Executive Summary Report of the Polar Monitoring study

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CLS headquarters
11 rue Hermès
Parc technologique du Canal
31520 Ramonville Saint-Agne
FRANCE

Tel. +33 (0)5 61 39 47 00
Fax +33 (0)5 61 75 10 14
Mail: info@cls.fr
www.cls.fr

CLS Brest Le Ponant
Zone du technopôle de Brest Iroise
Avenue La Pérouse
29280 Plouzané
FRANCE

Tel. 33 (0)2.98.05.76.80
Fax 33 (0)2.98.05.76.90

People involved in this issue:

Written by (*):	J.Aublanc P.Thibaut	Date + Signature 19/06/2020
Checked by (*):		Date + Signature
Approved by (*):	P.Thibaut	Date + Signature : [Approver]
Application authorized by (*):		Date + Signature

**In the opposite box: Last and First name of the person + company if different from CLS*

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1. Introduction

This document is an “executive summary report” giving a synthetic overview of the main analyses and results obtained in the framework of the PolarMonitoring study performed by a consortium led by Collect Localisation Satellite (CLS) and composed of the Finnish Meteorological Institute (FMI) in Helsinki, the University of Lancaster in United Kingdom (UK), the “Institut des Geosciences de l’Environnement” (IGE) from the University of Alps Grenoble and the Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS) in Toulouse.

The study was dedicated to the preparation of the CRISTAL mission (Copernicus polaR Ice and Snow Topography Altimeter), one of the 6 High Priority Candidate Missions (HPCM) of the Copernicus Space Component (CSC). This mission is of major interest given the Earth’s cryosphere critical role in the current climate change [Kern et al., 2020].

The payload of the mission is currently being defined based on scientific and user requirements. The main instrument of the mission is an innovative altimeter which name is IRIS (Interferometric Radar altimeter for Ice and Snow), currently being designed by Thales Alenia Space. This innovative altimeter brings high expectations for monitoring and improving our knowledge of the current changes in the Earth’s cryosphere.

Over the ice-covered ocean, dramatic improvements are expected in the snow depth estimation compared to previous altimeters, thanks to the dual Ku/Ka frequency bands, and a better vertical resolution in Ku band (~30cm vs ~47cm compared to previous altimeters). This will subsequently benefit to the radar freeboard and sea-ice thickness estimation. Over the polar ice sheets, improvements are also expected in the ice sheet topography accuracy, thanks to improvements in the understanding of the volume scattering observed in both Ku and Ka bands. Finally, Synthetic Aperture Radar Interferometry (SARIn) will also be highly valuable over ice sheets steep surfaces, and for estimating sea level over sea-ice leads. The secondary objective of the mission will concern observation over ocean. Requirements and benefits of the CRISTAL mission have also been analysed.

Ground segments algorithms will be chosen based on the current state of the art, and lessons learned from previous missions. It is highly important to assess how innovations and new features offered by CRISTAL will be efficiently exploited, and how the mission will successfully address the user requirements. Indeed, the final performance of the altimeter relies on the maturity of level-1 and level-2 algorithms to fully exploit the innovative CRISTAL assets.

This study aimed at answering this problematic and was divided in three Work Packages (WP):

- **WP1:** Review of the altimetry state of the art, with focus on Ka band & Doppler altimetry. User requirements for a future altimetry polar mission, along with the practical applications are also reviewed and analysed.

- **WP2:** Examination of the level 1 and level 2 preliminary product definitions listed in the Mission Requirement Document (MRD). The level of maturity of the associated algorithms has been discussed. The configuration of the mission system was also analysed: altimeter operating modes, orbit, need for a radiometer, synergy with the future altimeter constellation. This work led to a revision of the MRD.

- **WP3:** Development of an innovative simulator to reproduce CRISTAL measurements over snow surface. The simulator was developed in synergy between CLS & IGE, and is capable to realistically reproduce the volume scattering impacting radar waves when penetrating a snow cover. This study aimed at providing first answers about the potential benefits of a dual Ku/Ka band instrument over snow covered surfaces.

For each of these 3 WPs, a technical report has been delivered to the European Space Agency (ESA). The present executive summary provides the main conclusions of each WP. Extensive explanations, details and illustrations can be found in the 3 documents that have been provided.

2. WP1: Review of the state of the art and analysis of user requirements

2.1. Scope and purpose

In the early 2010's, the European commission initiated an user requirements process for the next generation of Copernicus Space Component (CSC). Monitoring the polar regions has been identified as a priority for the evolution of CSC planned for the mid-2020s to meet user needs not addressed by the existing observing system. In this context, the "Copernicus Polar and Snow Cover Applications User Requirements Workshop" was held in June 2016. User requirements, gaps in the observation system and several mission concepts meeting the most relevant requirements were discussed. Then, the European commission set up a group of European Polar and Snow Experts (Polar Experts Group or PEG) to review and refine the Copernicus Core User Requirements. Two reports have been written: the PEG reports [RD-1] [RD-2].

The main objective of this work package was to provide:

- A review of the altimetry state of the art, with focus on Ka band & Doppler altimetry
- A review of the user requirements, in particular those contained in the PEG reports
- An analysis of the gaps relative to the 2025 observing system

These tasks were addressed for the three different surfaces, by three different members of the consortium:

- Sea-Ice surface was addressed by FMI and LEGOS
- Ice sheet surface was addressed by Lancaster University
- Ocean surface was addressed by CLS

2.2. Main outcomes

Below are presented the main outcomes for each surface:

<u>Sea-ice:</u>

- **The main geophysical parameters derived from altimetry were detailed:** sea-ice freeboard, snow depth and sea-ice thickness
- **The main gaps relative to the 2025 constellation are the following:**
  - Lack of measurements beyond 81.5°N/S
  - Uncertainty in sea-ice thickness estimates due to uncertainty in snow load and ice type
  - Limitation of sea-ice thickness retrieval to winter months only
- **The main user requirements from PEG reports are:**
  - An improvement of the sea-ice thickness accuracy for climate research community and better short-range forecasts for ship routing. **Goal is 0.1m.** For that purpose, better estimations of snow depth and freeboard are mandatory.
  - A daily coverage of sea-ice thickness, and near real time availability for operational use
  - An improvement of the measurement of sea ice thickness distribution for models and operational services

Ice-sheets:

- **The main geophysical parameter derived from altimetry is the surface elevation.** The surface topography derived from altimetry is helpful for many scientific applications. In particular: Digital Elevation Model (DEM) definition, mass balance monitoring (global warming related), ice shelf thickness change, subglacial lake drainage, grounding line location.

- **The main gaps relative to the 2025 constellation are the following**:
    - Lack of measurements beyond 81.5°N/S
    - A lack of continuous coverage of ice sheet margins
    - A lack of accuracy in coastal regions with complex topography, due to an absence of interferometric Synthetic Aperture Radar (SAR) altimeter measurements
    - A demand for greater precision in resolving small elevation changes across large inland areas of the ice sheets.

- **The main user requirements from PEG reports are**:
    - The accuracy of surface elevation measurement (goal is 0.5 meters)
    - The accuracy & stability of surface elevation change measurement (goal is 0.1 m/year)
    - The latitudinal coverage (to within 2° latitude of the poles)
    - The temporal sampling frequency: Monthly-seasonal (ice margin); annual (interior).
    - The spatial resolution, goals are 1000 m (interior) and 50-100 m (ice margin).

Ocean:

- **The main geophysical parameters derived from altimetry is the sea elevation. A focus was given to polar ocean.** Compared to open ocean, specific problems add up over sea-ice areas:
    - A degradation of the **altimeter range accuracy**
    - Radiometric estimations are contaminated by the presence of ice-floe. Subsequently **wet tropospheric correction** is less accurate compared to open ocean
    - Concerns regarding the **Dynamic Atmospheric Correction** (DAC) accuracy

- **The main gap relative to the 2025 constellation is the lack of coverage of the Arctic Ocean,** where lot of uncertainties remain. In particular: the mean sea surface, the mean sea level trend, mesoscale circulation, oceanic tides, wind & wave forecast.

- **The main user requirements from PEG**:
    - Prime importance that the orbit configuration allowing covering the central Arctic Ocean
    - Desirable improvements wrt CS2 capabilities regarding the improvement of lead detection
    - **The accuracy of sea-level anomaly over open-ocean & leads** (goal is 2-3cm)
    - **The spatial sampling of Sea-Level Anomaly (SLA) and Mean Dynamic Topography (MDT):** Goals are 10km
    - **The temporal sampling of SLA and MDT:** Goals are from daily sampling (SLA over open-ocean) to 10 days (SLA over leads & MDT)
      Note: The multi-mission nature of requirements relative to spatial and temporal resolution of SLA and MDT was discussed in the study

3. WP2: Assessment and consolidation of mission requirements

3.1. Scope and purpose

The objective of the second work package was to examine the definitions of level 1 and level 2 preliminary products listed in the Mission Requirement Document [RD3]. Thereafter, the associated algorithms necessary to derive the geophysical parameters were identified, and their maturity was discussed. In fact, the choices of level-1 and level-2 processing applied on altimeter measurements are crucial for obtaining the best achievable performances for the mission.

The observation system was also reviewed. Mainly, the altimeter operating modes, the need for a radiometer, the synergy with the future altimeter constellation. The orbit was analysed in a dedicated Contract Change Notice (CCN).

Requirements present in the MRD regarding these aspects have been discussed. **The final objective of this task was to provide expert feedbacks and new inputs and elements to the Mission Requirements Document.**

Similarly to WP1, these tasks were addressed for three different surfaces, by three different partners:

- Sea-Ice surface was addressed by FMI and LEGOS
- Ice sheet surface was addressed by Lancaster University
- Ocean surface was addressed by CLS

3.2. Main outcomes

3.2.1. Level-1 and level-2 algorithms maturity

The main geophysical parameters were listed in the dedicated technical note, for each studied surface. The maturity level of each algorithm was discussed. A Scientific Readiness Level (SRL) was given to each algorithm, from 1 (initial scientific idea) to 9 (science impact qualification). Below is a table summarizing the most important/relevant algorithms:

	SRL- 4 Proof of concept	SRL- 6 Consolidated science	SRL- 7 Demonstrated science	SRL- 8 Matured science	SRL- 9 science impact quantification
Level-1 Doppler processing			- Fully Focused SAR - LR-RMC		- SAR unfocused - SARIn
Level-2 sea-ice algorithms		- Neural network waveform classification - Snow depth retrieval from Ku/Ka	- Physical RTK with Mean Square Slope (Adaptive, SAMOSA+)		- Empirical retrackers (TFMRA, ICE-1)
Level-2 ice sheets algorithms	- Ku band penetration using Ku/Ka			- Swath processing (SARIn) - Echo relocation (SARIn)	- Empirical retrackers (TFMRA, ICE-1) - Echo relocation (using DEM)
Level-2 ocean algorithms			- Numerical RTK - Mean Square Slope RTK - HFA algorithm	- SAMOSA RTK (SAR mode)	- Brown MLE4 RTK (LRM)

Figure 1: Summary table of the most important level-1/level-2 algorithms and their associated maturity level

Please note these SRL were defined using our current state-of-the-art knowledge. Therefore, for some algorithms the SRL cannot be directly transposed on Ka-band measurements, especially the SRL relative to Doppler processing: Fully Focused SAR, Low Resolution – Range Migration Correction (LR-RMC) mode, SARIn mode, SARIn swath processing. Nonetheless, in our knowledge there is no justification these processing would not work as efficiently as it does in Ku band. Except potentially for SARIn processing, which will be more sensitive to phase ambiguities over the ice margins steep surfaces.

3.2.2. Main recommendations and perspectives to prepare CRISTAL mission

- Above all, there is a clear need for improving our knowledge and undertanding of the **dual Ku/Ka band** behaviour over ice surfaces. In particular:
  - **to retrieve the altimeter range at snow/ice interface over sea-ice and ice sheets**, and subsequently to remove variable biases induced by volume scattering
  - to improve snow depth retrieval over **sea-ice floes** exploiting simultaneous Ku and Ka measurements

  ⇨ **These improvements can be assessed by comparing and analysing the measurements provided by the current altimetry constellation (Sentinel-3 ; CryoSat-2 ; AltiKa ; ICESat2) and simulations (see WP3 outcomes)**
- A **physical retracker** accounting for Mean Square Slope (linked to the roughness of the surface) is mandatory to provide **continuity of sea topography measurements from open ocean to leads into the sea-ice.** Several retracking algorithms are already available, research and development are still highly recommended for improving their performances and validating their outcomes.
- Research and development must also pursue **on the Fully-Focused algorithm**, providing a dramatic reduction of the along-track footprint, highly valuable over sea-ice (and inland water).
- **Over the ice sheets, benefits of the Ka-band have been poorly documented**, and only few publications can be found in the literature about SARAL/AltiKa performances [Remy et al., 2014 ; Suryawanshi et al. ,2019]. 7 years of AltiKa data (2013 - 2020) over ice sheets have to be studied in detail, along with Ku/Ka comparisons.
- Current concerns relative to the **Open Loop Tracking Command (OLTC) over ice sheets (in particular for Sentinel-3)** have to be overcome.
- **Open-burst (interleaved) chronogram** would be highly desirable over inland waters to largely benefit of the Fully Focused-SAR processing without ambiguities.
- **Similar performances expected between Sentinel-3 and CRISTAL over open-ocean** considering the similarity of altimeter configurations. Studies have to be made to anticipate how the dual Ku/Ka bands can be exploited.

3.2.3. Revision of the Mission Requirement Document (MRD)

As a conclusion to this work, several modifications were made on the Mission Requirement Document (version 2.0). These modifications were discussed by the Mission Advisory Group. A dozen of requirements were finally modified to be more consistent with CRISTAL capabilities and objectives. This led to a new version of the MRD (V3.0).

4. WP3: Simulation and Performance Analysis

4.1. Scope and purpose

Radar altimeter signals in Ku band are known to be affected by penetration and subsurface scattering into snow and ice. The mechanisms for radar-altimeter scattering are still poorly known, and this is a major issue when attempting to measure the surface elevation over ice sheets and sea-ice floes. As a result, the backscattered altimeter signal is a complex combination of energy backscattered from the surface and the subsurface, with contributions that may vary significantly in space and time depending on the density, the temperature, the stratification and the grain size of the snowpack. [Partington et al., 1989; Legresy and Remy, 1998]

With respect to Ku-band, Ka-band radar altimeter is much more reliable for providing consistent measurements of the surface. Indeed Ka-band waveforms are not, or only weakly, impacted on their leading edge by volume scattering because of a penetration depth lower than in Ku-band, which is well known in theory.

This study aimed at providing some answers about the potential benefits of a dual Ku/Ka band instrument for snow measurements. For that purpose, the first objective was to develop a dedicated numerical simulator, able to generate synthetic Ku/Ka waveforms (accounting for the instrumental configuration of CRISTAL), in both Low Resolution Mode (LRM) and SAR modes, and over different types of snowpack. The second objective was to use the simulator to study radar altimetry over ice sheets and sea ice surfaces, using the CRISTAL dual bands altimeter configuration.

The simulator was developed in synergy between IGE and CLS. IGE provided their expertise in glaciology, along with the Snow Model Radiative Transfer (SMRT) [Picard et al., 2018]. CLS provided their expertise in altimetry, along with its altimetry simulator (named AltiDop).

4.2. Main outcomes

- **SMRT has been successfully adapted by IGE for altimetry applications**

With its new features, SMRT is now able to simulate the vertical backscattering distribution of a snowpack, which after convolution with the Brown model gives the LRM radar waveform. The model accounts for first order scattering, which is valid when the snow grain size is smaller than 0.8, 0.5 and 0.2 mm in the S, Ku and Ka bands, respectively. SMRT was validated by comparing simulations with the Lacroix et al. 2008’s modeling, using the same configuration and inputs (normalized RMSE < 2%).

- **SMRT was coupled with the altimeter simulator (AltiDop) by CLS**

Among other advantages, the coupling of the SMRT model and AltiDop enables to perform simulations for different surface topography scenarii (at a meter resolution scale). AltiDop is also capable of performing simulations in **the SAR altimetry mode** that will be available embarked by the CRISTAL mission.

- **Two sensitivity analyses (looking at the impact of the snowpack characteristics on the altimeter waveform shape. Retracking output have not been considered at this point) were conducted using single-layer synthetic snowpacks,** theoretically representative of snow conditions observed over lake Vostok (Antarctica plateau):
    - A first sensitivity study was conducted using SMRT alone with the snowpack from Lacroix et al. [2008], in the AltiKa & Envisat altimeter configurations
    - In the second sensitivity analysis, the snowpack parameters were adjusted, in order that the simulated waveforms match with real acquisitions from CryoSat-2, AltiKa and Sentinel-3A (using realistic ranges of snowpack parameters magnitude). The sensitivity study was

conducted using the SMRT/AltiDop coupling, in the exact instrumental configuration of CRISTAL (LRM/SAR modes and Ku/Ka bands)

- **Results of the sensitivity analysis**

The results of the two sensitivity studies are slightly different but reach the same major conclusions. The altimeter measurement is very sensitive to snow grain size, snow density and surface roughness at small scales (mean square slope). These three parameters act differently on the waveform shape, depending on the mode (LRM/SAR) and the frequency band (Ku/Ka). Therefore, we anticipate that a dual band altimeter such as CRISTAL would be highly valuable to discriminate the different geophysical parameters that modify the waveform shape over snow surfaces.

4.3. Perspectives

This prospective study provided very promising results and suggests undertaking the following actions:

1) **Confirmation and refinement of the conclusions reached in this study with an extended evaluation of the AltiDop/SMRT simulator**. For that purpose, it would be necessary to define even more realistic synthetic snowpacks, built from in-situ snow measurements (over land ice AND sea ice). The waveforms, simulated using these snowpacks, must then be compared to real altimetry acquisitions overflying in-situ sites measurement.

   => IGE is currently writing a scientific publication following this workplan, with the support of CLS

2) **Simulations performed with SMRT can be improved in Ka band (and lower frequencies) by taking into account 2nd order scattering**. Progress has also to be made in the understanding of snow surface roughness and its impact into radar altimetry measurements.

3) **Sensitivity studies must be conducted at global scales** to account for the snow parameters variation over the cryosphere. Over ice sheets, seasonal variations of the snowpack must also be studied.

4) Most of the results have been obtained for ice sheet surfaces. **Sea-ice surfaces must be investigated as well.** Snow depth and freeboard estimations are among the main objectives of the CRISTAL mission. However, the lack of snow in-situ data over sea-ice prevents currently from precisely setting the synthetic snowpack.

5) **Specific level-2 algorithms employed for acquisitions made over snow surfaces still have to be improved, to reach user requirements.** In particular the waveform retracking, and the algorithms exploiting Ku/Ka measurements (to estimate snow depth and/or volume scattering). This is true for the future CRISTAL mission but also for improving the current altimetry dataset. The simulation analysis made on this study (WP3) demonstrates that the surface elevation derived from the waveforms is sensitive to several snowpack parameters (namely: snow density, snow grain size & mean square slope), for both LRM and SAR modes and both the Ku and Ka bands. Therefore, alternatives to empirical retrackers have to be carefully and urgently considered. We strongly recommend to define, develop and validate retrackers based on physical modeling of the backscattered signal. The number of parameters impacting the shape of the waveforms is great but we are confident that CRISTAL configuration, based on simultaneous Ku/Ka and LRM/SAR/SARin modes, will provide enough measurements to discriminate/retrieve these parameters. This is the big challenge we have to face for the CRISTAL mission. **Simulations must definitely help to do that job and the simulation tools (coupling radiometric and altimeter models) that have been developed must play an important role for better processing the future measurements over the cryosphere.**

6) **An important point that has not been exploited in this study is that that radiometric model used is valid for simulating altimeter measurements but also for generating radiometer brightness temperatures and thus simulating radiometer measurements as well. We already know the great benefit of exploiting simultaneous observations from altimeter and radiometer looking at the same surface. Studies have shown the interest of such an approach for determining properties of the snow pack (age of the ice, type of swow etc, …). [Tran et al., 2009 ; Tran et al., 2008]. CRISTAL will embark a radiometer. Working on the coupling of altimeter and radiometer simulation could be largely beneficial for improving the future performance of the CRISTAL mission.**

5. CRISTAL orbit CCN

5.1. Scope and purpose

The main objective of this CCN study was to define an optimal orbit for the future CRISTAL mission. This work was divided in two main tasks:

- **Research of new orbit candidates:** Before the study, several orbit cases have been suggested by ESA and CNES. A first task was to seek for new orbit candidates based on MAG requests (see below). CLS only was involved in this work.
- **Analyses of the orbit candidates:** The orbit candidates were analyzed side by side, and ranked based on their capabilities to fulfill MAG specifications. Analyses were made on different surfaces. Lancaster University was responsible for the ice sheet surface, FMI for the sea-ice surface and CLS for the ocean.

Before the study, the MAG made clear specifications of the orbit characteristics, to fulfil user requirements over different surfaces:

- **Weekly sampling** is first priority for sea ice thickness objective.
- **Monthly sampling** is first priority for land ice objective.
- For **Antarctica, monthly sub-cycle** will be sufficient; for **Greenland, <30 days sub-sampling** would be desirable.
- **Regular, homogeneous sampling** is generally favorable.
- Additional sub-cycles such as **4 days sub-cycle**, and **quarterly sub-cycles** are nice to have.
- **The orbit must complement Sentinel-3 orbit pattern.**
- **A 15 days sub-cycle for mid-latitude mesoscale** is desirable for oceanographic purposes and objectives but the lack of such sub-cycle **should not be a criterion** to reject an orbit.

In addition, the orbit must also be in adequation with two strong mission requirements: northern and southern poles must be covered (+/- 88° at least), along with a yearly cycle. Making the CRISTAL orbit similar to CryoSat-2 one, to ensure the continuity between the two missions.

5.2. Main outcomes

- **New orbit candidates research**

CLS made an exhaustive research of new orbit candidates, looking to the best options to address MAG specifications. As it was not possible to find a single orbit possessing all these specifications, **<u>three new orbit solutions were found</u>** (CLS1 ; CLS2 ; CLS3 in the tables below). These three orbits have different characteristics, and are promising trade-off that conform to most of the MAG requirements.

In the end, 8 orbit candidates were analysed side by side by the Polar Monitoring team. The table below shows the list of sub-cycles / cycle for each orbit candidate:

	< week	weekly	bi-weekly	monthly	quarterly	annual	others
Case 1	2	7	/	30	/	365	67
Case G2	5	/	14	33	/	372	113
Case 3	4	/	/	31	/	365	66
Case 5	/	7	/	29	/	363	167
ICESat-2	4	/	/	29	91		
CLS1	2	7	19	31	/	367	112
CLS2	5	/	19	33	85	373	/
CLS3	3	7	/	31	86	368	/

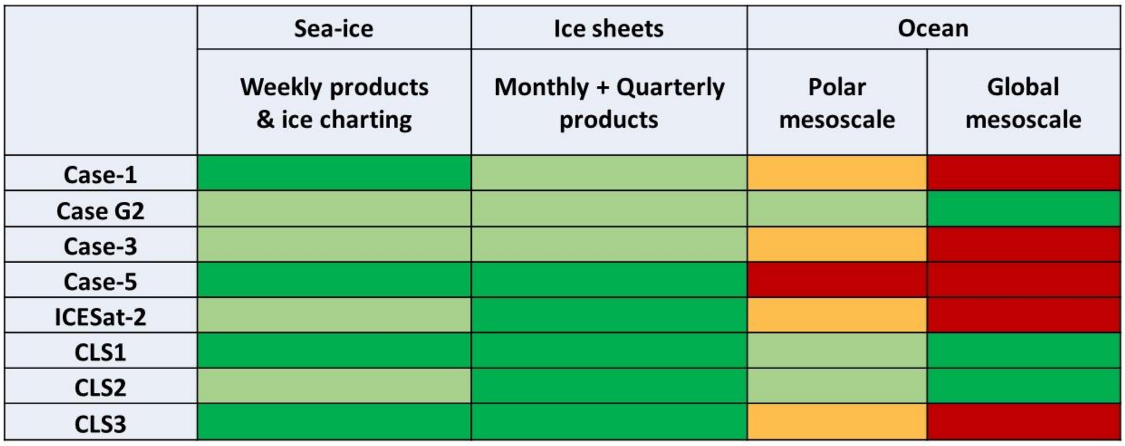
Table 1: List of sub-cycles for the orbit candidates proposed by ESA & CNES.

- **Evaluation of orbit candidates**

Different diagnoses were performed over the three surfaces:

- Ice charting sampling & weekly products capability **for sea-ice**
- Monthly & quarterly products capabilities **for ice sheets**
- Decorrelation of mesoscale signals in space/time & polar ocean analysis **for ocean**. Polar ocean analysis originating from G.Dibarboure (Centre Nationale d'Etudes Spatiales - CNES)
- A global sub-cycle analysis

The complementarity with Sentinel-3 was also analysed. The results were presented to the MAG members. The table below provides a summary of the results. The orbit candidates were ranked in the table as optimal (dark green), sub-optimal (light green) ; average (yellow) and not adapted (red).



	Sea-ice	Ice sheets	Ocean	
	Weekly products & ice charting	Monthly + Quarterly products	Polar mesoscale	Global mesoscale
Case-1	🟩	🟢	🟨	🟥
Case G2	🟢	🟢	🟢	🟩
Case-3	🟢	🟢	🟨	🟥
Case-5	🟩	🟩	🟥	🟥
ICESat-2	🟢	🟩	🟨	🟥
CLS1	🟩	🟩	🟢	🟩
CLS2	🟢	🟩	🟢	🟩
CLS3	🟩	🟩	🟨	🟥

Figure 2: Orbit evaluation summary table

When Sentinel-3 is added in the orbit analyses, all orbit candidates are optimal for ice sheet & sea ice surfaces, and thus fulfil the user requirements.

- **For sea-ice**, best candidates are **Case-1 ; Case-5 ; CLS1 & CLS3**, thanks to the 7 days sub-cycle
- **For ice-sheets**, best candidates are:
  - **ICESat-2** if total coverage over an annual cycle is deemed to be **not important**
  - **Case-5, CLS1, CLS2, CLS3** if annual coverage **is important**. Case-5 providing the best performances for monthly sampling. CLS1, CLS2, CLS3 very close with a better quarterly sampling
- **For ocean,** best candidates are **Case G2 ; CLS1 & CLS2** as they provide the most efficient sampling of oceanic mesoscale signals, and are adapted for a polar mesoscale multi-mission strategy. Case-5 is the worst.

Overall, the CLS1 orbit seems to be the best among all the orbit candidates when requirements for oceanography (polar mesoscale and global mesoscale) are taken into account.

5.3. Perspectives

The studied orbits, or at least a subset of the 8 orbits, would undergo a technical feasibility analysis (station visibility, altitude conflicts etc.) as well as ESA orbit experts. Since all orbits generally fulfil the performance and application needs (except Case-5 orbit), the orbit candidate with the best suitability to these user requirements as well as the technical constraints should be selected and presented to the MAG.

6. CRISTAL Science Traceability Matrix (STM)

Following the work made in the Polar Monitoring study, ESA decided to build a Science Traceability Matrix for the CRISTAL mission. This work was performed by Günther March (ESA). CLS supported this work by providing few comments and modifications. The STM is presented below.

CRISTAL - Science and Applications Traceability Matrix

Objectives, Requirements, Instruments & Data Products

Legend:	
Primary obj.	☐
Secondary obj.	▨

Science Objectives	Measurement Objectives	Measurements Requirements			Instruments Requirements	Mission Requirements	Data Products
		Spatial resolution	Temporal resolution	Uncertainty/accuracy			
PRI-OBJ-1. Measure and monitor variability of Artic and Southern Ocean **sea-ice thickness and its snow depth**.	Retrieve **sea ice freeboard** improving current retrieval accuracy and resolutions.	Horizontal resolution ≤80m (Goal: 20m) Range resolution ≈30cm.	6h latency	Uncertainty <0.5m. Detect sea ice freeboard with 0.03m accuracy along orbit segments ≤25km.	SARIn altimetry with dual Ku/Ka bands + open-burst chronogram	MRD-280; MRD-310; MRD-390	Sea ice freeboard
	Retrieve **snow depth** on sea ice.	Horizontal resolution identical to sea ice thickness.	24h latency Resolution synchronous with sea ice freeboard and thickness retrieval	Uncertainty ≤0.05m (Goal: 0.02m)		MRD-260; MRD-290; MRD-300; MRD-320; MRD-330; MRD-380; MRD-390; MRD-400; MRD-410	Snow depth and density
	Retrieve **sea ice thickness** measurements of the sea ice-covered oceans.	Grid-scale resolution: ≤3km (Threshold) & 1km (Goal) Horizontal resolution 80m (Threshold), 20m (Goal)	24h latency (Goal: 6h)	Vertical uncertainty goal: 2-10cm Geolocation accuracy ≤300m (10% of 3km of horizontal accuracy) Vertical uncertainty: <0.1m.		MRD-230; MRD-260; MRD-270; MRD-280; MRDM-290; MRD-300; MRD-320	Sea ice thickness; Sea ice volume;
	Iceberg detection; retrieve volume change and drift in open water and sea ice.	Horizontal resolution (gridded product) ≤25m for marginal ice zone and ≤50m for inner ice zone; Iceberg distribution and volume products resolution (gridded): 50km-weekly (Goal); 100 km-monthly (Threshold).	24h latency (Goal: 6h)	Accuracy of 85% (Threshold) and 95% (Goal).	SARIn altimetry with dual Ku/Ka bands + open-burst chronogram (complementary to SAR imagery or other high-resolution data from other missions).	MRD-530; MRD-540; MRD-550	Iceberg detection; Iceberg distrubution and volume
PRI-OBJ-2. Measure and monitor the **surface elevation and changes** therein of polar glaciers, ice caps and the Antarctic and Greenland ice sheets.	Monitor **elevation** over sea-ice, land ice, polar glaciers, ice caps and ocean **and their temporal change**.	Horizontal resolution: ≤100 m (Threshold), 50m (Goal); 1km for interior ice sheets Detect surface elevation from -200m to 9.000m w.r.t. the ellipsoid.	Temporal sampling ≥30 days. NTC products latency.	Absolute uncertainty: 2m Vertical accuracy threshold: 2m Absolute accuracy: 0.5m (relative accuracy: 0.2m).	SARIn altimetry with dual Ku/Ka bands + closed-burst chronogram	MRD-150; MRD-190; MRD-340; MRD-350; MRD-360; MRD-370	Surface elevation (topography)
SEC-OBJ-1. Contribute to the observation of **global ocean topography** as a continuum up to the polar seas.	**Mean sea level**, mesoscale and sub-mesoscale currents, wind speed and significant wave height.	Resolution of gridded product: 10km (Threshold), 1km (Goal);	Temporal resolution <10 days (Goal: 1day);	Vertical accuracy of SSH (open ocean and leads): 0.02m Uncertainty of 1-second averaged measurements of significant wave height (0.5-8m): <0.15m + 5% of the significant wave height Wind speed uncertainty of 1-second along-track averages <1.5m/s	SAR altimetry with dual Ku/Ka bands + closed-burst chronogram Microwave radiometer (for tropospheric correction at least up to 10km to the coast)	MRD-120; MRD-420; MRD-430; MRD-440; MRD-450; MRD-460; MRD-480; MRD-490; MRD-500; MRD-510	**Sea Level Anomaly** **Mean Dynamic Topography** **Absolute Dynamic Topography** **Mean Sea Surface** (MSS) **Significant Wave Height** (SWH) **Surface Geostrophic Current**
SEC-OBJ-2. Support applications related to **coastal and inland waters**.	Retrieve **elevation over inland water bodies**. Monitor of **global river discharge and its long-term trend contributes to global freshwater flux** for global climate change on a regional to global scale.	Resolution <10km; Regional to global coverage.		Along-track resolution sufficient to meet the vertical accuracy requirement over the coastal boundaries of the Antartic and Greenland Ice Sheets.	SAR altimetry with dual Ku/Ka bands + closed-burst chronogram	MRD-240	
SEC-OBJ-3. Support applications related to **snow cover and permafrost**.	Support and contribute to studies and services in relation to **seasonal snow cover and permafrost applications over land**. Identify snow presence, structure changes as well as land surface state (freeze/thaw) and their link with permafrost state. Monitor lake level as proxy for permafrost change.				Microwave radiometer (for ice/snow type classification) SARIn altimetry with dual Ku/Ka bands + open-burst chronogram	MRD-120	Surface type; Ice type

Higher level products (e.g. Level-3 & -4)

Mission requirements at system level: Operational lifetime: >7 years; Orbit sub-cylce: <10 days; Track spacing within a full orbit cycle < 5 km at 50 deg latitude; Repetitive orbit spatial sampling; Ground track shall be maintained to be within 1 km of the reference ground track at the equator;

Level 1b products: Stack/Full waveform parameters; Radiometer brightness temperature; Interferometry parameters (coherence, phase difference)

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Reference documents

RD1	PEG-1 Report, User Requirements for a Copernicus Polar Mission, Step 1 Report, Polar Expert Group, Issue: 12th June 2017
RD2	PEG-2 Report, Polar Expert Group, Phase 2 Report on Users Requirements, Issue: 31st July 2017
RD3	Copernicus polaR Ice and Snow Topography ALtimeter (CRISTAL) Mission Requirements Document, version 2.0, ESA-EOPSM-CPTM-MRD-3350, Issued 28/02/2019.