# PolarMonitoring study:

# WP1 Review of the state of the art and analysis of user requirements

# summary & outcomes

# Introduction:

# Context of the CRISTAL mission

# Introduction: CRISTAL mission context

## CRISTAL, a future component of the Copernicus program

- **Copernicus is the European Union's Earth observation programme** coordinated and managed by the European Commission in partnership with the European Space Agency (ESA), the EU Member States and EU Agencies Secondary Objectives

- Copernicus goals are to achieve a **global and continuous wide range Earth observation capacity**. Providing accurate and easily accessible information, in particular **to understand the effects of climate change**.

- ESA and the European Commission are now working on the next generation of Sentinel satellites, called **High Priority Candidate Missions (HPCM):** these 6 new missions will start in orbit operations from ~2026 on, and will implement new sensing techniques not yet present on the current Sentinel generation

***=> The Copernicus polaR Ice and Snow Topography ALtimeter (CRISTAL) is one of the 6 high priority candidate missions***

# Introduction: CRISTAL mission context

## CRISTAL objectives

### ➢ Primary Objectives

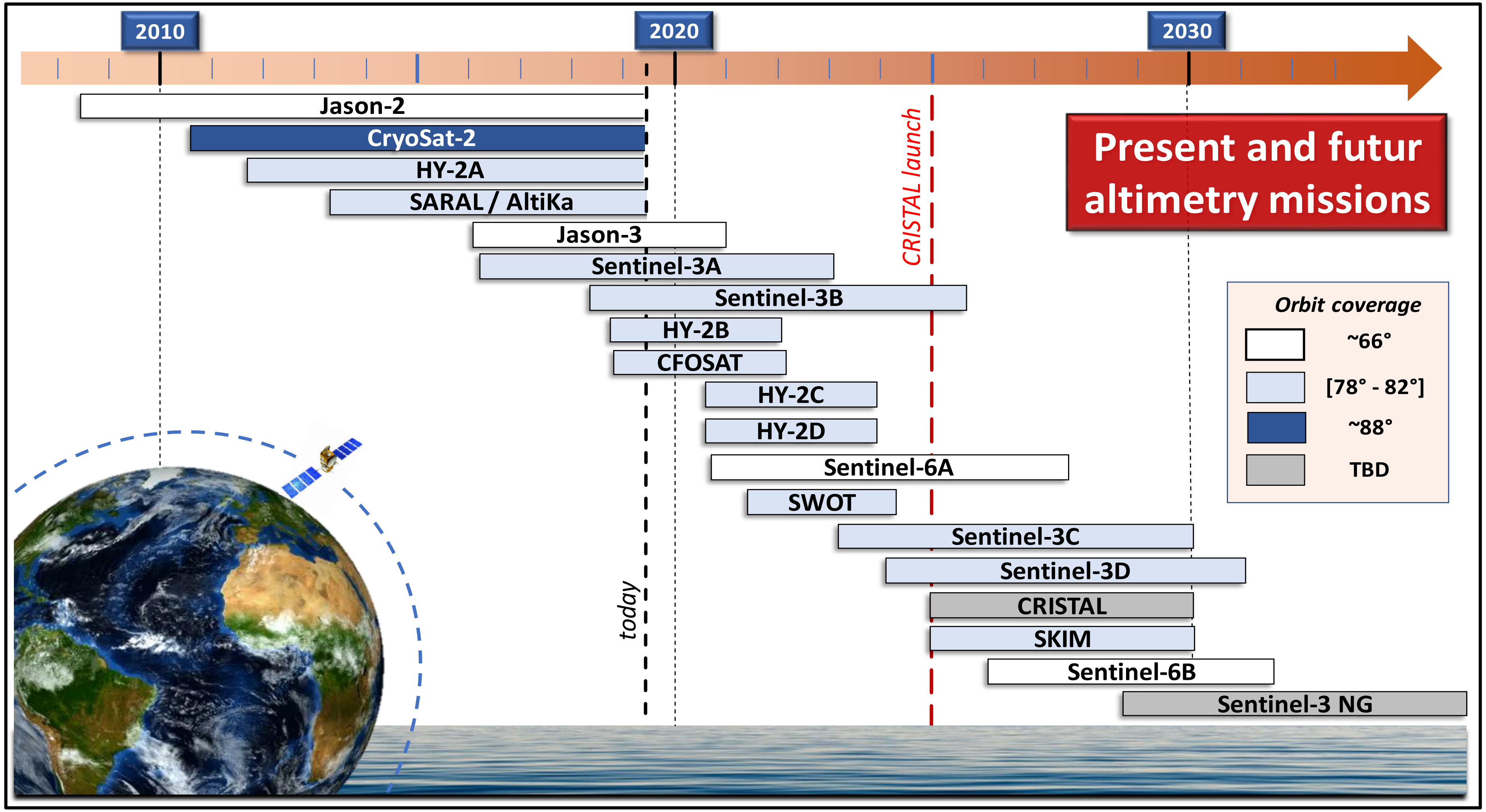
- To measure and monitor variability of Arctic and Southern Ocean sea-ice thickness and its snow depth.
- To measure and monitor the surface elevation and changes therein of glaciers, ice caps and the Antarctic and Greenland ice sheets.

### ➢ Secondary Objectives

- To contribute to the observation of global ocean topography as a continuum up to the polar seas.
- To support applications related to coastal and inland waters.
- To support applications related to snow cover and permafrost.

# Introduction: CRISTAL mission context

## Overview of the 2025 altimetry constellation



# Introduction: CRISTAL mission context

## CRISTAL altimeter configuration

To address the mission requirements, CRISTAL will embark an innovative dual-band Ku/Ka altimeter: IRIS, which stands for **"Interferometric Radar altimeter for Ice and Snow"**

| | *Open Ocean* | *Sea-ice & icebergs* | *Land Ice & Glaciers* |
|---|---|---|---|
| altimeter mode in **Ku-band** | **SAR closed-burst** | **SARIn interleaved** | **SARIn closed-burst** |
| altimeter mode in **Ka-band** | **SAR closed burst** | **SAR interleaved** | **SAR closed-burst** |
| Range window size | 256 samples / 64 m | 256 samples / 64 m | 1024 samples / 256m |
| Tracking window size | 256 samples / 64 m | 256 samples / 64 m | 2048 samples over ice sheet interior.<br>TBD for ice margins & glaciers |
| Tracking mode | Closed-Loop | Closed-loop | Closed loop over ice sheet interior<br>Open loop over ice margins & glaciers |

***IRIS key characteristics (from Kern et al. [2020], submitted status)***

**In addition Ku/Ka bandwidth will be 500MHz, improving vertical resolution compared to the others Ku-band altimeter (~30cm VS ~47cm)**

# WP1 objectives

- Radar altimetry from space: state of the art

  *results and lessons learned from previous missions, scientific applications relevant for a future altimeter polar mission*

- Gap analysis of the 2025 constellation wrt the cryosphere monitoring

- User requirements for a future altimetry polar mission

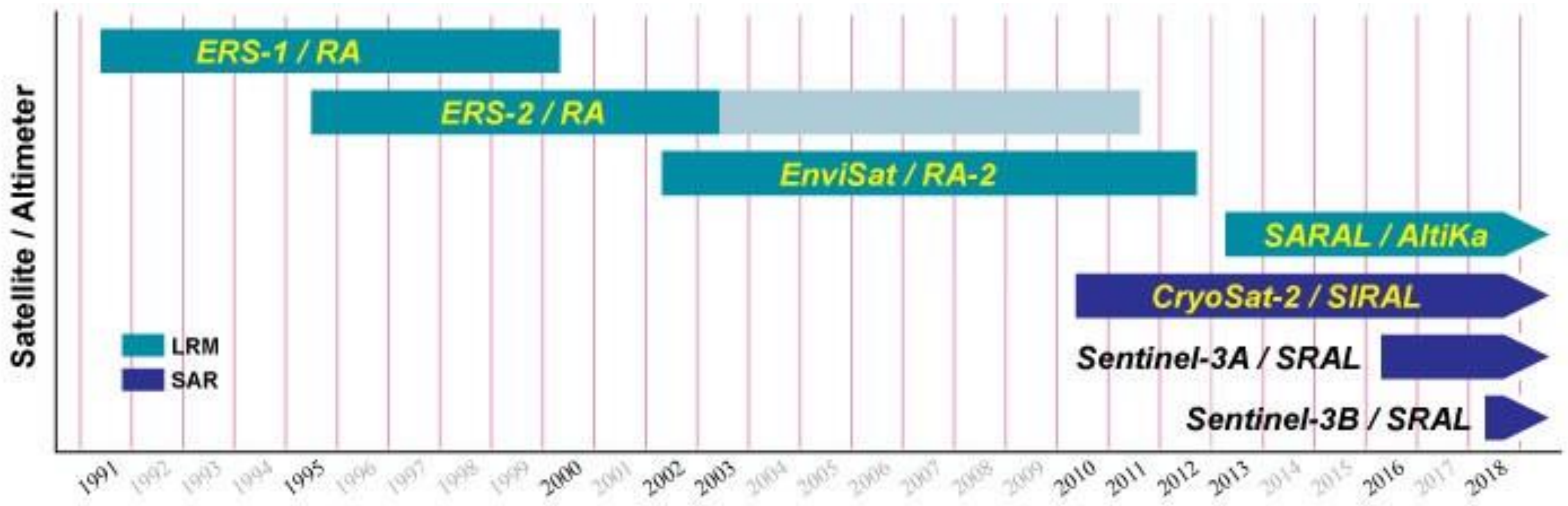
  *from Polar Expert Group reports [Duchaussois et al., 2017] ; Copernicus Marine Environment Monitoring Service (CMEMS) ; Copernicus Polar and Snow Cover Applications - User Requirements Workshop*

# WP1: Review of the state of the art and analysis of user requirements

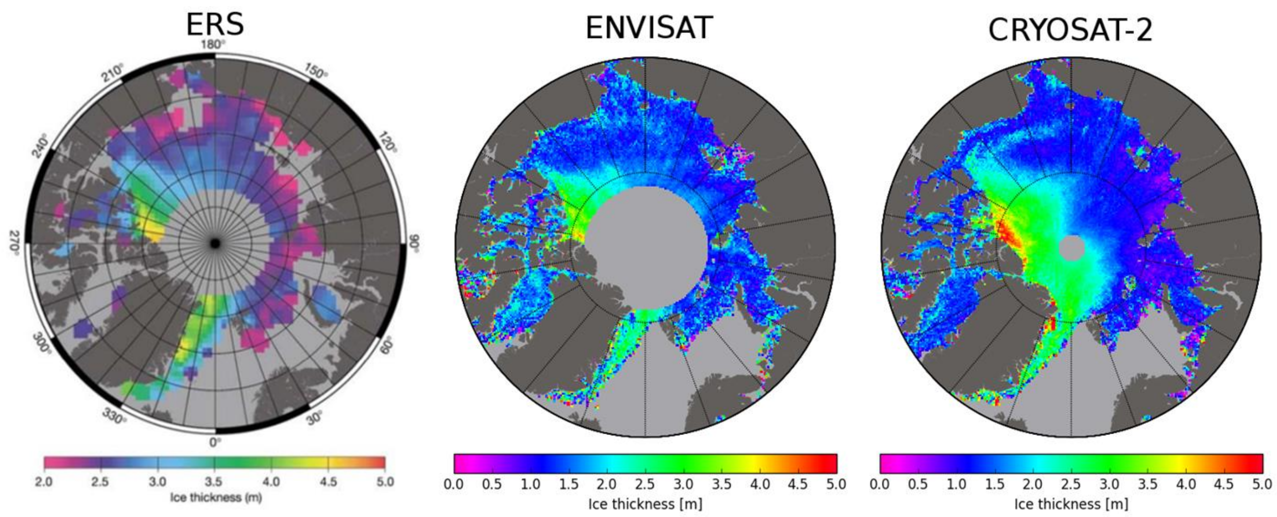
## *Sea ice surface*

# State of the art

**Sea-ice**



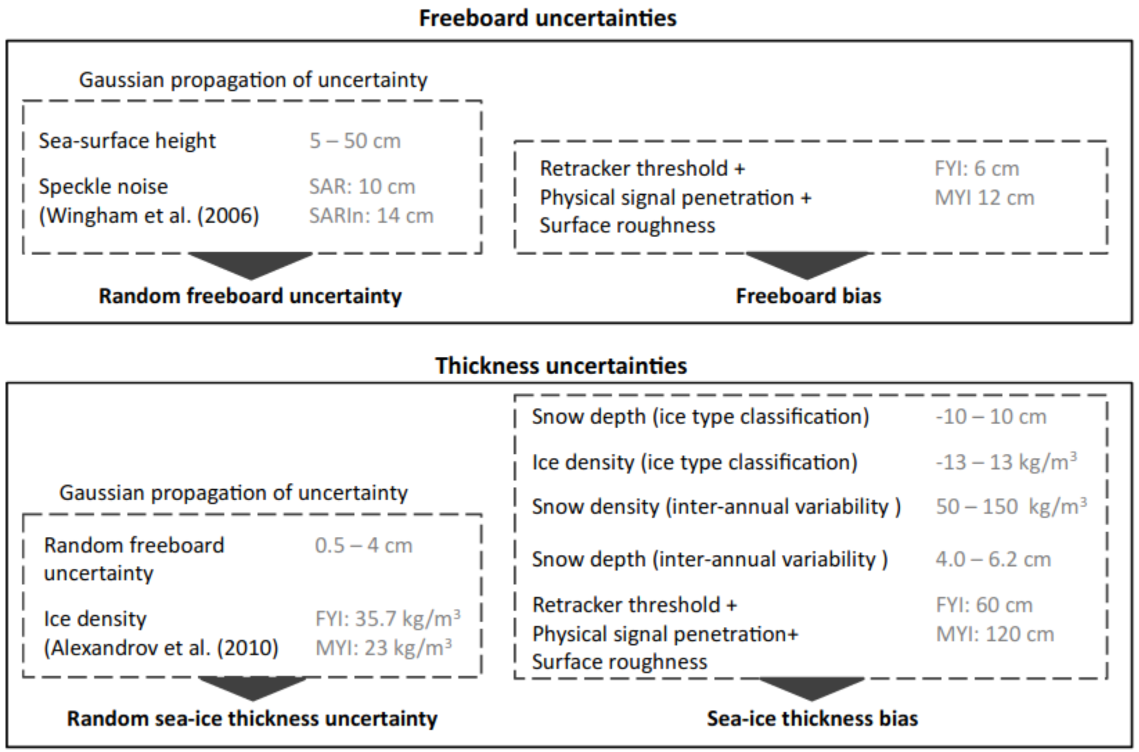

The past and current radar altimeter missions with an orbit poleward of 72°N and separated into traditional low-resolution measurement (LRM) and synthetic aperture radar (SAR): Years of mission launch and end are highlighted; ERS-2 only provided limited data after June 2003. (Figure from Quartly et al.,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




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

# State of the art

## *Sea-ice*




Flowchart of the CryoSat-2 uncertainty budget for freeboard and thickness, showing the typical range for the individual uncertainty of each parameter and referring to a single CryoSat-2 measurement. From Ricker, 2015.

| Factor | October error | October volume error | April error | April volume error |
|---|---|---|---|---|
| Snow Depth | 23.3% | 10.3% | 19.5% | 9.0% |
| Snow Density | 30.4% | 6.9% | 21.6% | 5.5% |
| FYI Density | 0.8% | 6.1% | 0.8% | 6.7% |
| MYI Density | 0.9% | 6.1% | 0.9% | 6.7% |
| Sea ice concentration | 5.0% | 4.5% | 5.0% | 3.4% |
| Inter-annual ice extent | 0.4% | 0.25% | 0.2% | 0.15% |
| Seasonal ice extent | 14.7% | 8.4% | 0.4% | 0.25% |
| TOTAL (root-sum-square) | | 14.5%[a] | | 13.0%[a] |

a

Excluding errors in seasonal ice extent.

give a value for the Arctic-wide error, with respect to the mean value, for each significant error source. The October volume error and April volume error columns show the contribution of each source to the total estimated sea ice volume error. These are then combined in a root-sum-square manner to give an estimate of the total monthly sea ice volume error. From Tilling et al., 2018

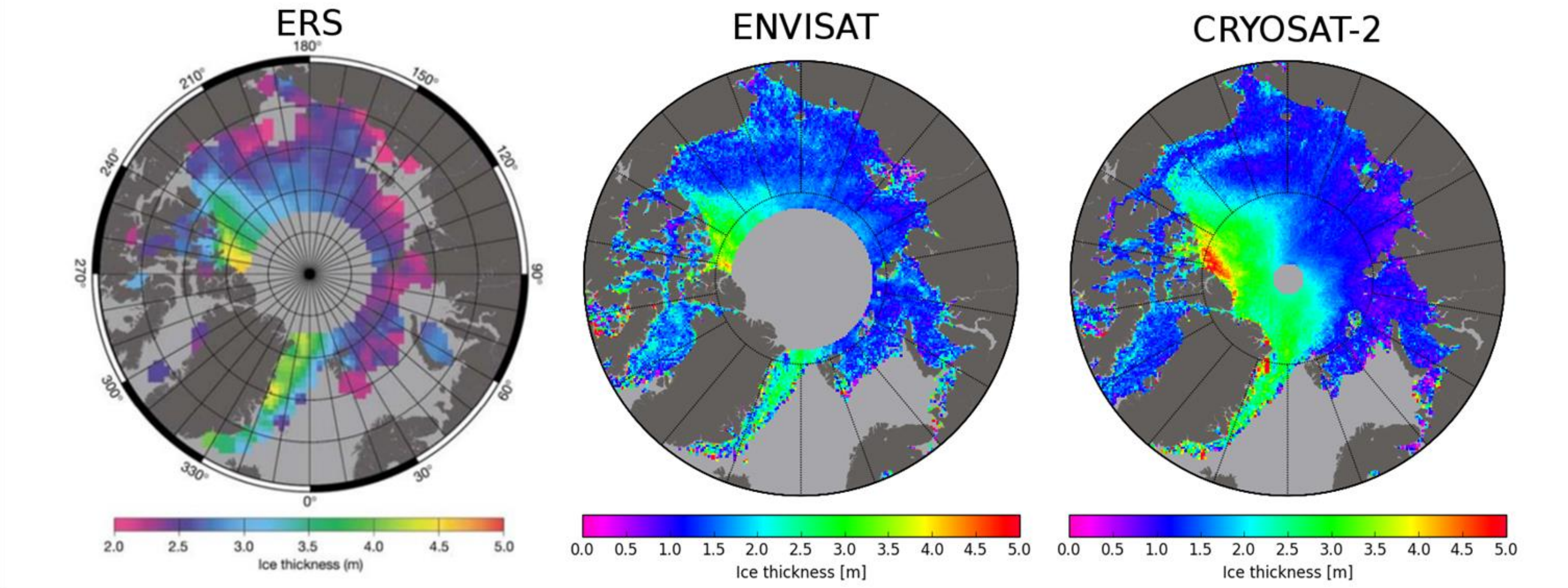
# Altimetry applications over sea-ice

**Sea-ice**

- Sea freeboard and thickness
- Monthly gridded products in  25 km x 25 km
- Not meeting the GCOS accuracy requirement of 0.1 m

Uncertainty of FYI: 6 cm MYI 12 cm in freeboard

scales up to FYI: 60 cm MYI: 120 cm in thickness

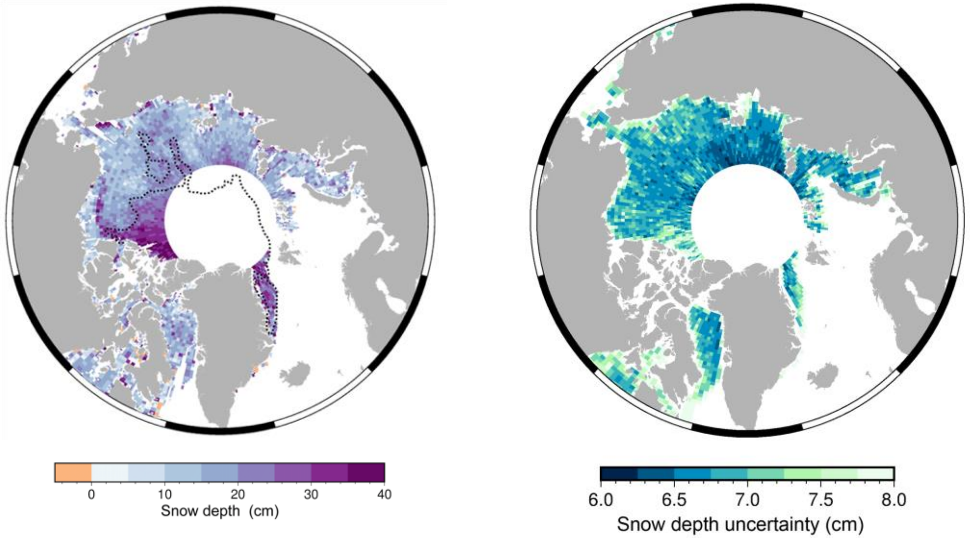


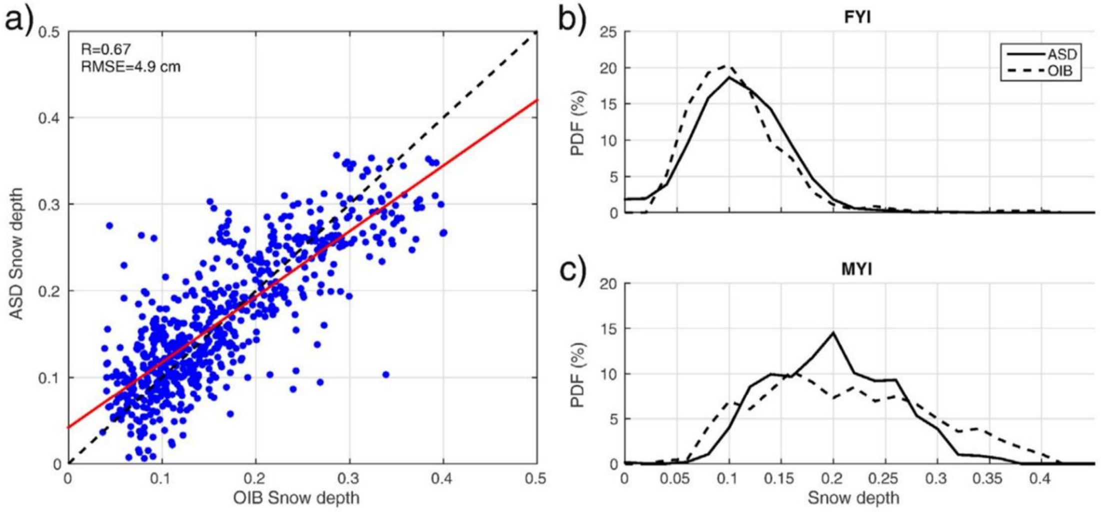
# Altimetry applications over sea ice

**Sea-ice**

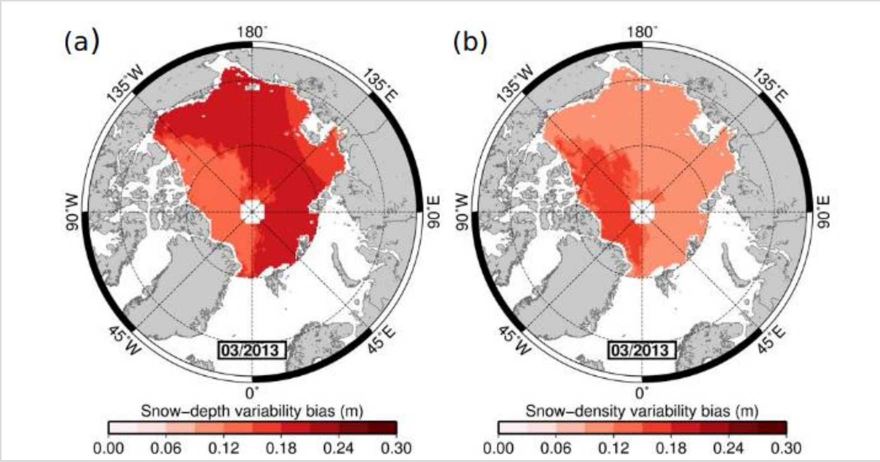
## Snow depth on sea ice

Snow depth and uncertainty for the dual-altimeter snow thickness product by Lawrence et al., 2018 (right) and comparison of combined Altimetric Snow Depth (ASD) to OIB snow depths, and probability distribution functions of snow depth for ASD and OIB over first year ice and multi year ice (below). From Guerreiro et al., 2016.




- Warren snow estimates from 1950's-1990's still the single most used
- Snow depth and density averages based on measurements from ~2 stations, high spatial and temporal variability of snow makes estimation of errors of the climatological means difficult (Shalina et al., 2018)
- Outdated over FYI (~0.2 m difference to OIB, Kern et al., 2015), could be improved over MYI (~0.02-0.12 m, Kern et al., 2015) (Kurtz and Farrell 2011, Shalina et al., 2018)
- Do not represent current conditions, especially not in NRT

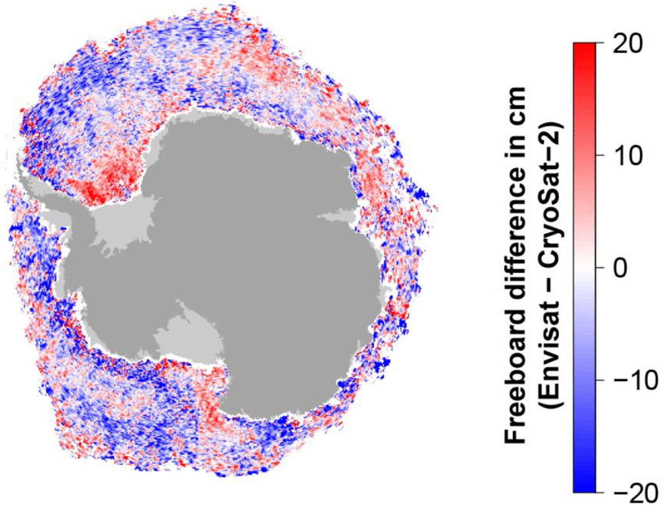



Contribution to the sea-ice thickness bias originating from (a) snow-depth variability,(b) snow-density variability. From Ricker 2015.

# Gaps of the 2025 constellation

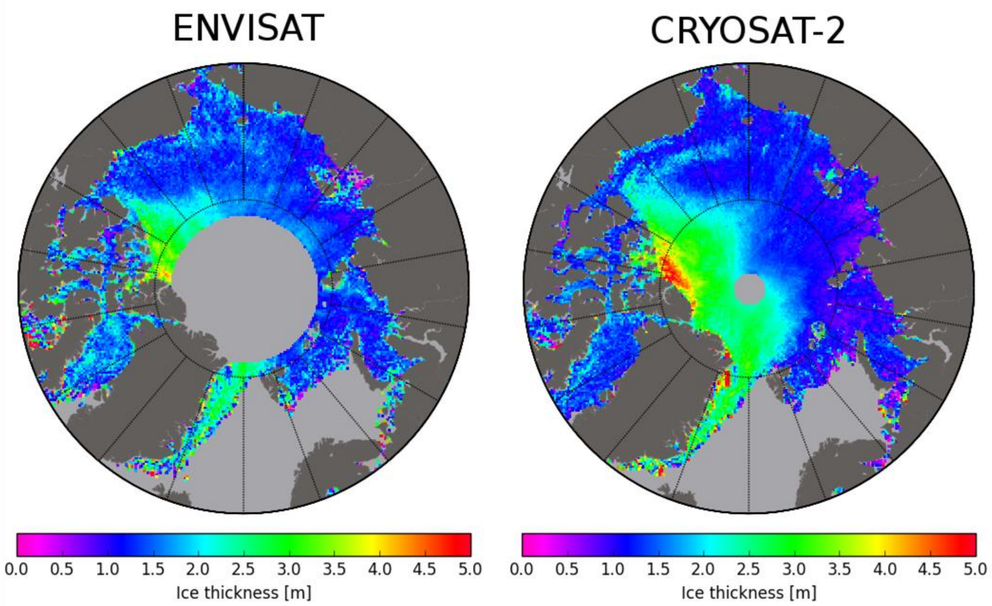
***Sea-ice***

**1)  Lack of measurements beyond 81.5°N/S**, resulting in no data over most of the Arctic September sea ice pack (minimum ice extent)
2)  Remaining uncertainty in Sentinel-3 based SIT estimates due to **uncertainty in snow load and ice type estimates**
**3)  Limitation of SIT retrieval to winter months only**
4)  Antarctic SIT retrieval




Freeboard differences in September 2011 for CS2 and Envisat (left) from Paul et al., 2018.

Sea ice thickness (right)



# User requirements for a future polar mission

**Sea-ice**

- Polar Expert Group (PEG) on sea ice:
  - Freeboard
    - Improved accuracy
  - Sea ice thickness
    - Continuity of measurements
    - Accurate measurements for climate research community, better short-range forecasts for ship routing
    - Daily coverage and NRT availability for operational use
    - Improved measurement of sea ice thickness distribution for models and operational
  - Snow on sea ice
    - Needed for accurate determination of sea ice freeboard, needed in SIT scale
- GCOS:
  - To address issues concerning sea ice's response to polar warming, GCOS (2011) propose a target **accuracy for sea ice thickness measurements of 10 cm**, although acknowledging that the accuracy achievable at that time was ~50 cm when averaged over a month.

# User requirements for a future polar mission

**Sea-ice**

- Comments on the PEG and GCOS requirements
  - Distinction between Level-2 (along-track) and Level-3 (gridded) requirements
    - Temporal sampling rarely relevant for Level-2
    - Daily coverage only as an improved estimate with combined sea ice velocities
  - Most of the accuracy requirements (improved accuracy) are without specific limits (however stated in MRDs)

# WP1: Review of the state of the art and analysis of user requirements

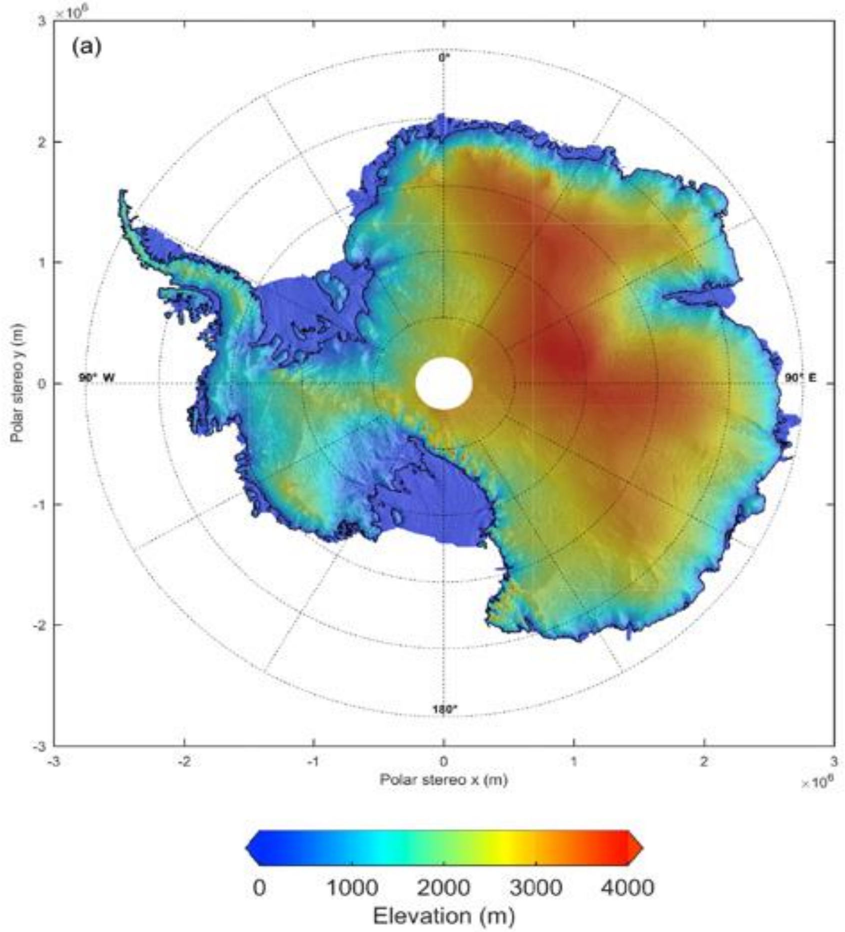
## *Ice sheet surface*

# Overview

*Ice-sheet*

1. Scientific Applications of the CRISTAL Mission.
2. User Requirements Analysis.
3. Gap Analysis at 2025.

## 1. Digital Elevation Models

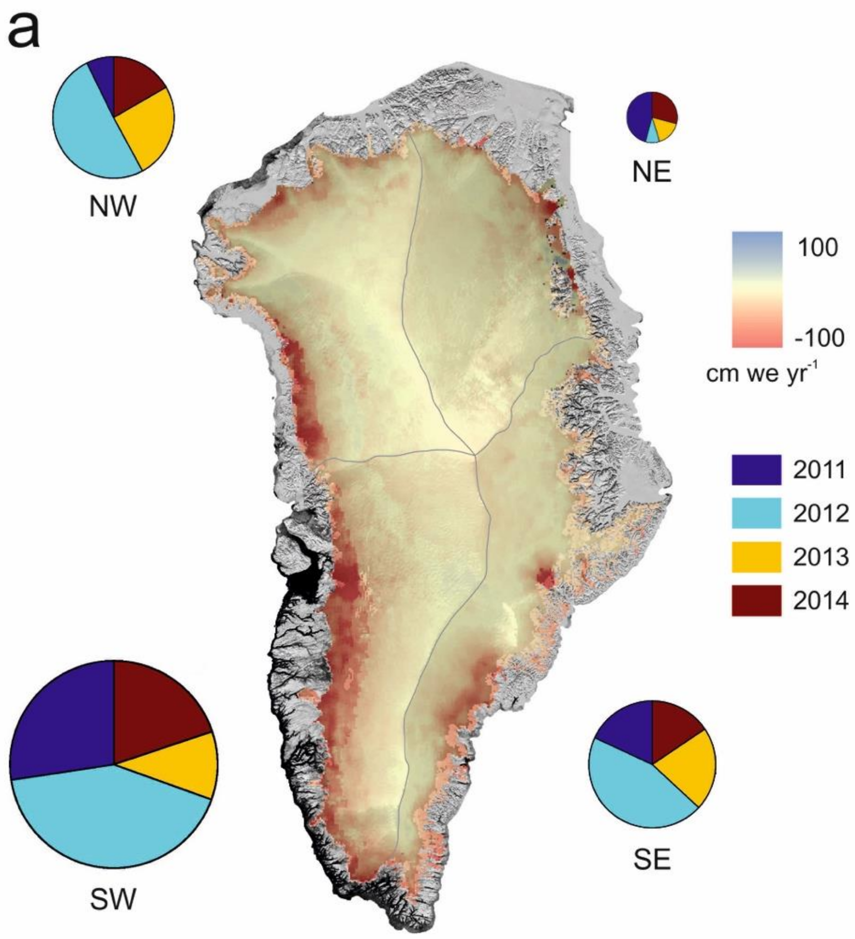



**CryoSat-2 DEM of Antarctica (Slater et al., 2018)**

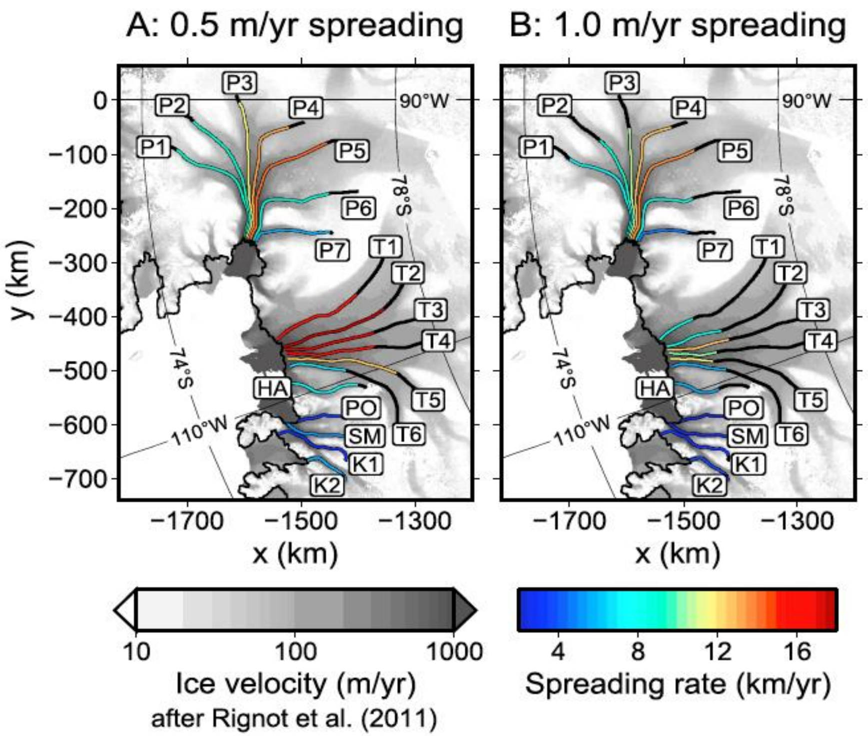
Scientific Applications

*Ice-sheet*

## 2. Surface Elevation Change & Mass Balance

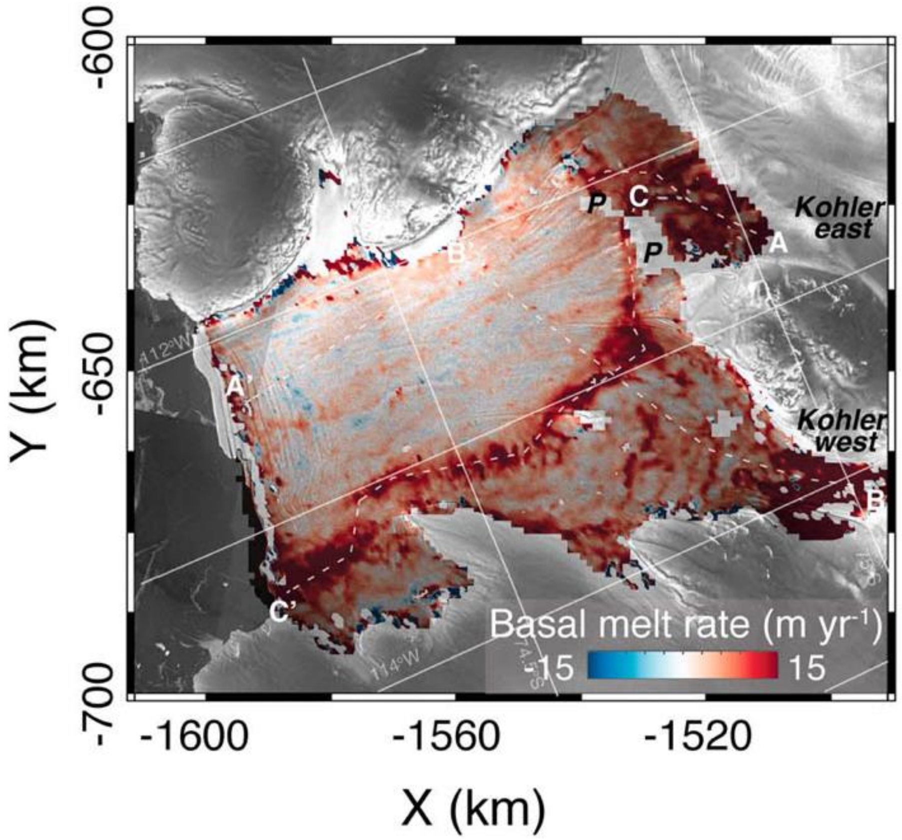



**Greenland specific mass balance from CryoSat-2 (McMillan et al., 2016)**



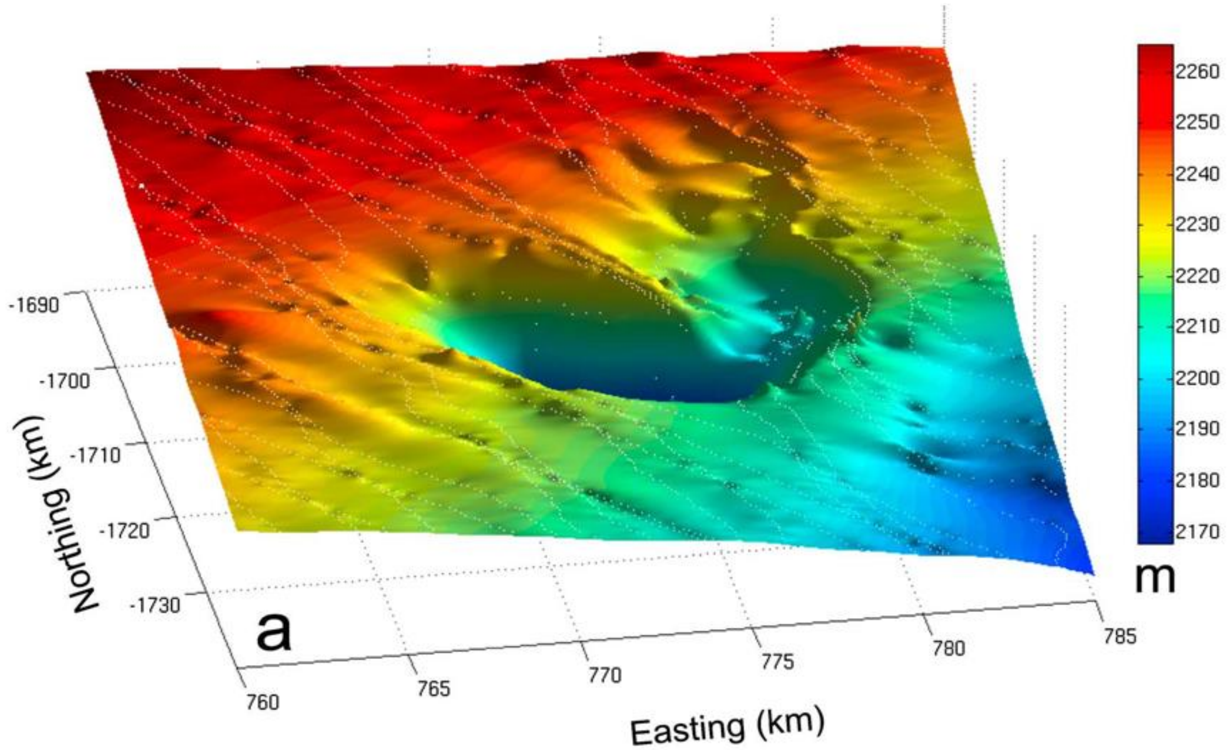

**Propagation rate of dynamic instability from CryoSat-2 (Konrad et al., 2017)**

## 3. Ice Shelf Thickness Change & Basal Melt



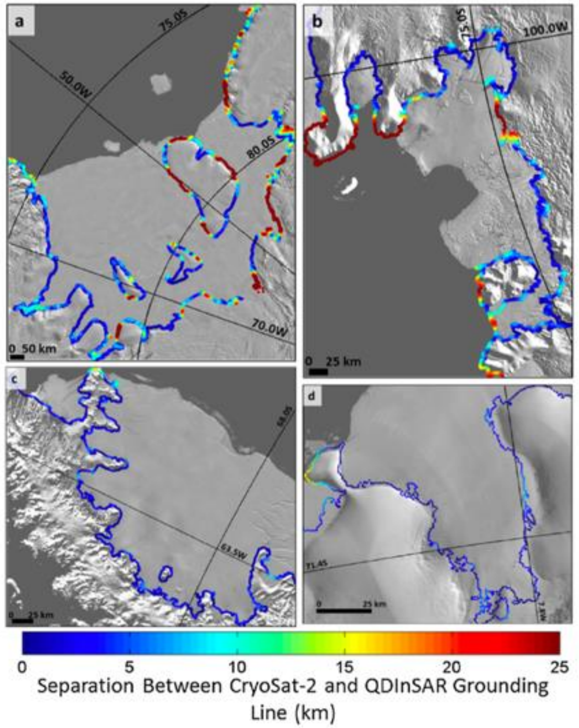

**Basal melt rate of Dotson Ice Shelf from CryoSat-2 swath processing (Gourmelen et al., 2017)**

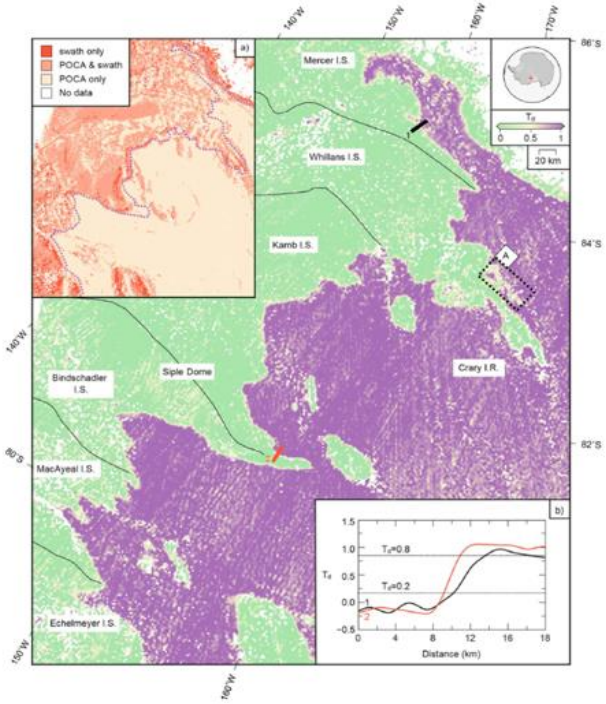
## 4. Subglacial Lake Drainage




Subglacial lake drainage crater in East Antarctica, mapped by CryoSat-2 (McMillan et al., 2013)

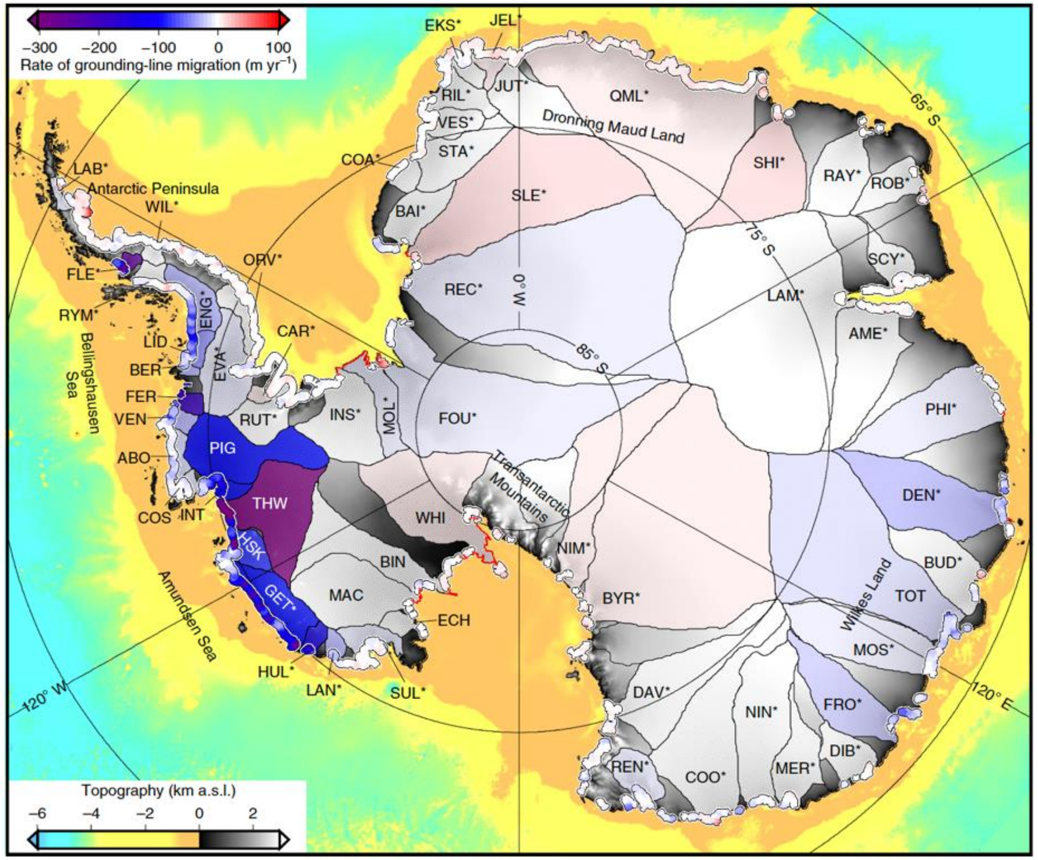
## 5. Grounding Line Location




**Antarctic Grounding Lines from CryoSat-2**
**(Hogg et al., 2018; Dawson et al., 2017)**

## 6. Grounding Line Migration




**Grounding Line migration rates from CryoSat-2 (Konrad et al., 2018)**

# User Requirements

**Ice-sheet**

2015 Update of Actions in
The Response of the Committee on Earth
Observation Satellites (CEOS) to the Global
Climate (

*Develope*
*Satellite*
*Satellites*
*Observing Syste*
*Convention*
*Sci*

European Commission
Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW)
Aerospace, Maritime and Defence Industries
Copernicus: Infrastructures

SPECIFIC CONTRACT No 2 - 30-CE-0747761100-24

ORGANISATION OF WORKSHOPS

FOR GATHERING SETS OF REQUIREMENTS TO BE FULFILLED BY THE NEXT GENERATION COPERNICUS SPACE COMPONENT

Implementing Framework Service Contract 386/PP/2014/FC (30-CE-0672813/00-46) of 05/12/2014, requirements framework for the next generation of the Copernicus space component

COP
AP

USER REQUIREMENTS

Phase 1 Report

USER REQUIREMENTS FOR A COPERNICUS POLAR MISSION

*Phase 2 Report*

31 July 2017

# User Requirements analysis

## Ice-sheet

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


**AD2.** PEG-1 Report, User Requirements for a Copernicus Polar Mission, Step 1 Report, Polar Expert Group, Issue: 12th June 2017.
**AD3.** PEG-2 Report, Polar Expert Group, Phase 2 Report on Users Requirements, Issue: 31st July 2017.
**AD4.** 2015 Update of Actions in The Response of the Committee on Earth Observation Satellites (CEOS) to the Global Climate Observing System Implementation Plan 2010 (GCOS IP-10), 10th May 2015.

# Potential users & services

*Ice-sheet*

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

# Gaps analysis at 2025

*Ice-sheet*

(1)A lack of measurements beyond 81.35°N/S.

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

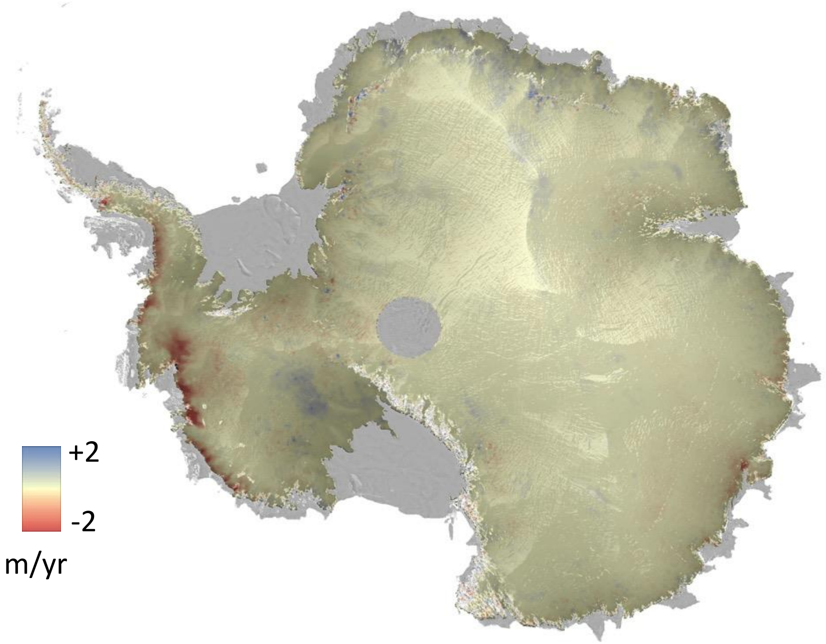
(3)A lack of certainty in coastal regions with complex topography, due to an absence of interferometric SAR altimeter measurements.

(4)A demand for greater certainty in resolving small elevation changes across large inland areas of the ice sheet.

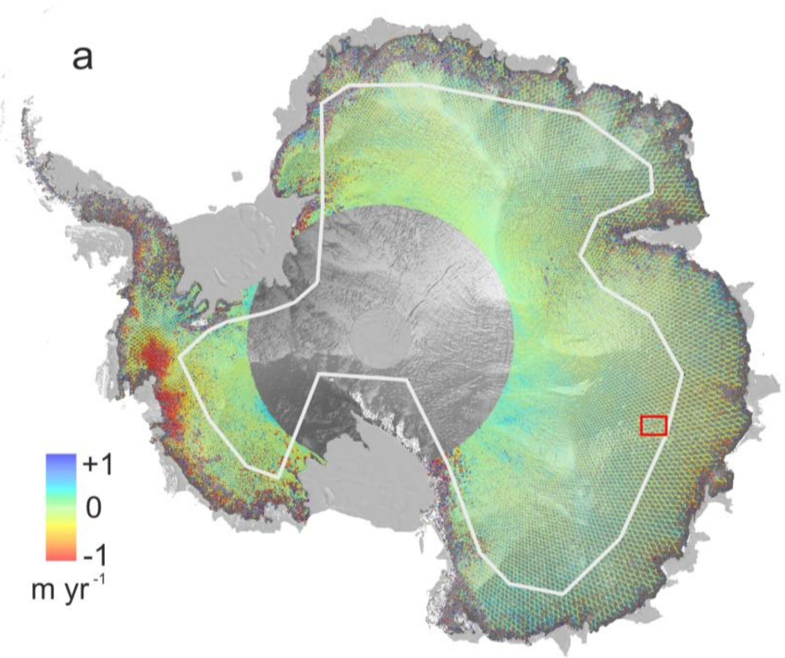
# Gaps analysis at 2025

## (1) A lack of measurements beyond 81.35°N/S

If altimeter coverage is dependent upon Sentinel-3, then it will be limited to 81.35°. This will mean that the User Requirement *Coverage of measurements to within 2° latitude of the poles* will not be met, and ~25% of Antarctica will not be observed.




**CryoSat-2 Antarctic elevation change (McMillan et al., 2014)**




**Sentinel-3 Antarctic elevation change (McMillan et al., 2019)**

# Gaps analysis at 2025

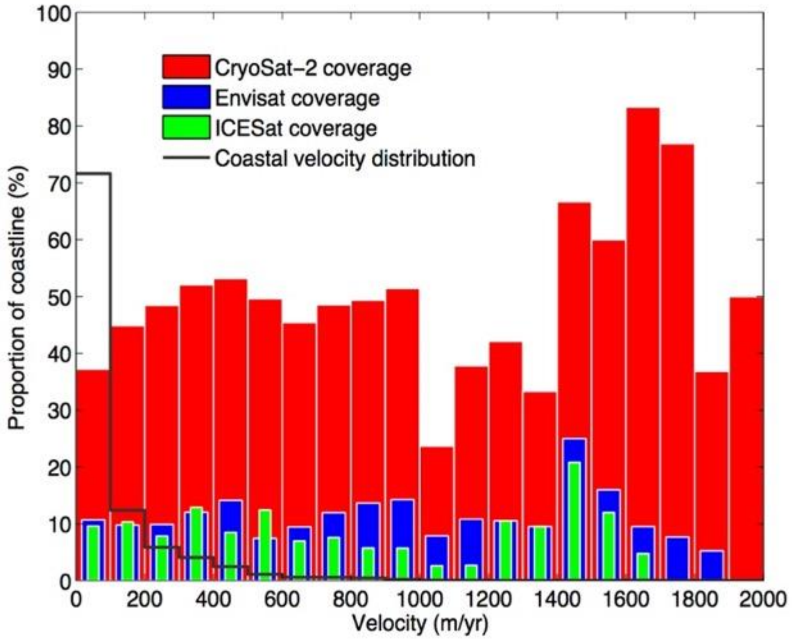
***Ice-sheet***

(2) <u>A lack of continuous coverage of ice sheet margins</u>

Satellites operating with a short orbital repeat period (e.g. Sentinel-3; 27 days) do not achieve continuous coverage of ground tracks at the ice sheet margin.

At a latitude of 75°S (Amundsen Sea coastal sector), a ground track spacing of the order of ~10 km can be expected (S3A+S3B).

Past missions with a short repeat period (e.g. Envisat) provide only ~ 8% coverage of the Antarctic ice sheet margin, as compared to 49% for a satellite in a CryoSat-2 orbit.



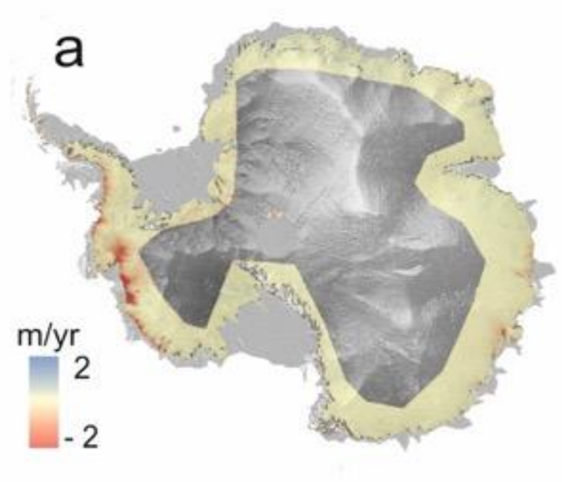

**Proportion of Antarctic coastline sampled by different missions (McMillan et al., 2014).**

# Gaps analysis at 2025

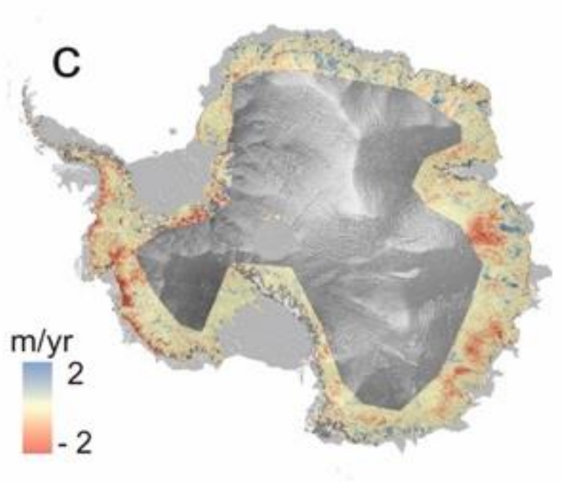
*Ice-sheet*

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

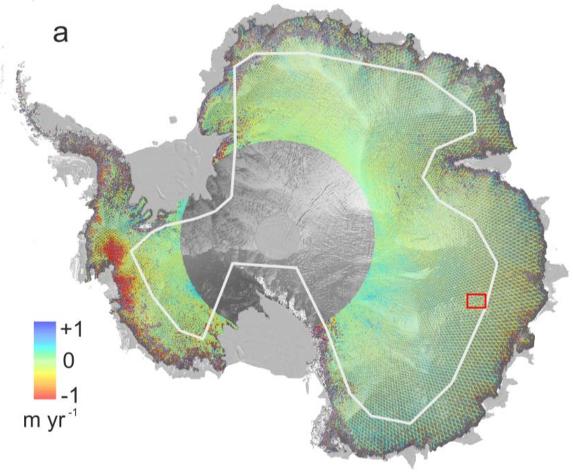
At 2025, coverage of the complex ice sheet margin regions will be limited to non-interferometric SAR mode acquisitions. This will make it difficult to achieve the User Requirements of an *absolute accuracy of approximately 0.5 metres* and *an accuracy and stability of 0.1 m/yr* in ice sheet margin regions.




CryoSat-2 SARIn mode elevation change (McMillan et al., 2018)




CryoSat-2 SID mode elevation change (McMillan et al., 2018)




Sentinel-3 SAR mode elevation change (McMillan et al., 2019)

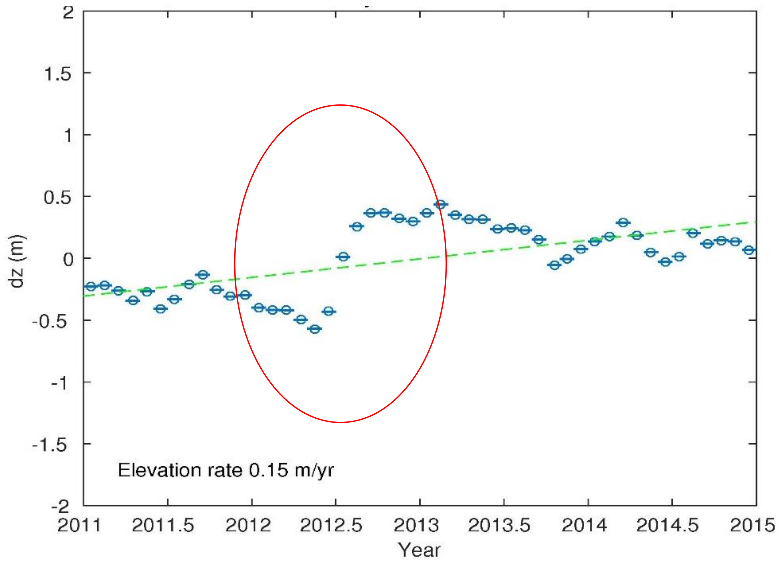
# Gaps analysis at 2025

**Ice-sheet**

(4) <u>A demand for greater certainty in resolving small elevation changes across large inland areas of the ice sheet.</u>

Small residual elevation changes due to poorly understood changes in Ku-band penetration and subsurface scattering are a principle source of uncertainty in altimetry-derived mass balance estimates.

At 2025, without dual Ku- and Ka-band retrievals it will be difficult to reduce this uncertainty, impacting the User Requirement of *absolute accuracy of approximately 0.5 metres* and *an accuracy and stability of 0.1 m/yr* in ice sheet interior regions.




CryoSat-2 changes in scattering horizon over the interior of Greenland.

# WP1: Review of the state of the art and analysis of user requirements

## *Ocean surface*

# State of the art

**Ocean**

- Full review of the altimetry from historical missions up to now, with synthesis on the evolution of altimetry technologies (LRM,SAR, Ku/Ka bands…), along with scientific & downstream applications

- **Focus on polar ocean.** Compared to open ocean, specific problems add up over sea-ice areas:
  - **Altimeter range:** degradation of the altimeter range accuracy
  - **Wet tropospheric correction:** Radiometric estimations contaminated by the presence of ice-floe
  - **Dynamic Atmospheric Correction (DAC):** Interrogations regarding the correction accuracy

- The lack of accurate altimetry measurements also complicates the computation of necessary corrections to estimate sea level:
  - **Oceanic tides correction**
  - **Mean Sea Surface (MSS) correction**

- Overall, the **GMSL uncertainty of the Arctic ocean**, over the 1993-2009 period is estimated at **1.3 mm/yr** [Prandi et al., 2012 ; Cheng et al. 2015]. Whereas, **GMSL uncertainty over open ocean** is estimated at **0.4 mm/yr** [Ablain et al., 2019]

# Applications of altimetry over open ocean

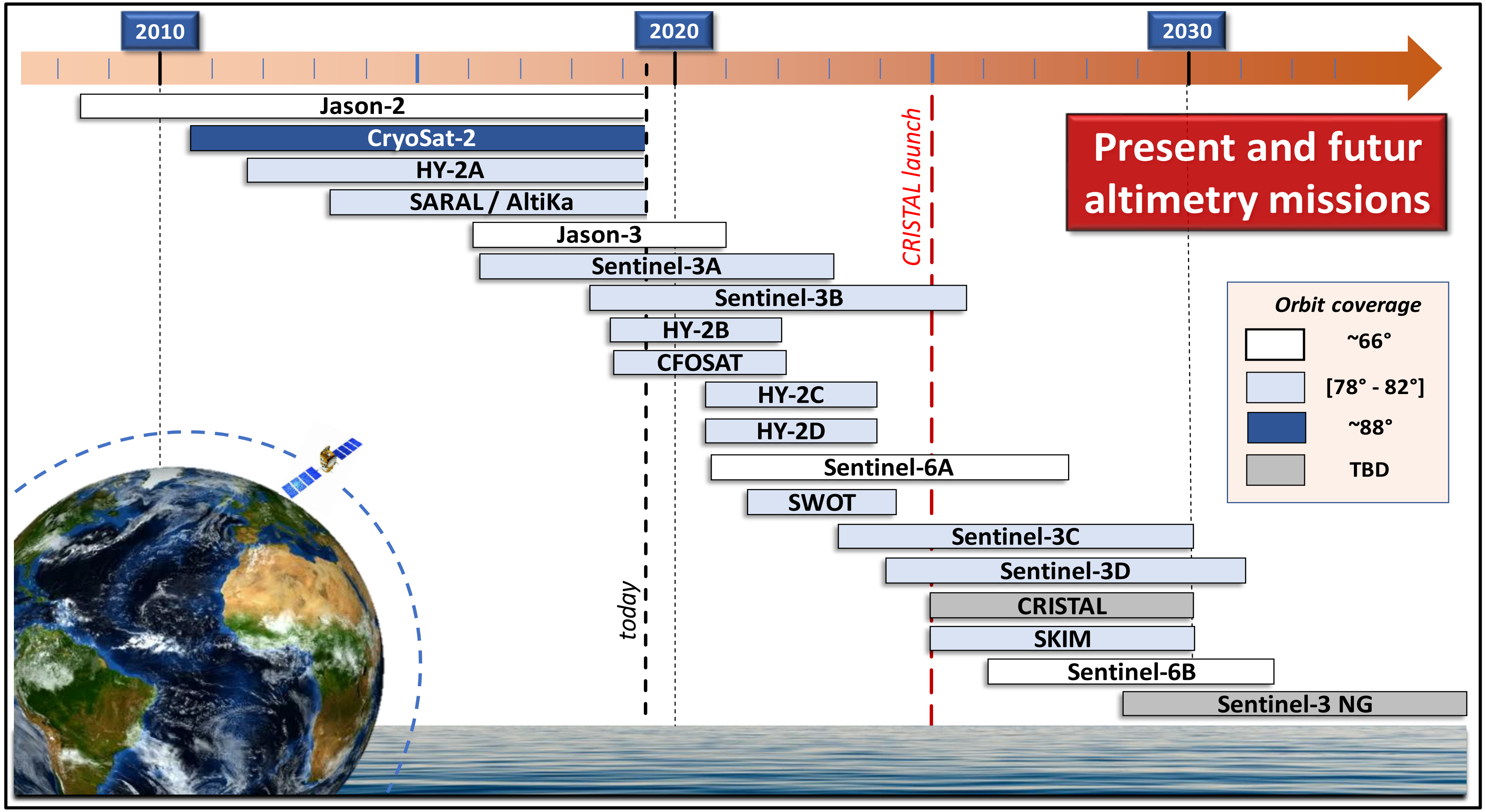
Ocean

- **Climate change:** Global Mean Sea Level Monitoring (GMSL), estimated at ~3 mm/year since 1992, with a 0.4mm/year uncertainty (for +/- 66° latitudes)
- **Geodesy:** satellite altimetry plays an important role in mapping Earth's geometric shape (Geoid, Mean Sea Surface)
- **Oceanic tides:** Ocean tides represent more than 80% of the surface variability in the open ocean.
- **Oceanic circulation:**
  - **Ocean eddies and mesoscale variability**
  - **Mean Dynamic Topography:** Quantity that bridges the geoid and the mean sea surface,
  - **Tropical ocean variability:** significant influence on the Earth's climate (ENSO)
- **Operational oceanography:**
  - development and implementation of scientific algorithms, analysis tools and information systems that routinely produce and deliver observation data and model-based information
  - used for near-real time monitoring, state assessment/reanalyses, ocean forecasts and for scientific research
- **And many downstream applications:**
  - Fishery management
  - Marine safety,
  - Offshore industry
  - Ship routing
  - pollution forecasting

# Gaps of the 2025 constellation

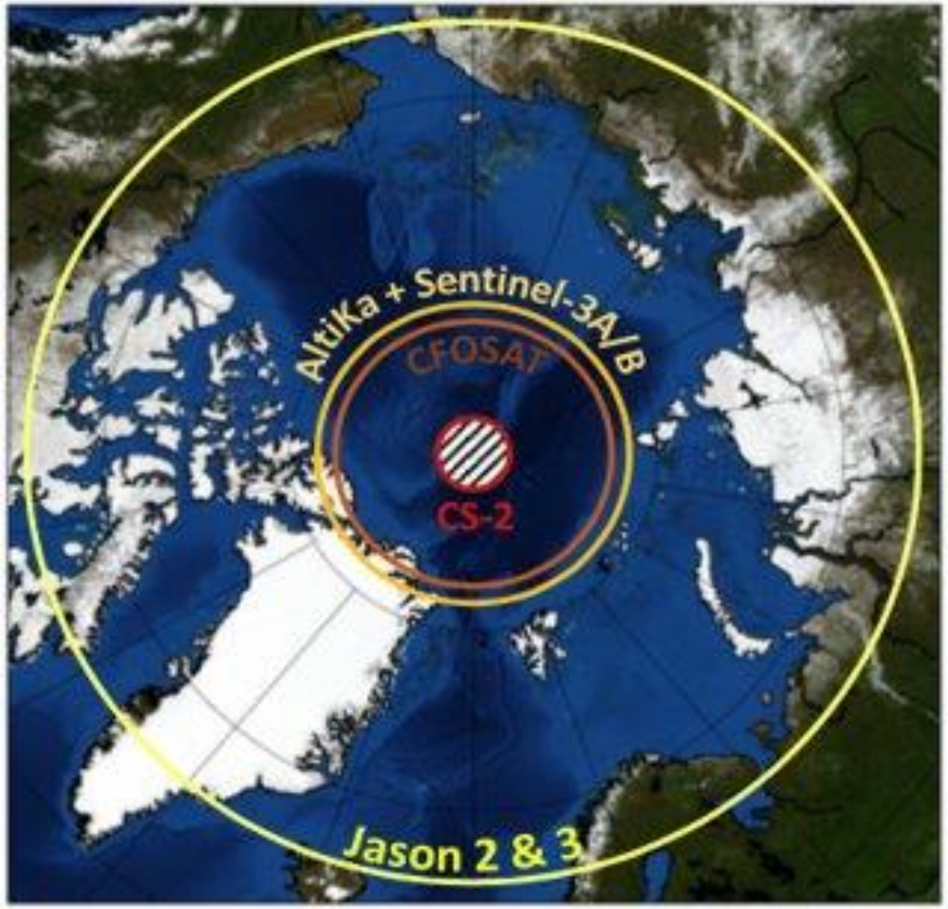
Ocean

## Overview of the 2025 altimetry constellation



# Gaps of the 2025 constellation

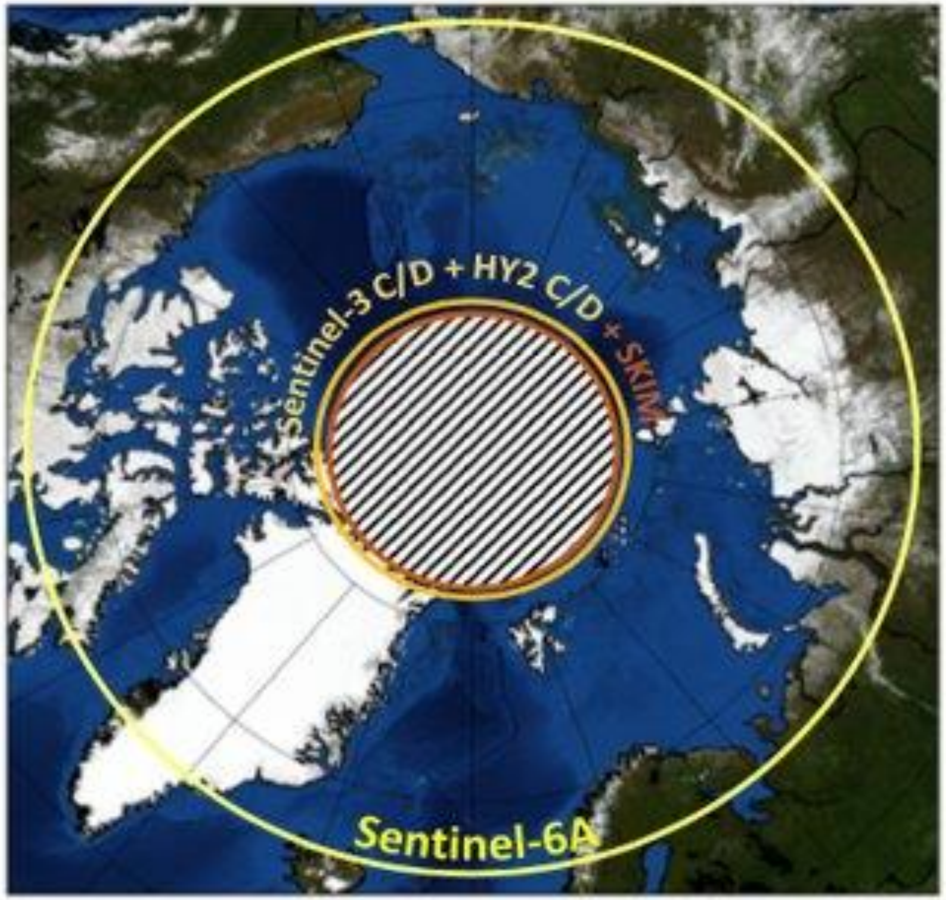
## Current polar area coverage

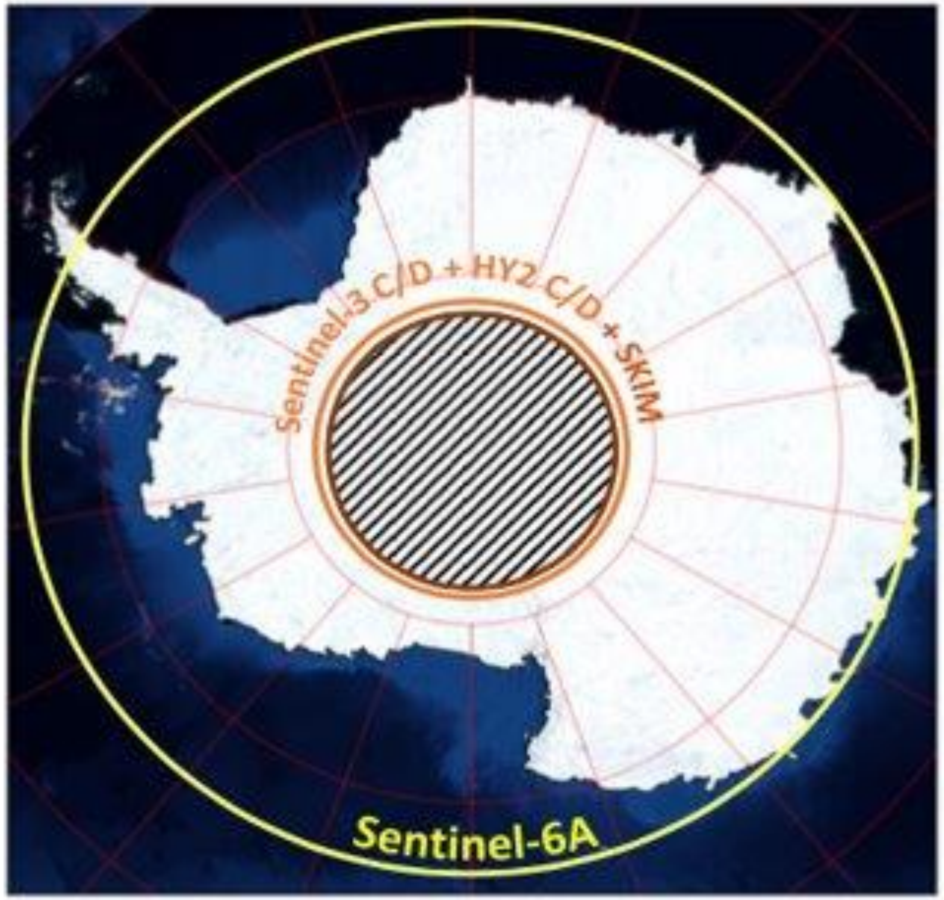



# Gaps of the 2025 constellation

Ocean

## 2025 polar area coverage



# Gaps of the 2025 constellation

Ocean

- **Future altimetry constellation should be composed of 4 to 6 missions in the 2025-2030 horizon** (2 Sentinel-6 ; 2 Sentinel-3 ; 2 HY)

- **For the open-ocean**, a dedicated study will be necessary to assess the added value of CRISTAL in the context of a 4-6 missions. The chosen orbit will also drive the benefits.

- **For the polar-ocean,** Sentinel-3 series covers most of the **Antarctic Ocean**, but not entirely. **Most of the Arctic ocean will not be monitored (Sentinel-3 coverage is up to 81° only)**

- With the absence of north pole coverage, large uncertainties will remain on the Artic ocean monitoring (MSL trend, mesoscale circulation, oceanic tides, Mean Sea Surface, wind & wave forecast…)

# User requirements for a future polar mission

Ocean

- **From the Polar Expert Group (PEG) reports** (Duchossois et al., 2018a, 2018b) on polar sea level:
  - "Actual data from the CMEMS catalogue does not allow a satisfactory sampling north of 82° N". "**Prime importance that the orbit configuration allows covering the central Arctic Ocean"**.
  - "Desirable improvements wrt CS2 capabilities would be to **improve lead detection** capabilities further (resulting in more measurements over sea ice) and to **observe sea surface topography at the scale of eddy fields** (1-5 km)."

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

# User requirements for a future polar mission

**Ocean**

## User requirements: goals expected for the oceanic parameters, from the PEG report

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

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Ocean

## Comments regarding the PEG goals

- Gridded products must be discussed in the context of a multi-mission constellation. For now, CMEMS current topographic gridded products are daily products, with a 0.25° spatial resolution.
- Temporal sampling for along-track products is not relevant.
- Mean dynamic topography cannot be computed along-track. *=> MDT to be substituted by ADT*

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- Mean dynamic topography cannot be computed along-track. *=> MDT to be substituted by ADT*
- Requirements should be discriminated between open-ocean / polar ocean.
- Requirements between along-track & gridded products should also be discriminated
- Impossible to observe dynamical features at the scale of eddy fields (1-5 km). Current observability by radar altimetry is 40km-50km at the best [Dufau et al., 2016].