Response to Anonymous Referee #1, received and published: 10 March 2020

13 March 2020

Please see our responses in blue color in the reviewers text.

Thank you for this careful review and the constructive comments below, which have been used to revise the paper.

Anonymous Referee #1
Received and published: 10 March 2020
————— Summary —————
This paper introduces the Copernicus polaR Ice and Snow Topography ALtimeter (CRISTAL), which is a Polar orbiting satellite that has been identified as a high-priority candidate mission by the European Commission (EC) in collaboration with the European Space Agency (ESA). CRISTAL will build on the heritage of previous Ku- and Ka-band satellite radar altimeters by operating at both frequencies, as well as flying a high-resolution passive microwave radiometer. Such a mission is crucial for the continuation and improvement of large-scale observations of the polar and terrestrial ice and snow cover, as well as ocean dynamics. Therefore, this paper will be of interest to a large and varied readership, and I am pleased to see an update on CRISTAL's progress being submitted. However, I do have some concerns and comments that should be addressed before publication.

Thank you for this careful review and the constructive comments.

My main concern is that this should be "the" paper highlighting the importance of CRISTAL, above and beyond other candidate satellite missions. Therefore, it needs to be clear, convincing, and accessible to a wide audience. The current manuscript reads too much like a copy and paste from an ESA report.

The paper is intended to inform the scientific and user community of this candidate mission in preparation. It is not the intention of the authors to rank or priortise this candidate mission above and beyond other candidate satellite missions in preparation. To address the comment from the reviewer, it is proposed to change the title, the abstract and to restructure/reorganise the paper has been considerably so that it reads better. We have tried to rework the paper so that it reads less like a white paper.

- The paper would benefit from being more concise, with improved coherence between sections, less repetition, and an early focus on the scientific benefits of CRISTAL instead of having them spread throughout

The mission is addressing operational user requirements and needs identified by the European Commission. A general background and context of the mission is considered important as it cannot be found anywhere else.

However, the authors acknowledge the concern of the reviewer and propose a considerable change in the paper (new title, now "The Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) High-Priority Candidate Mission", a better tailored abstract and to rework the paper (e.g. interchange sections 4 and 5).

- A number of acronyms are not introduced in the main text (e.g. GMES, EUMETSAT, OSTST), which assumes too much prior knowledge considering the wide readership
Potential

Ok. We have checked again the acronym list and tried to introduce them all at the first instance in the text. Also, a large number of acronyms are removed for clarity.

- It is very hard to digest such long sentences. I appreciate this is a style preference but it was an issue for me. This includes P2L43-46, P4 L120-122, P6170-186 (secondary objectives summary), P89L238-242, and many others.

Ok. We have re-arranged all sentences mentioned by the reviewer. We have also reworked the paper so that it becomes better readable.

————— Specific comments —————

P1L36: This makes it sound like the paper might be more technical than it is. Make it clear that the paper is primarily mission contributions, and does not include in-depth technical information (which can't be available at this time).

Ok. Modified.

P3L89: What is meant by "next generation of the current Sentinels 1 to 6 series"? Could do with a little more information, or relevant references.

Ok, reference added.

P4L105-106: What is "an integrated end-to-end system approach"? These more technical/ agency terms should be explained in a science journal.

Ok. A sentence is added.

P4L13: Remove "inhospitable". The Arctic human population is mentioned in the same sentence.

OK. done

P5L150: Who recorded this recommendation? Please provide a reference.

The OSTST in their closing session. Reference added.

Section 3: The beginning of Section 3 (up to P5L155) is very sea ice heavy. I encourage the authors to provide more on the importance (climatic and observationally) of glaciers, ice caps and ice sheets prior to introducing them as a primary mission objective.

Agreed. Floating ice are listed as the top priority in the PEG report. Therefore, this is more emphasised here. The importance of glaciers and ice caps is now further emphasised.

P6L179-180: Please provide some references for the evidence of frozen rivers and lakes being influenced by climate change

ok, new reference added as well as sentence slightly modified.

P7L202: The authors state that "Compared to heritage missions, the Ka-band channel (35.75 GHz) is added for snow: : :" but later in the paragraph, they describe SARAL (AltiKa) as a heritage mission, which could be confusing to readers who are not familiar with the history of Ka-band altimeters.

Ok, sentenced changed.

P7L208: Which radar system does the 500 MHz bandwidth apply to? As I read it, they mean just Ka. However, AltiKa also has a bandwidth of 500 MHz so I'm not sure how this would lead to an improved range resolution in comparison.

500 MHz applies to entire system and both frequencies, Ka-band and Ku-band. This is now better formulated.

P7L209: The reference to Egido and Smith (2017) should also be included here

Ok. Added.

P8L239: Add reference to Armitage and Davidson (2013) – DOI: 10.1109/TGRS.2013.2242082

Ok, added, Armitage and Davidson (2014).

P8L244-245: The authors state that “Retrievals are likely improved by a factor 2: : :” but it’s not clear what retrieval parameter they are referring to. The number of retrievals? Accuracy of individual retrievals?
Ok, updated.
P10L270-271: I understand that it is only Arctic sea ice that is a driving force of the global thermohaline circulation
ok, changed.
P10L278: The Perovich (2017) reference is over two years out of date. NSIDC, for example, can provide the most up-to-date statistics on sea ice extent decline.

Ok, added.

P11L311-313: Include some discussion/reference to Mallett et al. (2020) – DOI: 10.5194/tc-14-251-2020, which finds that assumptions concerning the time evolution of overlying snow density can lead to underestimates of sea ice thickness from radar altimetry. This will have the opposite impact of the salinity consideration of Nandan et al. (2017).
OK. Text added and Reference added. Please note that the Mallett et al reference was not available at the time of submission of this paper.
Section 5.1: Include a comment on the importance of sea ice in Antarctica. There are many examples relating to ecosystems/surface momentum exchange/ice shelf-ocean interactions etc.
Ok, one sentence is added.
Section 5.2: Currently this paragraph applies only to Arctic sea ice. The authors could address the difficulties of applying a dual-frequency snow depth retrieval method in Antarctica (much more complex penetration). Also, the first sentence needs tidying up.
First sentence corrected. Complex situation over Antarctica mentioned.
P13L372: Add reference to Foresta et al. (2016) – DOI: 10.1002/2016GL071485
Sections 5.1 and 5.3 are lacking in references. This needs to be addressed before publication in a scientific journal.
Foresta reference is added. It is noted that Section 5.1 now contains almost 25 references, Section 5.3 8 references. Please understand that the paper cannot provide a complete overview of all aspects studied in literature wrt sea ice and ice sheets; it is also not the intention of this paper but to introduce CRISTAL.
P14L407: The designed operational lifetime of CRISTAL (7.5 years) is key and interesting information, so I suggest mentioning this earlier in the manuscript, such as in the introduction and even the abstract
It is now added earlier in chapter 4.
P16L478-479: What is the timeframe of prototype and potential satellite development? A couple of tables would be useful in the paper: One that summarizes the current mission milestones and timeframe, and another with instrument information (not limited to altimeters)
This information cannot be provided at this point in time, as it is now yet known and/or depends on the consortiums and instrumentation selected for Phase B2, C/D, E1. More details on the instrument algorithms and performance could be subject for future publications.

————— Technical comments —————
P2L41: “: : :see Chen et al (2013)” -> “: : :(Chen et al., 2013)”
Ok, corrected.
P5L138: “: : :from SAR: : :” -> “: : :from SAR **altimetry**: : :”
Ok, corrected.
P5L149: Remove “at large”
Ok, corrected.
P6L180: “: : :context of global warming: : :” -> ““: : :context of climate change: : :”

Ok, corrected.
P6L189: “requisite” -> “required”
Ok, corrected.
P8L216: This opening bracket has no end
Ok, corrected.
P9L250: Define SLA here, not P14L388
OK, introduced earlier.
P9L252: RMC is already defined on P7L211
OK, corrected.
P9L261: “: : :delivery as **a** Level 1B: : :”
OK, corrected.
P11L286: “ice-infested” -> “ice-covered”
OK, corrected.
P13L370: “..horizontal resolution of less or equal than 100 m: : :” -> “horizontal resolution of less than or equal to 100 m: : :”
OK
P13L378: “: : :helping us understanding and monitoring: : :” -> “: : :helping us to understand and monitor: : :”
Ok, corrected.
P14L391: “: : :supporting **sea** ice thickness retrieval: : :”
Ok, corrected.
P14L393: “associated to” -> “associated with”
Ok, corrected.
General: Please be consistent between “sea-ice” and “sea ice” and the same for land Ice
OK, corrected.

Response to Anonymous Referee #2, received and published: 24 March 2020

27 March 2020

Please see our responses in blue color in the reviewers text.

Thank you for this careful review and the constructive comments below, which have been used to revise the paper.

Anonymous Referee #2
The paper presents an introduction and major update to the anticipated satellite mission, Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL). The key observables of the mission are sea-ice thickness and elevation measurements of ice sheets and glaciers. The motivation for these observables are described. The content of the paper is useful for the scientific and broader communities, and warrants publication. However, there are major issues in the clarity, organization, and redundancy of the text that require attention. These issues prevent the main points of the paper from being communicated.

Thank you for your suggestions and comments. We have re-organised the paper to take into account the reviewers comments by changing the title, the abstract, shortened section 2 considerable and interchanged sections 4 and 5. These structural changes help to reduce repetition.

My major recommendations are to: consolidate Section 5 with the mission objectives listed in Section 3 since much of the content is repetitive; break up numerous run-on sentences and rewrite for clarity; carefully proof the manuscript and correct the many typos and grammatical errors within.

Thank you. A re-organisation of the text has been done to account for this.

L24. Here and throughout the paper, it is not clear what is meant by "evolution." Please describe.
The term 'evolution' is now explained within abstract text, see line 30.

L28. "properties of snow cover on ice" I recommend changing this to snow depth since its retrieval has been demonstrated with Ku- and Ka-band data, whereas the other suggested property retrievals have not yet been fully demonstrated.
Ok, changed.

- Polar Regions, Polar Oceans, and Total Column Water Vapour should not be capitalized.
Ok, all capitalisations corrected.

L29. "foreseen" does not seem like the correct word here since it is not a prediction. "Planned" may be a better word.
Ok, changed to 'planned'.

L43-46. Here and throughout the paper, there are run-on sentences with mixed messages. Please rewrite these for clarity.
The sentence has been changed and shortened.

L50-51. I'd suggest changing this to stakeholders for inclusivity. Derived products may be useful for indigenous communities.
Ok, changed to stakeholders.

L51. While I understand this is a European effort, the listed motivations in this paragraph also apply to other countries. I'd suggest broadening this or adding a statement to be more inclusive of the international community, as it would strengthen the motivation and utility of such a mission.
Ok, understood and changed to be more inclusive.

L53. "It also has..." what does "it" refer to here?

Sentence removed. It referred to 'Europe'.

L57. These potential impacts are not limited to European weather. They may affect global weather patterns.
Ok, changed and 'European' removed.

L61-63. The following section is more about the history of the Copernicus programme, rather than an overview of the missions under development. I'd suggest editing either this sentence or the section to be consistent with one another. Depending on who the target audience is, the mission overviews may be more useful for the broader community than the history of the Copernicus programme.
Ok, the sentence was changed.

L70-82. Who is the target audience of this paper? Do they need to know the history of the Copernicus programme?
Ok, agreed. We have shortened the first two paragraphs in this section and merged them. We need some introductory sentences since otherwise we cannot introduce the concept of the HPCMs.

L84. This is vague. Potential for what?
Ok, shortened and changed to 'The intense use of Copernicus'.

L85. For future what? This is vague.
Ok, removed.

L103. What "so-called Long-Term Scenario" is this sentence referring to? It is unclear.
OK, it is now explained.

L105. "EC" and "RMC" elsewhere. Use acronyms consistently.
Ok, changed use of EC and RMC consistently.

L105-106. What does "integrated end-to-end system approach" mean? Here and throughout, such buzzwords are not informative.
The paragraph was removed.

L133. UNFCC. This and other acronyms are defined and used only once. I recommend deleting unnecessary acronyms such as this one for easier reading.
Ok, acronym UNFCC and several others removed from the list.

L150. OSTST in-text definition missing.
Ok, added in the text.

L155+ I suggest using bold font or italics for the first lines of each bullet point for easier reading.
OK, used 'bold font' to better highlight these lines.

L202-203. "is added for snow depth measurements to distinguish between snow and ice layers" needs rewriting for clarity.

Ok, sentence re-written.

L216-217. Is a parenthesis missing?
Ok, corrected.

L242. Add "over sea ice" after snow depth.
Ok, corrected.

L254. What does "on a best effort basis" mean?
It will be systematically observed if data volume /downlink capabilities allow so. “On a best effort basis” removed.

L272. "its presence limits human access" I suggest considering a different perspective of sea ice. It’s a platform enabling subsistence hunting and travel for indigenous coastal communities.
Ok, sentence changed.

L274. ice-infested. Why use a word with such negative connotations?
Ok, removed.

L280-281. "to safeguard both climate and operational data services" Safeguard does not seem like the right word. "extending" or "advancing" may be better.
Ok, we changed it to ‘extending’.

L282-289. Confusing, run-on sentences.
Ok, sentences shortened and changed.

L288. Essential Climate Variable sounds important, but what does that really mean?
It is a term used by GCOS. We will not change it in the text.

L308. Please clarify that this information relates to Copernicus sea ice thickness products.
Rewritten to ‘Most sea ice thickness products …’

L310. Please state which satellite this uncertainty pertains to.
CryoSat-2 data. Added to the text.

L319-322. Run-on, confusing sentence.
Shortened and corrected.

L320. This uncertainty value is not consistent with the one given in the preceding paragraph. Please provide more detail on why these are different values.
Paragraph was updated and more details provided.

L330-333. References are needed. The uncertainty in snow depth data from the historical period is as good as it can possibly get, on the order of 1 cm and less. The uncertainty is not halved over first year sea ice. Several studies have shown snow to be thinner over first year sea ice in areas where Operation IceBridge surveys were conducted. In other regions of the Arctic, deep snow can exist on first year sea ice.
Another reference added and the text was shortened to make it more readable.

L333 Giles et al. 2007 seems like a more appropriate reference here since it was the first study to demonstrate the propagating uncertainties associated with snow depth and other geophysical parameters.
Ok, the reference was added and the sentence shortened.

L338-341. Please rewrite for grammar.
Ok, sentences updated and changed.

L354-355. Computing mass balance and identifying mass imbalance seem like the same thing here.
Sentence updated and changed.

L360. The continuous record provides.... a long-term record. This is circular.
Ok, sentence changed.

L365-366. Are commas missing? Please rewrite for grammar.
Commas added. Sentences shortened.

L375. "agility of tracking" It's not clear what is meant by this. How is the satellite going to be agile?
Sentence changed.
L378. Grammar.
Changed.
L382-383. I suggest adding a little more detail here for clarity, e.g. retrieval accuracy of what exactly?
Ok, changed.

L386. "allow" seems like the wrong word here. "Have" may be better.
Ok, changed.

L389. It would be relevant to state the anticipated spatial resolutions here since leads come in all sizes.
Ok, added.

L399-401. This is unclear. Please rewrite.
L403. Reference needed for main causes...
Reference added. Shepherd, A., Fricker, H.A. & Farrell, S.L. Trends and connections across the Antarctic cryosphere. Nature 558, 223–232 (2018). https://doi.org/10.1038/s41586-018-0171-6
L404. Reference needed for largest uncertainty in the current prediction.
Reference added. Edwards, T.L., Brandon, M.A., Durand, G. et al. Revisiting Antarctic ice loss due to marine ice-cliff instability. Nature 566, 58–64 (2019). https://doi.org/10.1038/s41586-019-0901-4.
L414. Please rewrite for clarity.
Ok, sentence changed.
L427-428. These sentences are vague. Please be more direct. Is snow depth retrieval not possible over land with CRISTAL frequencies?
Text modified.
L432-433. What is meant by status?
ok
L434-435. Is it the spatial resolution that limits the wide use of altimetry data for snow and permafrost research or the frequencies used?
Text modified.

L460+ Wouldn't it be important to mention the relevance for monitoring the Antarctic cryosphere?
Antarctica also added to the text in a sentence.

L467. Is this true? ICESat-2 reaches 88-deg latitude.
Sentence changed.

L471. It'd be helpful to restate the along-track resolution here since it is a key element

for the mission.
Ok, added to the paper.

We would like to change the reviewer for providing such a thorough list of technical changes and suggestions. We have incorporated all of these changes in the revised version of the manuscript.

Response to Anonymous Referee #3, received and published: 26 March 2020

27 March 2020

Please see our responses in blue color in the reviewers text.

Thank you for this careful review and the constructive comments below, which have been used to revise the paper.

Anonymous Referee #2
Overview: This paper presents the justification for and early design candidate for the CRISTAL mission. The paper also presents on the individual science applications that will be serviced by such a mission.

Summary: Firstly, apologies for my tardy review, I could would like to blame it on the new situation the world finds itself in with COVID-19 but I procrastinated well before that became a factor. A thorough presentation of the need for, and technical capabilities of, the CRISTAL mission is a welcomed contribution to the community. The mission is very exciting and will provide invaluable data necessary to advance polar sciences in the coming decades.

Overall, I found this manuscript very difficult to review. I tried to review the manuscript multiple times but the first 4 sections were such a slog that it was unmotivating. The first 4 sections read like a cut and paste of multiple science agency white papers while the final section, section 5, provides a nice science justification for the mission but is completely decoupled from the first 4 sections. In my opinion the paper requires significant restructuring and more consideration as to what is included and why. I would start with a section (1) that provides the motivation for the mission: that is the science justification (essentially section 5) with a dedicated subsection that summarizes the EU Arctic Policy and primary user requirements that motivate the mission. (2) I would then summarize the geophysical observables that are needed to satisfy the science and application needs (maybe as a table). There is a table for radar specification but not for the geophysical observation requirements that are more relevant to an overview paper. This could be followed by a section (3) that describes the CRISTAL mission capabilities showing that it meets the needs presented in the prior section. The current section 2 could be reduced to 1 or 2 paragraphs that get included in the new section (3), no need to review the full Copernicus program. I think nearly all of the material is in the document, it just needs to be reworked into a coherent justification and description of the mission.

Thank you for this important comment. We have restructured the paper to address this comment. It should be noted, however, that addressing Copernicus services requirements (operational) in the context of the High-Priority Candidate Missions remain the predominant justification for the mission. The science needs are undoubtedly important.
To take into account the reviewers comment, we have re-organised the paper by changing the title, the abstract, shortened section 2 (into 3 paragraphs) and interchanged sections 4 and 5 after modifying them to reduce repetition.

I have many small comments on grammar and wording but I don't think the manuscript is at the point yet where those details would be all that useful. For that reason, I only list my major comments here:
- There is a reasonable amount of redundant text between section 5 and the rest of the manuscript. This is mostly a result of organization and can be fixed by structuring and being more selective on what's included

We have restructured the paper to remove repeating sentences and redundant text as much as possible.

- Sections 1-4 lack references supporting statements (I believe there is only 1 reference supporting the idea that the combination of ka- and ku- band altimeter will substantially improve measurements of snow on sea ice.
More references have been added. It is true that more experimental data is required further study the combination of Ka-band and Ku-band and its impact.

-Also several citations are outdated (e.g. Chen 2013), DeCanto and Pollard, 2016 is highly controversial and is not a representative citation for a current best estimate of future ice sheet change.
This has been changed and replaced with more representative citations.

- There is virtually no justification for including a microwave radiometer and no supporting literature, this should be shored up with a clear justification as to the applications (with list of geophysical observables) and science it will support with appropriate citations
Agreed. A justification is now added to the paper. There are perhaps two points to mention:

- Over sea ice, the active/passive synergy enables to classify the sea ice type
- Over open ocean, the radiometer is required to meet the range accuracy requirement.

- Observing mode “Land-ice and Glacier” doesn’t make a lot of sense since glaciers are Land-ice. I would suggest renaming this mode to “Land-ice” -or- glaciers and permafrost (GP) –or glaciers, ice sheets and permafrost (GISP)
Understood. However, the names for the observing modes have now been used throughout the mission preparation phase, with different study partners and industry. We would prefer to keep these names in order not to confuse partners involved. Acronyms have been removed for better clarity.

- It is not clear how CRYSTAL will handle range ambiguities over complex glacier and permafrost terrain as advertised.
The purpose of the interferometric mode is to allow the across-track angle offset of the echoing point to be determined directly (using interferometric phase information). Phase-wrapping can occur when the across track offset is great enough and this can have the effect of the echo appearing to come from the other side of the ground track. This restricts the method to areas with an average cross-track slope of ~ 0.5 to $\sim 2^{\circ}$. Normally, this is flagged by use of an ambiguity Digital Elevation Model.
A sentence is added.

- The colors for Figure 3 are difficult to distinguish (particularly magenta and purple). The figure should also include a colorbar and pole hole data gap.
Figure 3 shows the required masks for operation, which is the reason why the polar gap is not relevant here. The figure caption was updated and improved.

The Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) High-Priority Candidate Mission

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Michael Kern[1], Robert Cullen[1], Bruno Berruti[1], Jerome Bouffard[2], Tania Casal[1], Mark R. Drinkwater[1], Antonio Gabriele[1], Arnaud Lecuyot[1], Michael Ludwig[1], Rolv Midthassel[1], Ignacio Navas Traver[1], Tommaso Parrinello[2], Gerhard Ressler[1], Erik Andersson[3], Cristina Martin-Puig[4], Ole Andersen[5], Annett Bartsch[6], Sinead Farrell[7], Sara Fleury[8], Simon Gascoin[9], Amandine Guillot[10], Angelika Humbert[11], Eero Rinne[12], Andrew Shepherd[13], Michiel R. van den Broeke[14], John Yackel[15]

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[1]European Space Agency (ESA-ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
[2]European Space Agency (ESA-ESRIN), Via Galileo Galilei, Casella Postale 64, 00044 Frascati, Italy
[3]European Commission, BREY 09/154, 1049 Brussels, Belgium
[4]EUMETSAT, Eumetsat Allee 1, 64295 Darmstadt, Germany
[5]DTU Space, Elektrovej 28, 2800 Lyngby, Denmark
[6]b.geos, Industriestrasse 1, 2100 Korneuburg, Austria
[7]University of Maryland, 5825 University Research Court, 20740 College Park, MD, USA
[8]CTOH/LEGOS/CNRS, 14 avenue Edouard Belin, 31400 Toulouse, France
[9]CESBIO, CNRS, 18 avenue Edouard Belin, 31401 Toulouse, France
[10]CNES, 18 avenue Edouard Belin, 31400 Toulouse, France
[11]Alfred-Wegner-Institute Helmholtz Centre for Polar and Marine Research, Am Alten Hafen 26, 2758 Bremerhaven, Germany
[12]Finnish Meteorological Institute, PO Box 503, 00101 Helsinki, Finland
[13]Sheperd Space Ltd., 110 West End Avenue, HG2 9BT Harrogate, United Kingdom
[14]Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands
[15]University of Calgary, 2500 University Drive NW, Earth Sciences 356 Calgary, Alberta, Canada

Deleted: [7]CTOH/LEGOS/CNRS, 14 avenue Edouard Belin, 31400 Toulouse, France¶
[8]University

Correspondence to: M. Kern (Michael.Kern@esa.int)

Abstract.

The Copernicus polaR Ice and Snow Topography ALtimeter (CRISTAL) is one of six high-priority candidate missions (HPCMs) under consideration by the European Commission (EC) to enlarge the Copernicus Space Component (CSC). Together, the HPCMs fill gaps in the measurement capability of the existing CSC to address emerging and urgent user requirements in relation to monitoring anthropogenic CO_2 emissions, polar environments, and land surfaces. The ambition is to enlarge the CSC with the HPCMs in the mid-2020s to provide enhanced continuity of services in synergy with the next generation of the existing Copernicus Sentinel missions. CRISTAL will carry a dual-frequency synthetic aperture radar altimeter as its primary payload for measuring surface height, and a passive microwave radiometer to support atmospheric corrections and surface-type classification. The altimeter will have interferometric capability at Ku-band for improved ground resolution, and a second (non-interferometric) Ka-band frequency to provide information on snow layer properties. This paper outlines the user consultations that have supported expansion of the CSC to include the HPCMs, describes the primary and

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

secondary objectives of the CRISTAL mission, identifies the key contributions the CRISTAL mission will make, and presents a concept - as far as it is already defined - for the mission payload.

1 Introduction

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

A long-term programme to monitor the Earth's polar ice, ocean and snow topography is important to stakeholders with interests in the Arctic and Antarctic. While Europe has a direct interest in the Arctic due to its proximity (see https://ec.europa.eu/environment/efe/news/integrated-eu-policy-arctic-2016-12-08_en), the Arctic is also of interest to other countries and international communities. Changes in the Arctic environment affect strategic areas including politics, economics (e.g. exploitation of natural resources including minerals, oil and gas, fish) and security. Besides economic impacts of Antarctic and Arctic changes (Whiteman et al, 2013), Europe's interest in both polar regions is due to their influence on patterns and variability in global climate change, thermohaline circulation and the planetary energy balance. Last but not least, changes in the Arctic system have potential impacts on weather, with consequences for extreme events (Francis et al., 2017). The Copernicus polaR Ice and Snow Topography Altimeter (CRISTAL) mission, described in this paper, addresses the data and information requirements of these user communities with a particular focus on addressing Copernicus service requirements.

In the following section, we provide a background of the Copernicus programme and candidate missions that are being prepared by the European Space Agency (ESA) in partnership with the European Union (EU) in response to Copernicus user needs. In Section 3, we describe the objectives of the CRISTAL mission and its relation to the Copernicus services. We then discuss the key contributions from the CRISTAL mission, both in terms of specific mission objectives as well as expected scientific contributions towards improved knowledge of various state variables in Section 4. In Section 5, an overview of CRISTAL's currently known technical system concept and mode of operation is described. It also highlights the use of heritage

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technology and needs driving technical advancements to improve observational capabilities beyond current missions. Conclusions and a current mission status statement is provided in Section 6.

2 Expansion and evolution of the Copernicus Space Component

Copernicus was established to fulfil the growing need amongst European policymakers to access accurate and timely information services to better manage the environment, understand and mitigate the effects of climate change and ensure civil security. To ensure the operational provision of Earth-observation data, the Copernicus Space Component (CSC) includes a series of seven space missions called 'Copernicus Sentinels', which are being developed by ESA specifically for Global Monitoring for Environment and Security (GMES)/Copernicus. The Copernicus programme is coordinated and managed by the European Commission (EC). It includes Earth observation satellites, ground-based measurements, and services to process data to provide users with reliable and up-to-date information through a set of Copernicus Services related to environmental and security issues.

The intense use of Copernicus has generated high expectations for an evolved Copernicus system. There is now a large set of defined needs and requirements. With respect to the polar regions, user and observation requirements have been identified, structured and prioritised in a process led by the EC (Duchossois et al., 2018a; 2018b). Two distinct sets of expectations have emerged from this user consultation process. Firstly, stability and continuity, while increasing the quantity and quality of Copernicus products and services, led to one set of requirements. They are distinctly addressed in the considerations for the next generation of the current Sentinels 1 to 6 series, see e.g. European Commission (2017).

Emerging and urgent needs for new types of observations constitute a second distinct set of requirements that are mainly addressed through evolution of the Copernicus Space Segment service. This evolution corresponds to the enlargement of the present space-based measurement capabilities through the introduction of new missions to answer these emerging and urgent user requirements. After extensive consultation, six potential HPCMs have been identified (ESA, 2019b); the Copernicus Hyperspectral Imaging Mission for the Environment (CHIME), the Copernicus Imaging Microwave Radiometer (CIMR), the Copernicus Anthropogenic Carbon Dioxide Monitoring mission (CO2M), the Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL), the Copernicus Land Surface Temperature Monitoring mission (LSTM), and the L-band Synthetic Aperture Radar (ROSE-L).

3 Objectives of the CRISTAL mission

The strategic, environmental and socio-economic importance of the Arctic region has been emphasised by the European Union in their integrated policy for the Arctic (https://ec.europa.eu/environment/efe/news/integrated-eu-policy-arctic-2016-12-

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These new types of observations are addressed by six new potential Copernicus missions, so-called High Priority Candidate Missions (HPCMs), see e.g. ESA (2019b) for a more detailed overview:¶
- Anthropogenic CO_2 Monitoring (CO2M) mission¶
- High Spatio-Temporal Resolution Land Surface Temperature Monitoring (LSTM) mission¶
- Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) mission¶
- Copernicus Imaging Microwave Radiometer (CIMR) mission¶
- Copernicus Hyperspectral Imaging Mission for the Environment (CHIME)¶
- Radar Observing System for Europe, L-Band (ROSE-L) mission¶

The so-called Long-Term Scenario, is a multi-annual implementation plan describing the main elements of this architecture, which has been generated through close consultation with the EC and EUMETSAT (see, ESA 2019). In order to identify synergies, complementarities and the evolution paths for the missions in response to EC requirements, an integrated end-to-end system approach is adopted and four observational capability families are defined: Microwave Imaging Family, Optical Imaging Family, Topographic Measurement Family and Spectroscopic Atmosphere Measurement Family. It is emphasised that CRISTAL is an essential part of the Topographic Ocean and Ice Measurement Family, and the evolution in Copernicus capabilities to address polar user needs.¶
3 CRISTAL mission objectives and contributions to Copernicus services¶
"An integrated European Union policy for the Arctic" (https://ec.europa.eu/environment/efe/news/integrated-eu-policy-arctic-2016-12-08_en) emphasises the

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08_en), including the Arctic Ocean and its adjacent seas. Considering the sparse population and the lack of transport links, a capacity for continuous monitoring the Arctic environment with satellites is considered essential. In light of this, and of the importance of the polar regions more widely, guiding documents have been prepared in a European Commission-led user consultation process: the Polar Expert Group (PEG) User Requirements for a Copernicus Polar Mission Phase-I report Duchossois et al. (2018a), hereafter referred to as PEG-1 report, and the Phase 2 report on Users' requirements Duchossois et al. (2018b), hereafter referred to as PEG-2 report.

The required geophysical parameters for the polar regions are summarised and prioritised in the PEG-1 report, which addresses objectives as defined in the EU Artic Policy Communication, namely: climate change, environmental safeguarding, sustainable development, support to indigenous populations and local communities. Floating ice parameters were listed as the top priority for a polar mission considering the availability of existing Copernicus products and services, as well as their needs for improvement (e.g. in terms of spatial resolution, accuracy, etc) and the current level of their technical and/or scientific maturity. The specific parameters include sea ice extent, concentration, thickness, type, drift, and velocity, thin sea ice distribution, iceberg detection, drift and volume change as well as ice shelf thickness and extent. These parameters were given a top priority by the European Commission due to their key position in operational services such as navigation and marine operations, and in meteorological and seasonal prediction and climate model validation. In addition, the PEG-1 report also stresses the importance of a measuring capability for mountain glaciers and ice caps, seasonal snow, ice sheets, ocean, freshwater, and permafrost.

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

While the Copernicus Sentinel-3 mission provides partial altimetric measurements of the polar oceans, their inclination limits the coverage to latitudes between 81.5°N and 81.5°S. With the expected on-going loss of Arctic sea ice, these satellites will monitor only a small amount of the Arctic ice cover during summer periods by mid-2020, see e.g. Quartly et al (2019). Currently, ESA's CryoSat-2 (Drinkwater et al., 2004; Wingham et al., 2006, Parrinello et al. 2018) is the only European satellite to provide monitoring of the oldest, thickest multiyear ice. However, continued monitoring of the polar regions – and

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the Arctic Ocean north of 81.5°N in particular - are at risk, since CryoSat-2 has been operating in its extended mission scenario since its nominal end-of-mission lifetime of October 2013 (see Figure 1). This risk has widely been recognised by the polar and ocean surface topography community. For example, at the recent Ocean Surface Topography Science Team 2019 (OSTST 2019) meeting (held in Chicago, IL, US on 21-25 October 2019) a recommendation was recorded (at the plenary session, see OSTST 2019) in view of the preparations for CRISTAL and other missions currently in operation: "To minimise likelihood of a gap in polar ocean and ice monitoring, the OSTST encourages Agencies to strive to launch CRISTAL in the early 2020s and to maintain operation of CryoSat-2, ICESat-2, and Satellite with Argos and SARAL ALtiKa as long as possible."

Based on the user requirements and priorities outlined in the PEG-1 report, a set of high-priority mission parameters was defined by ESA's CRISTAL Mission Advisory Group (MAG) and ESA, which led to the CRISTAL mission objectives (Table 1). The primary objectives drive the design and main performance specifications of the CRISTAL mission, whereas the secondary objectives reflect the opportunity to support a wider range of users and services.

Table 1 CRISTAL mission objectives

Nature	Target	Objective
Primary	Sea ice	**To measure and monitor variability of Arctic and Southern Ocean sea ice thickness and its snow depth.** Seasonal sea ice cycles are important for both human activities and biological habitats. The seasonal to inter-annual variability of sea ice is a sensitive climate indicator; it is also essential for long term planning of any kind of activity in the polar regions. Knowledge of snow depth will lead to improved accuracy in measurements of sea ice thickness and is also a valuable input for coupled atmosphere-ice-ocean forecast models. On shorter timescales, measurements of sea ice thickness and information about Arctic Ocean sea state are essential support to maritime operations over polar oceans.
Primary	Land ice	**To measure and monitor the surface elevation and changes therein of polar glaciers, ice caps and the Antarctic and Greenland ice sheets.** The two ice sheets of Antarctica and Greenland store a significant proportion of global fresh water volume and are important for climate change and contributions to sea level. Monitoring grounding line migration and elevation changes of floating and grounded ice sheet margins is important to identify and track emerging instabilities. These instabilities can negatively impact the stability of the ice sheets, leading to ice mass loss and ultimately result in accelerated future sea-level rise.
Secondary	Ocean	**To contribute to the observation of global ocean topography as a continuum up to the polar seas.** This will contribute to the observation system for global observation of mean sea level, mesoscale and sub-mesoscale currents, wind speed and significant wave height. Information from

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<#>To measure and monitor the surface elevation and changes therein of polar glaciers, ice caps and the Antarctic and Greenland ice sheets. The two ice sheets of Antarctica and Greenland store a significant proportion of global fresh water volume and are important for climate change and contributions to sea level. Monitoring grounding line migration and elevation changes of floating and grounded ice sheet margins is important to identify and track emerging instabilities, which can negatively impact the stability of the ice sheets, leading to ice mass loss and ultimately result in accelerated future sea-level rise. ¶
<#>Secondary objectives of the

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<#>To support applications related to coastal and inland waters. Observation of water level at Arctic coasts as well as of rivers and lakes is a key quantity in hydrological research. Rivers and lakes not only supply freshwater for human use including agriculture but also maintain natural processes and ecosystems. The monitoring of global river discharge and its long-term trend contributes to the evaluation of global freshwater flux, which is critical for understanding the mechanism of global climate change. The frozen rivers and lakes are important circulation routes in the Arctic regions, which encountered dramatic changes in the context of global warming. Their observation could help forecasting their evolutions and organizing alternative modes of transport.¶
<#>To support applications related to snow cover and permafrost in Arctic regions. Snowmelt timing is a key parameter for hydrological research, since it modulates the river discharge of Arctic basins, see e.g. Shiklomanov et al (2007). Surface state change in permafrost regions indicates the initiation of ground thaw and soil microbial activities in the seasonally unfrozen up ...

		this mission serves as critical input to operational oceanography and marine forecasting services in the polar oceans.
Secondary	Inland water	**To support applications related to coastal and inland waters. Observation of water level at Arctic coasts as well as of rivers and lakes is a key quantity in hydrological research.** Rivers and lakes not only supply freshwater for human use including agriculture but also maintain natural processes and ecosystems. The monitoring of global river discharge and its long-term trend contributes to the evaluation of global freshwater flux, which is critical for understanding the mechanism of global climate change, see e.g. Prowse et al (2011), Zakharova et al (2020). Changes to seasonal freezing of Arctic river and lakes in the context of climate change will also be important to study and understand. Their observation could help forecasting their evolutions and organizing alternative modes of transport.
Secondary	Snow	**To support applications related to snow cover and permafrost in Arctic regions.** Snowmelt timing is a key parameter for hydrological research, since it modulates the river discharge of Arctic basins, see e.g. Shiklomanov et al (2007). Surface state change in permafrost regions indicates the initiation of ground thaw and soil microbial activities in the seasonally unfrozen upper soil (active) layer. The rapid evolution of the permafrost has also important impacts on human activities and infrastructures.

By addressing these objectives, the mission responds to a number of required parameters of interests and applications in Copernicus Services. A mapping of the services to the parameters of interest and applications is listed in Table 2.

Table 2 Copernicus Services addressed by CRISTAL.

Copernicus Service	**Relevant geophysical parameters of interest**	**Core information service addressed or affected (forecasting, monitoring or projections)**
Copernicus Marine Environmental Monitoring Service (CMEMS)	• Sea ice thickness and snow depth • Sea-level anomaly and geostrophic ocean currents in polar oceans • Significant wave height in polar oceans • Global sea level • Global sea surface wind and waves	Maritime safety, Coastal and Marine Environment, Marine Resources and Weather, Seasonal Forecasting and Climate activities
Copernicus Climate Change Service (C3S)	• Ice-sheet topography • Sea ice thickness and volumes	Observations, Climate reanalysis, seasonal forecasts and climate projections

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

4 Key contributions of the CRISTAL mission

The following sections describe the key contributions of the mission in more detail, including the key requirements that guide the implementation of the mission.

4.1 Sea ice freeboard and thickness

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

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

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A **synthetic aperture radar (SAR) altimeter operating at Ku-band and Ka-band** centre frequencies for global elevation and

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Global warming, and its Arctic amplification, continue to contribute to the decrease of multi-year ice in the central Arctic Ocean, (north of 81.5° N). It is therefore critical to obtain continuous, pan-Arctic observations of sea ice thickness, extending as close as possible to the North Pole. Continuous monitoring of Arctic Ocean sea ice conditions is necessary for safe navigation through ice-covered waters. When linked to previous measurements from CryoSat-2, the CRISTAL mission will deliver observations that will provide a long-term record of sea ice thickness variability and trends, which are critical to support climate services. Since sea ice thickness is an essential climate variable (see GCOS, 2011), its continuous measurement is required to understand the Arctic system and how ice loss is impacting climate at a global scale.

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

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Historically, satellite observations had primarily been used to monitor ice extent until Laxon et al. (2003) produced the first Arctic-wide sea ice thickness estimates from ERS radar altimetry. Since then, various methods for converting the received signal to physical variables have been established (Giles et al., 2008, Laxon et al., 2013; Kurtz et al., 2014; Ricker et al., 2014; Price et al., 2015; Tilling et al., 2018; Hendricks et al., 2018). The capability to obtain an estimate of freeboard and thickness, and converting it to volume, has enabled scientists to better understand the changing Arctic ice cover. Most recently, sea ice freeboard has been estimated from both Ka- and Ku-band measurements (Armitage and Ridout, 2015; Guerreiro et al., 2016; Lawrence et al., 2018).

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Most sea ice thickness products are currently provided on a 25 km grid (see e.g. Sallila,et al 2019 for an overview of different products currently available), which corresponds to the GCOS user requirements (GCOS, 2011), but do not meet the specified accuracy requirements of 0.1 m. Using CryoSat-2 data, it is estimated that the residual, systematic uncertainty in sea ice thickness is presently 0.6 m for first year ice and 1.2 m for multi-year ice. This uncertainty is caused mainly by the unknown penetration of the radar pulse into the snow layer as a result of variable snow properties (Nandan et al., 2017, Nandan et al., 2020), as well as the choice of retracker (Ricker et al., 2014). Reference is also made to Mallett et al. (2020), which finds that assumptions concerning the time evolution of overlying snow density can lead to underestimates of sea ice thickness from radar altimetry.

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While the focus of the Copernicus programme is on the Arctic, comprising all areas north of the southernmost tip of Greenland (~ 60° N), the parameters specified for polar regions should equally be provided for its southern counterpart the Antarctic, as well as all snow- and ice-covered surfaces.

The requirements for CRISTAL are currently stated to provide sea ice freeboard with an accuracy of 0.03 m along orbit segments of less than or equal to 25 km. Furthermore, the system shall be capable of delivering sea ice thickness measurements with a vertical uncertainty less than 0.1 m. The uncertainty requirement for sea ice thickness comes with a caveat, as the thickness uncertainty depends on the uncertainty of auxiliary products. In the case of CRISTAL, snow thickness will be measured by the system, but snow and ice densities will still have to be estimated by other means. In light of the current 0.2 m sea ice thickness uncertainty from CryoSat-2 data assessed by Tilling et al. (2018) for a gridded, monthly product and the anticipated improvement from the dual-altimetry technology, especially in the snow depth and propagation estimates, reaching a higher vertical uncertainty would seem reachable but requires further studies. Currently, the retrieval accuracy of sea ice freeboard is limited by the range resolution of a radar altimeter. The large bandwidth of 500MHz is an important driver for the CRISTAL instrument concept generation. A bandwidth of 500MHz will improve the range resolution from 50 cm (as for CryoSat-2 with 320 MHz bandwidth) to ~ 30 cm for CRISTAL. A radiometer helps in active/passive synergy to classify sea ice type, see e.g. Tran et al (2009) for further justification.

4.2 Snow depth over sea ice

An accurate estimate of snow depth over Arctic sea ice is needed for signal propagation speed correction to convert radar freeboard to sea ice freeboard as well as conversion of freeboard to sea ice thickness. The penetration aspects of a dual-frequency snow depth retrieval algorithm over Antarctica are complex and are not further elaborated here. In addition to uncertainty reduction for ice thickness/freeboard computation, the variation of snow depth is also a parameter highly relevant for both climate modelling, ice navigation and polar ocean research. The snow climatology of Warren et al., (1999) is still the single most used estimate of snow depth in sea ice thickness processing (Sallila et al., 2019). The uncertainty in the original Warren snow depth estimates are halved over first year ice (Kurtz and Farrell, 2011, Zhou et al., 2020), but snow still represents still the single most important contribution to uncertainty in the estimation of sea ice thickness and volume (Tilling et al., 2018). The studies of Lawrence et al. (2018) and Guerreiro et al (2016) show the possibility of using Ku- and Ka-bands in mitigating the snow depth uncertainty. Dual-frequency methods improve the ability to reduce and estimate the uncertainties related to snow depth and sea ice thickness retrieval. The modelling community is particularly interested in the uncertainty information according to the user requirement study in the PEG-1 report. Better abilities to estimate the related uncertainties improves prediction quality assessment of annual snowmelt over Arctic sea ice, see e.g. Blockley and Peterson (2018). The stratigraphy and electromagnetic properties of the snow layer contrast with that of the underlying ice can be exploited to retrieve information on the snow layer properties if contemporaneous measurements are acquired from multiple scattering horizons, see e.g. Giles et al 2007, which demonstrated the propagating uncertainties associated with snow depth and other

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geophysical parameters. A dual-frequency satellite altimeter, as proposed for the CRISTAL mission, will address this need. CRISTAL aims to provide an uncertainty of snow depth retrieval over sea ice of less than or equal to 0.05m. The additional measurements in Ka-band, with a 500MHz bandwidth, support the discrimination between the ice and snow interfaces.

4.3 Ice sheets, glaciers and ice caps

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

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

A unique and continuous record of elevation measurements is provided by radar altimeters, dating back to 1992. The maps are typically delivered in (1) high-resolution (5-10 km) rates of surface elevation change (for single or multiple missions, typically computed as a linear rate of change over a period of several years to decades), and (2) frequently (monthly-quarterly) sampled time series of the cumulative change, averaged across individual glacier basins. In addition to being used to quantify rates of mass balance and sea level rise, they also have a range of other applications, such as detection of subglacial lake drainage (Siegert et al., 2016) investigations of the initiation and speed of inland propagation of dynamic imbalance (Konrad et al., 2017), which in turn provides valuable information relating to the underlying physical processes that drive dynamical ice loss.

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CRISTAL will continue the generation of elevation measurements provided by altimeters. It will produce maps of ice surface elevation with an absolute uncertainty of 2 m, horizontal resolution of less than or equal to 100 m, and temporal sampling of at least 30 days. CRISTAL will be capable of tracking steep terrain with slopes less than 1.5° using its SARIn mode. High-resolution Swath processing over ice sheets (about 5 km wide) can reveal complex surface elevation changes, related to climate variability and ice dynamics, and subglacial geothermal and magmatic processes, see e.g. Foresta et al (2016). Elevation measurements of regions with smaller glaciers are often missing in CryoSat-2 data. Indeed, tracking algorithms are not efficient

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when rough terrain is encountered. Improvement in the tracking over glaciers is thus a key element in the instrument concept generation.

4.4 Sea level, coastal and inland water

Over the years and through constant improvement of the data quality, satellite altimetry has been used in a growing number of applications in Earth sciences. The altimeter measurements are helping us to understand and monitor the ocean: its topography, dynamics and variability at different scales. The need of satellite observations to study, understand and monitor the ocean is more than essential over polar areas, where in-situ data networks are very sparse, and where profound and dramatic changes occur. This has also been expressed and emphasised by CMEMS as “Ensuring continuity (with improvements) of the Cryosat-2 mission for sea level monitoring in polar regions” (CMEMS, 2017). “Reliable retrieval of sea level in the leads to reach the retrieval accuracy required to monitor climate change” is another CMEMS recommendation for polar and sea ice monitoring, see CMEMS (2017).

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

The high inclination orbit of CRISTAL associated with high-resolution SAR/SARIn bi-band altimetry measurements would extend considerably our monitoring capability over the polar oceans. The development of tailored processing algorithms should have not only to track the low-frequency sea level trend in presence of sea ice but also characterize ocean large scale and mesoscale variations over regions not covered by conventional ocean missions. Beyond the observations of ice elevation variations, CRISTAL would therefore offer the unique opportunity to improve our knowledge on the mutual Ocean-Cryosphere complex interactions over short and long-term time scales over both north and south poles. The Southern Ocean circulation indeed plays a key role in shaping the Antarctic cryosphere environment. First, it regulates sea ice production: as sea ice forms and reject brines into the ocean, the ocean destabilizes and warms underwater waters which reaches the ocean surface, hence limiting further ice production. Second, it impacts Antarctic ice sheet melt, when warm and salty ocean currents access the base of floating glaciers through bathymetric troughs of the Antarctic continental shelf. These ocean currents melt the ice shelves from below, and are the main causes of the current decline of floating ice-shelves (Shepherd et al., 2019). This ice sheet retreat induced by this melting represents the largest uncertainty in the current prediction of global sea-level change (Edwards et al., 2019), creating major ambiguity in our way to respond and adapt to future climate. Tightly linked with glacier melt, the polar shelf circulation and its interaction with largescale circulation also control the rate of bottom water production

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and deep ocean ventilation, which impact the world's oceans on timescale ranging from decades to millennia. Therefore, with a designed operational lifetime of at least 7.5 years (including in-orbit commissioning), the observation from the same sensor of each components of these multi-scale ice-ocean interactions would make CRISTAL unique in its capability to address climate issues of regional and worldwide relevance. Over oceans, which represents a secondary objective for the mission, the satellite will be able to measure sea surface height with an uncertainty of less than 3 cm. The main advantages and drawbacks of the Ka-band over the oceanic surface have been reviewed in Bonnefond et al (2018). Given its high along-track resolution of less than 10 km and high temporal resolution of sea level anomalies, the mission can further contribute a suite of sea level products including sea surface height and mean sea surface (vertical accuracy in sea level anomaly retrieval of less than 2 cm is requested).

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

4.5 Icebergs

Iceberg detection, volume change and drift have been listed as a priority user requirement (Duchossois et al., 2018a; 2018b). Icebergs present a significant hazard to marine operations in those ocean areas where they occur. Detection of icebergs in open water and in sea ice generally places a priority on wider satellite swaths to obtain greater geographic coverage. There is a need for automatic detection of icebergs for the safety of the navigation and chart production. Iceberg concentration is given in CMEMS' catalogue at 10 km resolution covering Greenland waters. SAR imagery is the core input for icebergs detection. However, iceberg detection (in particular small icebergs) is also possible using high-resolution altimeter waveforms. Tournadre et al. (2018) demonstrated detection of icebergs from CryoSat-2 altimeter data using several modes, and mention promising results with the Sentinel-3 data, which would result into a comprehensive dataset, already built under ALTIBERG project (Tournadre et al., 2016). The volume of an iceberg is valuable information for operational services and climate monitoring. For climate studies, the freshwater flux from the volume of ice transported by icebergs is a key parameter, with large uncertainties related to the volume of the icebergs. Measuring volume is currently possible only with altimetry, by providing the iceberg freeboard elevation from the ocean surface. Iceberg volume has been calculated with altimetry with Envisat, Jason-1 and Jason-2, see for example by Tournadre et al. (2015).

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5.5 Snow on land and permafrost¶
While these are considered a secondary objective for the mission, with its dual-frequency altimeter payload and high-resolution passive microwave radiometer, CRISTAL will be able to support and contribute significantly to studies and services in relation to seasonal snow cover and permafrost applications over land. Dual-frequency Ku-/Ka-band backscatter measurements as provided by CRISTAL may be useful in retrieving internal properties of the snowpack. Snow presence, structure changes as well as land surface state (freeze/thaw) as can be identified with microwave sensors are closely interlinked with permafrost state (e.g.

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5.6

CryoSat-2 tracking over icebergs is operational but icebergs with high freeboards may be missed in the current range window. The range window definition for CRISTAL is defined in order to ensure that echoes from icebergs are correctly acquired. In-flight performances for the measurement of the Angle of Arrival from CryoSat-2 are around 25 arcsec. An equivalent performance is necessary to retrieve across-track slopes and elevations. The CRISTAL design of the instrument and the calibration strategy will be designed to comply with the specification of 20 arcsec. CRISTAL will provide the unprecedented capability to detect icebergs at a horizontal resolution (gridded product) of at least 25 m. The products will be produced every 24 hours in synergy with other high-resolution data such as SAR imagery. Iceberg distribution and volume products will be produced at 50 km resolution (gridded) on a monthly basis.

4.6 Snow on land and permafrost

CRISTAL may support and contribute to studies and services in relation to seasonal snow cover and permafrost applications over land. These are considered a secondary objective for the mission. The ability for the retrieval of snow depth with Ku-/Ka-band altimeter is limited over land (Rott et al. 2018). Snow studies over land area are so far largely limited to scatterometer in case of Ku-band (examples are reviewed e.g. in Bartsch, 2010). Measurements as provided by CRISTAL may, however, be useful in retrieving internal properties of the snowpack. Snow structure anomalies as well as land surface state (freeze/thaw) are expected to be identified by time series analyses as such processes alter penetration depth. Information from altimeter is currently also rarely used for permafrost studies. It can be applied for monitoring lake level as proxy for permafrost change (Zakharova et al. 2017). Surface status is closely interlinked with ground temperature (e.g. Kroisleitner et al. 2018) but usage of altimeter in this context remains unexplored. Signal interaction with vegetation limits the applicability of Ku- and Ka-band for soil observations regarding freeze/thaw status (Park et. al. 2011) and also surface height. Wider use of altimetry for snow and permafrost applications does also require higher spatial resolution and temporal coverage than available to date. An improvement regarding the latter issues is expected with CRISTAL, what will expand the utility of altimeter observations for permafrost and snow monitoring over land.

5 CRISTAL mission concept

This section summaries the envisaged primary payload complement to address the CRISTAL mission objectives. The design draws from the experience of several in-orbit missions in addition to the ongoing developments within the Sentinel-6 and MetOp-SG programmes, and has a 7.5 years lifetime. CRISTAL's primary payload complement consist of:

- A **synthetic aperture radar (SAR) altimeter operating at Ku-band and Ka-band** centre frequencies for global elevation and topographic retrievals over land and marine ice, ocean and terrestrial surfaces (see Figure 2 and Figure 3). In Ku-band (13.5 GHz), the SAR altimeter can also be operated in interferometric (SARIn) mode to determine across-track echo location. The Ka-band channel (35.75 GHz) has been introduced to improve snow depth retrievals over sea ice, see e.g. Guerreiro et al (2016). A range (vertical) resolution of about 31 cm will be achieved to enhance freeboard measurement accuracy. Also, a high along-track resolution of about 20 m is envisaged to improve ice floe discrimination. Heritage missions include CryoSat-2 (SAR/Interferometric Radar Altimeter (SIRAL)), Sentinel-6 (Poseidon-4) and SARAL (AltiKa). The CRISTAL Altimeter (IRIS) is based on Poseidon-4 (Sentinel-6) and SIRAL (CryoSat-2) together with the addition of a Ka-band channel (analogous to AltiKa) and a bandwidth of 500MHz (at both frequencies) to meet the improved range resolution requirement in comparison to heritage altimeters. It has the capability for fully focused SAR processing for enhanced along track resolution by means of resolving full scatterer phase history, see Egido and Smith (2017). Digital processing will be implemented including matched filter range compression and on-board Range Cell Migration (RCM) compensation by means of a RMC mode for on-board data reduction (heritage from Poseidon-4) reducing downlink load. With respect to the dual frequency antenna (Ku- and Ka-band), an enhanced antenna mounting baseplate for improved baseline stability over CryoSat-2 will be required (20 arcsec vs ~30 arcsec for CryoSat-2).

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- A high-resolution **passive microwave radiometer** is included with the capability to provide data allowing optimal retrievals of total column water vapour over the global ocean and up to 10 km from the coast (by means of improving the measurement system with high frequency channels). The radiometer may also support cryosphere applications such as sea ice type classifications, see Tran et al. (2009). Concerning the Microwave Instrument selection, potential options include: a potential US Custom Furnished Item based on the National Aeronautics and Space Administration (NASA)- Jet Propulsion Laboratory (JPL) AMR-C (Advanced Microwave Radiometer – Climate quality); development of an EU High Resolution radiometer solution; or a two-channel solution derived from the Sentinel-3 microwave radiometer. The feasibility of each of these options will be further evaluated in the next mission phase (Phase B2 at the time of the system Preliminary Design Review, expected late 2021).
- A **Global Navigation Satellite System (GNSS) receiver** compatible with both Galileo and Global Positioning System (GPS) constellations providing on-board timing, navigation and provision of data for on-ground precise orbit determination. Heritage GNSS solutions exist such as those based upon the GPS and Galileo compatible Sentinel-1,-2,-3 C/D, Sentinel-6 A/B receivers. Precise Orbit Determination products will be provided by the Copernicus Precise Orbit Determination service.
- A **Laser Retro-reflector Array** (LRA) for use by the Satellite Laser Ranging network and by the International Laser Ranging Service for short arc validation of the orbit. Heritage concepts suitable for CRISTAL include CryoSat-2/Sentinel-3 LRAs.

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

- **Sea ice and iceberg mode**: In Figure 3, the proposed coverage is shown in orange. It is proposed that this mode makes a step forward in ice-thickness retrieval by operating the instrument with the SAR interferometer configuration in Ku-band, i.e. a two-antenna cross-track interferometric principle. The measurement mode will be in an open burst, or interleaved arrangement, in which receptions occur after each transmitted pulse. This results in an along-track resolution by ground processing to up to a few metres, which enables small sea ice sheets to be distinguished and the detection of narrow leads between them. The disadvantages of the open burst transmission versus a closed burst operation mode include a larger data volume and the power demand and variations of the Pulse Repetition Frequency around the orbit. The interferometric operation allows the location of across-track sea ice leads, whilst open-burst timing allows full scatterer phase history re-construction for fully focussed processing (Egido and Smith, 2017). This improves sea ice lead discrimination (by means of improvement in sampling and resolution), and hence retrievals of elevation, and thus polar Sea Level Anomalies (SLA) by a significant factor, Armitage and Davidson (2014). Open-burst Ka-band SAR is also provided to also allow for improving retrieval of snow depth over sea ice.
- **Land ice and Glacier mode**: In Figure 3, the proposed coverage is shown in magenta. Ice sheet and cap elevation is retrieved by means of improved surface tracking based on the large range window. The accuracy of elevation retrievals are likely improved by a factor 2 by means of increasing the number of echoes per unit time by a factor 4 over the CryoSat-2 heritage design. The Ku-band SAR interferometer is used to retrieve the across-track point of closest approach supplemented with Ka-band SAR. Closed-burst operation (see e.g. Raney 1998) is used over this surface type, in which the reflections arriving back at the radar are received after each transmitted burst has finished.
- **Open and coastal ocean mode**: In Figure 3, the proposed coverage shown in magenta provides Arctic and southern polar ocean retrieval of SLA and precision SAR altimetry to complement other ocean topography missions including Sentinel-3, Sentinel-6 and next generation topographic missions. In the case of open ocean, closed-burst SAR operation at Ku-band and Ka-band is used and the RMC on-board processing is applied, first implemented in the frame of Sentinel-6, which provides a considerable gain in instrument data rate reduction. In addition, data will be collected over inland water regions using one of the above modes.

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Table 3 Key altimeter characteristics in the different modes of operation (Credits: Thales Alenia Space, France).

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

The latency of CRISTAL data products follows the requirements expressed in the PEG-1 and PEG-2 reports, and provides measurements of different latencies according to the application area need. The product latencies range from 3 hours (some ocean L2 products), to 6 hours (sea ice freeboard products), 24 hours (sea ice thickness, sea ice snow depth, and iceberg detection products), 48 hours (some ocean L1 and L2 products), and up to 30 days (surface elevation and some ocean L1 products). These data latencies indicate the time interval from data acquisition by the instrument to delivery as a Level 1B data product to the user.

6 Conclusions and CRISTAL mission status

CRISTAL directly addresses the EU Arctic Policy and primary user requirements collected by the European Commission and provides sustained, long-term monitoring of sea ice thickness and land ice elevations. It thereby responds to needs for continuous pan-Arctic altimetric monitoring including the region of the Arctic Ocean north of 81.5°N. Antarctica will be equally well covered. The mission serves several key Copernicus operational services in particular the Climate Change service, Marine Environmental Monitoring Service and makes contributions to the Land Monitoring Service, Atmospheric Monitoring Service and Emergency Management Service.

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CRISTAL will cover the polar regions with a Ku-band Interferometric Synthetic Aperture Radar Altimeter with supporting Ka-band channel. In addition, the payload contains a high and low frequency passive microwave radiometer to perform wet troposphere delay correction, and surface-type classification over sea ice and ice sheets. The mission is designed for a 7.5 years design lifetime and will fly in an optimized orbit covering polar regions (omission <= 2°; sub-cycle < 10 days). A key element is the high along-track resolution (by ground processing up to a few meters when the novel interleaved SAR operation mode is used) to distinguish open ocean from sea ice surfaces. Thanks to the dual-frequency SAR altimetry capability, a snow depth product will be produced over sea ice with high accuracy in response to long-standing user needs.

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

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

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Competing interests. The authors declare that they have no conflict of interest.

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Appendix A: List of acronyms

AltiKa	Altimeter Ka-band
AMR-C	Advanced Microwave Radiometer-Climate Quality
C3S	Copernicus Climate Change Service
Cal/Val	Calibration and Validation
CAMS	Copernicus Atmospheric Monitoring Service
CEMS	Copernicus Emergency Management Service
CGLS	Copernicus Global Land Service
CIMR	Copernicus Polar Passive Microwave Imaging Mission
CLS	Collecte Localisation Satellites
CMEMS	Copernicus Marine Environmental Monitoring Service
COP21	United Nations Framework Convention on Climate Change, 21st Conference of the Parties
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter
CSC	Copernicus Space Component
dB	Decibel
EC	European Commission
EO	Earth Observation
ESA	European Space Agency
EU	European Union
EUMETSAT	EUropean Organisation for the Exploitation of METeorological SATellites
FMI	Finnish Meteorological Institute
GCOS	Global Climate Observing System
GMES	Global Monitoring for Environment and Security
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HPCM	Copernicus High Priority Candidate Mission
IPCC	Intergovernmental Panel on Climate Change
IRIS	Interferometric Radar altimeter for Ice and Snow
JPL	Jet Propulsion Laboratory
LRA	Laser Retro-reflector Array
MetOp-SG	Meteorological Operational Satellite - Second Generation
NASA	National Aeronautics and Space Administration
NSIDC	National Snow & Ice Data Center
OCO	Open and coastal ocean

Deleted: CFI Custom Furnished Item¶

Deleted: CRISTAL Copernicus Polar Ice and Snow Topography Altimeter¶

Deleted: ECV Essential Climate Variable¶

Deleted: HPOC High Precision Ocean Constellation ¶

Deleted: LIG Land ice and glacier¶

Deleted: LST Land Surface Temperature¶

Deleted: MRD Mission Requirements Document¶
MWR Microwave Radiometer¶

Deleted: NIR Near InfraRed¶
NRT Near-Real Time¶
NTC Non-Time Critical ¶

OSTST2019	Ocean Surface Topography Science Team Meeting 2019
PEG	Polar Expert Group
RADAR	Radio Detection and Ranging
RCM	Rang Cell Migration
RMC	Range Migration Compensation
SAR	Synthetic Aperture Radar
SARIn	Interferometric SAR
SARAL	Satellite with ARgos and ALtiKa
SIRAL	SAR/Interferometric Radar Altimeter
SLA	Sea Level Anomaly
STC	Short Time Critical

Deleted: POD Precise Orbit Determination¶
PRF Pulse Repetition Frequency¶

Deleted: RFP Request for Proposals¶

Deleted: SII Sea-ice and iceberg¶

Deleted: SLR Satellite Laser Ranging ¶
SRL Scientific Readiness Level¶
SSH Sea Surface Height¶
SST Sea Surface Temperature¶

Deleted: TIR Thermal infrared¶
UNFCCC United Nations Framework Convention on Climate Change¶
VIS Visible¶

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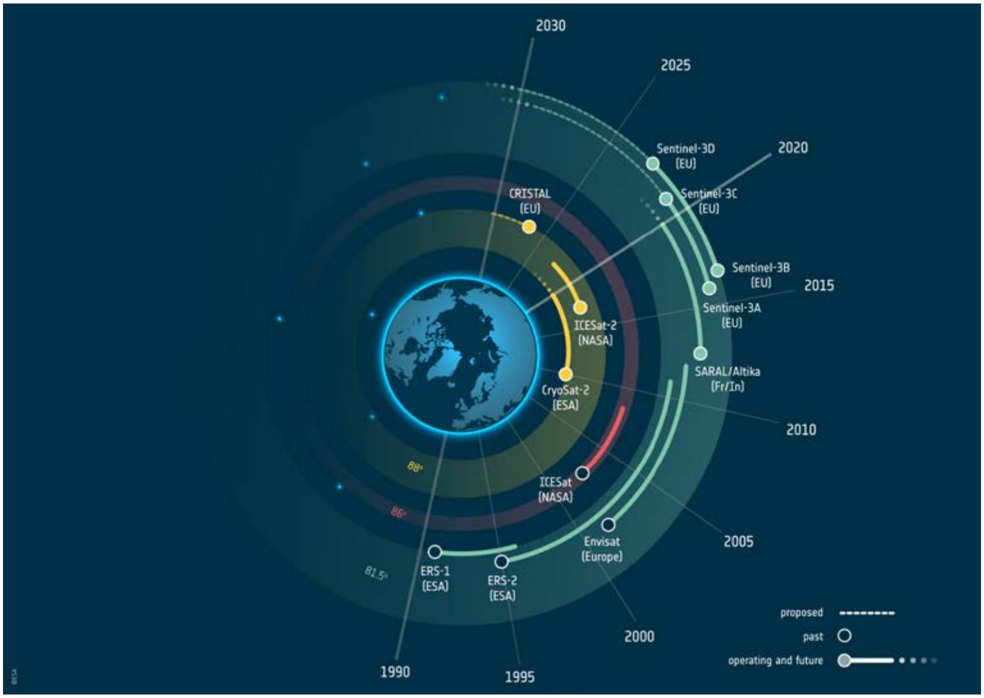

Figure 1. The image shows the past, operating, approved and proposed polar topography altimeter missions. By mid 2020s, CRISTAL will fill the gap acquiring climate-critical data over polar ice north or south of 81.5° latitude (Image: EOBG/ESA).

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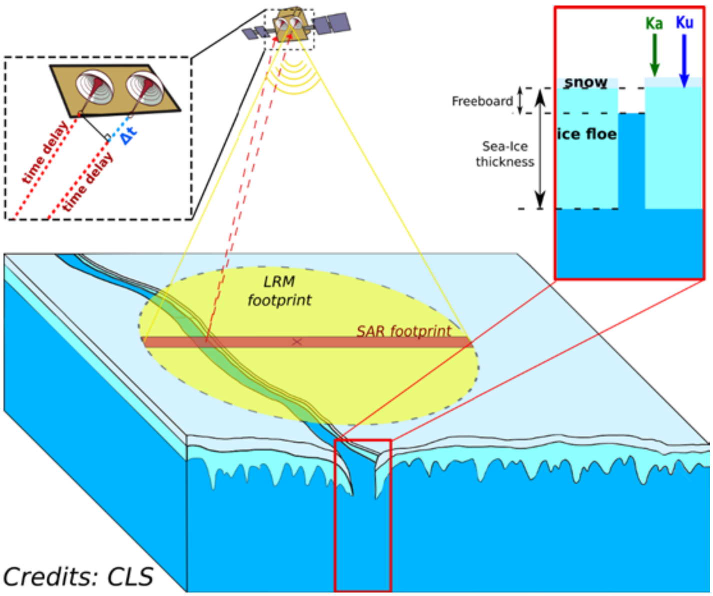

Figure 2. Illustration of the CRISTAL observation concept over sea ice employing a twin-frequency, twin antenna SAR radar altimeter with interferometric capability at Ku-band (Image Credits: CLS).

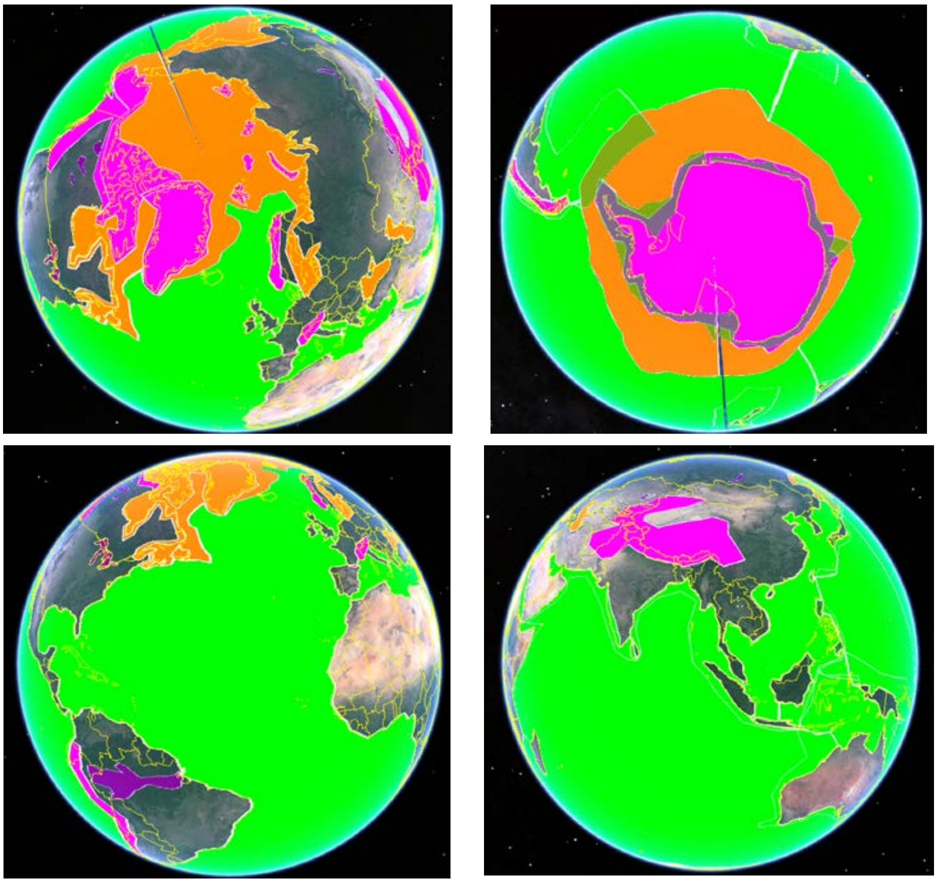

Figure 3. Indicative mission geographic operating mode mask used in CRISTAL altimeter data volume sizing: Magenta = Land Ice and Glacier closed-burst SARIn mode, also including smaller ice-caps; Orange = Sea-Ice and Icebergs open-burst SARIn mode (maximum coverage in North/Southern hemisphere); Green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

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