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User Requirements for a Copernicus Polar Mission

Phase 2 Report - High-level mission requirements

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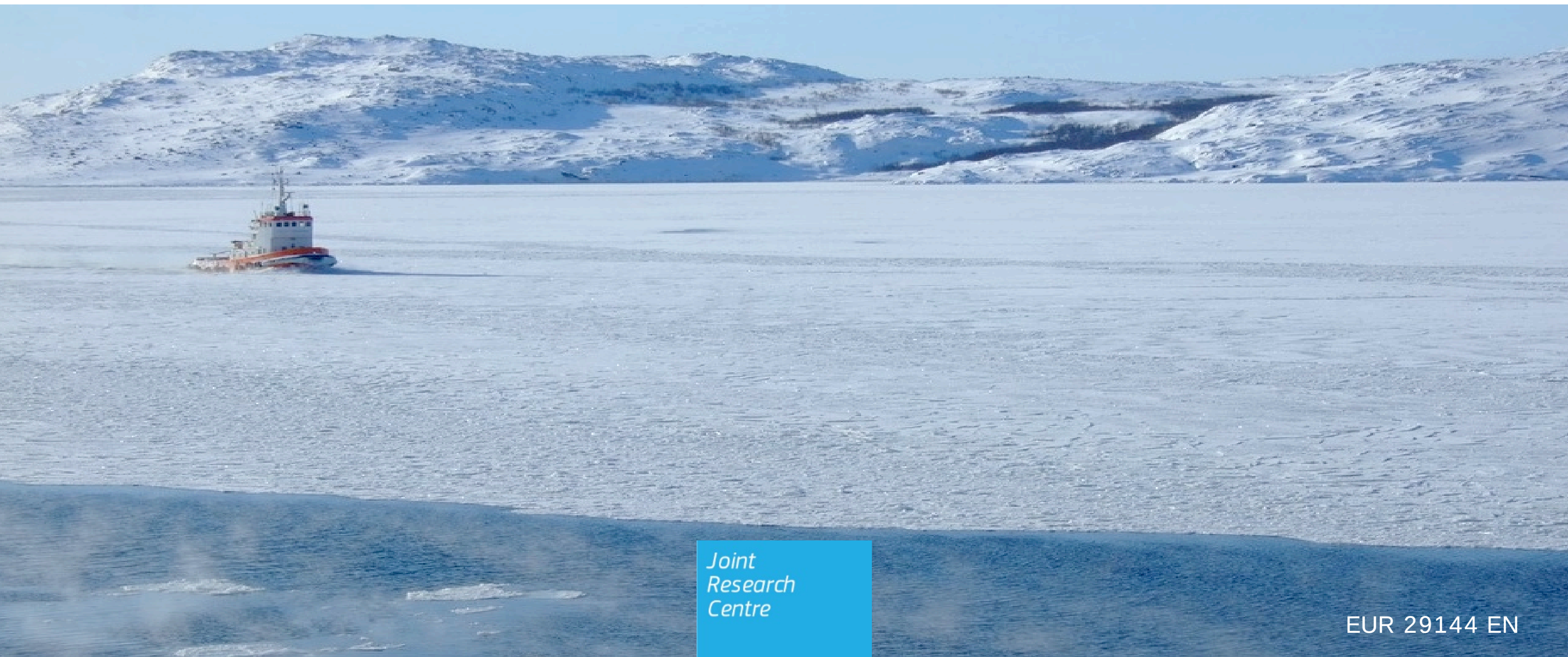

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Table of Contents

1 Background

The joint communication by the European Commission and the High Representative of the Union for Foreign Affairs and Security Policy issued on 27 April 2016 to the European Parliament and the Council, proposing 'An integrated European Union policy for the Arctic', highlights the strategic, environmental and socioeconomic importance of the Arctic region including the Arctic Ocean and adjacent seas. The Arctic's fragile environment is also a direct and key indicator of the climate change, which requires specific mitigation and adaptation actions as stipulated by the global agreement reached during the conference of the parties (COP)-21 held in Paris in December 2015. To this end, the 'integrated EU Arctic policy' has identified and is addressing three priority areas.

1) Climate change and safeguarding the arctic environment (livelihoods of indigenous peoples, Arctic environment)
2) Sustainable development in and around the Arctic (exploitation of natural resources e.g. fish, minerals, oil and gas), 'the Blue economy', safe and reliable navigation (north-east (NE) passage etc.)
3) International cooperation on Arctic Issues (e.g. scientific research, EU and bilateral cooperation projects, fisheries management/ecosystems protection, commercial fishing).

To monitor on a continuous basis the vast and harsh Arctic environment, considering the sparse population and the lack of transport links, space technologies are definitely essential tools including Earth observation (EO), navigation and communication satellites. Although the existing Copernicus programme already offers operational thematic services in the fields of atmosphere monitoring, marine environment monitoring, land monitoring, climate change, emergency management and security, new requirements from key Arctic user communities for a dedicated polar and snow satellite mission have emerged over a recent past. These requirements were reviewed at a polar and snow workshop held in June 2016 and organised at the initiative of the Directorate-General (DG) for Internal Market, Industry, Entrepreneurship and SMEs and involving relevant EU DGs as well as 70 attendees coming from EU Member States and working on various domains.

This strong interest for a polar and snow mission was further reinforced when discussed in a wider international context, considering UN conventions and pan-Arctic cooperation activities. This situation led DG Internal Market, Industry, Entrepreneurship and SMEs in spring 2017 to set up a new group of European polar experts with the mandate to update and/or complete the review and analysis of user needs, thus allowing the Commission to assess the relevance of the development of a Sentinel expansion mission dedicated to polar and snow monitoring.

2 Assumptions for phase 2 of the expert-group process

Following phase 1 of the expert-group process led in April 2017, the group entering Phase 2 of its activities has been extended to include space experts from the European Space Agency (ESA) and European Organisation for the Exploitation of Meteorological Satellites (Eumetsat). It met in early May 2017 for a kick-off meeting in order to finalise the phase 1 exercise and initiate the phase 2 activities. On this occasion, some key guidelines and assumptions have been given/recalled so that the work expected during phase 2 is more precisely framed. This outline is described in the present section.

The terms of the Copernicus regulation (Regulation (EU) No 377/2014) constitute some key driver for the actions of the polar expert group, in particular in its phase 2. Special attention should be given to some of the articles of this regulation, in particular regarding the following extracts.

- Article 2:
  - 'Copernicus is a civil, user driven programme',
  - 'Copernicus consists of the following components:

    (a) a service component ensuring delivery of information in the following areas: atmosphere monitoring, marine environment monitoring, land monitoring, climate change, emergency management and security;

    (b) a space component ensuring sustainable spaceborne observations for the service areas referred to in point (a);

    (c) an *in situ* component ensuring coordinated access to observations through airborne, seaborne and ground based installations for the service areas referred to in point (a).'
- Article 3 which details definitions is given in full.

  'For the purposes of this regulation the following definitions apply:

  (1) 'dedicated missions' means the space-based Earth observation missions for use and operated in Copernicus, in particular the Sentinel missions;

  (2) 'contributing missions' means space-based Earth observation missions providing data to Copernicus complementing data provided by the dedicated missions;

  (3) 'dedicated mission data' means spaceborne Earth observation data from dedicated missions for use in Copernicus;

  (4) 'contributing mission data' means spaceborne Earth observation data from contributing missions licensed or provided for use in Copernicus;

  (5) '*in situ* data' means observation data from ground-, sea- or air-borne sensors as well as reference and ancillary data licensed or provided for use in Copernicus;

  (6) 'third party data and information' means data and information created outside the scope of Copernicus and necessary for the implementation of its objectives;

  (7) 'Copernicus data' means dedicated mission data, contributing mission data and *in situ* data;

(8) 'Copernicus information' means information from the Copernicus services referred to in Article 5(1) following processing or modelling of Copernicus data;

(9) 'Copernicus users' means:

(a) Copernicus core users: Union institutions and bodies, European, national, regional or local authorities entrusted with the definition, implementation, enforcement or monitoring of a public service or policy in the areas referred to in point (a) of Article 2(2);

(b) research users: universities or any other research and education organisations;

(c) commercial and private users;

(d) charities, non-governmental organisations and international organisations.'

- Article 6 focuses on the Copernicus space component (CSC) and its evolution of which the polar mission might be part and the following statements should be considered.
  - 'The Copernicus space component shall provide spaceborne observations, serving primarily the services referred to in Article 5(1) ([1]).' (…)
  - 'The Copernicus space component shall consist of dedicated missions and contributing mission data, and include the following activities:
    (a) provision of spaceborne observations, (…)
    (b) activities in response to evolving needs of the users, including:
      (i) identification of observation gaps and specification of new dedicated missions on the basis of user requirements;
      (ii)developments aiming at modernising and complementing the dedicated missions, including design and procurement of new elements of the related space infrastructure; (…)'
- Article 10 sets the tasks entrusted to ESA and points (a) and (b) given below clearly frame the respective role of ESA and the Commission:
  - 'The Commission shall conclude a delegation agreement with ESA entrusting it with the following tasks:
    (a) ensuring the technical coordination of the Copernicus space component;
    (b) defining the overall system architecture for the Copernicus space component and its evolution on the basis of user requirements, coordinated by the Commission.'

Based on these elements provided by the Copernicus regulation,

- The mandate of the expert group organised by the Commission shall focus on user-requirements consolidation. The advanced description or technical choices of the polar mission are to be encompassed in a forthcoming round of activities to be coordinated by ESA (cf. Article 10).

([1]) Article 5 of the Copernicus regulation is entitled 'Copernicus service component' and paragraph 1 of the article details the 6 thematic Copernicus services namely the atmosphere monitoring service, the marine environment monitoring service, the land monitoring service, the climate change service, the emergency management service, *the* security service.

— The requirements shall reflect the user needs, the highest priority being set on those expressed by the Copernicus services and the core users.
— The polar mission shall be considered in the context of the expansion mission only but it is also to be deeply studied in the wider context of the CSC, which includes dedicated missions, contributing missions and third-party missions (i.e. not owned or operated by entities responsible for the Copernicus space component namely ESA and Eumetsat) .

In addition to this legal basis, some programme and technical elements based on facts or existing components have been included when defining the baseline for phase-2 activities.

(a) The Sentinel expansion missions (see Figure 1) (the polar mission will be part of them) will be operated in parallel with the Sentinel constellation currently under deployment and/or in operation. In this context, we make the assumption that the same paradigm will be applied to the Sentinel expansion constellation as was applied to the current Sentinel constellation, i.e. it will be based on a monitoring approach with a stable operation plan, provision of operational products and services including calibration/validation (CalVal) activities. In addition, this assumption implies that the polar expansion mission will not plan for the possibility for on-demand rapid tasking of the satellite. The global architecture (payload data ground segment and its operations) should follow the same standards as the current constellation.

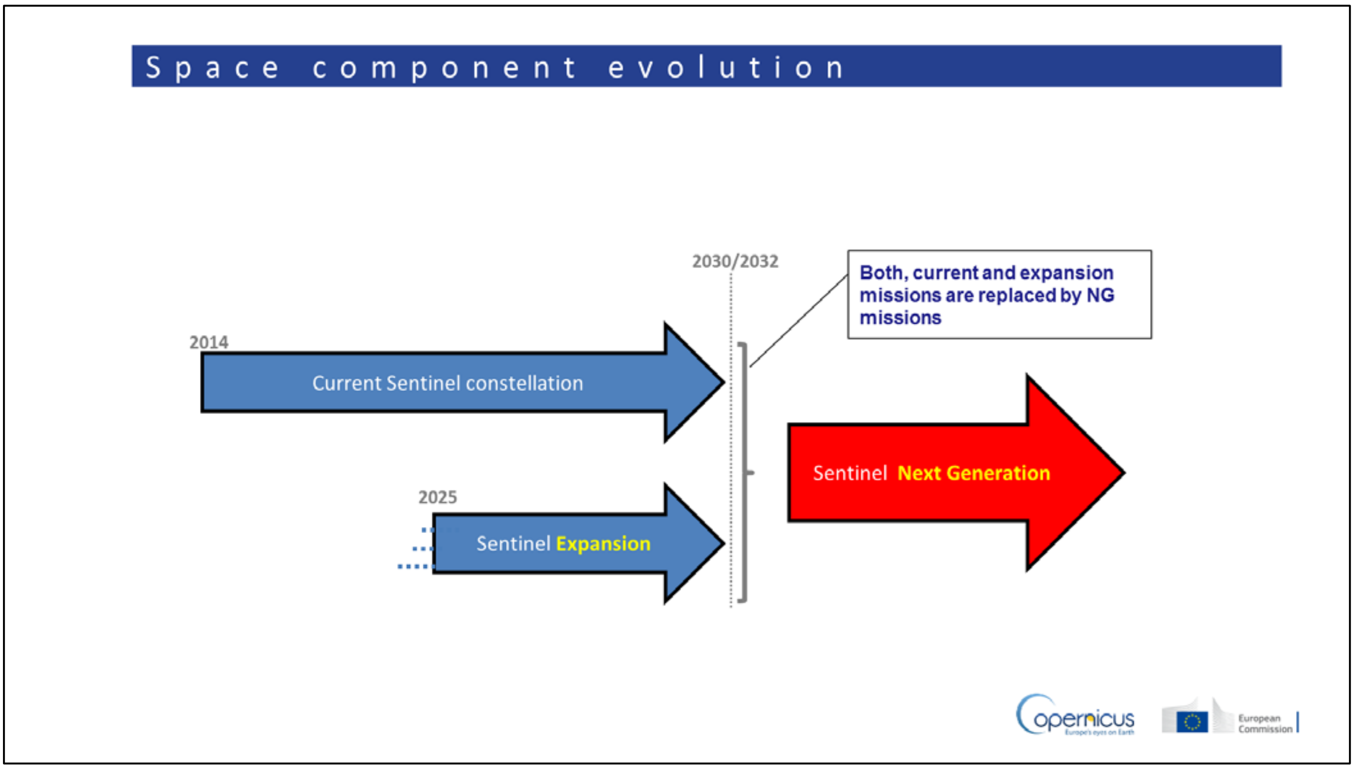


Figure 1: Evolution of the Copernicus space component

(b) In addition, near real time (NRT) in-orbit tasking and quasi real-time delivery of the products (e.g. as specified by the European Maritime Safety Agency (EMSA)) have not been considered by this expert group. They will be specifically addressed in another expert group or task force dedicated to the security domain.

(c) The Arctic policy document being a baseline driver for the expert group, in contrast to the Antarctic being more related to climate change (when considered together with the Arctic), the focus has been given to the Arctic and related areas (adjacent seas etc.). Nevertheless, the observations over the Antarctic area have not been omitted: they have been considered as much as possible.

(d) The panel was composed of Copernicus core users, representing national services, Copernicus services, and the scientific community. Copernicus being an operational programme deploying earth monitoring services, the priority when having to sort the requirements will be put on operational services in any case of technical conflicts of requirements.

(e) Following a set of meetings between the European Commission and the Entrusted Entities in charge of the CSC, i.e. ESA and Eumetsat, a joint document on the evolution of the CSC has been prepared and presented to the Member States of each organisation. Figure 2, which constitutes a first schematic view of work, has been extracted from this document in order to further explain how the CSC should evolve and how the different missions could be reshuffled and organised. The expert group shall express the highest priority requirements. Some of them — at least the number 1 priority — will be taken on board by the polar mission, which will be developed as an expansion mission. Due to the number and variety of requirements, it is however technically not feasible that a single such mission immediately addresses the full set of requirements. Remaining requirements will be kept for the next generation missions, which are to ensure the continuity of both the current Sentinel constellation and the expansion missions.

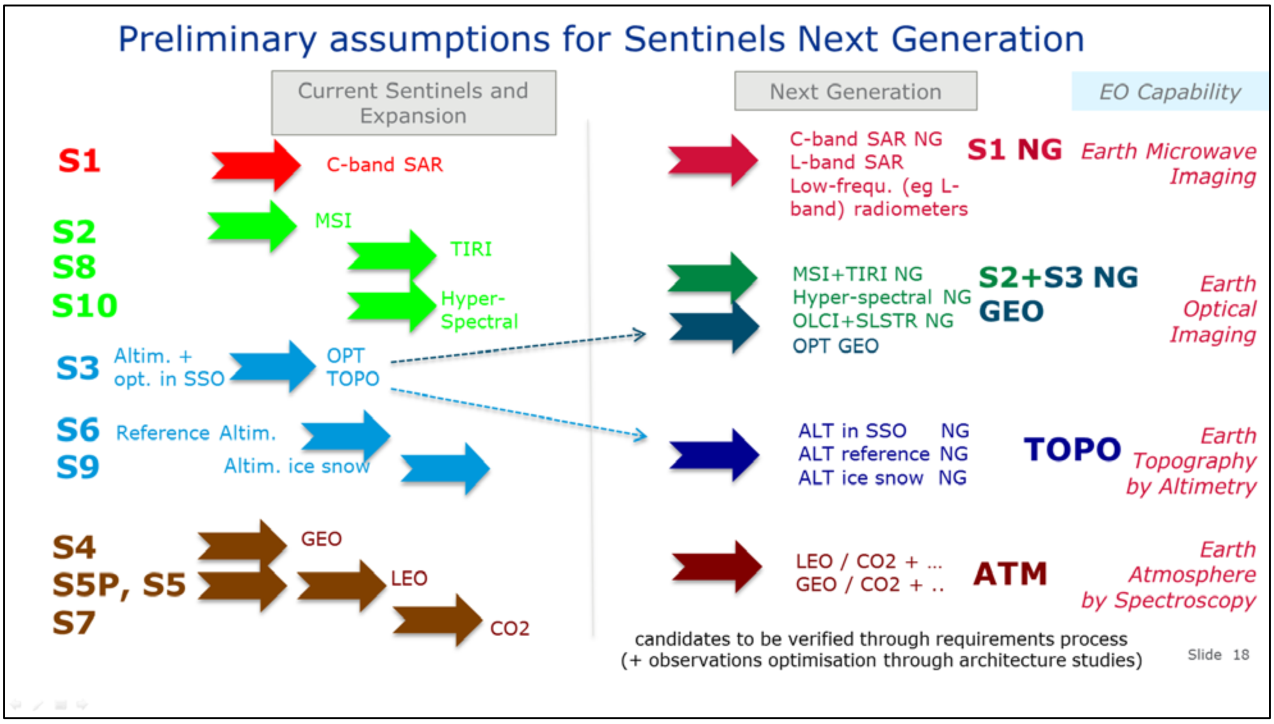


Figure 2: Evolution of the Copernicus dedicated missions, draft scheme

(f) Finally, the requirements analysis is to be considered relying on a **multi-missions approach** as pointed out at the 2016 polar and snow workshop organised by the European Commission. In addition, the gap analysis shall be performed in the context of the existing missions, planned missions, third country (non-EU) programmes as already pointed out earlier in this section.

2.1 Prioritised requirements

During phase 1 of the expert group's proceedings, the following list of monitoring requirements was established (in order of priority).

1. **Floating ice** parameters including sea-ice extent/concentration/thickness/type/drift velocity, thin sea-ice distribution, iceberg detection/volume change and drift, ice-shelf thickness and extent**.**
2. **Glaciers, caps and ice-sheet** parameters including extent/calving front/grounding line/surface elevation and surface elevation change/surface velocity/mass balance and mass change/melt extent.
3. **Sea level/sea-level anomaly (SLA)** parameters.
4. **All-weather sea-surface temperature (SST)** parameter.
5. **Surface albedo** parameter.
6. **Surface freshwater** parameters including river run-off and discharge, river and lake ice thickness.
7. **Snow** parameters including extent/fraction and snow-equivalent water, melt extent.
8. **Permafrost** parameters including extent/fraction and topography/deformation.

This list was further detailed and analysed at the phase-2 kick-off meeting. To this end the expert panel was divided into 2 subgroups, each one having to describe, in their respective domains of competence, the status of existing parameters/derived products and identified gaps/shortfalls of the current (satellite) observation capacities. The two domains are 'floating ice' and 'ice sheets, glaciers/ice caps, snow, permafrost, fresh water'. The reports of the two subgroups are attached as Annexes 3 and 4.

From these reports, it appears that a large number of parameters/products are currently made available to users on an operational basis. However, these reports also identify shortfalls/weaknesses of varying importance for most of them e.g. in terms of spatial and temporal resolution, of accuracies, of revisit frequencies and timeliness.

It is clear that a single Copernicus expansion polar and snow mission, although operating in parallel with the current Copernicus Sentinels (and the contributing missions), **will not solve all these requirements** for improvements.

As a consequence, **such a mission has to concentrate on a smaller number of top operational priority objectives** as emerging from the subgroup reports.

- **Floating ice and** in particular **sea-ice concentration (SIC)** as justified here by the expert subgroup.

‘[SIC] is the most important parameter for both operational (e.g. ice breakers and/or search and rescue services) and climate-monitoring use. Currently automatic routines providing ice concentration exist for passive microwave sensors like SSMI(S) and AMSR-2. Standard SIC is computed by a combination of 18 and 36 GHz channels, whereby the effective spatial resolution of the SIC is close to 10 km using an AMSR-2 sensor. Utilising the 89 GHz channel on AMSR-2 with an [instantaneous field of view] IFOV of 3 × 5 km can provide a spatial resolution of ~ 6 km, although this has disadvantages with respect to the atmospheric influence. The microwave imaging (MWI) instrument on MetOp-SG [second generation] will have an antenna of 75 cm versus a 2 m antenna on AMSR-2. A standard SIC algorithm using the low frequencies on MWI will therefore only be able to provide a ~ 60 km spatial resolution. Utilising the 89 GHz on MWI could provide a spatial resolution of ~ 16 km.

From synthetic aperture radar (SAR) data high-resolution SIC can be derived by separating ice/water on a per-pixel basis and estimating the amount of ice pixels within a given area. This method is however not yet operational. Using a dual polarisation ([horizontal transmit and horizontal receive] HH/[horizontal transmit and vertical receive] HV) SAR has improved the ability for separating ice/water and some studies have shown that quad polarisation performs even better. But again, this is still subject of ongoing research’

- **Ice sheets, glaciers/ice caps and snow** as justified by the expert subgroup.

‘For ice sheets, glaciers/ice caps and permafrost regions there is an urgent need for monitoring the surface elevation and its temporal change. The change of glacier mass over time (typically over annual intervals) is the basis for determining the mass balance of the ice bodies and compiling the contributions to sea level rise. Precise, regularly updated [digital elevation models] DEMs are required as essential auxiliary data for deriving ice-velocity maps from displacements in repeat-pass satellite imagery, for retrieving calving fluxes and ice discharge, for estimating iceberg mass, etc. There are two major needs for data.

— High spatial resolution surface elevation (50 to 100 m posting) and regular repeat observations for regions where major changes in surface elevation occur: outlet glaciers, boundaries of ice sheets and caps, mountain glaciers, zones that are subject to permafrost erosion, icebergs. [TerraSAR-X add-on for digital elevation measurement] TanDEM-X delivered repeat acquisitions of topographic data on demand, but there is no systematic acquisition plan for this task and mission continuation is not guaranteed.

— Low to moderate spatial resolution and an acquisition interval of a few months to get coverage: ca. 1 km, for terrain with gentle topography in the interior of ice sheets. Current mission: CryoSat-2 (footprint ca. 300 m x 1000 m in SAR Interferometric (SARIn) mode, along narrow tracks); continuation by Sentinel-3 (S3), but S3 has observational gap above 82 deg. latitude and no moderate resolution SARIn mode’

When analysing the subgroups reports, one can identify clear requirements for a limited number of 'generic instrumentation families' including passive multi-frequency microwave radiometer (PMR) imaging, multi-frequency/multi-polarisation SAR, advanced radar altimeter, L-band radiometer, use of SAR interferometric (SARIn) technique etc.

The analysis of the space experts should define and explore the merits of various instrumentation combinations/clusters meeting the above top priority objectives and parameter performance targets (as defined in tables of the phase 1 report). For that purpose they should take into account existing and not yet fully exploited capacities, and indicate where satellite platforms might reach their operational limits, thus elaborating different mission concepts. For each identified candidate mission concept the analysis should cover benefits for non-priority objectives (side benefits e.g. for snow or permafrost).

3 Space technologies

3.1 Selection of instrument types

The state-of-the-art space technologies have been analysed and presented at the phase 2 kick-off meeting. To present the state of the art of available technologies for polar/arctic observation in a concise manner is challenging, since many different observations are of relevance in polar regions, and each of them will rely on many different technologies. The information is presented here with the aid of loosely defined observation and technology clusters. It is important to understand that the clusters are not mission concepts, but merely convenient groupings to present what would otherwise become an unwieldy amount of information with much repetition. These 'clusters' are described in terms of:

1. state-of-the-art, by reviewing development activities, mission studies and heritage from other missions;
2. available technologies, by analysing the maturity of technology, the maturity of science and processing;
3. polar/Arctic observation, i.e. any mission and relevant type of instrument observing (parts of) the cryosphere.

The observation and technology clusters bundle together several observation techniques into groups relevant for 'ice monitoring', 'snow monitoring', 'soil and freeze/thaw state', 'pseudo-geosynchronous applications', and 'mass transport'. The presentation was updated after the kick-off meeting to better include relevant space technologies for SIC and can be found in Annex 5 of this report.

In the following, a subset of the technology clusters is matched to the high-priority geophysical parameters from Section 3 and subsequently further analysed. For each of the high-priority parameters, the instrument type is identified that can address the associated data-gap and user requirements as specified in Annexes 3 and 4. This is shown in the tables displayed below.

High-priority geophysical parameters	Instrument type	Heritage missions	Relevant cluster in Annex 5
Floating ice (priority 1)			
Sea ice concentration	Passive microwave imaging multi-spectral radiometer (PMR)	AMSR-E, AMSR-2, SSM/I, SSMIS, MWI	C2
Ice sheet, glaciers/ice caps and snow (priority 2)			
Surface elevation	Advanced radar altimeter (SARIn)	CryoSat-2	C3
	Single-pass interferometric synthetic aperture radar	TanDEM-X	C1

Table 1 Instrument types for highest priority observations

Three types of instrument have been identified that are capable to observe the top-priority geophysical parameters with the required spatio-temporal resolutions and coverage requirements.

1. **Imaging passive microwave imaging multi-spectral radiometer (PMR)**: A PMR with ~ 10 km resolution and spectral channels for SIC and SST retrievals and a swath width that offers at least daily revisits in the polar regions.
2. **SARIn altimeter**: A follow-on mission to CryoSat-2, specialised in nadir altimetry in polar regions.
3. **Single pass interferometric synthetic aperture radar (SP-InSAR)**: A SAR imager that includes single-pass interferometric capabilities as demonstrated with Tandem-X. Such capability could be implemented as a passive bistatic follower with Sentinel-1.

It is important to note that these are not the only instruments that can measure the geophysical parameters listed in Table 1, but only those instruments listed have the potential to address the user requirements from Annexes 3 and 4. For instance, SAR sensors can measure SIC also, but with the technology available today this type of sensor would not be able to cover the polar regions at least once per day. Likewise, surface elevation can also be measured with different sensors (Laser, optical stereogrammetry, etc.) but due to frequent cloud cover only SAR instruments can guarantee high-resolution DEMs in the polar regions with an update frequency of 1-3 times per month.

In the next subsection the three instrument types will be described in more detail, in particular in terms of their technology and scientific readiness. However, there is no one-to-one mapping between the geophysical parameters and the instrument types, as each type can contribute to more than one of the geophysical parameters listed in Annexes 3 and 4. The driving parameters are obviously the high-priority ones identified above. Depending on which set of primary and secondary parameters are added, the requirements will be different, and so might also be the technological readiness of the instrument. Therefore in what follows we will assume that the requirements for each instrument type are driven by the primary geophysical parameters only. To what extent secondary geophysical parameters can be observed or to what extent the instrument and mission should be adapted to observe secondary geophysical parameters is a subject for further study. The Table 2 identifies for each instrument type the primary and secondary observable geophysical parameters. The logic to identify primary and secondary parameters is as follows.

1. The primary parameters in the blue lines are clearly identified as such by the prioritisation in section 3 and the corresponding entries in Annexes 3 and 4.
2. Secondary parameters are identified wherever an instrument is mentioned in Annexes 3 or 4 as being able to address this parameter fully or partially.
3. Where a mission concept is also uniquely placed to address a secondary parameter it is also added as a primary parameter. These are identified as green cells in the table.

Geophysical parameters that can be observed with SAR imagers have been added as secondary parameters in the SAR/SP-InSAR column, even if not specific to SP-InSAR mode operation.

		Imaging PMR	SARIn altimeter	SAR/SP-InSAR
Floating ice	Sea ice concentration	**1**		2
	Sea ice topography	2	**1**	
	Ice type	2		**1**
	Icebergs		2	2
	Ice drift			2
	Sea level anomaly (SLA)		2	
	Snow depth on sea ice	2	2	
	Sea surface temperature (SST)	**1**		
Ice sheets, glaciers/ice caps and snow	Extent			2
	Surface elevation change		**1**	**1**
	Snow melt	2		2
	Grounding line		2	2
	Ice velocity			2
	Mass balance		2	2
	Snow area (dry)	2		
	River and lake ice thickness		2	2

Table 2 Instrument types with primary and secondary applications

3.2 PMR

3.2.1 Description

PMRs uniquely observe a wide range of parameters, in particular sea-ice concentration, and serve operational systems in almost all weather conditions, day and night. While the future MWI on MetOp-SG will secure the provision of SSMI(S) type of missions of coarse resolution radiometry, improved continuity of AMSR-type of missions is requested, in particular in terms of spatial resolution (15 km), temporal resolution (sub-daily) and accuracy (in particular near the ice edges). A passive microwave with a very wide swath, most likely enabled by a conical scanner, is the only possibility to address the sub-daily revisit requirements. The threshold requirements as identified in Annex 3 correspond to the continuation of AMSR-2 type measurements. The spectral channels of AMSR-2 are listed in Table 3 below, together with their footprint size. These correspond to an antenna size of 2 m and an incidence angle of 55 degrees as illustrated in Figure 3. A more detailed study is required to optimise the spectral channels to be included, taking into account formation flying options and antenna size. A convoy concept with MetOp-SG would be highly synergistic, with MetOp-SG MWI offering high-frequency channels with high accuracy, as well as scatterometer measurements that are very important to discriminate the effects of wind speed. Including a C-band channel (6.9 GHz) would be highly recommended since it offers accurate measurement of SIC, as demonstrated in Figure 4 below. Furthermore, with the addition of a C-band channel, SST can be measured in the polar regions (at higher frequencies the brightness temperature is insensitive to changes in SST below 10 degrees Celsius). The antenna is the key enabling technology for this type of high-resolution radiometer, as can be seen from Figure 3. ESA has a large number of technology development activities running related to large antennas. Two types of reflector antennas can be considered.

1. Rigid antennas. A very mature technology, but the antenna size is limited by the launcher fairing (between 2 and 3 m in VEGA-C). To access higher spatial resolutions, the higher frequency channels are mandatory (multifrequency imaging microwave radiometer (MIMR) can be considered as a reference design, with 6 bands from 6.8 GHz to 89 GHz).
2. Large flexible antennas (‘unfurlable’). The higher frequency channels could potentially be omitted, particularly if flying in convoy with MetOp-SG.

Finally, a third antenna option that can be considered for this type of instrument is the multi-beam pushbroom concept. It has the advantage of not having any moving parts and better performance in coastal areas due to beam shaping. The technology maturity is lower, but a breadboard for this type of antenna feed is currently being developed under an ESA contract.

Central frequency (GHz)	Bandwidth (MHz)	Polarisations	NEΔT	IFOV
6.925	350	V, H	0.3 K	35x62 km
7.3	350	V, H	0.3 K	35x62 km
10.65	100	V, H	0.6 K	24x42 km
18.7	200	V, H	0.6 K	14x22 km
23.8	400	V, H	0.6 K	11x19 km
36.5	1000	V, H	0.6 K	7x12 km
89.0	3000	V, H	1.1 K	3x5 km

Table 3 AMSR-2 channels (source: https://www.wmo-sat.info/oscar/instruments/view/28)

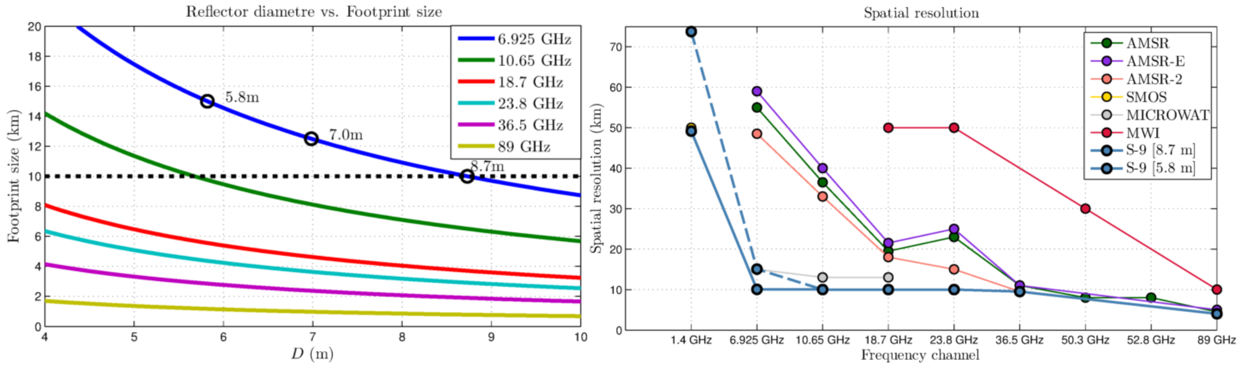


Figure 3 Spatial resolution versus antenna size for different channels (left) and spatial resolution obtained with heritage missions as well as two possible instrument designs with antenna sizes of 8.7 m and 5.8 m respectively.

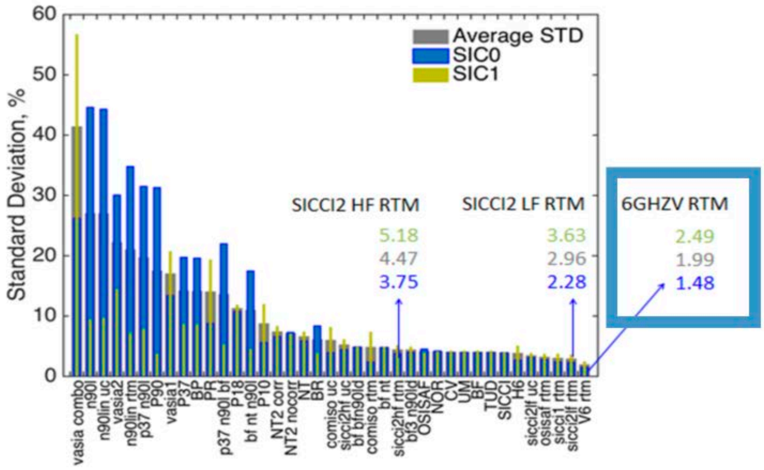


Figure 4 Performance of 40 ice concentration retrieval algorithms on 100 % ice concentration (SIC1, green) and open water (SIC0, blue). The 6 GHz algorithm has the lowest Standard Deviation error of all investigated algorithms. Source: Ivanova et al. 2015.

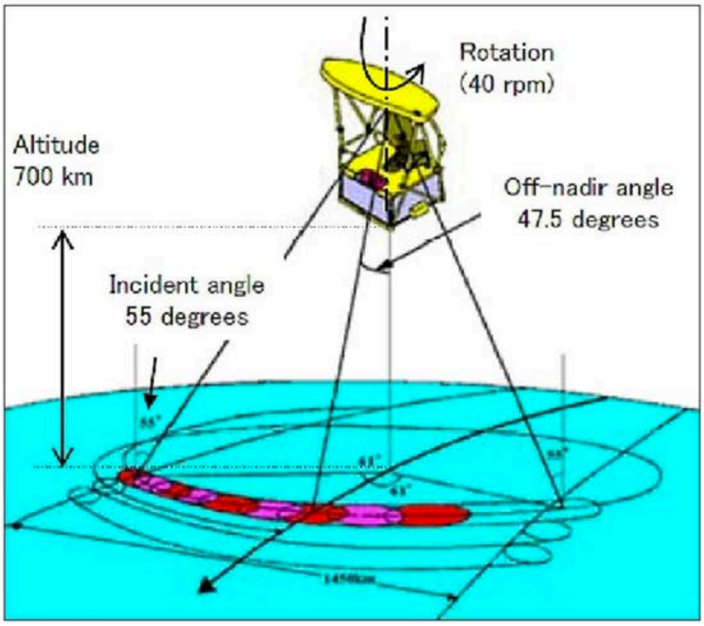


Figure 5 AMSR-2 instrument description (source: https://directory.eoportal.org/web/eoportal/satellite-missions/g/gcom#H5I4F132cHerb)

3.2.2 Planned missions and data buy possibilities

The Japanese global change observation mission — water (GCOM-W) series that hosts the AMSR-2 instrument is likely to be discontinued, as the GCOM-W1 is at its end-of-life period and there are no firm plans to continue with GCOM-W2. There are also no other missions planned by any of the other agencies that can offer comparable spatial resolution. A second option could be to build a partnership with the Chinese or Russian space agency and include their programmes as contributing missions into Copernicus. This would give access to data from instruments that have similar and even slightly better resolution than the American SSM/I instrument, which has been the workhorse for SIC products in the past. This second option would however not meet the threshold requirements formulated in Annex 3. Also, only the Chinese HY-2 includes C-band and this channel is less sensitive than the C-band channel on AMSR-2 (Noise Equivalent delta Temperature - NEdT of 0.5 Kelvin and 0.3 Kelvin respectively).

series	agency	status	sustained	instrument	frequencies	antenna	swath	resolution
GCOM-W	JAXA	considered	?	AMSR-2	6.9 - 89 GHz, 7 bands	2 m	1450 km	5 - 50 km
Meteor-MP	ROSHYDROMET	planned	YES	A-MTVZA	10.6 - 183.3 GHz, 26 bands	65 cm	2600 km	12 - 75 km
DMSP	NOAA / USAF	considered	?	SSM/IS	19 - 183 GHz, 24 bands	65 cm	1700 km	30 - 82 km
FengYun-3	NSMC-CMA	planned	YES	MWRI	10.6 - 150 GHz, 6 bands	90 cm	1400 km	14 - 100 km
HaiYang-2	SOA/NSOAS	planned	YES	MWRI	6.6 - 37 GHz, 5 bands	1.2 m	1600 km	18 - 100 km

Table 4 List of candidate operational satellite series that could offer a sustained source of PMR data for sea ice concentration. The only series that meets the threshold requirements is the Japanese GCOM series, but its continuation is uncertain. Source: Committee on Earth Observation Satellites (CEOS) database.

3.2.3 Technology and scientific readiness

Europe has produced various radiometers and overall their technical maturity can be considered to be very high. An AMSR-2 type instrument, MIMR, has been developed and qualified in Europe in the late 1990s. The current availability of this technology is to be investigated. More recently, the pre-development activities in support of MWI on MetOp-SG are offering state-of-the-art technology for the receivers covering channels between 18 GHz and 89 GHz. The lower frequency channels and associated large-antenna options have been studied extensively as part of the MicroWat-related activities in ESA (ref: C. Prigent et. al. 2013, JGR). A feasibility study is required to identify the optimum configuration and working point for such an instrument. As mentioned earlier, a trade-off is required between using a larger deployable reflector antenna with the lower frequency channels, and a medium-sized rigid antenna with channels up to 89 GHz. Technology readiness is part of this trade-off. The large deployable antenna technology is currently not available in Europe, but can be sourced from the United States (US). Medium-sized rigid reflectors are readily available. Depending on the moment of inertia of the antenna, the rotation mechanism from MWI on MetOp-SG can be re-used. The momentum compensation required on board the spacecraft also requires some further study.

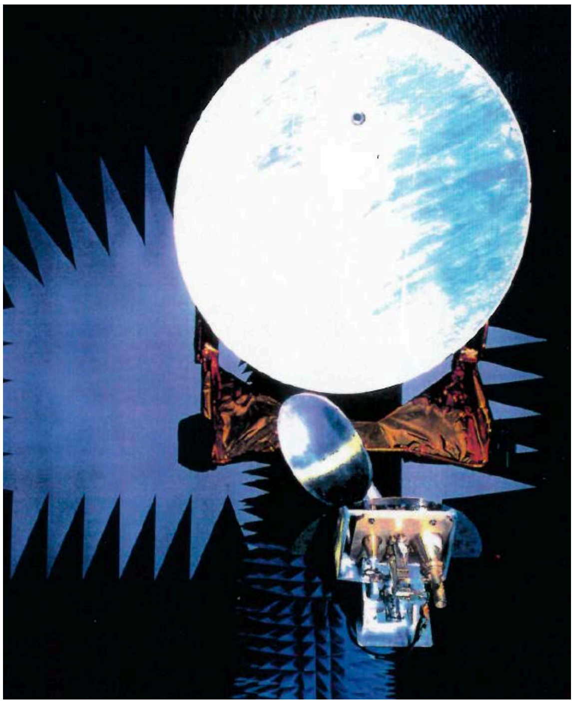


Figure 6 MIMR antenna breadboard being tested in antenna range. The reflector had a diameter of ~ 1.5 m.

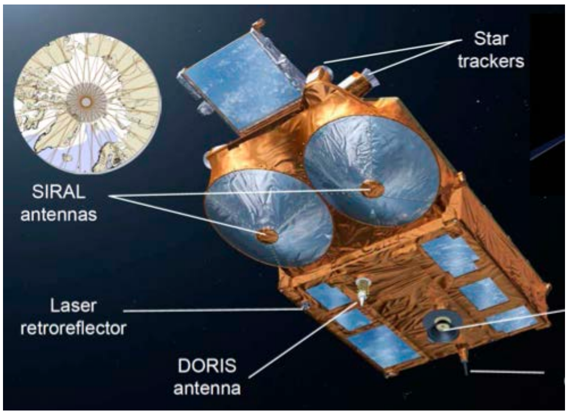
In terms of algorithm/processing maturity, a high readiness is obtained thanks to the available heritage missions. Sea ice concentration algorithms are readily available for the 18 and 36 GHz channels on AMSR-2 and previous missions. Adding lower frequency bands including C-band would be an enhancement, but scientific readiness is slightly less.

To conclude, the technology building blocks to fly an AMSR-2 type instrument is available in Europe, but a feasibility study is required to define the mission and the instrument in further detail in order to confirm this. Assuming that some pre-development activities will be started in parallel with the phase A study, a mission launch date in the 2027 timeframe should be possible.

3.3 SARIn altimeter

3.3.1 Description

Measurements of land ice elevation and sea ice thickness are essential to monitor critical and direct climate change signals: ice cap melting and sea level. With a footprint of about 300 m × 1 650 m (Doppler beam) with CryoSat-2, high spatial resolution sea ice freeboard measurements can be obtained with high accuracy. Altimeters (Laser or microwave) are the only instruments that are capable of measuring sea-ice thickness for thicker sea ice (> 0.5 m).



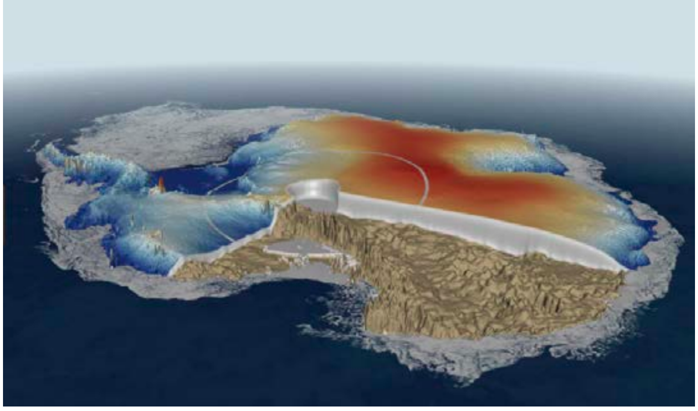


Figure 7: CryoSat-2 was launched in 2010 as an ESA explorer mission and has been the main instrument to deliver the climate records on ice-sheet thickness and sea-ice volume.

CryoSat-2 is currently the only satellite that is able to provide comprehensive coverage of the whole sea-ice pack up to 88 degrees latitude that is fundamental for the correct estimation of the ice-volume trends. CryoSat-2 can measure directly 95 % of the sea-ice volume in the Arctic, while the European remote sensing (ERS) satellite, Envisat and Sentinel-3 observe on average 60 % of total sea ice. CryoSat-2 makes a number of important contributions (see also CryoSat-2 mission extension report, ESA/PB-EO(2014)14, rev.1) which are summarised below:

Improved sea-ice-volume estimation. CryoSat has demonstrated its ability to better discriminate sea-ice floes from leads thanks to the improved resolution afforded by its enhanced SAR capability. It is estimated that with CryoSat, the number of observed leads has increased by a factor of ten when compared with conventional missions. This produces a direct improvement in the estimation of the sea-ice volume and a significant increase of the signal-to-noise ratio (SNR) of the freeboard signal.

Improved ability of SAR interferometric (SARIn). The gap of knowledge in alpine and peripheral glaciers is decreasing substantially, thanks to the increased use of CryoSat SARIn data. There is evident prospect of improving ground resolution with SARIn-swath in regions of complex terrain, extending the mission to include novel applications such as mapping the complete hydrological system of sub-glacial lakes in Antarctica.

High capacity of detecting changes over complex dynamic areas. CryoSat covers well the Antarctic ice-sheet margin where more than 95 % of the mass change is located, a major improvement in capacity for detecting elevation changes in these key areas.

Apart from maintaining the climate records, CryoSat-2 has demonstrated its capacity to support a number of **secondary applications in the oceanography, bathymetry and hydrology domains**. CryoSat-2 is part of the global altimetry constellation. CryoSat-2 is providing high data quality for oceanography (i.e. mean sea surface (MSS), dynamic topography, circulation, etc.) with a vital input to key climate change indicators at global and regional scale. Its high inclination orbit is essential to provide sustained sea-surface height and SLA observations in the Polar Regions. Since its launch, the uptake of the CryoSat-2 data has been high and the user community has increased dramatically. Continuing the unique capability of tracking and monitoring changes that are occurring in the most dynamic regions of the Earth’s land and sea ice fields is very important.

3.3.2 Planned missions and data buy possibilities

The US ICESat-2 mission is a multi-angular laser instrument that will measure ice elevation and is due for launch in 2018 but has a limited expected lifespan of 3 years. The current CryoSat-2 mission is already in extension phase. Beyond these two missions, there are no known plans for continuation of either type of ice altimetry close to the poles.

3.3.3 Technology and scientific readiness

Since CryoSat-2 is currently flying and nearing the end of its lifetime as an Earth-explorer mission, both the technology and scientific readiness are very high. A follow-on mission can be implemented immediately. Just like CryoSat-2, this mission should have the following characteristics-

- Orbit with polar gap no larger than 2 degrees.
- Fine along-track resolution from synthetic aperture processing.
- Across-track interferometric capability to detect across-track slopes.

A phase-A study would be required to update the payload and spacecraft taking into account hardware obsolescence as well as enhancements to the current mission. A number of enhancements to CryoSat-2 can be considered, including the following.

- Optimised instrument operating modes with updated instrument architecture.
- Higher spatial resolution for improved lead detection.
- Addition of Ka-band (currently operating at Ku-band) to determine snow loading on sea ice.
- Addition of radiometer for all-round oceanographic use and coastal altimetry.
- Improved on-board tracking systems for operation in rough terrain.

In addition, the product and processing algorithm status is very high thanks to the demonstration mission CryoSat-2, though enhancements such as swath processing are also ongoing here.

3.4 SP-InSAR

3.4.1 Description

Bistatic SAR applications in the polar regions range from glacier topography, dynamic topography of ice sheets/caps to 2D velocity measurements relevant for ocean currents and sea-ice motion.

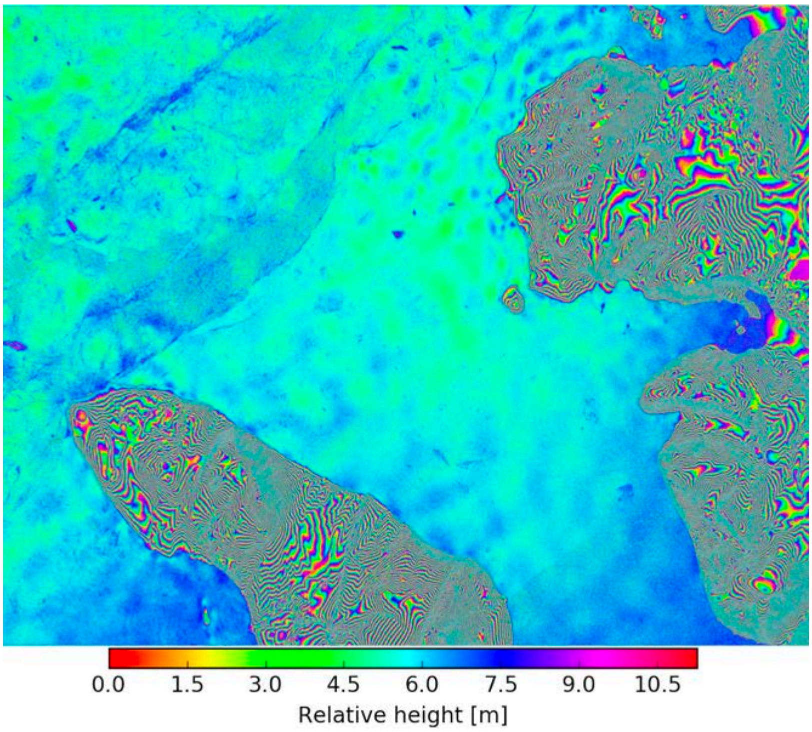


Figure 8 An example of a preliminary TanDEM-X InSAR image over sea ice close to the Axel-Heiberg-Island in the Canadian Arctic Archipelago (source: https://seaice.uni-bremen.de/junior-research-group/sea-ice-topography/)

An interesting concept to be fitted in Copernicus is to fly a small passive satellite in tandem with a Sentinel-1 satellite and use the latter as a transmitter of opportunity. This type of opportunistic mission concept has the potential to multiply the useful output from existing assets at a fraction of the cost, and therefore such missions have been studied already in several contexts and for different applications. Examples include SAR observation and communications satellite — companion satellite (Saocom-CS) and Sentinel-1-CS.

For operational sea-ice applications, dynamic topography products are required at high spatial (< 80 m) and temporal resolutions (< 2 days) (see Annex 3). In addition, for surface features to be visible in the images, the signals should not penetrate too deeply into the ice. For these applications C-band or higher frequencies should be considered.

3.4.2 Planned missions and data buy possibilities

Two advanced bistatic SAR concepts being studied in Europe are Saocom-CS and TanDEM-L, but both operating at L-band. No firm plans exist yet to fly a bistatic SAR mission. With Sentinel-1 a transmitter satellite is available for which continuity is guaranteed. This would form an excellent choice to serve as a master satellite in a bistatic pair.

3.4.3 Technology and scientific readiness

The maturity of bistatic SAR itself is very high, as demonstrated by TanDEM-X. The maturity of flying a passive bistatic follower with an existing asset is low, since it has not been done yet. From a technology point of view, a passive SAR instrument is just the receiving part of a complete SAR instrument, so in principle the technology readiness can be considered to be very high. There are some specific complexities involved with clock synchronisation between transmitter and receiver, but these have been studied extensively as part of recent studies in CS concepts and several solutions exist. It would be feasible to fly such a mission in the 2026 timeframe, which would be compatible with a tandem with Sentinel-1D.

The maturity of science and data products is high for individual SAR imagers operating at L-band and C-band. The maturity of bistatic data products for the applications under consideration here is fairly low, and limited to some acquisitions with TanDEM-X for demonstration purposes. Some work would be required to feed this kind of data into operational systems.

3.5 Summary of technology part

In this section, three instrument types that observe the geophysical parameters identified in Section 3 as top priority have been identified. These three instrument types are described in some detail, and alternative data sources from already planned missions are listed where available. The technical and scientific readiness levels are also discussed for each. The following conclusions can be drawn.

1. We have the technology to address any of the top-priority parameters and meet the user requirements for one or more parameters, but it is not possible to observe all of the parameters with any one type of instrumentation.
2. The user requirements cannot be fully met for any of the top-priority parameters with current or planned sustained observation systems.
3. From a technological maturity point of view, each of the three proposed solutions is compatible with a mission in the 2025-2030 timeframe. The actual launch date is more likely to be driven by programmatic considerations than by technology readiness or scientific readiness.

Instrument types	Main geophysical parameters	TRL	SRL	Data availability in 2025-2030	Compatibility with launch in 2025-2030
I-PMR	Sea ice concentration, SST	High	Very high	Only coarse-scale MWI data available	Yes
SARIn-ALT	Sea ice topography, surface elevation change	Very high	Very high	CryoSat-2 mission extension up to 2022-2023 (EOEP-5) foreseen	Yes
SPInSAR	Ice type, surface elevation change	High	Low to high		Yes

Table 5 Summary of the available technologies and link to the main geophysical parameters. TRL and SRL stand for technical and scientific readiness respectively.

4 Conclusions/Recommendations

In April 2017 the Phase 1 activity, with the participation of the polar expert group (PEG), has enabled a thorough review/update of the key user requirements in terms of parameters/observations and services.

A list of high-priority parameters together with their associated performance requirements was established taking into account the high-level objectives of the EU Arctic policy communication as well as those of the Copernicus programme for the provision of operational products and services to well-identified user communities. This list includes in order of priority the following elements:

1. floating-ice parameters,
2. glaciers, caps and ice-sheet parameters,
3. sea level/SLA parameters,
4. all weather SST,
5. surface albedo,
6. surface fresh water,
7. snow,
8. permafrost.

Phase 1 outlined a number of points deserving further consideration, namely the following.

- Geographical coverage: focus was placed on the Arctic and adjacent seas (latitude > 59-60° north) in line with the joint communication but Greenland and Antarctica regions will have to be included with regard to their key role as indicators of climate change.
- Product performances: many ‘polar parameters/products’ already exist today and are available on an operational or quasi-operational basis. However users often look for improved performances/quality (e.g. spatial and temporal resolution and accuracies). Particular attention shall be given to the provision of uncertainty estimates for each selected parameter/product.
- Long-term continuity of space observations: major concern was expressed about the situation/status of some space observations (e.g. AMSR-2) requiring strong and close coordination between space agencies to tackle these issues.
- Need for new products derived from new/improved space observations: This should be analysed, taking into account the experience gained since operational Copernicus services have been delivered to users (importance of regular user feedback)
- Maintenance of in situ observation capacities: these are essential not only for the parameter validation and calibration but as an essential complement to space observations.

In May 2017 Phase 2, starting from the high-priority-parameter requirements established during Phase 1 and associating additional representatives from space agencies (ESA and Eumetsat) to PEG, aimed to identify possible space instrumentation/clusters meeting the specified parameter-performance requirements and leading to the development of a ‘Copernicus Expansion mission’ dedicated to polar and snow monitoring.

In order to frame the objectives of Phase 2 a set of constraints and assumptions for the expansion mission was identified and is fully detailed in Section 0 of this document.

To further refine the contributions of current space missions, two expert subgroups were set up focusing respectively on ‘floating ice’ and ‘ice sheets, glaciers/ice caps and snow’, each subgroup was charged with reviewing the status of each individual parameter/product and to identify gaps/needs for improvements.
From this analysis, it became clear that a single expansion mission, operating with the current Copernicus Sentinels (and the contributing missions), will not meet all the parameter-specification requirements. As a consequence, such an expansion mission has to concentrate on a smaller number of top-operational-priority objectives as emerged from the two subgroup reports, namely the following.

- Floating ice and in particular sea-ice concentration, the most important parameter for operational navigation in sea-ice infested zones and climate service.
- Ice sheets, glaciers/ice caps and snow with the urgent need for monitoring the surface elevation and its temporal change in order to determine the mass balance of the ice bodies.

Based on these two priority requirements, space experts identified three generic instrumentation families capable of observing the associated geophysical parameters with the required spatio-temporal resolutions and coverage requirements.

1. **Imaging PMR**: a passive microwave imaging multi-spectral radiometer with ~ 10 km resolution and spectral channels for SIC and SST retrievals and a swath width that offers at least daily revisits in the polar regions.
2. **SARIn altimeter**: a follow-on mission to CryoSat-2, specialised in nadir altimetry in polar regions.
3. **SP-InSAR**: a SAR imager that includes single-pass interferometric capabilities as demonstrated with TanDEM-X. Such capability could be implemented as a passive bistatic follower with Sentinel-1.

For each considered instrumentation, the experts have proposed a detailed description of the following.

1. The current state of play; by reviewing development activities, mission studies and heritage from other missions.
2. Available technologies; by analysing the maturity of technology (TRL), the maturity of science (SRL) and processing.
3. Compatibility with a launch into 2025-2030 timeframe.

This is reported in Table 5 Summary of the available technologies and link to the main geophysical parameters. TRL and SRL stand for technical and scientific readiness respectively.

The Phase 2 analysis provided a list of the primary and secondary observable geophysical parameters in addition for each instrumentation as per Table 2 Instrument types with primary and secondary applications with associated scoring numbers as explained in section 3.1.

Based on these elements, the expert group recommends retaining as **first priority** the proposed imaging PMR solution which complies with the following.

- Meets the joint EU communication high priorities, in particular the provision of **operational sea-ice services** which are of prime importance for navigation safety in the Arctic and adjacent seas with at least daily revisits in polar regions.
- Offers the best solution from technical, scientific and operational viewpoints (operational daily observations of polar regions in almost all weather conditions, day and night).
- Provides high synergy with MetOp-SG MWI and Scatterometer.
- Ensures improved continuity of AMSR-type instrument and of AMSR-2 data onGCOM-W1 close to end of life.
- Takes advantage of the longstanding experience of PMR development and data utilisation in Europe (starting with scanning multichannel microwave radiometer (SMMR) on Nimbus 7 between 1978 and 1987, DMSP/SSMI).

In addition to the provision of key polar parameters, the I-PMR mission, through the selection of a well-validated set of channels (e.g. frequencies between 6.8 and 89 GHz and dual polarisation) will also be of high interest for the observation of non-polar regions, in particular for the oceans (SST) and for land applications such as hydrology, snow-cover extent, large-scale soil characteristics (moisture), large-scale vegetation-extent monitoring and biomass, land-surface temperature, flooding extent etc.

More generally, the use of I-PMR in synergy with active microwave sensors (e.g. wind scatterometer, radar altimeter and SAR) and with optical visible (VIS)/infrared (IR) sensors will provide powerful tools/techniques for the provision of improved-accuracy geophysical ocean, land and atmosphere parameters.

In addition to the points listed above, the development of an advanced I-PMR in Europe will offer many advantages/benefits including the following.

- Provision of European-produced passive microwave radiometer data for scientific and operational applications in polar and non-polar regions.
- Development of European space industry capacity and skills, complementing the existing experience acquired for the development of active microwave (SAR, altimeter, scatterometer etc.) and optical imagers (VIS, IR, hyperspectral etc.).
- European autonomy and independence from non-European sources (China, Japan, US, etc.) for the provision of PMR data meeting Copernicus and EU Arctic policy objectives.

Annex 1: List of participants

Chairpersonship	
Name	**Affiliation**
Thomas Diehl	Joint Research Centre
Peter Strobl	Joint Research Centre
Vincent Toumazou	European Commission

Experts Users		
Name	**Affiliation**	**Domains**
Guy Duchossois		Rapporteur
Patrick Eriksson	Finnish meteorological institute	European ice services
Frode Dinessen	Norwegian ice service	Search and rescue
Annett Bartsch	Austrian polar research institute	Climate change, cryosphere
Marie-Noëlle Houssais	LOCEAN	Polar ocean, sea ice

Copernicus services		
Name	**Affiliation**	**Domains**
Gilles Garric	Mercator Ocean	Marine
Joaquín Muñoz-Sabater	ECMWF	Atmosphere, climate
Sonia Antunes	EMSA	Maritime security
Marketa Jindrova	EEA	
Thomas Nagler	LAND/ENVEO	Land

Commission DGs	
Name	**Affiliation**
Amanda Regan	Research and Innovation
Rikke Nielsen	Mobility and Transport

Space agencies	
Name	**Affiliation**
Michael Kern	ESA
Erik de Witte	ESA
Kenneth Holmlund	Eumetsat

Copernicus unit	
Name	**Affiliation**
Peter Breger	European Commission
Ola Nordbeck	European Commission
Lieven Bydekerke	European Commission

Annex 2: Agenda of kick-off meeting

EUROPEAN COMMISSION
Directorate General for Internal Market, Industry, Entrepreneurship and SMEs
Space policy, Copernicus and defence
Copernicus

Brussels, 8 May 2017
Grow.i2/VT

KICK-OFF MEETING: POLAR EXPERT GROUP

16-17 May 2017

Breydel Building

Draft agenda

Tuesday 16 May 2017 — Morning session, Room BREYDEL 12/M. Ayral		
1. Welcome and introduction by the European Commission, Copernicus unit	V. Toumazou	10:30
2. Summary of Step 1 of the expert group meeting: top priorities of requirements, focus on gaps	Guy Duchossois	10:45
Lunch break		12:30
Tuesday 16 May 2017 — Afternoon session, Room BREYDEL2 12/405		
3. Space technologies for polar observations including currently flying, planned satellites and future satellites with advantages, drawbacks, limitations.	Space Experts	13:30
4. Discussion on requirements prioritisation and feasibility in terms of space observations.	Moderator + all	15:30
5. Summary of Day 1 and identification of sub-groups for Day 2.	Moderator + all	17:30
End of Day 1		18:00
Wednesday 17 May 2017 — Room BREYDEL2 9/405		
6. Brainstorming of sub-groups a. Identification of space technologies addressing the different sets of requirements. b. High-level description of a dedicated mission and if necessary description of a multi-mission scenario.	Sub-groups	9:00
7. Presentation of sub-groups conclusions	Sub-groups	11:00
Lunch break		12:00
8. Requirements for a mission achieving the best trade-off between missions identified at point 6.	Moderator + all	13:30
9. Next steps and specification of expected contributions	Moderator + all	17:00
End of Day 2		18:00

Annex 3: Report of the 'sea ice' sub-group

Conclusions — status and gaps for sea ice

For all parameters and quantities mentioned below, uncertainties are to be delivered together with the data. This is critical for the design and setup of assimilation systems and for prediction assessment to users.
For all parameters and quantities mentioned below, polar regions encompass a pan-Arctic domain including all longitudes to a southernmost latitude > 60º N and longitudes around Greenland and Baltic to a latitude > 55º N. It has to be mentioned that even if the focus of the Copernicus programme is put in the Arctic, the parameters and quantities below should be provided in the polar southern counterpart with the same characteristics.
Future polar missions should be planned to complement intended in situ based measurements; the latter being different from the calibration and validation activities of the satellite instruments.
Distinction is made between requirements related to navigation services and requirements related to climate services, since both sets contain very different requirements and both relate to key Copernicus services.

The list of parameters corresponding to climate requirements has been limited to those products needed for assimilation in operational products such as sea-ice ocean reanalyses. Additional parameters also essential to climate research (surface albedo, melt pond fraction, ocean colour, etc.) but are not assimilated so far in these reanalyses or were not considered, nor were specific requirements from climate change services.

SIC is the most important parameter for both operational and climate use. Currently there exist automatic routines providing ice concentration from passive microwave sensors such as SSMI(S) and AMSR-2. Standard SIC is computed by a combination of 18 and 36 GHz channels, and the effective spatial resolution of the SIC is close to 10 km using the AMSR-2 sensor. By utilising the 89 GHz channel on AMSR-2, with an IFOV of 3 × 5 km, can provide a spatial resolution of ~ 6 km although this has disadvantages with respect to the atmospheric influence. The MWI instrument on MetOp-SG will have an antenna of 75 cm versus a 2 m antenna on AMSR-2. A standard SIC algorithm using the low frequencies on MWI will only be able to provide a ~ 60 km spatial resolution. Utilising the 89 GHz on MWI could provide a spatial resolution of ~ 16 km

High-resolution SIC can be derived from SAR data by separating ice/water on a pixel-based resolution and estimating the amount of ice pixels within a given area. The robustness of these kinds of algorithms are still not sufficient. Using a SAR dual-polarisation (HH/HV) has improved the ability for separating ice/water and some studies have showed that quad pole are even better. This is still a field of ongoing research.

Operational requirements

Parameter	Existing products	Gaps	AOI/temporal and spatial resolution.
Sea-ice concentration	Sea-ice concentration is the most important variable for operational oceanography. ● Passive microwave products are currently assimilated in Copernicus marine environment monitoring service (CMEMS) operational systems. ● High-resolution concentration from the manually derived ice charts. These products are mainly based on Sentinel-1 in extra-wide-swath dual polarisation but also on corresponding data from Copernicus-contributing missions.	● The future availability of multi-frequency microwave radiometry (AMSR-2) is uncertain and reason for concern. The future MWI in MetOp SG will eventually secure continuation of the SSMI(S) series of coarse resolution radiometry for climate monitoring, but will not fulfil the requirements for medium resolution (< 10 km). ● Reliable automated sea ice-chart-like products that can be delivered in NRT for navigational aid and for high-resolution input to numerical forecasting models are needed. Such a product will probably need a multisensor approach where SAR will be the core input in combination with PMW.	● Actual PMW data from CMEMS catalogue are available at coarse resolution. It will be likely that increase in resolution and time availability of products from operational systems will require sub-daily and resolution less than 10 km in the future with at least a continuation of observations with a spatial resolution no less than those provided by the AMSR-2 instrument (threshold). Area: pan-Arctic, frequency: at least daily, threshold resolution < 10 km/. ● SAR requirements: Area: Pan Arctic; Frequency: At least daily or 2-4 times in key areas. Resolution: 20 m or at least no less than those provided by Sentinel-1
Sea-ice thickness (freeboard) (including summer ice and thin ice)	Pan-Arctic data does not exist presently in the CMEMS catalogue. Assimilation of sea ice thickness data (soil moisture ocean salinity (SMOS)-like one) is underway in operational systems. High-resolution product for navigation purposes does not exist for the Arctic Ocean.	A need to solve the knowledge gap in snow depth estimation over sea ice. For operational navigation purposes it is difficult to utilise CryoSat data due to its temporal and spatial resolution and too large uncertainty. It is noted that the spatial and temporal resolution requirements needed may not be achievable with today's technology. However, some	Area: Pan Arctic Temporal resolution: 1 day (G), 2 days (T) Coverage: pan-Arctic Spatial resolution: 20 m (G), 80 m (T)

		studies have shown a potential of using ice type as a proxy to derive ice thickness. This will need to be investigated further. Requirements related to ice type are included below.	
Stage of development/Ice type	Ice services are making a visual interpretation based on the SAR backscatter values.	Automatic products should be available. Fully polarimetric SAR observations are required in order to enable automation of product generation. Dynamic topography products are required at high spatial and temporal resolutions. These can be provided by single pass interferometric SAR (bistatic SAR).	Accuracy: Fractions of deformed ice has to be measured with an accuracy of 10 %. Coverage: pan-Arctic (G), areas near shipping routes and marginal ice zone (T) Frequency: 1 day(G), 2 days (T) Spatial resolution: 20 m(G), 80 m (T)
Iceberg detection, volume change and drift	Currently there exists a CMEMS product providing iceberg density maps with the ability to resolve 100 m icebergs and provide iceberg density at a spatial resolution of 10 × 10 km covering the Greenland waters.	Higher spatial resolution is required to detect smaller icebergs (5-10 m). There is also a need to detect Icebergs in other part of the Arctic ocean such as the Barents sea where icebergs appear more scattered and are generally smaller in size.	Area: Greenland and European Arctic Frequency: At least daily Resolution: 20 m(G) or at least no less than those provided by Sentinel-1(T)
Sea ice drift	CMEMS' operational systems	It will be likely that increase in	Coverage: Pan Arctic

	assimilate pan-Arctic coarse resolution (60 km) and 3 day-lag datasets. Currently CMEMS provide a pan Arctic high resolution ice drift product based on Sentinel-1 data in HH polarisation that meets the current high-priority requirements.	resolution and time availability of products from operational systems will require higher resolution and frequency. Higher resolution could be used to increase the drift resolution. For planning of a next generation of S1 this should be taken into consideration.	Temporal resolution: At least daily Spatial resolution: Corresponding to Sentinel-1
Sea level/sea level anomaly	Sea level anomaly is an essential variable for oceanic operational system as it gives outstanding information both on the small scales dynamics and climate change. Global ocean along-track sea surface heights is a CMEMS' product given at 14 km resolution in NRT	Actual data from the CMEMS' catalogue does not allow a satisfactory sampling north of 82°N. It is of prime importance that the orbit configuration allows covering the central Arctic Ocean. The sea level anomalies (SLAs) over frozen seas can only be provided by measurements in the leads, such as those made by CryoSat-2. The continuation of a CryoSat-type mission is not guaranteed. Desirable improvements wrt CS2 capabilities would be to improve lead detection capabilities further (resulting in more measurements over sea ice) and to observe sea surface topography at the scale of eddy fields (1-5 km).	Continuity of SL/SLA measurements in the leads is required. Coverage: Pan-Arctic, with polar gap no greater than 2 deg. Temporal resolution of gridded product: At least daily. Resolution: for gridded data < 10 km Accuracy for 10 km gridded product: TBC cm Note that requirements above have to be translated to requirements on L1 products. Note2: It may be better to specify an rms accuracy on sea level for a certain spatial scale, and leaving the temporal and spatial resolutions unspecified for now.
Snow depth and density on sea ice			Snow depth measurements are needed to best measure sea ice freeboard. The specification should follow the ice thickness specifications in terms of resolution

			and time sampling.
All weather SST	SST is a key variable for short term forecasts but also seasonal forecast applications. These data also are likely the oldest variables being assimilated in oceanic systems. Global daily ocean SST (L4) from Pathfinder advanced very high resolution radiometer (AVHRR) and (A)ASTR instrument is a CMEMS' product given at 1/20° horizontal resolution (~ 5 km) in NRT and presently assimilated Ice surface temperature (IST) is a CMEMS' product.	MWI also lack the necessary frequencies to measure all weather SST. A potential future C-band microwave radiometer (EE-10 suggestion) could fulfil the SST requirements, but resolution better than 5 km at frequencies below 40 GHz is not foreseen and still will be needed. Other Status of Pathfinder instruments? There is a gap in operational Sentinel-3 products where no sea and land surface temperature radiometer (SLSTR) IST product is planned for over sea ice.	A continuity is at least required. Infrared IST is also required. Area: Pan-Arctic Frequency: At least daily; Sub-daily sampling shall be monitored to sample diurnal cycle. Resolution: for gridded data: < 5 km

Climate requirements

Parameter	Existing products	Gaps	AOI/temporal and spatial resolution.
Sea ice concentration	Core resolution ~ 25 km Resolution of 6 km (12 km) is provided by AMSR (SSM/I) products in case they use radiometric measurements in the 89 GHz (85 GHz) channels Sea ice concentration is the most important sea ice variable for climate studies as it provides the longest satellite time series available to assess the sea ice variability. It is also the parameter now predicted by all climate models and routinely assimilated in ocean and atmosphere reanalyses	MWI on MetOp SG will eventually secure continuation of the SSMI(S) series, but will not fulfil a requirement for medium resolution (< 10 km) as is currently available on AMSR-2. A continuation of AMSR-2-like sensor is highly uncertain. Accuracy in the small-concentration range (marginal ice zone (MIZ) and near the ice edge) should be improved by an order of magnitude. This will require in situ infrastructure as well as space infrastructure. A PMW with < 10 km resolution could have been an important contribution for a high-resolution concentration product for operational navigation. (See separate table for operational needs).	Area: pan Arctic Frequency: at least daily Resolution: 25 km with a goal of < 5 km (depending on the channel used).
Sea ice thickness (freeboard) (including summer ice and thin ice)	CryoSat-2 for thick ice (medium resolution, 25 km?) and SMOS estimates of thin (< 0.5-1 m) sea ice	CryoSat estimates are too uncertain in the melt season (due to melt pond effects). Complete coverage of the Arctic is only available at the expense of the time resolution (monthly means). SMOS estimates are limited to small-thickness ranges (< 1 m). Revisit and resolution should be similar as described by the climate community.	The threshold requirements in terms of revisit, coverage and precision are the same as those specified for CryoSat-2. The goal requirements would also include extending temporal coverage over the melt season, to reduce uncertainties due to snow loading and ice density by a TBC amount, and to be able to measure over the entire range of ice thicknesses.

		Uncertainty due to snow cover in CS2 ice-thickness estimates must be reduced	
Ice type	Multi-year ice concentration is available from PMW. Distinction of deformed/levelled ice is available via scatterometer data.	Continuity of the PMW brightness temperature at different polarisations.	Accuracy: fractions of deformed ice have to be measured with an accuracy of 10 %. Coverage: pan-Arctic Frequency: daily (for monitoring of ice kinematics). Spatial resolution: same as for ice drift (order 10 km), ultimate goal would be 1 km.
Iceberg detection, volume change and drift	Iceberg trajectories are available for large icebergs over the period from 1978 using scatterometers. Products for estimating small (100 m < l < 3 km) iceberg volumes are available from analysis of altimeter waveforms.	Small iceberg probability and volume available since 2002 on a low-resolution basis (100 × 100 km). Volume parameter is derived from altimetry data, the continuation of which is not ensured beyond CS-2.	Area: Greenland and European Arctic Resolution: for climate and ice-ocean models, resolution of iceberg volume (necessary for the fresh water flux to the ocean) should be at least equal to that of the air-sea fluxes (typically 50 km in the Japanese 55-year reanalysis (JRA), even 15 km for the latest ASR).
Sea-ice drift	Pan-Arctic coarse resolution (25-60 km) (combination of active and passive sensors) gridded datasets. High resolution Lagrangian products deduced from processed SAR images (e.g. Radarsat GPS)	Resolution of gridded products is too low. Products deteriorate near the ice edge or in summer. SAR data do not provide global coverage: improve on the use of these data.	Area: pan Arctic Frequency: daily Resolution: 10 km, as for SIC

	are also extremely useful for process studies on sea-ice mechanics as well as validation of drift/deformation fields produced by sea-ice models		
Sea level/SLA	Gridded SLA is an essential variable for mapping surface ocean current variability. Gridded, multi-mission products which offer the longest time series (since 1993) are now available at 0.25° resolution. Along track SLA products at 14 km resolution are also available. No data are available in the leads or close to the ice edge.	At high latitude, the 0.25° resolution of the delayed-time Aviso gridded products is to crude for adequate sampling of the mesoscale circulation activity (eddies, fronts, etc.). Along track SLA may be helpful although not providing consistent time series over the full period, nor a 2D vision of the surface currents.	A continuity is at least required. Area: pan-Arctic Frequency: At least daily. Resolution: for gridded data < 10 km. Ultimate goal: 1 km, daily NB: It may be better to specify an RMS accuracy on sea level for a certain spatial scale, and leaving the temporal and spatial resolutions unspecified for now.
Snow depth and density on sea ice	Empirical method exist based on PMW brightness temperatures measured at different frequencies for SSM/I or AMSR-E.	The current estimates of snow over ice are empirical and medium resolution. They do not work for thick snow cover	Snow-depth measurements are needed to better assess snow loading and altimeter freeboard measurements, as well as the role of snow in the evolution of the sea-ice cover. The specification should follow the ice-thickness specifications in terms of resolution and time sampling.
All weather SST/IST	All weather SST/IST are available at low resolution based on PMW. High-resolution, weather-dependent IR products are available at 1 km resolution	High-resolution (1 km) IST are useful to estimate heat transfer through sea ice and sea-ice growth rates but are hardly available in cloudy high latitudes.	Continuity of the PMW-retrieved SST/IST is required together with high-resolution weather-dependent SST/IST as this parameter is crucial for climate studies and model validation

Annex 4: Report of the ‘ice sheets, glaciers/ice caps, snow, permafrost, fresh water’ sub-group

Conclusions — status and gaps for ice sheets, glaciers/ice caps, snow, permafrost, fresh water

1. For ice sheets, glaciers/ice caps and permafrost regions there is an urgent need for monitoring the surface elevation and its temporal change. The change of glacier mass over time (typically over annual intervals) is the basis for determining the mass balance of the ice bodies and compiling the contributions to sea-level rise. Precise, regularly updated DEMs are required as essential auxiliary data for deriving ice-velocity maps from displacements in repeat-pass satellite imagery, for retrieving calving fluxes and ice discharge, for estimating iceberg mass, etc. There are two major needs for data.

    - High spatial-resolution surface-elevation (50 to 100 m posting) and regular repeat observations for regions where major changes in surface elevation occur: outlet glaciers, boundaries of ice sheets and caps, mountain glaciers, zones that are subject to permafrost erosion and icebergs. TanDEM-X delivered repeat acquisitions of topographic data on demand, but there is no systematic acquisition plan for this task and mission continuation is not guaranteed.
    - Low to moderate spatial resolution and an acquisition interval of a few months to get coverage: ca. 1 km, for terrain with gentle topography in the interior of ice sheets. Current mission: CryoSat-2 (footprint ca. 300 m × 1000 m in SARIn mode, along narrow tracks); continuation by Sentinel-3, but S3 has an observational gap above 82º latitude and no moderate resolution SARIn mode.

2. There is an urgent need for high-resolution snow water equivalent (SWE), which cannot be measured by current spaceborne sensors. Demonstrations of experimental work for monitoring SWE exist but need to be further studied for operational capabilities (e.g. dual frequency X- and Ku-Band SAR; L-Band repeat-pass SAR interferometry).

3. Several relevant parameters can be derived from data of current Sentinel satellites. Further substantial benefits for products and services can be expected from technical advancements in the next generation of Sentinel satellite series as addressed, such as the following.

    - Sentinel-1 next generation (C-Band SAR): higher spatial resolution (ca. 3 m spatial resolution) and wider swath (~ 400 km); for ice velocity and snow-melt extent, subsidence, etc.
    - Passive SAR companion to Sentinel-1: For regular acquisition and update of DEMs, applying the single-pass InSAR technique (repeat-pass InSAR suffers from rapid temporal decorrelation over ice bodies)
    - Details and further options are described in the tables.

4. Adaptation of acquisition strategy of current Sentinels

    - (see tables for details)

Table 6: Summary of relevant parameters by theme, priority ones are highlighted in red

Floating ice (sea ice/iceberg)	Glaciers/caps	Ice sheets	Snow (seasonal)
Extent/fraction/conc.	Extent	Extent/calving front	Extent/fraction
Polynias/leads		Grounding line	
Sea-ice (Iceberg) drift	Surface velocity	Surface velocity	
Sea level in leads	Surface elevation (topography)	Surface elevation (topography)	
Thickness (freeboard)	Bedrock topography/ ice thickness	Bedrock topography/ ice thickness	Depth
Surface roughness			
Surface temperature		Surface temperature	Surface temperature
Melt pond fraction/depth	Surface melt extent	Surface melt extent	Snow melting extent (dry or wet)
Snow depth and density (liquid water)	Mass balance (mass, mass change)	Mass/mass change	Snow water equivalent (*)
	Accumulation	Surface accumulation	Accumulation (snowfall)
		Loss (melt, evap., calving)	
Deformation/ridging		Calving mass flux (*) (derived from velocity and thickness	
Surface albedo	Surface albedo	Surface albedo	Surface albedo
Salinity/brine distribution			
Type (First Year (FY) / Multiyear (MY) / new / thin ice) crystal structure, air bubble content		Ice-sheet morphology (crevasses, shear margins)	Impurity (*)
		Basal melt	Grainsize (*)
Floe size distribution			Density (*)
Fast ice detection			

(*) Parameters that are normally a function of the layer depth, where applicable it is to be mentioned whether surface values or columnar means may serve as proxies and specify accordingly.

Table 7: Summary (continued) of relevant parameters by theme, priority ones are highlighted in red

Atmosphere	Ocean	Surface water (freshwater)	Land surface/ vegetation	Permafrost and soils
		Extent/fraction	Extent/fraction	Extent/fraction
		Bathymetry		Permafrost table
	Surface currents	Water body shape	Coast lines	Taliks
	Sea Level and Anomalies	Water level	Surface elevation (Topography)	Surface elevation (Topography)
	Waves	Waves		
	Surface roughness		Surface roughness	
Temperature (*)	Temperature (*)	Temperature (*)	Temperature	Temperature (*)
	Salinity	Salinity	Liquid water content	Ice and liquid water content (*)
Precipitation	Swell	Discharge	Interception	Loss (melt)
Wind (*)	Surface wind	Surface wind	Surface displacement	Surface displacement
Albedo	Albedo	Albedo	Albedo	
Cloud (*)	Objects, oil on surface	Ice thickness	Land cover	Thickness
	Size/type of objects and debris [ice, wood, metal, synthetic polymer (plastic), oil] (**)		Size (incl. height) /type of objects vegetation/buildings	
	Acidification	Mass	Biomass (above/ below ground)	Mass
Earth radiation budget (*)	Ocean colour (including in MIZ-marginal ice zones)	Lake colour	Plant funct. type veg. structure (layers, communities, canopy types, shading etc.)	Ice type: pore, segregated, intrusive, vein ice
Constituents (*): [H_2O,O_3,NO_x,GHG, C, etc.]	Total Suspended Matter (TSM) (Particulate Organic Carbon (POC)/Particulate Inorganic Carbon (PIC)) (*), Chromophoric Dissolved Organic Matter (CDOM) (*)	Light penetration		Heat conductivity (*)
	Chlorophyll, fluorescence primary production phytoplankton types	Impurity (*) (anorganic), impurity (*) (organic)	Leaf area (*) carbon uptake/loss, water uptake/loss	Soil composition (*) (anorganic), soil composition (*) (organic)

(*) Parameters that are normally a function of the layer depth, where applicable it is to be mentioned whether surface values or columnar means may serve as proxies and specify accordingly.

(**) This box includes EMSA requests on detection of fish cages, containers, vessels and oil spills which will be treated under a separate Copernicus service (Security)

Ice sheets

ICE SHEETS	Status	Gaps
Extent/calving front	Manual delineation of ice edge/calving front in SAR (S1) and VIS (S2, LS8) images. VIS limited by clouds and not available during polar night; SAR has sometimes problems with sea ice (and ice melange) in front of ice edge.	Robust automatic delineation of ice front in SAR and VIS images is still not available. DEMs might support automatic delineation of ice front for maritime outlet glaciers, but frequently updated DEMs not available.
Surface elevation/change	Surface-elevation maps and change is measured operationally by altimeter at coarse resolution along ground tracks (~ 1 km) (CryoSat-2, Sentinel-3, etc.). Outlet glaciers show major changes in surface elevation but as they are often located in complex terrain high-resolution DEMs (ca. 50-100 m grid) are needed. Current DEMs from TanDEM-X, stereo optical satellites) have only limited repeat-observation capability.	**Interior of Ice sheets:** Altimeter limited to annual intervals of mass changes due to coverage. CryoSat-2 ground tracks provide good spatial coverage close to poles but gaps between tracks increasing towards lower latitudes. Provides also SARIn mode with medium resolution. Continuation by S3, which provides altimeter data over ice sheets, but has no coverage above 82° latitude and no SARIn mode. **Outlet glaciers/margins:** they show major elevation changes and need to be covered systematically and frequently (~ 1-3 monthly) at high spatial resolution (50-100 m) and short acquisition intervals. Currently DEMs are provided by TanDEM-X (single-pass InSAR) for case studies (on demand) over limited areas, continuation of mission not guaranteed.

Snow melt	PMW and scatterometer used for mapping melt extent on daily basis at coarse resolution. C Band SAR (S1) provides data for retrieval of melt extent at high resolution, currently used for regional applications.	Continuation of PMW and SCAT on MetOP. High-resolution melt-extent maps from S1 require acquisition strategy over ice sheets to improve the coverage. S1 can be complemented by other SAR sensors.
Grounding line	Various methods exist for mapping grounding line, including InSAR (S1, etc.); also high-resolution optical images (shape from shading; but these are less accurate). Experimental coarse resolution grounding line product from CryoSat-2 altimetry using breaking slope.	Continuous S1 acquisitions with 6/12 days of the complete grounding zones of Antarctica needed; S1 — SAR with 6 day repeat decorrelate in regions with high ice-flow velocity, and due to snowfall and wind drift. Shorter time intervals show higher coherence (known from 1 day InSAR for ERS tandem), L-Band SAR may also be suitable, being less affected by temporal decorrelation.
Ice velocity	SAR offset tracking (S1), optical offset tracking (S2, Landsat 5,6,8), and InSAR provided reginal and ice-sheet-wide products. Horizontal components of velocity vector or slope parallel velocity products are provided.	Repeat pass acquisitions of S1 with 6/12 days needed for ice-velocity retrieval. Offset tracking mature and robust. InSAR is limited by effects of temporal decorrelation, therefore requires very-short repeat observation intervals. Regularly updated DEMs at same resolution as ice-velocity maps needed for accurate products (in general not available). Data gap of S2 over ice sheets, continuous S2 acquisitions over ice sheets needed. 3D ice-velocity retrieval requires multiple tracks and high-resolution updated DEM needed.

Mass/mass change	Gravimetry: integrated/regional mass and mass change estimates provided by gravimetry. Mass changes by means of altimeter are derived by observing volume changes (surface-elevation change) and conversion to mass changes. Input/output method for estimating mass changes for single glaciers with temporal resolution; requires ice velocity, ice thickness and surface mass balance (net accumulation or ablation over the basin, the grounding line position, and ice thickness at the grounding line	Grace follow-on mission planned for launch in 2018, long-term continuity needed. Uncertainties are due to glacial isostatic adjustment models; they do not allow the mass changes on ice drainage basins scale to be detailed. **Mass changes from altimetry: conversion from volume change to mass change is critical, currently only annual mass changes are available due to coverage of altimeter data. See also surface-elevation change for S3 and CryoSat-2 observational gaps.** **Input/output method: S1 provides ice-velocity variations on weekly basis, but contemporary ice thickness at grounding lines (e.g. from bedrock topography of airborne radar sounding and current ice-surface elevation) and surface-mass balance (usually based on regional numerical climate models driven by global meteorological data) required. Need for high-resolution surface-elevation data and time series of surface-elevation change products, can be provided by single-pass interferometry (e.g. TanDEM-X; but continuation of mission not guaranteed).** **Closure of gaps in mass-change estimates from different methods needed.**

Potential contributions by current Sentinel and MetOP

Ice sheets	S1	Sentinel-.2		Sentinel-3		MetOP				
	SAR	MSI	OLCI	SLSTR	SRAL	VII	IRS	SCA	MWI	3MI
Extent/calving front	✓	✓								
Surface elevation/change					✓ < ~ 80° lat. coarse					
Snow melt extent	✓							✓ coarse	✓ coarse	
Grounding line	✓ InSAR				✓ coarse					
Ice velocity	✓	✓								
Mass/mass change										

Glaciers and ice caps

Glaciers/icecaps	Status	Gaps
Extent	Semi-automatic delineation of glacier extent using VIS (S2, LS8) images.	VIS images required at period with maximum ablation, which is often not available due to cloudiness. Manual correction for debris cover needed. Rectification of VIS images with closely acquired DEMs needed, but not available in general.
Surface elevation/change	Surface elevation and change for ice caps is measured operationally by altimeter at coarse resolution (CryoSat-2), but limited applicability to mountain glaciers Surface elevation changes by DEM differencing from various sources like TanDEM-X, HR Optical DEMs, but time series not systematically acquired.	**Ice caps-interior:** altimeter limited to areas ranging from smooth to gentle of the interior and annual intervals of mass changes, as gaps between tracks become larger at lower latitudes. CS-2 SARIn mode with higher spatial resolution is preferred. Continuation by S3, but S3 does not have SARIn mode. For ice caps with fast melting rates shorter acquisition intervals needed to get coverage (e.g. TanDEM-X single-pass interferometry). **Mountain glaciers/outlet glaciers of ice caps:** show significant changes, due to complex and sometimes rugged terrain. High-resolution DEMs (~ 50-100 m) should be generated at least annually (goal: monthly) at high resolution as e.g. provided by TanDEM-X, but continuation of TanDEM-X not guaranteed.
Snow Melt Extent	C Band SAR (S1) provides snapshot of melt extent at high resolution for regions.	High resolution melt maps from S1 require acquisition strategy with an improved coverage. S1 can be complemented by other SAR sensors (third-party missions).

Surface Ice velocity	Ice caps and large mountain glaciers: S1 InSAR suitable, but limited by temporal decorrelation for 6/12 days. S1 SAR offset tracking in principle applicable, but higher resolution SAR preferred. Optical offset tracking (S2, LS 8) works, but limited by clouds. Mountain glaciers high resolution SAR like (TerraSAR-X SM, CSK) or InSAR (1 day repeat) applied.	Short repeat pass acquisitions of S1 with 6/12 days needed for ice velocity retrieval. InSAR limited by signal decorrelation and requires very short intervals of a few days (1 day preferred). Contemporary DEMs at same resolution as ice-velocity maps often not available. For offset tracking: high resolution SAR needed (as TSX, CSK Stripmap Mode) Systematic acquisitions of S2 over glaciers needed during ablation period, but affected by clouds.
Glacier Facies	Based on automatic classification of winter snow, firn and glacier ice using VIS (S2, LS). Retrieved together with glacier extent. C-Band and X-Band SAR are suitable for discriminating snow/firn versus glacier ice.	Requires acquisition planning of Sentinel-2 over glaciers during period of maximum ablation. Accurate rectification of images with contemporary and high-resolution DEM needed.
Mass balance	Volume changes retrieved from DEM-differencing using TanDEM-X, Optical stereo DEMs converted to mass changes. Experimental products of volume changes by means of swath mode of CryoSat-2 generated.	Systematic acquisition of DEMs (~ 50-100 m, annually) over glaciers required. TanDEM-X acquisitions not guaranteed in future, optical Stereo DEMs limited by clouds, and problems in matching in accumulation areas. CryoSat-2 SARIn mode resolution too coarse and large gaps between tracks at mid-latitudes.

Potential contributions by current Sentinel and MetOP

Glaciers/icecaps	S1	Sentinel-.2		Sentinel-3		MetOP				
	SAR	MSI	OLCI	SLSTR	SRAL	VII	IRS	SCA	MWI	3MI
Extent	✓	✓								
Surface elevation/change					✓ coarse Not all ice caps					
Snow melt extent	✓							✓ coarse	✓ coarse	
Ice velocity	✓ InSAR									
Glacier facies	✓	✓								
Mass balance										

Permafrost

Permafrost	Status	Gaps
Permafrost extent	The use of surface temperature from IR optical satellite data (from SLSTR S3, Modis, VIIRS) and coarse SWE from PMW, and land cover maps is tested for support of permafrost modelling. Near-surface freeze/thaw maps (coarse) from scatterometer and PMW are also tested for mapping permafrost extent, but penetration depth is insufficient and surface status information alone is not applicable in transition zones. Taliks (unfrozen parts) monitoring can be supported by using SAR for ground-fast-ice extent of lakes.	Improvement of spatial resolution of thermal IR (~ 10 m) required. Main deficiencies are in mapping permafrost extent in the transition zone. For modelling, only coarse resolution SWE from PMW is available, high resolution SWE is needed (see Snow). High resolution and quality land cover products can be used in addition for modelling of permafrost, but current products which cover the entire Arctic are not sufficient regarding thematic content. Adaptations of S1 acquisition strategy for mapping lake properties (summer and winter) are needed. → regarding thematic content SEE FRESHWATER
Surface elevation/change (motion/displacement)	InSAR using S1 and TPM SAR (L-Band and X-SAR) are used for mapping motion fields; time intervals range from weeks to years depending on type of motion, but coherence between InSAR image pairs is needed. **Surface-elevation change can be observed by time series of DEMs**.	S1 can be used, but acquisition strategy needs to be adjusted to get frequent/continuous coverage. Higher spatial resolution SAR is needed; coherence is a prerequisite, better preserved for lower frequencies (L-band). **Time series of DEMs not acquired regularly over polar regions. TanDEM-X DEM acquisitions not guaranteed in the future. Availability of high resolution optical stereo images limited by cloudiness.**

Potential contributions by current Sentinel and MetOp

Permafrost	S1	Sentinel-.2		Sentinel-3		MetOP				
	SAR	**MSI**	**OLCI**	**SLSTR**	**SRAL**	**VII**	**IRS**	**SCA**	**MWI**	**3MI**
Permafrost extent	✓ **via ground-fast ice**	✓ **via land cover**		✓ **via temp**		✓ **via temp**		✓ **via surface freeze/thaw coarse**	✓ **via SWE coarse**	
Surface-elevation change (motion)	✓ **InSAR**									

Seasonal snow

Seasonal snow	Status	Gaps
Total snow area	Vsible (VIS), near infrared (NIR) and thermal infrared (TIR) imager, some problems with cloud/snow discrimination; available products show significant differences.	Higher resolution required for complex terrain (mountains); cloudiness/polar night; in some products filled with coarse integrated management of water resources (IMWR).
Snow mass (SWE) on land	Low-spatial-resolution SWE maps available from IMWR, but at comparatively large uncertainty. Operational products available (GlobSnow, etc.), continuity of PMW on MetOP.	IMWR SWE: accuracy needs to be improved; problems with spatial resolution in complex terrain, forests, saturation over deep snow. High-resolution product needed, not covered by current sensors.
Snow melt extent	C Band SAR (S1, ERS, ENVISAT) provide snapshot, algorithms mature for mountain regions.	Problems in forests. Melt extent depends on acquisition time.

Potential contributions by current Sentinel and MetOP

	S1	Sentinel-.2		Sentinel-3		MetOP				
	SAR	MSI	OLCI	SLSTR	SRAL	VII Metimage	IRS	SCA	MWI	3MI
Snow extent		✓	✓	✓		✓				
Snow melt area	✓							✓coarse	✓coarse	
SWE								✓coarse	✓coarse	

Albedo and surface temperature products; sea ice, glaciers, ice caps, ice sheets, land, permafrost

Parameter	Status	Gaps
Spectral-surface albedo	Hemispheric snow albedo derived from medium resolution spectral imagers (Sentinel-3, Modis, Viirs). Available global products assume flat Earth. High-resolution products from S2, LS, but only regional and experimental products	Accuracy impaired by angular effects of surface reflection (BRDF) and of atmosphere (aerosol scattering), requiring multi-angular measurements. High-resolution spectral albedo maps needed for supporting impact assessment of disturbances (e.g. fires) and long-term change (e.g. vegetation composition) on the energy balance and thus changes in subsurface temperatures.
Surface temperature	Products from medium-resolution IR, TIR (S3, Modis) available. High-resolution maps not generated operationally.	High resolution products needed for permafrost extent modelling.

Potential contributions by current Sentinel and MetOP

	S1	Sentinel-.2		Sentinel-3		MetOP				
	SAR	MSI	OLCI	SLSTR	SRAL	VII	IRS	SCA	MWI	3MI
Spectral-surface albedo		✓	✓	✓		✓				✓
Surface temperature				✓		✓				

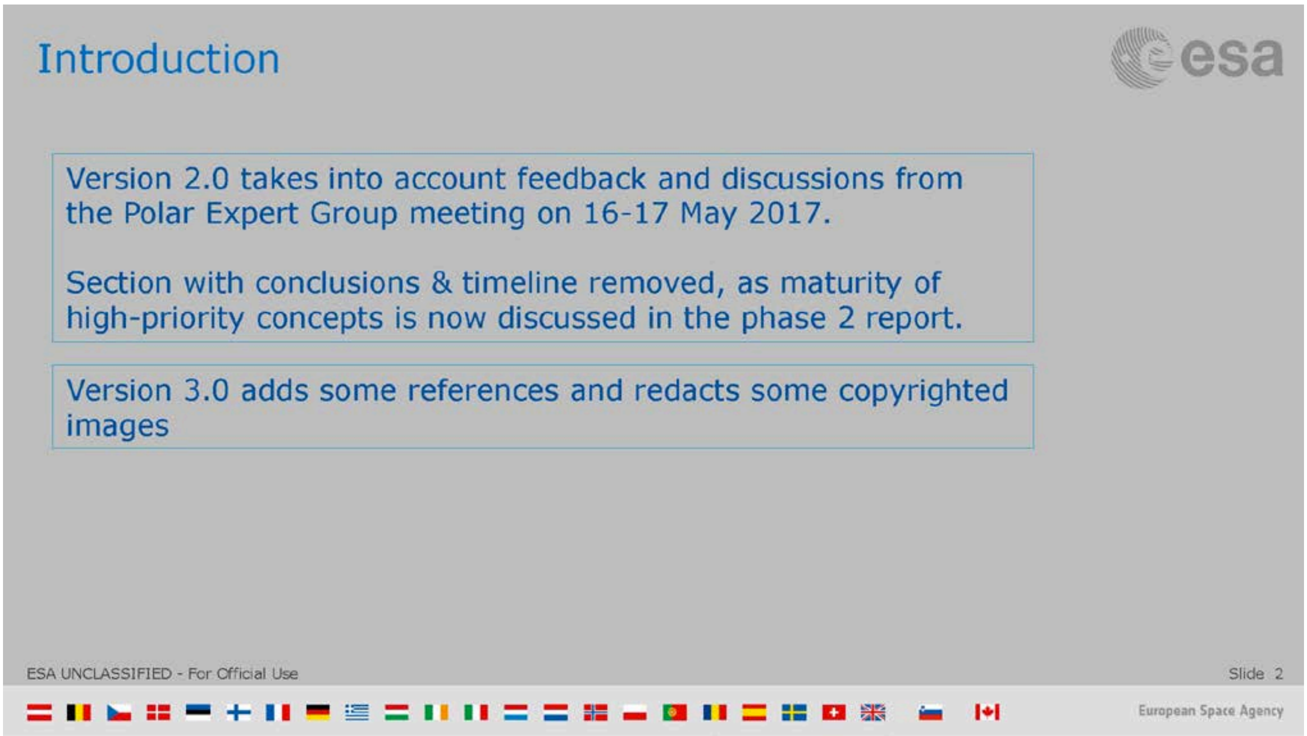
Freshwater water

Freshwater	Status	Gaps
River-runoff discharge	Water-level observation by altimetry and cross section. Tracking of debris/ice with high resolution VIS.	High-temporal-repeat observations needed. VIS: time series not guaranteed due to clouds.
River ice (thickness)	Mapping of ice jams and unfrozen parts, tracking of debris/ice with high resolution VIS.	Using S1 SAR, but higher resolution recommended; high-temporal-repeat observations. VIS: time series not guaranteed due to clouds.
Lake-ice thickness	Altimeter, CS2, can be utilised to derive ice thickness for large lakes. Lake-ice thickness measured by means of C-band SAR, e.g. S1, in combination with models (bathymetry needed) for small and shallow lakes. Relative changes in freezing depth also from SAR, S1, and TPM (L-band, X-SAR).	S1 acquisition strategy needs to be adjusted to provide time/spatial coverage requirements. Continuation of CryoSat-2 not guaranteed in future.

Potential contributions by current Sentinel and MetOP

Freshwater	**S1**	**Sentinel-2**		**Sentinel-3**		**METOP**				
	SAR	**MSI**	**OLCI**	**SLSTR**	**SRAL**	**VII Metimage**	**IRS**	**SCA**	**MWI**	**3MI**
River runoff discharge		✓			✓ **coarse**					✓
River Ice (thickness)	✓	✓								
Lake-ice thickness	✓									

Annex 5: State of the art of available technologies for Polar/Arctic observation

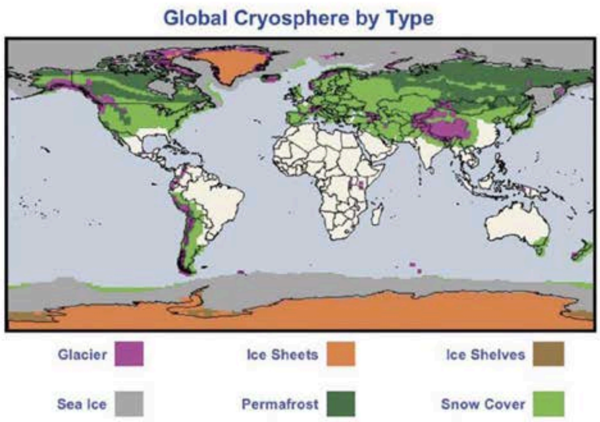


State of the art of available technologies for Polar/Arctic observation

- *State of the art…*
  - Heritage from other missions
  - Mission studies
  - Development activities
- *of available technologies…*
  - Maturity of technology (TRL)
  - Maturity of science / data processing (SRL)
  - Technology: observation concepts, rather than in-depth
- *for Polar/Arctic observation*
  - Any mission, and type of instrument
  - Observing the cryosphere and/or polar atmosphere
  - Flying over the poles

Components of the Cryosphere

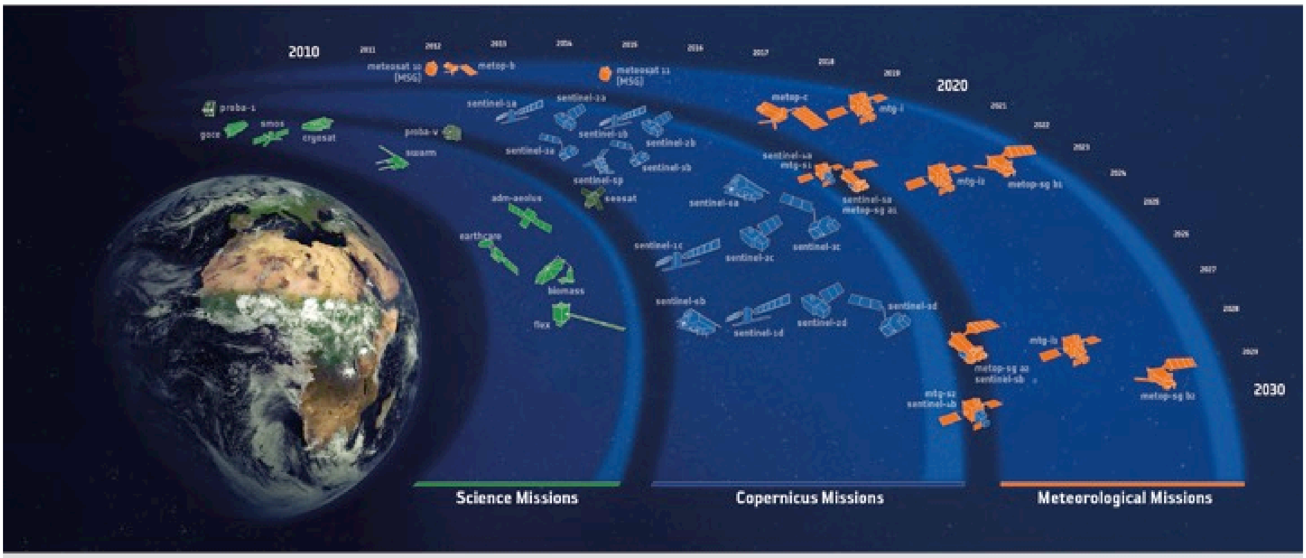
- Terrestrial snow
- Sea ice
- Lake and river ice
- Ice sheets
- Glaciers and ice caps
- Surface temperature and albedo in cold regions
- Permafrost and seasonally frozen ground
- Solid precipitation in cold regions



From: IGOS Cryosphere Theme Report 2007

Space observations are essential for the observation of many key components of the polar cryosphere, but which ones take priority?

European Earth Observation Programmes



European Space Agency

Ice and Snow Capabilities with (planned) European Satellite Missions in mid-2020s

Parameter	Sentinel-1 (SAR)	Sentinel-2(*) (MSI)	Sentinel-3 (SLTSR, OLCI, SRAL)	MetOp-SG (SCA, MWS, MWI, ICI, MetImage)
Ice sheets(***)	Motion, Extent, topography, facies, lakes, calving front		Elevation, Thickness, Surface Temperature	Extent, Snow/ice facies, Melt/freeze onset, Surface Temperature
Glaciers and ice caps	Velocity	Extent, velocity, snowline	Surface topography & change	Facies
Sea ice	Motion, Extent, Floe size, Distribution		Freeboard/thicknes, Surface Temperature	Extent, Melt/Freeze, Onset, Concentration
Snow and SWE(**)	Melt facies	Extent, Albedo, Grain size	Extent, Albedo, Grain size	Accumulation, Extent, Albedo, Grain size
Solid precipitation(***)			Surface Temperature	Thickness (coarse), Ice/ water cloud
Lake and river ice	Ice jams, ice on/off	Floe size, distribution, meltponds		Extent, Melt/Freeze, Onset
Permafrost and frozen ground	Motion, surface deformation, subsidence	Coastal erosion, surface indicators	Near surface temperatures	Freeze-thaw status of active layer

*Not officially part of HLOP-excluded by MRD, latitude limits
**GRACE-FO provides additional information regarding mass transport
***MSG/MTG and EarthCARE provide additional information for solid/precipitation albeit limited latitude

Table adapted from IGOS-Cryosphere report

Slide 6

European Space Agency

Observation and Technology Clusters

	OBSERVATION	TECHNOLOGY	
Ice monitoring	Ice imaging	SAR bistatic SAR	C1
	Sea ice parameters (concentration, thickness,..)	Passive Microwave Radiometry (PMR)	C2
	Ice topography (sea ice, ice sheets/caps, glaciers)	Polar interferometric altimetry Single-Pass Interferometric SAR (SP-InSAR)	C3
Snow monitoring	Snow on sea ice (thickness)	Polar multi-frequency altimetry	
	Terrestrial snow (SWE and SE)	Passive Microwave Radiometry (PMR) Multi-frequency SAR IR radiometry	C4
Soil freeze/thaw state (permafrost)		Low-frequency PMR SAR Bistatic interferometric SAR	C5
Pseudo-geosynchronous applications		Hosted Payload on Highly Elliptical Orbit	C6
Mass transport		Gravimetry	C7

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Slide 7

European Space Agency

Cluster 1: Ice monitoring – Ice imaging(*)

(*) All weather, high-resolution ice imaging, not including maritime surveillance

Technology

- High Resolution Wide Swath
- Multi-frequency SAR
- Bistatic SAR

Heritage missions

- ERS-1/2
- Envisat
- Sentinel-1

ESA activities

- Polaris P-train
- Ocean and Sea Ice Convoy
- High Resolution Wide Swath Applications

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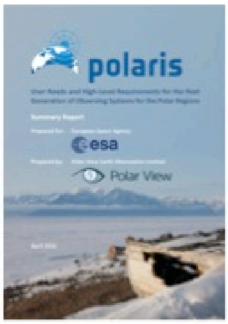
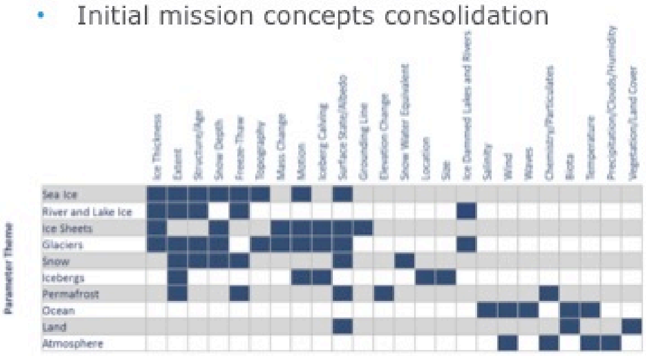
Polaris

- Comprehensive survey of user needs and high-level observation requirements by end-users and providers of operational services in polar regions
- multi-frequency SAR and InSAR observations of sea-ice ranked highly for operational services
- Initial mission concepts consolidation



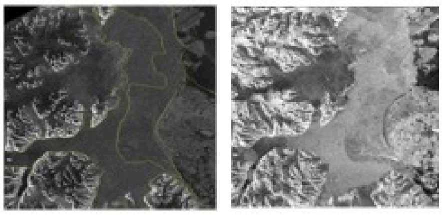


Integrated Service	SAR	Dual SAR	Tri SAR	InSAR	Multi-Spectral	Altimeter	Meteorology	AIS
Sea Ice	1.8	4.0	5.0	3.0	2.0	1.8	0.0	0.0
Icebergs	3.2	4.4	5.0	3.6	2.2	1.6	0.0	0.6
River and Lake Ice	1.9	4.4	5.0	2.8	0.8	1.1	0.0	0.0
Ice Sheets	1.5	3.3	5.0	4.4	2.3	3.8	0.0	0.0
Glaciers	2.0	3.8	5.0	4.1	2.4	2.9	0.0	0.0
Snow	1.7	4.1	5.0	1.1	1.7	1.3	0.0	0.0
Permafrost	2.9	4.6	5.0	2.5	4.6	1.8	0.0	0.0
Land	0.7	1.0	1.3	1.3	5.0	0.0	0.0	0.0
Ocean	3.3	3.8	3.8	2.9	4.6	2.1	5.0	0.0
Atmosphere	1.4	2.1	2.5	0.7	3.6	0.0	5.0	0.0

Polar Ice: Polaris Train L-band

- Polaris studies of observation gaps ranked multi-frequency (near-simultaneous) L+C- (L+X-) band SAR observations of thick perennial ice as crucial for polar applications like navigation safety
  - better ice penetration and discrimination between ice types
  - added bands improve characterisation
  - detection of melting ponds in summer and better classification with summer or thin ice (higher frequency for winter ice)
- recurrent goal of users: e.g. NASA/ESA proposed missions (EOS-C, CLIMACS for sea ice) after experience of Shuttle SIR-C (L, C, X) in 1990s and airborne multifrequency SARs (P,L,C,X,Ku,Ka)
- Maturity of multi-frequency retrievals is relatively low (few co-temporal observations)

RadarSat 1, 15 July '07 C-Band SAR PALSAR, 16 July '07 L-Band SAR



A “polar train” (Polaris) concept

- Polaris concept is strongly operationally oriented and considers context: Sentinel-1, Radarsat Constellation Mission, other (commercial) SAR…
- Evolutive convoy concept leading to a polar convoy or “P-train”
- Ongoing work on main element: L-band SAR satellite companion to Sentinel-1 enabling L+C dual-frequency SAR (spin-off: many products for other non-polar/cryo sectors)

Sentinel-1 A+B	P-train Main element L-Band SAR	P-Train Secondary Passive C-band SAR	P-Train Secondary Ku-band SAR
Sea Ice daily Extent Concentration Type Thickness (coarse; only altimetry measures it directly) drift	**Full Sea Ice daily** +Meltponds +Iceberg ~~drift~~ (improved detection) +Ridges, structure	**3D Ice mapping** +Topography +Fine structure +Edges *+Motion (along-track)*	**Snow Cover** +Snow Water Equivalent (TBC) ~~+Snowmelt~~ (requirements met by S-1?)

(table includes minor edits from Polaris output)

Bistatic SAR Cryosphere Applications

- Interferometric
  - Sea ice topography (ice type)
  - Glacier topography
  - Dynamic topography of ice sheets/caps
  - Dynamic topography of permafrost regions
  - Digital Elevation Models
    - for rectification of all other image data
- Imaging
  - Ice motion/movement
  - Wave spectral information
  - Wind vectors
- 2D velocity measurements (2x LoS velocity)
  - Ocean currents
  - Sea ice motion

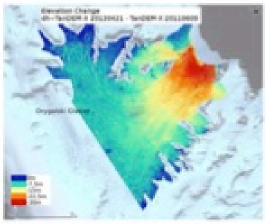
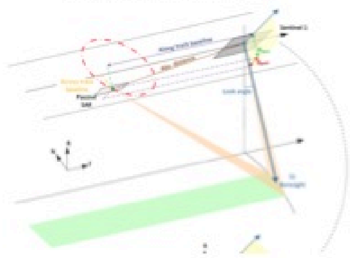


Figure 3-1. Surface Elevation change between 9 June 2011 and 21 April 2013 for Drygalski Glacier, Larsen Iceshelf, Antactic Peninsula, derived by DEM differencing using digital elevation models acquired by the TanDEM-X/TerraSAR-X formation.



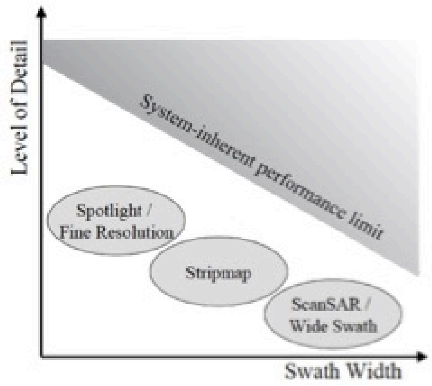
Bistatic SAR Activities

1. SAOCOM Companion Satellite (L-band)
    - Mission concept went through successful PDR
    - Detailed study of critical technology aspects for bistatic SAR (e.g. synchronisation)
    - Conclusion: technology readiness is very high (1/2 SAR instrument)
2. Sentinel-1 Companion Satellite (C-band)
    - "Swiss-knife" mission concept
        - Ocean currents
        - Ice classification
        - Ice topography

- Scientific readiness level: depends heavily on the application

High Resolution Wide Swath

- Coverage and Revisit are key requirements for sea ice applications
- Limitations of conventional SAR are overcome by HRWS systems
- Single system enabling
    - Wider coverage
    - Faster revisit
    - Finer resolution
- 4x Sentinel-1 resolution
- 2x Sentinel-1 coverage in polar areas



From the first generation to the new generation of SAR systems

High Resolution Wide Swath for Polar Applications

- Wide swath
  - Faster revisit without sacrificing resolution
  - Enables sub-daily revisit in the Arctic (with 2 sats)
  - Ice drift
    - Note: limitations due to geolocation accuracy will still apply
- Fully polarimetric
  - Better feature detection → automation of ice map generation
  - May enable some level of ice thickness measurements (experimental)
  - Trade-off with revisit time
- Spatial resolution
  - Smaller icebergs detection (~10 m from current 100 m)
  - Useful for ice deformation applications

High Resolution Wide Swath

Technology development activities

- Digital Beamforming to enable wide swath and high resolution in single system
  - Breadboarding of a single antenna tile on-going to demonstrate feasibility of critical components
- HRWS require higher peak RF power than current systems
  - GaN technology needed for transmit power generation
  - Breadboarding of GaN HPA and GaN Transmit/Receive Module

- Technology development timeline targeting Sentinel-1 second generation

Cluster 1: Maturity & Programmatics

- Both the technology maturity and the maturity of science an data products is very high for individual L-band and C-band missions
- Maturity of Ku-band SAR is low (technology + scientific)
- Maturity of combined multispectral SAR data products is not ready for operational use
- Technology maturity of bistatic SAR is high (TerraSAR-X)
- Scientific maturity (data processing) of bistatic SAR is mixed. Some applications have been demonstrated with T-X (e.g. dynamic topography)
- Technology evolving towards High Resolution Wide Swath

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Cluster 2: Ice monitoring – Sea ice parameters

Technology	Heritage missions	ESA activities
• Passive Microwave Radiometry (PMR) • Multi-frequency • Low-frequency	• Multi-frequency • MWI • AMSR-2 (JAXA) • Low-frequency • SMOS	• MIMR • MicroWat • SMOS+ Cryosphere • SMOS+ Sea Ice • ECMWF Data Assimilation Study • SMOS+ Follow-on

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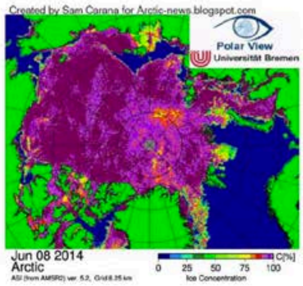
Passive Microwave Radiometry

- All-weather technique capable to observe many relevant parameters e.g. sea ice concentration, sea ice thickness, frost depth, snow parameters, storm tracking,..
- Backbone: long data record of passive microwave sea ice parameters (~37 y)
- Complemented by active sensors e.g. scatterometers (for operational products like sea ice drift from OSI SAF) or imaging SAR
- Typ. low resolution; supports other measurements (SST, near-surface wind)
- Europe will continue to contribute with suite of sensors of EUM polar missions e.g. on MetOp-SG: MicroWave Imager (MWI), Ice Cloud Imager (ICI), Scatterometer (SCA)
- Major gap at low-frequency (<~10 GHz)

Sea Ice Concentration (SIC) with PMR

- Most accurate retrievals at C-band
- Higher frequencies used because of spatial resolution
  - "bootstrap algorithm" to remove atmospheric disturbances
- Best Compromise is to have C-band + higher frequencies
- Still requires large antenna (>2m)
  - AMSR-2: 2m
  - MWI: 75cm
  - SSMI: ~65cm
- (sub-)daily coverage achieved with ultra-wide swath (~1500km)
  - Conical scanner concept



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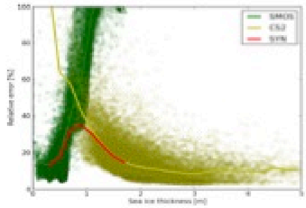
atmospheric disturbances

Low-frequency Passive Microwave

- **SMOS (Soil Moisture and Ocean Salinity) Earth Explorer**
  - L-band (1.4 GHz)
  - Salinity and Soil Moisture
    - Low sensitivity to salinity in polar regions (cold water)
- **Cryosphere applications**
  - Sea Ice (thin ice)
    - thickness
    - snow depth
  - Land Ice
    - internal ice temperature
    - bedrock topography
    - surface characteristics
  - Ice Shelves
    - ice temperature
    - marine ice
    - large iceberg tracking
  - Terrestrial Cryosphere
    - freeze / thaw state
    - snow density/ground permittivity
    - temperature gradient

SMOS-derived sea ice thickness for February and March (average). Credit: University of Hamburg



Cluster 2 Maturity & Programmatics

- L-band / SMOS
  - Full range of SRL, some products used operationally by CMEMS
  - SMOS mission extension to end EOEP-5 (2023)
  - Very high TRL (SMOS Earth Explorer), with technological enhancements
    - RFI mitigation (new on interferometric system)
- Multi-Frequency heritage in Europe
  - MIMR
    - EQM instrument developed in late 90's, requires study to assess state of the art with current technology
  - Microwat studies
  - MWI instrument on MetOp-SG
  - Long history of PM instruments
  - Main challenge in large conically scanning reflector antenna

Cluster 3: Ice/snow monitoring – Ice topography

Technology	Heritage missions	ESA activities
• altimetry • bistatic interferometric SAR	• CryoSat-2	• Concepts for Cost-Effective Enhanced CryoSat Continuity • Interferometric antennas at Ku and Ka band • Polaris - Polar Altimetry Platform • Arctic+: Improving observations and understanding of snow on Arctic sea ice • Arctic+: Towards a reconciled estimate of Arctic sea ice mass • STSE CryoTop (DEM from Swath processing) • CryoVEx campaigns

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Polar Ice and Sea Topography

Main objectives:

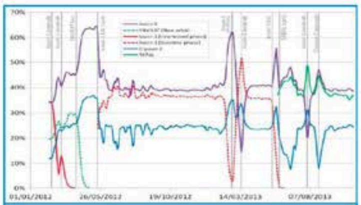
- Monitor climate change signals: ice cap melting and sea level rise
- Support monitoring Arctic sea ice and open ocean conditions
- Support applications related to coastal and inland waters
- Support Arctic policies for environmental protection, sustainable development and international cooperation, operational services

Required observations:

- Continuity of rate of change in ice elevation and ice thickness
- Snow depth and snow cover
- High-latitude ocean circulation
- Lakes, rivers, glaciers, and coastal water levels

Cryosat-2 unique capabilities:

- Observe multi-year ice with near-polar orbit
- High along-track resolution from SAR operation
- Interferometric capability to resolve POCA in across-track direction



In blue: relative contribution of CS-2 to sea level maps (source: GODAE OceanView)

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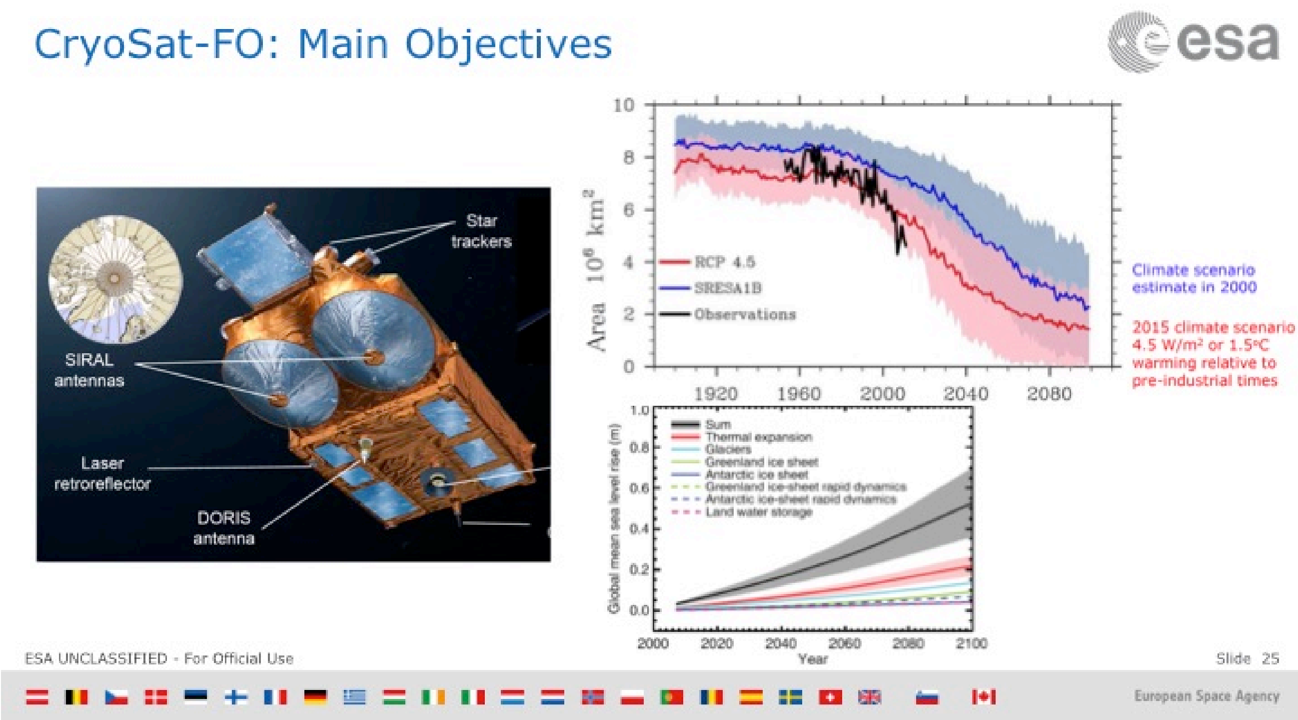
CryoSat-FO: Main Objectives
esa
Star trackers
SIRAL antennas
Laser retroreflector
DORIS antenna
Area 10⁶ km²
RCP 4.5
SRESA1B
Observations
Climate scenario estimate in 2000
2015 climate scenario 4.5 W/m² or 1.5°C warming relative to pre-industrial times
Global mean sea level rise (m)
Sum
Thermal expansion
Glaciers
Greenland ice sheet
Antarctic ice sheet
Greenland ice-sheet rapid dynamics
Antarctic ice-sheet rapid dynamics
Land water storage
Year
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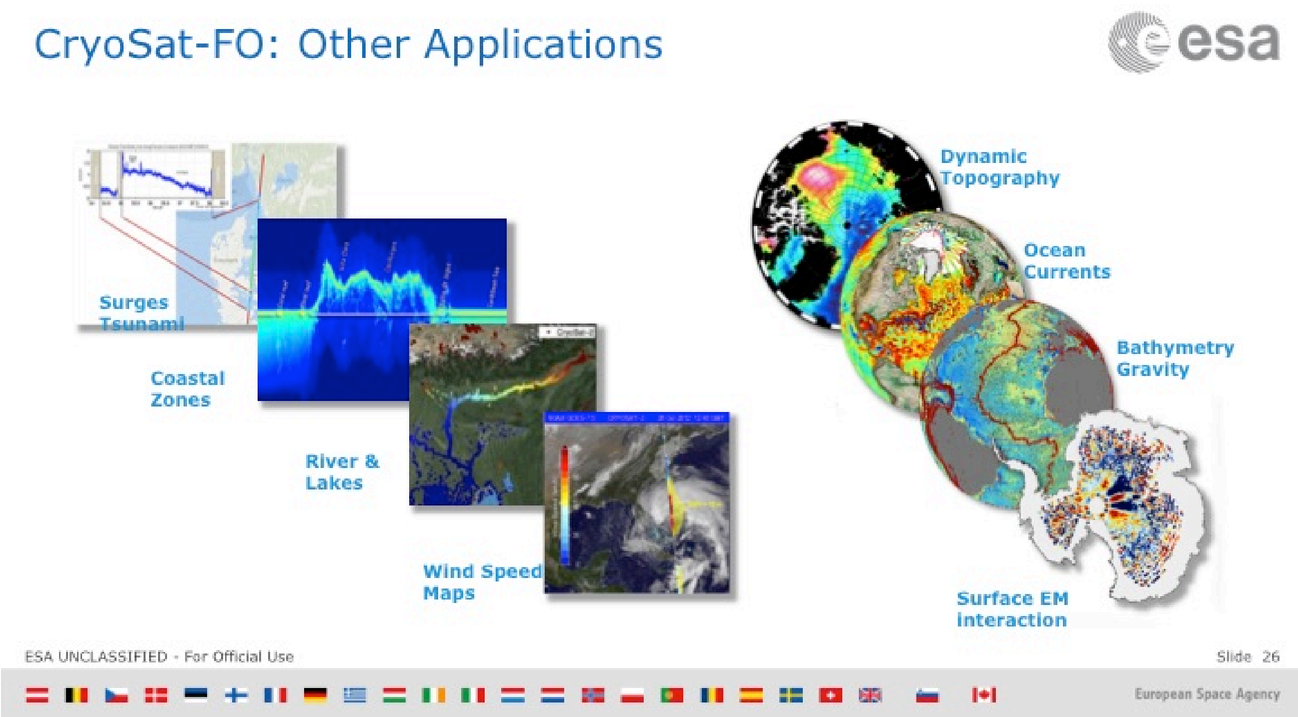
CryoSat-FO: Other Applications
esa
Surges Tsunami
Coastal Zones
River & Lakes
Wind Speed Maps
Dynamic Topography
Ocean Currents
Bathymetry Gravity
Surface EM interaction
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Enhanced Continuity

	Enhancement	Mission heritage	Applications/Benefits	Technology Enablers/Improvements
1	Optimisation of altimeter modes, continuous operation SAR(In), Interleaved mode	Poseidon-4 (Sent-6)	• Improved performance • Backwards compatibility with LRM data records	• Digital architecture → flexibility over waveform parameters, bands used
2	Higher spatial resolution	SIRAL (CryoSat-2)	• Enabling wider set of applications that require dense spatial sampling (e.g. glaciers in valleys)	• Swath processing mode • Larger bandwidth • Capacity improvement in data handling • Optimisation of instrument parameters
3	Addition of Ka-band channel	AltiKa Poseidon-4 (Sent-6) [GPM, OIB and Cryovex campaigns]	• Snow thickness • Improved ice thickness • Coupling ice-atmosphere • Glacier topography • Inland waters (lakes, rivers) • Ionospheric correction	• Ka band electronics (AltiKa) • Digital architecture (Poseidon-4) • Dual-band antenna
4	Dual- or tri-band radiometer	MWR (Sent-3) AMR-C (Sent-6)	• Ocean and coastal altimetry • Sea level rise (global) • Atmospheric correction in NRT products	
5	High resolution multi-frequency radiometer (as extension to 4)	MHS (MetOp) MWS (MetOp-SG)	• Coastal & inland altimetry • Glacier topography • Sea ice concentration • Snow cover and water content	
6	Improved On-Board Tracking	SIRAL (CryoSat-2)	• More observations over rough terrain (ice margins)	• On-board processing capabilities

Cluster 3 Maturity & Programmatics

- Technological maturity very high: CryoSat-2 Earth Explorer
- Technology advances are readily available to extend/improve current capability
- Same is true for maturity of science & data products (e.g. swath processing)
- Data products are available for operational use and already used for validation activities by existing Copernicus services (CMEMS)

- Note: LIDAR not included. ICESat-2 (NASA) demonstrator to be launched 2018.

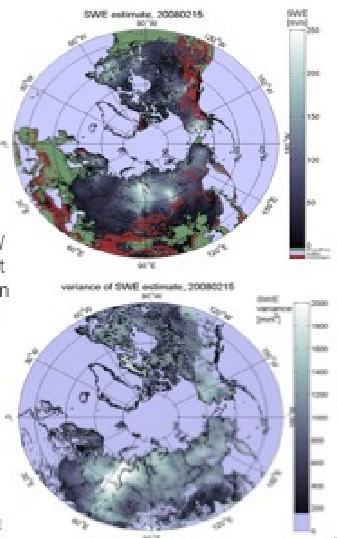
Cluster 4: Snow monitoring – terrestrial snow

Technology	Heritage missions	ESA activities
• Passive Microwave • SAR • IR radiometry		• SnowLab campaign • SCADAS • Microstructural origin of snow • SnowPEx • Scientific evaluation of mission concepts snow mass

Technologies for Mapping Snow Water Equivalent over Land

- The satellite passive microwave data record is long and robust.
- Significant progress in recent years has been made from innovative field campaigns, improved modeling (physical; emission), and new retrieval approaches.
- Global Snow Water Equivalent data sets are available **at coarse scale** (25 km resolution; time-series for 1979-today).
- The nature of the brightness temperature versus SWE relationship, combined with the characteristics of current spaceborne passive microwave measurements, means retrieval challenges remain:
    - regional variability in land cover, snow properties
    - temporal variability (snowpack evolution)
- While valuable for some climate and hydrological applications, the **current generation of satellite-derived SWE products are not suitable to address user needs in many applications and locations**.

GLOBSNOW SWE product over Northern Hemisphere: Greenland, glaciers & mountains masked out



Ref. for image: Takala et. al. doi: 10.1016/j.rse.20[illegible]

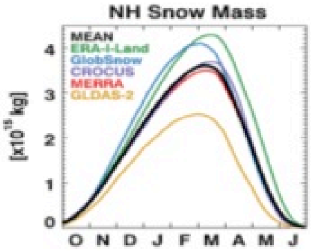
Status SWE and SE products

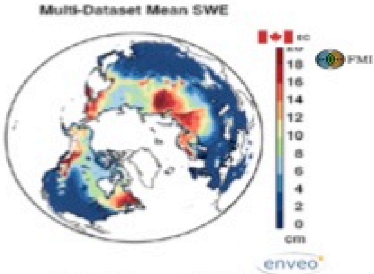
Main reasons for differences and errors in (satellite) SWE products:

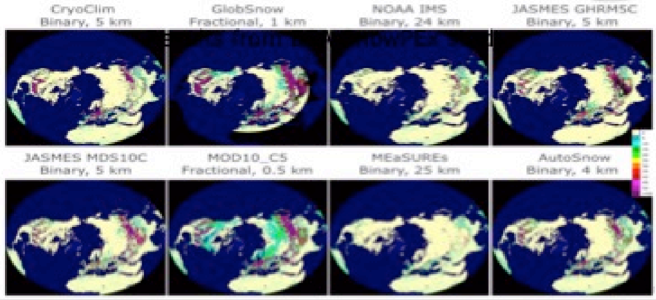
- Limited spatial resolution of satellite passive microwave measurements,
- Deep snow (passive microwave typically saturates at >120 mm SWE),
- Dense forest cover,
- Glaciers, mountains and all areas with some topography requiring higher resolution data

Main reasons for differences and errors in satellite snow extent products:

- Cloud cover,
- dense forest cover,
- and low solar elevation angle (due to topography and in winter months in high latitudes regions in general)
- temporal and spatial variations of snow albedo, and anisotropy of snow reflectance







Cluster 4 Maturity & Programmatics

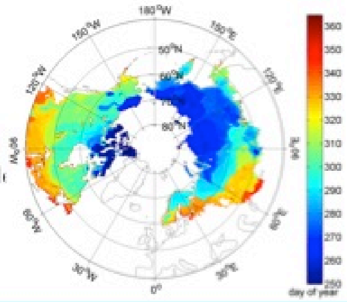
- Maturity of snow products from passive microwave data is very high, but they do not answer fully to the user needs
- Scientific maturity of snow retrievals from active microwave data is low
- Several activities ongoing related to investigating new mission concepts that in the future will demonstrate SWE and SE retrievals at the time/space scale required by operational users:
  - Following on from past CoReH$_2$O activities and other ideas
  - Scientific evaluation of mission concepts for snow mass and other cryospheric parameters
  - Canadian Space Agency Phase A study (Airbus UK): Terrestrial Snow Mass Mission (TSSM)
  - Demonstration mission will likely precede operational concept

Cluster 5: soil freeze/thaw state

Technology	Heritage missions	ESA activities
• Low-frequency passive microwave radiometry • SAR • bistatic interferometric SAR • Scatterometry	• SMOS • ASCAT	• DUE GlobPermafrost • SMOS+ Frost studies 1 and 2

Soil Freeze/Thaw & Permafrost

- **Soil Freeze/Thaw**
- Areas affected by soil freezing cover ~50% of Earth's landmass
- Information on soil freezing and thawing is important to forest industry (harvesters) and hydro power plants (river runoff)
- Possibility to acquire daily information on soil freeze/thaw state in global scale is verified using SMOS observations
- Currently only two demonstration L-band radiometry missions: SMOS (ESA) and SMAP (NASA)
- Additional information and better spatial resolution possible with combined use of L-band passive and C-band active instruments (e.g. Sentinel-1)
- **Permafrost**
- Cannot be observed directly
- Subsidence from dynamic topography (DEMs)
- Bistatic follower to S-1



Soil freeze onset date for year 2013, determined using SMOS-based soil freeze/thaw product

Cluster 5 Maturity & Programmatics

- Technology maturity: see comments regarding SMOS with Cluster 2
- Maturity of science and data products is moving from scientific use into operational use

Cluster 6: Pseudo-geosynchronous applications

Technology	Heritage missions	ESA activities
• Hosted Payload on Highly Ellipitcal Orbiting platform • Polar orbiting MetOp sats	• MSG (SEVIRI)	• Polaris - Hosted Arctic Imager

Highly Elliptical Orbit Mission

esa

- The HEO imaging mission is primarily a meteorological mission
- Next Generation geostationary satellites already show large consistency across imagery missions
    - Resolution, repeat cycle, channel selection
    - EUMETSAT MTG, CMA FY-4A, NOAA/JMA/KMA ABI/AHI/AKI
- Synergies with Highly Elliptical Orbits (HEO) are strongly requested by potential user communities
    - Instrument capabilities
    - Core channels to be the same as on the next generation geostationary satellites
- EUMETSAT is already collaborating with potential future HEO mission operators

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Highly Elliptical Orbit Mission

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- Basic data for weather and climate (and crucial for extreme events at mid-latitudes), but applications also for e.g. land and emergency management sensor
- SEVIRI on MSG has already demonstrated a lot of the capabilities becoming available on next generation GEO satellites: 12 channels, 3 km GSD, full disk imaging every 15 min
- Phase A study to start in 2017: update payload to FCI (MTG)

Images redacted

- atmospheric motion vectors
- aerosols
- land ice
- jet stream
- ozone
- sea surface temp
- Main advantage: high probability of cloud-free observations

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Cluster 6 Maturity & Programmatics

- Maturity of technology is very high with regards to instrument
- Hosted payload concept comes with specific programmatic constraints that will also influence timing and operational use
- Hosted payload concept also impacts interface requirements and resource constraints, and therefore on instrument maturity
- Highly elliptical orbit may also impact instrument and platform design
- Requires restartable launcher (Ariane 6)
- More studies required to investigate technical maturity, complexity and cost
    - Phase A planned
- Impact of ingesting this data on operational forecasting is expected to be significant. Does this require further study/demonstration?

Cluster 7: Mass transport

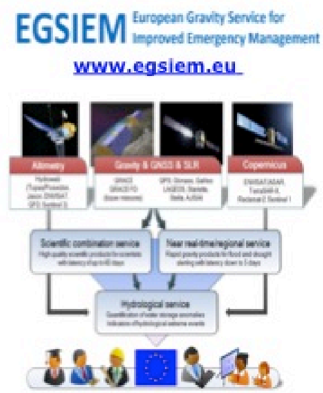
Technology	Heritage missions	ESA activities
• Gravimetry	• GOCE • GRACE (TPM)	• Next Generation Gravity Mission (NGGM) studies

Spatial and temporal scales associated with gravity changes relevant to cryosphere

Cross-cutting: mass transport is an integrated signal that is influenced by dynamics of water, snow,…

Signal	Time scales	Expected signals: temporal variation in equivalent water height (EWH)	Spatial scale
Changing ice flow dynamics of ice sheets	Long-term	10 m/year 10 cm/year	10 km 500 km
	Monthly to interannual	10 m 10 cm	10 km 500 km
	Daily to weekly	10 m	10 km
Changing SMB of ice sheets	Long-term	2 m/year 20 cm/year	50 km 1000 km
	Seasonal and interannual	2 m 20 cm	50 km 1000 km
	Daily to weekly	1 m 20 cm	10 km 1000 km
Supraglacial, englacial, and subglacial hydrology of ice sheets	Seasonal and interannual	5 m 50 cm	10 km 200 km
	Daily to weekly	10 m	10 km
Glacier mass changes	Long-term	10 m/year 1 m/year	10 km 200 km
	Monthly to interannual	10 m 1 m	10 km 200 km
	Daily to weekly	1 m 10 cm	10 km 50 km
GIA (as a disturbing signal for ice mass balance estimates)	Long-term	5 cm/year 1 cm/year	100 km 1000 km

Source: Pail, R. et al, DOI 10.1007/s10712-015-9348-9



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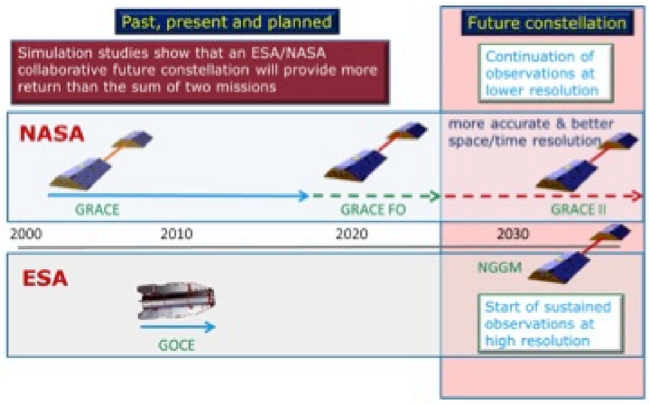
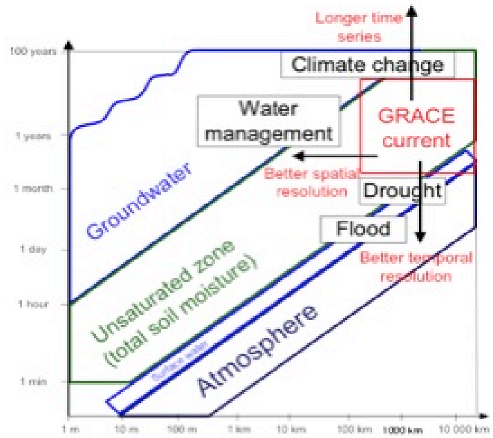
Past, present and "near" future: ideas to meet community science and application needs?





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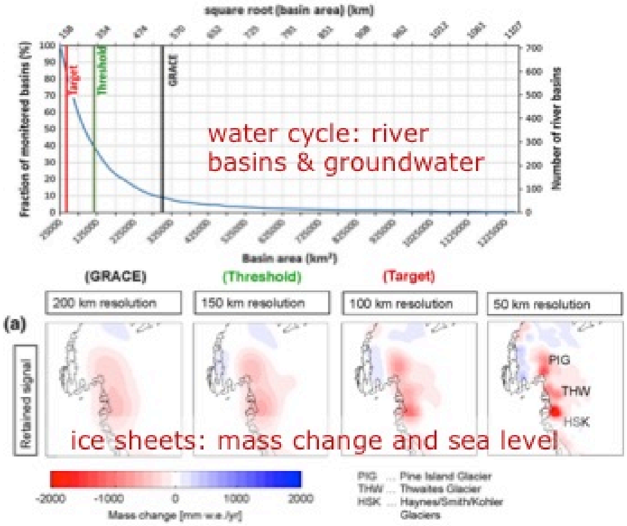
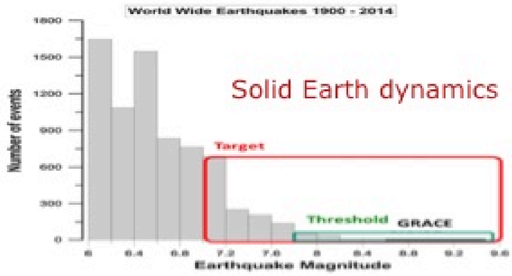
Potential of a future mass transport constellation with some examples

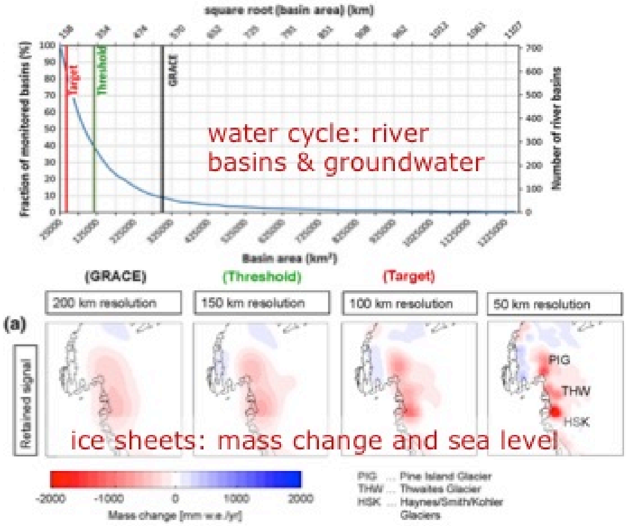


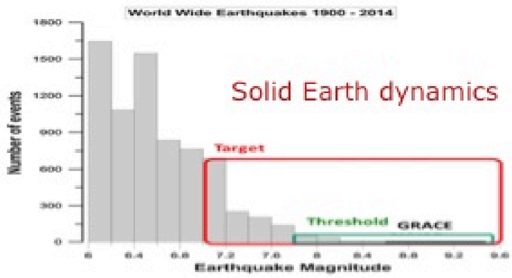


Cluster 7 Maturity & Programmatics

- Technological maturity very high due to GRACE demonstrator mission and GRACE Follow-On mission (currently being completed)
- User community developing a service under H2020 based on GRACE data
- Next step is to fly 2 pairs of satellites, requiring inter-agency/governmental collaboration

Potential of a future mass transport constellation with some examples





Cluster 7 Maturity & Programmatics

- Technological maturity very high due to GRACE demonstrator mission and GRACE Follow-On mission (currently being completed)
- User community developing a service under H2020 based on GRACE data
- Next step is to fly 2 pairs of satellites, requiring inter-agency/governmental collaboration

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