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The Cryosphere
Discussions

The Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL): Expected Mission Contributions

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Abstract. One of the candidate missions in the evolution of the Copernicus Space Component (CSC) is the Copernicus polaR Ice and Snow Topography ALtimeter (CRISTAL). The aim of this mission is to obtain high-resolution sea-ice thickness and land ice elevation measurements and includes the capability to determine the properties of snow cover on ice to serve Copernicus' operational products and services of direct relevance to the Polar Regions. The evolution of the CSC is foreseen in the mid-2020s to meet priority user needs not addressed by the existing infrastructure, and to reinforce the Copernicus services by expanding the monitoring capability in the thematic domains of anthropogenic emissions (CO_2), polar and agriculture/forestry/emergency. This evolution will be synergetic with the enhanced continuity of services foreseen with the next generation of the existing Copernicus Sentinels. New high-priority candidate satellite missions have been identified by the European Commission (EC) for implementation in the coming years to address gaps in current capability and emerging user needs. This paper describes the CRISTAL mission objectives, main mission requirements driving its design, the payload complement currently under development and its expected contributions to the monitoring of important components of Earth's cryosphere.

1 Introduction

Earth's cryosphere plays a critical role in our planet's radiation and sea level budgets. Loss of Arctic sea ice is exacerbating planetary warming owing to the ice-albedo feedback (e.g. Budyko, 1969; Serreze and Francis, 2006; Screen and Simmonds 2010), and loss of land ice is the principal source of global sea level rise, see Chen et al (2013). The rates and magnitudes of depletion of Earth's marine and terrestrial ice fields are among the most important elements of future climate projections (IPCC/ SROCC, 2019, Meredith et al, 2019). The Arctic provides fundamental ecosystem services (including fisheries management and other resources), sustains numerous indigenous communities, and due to sea-ice loss is emerging as a key area for economic exploitation but the fragile ecosystems are subject to pressures from a growing number of maritime and commercial activities. The potentially devastating contribution of the Antarctic ice sheet to global sea level rise is also subject to large uncertainties in ice mass loss, with high-end estimates of sea-level contribution exceeding a metre of global mean sea-level rise by 2100 (DeConto and Pollard, 2016).

A long-term programme to monitor the Earth's polar ice, ocean and snow topography is important to both operational and scientific communities with interests in the Arctic and Antarctic. Europe has a direct interest in the Arctic due to its proximity. Changes in the Arctic environment affect strategic areas including politics, economics (e.g. exploitation of natural resources including minerals, oil and gas, fish) and security. It also has an indirect interest in the Antarctic due to the Antarctic Treaty, which permits international access in support of science. Besides economic impacts of Antarctic and Arctic changes (Whiteman et al, 2013), Europe's interest in both Polar Regions is due to their influence on patterns and variability in global climate change, thermohaline circulation and the planetary energy balance. Last but not least, changes in the Arctic system have potential impacts on European weather, with consequences for extreme events (Francis et al., 2017). The Copernicus polaR Ice and Snow Topography Altimeter (CRISTAL) mission, described in this paper, addresses the data and information requirements of these user communities.

In the following section, we provide an overview of satellite missions and developments that are being prepared by the European Space Agency (ESA) in partnership with the European Union (EU) in response to user needs expressed by the Copernicus user community. In Section 3, we describe the objectives of the CRISTAL mission and its relation to the Copernicus services. In Section 4, an overview of CRISTAL's technical systems is described highlighting the use of heritage technology and needs driving technical advancements to improve observational capabilities beyond current missions. We then discuss the key contributions from the CRISTAL mission, both in terms of specific mission objectives as well as expected scientific contributions towards improved knowledge of various state variables in Section 5. Conclusions and a current mission status statement is provided in Section 6.

2 Copernicus evolution

Copernicus was established to fulfil the growing need amongst European policy-makers to access accurate and timely information services to better manage the environment, understand and mitigate the effects of climate change and ensure civil security. To ensure the operational provision of Earth-observation data, the Copernicus Space Component (CSC) includes a series of seven space missions called 'Copernicus Sentinels', which are being developed by ESA specifically for GMES/Copernicus. Some of these missions have already entered their operational life, some are being commissioned, and the remaining ones are targeted for launch in the coming years.

The Copernicus programme is coordinated and managed by the European Commission (EC). It includes Earth observation satellites, ground-based measurements, and services to process data to provide users with reliable and up-to-date information through a set of Copernicus Services related to environmental and security issues. Services provide critical information to support a wide range of applications, including environmental protection, management of urban areas, regional and local planning, agriculture, forestry, fisheries, health, transport, tourism, climate change, sustainable development, emergency management response to disasters, risk management and civil protection.

The intense use and increased awareness for the potential of Copernicus have generated high expectations for an evolved Copernicus system. There is now a large set of defined needs and requirements for the future. With respect to the Polar Regions, user and observation requirements have been identified, structured and prioritised in a process led by the EC (Duchossois et al.,2018a; 2018b). Two distinct sets of expectations have emerged from this user consultation process. Firstly, stability and continuity, while increasing the quantity and quality of Copernicus products and services, led to one set of requirements. They are distinctly addressed in the considerations for the next generation of the current Sentinels 1 to 6 series. Emerging and urgent needs for new types of observations constitute a second distinct set of requirements. They are mainly addressed in the considerations for the timely Evolution of the Copernicus space segment service. This evolution corresponds to the enlargement of the present space-based measurement capabilities through the introduction of new missions to answer these emerging and urgent user requirements.

These new types of observations are addressed by six new potential Copernicus missions, so-called High Priority Candidate Missions (HPCMs), see e.g. ESA (2019b) for a more detailed overview:

- Anthropogenic CO_2 Monitoring (CO2M) mission
- High Spatio-Temporal Resolution Land Surface Temperature Monitoring (LSTM) mission
- Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) mission
- Copernicus Imaging Microwave Radiometer (CIMR) mission
- Copernicus Hyperspectral Imaging Mission for the Environment (CHIME)

- Radar Observing System for Europe, L-Band (ROSE-L) mission

The so-called Long-Term Scenario, is a multi-annual implementation plan describing the main elements of this architecture, which has been generated through close consultation with the EC and EUMETSAT (see, ESA 2019). In order to identify synergies, complementarities and the evolution paths for the missions in response to EC requirements, an integrated end-to-end system approach is adopted and four observational capability families are defined: Microwave Imaging Family, Optical Imaging Family, Topographic Ocean and Ice Measurement Family and Spectroscopic Atmosphere Measurement Family. It is emphasised that CRISTAL is an essential part of the Topographic Ocean and Ice Measurement Family, and the evolution in Copernicus capabilities to address polar user needs.

3 CRISTAL mission objectives and contributions to Copernicus services

"An integrated European Union policy for the Arctic" (https://ec.europa.eu/environment/efe/news/integrated-eu-policy-arctic-2016-12-08_en) emphasises the strategic, environmental and socio-economic importance of the Arctic region, including the Arctic Ocean and adjacent seas. Continuously monitoring the vast and inhospitable Arctic environment with satellites (considering the sparse population and the lack of transport links) is considered essential. Following this, several guiding documents have been prepared in a European Commission-led user consultation process: Polar Expert Group (PEG) User Requirements for a Copernicus Polar Mission Phase-I report (12th June 2017), Duchossois et al. (2018a), hereafter referred to as PEG-1 report, and the Phase 2 report on Users' requirements (31st July 2017), Duchossois et al. (2018b), hereafter referred to as PEG-2 report.

The PEG-1 report has summarised and prioritised the required geophysical parameters addressing objectives as defined in the EU Artic Policy Communication, namely: climate change, environmental safeguarding, sustainable development, support to indigenous populations and local communities (see PEG-1 report). Floating ice parameters were listed as the top priority for the polar mission user requirements by a collective of polar experts. These parameters were selected considering the availability of existing Copernicus products and services of direct relevance to the Artic as well as their needs for improvement (e.g. in terms of spatial resolution, accuracy, etc) and the current level of technical and/or scientific maturity for some candidate parameters. The specific 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 by the European Commission due to their key position in operational services such as navigation and marine operations, and in meteorological and seasonal prediction and climate model validation.

Earlier, 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). 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 that 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 to as variables for future improvement.

While Copernicus Sentinel-3A and B missions provide partial altimetric measurements of the polar oceans, their inclination limits the coverage of the Arctic Ocean to only 81.5°N. With the expected on-going loss of Arctic sea ice, these satellites will monitor only a small amount of the Arctic ice cover during summer periods by mid-2020, see e.g. Quartly et al (2019). Currently, CryoSat-2 (originally a three year experiment as an ESA Earth Explorer mission, e.g. Drinkwater et al., 2004; Wingham et al., 2006, Parrinello et al. 2018) is the only European satellite to provide monitoring of the oldest, thickest multiyear ice based on mission extension and availability following October 2013 end of nominal mission. However, continual monitoring of the Arctic Ocean north of 81.5°N is at risk, since CryoSat-2 has been operating in its extended mission scenario since October 2013, see Figure 1.

This risk has widely been recognised by the polar and ocean surface topography community at large. For example, at the recent OSTST 2019 meeting (held in Chicago, IL, US on 21-25 October 2019) a recommendation was recorded in view of the preparations for CRISTAL and other missions currently in operation: “To minimise likelihood of a gap in polar ocean and ice monitoring, the OSTST encourages Agencies to strive to launch CRISTAL in the early 2020s and to maintain operation of CryoSat-2, ICESat-2, and SARAL/AltiKa as long as possible.”

Based on the user requirements and priorities outlined in the PEG-1 report, a set of high-priority mission parameters was defined by ESA’s CRISTAL Mission Advisory Group (MAG) and ESA, which led to the CRISTAL mission objectives. The primary objectives of the mission are:

- To measure and monitor variability of Arctic and Southern Ocean sea-ice thickness and its snow depth. Seasonal sea ice cycles are important for both human activities and biological habitats. The seasonal to inter-annual variability of sea ice is a sensitive climate indicator; it is also essential for long term planning of any kind of activity in the Polar Regions. Knowledge of snow depth will lead to improved accuracy in measurements of sea-ice thickness and is also a valuable input for coupled atmosphere-ice-ocean forecast models. On shorter timescales, measurements of sea-ice thickness and information about Arctic Ocean sea state are essential support to maritime operations over polar oceans.
- To measure and monitor the surface elevation and changes therein of polar glaciers, ice caps and the Antarctic and Greenland ice sheets. The two ice sheets of Antarctica and Greenland store a significant proportion of global fresh water volume and are important for climate change and contributions to sea level. Monitoring grounding line migration and elevation changes of floating and grounded ice sheet margins is important to identify and track

emerging instabilities, which can negatively impact the stability of the ice sheets, leading to ice mass loss and ultimately result in accelerated future sea-level rise.

Secondary objectives of the CRISTAL mission include:

- To contribute to the observation of global ocean topography as a continuum up to the polar seas. This will contribute to the observation system for global observation of mean sea level, mesoscale and sub-mesoscale currents, wind speed and significant wave height. Information from this mission serves as critical input to operational oceanography and marine forecasting services in the polar oceans.
- To support applications related to coastal and inland waters. Observation of water level at Arctic coasts as well as of rivers and lakes is a key quantity in hydrological research. Rivers and lakes not only supply freshwater for human use including agriculture but also maintain natural processes and ecosystems. The monitoring of global river discharge and its long-term trend contributes to the evaluation of global freshwater flux, which is critical for understanding the mechanism of global climate change. The frozen rivers and lakes are important circulation routes in the Arctic regions, which encountered dramatic changes in the context of global warming. Their observation could help forecasting their evolutions and organizing alternative modes of transport.
- To support applications related to snow cover and permafrost in Arctic regions. Snowmelt timing is a key parameter for hydrological research, since it modulates the river discharge of Arctic basins, see e.g. Shiklomanov et al (2007). Surface state change in permafrost regions indicates the initiation of ground thaw and soil microbial activities in the seasonally unfrozen upper soil (active) layer. The rapid evolution of the permafrost has also important impacts on human activities and infrastructures.

The primary objectives drive the design and main performance specifications of the CRISTAL mission.

By addressing these objectives, the mission responds to a number of requisite parameters of interests and applications in Copernicus Services. A mapping of the services to the parameters of interest and applications is listed in Table 1.

Table 1 Copernicus Services addressed by CRISTAL.

Copernicus Service	**Relevant Parameters of Interest**	**Core information service addressed or affected (forecasting, monitoring or projections)**
Copernicus Marine Environmental Monitoring Service (CMEMS)	• Sea-ice thickness and snow depth • Sea-level anomaly and geostrophic ocean currents in polar oceans • Significant wave height in polar oceans • Global sea level • Global sea surface wind and waves	Maritime safety, Coastal and Marine Environment, Marine Resources and Weather, Seasonal Forecasting and Climate activities

Copernicus Climate Change Service (C3S)	• Ice-sheet topography • Sea-ice thickness and volumes • Global sea level • Snow depth over sea ice	Observations, Climate reanalysis, seasonal forecasts and climate projections
Copernicus Land Monitoring Service (CLMS)	• Ice-sheet and glacier topography	Biophysical monitoring, Land cover & land use mapping, Thematic hotspot mapping, Reference data, Ground motion service
Copernicus Atmospheric Monitoring Service (CAMS)	• Snow depth on sea ice	Meteorology and climatology seasonal forecasts and climate projections
Copernicus Emergency Management Service (CEMS)	• Lakes and rivers level/stage	Flood awareness forecast, Emergency Management System Mapping

4 System concept

The primary topography payload envisaged for this mission comprises an Interferometric Radar altimeter for Ice and Snow (IRIS) and a microwave radiometer (MWR). The mission draws from the experience of several in-orbit missions in addition to the ongoing developments within the Sentinel-6 and MetOp-SG programmes. CRISTAL's primary payload complement consist of:

- A **synthetic aperture radar (SAR) altimeter operating at Ku-band and Ka-band** centre frequencies for global elevation and topographic retrievals over land and marine ice, ocean and terrestrial surfaces (see Figure 2 and Figure 3). In Ku-band (13.5 GHz), the SAR altimeter can also be operated in interferometric (SARIn) mode to determine across-track echo location. Compared to heritage missions, the Ka-band channel (35.75 GHz) is added for snow depth measurements to distinguish between surface snow and ice layers, see e.g. Guerreiro et al (2016). A range (vertical) resolution of about 31 cm will be achieved to enhance freeboard measurement accuracy. Also, a high along-track resolution of about 20 m is envisaged to improve ice floe discrimination. Heritage missions include CryoSat-2 (SIRAL), Sentinel-6 (Poseidon-4) and SARAL (AltiKa). The CRISTAL Altimeter (IRIS) is based on Poseidon-4 (Sentinel-6) and SIRAL (CryoSat-2) together with the addition of a Ka-band channel (analogous to AltiKa) and a bandwidth of 500MHz to meet the improved range resolution requirement in comparison to heritage altimeters. It has the capability for fully focused SAR processing for enhanced along track resolution by means of resolving full scatterer phase history. Digital processing will be implemented including matched filter range compression and on-board Rang Cell Migration (RCM) compensation by means of a Range Migration Compensation (RMC) mode for on-board data reduction (heritage from Poseidon-4) reducing downlink load. With respect to the dual frequency

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antenna (Ku- and Ka-band), an enhanced antenna mounting baseplate for improved baseline stability over CryoSat-2 will be required (20 arcsec vs ~30 arcsec for CryoSat-2).

- A high-resolution **passive microwave radiometer** is included with the capability to provide data allowing global ocean retrievals of Total Column Water Vapour up to 10 km from the coast (by means of improving the measurement system with high frequency channels and with potential cryosphere applications as sea ice type classifications. Concerning the Microwave Instrument selection, potential options include: a potential US Custom Furnished Item (CFI) based on the NASA-JPL AMR-C (Advanced Microwave Radiometer – Climate quality); development of an EU High Resolution radiometer solution; or a two-channel solution derived from the Sentinel-3 microwave radiometer (MWR). The feasibility of each of these options will be further evaluated in the next mission phase (Phase B2 at the time of the system Preliminary Design Review, expected late 2021).
- A **Global Navigation Satellite System (GNSS) receiver** compatible with both Galileo and GPS constellations providing on-board timing, navigation and provision of data for on-ground precise orbit determination. Heritage GNSS solutions exist such as those based upon the GPS and Galileo compatible Sentinel-1,-2,-3 C/D, Sentinel-6 A/B receivers. Precise Orbit Determination (POD) products will be provided by the Copernicus POD service (CPOD).
- A **Laser Retro-reflector Array** (LRA) for use by the Satellite Laser Ranging (SLR) network and by the International Laser Ranging Service for short arc validation of the orbit. Heritage concepts suitable for CRISTAL include CryoSat-2/Sentinel-3 LRAs.

Three modes of radar operation are envisaged, which are automatically selected depending on the geographic location over the Earth's surface (see Table 2 and Figure 3), prioritising the retrieval of relevant geophysical parameters of interest:

- **Sea-ice and iceberg (SII) mode**: In Figure 3, the proposed coverage is shown in orange. It is proposed that this mode makes a step forward in ice-thickness retrieval by operating the instrument with the SAR interferometer configuration in Ku-band, i.e. a two-antenna cross-track interferometric principle. The measurement mode will be in an open burst, or interleaved arrangement, in which receptions occur after each transmitted pulse. The disadvantages of the open burst transmission versus a closed burst operation mode include a larger data volume and the power demand and variations of the PRF (Pulse Repetition Frequency) around the orbit. The interferometric operation allows the location of across-track sea-ice leads, whilst open-burst timing allows full scatterer phase history re-construction for fully focussed processing (Egido and Smith, 2017) to improve sea-ice lead discrimination (by means of improvement in sampling and resolution), and hence retrievals of elevation, and thus polar Sea Level Anomalies (SLA) by a significant factor. Open-burst Ka-band SAR is also provided to also allow for improving retrieval of snow depth.
- **Land-ice and Glacier (LIG) mode**: In Figure 3, the proposed coverage is shown in magenta. Ice sheet and cap elevation is retrieved by means of improved surface tracking based on the large range window. Retrievals are likely improved by a factor 2 by means of increasing the number of echoes per unit time by a factor 4 over the CryoSat-2 heritage design. The Ku-band SAR interferometer is used to retrieve the across-track point of closest approach

(POCA) supplemented with Ka-band SAR. Closed-burst operation (see e.g. Raney 1998) is used over this surface type, in which the reflections arriving back at the radar are received after each transmitted burst has finished.

- **Open and coastal ocean mode (OCO) mode**: In Figure 3, the proposed coverage shown in magenta provides Arctic and southern polar ocean retrieval of SLA and precision SAR altimetry to complement other ocean topography missions including Sentinel-3, Sentinel-6 and next generation topographic missions. In the case of open ocean, closed-burst SAR operation at Ku-band and Ka-band is used and the Range Migration Correction (RMC) on-board processing is applied, first implemented in the frame of Sentinel-6, which provides a considerable gain in instrument data rate reduction. In addition, data will be collected over inland water regions on a best effort basis using one of the above modes.

Table 2 Key altimeter characteristics in the different modes of operation (Credits: Thales Alenia Space, France).

	Open Ocean (OCO)	**Sea Ice and Icebergs (SII)**		**Land Ice & Glaciers (LIG)**		
		Sea ice	Icebergs	Ice sheet interior (Ice sheet/ Ice caps)	Ice margin	Glaciers
σ_0 range in Ku-band	6 dB to 25 dB	0 dB to 55 dB		0 dB to +40 dB	-10 dB to +40 dB	-10 dB to +40 dB
σ_0 range in Ka-band	+8 dB to +27 dB	+2 dB to +57 dB		2 dB to +42 dB	-8 dB to +42 dB	-8 dB to +42 dB
Measurement mode in Ku-band	SAR Closed Burst	SARIn Interleaved		SARIn Closed burst		
Measurement mode in Ka-band	SAR Closed Burst	SAR Interleaved		SAR Closed burst		
Range window size	256 points	256 points	256 points	1024 points	1024 points	1024 points
Tracking window size	256 points	256 points	256 points	2048 points	N/A	N/A
Range window size	64 m	64 m	64 m	256 m	256 m	256 m
Tracking window size	64 m	64 m	64 m	512 m	N/A	N/A
Tracking mode	Closed loop	Closed loop	Closed loop	Closed loop	Open loop	Open loop
On-board processing	RMC	RMC	N/A	N/A	N/A	N/A
Optional On-board processing	Yes	N/A	N/A	N/A	N/A	N/A

CRISTAL follows the requirements expressed in the PEG-1 and PEG-2 reports and provides products with different latency requirements for each of the respective application areas. The data latency requirements shown in Table 3 indicate the time interval from data acquisition by the instrument to delivery as Level 1B data product to the user.

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Table 3 CRISTAL product latency requirements for different application areas, following from PEG-1 report requirements in Duchossois et al. (2018a). In most cases, these requirements are conservative figures to what can already be achieved with currently flying missions and further improvements could be envisaged.

Applications/ Geophysical Products	Timeliness requirements
Sea ice freeboard	6 hours
Sea ice thickness	24 hours
Snow depth on sea ice	24 hours
Surface elevation	30 days
Iceberg detection products	24 hours
Ocean L2 products	3 hours, 48 hours and 30 days
Ocean L1 products	48 hours and 30 days

5 CRISTAL's key contributions

5.1 Sea ice freeboard and thickness

Sea ice plays a critical role in Earth's climate system since it provides a barrier between the ocean and atmosphere, restricting the transfer of heat between the two. Due to its high albedo, the presence of sea ice reduces the amount of solar energy absorbed by the ocean. Sea ice rejects brine during formation and fresh water during melting and it is therefore a driving force of the global thermohaline circulation as well as the stratification of the upper layer of the ocean. The sea-ice provides a critical habitat for marine mammals and for biological activity (see e.g. Tynan et al (2009)), and its presence limits human access and maritime activities in the ice-infested polar oceans.

The sea-ice cover of the Arctic Ocean is waning rapidly, and in the Southern Ocean sea ice is undergoing regional changes, with a decline observed in the Amundsen and Bellingshausen Seas. By 2017, the decline in September Arctic sea ice extent was 13.2% per decade, relative to the 1981–2010 average, and the older, thicker, multi-year ice cover comprised ~ 20 % of the winter ice pack, compared to ~ 45 % in the 1980s (Perovich et al., 2017). These losses are triggering extensive change and are having a profound impact on the climate, environment and ecosystems of both polar regions. Monitoring the polar oceans is therefore of regional and global importance, and the long-term continuity of sea ice measurements is essential to safeguard both climate and operational data services.

As global warming, and its Arctic amplification, continue to contribute to the decrease of multi-year ice in the central Arctic Ocean, (north of 81.5° N), it is critical to obtain continuous, pan-Arctic observations of sea-ice thickness, extending as close

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as possible to the North Pole. Continuous monitoring of Arctic Ocean sea-ice conditions is necessary for safe navigation through ice-infested waters and, when linked to previous measurements from CryoSat-2, the CRISTAL mission will deliver observations that will provide a long-term record of sea-ice thickness variability and trends, which are critical to support climate services. Since sea ice thickness is an essential climate variable (ECV) (see GCOS, 2011), its continuous measurement is required to understand the Arctic system and how ice loss is impacting climate at a global scale.

Shipping in ice-covered Arctic waters has increased significantly in recent years and is expected to increase in coming years. In addition to traditional maritime operations and fishing in the high Arctic, several polar-class cruise liners are under construction. This means an increase in the need and scope of operational ice information services. A primary data source for national ice services is currently synthetic aperture radar (SAR) imagery, specifically data acquired by Sentinel-1A and 1B, RadarSAT-2 and RADARSAT Constellation Mission. Thus, independent measurements of sea-ice thickness distribution at reasonable latencies provided by CRISTAL will complement existing SAR measurements and benefit operational ice charting. Furthermore, observed sea-ice thickness or freeboard distributions can be assimilated into sea-ice models to generate ice forecasts for the needs of ice navigation and offshore operations.

Historically, satellite observations had primarily been used to monitor ice extent until Laxon et al. (2003) produced the first Arctic-wide sea ice thickness estimates from ERS 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 obtain an estimate of freeboard and thickness, and converting it to volume, has enabled scientists to better understand the changing Arctic ice cover. Most recently, sea-ice freeboard has been estimated from both Ka- and Ku-band measurements (Armitage and Ridout, 2015; Guerreiro et al., 2016; Lawrence et al., 2018).

Sea ice thickness products are currently provided on a 25 km grid (see e.g. Sallila,et al 2019 for an overview of different products currently available), which corresponds to the GCOS user requirements (GCOS, 2011), but do not meet the specified accuracy requirements of 0.1 m. It is estimated that the residual, systematic uncertainty in sea ice thickness is presently 0.6 m for first year ice and 1.2 m for multi-year ice. This uncertainty is caused mainly by the unknown penetration of the radar pulse into the snow layer as a result of variable snow properties (Nandan et al., 2017), as well as the choice of retracker (Ricker et al., 2014).

The requirements for CRISTAL are currently stated to provide sea ice freeboard with an accuracy of 0.03 m along orbit segments of less than or equal to 25 km. Furthermore, the system shall be capable of delivering sea ice thickness measurements with a vertical uncertainty less than 0.1 m. The uncertainty requirement for sea ice thickness comes with a caveat, as the thickness uncertainty depends on the uncertainty of auxiliary products. In the case of CRISTAL, snow thickness will be measured by the system, but snow and ice densities will still have to be estimated by other means. In the light of the current 0.2 m sea ice thickness uncertainty from CryoSat-2 data assessed by Tilling et al. (2018) for a gridded, monthly product and the anticipated improvement from the dual-altimetry technology, especially in the snow depth and propagation estimates, reaching a higher vertical uncertainty would seem reachable but requires further studies. Currently, the retrieval accuracy of sea-ice freeboard is limited by the range resolution of a radar altimeter. The large bandwidth of 500MHz is an important driver for the instrument concept generation, as it will improve the range resolution from 50 cm (as for CryoSat-2) to ~ 30 cm for CRISTAL.

5.2 Snow depth over sea ice

An accurate estimate of snow depth over sea ice is for signal propagation speed correction to convert radar freeboard to sea ice freeboard as well as conversion of freeboard to sea-ice thickness. In addition to uncertainty reduction for ice thickness/freeboard computation, the variation of snow depth is also a parameter highly relevant for both climate modelling, ice navigation and polar ocean research. The snow climatology of Warren et al., (1999) is still the single most used estimate of snow depth in sea-ice thickness processing (Sallila et al., 2019). The uncertainty in the original Warren snow depth estimates are halved over first year ice (Kurtz and Farrell, 2011), but snow still represents still the single most important contribution to uncertainty in the estimation of sea ice thickness and volume (Tilling et al., 2018). The study of Lawrence et al. (2018) and Guerreiro et al (2016) show the possibility of using Ku- and Ka-bands in mitigating the snow depth uncertainty. Dual-frequency methods improve the ability to reduce and estimate the uncertainties related to snow depth and sea-ice thickness retrieval. The modelling community is particularly interested in the uncertainty information, which according to the user requirement study in the PEG-1 report is required alongside the parameters and is critical when designing and setting up assimilation systems. Better abilities to estimate the related uncertainties improves prediction quality assessment of annual snowmelt over Arctic sea ice, the stratigraphy and electromagnetic properties of the snow layer contrast with that of the underlying ice, and this can be exploited to retrieve information on the snow layer properties if contemporaneous measurements are acquired from multiple scattering horizons. A dual-frequency satellite altimeter, as proposed for the CRISTAL mission, will address this need. CRISTAL aims to provide an uncertainty of snow depth retrieval over sea ice of less than or equal to 0.05m. The additional measurements in Ka-band, with a 500MHz bandwidth, support the discrimination between the ice and snow interfaces.

5.3 Ice sheets, glaciers and ice caps

Earth’s land ice responds rapidly to and in turn affects global climate change. For example, melting of glaciers, ice caps, and ice sheets over recent decades has altered local hydrological systems, and has impacted sea levels and patterns of global ocean circulation. The Antarctic and Greenland ice sheets are Earth’s primary freshwater reservoirs and, due to their progressive imbalance, have made an accelerating contribution to global sea level rise during the satellite era. Although ice dynamical models have improved, future losses from the polar ice sheets remain the largest uncertainty in global climate and sea level projections. Due to their scale, remote location, and hostile climatic environment, satellite measurements are the only practical solution for spatially and temporally complete monitoring of the polar ice sheets.

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 ice sheets of Greenland and Antarctica (McMillan et al., 2014, 2016; Shepherd et al., 2012), for identifying emerging signals of mass imbalance (Flament and 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 models 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. The maps are typically delivered in (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 detection of subglacial lake drainage (Siegert et al., 2016) 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 dynamical ice loss.

CRISTAL will continue the generation of elevation measurements provided by altimeters and will produce maps of ice surface elevation with an absolute uncertainty of 2 m, horizontal resolution of less or equal than 100 m and temporal sampling of at least 30 days. CRISTAL will be capable of tracking steep terrain with slopes less than 1.5° using its SARIn mode. High-resolution Swath processing over ice sheets (about 5 km wide) can reveal complex surface elevation changes, related to climate variability and ice dynamics, and subglacial geothermal and magmatic processes. Elevation measurements of regions with smaller glaciers are often missing in CryoSat-2 data. Indeed, tracking algorithms are not efficient when rough terrain is encountered. Improvement in the agility of tracking over glaciers is thus a key element in the instrument concept generation.

5.4 Sea level, coastal and inland water

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 measurements are helping us understanding and monitoring the ocean: its topography, dynamics and variability at different scales. The need of satellite observations to study, understand and monitor the ocean is more than essential over polar areas, where in-situ data networks are very sparse, and where profound and dramatic changes occur. This has also been expressed and emphasised by CMEMS as "Ensuring continuity (with improvements) of the Cryosat-2 mission for sea level monitoring in polar regions" (CMEMS, 2017). 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, see CMEMS (2017).

Actual data from the CMEMS catalogue does not allow a satisfactory sampling north of 81.5°N. It is of prime importance that the CRISTAL orbit configuration allows measurement coverage of the central Arctic Ocean with an omission not exceeding 2° of latitudes around the poles. The Sea Level Anomaly (SLA) over frozen seas can only be provided by measurements in the leads. With its high spatial resolution dual-frequency altimeter system, CRISTAL will contribute to the observation system for global observation of mean sea level, (sub-)mesoscale currents, wind speed and significant wave height as a critical input to operational oceanography and marine forecasting services, as well as supporting ice thickness retrieval in the Arctic.

The high inclination orbit of CRISTAL associated to high -resolution SAR/SARIn bi-band altimetry measurements would extend considerably our monitoring capability over the Polar Oceans. The development of tailored processing algorithms should allow not only to track the low-frequency sea level trend in presence of sea ice but also characterize ocean large scale and mesoscale variations over regions not covered by conventional ocean missions. Beyond the observations of ice elevation variations, CRISTAL would therefore offer the unique opportunity to improve our knowledge on the mutual Ocean-Cryosphere complex interactions over short and long-term time scales over both north and south poles. The Southern Ocean circulation indeed plays a key role in shaping the Antarctic cryosphere environment. First, it regulates sea-ice production: as sea-ice forms and reject brines into the ocean, the ocean destabilizes and warms underwater waters which reaches the ocean surface, hence limiting further ice production. Second, it impacts Antarctic ice sheet melt, when warm and salty ocean currents access the base of floating glaciers through bathymetric troughs of the Antarctic continental shelf. These ocean currents melt the ice shelves from below, and are the main causes of the current decline of floating ice-shelves. This induced melt represents the largest uncertainty in the current prediction of global sea-level change, creating major ambiguity in our way to respond and adapt to future climate. Tightly linked with glacier melt, the polar shelf circulation and its interaction with largescale circulation also control the rate of bottom water production and deep ocean ventilation, which impact the world's oceans on timescale ranging from decades to millennia. Therefore, with a designed operational lifetime of at least 7.5 years (including in-orbit commissioning), the observation from the same sensor of each components of these multi-scale ice-ocean interactions would make CRISTAL unique in its capability to address climate issues of regional and worldwide relevance. Over oceans, which represents a secondary objective for the mission, the satellite will be able to measure sea surface height with an uncertainty of less than 3 cm. The main advantages and drawbacks of the Ka-band over the oceanic surface have been reviewed in Bonnefond et al (2018). Given its high along-track resolution of less than 10 km and high temporal resolution of sea level anomalies of less than 10 days, the mission can further contribute a suite of sea level products including mean dynamic topography and a sea level anomalies vertical uncertainty of less than 2 cm.

Observation of water level at the (Arctic) coast as well as of rivers and lakes is a key quantity in hydrological research, (e.g. Jiang et al 2017). Rivers and lakes not only supply freshwater for human use including agriculture but also maintain natural processes and ecosystems. The monitoring of global river discharge and its long-term trend contributes to the monitoring of global freshwater flux, which is critical for understanding the mechanism of global climate change. Satellite radar altimetry is a promising technology to do this on a regional to global scale. Satellite radar altimetry data has been used successfully to observe water levels in lakes and (large) rivers, and has also been combined with hydrologic/hydrodynamic models. Combined with gravity-based missions like GRACE and GRACE-FO the joint use of the data will give fundamental information for ground water monitoring in the future.

5.5 Snow on land and permafrost

While these are considered a secondary objective for the mission, with its dual-frequency altimeter payload and high-resolution passive microwave radiometer, CRISTAL may support and contribute to studies and services in relation to seasonal snow cover and permafrost applications over land. The ability for the retrieval of snow depth with Ku-/Ka-band altimeter is limited over land (Rott et al. 2018). Snow studies over land area are so far largely limited to scatterometer in case of Ku-band (examples are reviewed e.g. in Bartsch, 2010). Measurements as provided by CRISTAL may, however, be useful in retrieving internal properties of the snowpack. Snow structure anomalies as well as land surface state (freeze/thaw) are expected to be identified by time series analyses as such processes alter penetration depth. Information from altimeter is currently also rarely used for permafrost studies. It can be applied for monitoring lake level as proxy for permafrost change (Zakharova et al. 2017). Surface status is closely interlinked with ground temperature (e.g. Kroisleitner et al. 2018) but usage of altimeter in this context remains unexplored. Wider use of altimetry for snow and permafrost applications does require higher spatial resolution and temporal coverage than available to date. It is therefore expected that CRISTAL will expand the utility of altimeter observations for permafrost and snow monitoring over land.

5.6 Icebergs

Iceberg detection, volume change and drift have been listed as a priority user requirement (Duchossois et al., 2018a; 2018b). Icebergs present a significant hazard to marine operations in those ocean areas where they occur. Detection of icebergs in open water and in sea ice generally places a priority on wider satellite swaths to obtain greater geographic coverage. There is a need for automatic detection of icebergs for the safety of the navigation and chart production. Iceberg concentration is given in CMEMS' catalogue at 10 km resolution covering Greenland waters. SAR imagery is the core input for icebergs detection. However, iceberg detection (in particular small icebergs) is also possible using high-resolution altimeter waveforms. Tournadre et al. (2018) demonstrated detection of icebergs from CryoSat-2 altimeter data using several modes, and mention promising results with the Sentinel-3 data, 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, by providing the iceberg freeboard elevation from the ocean surface. Iceberg volume has been calculated with altimetry with Envisat, Jason-1 and Jason-2, see for example by Tournadre et al. (2015).
CryoSat-2 tracking over icebergs is operational but icebergs with high freeboards may be missed in the current range window. The range window definition for CRISTAL is defined in order to ensure that echoes from icebergs are correctly acquired. In-flight performances for the measurement of the Angle of Arrival from CryoSat-2 are around 25 arcsec. An equivalent performance is necessary to retrieve across-track slopes and elevations. The CRISTAL design of the instrument and the calibration strategy will be design to comply with the specification of 20 arcsec.

CRISTAL will provide the unprecedented capability to detect icebergs at a horizontal resolution (gridded product) of at least 25 m. The products will be produced every 24 hours in synergy with other high-resolution data such as SAR imagery. Iceberg distribution and volume products will be produced at 50 km resolution (gridded) on a monthly basis.

6 Conclusions and status

CRISTAL directly addresses the EU Arctic Policy and primary user requirements collected by the European Commission and provides sustained, long-term monitoring of sea ice thickness and land ice elevations. It thereby responds to needs for continuous pan-Arctic altimetric monitoring including the region of the Arctic Ocean north of 81.5°N. The mission serves a number of key Copernicus operational services in particular the Climate Change service, Marine Environmental Monitoring Service and makes contributions to the Land Monitoring Service, Atmospheric Monitoring Service and Emergency Management Service.
CRISTAL will cover the Polar Regions not observed by other altimetry mission, including a Ku-band Interferometric Synthetic Aperture Radar Altimeter with supporting Ka-band channel. In addition, the payload contains a high and low frequency passive microwave radiometer to perform wet troposphere delay correction, and surface-type classification over sea ice and ice sheets. The mission is designed for a 7.5 years design lifetime and will fly in an optimized orbit covering Polar Regions (omission <= 2°; sub-cycle < 10 days). A key element is the high along-track resolution to distinguish open ocean from sea-ice surfaces and a track spacing of 5 km at 50° latitude and less for higher latitudes. Thanks to the dual-frequency SAR altimetry capability, a snow depth product will be produced over sea ice with high accuracy in response to long-standing user needs.

CRISTAL has undergone and completed parallel preparatory (Phase A/B1) system studies in which mission and system requirements have been investigated and consolidated. The intermediate system requirements review has been completed with parallel industrial consortia compliant with the mission and system requirements. Next steps include the full definition, implementation and in-orbit commissioning of CRISTAL (Phases B2, C/D and E1) where a prototype and recurrent satellite will be developed.

Author contributions. M. Kern, as ESA Mission Scientist is responsible for the mission requirements for the CRISTAL mission and was responsible for the overall conceptualisation and structure of the paper. He drafted the manuscript and completed revisions based on co-author contributions and review. R. Cullen led the CRISTAL technical activities and contributed to the system concept description in section 5. B. Berruti, J. Bouffard, T. Casal, M.R. Drinkwater, A. Gabriele, A. Lecuyot, M. Ludwig, R. Midhassel, I. Navas Traver, T. Parrinello, G. Ressler were involved in the supporting scientific and campaign activities or in the technical activities with industry. They contributed in particular to sections 5 and 6 of this manuscript and to the overall pre-publication critical review of the work. E. Andersson and C. Martin-Puig described and provided input and critical review of the Sections 1 and 2, which pertain mostly to the European Commission and EUMETSAT's involvement in the mission preparation and setup. O. Andersen, A. Bartsch, S. Farrell, S. Fleury, S. Gascoin, A. Guillot, A. Humbert, E. Rinne, A. Shepherd, M. R. van den Broeke, and J. Yackel were members of ESA's Mission Advisory Group in Phase A/B1 and provided input and critical review and assistance with the manuscript.

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Appendix A: List of acronyms

AltiKa	Altimeter Ka-band
AMR-C	Advanced Microwave Radiometer-Climate Quality
C3S	Copernicus Climate Change Service
Cal/Val	Calibration and Validation
CAMS	Copernicus Atmospheric Monitoring Service
CEMS	Copernicus Emergency Management Service
CFI	Custom Furnished Item
CGLS	Copernicus Global Land Service
CIMR	Copernicus Polar Passive Microwave Imaging Mission
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter
CMEMS	Copernicus Marine Environmental Monitoring Service
COP21	United Nations Framework Convention on Climate Change, 21st Conference of the Parties
CSC	Copernicus Space Component
dB	Decibel
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
EU	European Union
EUMETSAT	EUropean Organisation for the Exploitation of METeorological SATellites
FMI	Finnish Meteorological Institute
GCOS	Global Climate Observing System
GMES	Global Monitoring for Environment and Security
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HPCM	Copernicus High Priority Candidate Mission
HPOC	High Precision Ocean Constellation
IPCC	Intergovernmental Panel on Climate Change
IRIS	Interferometric Radar altimeter for Ice and Snow
JPL	Jet Propulsion Laboratory
LIG	Land ice and glacier
LRA	Laser Retro-reflector Array
LST	Land Surface Temperature
MetOp-SG	Meteorological Operational Satellite - Second Generation

MRD	Mission Requirements Document
MWR	Microwave Radiometer
NASA	National Aeronautics and Space Administration
NIR	Near InfraRed
NRT	Near-Real Time
NTC	Non-Time Critical
OCO	Open and coastal ocean
OSTST2019	Ocean Surface Topography Science Team Meeting 2019
PEG	Polar Expert Group
POD	Precise Orbit Determination
PRF	Pulse Repetition Frequency
RADAR	Radio Detection and Ranging
RCM	Rang Cell Migration
RFP	Request for Proposals
RMC	Range Migration Compensation
SAR	Synthetic Aperture Radar
SARIn	Interferometric SAR
SARAL	Satellite with ARgos and ALtiKa
SII	Sea-ice and iceberg
SLA	Sea Level Anomaly
SLR	Satellite Laser Ranging
SRL	Scientific Readiness Level
SSH	Sea Surface Height
SST	Sea Surface Temperature
STC	Short Time Critical
TIR	Thermal infrared
UNFCCC	United Nations Framework Convention on Climate Change
VIS	Visible

References

Bartsch, A.: Ten Years of SeaWinds on QuikSCAT for Snow Applications. Remote Sens. 2, 1142-1156, 2010.

Bonnefond, P.; Verron, J.; Aublanc, J.; Babu, K.N.; Bergé-Nguyen, M.; Cancet, M.; Chaudhary, A.; Crétaux, J.-F.; Frappart, F.; Haines, B.J.; Laurain, O.; Ollivier, A.; Poisson, J.-C.; Prandi, P.; Sharma, R.; Thibaut, P.; and Watson, C.: The Benefits of the Ka-Band as Evidenced from the SARAL/AltiKa Altimetric Mission: Quality Assessment and Unique Characteristics of AltiKa Data. Remote Sens., 10(1), 83, 2018. https://doi.org/10.3390/rs10010083

Budyko, M.I.: The effect of solar radiation variations on the climate of the Earth, Tellus, 21, 5, 611-619, 1969. DOI: 10.3402/tellusa.v21i5.10109

Chen, J. L., Wilson, C. R., and Tapley, B. D.: Contribution of ice sheet and mountain glacier melt to recent sea level rise. Nature Geoscience, 6, 7, 549-552, 2013. https://www.nature.com/articles/ngeo1829.

CMEMS. Copernicus Marine Environmental Monitoring Service. http://marine.copernicus.eu.

CMEMS-1. Copernicus Marine Environmental Monitoring System (CMEMS) requirements for the Evolution of the Copernicus Satellite Component, 21th February 2017. http://marine.copernicus.eu/wp-content/uploads/2019/01/CMEMS-requirements-satellites.pdf

United Nations Framework Convention on Climate Change, 21st Conference of the Parties (2014). http://www.cop21paris.org/

Copernicus Land Monitoring Service (CLMS [http://land.copernicus.eu]).

Copernicus Atmospheric Monitoring Service (CAMS [https://atmosphere.copernicus.eu]).

Copernicus Emergency Management Service (CEMS) ([http://emergency.copernicus.eu]).

Copernicus Climate Change Service (C3S) ([http://climate.copernicus.eu]).

ESA (2019). Long-term Scenario. https://www.copernicus.eu/sites/default/files/2019-01/Copernicus_Work_Programme_2019.pdf

ESA (2019b). Copernicus High Priority Candidates. Mission Requirements Documents for the sixe candidate missions. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Copernicus_High_Priority_Candidates

DeConto, R. M., and Pollard, D.: Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), 591, 2016.

Drinkwater, M., Francis, R., Ratier, G., and Wingham, D.; The European Space Agency's Earth Explorer Mission CryoSat: Measuring variability in the cryosphere. Annals of Glaciology, 39, 313-320. doi:10.3189/172756404781814663, 2004.

Duchossois G., Strobl, P., Toumazou ,V., Antunes, S., Bartsch, A., Diehl, T., Dinessen, F., Eriksson, P., Garric, G., Houssais, M-N., Jindrova, M., Muñoz-Sabater J., Nagler T., Nordbeck, O., User Requirements for a Copernicus Polar Mission - Phase 1 Report, EUR 29144 EN, Publications Office of the European Union, Luxembourg. ISBN 978-92-79-80961-3,doi:10.2760/22832,JRC111067, 2018a. https://ec.europa.eu/jrc/en/publication/user-requirements-copernicus-polar-mission-0.

Duchossois, G., Strobl P., Toumazou V., Antunes, S., Bartsch, A., Diehl, T., Dinessen, F., Eriksson, P., Garric, G., Holmlund, K., Houssais, M.-N., Jindrova, M., Kern, M., Muñoz-Sabater, J., Nagler, T., Nordbeck, O., de Witte, E.: User Requirements for a Copernicus Polar Mission - Phase 2 Report EUR 29144 EN, Publications Office of the European Union, Luxembourg.

ISBN 978-92-79-80960-6, doi:10.2760/44170, JRC111068, 2018b. https://ec.europa.eu/jrc/en/publication/user-requirements-copernicus-polar-mission.

Egido, A. & Smith, W. H. F., 2017. Fully Focused SAR Altimetry: Theory and Applications. IEEE Transactions on Geoscience and Remote Sensing, vol. 55, Issue 1, January, pp. 392-406.

Flament, T., and Rémy, F. (2012). Dynamic thinning of Antarctic glaciers from along-track repeat radar altimetry. Journal of Glaciology, 58(211), 830–840. https://doi.org/10.3189/2012JoG11J118.

Francis, J. A., Vavrus, S. J., and Cohen, J.: Amplified Arctic warming and mid-latitude weather: new perspectives on emerging connections. Wiley Interdisciplinary Reviews: Climate Change, e474. 2017. https://doi.org/10.1002/wcc.474

GCOS: Systematic observation requirements for satellite-based products for climate 2011 update: Supplemental details to the satellite-based component of the "Implementation plan for the global observing system for climate in support of the UNFCCC (2010 update). GCOS Rep. 154, 2011. https://library.wmo.int/index.php?lvl=notice_displayandid=12907#.XduguuhKj-g

Giles, K. A., Laxon, S. W., and Ridout, A. L.: Circumpolar thinning of Arctic sea ice following the 2007 record ice extent minimum, Geophys. Res. Lett., 35, L22502, https://doi.org/10.1029/2008GL035710, 2008.

Gourmelen, N., Escorihuela, M. J., Shepherd, A., Foresta, L., Muir, A., Garcia-Mondejar, A., Roca, M., Baker, S. G., Drinkwater, M. R. (2017). CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change. Advances in Space Research, doi: 10.1016/j.asr.2017.11.014.

Guerreiro, K., Fleury, S., Zakharova, E., Rémy, F., Kouraev, A.: Potential for estimation of snow depth on Arctic sea ice from CryoSat-2 and SARAL/AltiKa missions. Remote Sensing of Environment. 186. 339-349. 10.1016/j.rse.2016.07.013, 2016.

Hendricks, S., Ricker, R., and Helm, V.: User Guide –AWI CryoSat-2 Sea Ice Thickness Data Product (v1.2), https://doi.org/10013/epic.48201, 2016.

Hurkmans, R. T. W. L., Bamber, J. L., Davis, C. H., Joughin, I. R., Khvorostovsky, K. S., Smith, B. S., and Schoen, N.. Time-evolving mass loss of the Greenland ice sheet from satellite altimetry. The Cryosphere, 8, 1725–1740. https://doi.org/10.5194/tcd-8-1057-2014, 2014.

IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (eds.)]. In press.

Jiang, L., Schneider, R., Andersen, O. B., and Bauer-Gottwein, P. : CryoSat-2 Altimetry Applications overRivers and Lakes. Water, 9(3), [211], 2017. DOI: 10.3390/w9030211.

Konrad, H., Gilbert, L., Cornford, S. L., Payne, A., Hogg, A., Muir, A., and Shepherd, A: Uneven onset and pace of ice-dynamical imbalance in the Amundsen Sea Embayment, West Antarctica. Geophysical Research Letters, 44(2), 910–918, 2017. https://doi.org/10.1002/2016GL070733

Kurtz, N. T., Galin, N., and Studinger, M.: An improved CryoSat-2 sea ice freeboard retrieval algorithm through the use of waveform fitting, The Cryosphere, 8, 1217–1237, https://doi.org/10.5194/tc-8-1217-2014, 2014.

Kroisleitner, C., Bartsch, A., and Bergstedt, H.: Circumpolar patterns of potential mean annual ground temperature based on surface state obtained from microwave satellite data, The Cryosphere, 12, 2349–2370, https://doi.org/10.5194/tc-12-2349-2018, 2018.

Lawrence, I. R., Tsamados, M. C., Stroeve, J. C., Armitage, T. W. K., and Ridout, A. L.: Estimating snow depth over Arctic sea ice from calibrated dual-frequency radar freeboards, The Cryosphere, 12, 3551-3564, https://doi.org/10.5194/tc-12-3551-2018, 2018.

Laxon S W, Peacock N, Smith D.: High interannual variability of sea ice thickness in the Arctic region. Nature, 425, 6961, 947–950, 2003.

Laxon S. W., Giles, K. A., Ridout, A. L., Wingham, D. J., Willatt, R., Cullen, R., Kwok, R., Schweiger, A., Zhang, J., Haas, C., Hendricks, S., Krishfield, R., Kurtz, N., Farrell, S., and Davidson, M.: CryoSat-2 estimates of Arctic sea ice thickness and volume, Geophys. Res. Lett., 40, 732–737, https://doi.org/10.1002/grl.50193, 2013.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019: Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

McMillan, M., Shepherd, A., Sundal, A., Briggs, K., Muir, A., Ridout, A., Hogg, A. Wingham, D.: Increased ice losses from Antarctica detected by CryoSat-2. Geophysical Research Letters, 41, 11, 1–7. https://doi.org/10.1002/2014GL060111, 2014.

McMillan, M., Leeson, A., Shepherd, A., Briggs, K., Armitage, T. W. K. T. W. K., Hogg, A., Munneke, P.K., van den Broeke, M., Noel, B., van den Berg, W. J., Ligtenberg, S., Horwarth, M., Groh, A. Muir, A., Gilbert, L.: A high-resolution record of Greenland mass balance. Geophysical Research Letters, 43, 13, 7002–7010. https://doi.org/10.1002/2016GL069666, 2016.

Nanda, V., Geldsetzer, T., Yackel, J., Mahmud, M., Scharien, R., Howell, S., King, J., Ricker, R., and Else, B.: Effect of snow salinity on CryoSat-2 Arctic first-year sea ice freeboard measurements. Geophysical Research Letters, 44, 10419-10426, https://doi.org/10.1002/2017GL074506, 2017.

Ocean Surface Topography Science Team Meeting (OSTST): https://cpaess.ucar.edu/meetings/2019/ocean-surface-topography-science-team-meeting-ostst, 2019.

Parrinello, T., Shepherd, A., Bouffard, J., Badessi, S., Casal, T., Davidson, M., et al. (2018). CryoSat: ESA's ice mission – Eight years in space. Adv. Space Res. 62, 1178–1190. doi: 10.1016/j.asr.2018.04.014

Perovich, D., W. Meier, M. Tschudi, S. Farrell, S. Gerland, S. Hendricks, T. Krumpen and C. Haas: Sea ice cover [in "State of the Climate in 2016"], Bull. Amer. Meteor. Soc., 98, 8, S131–S133, 2017.

Price, D., Beckers, J., Ricker, R., Kurtz, N., Rack, W., Haas, C., Helm, V., Hendricks, S. Leonard, G., and Langhorne, P. J.: Evaluation of CryoSat-2 derived sea-ice freeboard over fast ice in McMurdo Sound, Antarctica, J. Glaciol., 61, 285–300, https://doi.org/10.3189/2015JoG14J157, 2015.

Sallila, H., Farrell, S. L., McCurry, J., and Rinne, E.: Assessment of contemporary satellite sea ice thickness products for Arctic sea ice, The Cryosphere, 13, 1187-1213, https://doi.org/10.5194/tc-13-1187-2019, 2019.

Screen, J. A. and Simmonds, I.: The central role of diminishing sea ice in recent Arctic temperature amplification. Nature 464, 1334–1337, doi: 10.1038/nature09051, 2010.

Raney, R. K., The Delay/Doppler Radar Altimeter. IEEE Trans. Geoscience and Remote Sensing, 36 (5), 1578-1588, 1998.

Ricker, R., Hendricks, S., Helm, V., Skourup, H., and Davidson, M.: Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation, The Cryosphere, 8, 1607–1622, https://doi.org/10.5194/tc-8-1607-2014, 2014.

Rott, H., Shi, J., Xiong, C., Cui, Y.: Snow properties from active remote sensing instruments. In S. Liang (Ed.), Comprehensive Remote Sensing, Vol. 4, pp. 237-257. Oxford: Elsevier. ISBN: 978-0-12-803221-3. doi: 10.1016/B978-0-12-409548-9.10359-8, 2018.

Shepherd, A., Ivins, E. R., Geruo, A., Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. A., Lenaerts, J. T.M., Li, J., Ligtenberg, S. R. M., Luckman, A., Luthcke, S. B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Nicolas, J. P., Paden, J., Payne, A. J., Pritchard, H., Rignot, E., Rott, H., Sandberg Sørensen, L., Scambos, T.A., Scheuchl, B., Schrama, E.J.O., Smith B., Sundal, A. V., van Angelen, J. H., van de Berg, W. J., van den Broeke, M. R., Vaughan, D. G., Velicogna, I., Wahr, J., Whitehouse, P. L., Wingham, D. J., Yi, D., Young, D., Zwally, H. J.: A reconciled estimate of ice-sheet mass balance. Science, 338(6111). https://doi.org/10.1126/science.1228102, 2012.

Serreze, M.C. and Francis, J.A. (2006) Climatic Change, 76, 241-264. https://doi.org/10.1007/s10584-005-9017-y

Siegert, M. J. Ross, N., Le Brocq, A. M. (2016) Recent advances in understanding Antarctic subglacial lakes and hydrology. Philosophical transactions of the Royal Society A. The Royal Society. https://doi.org/10.1098/rsta.2014.0306.

Shiklomanov, A. I., R. B. Lammers, M. A. Rawlins, L. C. Smith, and T. M. Pavelsky (2007), Temporal and spatial variations in maximum river discharge from a new Russian data set, J. Geophys. Res., 112, G04S53, doi:10.1029/2006JG000352.

Sørensen, L. S., Simonsen, S. B., Meister, R., Forsberg, R., Levinsen, J. F., and Flament, T.: Envisat-derived elevation changes of the Greenland ice sheet, and a comparison with ICESat results in the accumulation area. Remote Sensing of Environment, 160, 56–62. https://doi.org/10.1016/j.rse.2014.12.022, 2015.

Tilling, R. L., Ridout, A., and Shepherd, A.: Estimating Arctic sea ice thickness and volume using CryoSat-2 radar altimeter data, Adv. Space Res., 62, 1203–1225, https://doi.org/10.1016/j.asr.2017.10.051, 2018.

Tournadre, J., Bouhier, N., Girard-Ardhuin, F., and Rémy, F.: Large icebergs characteristics from altimeter waveforms analysis, J. Geophys. Res. Oceans, 120, 1954–1974, doi:10.1002/2014JC010502, 2015.

Tournadre, J., Bouhier, N., Girard-Ardhuin, F., and Remy, F.: Antarctic icebergs distributions 1992-2014. J. Geophys. Res. 121 (1), 327–349, 2016.

Tournadre, J., Bouhier, N., Boy, F., and Dinardo, S.: Detection of iceberg using Delay Doppler and interferometric Cryosat-2 altimeter data. Remote Sens. Environment. 212, 134-147, 2018. https://doi.org/10.1016/j.rse.2018.04.037

Tynan, C.T., Ainley, D.G., and Stirling, I.: Sea ice: a critical habitat for polar marine mammals and birds. In: Chapter 11, Sea Ice, Second Edition, Editors Thomas D. N., Dieckmann, G. S. https://doi.org/10.1002/9781444317145.ch11, 2009.

Quartly, G. D., Rinne, E., Passaro, M., Andersen, O. A., Dinardo, S., Fleury S., Guillot, A., Hendricks, S., Kurekin, A. A., Müller, F. L., Ricker, R. , Skourup, H., Tsamados, M.: Retrieving Sea Level and Freeboard in the Arctic: A Review of Current Radar Altimetry Methodologies and Future Perspectives. Remote Sens. 2019, 11, 881; doi:10.3390/rs11070881.

Warren, S. G., Rigor, I. G., Untersteiner, N., Radionov, V. F., Bryazgin, N. N., Aleksandrov, Y. I., and Colony, R.: Snow depth on Arctic sea ice, J. Climate, 12, 1814–1829, 1999.

Whiteman, G., C. Hope, and P. Wadhams. 2013. Vast costs of Arctic change. Nature News and Comment 499: 401–403.

Wingham, D., Wallis, D., and Shepherd, A. (2009). Spatial and temporal evolution of Pine Island Glacier thinning, 1995-2006. Geophysical Research Letters, 36, L17501. https://doi.org/L17501 10.1029/2009gl039126

Wingham, D. J., Francis, C. R., Baker, S., Bouzinac, C., Brockley, D., Cullen, R., de Chateau-Thierry, P., Laxon, S. W., Mallow, U., Mavrocordatos, C., Phalippou, L., Ratier, G., Rey, L., Rostan, F., Viau, P., Wallis, D. W.: CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields. In M. Singh, RP and Shea (Ed.), Natural Hazards and Oceanographic processes from satellite data, 37, pp. 841–871. Elsevier science ltd. https://doi.org/10.1016/j.asr.2005.07.027, 2006.

Zakharova, E. A., Kouraev A.V., Stephane G., Franck G., Desyatkin, R. V., Desyatkin A.R.: Recent dynamics of hydro-ecosystems in thermokarst depressions in Central Siberia from satellite and in situ observations: Importance for agriculture and human life, Science of The Total Environment, Volume 615, pages 1290-1304, 2018.

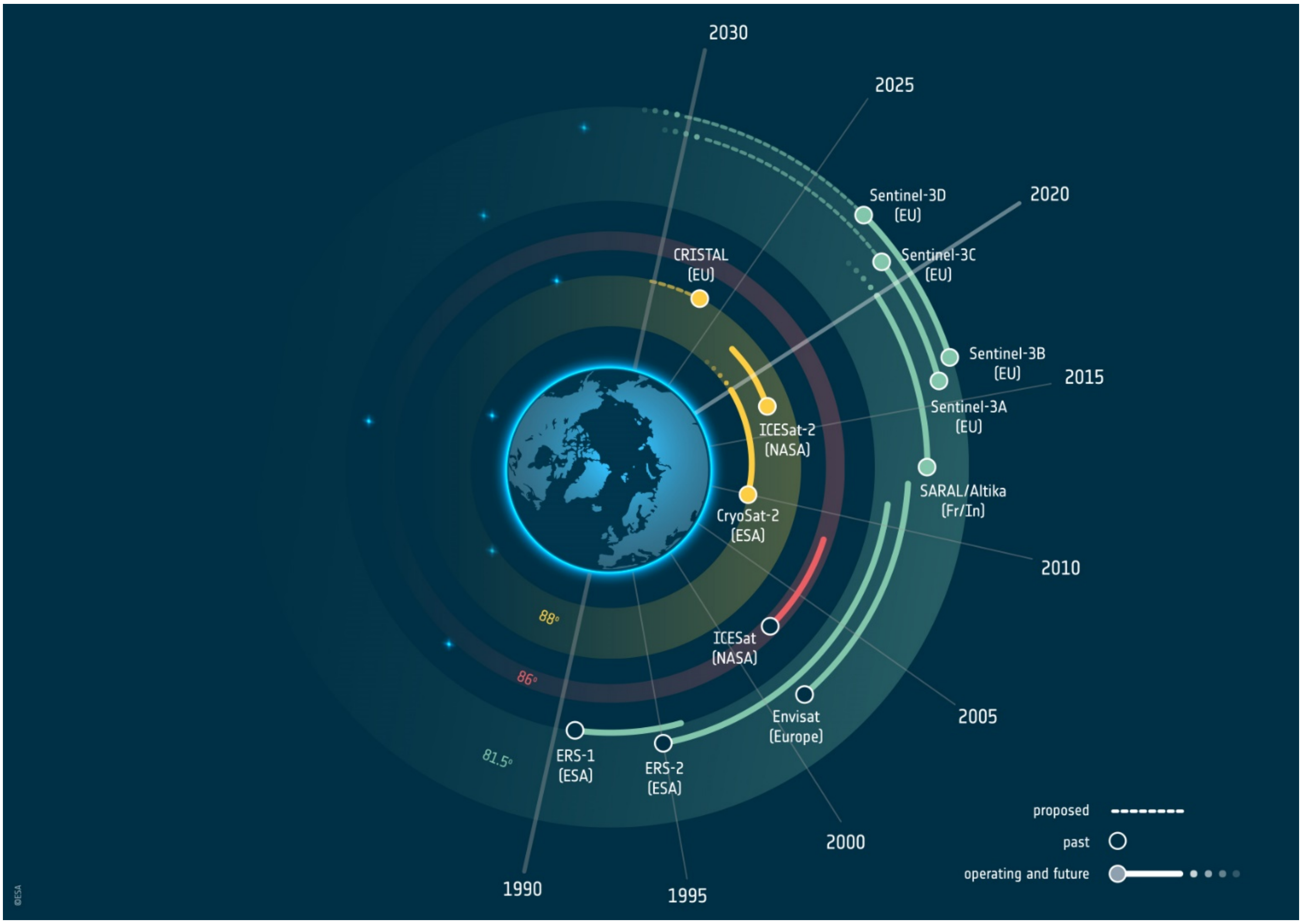

Figure 1. The image shows the past, operating, approved and proposed polar topography altimeter missions. By mid 2020s, CRISTAL will fill the gap acquiring climate-critical data over polar ice north or south of 81.5° latitude [Image: EOBG/ESA].

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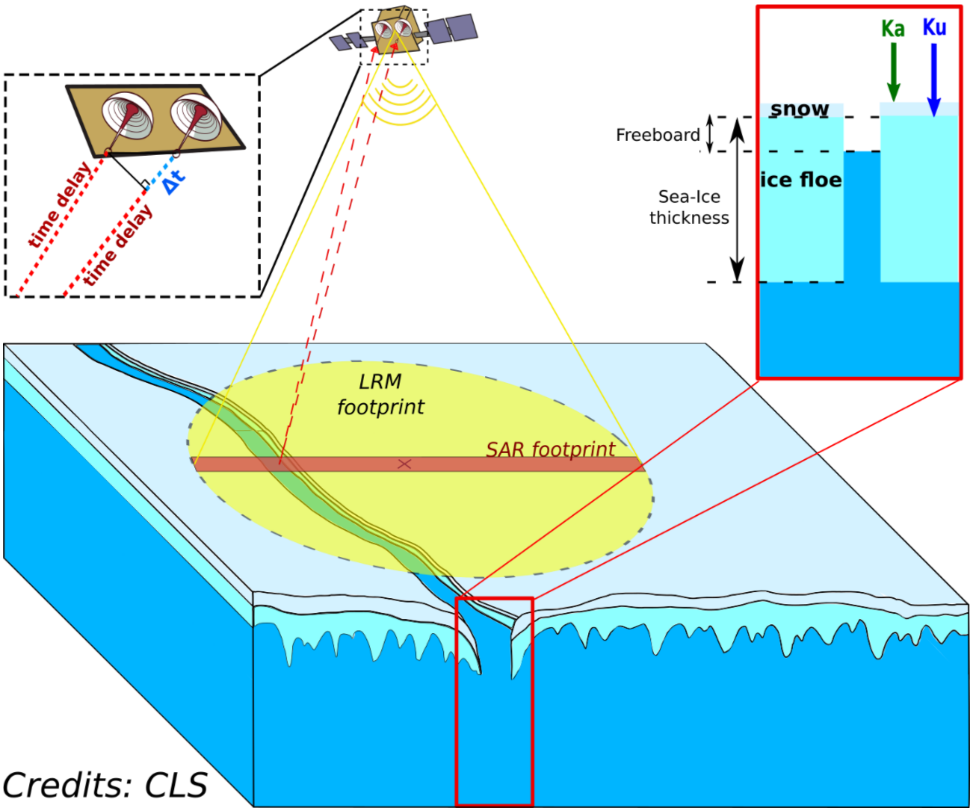

720 **Figure 2. Illustration of the CRISTAL observation concept over sea ice employing a twin-frequency, twin antenna SAR radar altimeter with interferometric capability at Ku-band (Image Credits: CLS).**

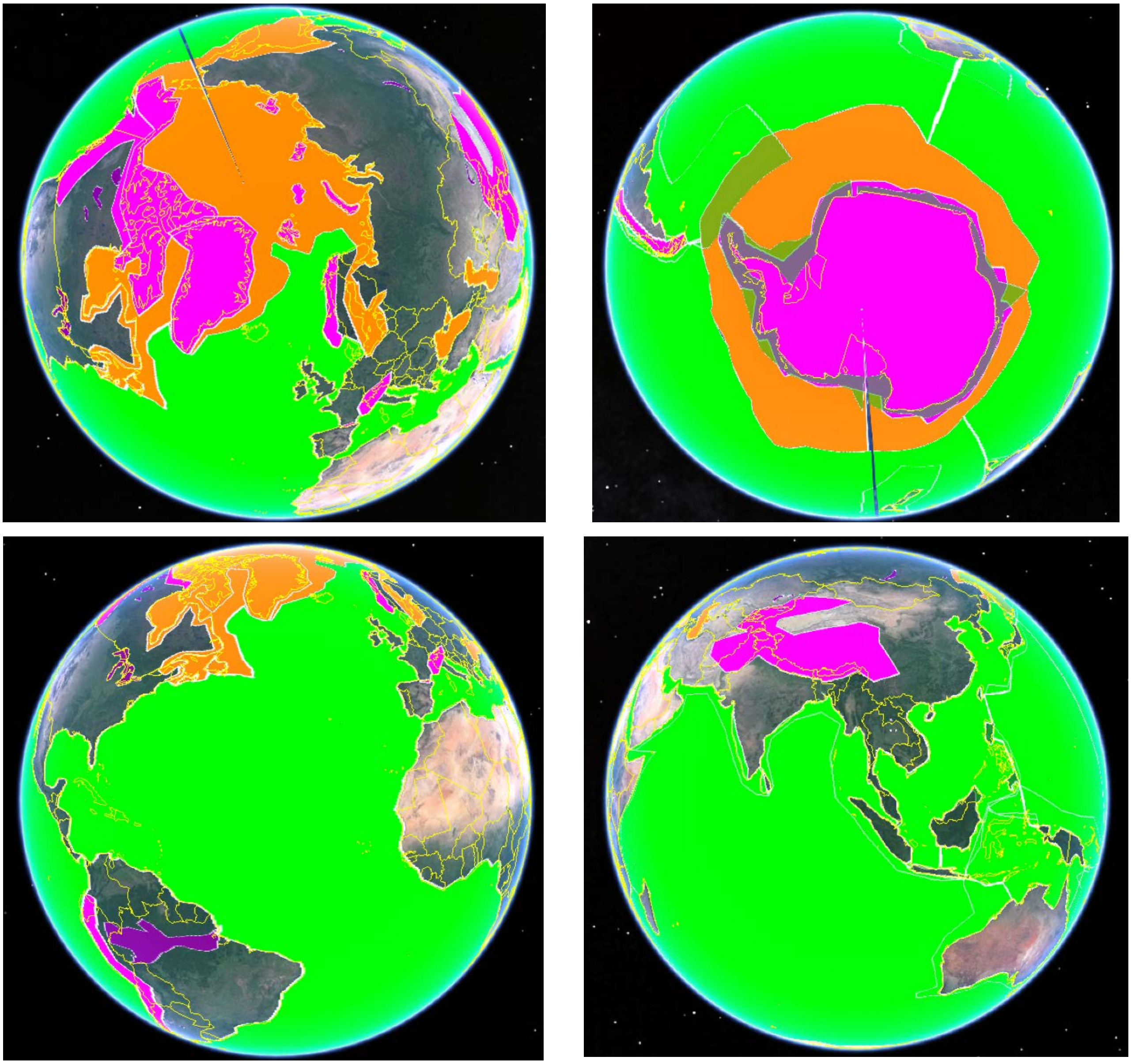

Figure 3. Indicative mission geographic operating mode mask used in CRISTAL altimeter data volume sizing: Magenta = Land-Ice and Glacier (LIG) closed-burst SARIn mode, also including smaller ice-caps; Orange = Sea-Ice and Icebergs (SII) open-burst SARIn mode (maximum coverage in North/Southern hemisphere); Green = Open and Coastal Ocean (OCO) SARIn reduced window mode; Purple = Inland water – this is not anticipated as a mode but may be derived from one of the three key modes. Note: The wedge type feature in some of the images is an artefact of the display software.