PolarMonitoring study:

WP2 Assessment and consolidation of mission requirements

Summary & Outcomes

WP2 objectives

1 - Examination of **level 1 and level 2 preliminary products** described in the Mission Requirement Document (MRD)

2 - Inventory of existing **level-1 and level-2 ground segment algorithms** to derive the geophysical parameters provided in the products

3 - Analysis of the CRISTAL **observation system concept** and its assets to address user/mission requirements

4 - Analysis of the CRISTAL **Mission Requirement Document** and **updates proposal**

WP2: Assessment and consolidation of mission requirements

Sea ice surface

Level-1 and Level-2 parameters

Sea-ice

Level-2 geophysical parameters (listed for L1 and L2 in TN2)

- Geophysical corrections: e.g. atmospheric and tidal
- Measurement parameters: frequency ranges for Ka and Ku, sigma0, locations of echoing point and surface elevation
- Auxiliary data from external sources for: sea ice concentration, sea ice type, mean sea surface height

Level-1 and Level-2 parameters

Sea-ice

Level-2 geophysical parameters (listed for L1 and L2 in TN2)

- **Local sea level:** function of distance to the next lead (local sea surface height) detected
- **Ice floe elevation** (interpolation between sea ice height)
- **Surface type** (from altimeter; lead/floe/open ocean/undefined), **ice type** (from altimeter + radiometer; FYI/MYI/mixed): with (physical) retracker, MWR
- **Distance to the closest lead along-track** (used for freeboard computation): from local sea level measurements
- **Radar freeboard for both frequencies and uncertainties**: from local sea level and the ice floe elevation
- **Radar-derived snow depth, snow load correction correction for slow propagation in snowpack** (Ku-band): mainly from Ka-Ku -band differences (need of dedicated retrieval method)
- **Sea ice freeboard, thickness, volume:** derived from the other variables
- Auxiliary data: needed for freeboard to sea ice thickness conversion: snow, sea ice, water densities, ice type

Level-2 algorithms

Retracking

Existing options mainly include **empirical** and **physical** retrackers, of which the physical retrackers are likely to gain more in terms of accuracy when applied to CRISTAL measurements

Snow depth retrieval

Available algorithms are developed for mainly CryoSat-2 and AltiKa, and the related uncertainties (~0.08m) in the estimates are likely reduced with simultaneous Ku- and Ka-band measurements from CRISTAL

Level-2 algorithms

Sea-ice

Retracking

	Empirical			Physical					Numerical
Retracking algorithm	Surface-type specific retrackers	TFMRA	Waveform centroid retracker	Waveform fitting using waveform model	SAMOSA +	ALES+	Neural network supervised classification	K-medoids clustering	Facet-based model
SRL Ku/Ka	9/9	9/9	9/1	9/1	7/1	7/1	6/6	6/1	6/2

Snow depth retrieval

Method	SRL Ku/Ka
Altimetric Snow Depth (ASD)	7/7
Dual-altimeter snow thickness (DuST)	7/7

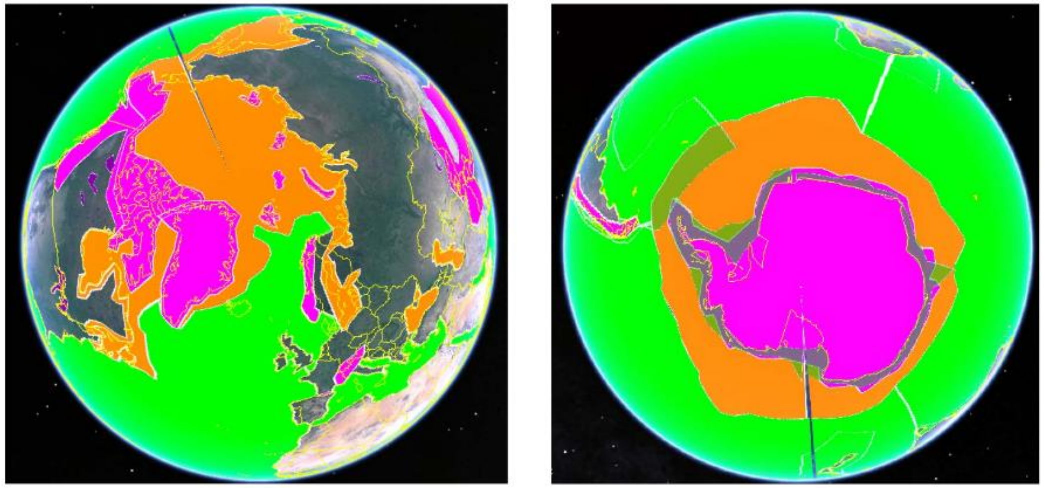
Scientific readiness level (SRL)
9: Science impact qualification
8: Validated and matures science
7: Demonstrated science
6: Consolidated science and products
...
2:Consolidation of scientific ideas
1: Initial scientific idea

Altimeter configuration over sea ice

➢Sea-Ice and Icebergs (SII) **open-burst or SARIn mode** over potentially sea ice covered areas **for Ku-band**

➢Land-Ice and Glacier (LIG) closed-burst SARIn mode over ice caps, potentially covering some coastal sea ice areas e.g. around Greenland and Canadian Archipelago

➢**Open-burst SAR mode in Ka-band** for improving snow depth retrieval over SII and closed-burst over LIG



Indicative mission geographic operating mode mask used in CRISTAL altimeter data volume sizing:
Magenta = Land-Ice and Glacier (LIG) closed-burst SARIn mode
Orange = Sea-Ice and Icebergs (SII) open-burst SARIn mode
From Kern et al., 2020.

CRISTAL over sea ice

Sea-ice

MRD-110: The payload shall include a SAR Radar Altimeter with the capability of interferometry.

- SARIn used to locate the echoing point over leads, improving the detection of across-track leads
  - MRD-080: The along-track resolution shall be sufficient to distinguish ocean (open ocean) from sea ice surfaces.
  - MRD-260: The mission shall be capable of retrieving year-round elevation measurements of the sea ice-covered oceans. **Improved elevation retrieval from SARIn**
- Open-burst timing improves sea-ice lead discrimination, leading to improved elevation and polar sea level anomalies

CRISTAL over sea ice

Sea-ice

Large bandwidth (500 MHz) planned for CRISTAL

- Will improve the **range resolution from 0.5 m (CryoSat-2) to ~0.3 m**
  - Improved accuracy of sea-ice freeboard retrieval

- Supports **discriminating ice and snow interfaces in Ka-band**
  - Improved snow depth retrieval
  - Reduction in overall uncertainties in freeboard and sea ice thickness retrieval

Mission requirements document

Sea-ice

MRD-280: The system shall be capable of retrieving sea ice freeboard to an accuracy of 0.03 m along orbit segments ≤ 25 km

- The freeboard accuracies have been mainly analysed for **monthly gridded products** over winter months, where uncertainty of **0.02 m** was concluded (Tilling et al., 2018)
  - This is different to orbit segments
  - For **single freeboard retrieval** from CS2 uncertainty has been calculated to be in the **range of 0.1 m** (Ricker 2015)

- This MRD could profit from a dedicated study on the orbit segment accuracy and possible improvements with SARIn and Ku/Ka combination

- Suggestions:

1) Keep as it is, but reserve resources for dedicated studies about the orbit segment accuracy and possible improvements with SARIn and Ku/Ka combination.

2) Add another, relaxed accuracy requirement for summer months.

Mission requirements document

Sea-ice

MRD-330: The system shall be capable of delivering sea ice thickness measurements with a vertical uncertainty less than 0.1 m.

- Heavily dependent on the freeboard requirement (MRD-280) as well as on the improvements from Ku/Ka combination
- For **monthly gridded sea ice thickness** product, **0.2 m thickness uncertainty** has been currently confirmed (Tilling et al., 2018)
- The uncertainty is certain to reduce, however the 0.1 m might be too strict e.g. for summer months
- Suggestions:

1) Relax the vertical uncertainty requirement to be “less than 0.5 m”.

2) Include different requirements for winter and summer, FYI and MYI.

Mission requirements document

Sea-ice

MRD-410: The uncertainty of snow depth measurements over sea ice shall be less than 0.05m.

- Once again, **monthly gridded** products have been studied and resulted in **0.08 m uncertainty** estimates
  - The snow depth estimates are likely to gain the most from the simultaneous Ku/Ka measurements -> improvements for MRD-330 and MRD-280
  - **0.05 m uncertainty seems reasonable for monthly gridded snow depth**
- Suggestions:

1) Keep as it is, but add a note that the snow depth requirement is for monthly 25 km gridded snow depth estimate.

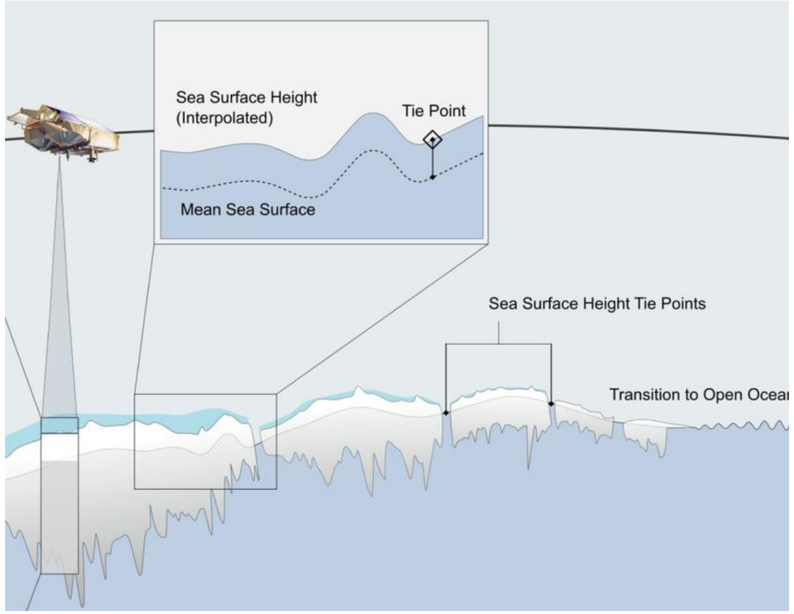
2) Keep as it is and have a dedicated study for the orbit segment accuracy for combined Ku/Ka band performance with e.g. a flight campaign. Possibly relax if the 0.05 m requirement is not met after this.

Mission requirements document

Sea-ice

MRD-460: The vertical uncertainty in sea level anomaly retrieval from Ku band (including sea-ice leads) shall be 0.02m.

- Sea level anomaly within sea ice is interpolated from the sea surface measurements in leads
- An accuracy of **0.02 m seems achievable** with **InSAR mode** (Di Bella, 2019) and using a **physical retracker**
  - 0.021 m mean error noted in a small scale study for Envisat



- Suggestions:

  1) Study performance and capabilities of physical retrackers for leads to ensure the improved vertical uncertainty

WP2: Assessment and consolidation of mission requirements

Ice sheet surface

Overview

Ice-sheet

1. Definition of Level-1b & Level-2 Parameters.
2. Level 2 Algorithms & Maturity Assessment.
3. Observation Concept over Ice Sheets.
4. Mission Requirements Analysis.

1. Definition & Traceability of Level-1b and Level-2 Parameters

Ice-sheet

User Requirements → Mission Requirements → Level-2* Parameters → Level-1b* Parameters

Level-1b*: Level 1A data that have been quality controlled and reformatted but not resampled. Calibration has been applied. Geometric information is computed, appended but not applied.

Level-2*: Derived geophysical variables at the same resolution and location as Level 1 source data.

* Definitions taken from MRD: Copernicus polaR Ice and Snow Topography ALtimeter (CRISTAL) Mission Requirements Document, version 2.0, ESA-EOPSM-CPTM-MRD-3350, Issued 28/02/2019.

1. Definition & Traceability of Level-1b and Level-2 Parameters

Ice-sheet

User Requirements → Mission Requirements → Level-2* Parameters → Level-1b* Parameters

MRD ID	Requirement	Level-2 parameters	Level-1b parameters
MRD-020	The mission shall acquire measurements of elevation over sea-ice, land ice, polar glaciers, ice caps and ocean.	Ku-band echoing point location. Ku-band echoing point elevation. Ku-band waveform parameters. Ku-band swath elevation. Ka-band echoing point location. Ka-band echoing point elevation. Ka-band waveform parameters.	Satellite ground track location. Satellite altitude. Interferometer orientation. Ku-band waveform. Ku-band phase difference. Ku-band coherence. Ku-band window delay. Ku-band geophysical & instrument corrections. Ka-band waveform. Ka-band window delay. Ka-band geophysical & instrument corrections.
MRD-110	The payload shall include a SAR Radar Altimeter with the capability of interferometry.	Ku-band echoing point location. Ku-band echoing point elevation. Ku-band waveform parameters. Ku-band swath elevation. Across-track surface slope.	Satellite ground track location. Satellite altitude. Interferometer orientation. Ku-band waveform. Ku-band phase difference. Ku-band coherence. Ku-band window delay. Ku-band geophysical & instrument corrections

Level-1b*: Level 1A data that have been quality controlled and reformatted but not resampled. Calibration has been applied. Geometric information is computed, appended but not applied.

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2. Level 2 Algorithms & Maturity Assessment

Ice-sheet

The purpose of this task was to:

1. Identify the algorithms that currently exist for the main L2 processing steps.
2. Make an assessment of their maturity (both current maturity, and expected matur
3. Ensure full traceability via references to supporting literature.
4. Highlight needs for future algorithm development activities.

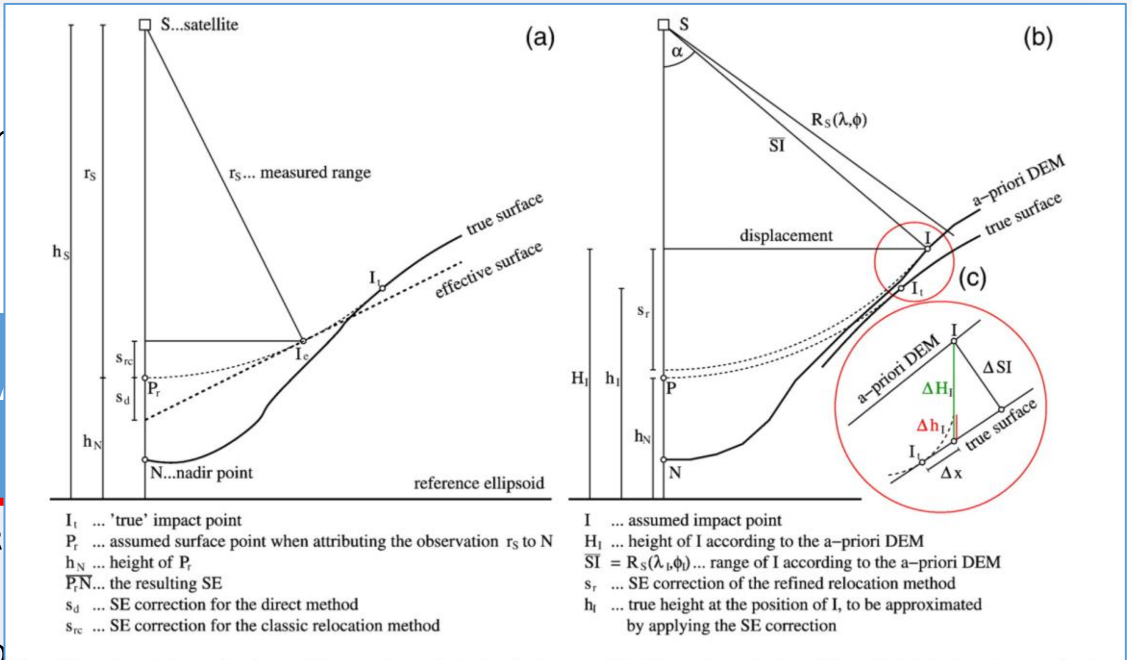

Fig. 2. Illustration of slope induced error (SE) correction methods. For details not explained here refer to Sections 3.2.1 and 3.2.2. Surface slopes are largely exaggerated. (a) Overall situation with classic relocation method and direct method. (b) Refined relocation method. (c) Detail of (b) showing the effects of errors in the vertical and horizontal positions if *I* described by Eqs. (5) and (6).

Processing Step	Algorithm	Description	Maturity (expected maturity at 2025)	Existing SRL	
Echo relocation	Non-interferometric echo relocation using point of closest approach within the beam footprint.	Uses a DEM to identify the point of closest approach within the beam footprint, and thus relocate the echoing point; advantageous over the previous approach because it accounts for non-linear topography.	Ku: Mature (mature) Ka: Immature (mature)	9 7	R O
Echo relocation	Interferometric echo relocation.	Point of closest approach identified using interferometric phase difference at the retracking point.	Ku: Mature (mature) Ka: Untested (untested)	8 1	Bouzinac, 2004; Wingham et al., 2006. -

2. Level 2 Algorithms & Maturity Assessment

Ice-sheet

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4. Highlight needs for future algorithm development activities.

Processing Step	Algorithm	Description	Maturity (expected maturity at 2025)	Existing SRL	Algorithm reference (where exists)
Echo relocation	Non-interferometric echo relocation using point of closest approach within the beam footprint.	Uses a DEM to identify the point of closest approach within the beam footprint, and thus relocate the echoing point; advantageous over the previous approach because it accounts for non-linear topography.	Ku: Mature (mature) Ka: Immature (mature)	9 7	Roemer et al., 2007. Otosaka at al., 2019.
Echo relocation	Interferometric echo relocation.	Point of closest approach identified using interferometric phase difference at the retracking point.	Ku: Mature (mature) Ka: Untested (untested)	8 1	Bouzinac, 2004; Wingham et al., 2006. -

- Most of the low SRL's relate to Ka SARIn:
  - SARIn retracker.
  - Interferometric echo relocation.
  - Swath processing.
- A low SRL does not necessarily warrant further work within the frame of CRISTAL, since CRISTAL will not include a Ka interferometer.

2. Level 2 Algorithms & Maturity Assessment

Ice-sheet

Processing Step	Algorithm	Description	Maturity (expected maturity at 2025)	Existing SRL	Algorithm reference (where exists)
Retracking	Threshold Centre of Gravity	'ICE-1' retracker, as applied in ERS-1, ERS-2, Envisat, CryoSat-2 (LRM; baseline-c onwards), AltiKa and Sentinel-3 ground segments; retracks based on a threshold of the Offset Centre of Gravity amplitude.	Ku: Mature (mature) Ka: Mature (mature)	9 8	Wingham, 1995; Wingham et al., 1998. Yang et al., 2018; Otosaka et al., 2019.
Retracking	Threshold First Maximum	Retracks based on a threshold of the first maximum amplitude; has been applied to both LRM and SAR measurements.	Ku: Mature (mature) Ka: Immature (mature)	9 7	Davis, 1997; Helm et al., 2014; Gray et al., 2015; Nilsson et al., 2015. Yang et al., 2018;

2. Level 2 Algorithms & Maturity Assessment

Ice-sheet

Processing Step	Algorithm	Description	Maturity (expected maturity at 2025)	Existing SRL	Algorithm reference (where exists)
Retracking	ICE-2	'ICE-2' retracker, currently applied to ERS-1, ERS-2, Envisat and AltiKa; fits a Brown model.	Ku: Mature (mature) Ka: Immature (mature)	9 7	Brown, 1977; Legresy et al., 2005. Yang et al., 2018; Suryawanshi et al., 2019.
Retracking	SARIn retracker	6-parameter functional fit used to retrack CryoSat-2 SARIn mode echoes; designed to mimic the theoretical echo shape.	Ku: Mature (mature) Ka: Untested (untested)	8 1	Bouzinac, C., 2004; Wingham et al., 2006. -
Retracking	β-parameter retracker	An empirical formulation, but shows some similarity to the theoretical shape of the Brown-Hayne model.	Ku: Mature (mature) Ka: Untested (untested)	9 1	Martin et al., 1983. -
Retracking	CFI ocean retracking, based on analytical model fit.	CFI MLE retracking; used to retrack CryoSat-2 land ice LRM echoes.	Ku: Mature (mature) Ka: Immature (mature)	9 7	Hayne et al., 1980. Yang et al., 2018.

2. Level 2 Algorithms & Maturity Assessment

Ice-sheet

Processing Step	Algorithm	Description	Maturity (expected maturity at 2025)	Existing SRL	Algorithm reference (where exists)
Sigma-0 calculation	Sigma-0 from retracker amplitude.	Standard approach based on the amplitude calculated by each retracker.	Ku: Mature (mature)	9	CryoSat L2 Processor Design Summary Document, Issue 6.0, 22nd Nov. 2012, Mullard Space Science Laboratory.
			Ka: Mature (mature)	8	AltiKa Algorithm Theoretical Baseline Definition: Altimeter Level 2 Processing SALP-ST-M2-EA-15886-CN.
Echo relocation	Non-interferometric echo relocation using linear slope.	Uses a DEM-based estimate of the linear slope at nadir to relocate the echoing point to the point where the surface is orthogonal to the incident radar beam; used in LRM ground segment processing for ERS-1, ERS-2, Envisat and CryoSat-2 (LRM), and in SAR processing for Sentinel-3.	Ku: Mature (mature)	9	Bamber, 1994.
			Ka: Immature (mature)	7	Suryawanshi et al., 2019.

2. Level 2 Algorithms & Maturity Assessment

Ice-sheet

Processing Step	Algorithm	Description	Maturity (expected maturity at 2025)	Existing SRL	Algorithm reference (where exists)
Geophysical corrections	Based on physical model simulations.	Typically, corrections are derived from physical models and applied to the range measurement.	Ku: Mature (mature)	9	Wingham et al., 2006; CryoSat-2 Product Handbook, Baseline-D 1.0, 3/4/2018; see also summary provided in Table 3.
			Ka: Mature (mature)	8	SARAL/AltiKa Products Handbook, SALP-MU-M-OP-15984-CN, Issue 1.2, 12/12/2011.
Swath processing	Interferometric swath processing.	Uses interferometric phase difference and coherence at delay times beyond the point of closest approach to map elevation across a swath.	Ku: Mature (Mature)	8	Gray et al., 2013; Gourmelen et al., 2018.
			Ka: Untested (untested)	1	-
Ku radar penetration	Ku-Ka range difference.	Use range difference between Ku and Ka-band to estimate the Ku-band penetration into the near surface snowpack.	Untested (tested for airborne systems).	4	-

2. Level 2 Algorithms & Maturity Assessment

Ice-sheet

In addition to the Level 2 algorithms, we also performed a similar assessment for the auxiliary models used as corrections within the Level 2 processing chain.

Correction	Description	Typical magnitude	Auxiliary Product	Reference
Ocean Tide	Accounts for ocean tide; for ice sheets, applicable over ice shelves only.	-0.5 – 0.5 metres.	FES2014 ocean tide model.	Lyard F., L. Carrere, M. Cancet, A. Guillot, N. Picot: FES2014, a new finite elements tidal model for global ocean, in preparation, to be submitted to Ocean Dynamics in 2017.
Ocean Loading Tide	Accounts for the deformation of Earth's crust due to ocean tides.	-0.02 – 0.02 metres	FES2014 ocean tide model.	Lyard F., L. Carrere, M. Cancet, A. Guillot, N. Picot: FES2014, a new finite elements tidal model for global ocean, in preparation, to be submitted to Ocean Dynamics in 2017.
Echo relocation.	Echo relocation, or slope correction; applied to account for the echoing point being upslope of the nadir track.	Variable depending upon method and topography within the beam footprint.	CryoSat-2 DEM ArcticDEM REMA DEM	Helm et al., 2014.; Slater et al., 2018. Porter et al., 2018. Howat et al., 2019.

3. Observation Concept over Ice Sheets

The purpose of this task was to assess the CRISTAL observation concept over ice sheets, in order to:

1. Identify the design aspects that meet the User Requirements.

2. Highlight any novel aspects of the observation concept that have yet to be tested in orbit.

Recall the User Requirements from WP1

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 regi[...] 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 Antarctic[...] (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 up[...] surface roughness). Techniques such as fully-focused SAR have the potential to improve along-track resolution by several orders of magnitude; swath processing [...] improve across-track resolution by up to an order of magnitude.

Ice sheet wide Ku SARIn
Ice sheet wide Ka SAR
OLTC in ice sheet margins

CCN

Mission Requirements Analysis

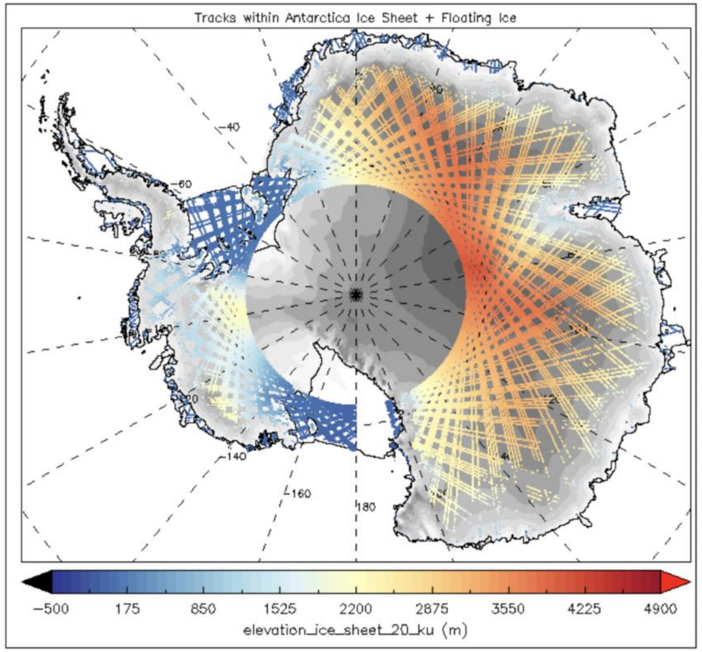
AD2. PEG-1 Report, User Requirements for a Copernicus Polar Mission, Step 1 Report, Polar Expert Group, Issue: 12th June 2017.
AD3. PEG-2 Report, Polar Expert Group, Phase 2 Report on Users Requirements, Issue: 31st July 2017.
AD4. 2015 Update of Actions in The Response of the Committee on Earth Observation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

CRISTAL Observation Concept

Ice-sheet

1. Over ice sheet margins CRISTAL will operate in **Open Loop tracking mode**.

MRD-150. The altimeter shall include tracking ability over steep terrain and as a minimum be able to track ice surfaces/glaciers with slopes <1.5°.



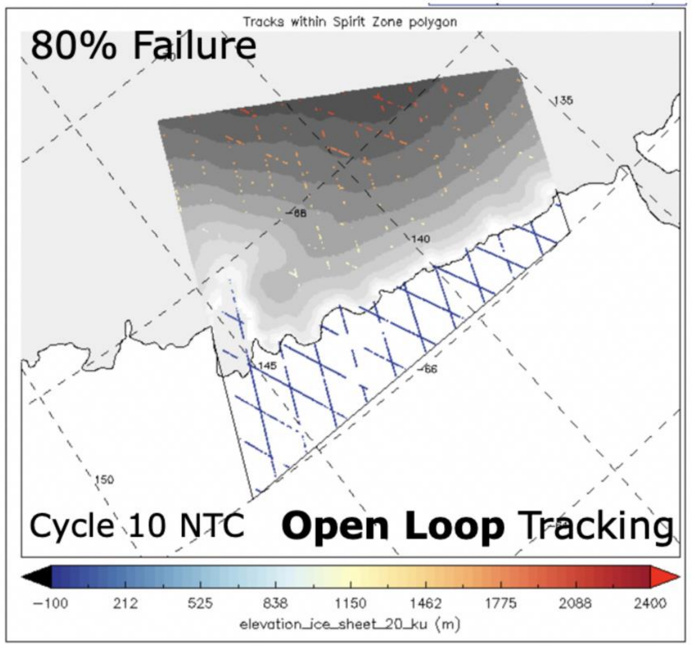
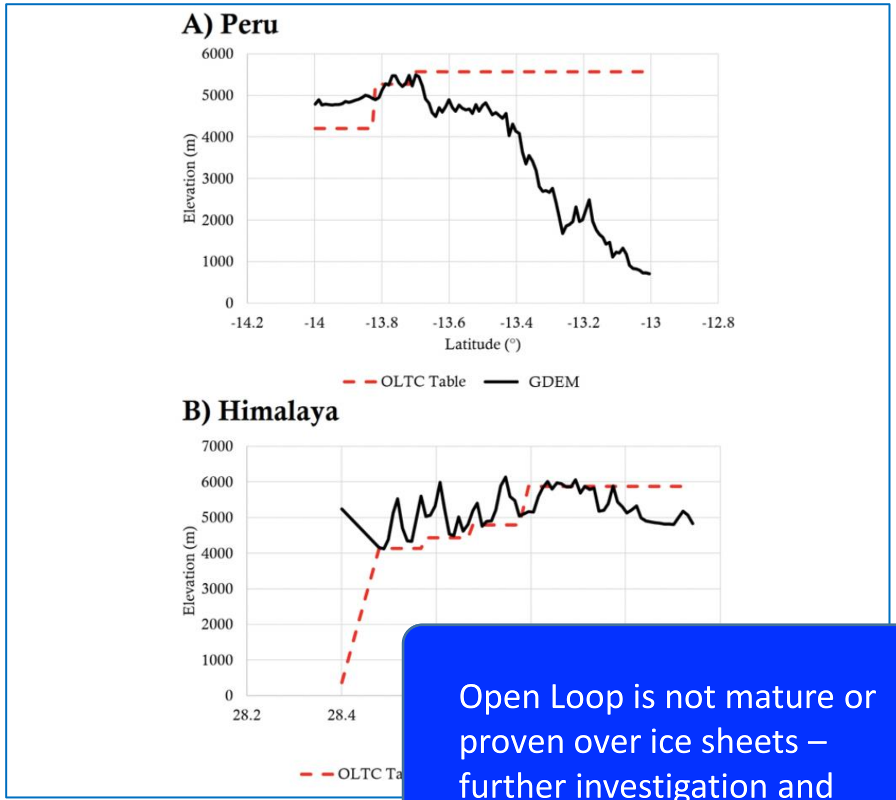


Figure 2. Example of loss of coverage in coastal regions for Sentinel-3A Open Loop tracking, for the whole of Antarctica (left panel) and for the Spirit site in East Antarctica (right panel). Coloured tracks show elevations retrieved during Cycle 10; with a lack of measurements in the high sloped margin regions, where the altimeter lost track of the ice surface.

[credit: A. Muir/CPOM]



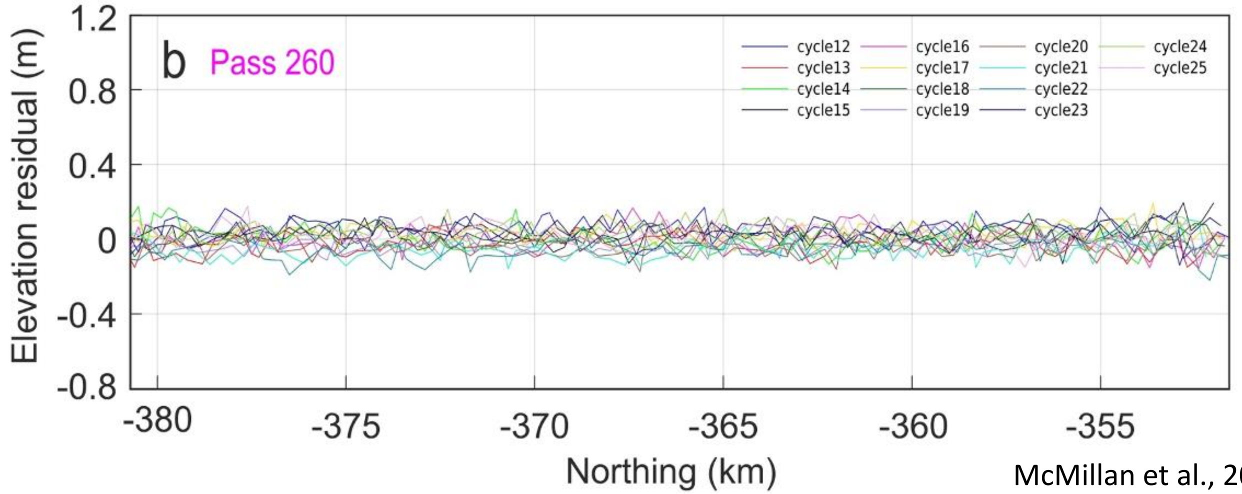
[credit: L. Taylor/CP

Open Loop is not mature or proven over ice sheets – further investigation and optimisation recommended.

CRISTAL Observation Concept

2. Over **all ice sheet surfaces** CRISTAL will operate a **Ku-band SARIn** Closed Burst configuration.

- Closed Burst Ku-band SARIn is now mature as a technique, given the ~10 years of operation by CryoSat-2 in this mode.
- The performance of this mode is well-evaluated over coastal regions with complex topography (e.g. Helm et al., 2014; McMillan et al., 204; McMillan et al., 2016), across both Greenland and Antarctica.
- The accuracy of CryoSat-2 should be bettered by CRISTAL, due its larger 500 MHz bandwidth, and associated improved range resolution (31 cm for CRISTAL compared to 47 cm for CryoSat-2).
- Although this mode of operation is untested over inland regions, given that SAR has been shown to perform well (McMillan et al., 2019) and that the topography tends to be simpler than at the coast, it is reasonable to expect good performance here.
- Nonetheless, several orbits of SARIn have been acquired by CryoSat-2 and so further assessment could be performed in anticipation of CRISTAL, using these dedicated acquisitions.



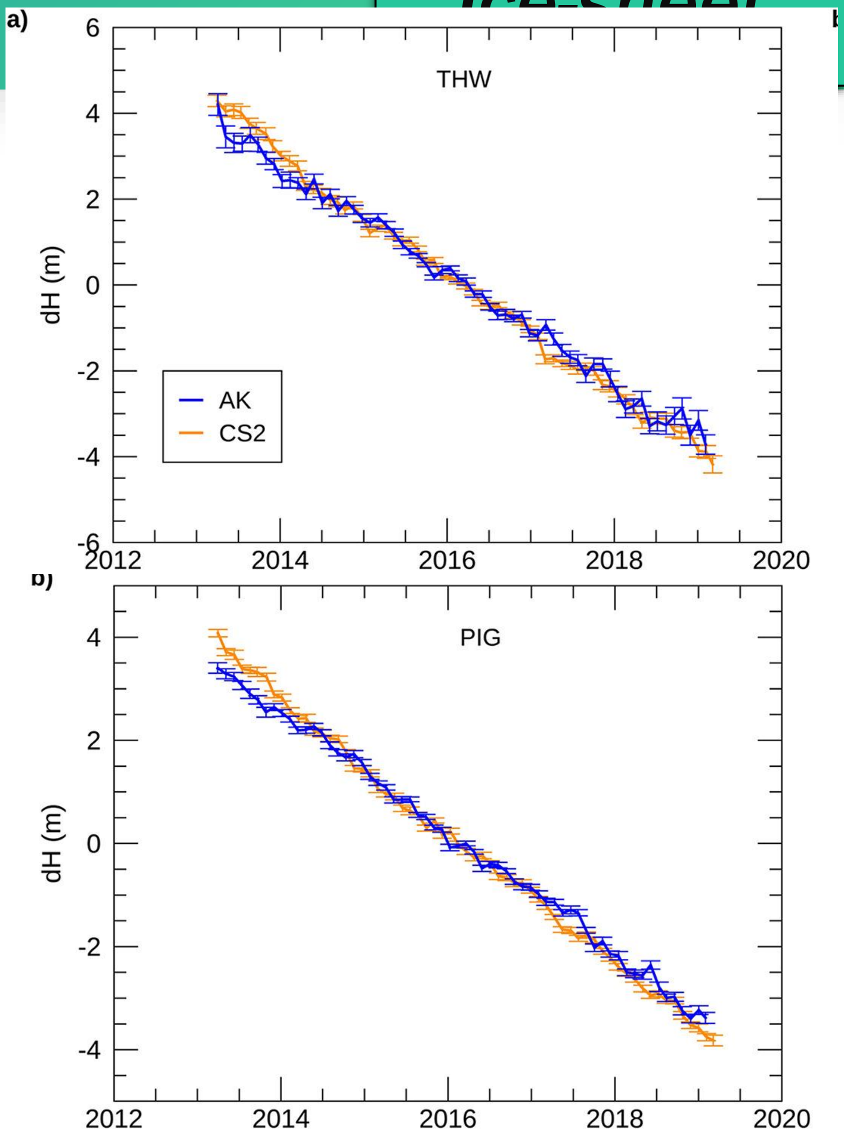
McMillan et al., 2019

CRISTAL Observation Concept

Ice-sheet

3. Over **all ice sheet surfaces** CRISTAL will operate a **Ka-band SAR** Closed Burst configuration.

- Ka-band SAR is untested in an Earth orbit and its performance is currently unknown.
- Given our experiences of comparing Ku LRM and Ku SAR, it is reasonable to expect **Ka SAR to be equivalent or better than Ka LRM**, as operated by AltiKa.
- At **low slope, inland sites** Ka LRM elevations exhibit a bias and dispersion of the order of 10 cm (Aublanc et al., 2017).
- At **higher slope, coastal sites**, Ka LRM elevations exhibit a bias of the order of metres and dispersion of the order of tens of metres (Otosaka et al., 2019).
- When **rates of elevation change** are computed, the agreement with airborne data improves (Otosaka et al., 2019), with a bias of the order of 1 cm/yr, and a dispersion of several 10’s of cm/yr.
- These statistics represent our best current estimate of Ka performance. However, they should be treated as a ‘worst-case’ bound on the performance of CRISTAL; the switch from LRM to SAR, improvements to onboard tracking and a larger range window all offer the potential to further enhance measurement quality.



A comparison of Ku and Ka band derived surface elevation changes over the Thwaites and Pine Island glaciers in West Antarctica (Otosaka et al., 2019).

4. Mission Requirements Analysis

Ice-sheet

MRD-150: *The altimeter shall include tracking ability over steep terrain and as a minimum be able to track ice surfaces with slope <1.5 degrees.*

- Imprecisely defined; recommended that the length scale over which the slope is calculated is specified.

- Tracker performance is not simply a function of slope; i.e. the linear rate of elevation change. Tracking is about the ability to follow the variation in surface elevation, which includes non-linear variability.

- A refined Requirement Definition would be to simply state that the tracker should be capable of keeping XX% of the ice sheet within the range window. This could be demonstrated based upon the proposed OL tracker via a simulation study.

4. Mission Requirements Analysis

Ice-sheet

***MRD-360:** The system shall be capable of delivering surface elevation with a horizontal resolution of at least 100 m.*

<u>Along-track</u>

100 m is not achievable with a conventional Ku unfocused SAR in the CryoSat-2 orbit. Possible options to address this include:

1. This Mission Requirement is relaxed to specify a horizontal resolution ~300 m, thus reflecting current unfocussed SAR capability.

2. Fully-focused SAR processing is implemented within the ground segment.

3. At Ka-band the unfocused SAR azimuth resolution would be ~ 100 m; thereby meeting the requirements of the existing MRD, should it be defined in terms of either the Ku- or Ka-band acquisition.

4. Flying the satellite at lower altitude would improve the azimuth resolution, albeit not to a point where the 100 m requirement could be met; for example at a 500 km ICESat-2-like orbit altitude, the Ku-band azimuth resolution would be ~ 185 m.

4. Mission Requirements Analysis

Ice-sheet

MRD-360: *The system shall be capable of delivering surface elevation with a horizontal resolution of at least 100 m.*

Across-track

- Considering the across-track component, the conventional pulse-limited footprint at the point of closest approach will exceed 1.3 km for a 500 Hz measurement bandwidth instrument, under the assumption that the satellite flies at 700 km altitude.
- With swath processing, the across track resolution can be improved, depending upon the local incidence angle or the radar wave at each resolution cell. Swath processing over flat surfaces, however, may not be possible.

Supplementary

Supplementary – Definition of Level-1b and Level-2 Parameters

Ice-sheet

MRD ID	Requirement	Level-2 parameters	Level-1b parameters
MRD-020	The mission shall acquire measurements of elevation over sea-ice, land ice, polar glaciers, ice caps and ocean.	Ku-band echoing point location. Ku-band echoing point elevation. Ku-band waveform parameters. Ku-band swath elevation. Ka-band echoing point location. Ka-band echoing point elevation. Ka-band waveform parameters.	Satellite ground track location. Satellite altitude. Interferometer orientation. Ku-band waveform. Ku-band phase difference. Ku-band coherence. Ku-band window delay. Ku-band geophysical & instrument corrections. Ka-band waveform. Ka-band window delay. Ka-band geophysical & instrument corrections.
MRD-110	The payload shall include a SAR Radar Altimeter with the capability of interferometry.	Ku-band echoing point location. Ku-band echoing point elevation. Ku-band waveform parameters. Ku-band swath elevation. Across-track surface slope.	Satellite ground track location. Satellite altitude. Interferometer orientation. Ku-band waveform. Ku-band phase difference. Ku-band coherence. Ku-band window delay. Ku-band geophysical & instrument corrections.
MRD-160	The altimeter shall be capable of operating at two frequency channels.	Ku-band echoing point location. Ku-band echoing point elevation. Ku-band waveform parameters. Ka-band echoing point location. Ka-band echoing point elevation. Ka-band waveform parameters.	Satellite ground track location. Satellite altitude. Ku-band waveform.. Ku-band window delay. Ku-band geophysical & instrument corrections. Ka-band waveform. Ka-band window delay. Ka-band geophysical & instrument corrections.
MRD-230	The altimeter shall be able to measure variations of backscatter coefficient ranging from 0dB to 50dB.	Ku-band sigma-0. Ka-band sigma-0.	Ku-band waveform. Ka-band waveform. Ku-band scaling factor to convert from waveform units to dB. Ka-band scaling factor to convert from waveform units to dB

Level-1b*: Level 1A data that have been quality controlled and reformatted but not resampled. Calibration has been applied. Geometric information is computed, appended but not applied.

Level-2*: Derived geophysical variables at the same resolution and location as Level 1 source data.

* Definitions taken from MRD: Copernicus polaR Ice and Snow Topography ALtimeter (CRISTAL) Mission Requirements Document, version 2.0, ESA-EOPSM-CPTM-MRD-3350, Issued 28/02/2019.

Definition & Traceability of Level-1b and Level 2 parameters

Ice-sheet

MRD-240	The altimeter in Ku-band shall be able to measure low backscatter coefficient values down to -10dB.	Ku-band sigma-0.	Ku-band waveform. Ku-band scaling factor to convert from waveform units to dB.
MRD-340	The mission shall be capable of retrieving surface elevation and surface elevation change over ice sheets, glaciers and ice caps.	Time of acquisition. Ku-band echoing point location. Ku-band echoing point elevation. Ku-band waveform parameters. Ku-band swath elevation. Ka-band echoing point location. Ka-band echoing point elevation. Ka-band waveform parameters.	Time of acquisition. Satellite ground track location. Satellite altitude. Ku-band waveform. Ku-band phase difference. Ku-band coherence. Ku-band window delay. Ku-band geophysical & instrument corrections. Ka-band waveform. Ka-band window delay. Ka-band geophysical & instrument corrections.
MRD-360	The system shall be capable of delivering surface elevation with a horizontal resolution of at least 100 m.	Ku-band swath elevation.	Satellite ground track location. Satellite altitude. Interferometer orientation. Ku-band waveform. Ku-band phase difference. Ku-band coherence. Ku-band window delay. Ku-band geophysical & instrument corrections.

Table 1. Correspondence between Mission Requirements and principal Level-1b and Level-2 parameters relevant to ice sheets. Note that each parameter can be provided at different along-track resolutions, depending upon the delay-doppler processing applied, for example fully-focused vs unfocused SAR.

WP2: Assessment and consolidation of mission requirements

Ocean surface

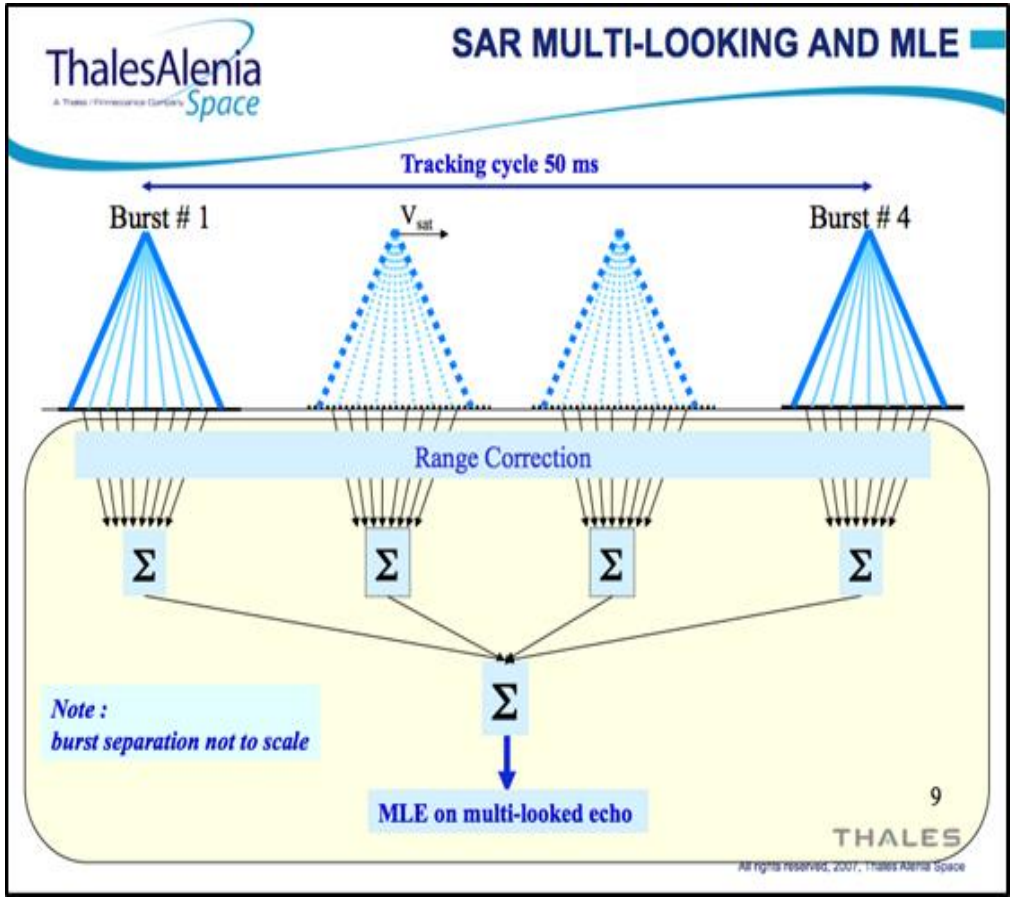
Level-1 & level-2 products

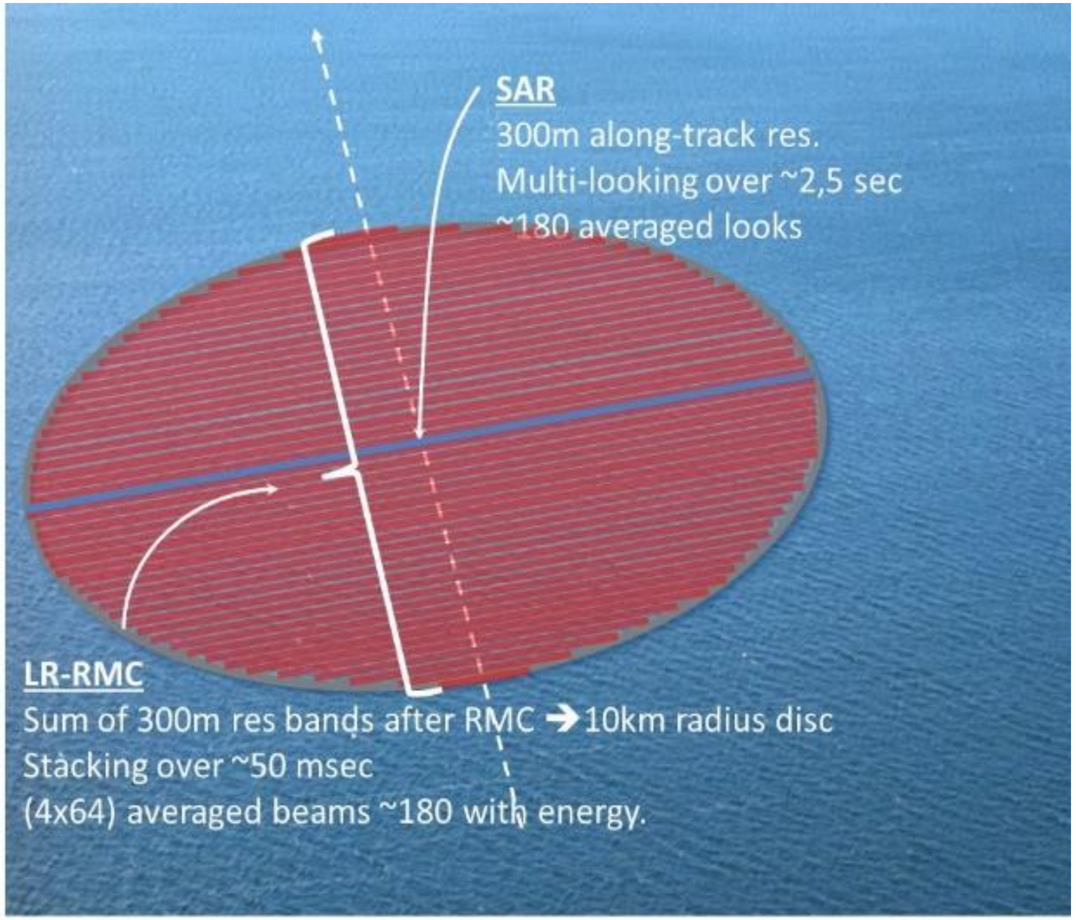
Ocean

Level-2 geophysical parameters for the oceanic surface (listed in the MRD)

- **Sea Surface Height (SSH):** From the estimated altimeter range, with all necessary geophysical corrections applied
- **Sea Level Anomaly (SLA):** Difference between SSH & Mean Sea Surface
- **Significant Wave Height (SWH):** Directly from the level-2 retracking outputs
- **Sigma-0:** Backscattering coefficient of the surface, estimated by the level-2 retrackers
- **Wind speed:** Derived from Sigma-0 & SWH
- **Liquid water & water vapor content:** Derived from radiometer measurements
- **Rain rate & probability**: Derived from radiometer measurements

Focus on the LR-RMC processing [Phalippou & Demestere, 2015]





Focus on the LR-RMC processing [Phalippou & Demestere, 2015]

Very promising results with Sentinel-3A

- SWH & SSH noise reduction (~20% for SSH & SWH, at 2 meters SWH)
- In contrast to the SAR unfocused mode, SLA noise is much less sensitive to swell conditions.
- Spectral analysis:
  - Large noise reduction at high frequencies (correlated with first result)
  - Despite its large footprint, no observable short wavelength correlated errors (bump)
  - **As a result, mesoscale signals are better resolved**
- Compared to SAR unfocused mode, a slight degradation is expected over coastal areas. First results show that the degradation would be negligible.
- This algorithm has been awarded in the Sea State CCI for SWH, as the SAR processing providing the best results

Focus on the level-1 Fully-Focused SAR processing

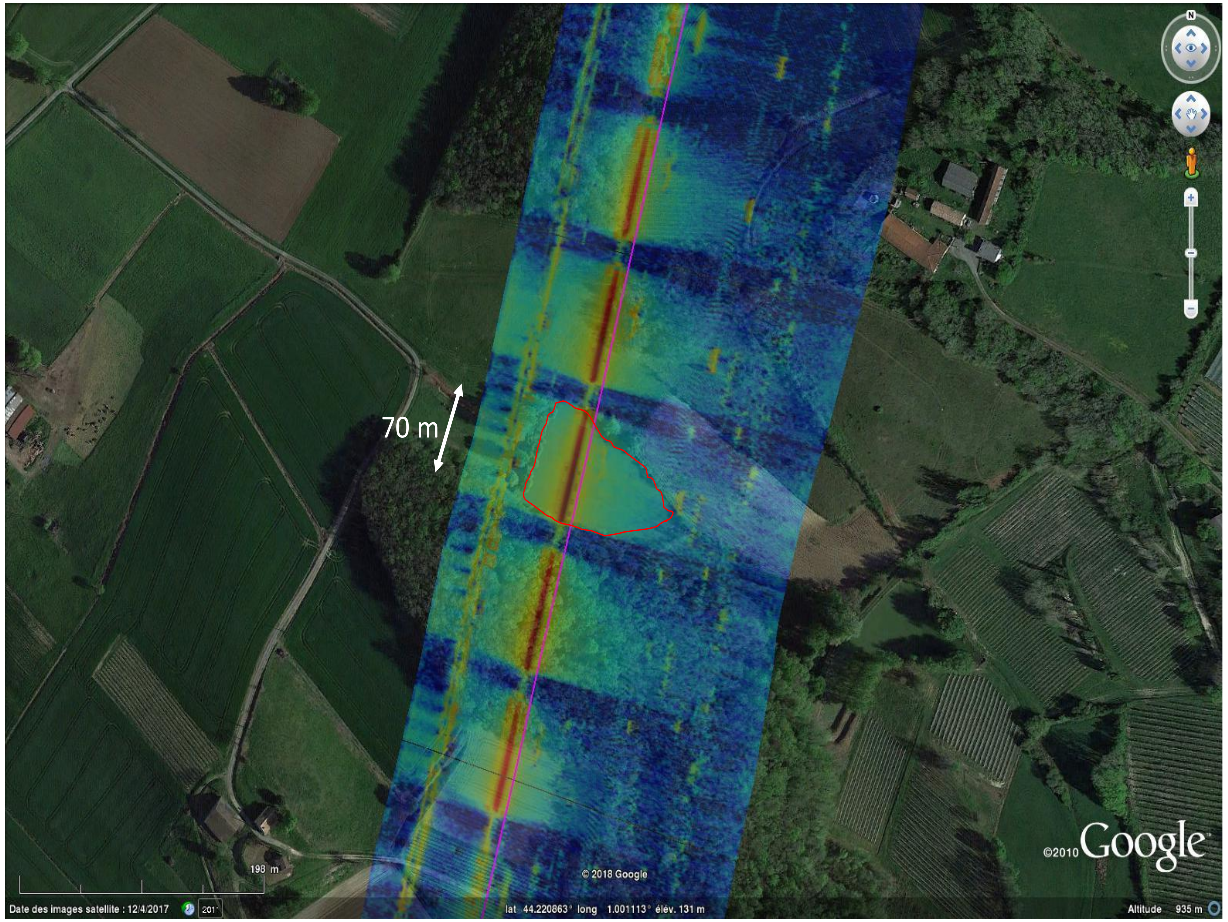
- FF-SAR processing exploits the entire illumination time of a scatterer on the surface. The Doppler processing is thus done over around 2.5 sec instead of only one burst length for the UF-SAR processing
- FF-SAR waveforms can then be averaged (or not) to reduce the speckle noise, depending on the expected on-ground resolution
- For instance, the altimeter configuration of Sentinel-3 can reach an along-track resolution of ~50cm.
- CRISTAL configuration would allow to reach an along-track resolution of about ~70cm
- The FF-SAR provides optimal performances with an interleaved chronogram (open-burst), as planned for the **sea-ice surface** with CRISTAL configuration
- Over open-ocean & ice sheet, regarding the CRISTAL configuration planned, the intermittent burst emission (closed-burst) introduces replica which creates correlation between measurements

Focus on the level-1 Fully-Focused SAR processing

- In the FF-SAR processing, it is possible to adjust the along-track resolution, which will depend on the number of individual pulses kept in the coherent doppler processing

- The optimal FF-SAR along-track resolution of the CRISTAL mission (as already defined) will probably be a trade-off between ~70 cm and a hundred of meters

- Guccione et al. [2018] developed an innovative method to perform delay-Doppler processing to solve the high computational effort required. CLS is implementing and validating this solution as well (ESA FF-SAR study with F.Borde) over a very large number of hydrological targets



Level-1 algorithms

State of the art of the level-1 processing: recommendations for each surface

		Ocean	Ice-sheets	Sea-Ice	Hydrology
Delay Doppler Processing	SAR unfocused				
	LR-RMC				
	FF-SAR				
	SARIn				
Specific L1 processing	Zero-Padding				
	Hamming				

Green: Recommended; Orange: to be studied;
Red: Not recommended; Gray: no specific positive/negative impact

For Hamming and Zero-Padding, large consensus from the community to implement them for sea ice regions and inland waters.

Level-1 algorithms

Ocean

Can we perform all the recommended level-1 processing with CRISTAL ?
=> For Doppler processing that will depend on the operating mode (✓ or ✘)

		Ocean	Ice-sheets	Sea-Ice	Hydrology
CRISTAL operating modes	**Ku band** **Ka band**	**SAR-CB** **SAR-CB**	**SARIn CB** **SAR CB**	**SARIn-OB** **SAR-OB**	**SAR-CB** **SAR-CB**
Delay Doppler Processing	**SAR unfocused**	✓	✓	✓	✓
	LR-RMC	✓			
	FF-SAR	✘	✘	✓	✘
	SARIn	✘	✓ Ku	✓ Ku	✘

Green: Recommended; Orange: to be studied;
Red: Not recommended; Gray: no specific positive/negative impact

- **Open-burst (interleaved) chronogram** would be desirable over inland waters to perform FF-SAR without ambiguities. In addition SARIn would be also desirable over inland waters. *But hydrology is not a primary objective of CRISTAL.*
- Otherwise the configuration of the CRISTAL altimeter is optimal to apply the recommended level-1 delay Doppler processing

Level-2 main algorithms: Retracking

- **A numerical retracker** would be a relevant choice to avoid potential issues linked to instrument ageing. Instrumental drifts are not fully accounted for by current retrackers. **Estimated impact on the SSH is ~0.3 mm/year in SAR mode for Sentinel-3, which could prevent the mission from being used for climate studies**

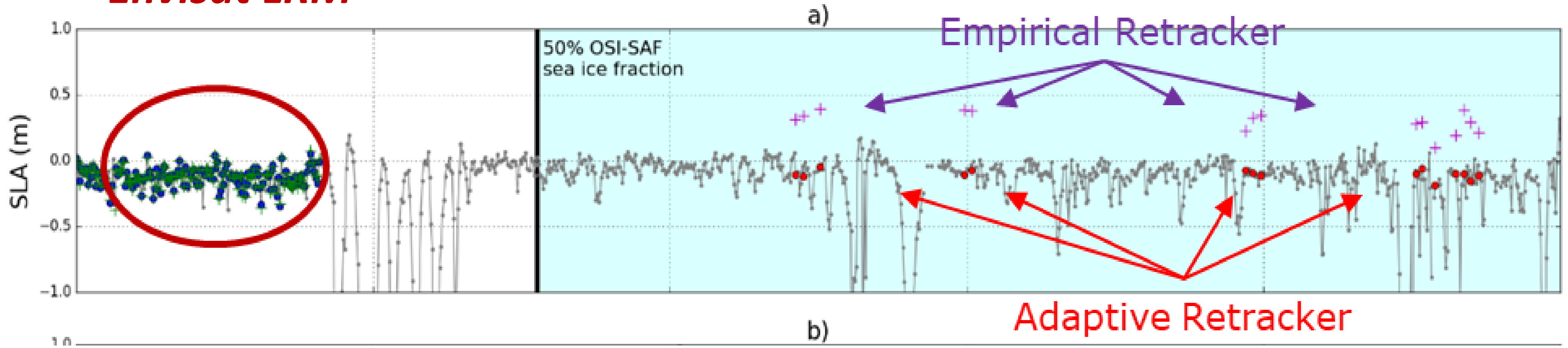
- **Continuity between open ocean / leads** is crucial, at least for SLA observations, to guaranty the measurement consistency when moving from open ocean to sea ice surfaces. Recently, CLS has developed and fully validated a new solution called "**Adaptive Retracker**" for LRM or SAR measurements, implementing a physical waveform model accounting for the surface roughness (mss). Equivalent solutions from the **SAMOSA** model can be derived. SAMOSA++ (Dinardo et al, 2019) provides an equivalent solution.

Level-2 algorithms

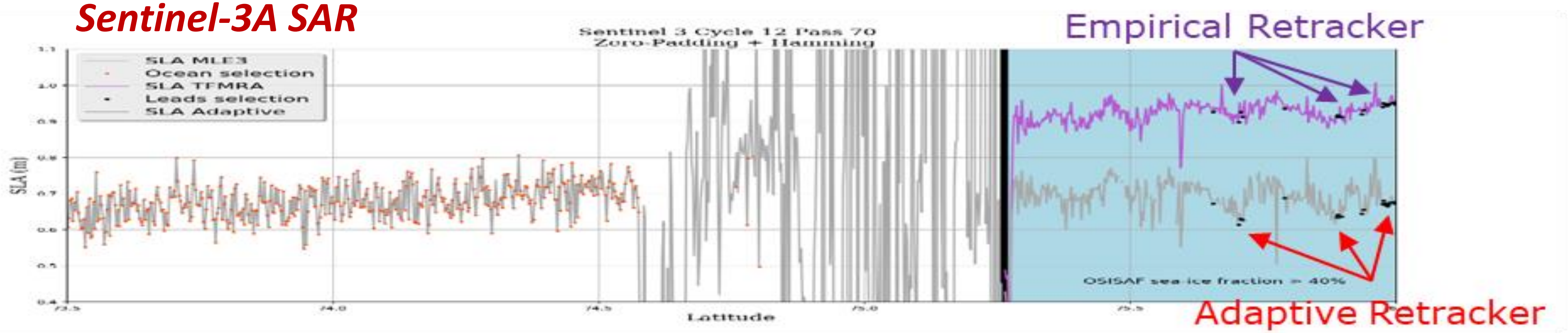
Ocean

Illustration of the continuity between open ocean / leads with the CLS adaptive retracker

Envisat LRM



Sentinel-3A SAR



Level-1 and level-2 algorithms maturity

Ocean

Summary table of algorithms & maturity regarding SRL

Level-1 algorithms

	delay Doppler processing				Specific	
Level-1 processing	SAR unfocused	LR-RMC	FF-SAR	SARIn	0-padding	hamming
SRL level of maturity	9	7	6	9	8	8

Level-2 retracking algorithms

	Retracking algorithms				
Level-2 processing	Brown MLE4	SAMOSA	Numerical retracker	with mean square slope	with orbital wave
SRL level of maturity	9	8	7	7	5

other level-2 algorithms

	other algorithms		
Level-2 processing	Wind speed retrieval	Sea state bias	HFA
SRL level of maturity	9	9	7

Scientific readiness level

9: Science impact quantification

8: Validated and matured science

7: Demonstrated science

6: Consolidated science and products

5: End to end performance simulations

CRISTAL observation concept

Ocean

Observation concept: altimeter configuration over open ocean

The instrumental configuration proposed by Thales, is following one for open ocean:

- **Closed-bursts of 64 pulses** emitted at **18 kHz**, in both Ku & Ka bands
- **500MHz Ku & Ka bandwidths**, leading to a vertical resolution of ~30cm
- Range window size of 256 samples / 64 meters
- Closed-loop tracking mode

SAR unfocused: Doppler-bandwidth / Along-track footprint / optimal on-ground sampling

500km satellite altitude (as ICESat-2)	725km satellite altitude (as CryoSat-2)	1300km altitude (as Jason series)
Ku band: **184m**	Ku band: **268m**	Ku band: **491m**
Ka band: **69m**	Ka band: **101m**	Ka band: **185m**

CRISTAL over open ocean

Ocean

Observation concept: altimeter configuration over open ocean

- **SAR mode suitable for sea level measurement**, bringing improvement wrt LRM. But still some issues to solve regarding:
  - wave estimation (*swell sensitivity & decimeter bias in SWH wrt LRM => on-going studies at CNES/CLS*)
  - Drift of sea-level estimations due to instrumental ageing
- **On-board RMC valuable to reduce telemetry data (as on Sentinel-6)** without impacting SAR mode performances as already demonstrated
- But, is there a benefit to have dual frequency Ku/Ka measure over ocean ? *Possibly to reduce noise level and get information of surface roughness at small scales (internal waves ? …)*
- **An interleaved chronogram would be preferable** to keep the possibility to process LRM / SAR simultaneously & perform FF-SAR processing without ambiguities (benefits over inland waters [Egido et al. 2017])

Expected performances over open ocean

- In SAR Ku band, **performances at least equivalent to Sentinel-3 ones are expected.** Less individual looks will be stacked due to the narrower antenna aperture (1.04° vs 1.35°). ~160 looks for CRISTAL vs ~180 for Sentinel-3A (from simulations).
- But the finer vertical resolution (~30cm) of IRIS will improve the global performances
- Which band Ku or Ka will provide the best performances ?
  - The **number of individual looks** contained in the stack will be higher in Ku band due to the wider antenna aperture. **Ratio is 2.42 (1.04° Ku / 0.43° Ka)**
  - **Ka band is supposed to provide a better noise level reduction compared to Ku band** (but Ka is more impacted by rain cells)
  - The Doppler band width in Ka-band (100m with the CryoSat-2 orbit) will allow to provide estimations at **~66Hz frequency rate,** compared to **~25Hz in Ku band** (ratio is 2.6).

Some advantages/disadvantages of both Ku/Ka bands could cancel each other out, and <u>perhaps a similar noise level will be reached</u>
=> need of a dedicated study to draw robust conclusions

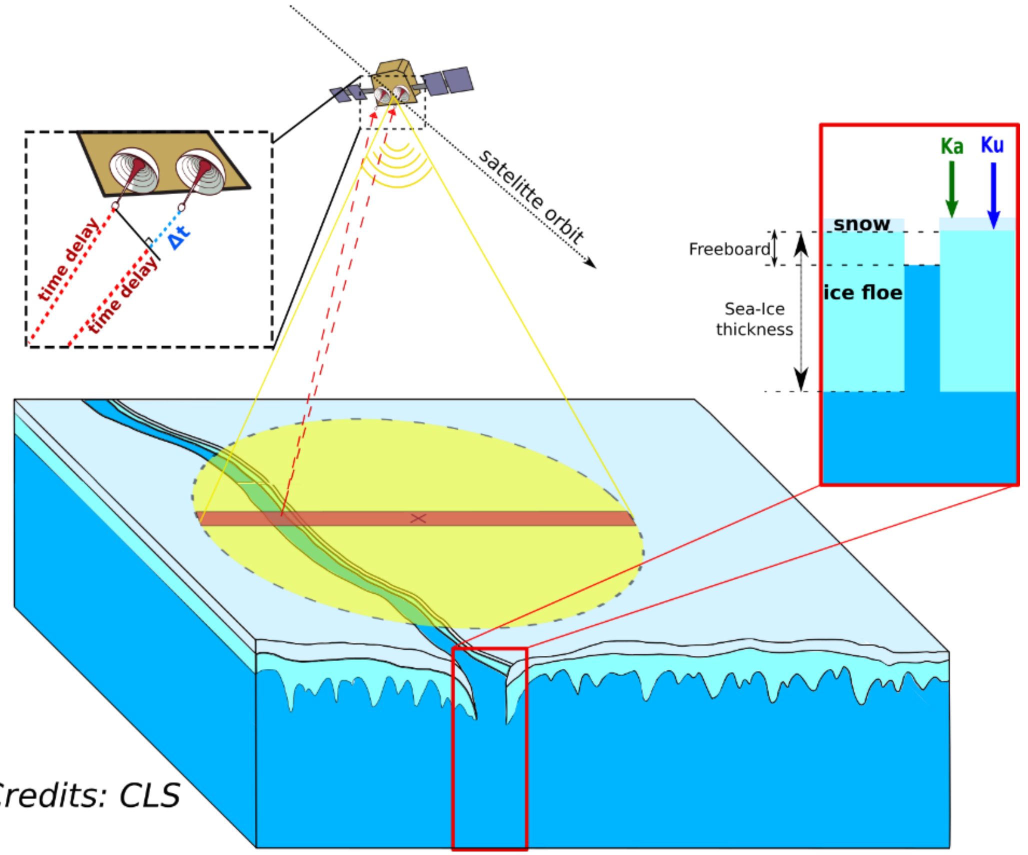
CRISTAL over the polar ocean

Ocean

Planned configuration: SARIn interleaved in Ku band & SAR interleaved in Ka band

CRISTAL benefits over ice covered ocean:

- SARIn mode enables a more optimal detection of the leads within the radar footprint. From [Armitage et al., 2014]:
  - *"Despite the relatively large error on the mean bias, correcting for off nadir ranging* ***contributes only a small amount to the elevation uncertainty****".* A CLS study concords with this result.
  - *"interferometric mode over sea ice* ***ultimately decreases the uncertainty*** *on the area averaged ocean elevation by* ***allowing the inclusion of more waveforms in the analysis****"*
- In addition, the Ku/Ka dual frequency is in theory valuable to estimate more accurately snow depth and the freeboard subsequently. **But we have to clearly master how snow impacts the LRM/SAR Ku/Ka measurements, and how a snow depth can be accurately retrieved from retracking algorithms.**



Credits: CLS

Mission requirements document

Ocean

MRD-480: *The standard deviation of the 1-second along-track averaged corrected measurements of sea surface height shall be less than 0.0294 m*

- If we keep the requirement as it is, it would be preferable to take Sentinel-3A value (0.035m) as the 0.0294m value originates from Sentinel-6 [Scharoo et al., 2016], in interleaved mode over open ocean.

- Moreover, there are few inconsistencies between the 0.0294m value (which is a residual sum of squares) and the error/noise specified for the individual components.

- BUT, the different components noises/errors that are integrated to derive a single noise value for the SSH do not have the same magnitude, depending on the spatial/time scales considered. A study performed in the frame of PolarIce established more precisely the CRISTAL SSH errors, as function of different time & spatial scales.

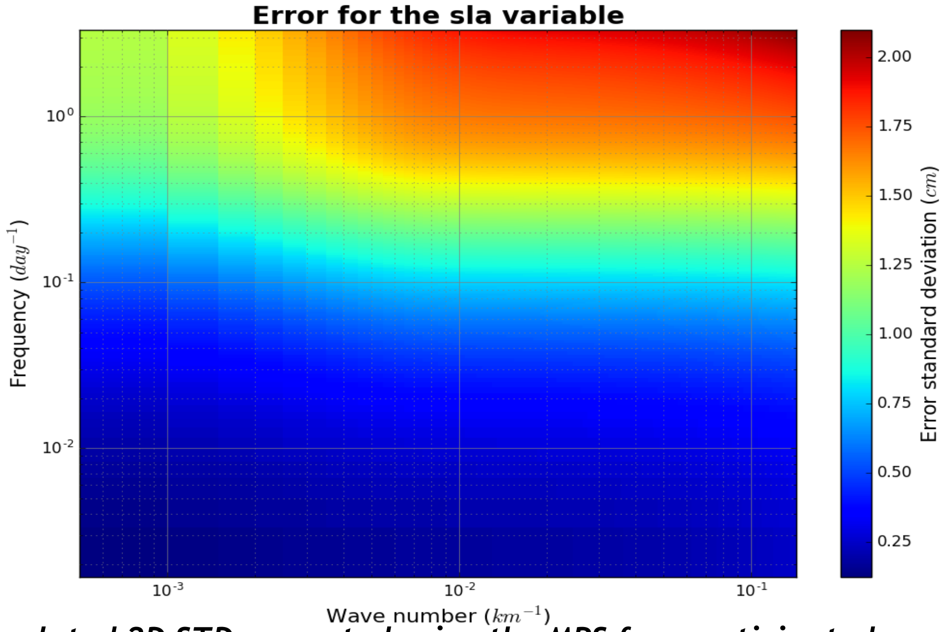
Mission requirements document

Ocean

MRD-480: *The standard deviation of the 1-second along-track averaged corrected measurements of sea surface height shall be less than 0.0294 m*

Error source	STD	Spatial correlation length	Temporal correlation length
Altimeter random	0.9 cm	0 km	0 day
SSB noise	0.3 cm	300 km	Inf.
SSB correlated	1 cm	100 km	1 day
Ionosphere	0.25 cm	600 km	0 day
Wet Troposphere	1 cm	50 km	1 hour
Dry Troposphere	0.2 cm	600 km	2 days
Mean Sea Surface	0.5 cm	1 km	Inf.
Ocean Tides	1 cm	1000 km	< 1 day
Orbit solutions	1.5 cm	>10 000 km	< 1 day

CRISTAL Ku-band SLA error characterization (anticipated)



Simulated 2D STD computed using the MPS from anticipated uncertainty characteristics of the CRISTAL mission over ocean in Ku band

Error budget for the CRISTAL mission over the ocean in Ku band is:
~2 cm at very short scales
between 0.3 and 0.7 cm at mesoscales
<0.3 cm at climatic scales.

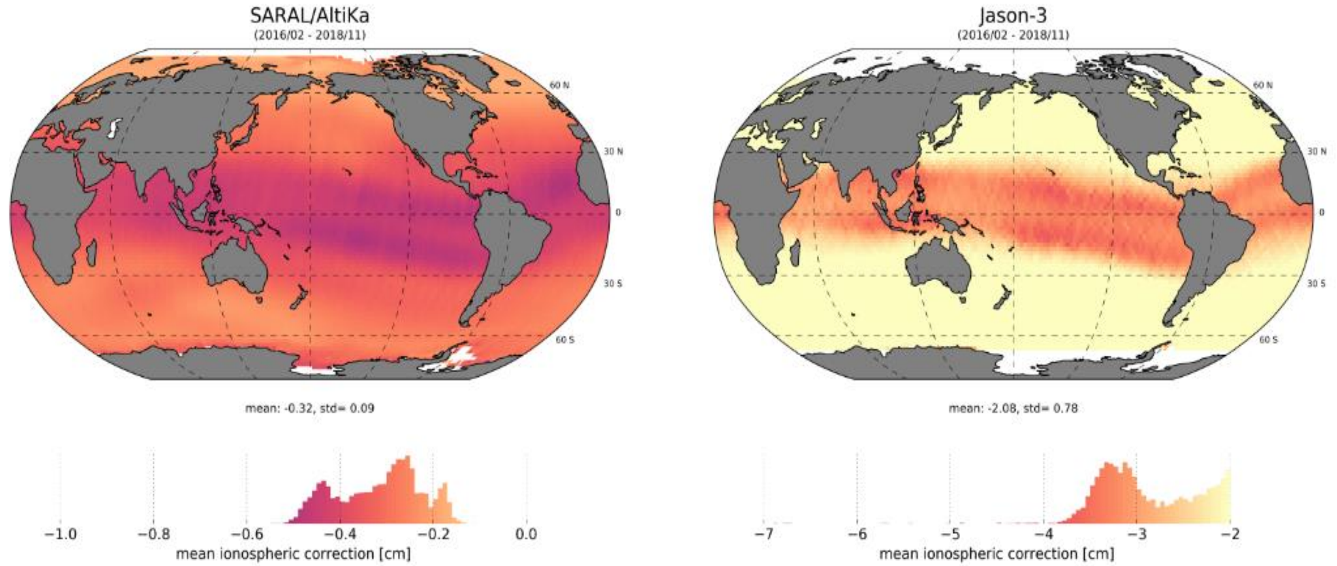
Mission requirements document

Ocean

MRD-480: *The standard deviation of the 1-second along-track averaged corrected measurements of sea surface height shall be less than 0.0294 m*

Note 1: ionosphere correction 1Hz STD less than 0.5 cm at NTC

- Correction that takes into account the path delay in the radar return signal due to **electron content in the atmosphere**
- Order of magnitude: **0 to 5 cm in Ku** band **& 0 to 0.5cm in Ka** band



Mission requirements document

Ocean

***MRD-480:** The standard deviation of the 1-second along-track averaged corrected measurements of sea surface height shall be less than 0.0294 m*

Note 1: ionosphere correction 1Hz STD less than 0.5 cm at NTC

- Correction noise follow the relationship:

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

20hz ionospheric noise level

Freq2 \ Freq1	C band (cm)	Ku band SAR (cm)	Ka band SAR (cm)
C band (cm)	X	3.4	0.4
Ku band SAR (cm)	22.2	X	1.3
Ka band SAR (cm)	19.2	9.1	X

Filtered ionospheric noise level (250km)

Freq2 \ Freq1	C band (cm)	Ku band SAR (cm)	Ka band SAR (cm)
C band (cm)	X	0.13	0.015
Ku band SAR (cm)	0.83	X	0.05
Ka band SAR (cm)	0.72	0.34	X

With:

σ range in SAR Ku : 5.5cm
σ range in SAR Ka : 5.5cm
σ range in C : 18cm

(numbers from S3A & Jason-3, anticipated to CRISTAL)

Using the Ka band, filtered ionospheric correction in Ku band should be lower than 0.05cm

Mission requirements document

Ocean

***MRD-460:** The vertical uncertainty in sea level anomaly retrieval from Ku band (including sea-ice leads) shall be 0.02m.*

- Sentinel-3A mean SSH accuracy of **+0.022m** & +0.007m, respectively in **SAR mode** & PLRM [Bonnefond et al., 2018] (validation made at Senetosa Cape, Corsica, with radar tide gauge & pressure tide gauges)
- Updated results at 2019 OSTST show a mean bias of **+0.008m** for **SAR Sentinel-3A** & **-0.0014m** for **SAR Sentinel-3B**
- By providing an even better vertical resolution than Sentinel-3A (~31cm vs ~47cm), CRISTAL should therefore meet the requirement over open-ocean.

Mission requirements document

Ocean

MRD-430 The temporal resolution of sea level anomaly (including in ice covered water) shall be less than 10 days.

MRD-450 The temporal resolution of absolute dynamic topography (ADT) retrieval shall be less than 10 days.

=> the temporal resolution of SLA & ADT must be discussed in a multi-missions context, where CRISTAL will be included in a 5-7 satellites constellation

MRD-420 The mission shall be capable of retrieving sea level anomaly at an along-track resolution better than 1o km.

MRD-440: The mission shall be capable of retrieving mean dynamic topography (MDT) at an along-track resolution better than 1o km.

=> The along-track resolution (sampling) depends of the Doppler band width in SAR unfocused & also on-ground sampling chosen. But the along-track resolution must be put in perspective with its inherent noise level.

Mission requirements document

Ocean

MRD-500 The uncertainty of 1-second along-track averages of 10 m wind speed over ocean surfaces shall be better than 1.5 m/s for winds in the range 3 to 20 m/s.

MRD-510 The uncertainty of 1-second averaged measurements of significant wave height in the range 0.5 to 8 m shall be less than 0.15 m plus 5% of the significant wave height.

⇒ **MRD 510** must be achieved based on Sentinel-3A performances

⇒ We don't have elements to evaluate **MRD 500** feasibility. The uncertainty of the wind-speed is directly linked to the Sigma-0 uncertainty as well with the algorithm employed.

Error type	specification	1Hz precision measured
altimeter random error	1.3 cm	1.1 cm
Sea State Bias	2.0 cm	0.50 cm
Ionosphere propagation correction error	0.7 cm	1.4 cm / 0.2 cm
Dry troposphere prop. correction error	0.7 cm	0.1 cm
Wet troposphere prop. correction error	1.4 cm	0.25 cm
Total range error (rms)	2.94 cm	2 cm
Significant Wave Height	4% or 20 cm	9 cm
Backscatter coefficient	< 1 dB	0.12 dB

Table derived from the ESA GMES system requirements for SWH=2m and backscatter coefficient = 8 dB (source is ESA GMES Sentinel-3 System Requirement Document issue 4 r0)