band to be corrected (freq 1) depending on the secondary band (freq 2) used to derive the correction (**20Hz noise level**):

Freq 1 / ***Freq 2***	C band (cm)	Ku band SAR (cm)	Ka band SAR (cm)
C band (cm)		3.4	0.4
Ku band SAR (cm)	22.2		1.3
Ka band SAR (cm)	19.2	9.1	

Table 4: 20hz ionospheric noise level as function of the dual frequency bands chosen

Based on the numbers estimated in the table above, the following table shows the expected noise level for the filtered ionospheric correction which is performed based on a Lanczos filter over a 250km spatial scale.

Freq 1 / ***Freq 2***	C band (cm)	Ku band SAR (cm)	Ka band SAR (cm)
C band (cm)		0.13	0.015
Ku band SAR (cm)	0.83		0.05
Ka band SAR (cm)	0.72	0.34	

Table 5: Filtered ionospheric noise level (250km) as function of the dual frequency bands chosen

CRISTAL will exclusively operate in Ku/Ka bands, the C band is not considered. Therefore, several comments can be made from these expected noise levels:

- The bi-frequency ionospheric correction **in Ka band** can be completely derived using the Ku-band, as its noise level remains **below 1mm** (0.05cm, Table 5)

- On the other hand, the bi-frequency ionospheric correction **in Ku band** will be noisier than the usual correction derived from C-band. The order of magnitude of the degradation is a ~2.6 ratio (**0.34cm Ku/Ka** noise level vs **0.13cm Ku/C** noise level). **This element has to be considered for the choice of the future ionospheric correction**. An estimation from model could be another option it the 0.34cm noise level is considered too high.

The ionospheric correction provided by the GIM model is very smooth and does not have a high frequency noise level. But on the other hand, the model is not able to account for local variations of the atmosphere ionospheric content. From our knowledge there is no study clearly comparing the performances of the GIM model correction vs the bi-frequency correction. Studies are on-going at CLS thereon.

Note that over polar regions, the GIM model correction is usually used as the altimeter is not able to consistently retrieve an accurate & precise altimeter range.

Note on the on-board radiometer

The wet tropospheric correction (WTC) is a major source of uncertainty on altimetry budget error, due to its large spatial and temporal variability. Therefore, the main altimetry missions embed a microwave radiometer (MWR) to provide an estimation of WTC simultaneously to the altimeter range measurement.

All the informations presented below are extracted from the technical note “PolarIce: Radiometer Frequency channels recommendations”, reference : “CLS-SPA-NT-18-0044”. The technical note was written by CLS, in the frame of the PolarIce project funded by ESA.

System requirements and discussion

The wet tropospheric correction (WTC) relevant requirements in the SRD are:

“

- ***OBS-500:*** *The system shall include algorithms for wet tropospheric correction to within 10 km TBC of the coastline. Note that this implies a high-resolution radiometer (SRD p23)*
- ***PER-080:*** *For average sea states, the combined standard uncertainty of the 1-Hz sea surface height measurements shall be less than 2.94 cm TBC for altimeter products. […] Note that the value of 2.94 cm breaks down to (at 1 Hz): […] Wet troposphere: 1.0 cm. (SRD p 24)*
- ***PER-090:*** *The contribution of the wet troposphere path delay to the overall altimeter-derived sea surface height error budget shall be less than 0.8 cm TBC (RMS for a typical sea of 2 m significant wave height and 11 dB sigma-0) at 1/sec along-track data rate. (SRD p 24)*

> *It appears that there is a contradiction on the SRD between the 1.0 cm in PER-080 and the 0.80 cm in the PER-090.*
>
> *The need for a radiometer over ice, at latitudes higher than 60° is questionable because the atmosphere is very dry, but high-frequency observations would bring valuable information for surface characterization.*
>
> *[…]*
>
> *There is no updated results allowing to clearly affirm that high resolution frequency observations are required to fulfill the requirements over ocean, but the latest results suggest that they are needed, especially if a 0.80 cm goal is retained.*
>
> *Over coastal areas, the studies performed in the frame of “Radiometer for Coastal Regions” ESA/ETEC study clearly showed that high frequency observations are required to achieve the performances in terms of accuracy and distance to the coast.*
>
> *Considering all these areas and in order to comply with the SRD requirements, we are convinced that a radiometer on board of PolarIce is required.*

“

Channels recommendations

In the PolarIce study two considerations are taken into account to draw a list of relevant channels:

"

- *First, a "reasonable" number of channels, with respect to instrumental design consideration*
- *and secondly the strategies that will be deployed for WTC retrieval over different surface coverage, including coastal areas.*

With this, it is possible to propose an ideal channel combination, providing relevant information on the surface – atmosphere system, and for which previous knowledge exists:

- *18.7, 23.8, 36.5 GHz: three classic low frequency channels*
- *50 and 53.6GHz channels as they provide surface emissivity and troposphere temperature,*
- *89GHz for surface emissivity and clouds*
- *183-11GHz with 165GHz for low atmosphere humidity and surface emissivity and near surface humidity with good resolution.*

  Note that:

  - *The 50 GHz channel is added for emissivity inversion strategy on mixed surface which was not considered during the selection process*
  - *the 172 GHz channel (183-11 GHz) is preferred to the classical 183+/- 11 GHz in order to maximize the sensitivity to the lower part of the atmosphere, the continuum on each side of the absorption line being not symmetrical (Figure 6).*
  - *118GHz was not retained because this contribution is very similar to 53.6GHz and with increased sensitivity to cloud making it marginal compared to the others.*

Channel	Central Frequency [GHz]	Geophysical Parameter
MWR-1	18.7	Surface conditions (Water Vapor)
MWR-2	23.8	Water vapor
MWR-3	36.5	Clouds (Water Vapor)
MWR-4	50.3	Surface emissivity (low frequency)
MWR-5	53.596	Atmospheric temperature
MWR-6	89	Surface emissivity (high frequency)
MWR-7	165	Clouds
MWR-8	183.3-11	Water vapor

Table 6: Recommended observation frequency list

"

4.4 Summary of the added value offered by the proposed system and mission characteristics.

In conclusion, CRISTAL will be beneficial for oceanic needs, and especially over the Arctic ocean where a large area would not be monitored after the CryoSat-2 life and a fortiori at the 2025-2030 horizon. The foreseen altimeter embarked on the CRISTAL mission is giving promising expectations, especially with the SAR Interferometric mode planned for sea-ice areas. Below are summarized main conclusions of this chapter:

- The mission addresses one of the recommendations/priorities for the evolution of the Copernicus satellite component, which is the continuity of the Cryosat-2 mission for sea level monitoring in polar regions [RD-1], in particular regarding its high latitude coverage.
- User requirements from PEG state that *"desirable improvements with regards to CryoSat-2, would be to improve lead detection capabilities further"*. In response, it is expected that SAR Interferometry technology will be valuable over the ice-covered ocean to improve the SSH accuracy and recover more valid data.
- Only sea level anomaly & dynamic topography parameters are covered in the user requirements from PEG. There are high expectations in terms of gridded products spatial resolution (10km as minimum goal). In fact, current global products spatial resolution is commonly 0.25° (~28km). A dedicated study should be performed regarding the capabilities bring by the future constellation to address this problematic
- Still from the PEG user requirements, the 2-3 cm accuracy required for the open-ocean SLA is in line with the current altimeters accuracy (Sentinel-3A & Jason-3A for instance). However, reaching the same accuracy over lead measurements appears currently unrealistic. Only the development of a physical retracker adapted to SAR/SARIn waveforms might allow to reach the requirement.
- The future altimetry constellation should be composed of 5 missions in the 2025-2030 horizon. Adding another mission with a different orbit definition will be still beneficial for better sampling oceanic mesoscales signals over open ocean, and especially for purposes that need frequent satellite revisit (wave assimilation).
- Collected observations from the CRISTAL mission are clearly expected to improve the definition of the MSS and tide models at high latitudes. Retroactively, the mission is therefore expected to reduce the uncertainty on the polar GMSL, currently three times greater than the global GMSL.
- SAR Interferometry technology will also be valuable to improve sea level accuracy over coastal areas compared to LRM and SAR mode. This addresses one of the mission secondary priorities.

Orbit definition will be of critical importance as it drives the mission capabilities over open ocean in particular when considering the CRISTAL mission as one component of an existing altimetry mission constellation.

4.5 Chapter 4 References

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