European Commission

USER REQUIREMENTS FOR A COPERNICUS POLAR OBSERVING SYSTEM

PHASE 3 REPORT – TOWARDS OPERATIONAL PRODUCTS AND SERVICES

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DEFIS

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PHASE 3 REPORT – TOWARDS OPERATIONAL PRODUCTS AND SERVICES

EN 2021

FOREWORD

Copernicus is a world leader in providing Earth Observation (EO) space data and information to user communities worldwide, based on state-of-the-art space technologies and world-leading expertise. The output information is channelled through the Copernicus Services and tailored to the needs of policy makers to help them understand the continuous changes to our environment.

With Arctic air temperatures rising twice as fast as global temperatures, the importance of EO data and information to understand both long and short-term environmental changes in the Arctic is clear. Arctic populations are being faced with new challenges. For example indigenous people need to plan safe journeys for their migrating herds. At the same time, new opportunities are being created for the shipping industry with the Northern Sea Route becoming increasingly ice-free during summer.

Copernicus currently has eight operational satellites, known as the Sentinels, which measure and acquire large amounts of data over most of the polar areas. This is then translated into a broad range of actionable information by the Copernicus Services. Nevertheless, Copernicus remains partially reliant on third-party satellite missions to complement the Sentinels, essentially exploiting research satellites via international data exchange agreements. However, this way of operating is mainly based on a best-effort approach and not sufficiently reliable for operational services. Indeed, many users in the downstream and research sectors have expressed significant concern regarding the lack of continuity of some crucial third-party missions, and have reiterated their need for reliable solutions to support their activities.

Over the last few years, the Commission has carried out various initiatives to capture EO needs for data and value-added services related to the polar regions. The Copernicus Polar Expert Group's work, in particular, has made an important contribution to the Copernicus programme. It has not only ensured that the requirements of the user communities in the Arctic are understood. It has also laid the groundwork for defining an operational Copernicus Polar Observing System, based both on space-based and in-situ observing assets, that is best suited to support the fight against climate change. And importantly, it places the EU and the European space sector at the heart of this fight. This has also helped define potential new satellite missions relevant to the Arctic. ESA is currently assessing six new satellite missions, of which three could have a clear added value for the Arctic. The decision on which missions will be selected will be taken later in 2021.

The current Copernicus polar activities and planned enhanced EO capabilities are crucial for understanding the impact of climate change in the Arctic, Antarctica and Greenland. They also serve the EU's political priorities. I refer to the call for the EU to support the fight against climate change in the EU's Arctic Policy ("An integrated European Union Policy for the Arctic" 2016) and in the Council of the European Union's conclusions ("Space solutions for a sustainable Arctic" of November 2019). The importance of the Polar Regions in Europe was reaffirmed at the highest political level with the announcement of the European Green Deal and the European Climate Pact adopted in 2020 by the Council. The Arctic Policy's relevance was also reiterated in President von der Leyen's State of the Union address of 2020, and was spelled out in the 2021 Commission Work Programme under the thematic pillar "A stronger Europe in the world". The case is therefore clear for ensuring that the EU, through its space programme, takes all necessary steps to deliver space services that meet the needs of user communities in the polar regions. It will also help the EU to support scientific endeavours, which are of fundamental importance to improve the observation of the environment in these remote regions, and have far-reaching implications for all of Europe, the world and indeed for life as we know it.

The findings in this report are timely and well elaborated based on useful intelligence gathered from the Copernicus entrusted entities. This material provides an overview of key elements for a long-term operational Copernicus Polar Observing System and is highly valuable for upcoming programmatic decisions of Copernicus.

Matthias Petschke

EXECUTIVE SUMMARY

POLAR EXPERT GROUP (PEG) III REPORT

Monitoring the rapid changes of the Arctic environment and polar regions in general (including Greenland and Antarctica), is a high priority for the EU, as spelled out in the EU Space Programme entering into force in 2021. The assessment of the socio-economic consequences of this evolution is highlighted as a priority in the Council conclusions on "Space solutions for a sustainable Arctic[1]" from November 2019 and, more recently, in the European Green Deal which further highlights the geopolitical dimension of the Arctic and the need for an integrated European Union Policy for the Polar regions.

It is unanimously recognised that space-based observations are essential tools to collect and provide continuous observations of this sensitive and harsh environment, as basis, both, for reliable operational services and for climate- and environmental modelling and forecasting.

The Copernicus programme, with today eight operational Sentinels satellites in orbit and complemented by European and other third-party Earth Observation missions, serves and encompasses key operational services for the polar regions. This high global and EU interest for the Arctic, combined with evolving user needs, was a strong incentive for the Commission to regularly assess the needs and requirements for space assets and applications.

POLAR EXPERT GROUP I AND II

In 2017, the European Commission set up two rounds of a Polar Expert Group (PEG) to define requirements for a Polar mission and its observation priorities. The first PEG was composed of representatives of national operational agencies and of Copernicus services and was complemented by staff from ESA and EUMETSAT in PEG II. The first report[2] identified the critical variables to be observed in polar areas namely floating ice, glaciers, caps and ice sheets, sea level, sea surface temperature, surface albedo, surface fresh water, snow and permafrost.

The second report[3] of the PEG recommended, as a priority, a further set of microwave instrumentation, providing day-and-night and near all-weather observations, to best complement the existing Sentinels so as to meet the user requirements. This microwave instrumentation included a Passive Microwave Radiometer (PMR), an advanced SAR interferometric Altimeter and a Single Pass Interferometric Synthetic Aperture Radar (SP-InSAR). Out of the three types of instrumentation, the imaging PMR was recommended as the most promising solution to meet the observation requirements for the priority variables.

EVOLUTION OF THE COPERNICUS SPACE COMPONENT AND PLANS

Consultations between the European Commission, ESA and EUMETSAT, all three working on the evolution of the Copernicus Space Component (CSC), concluded that, in order to meet emerging needs of users, additional High Priority Candidate Missions (HPCM), also called Expansion Missions, with planned launch in the 2026-2028 timeframe prior to the Next Generation of Sentinels planned for the 2030s. Six HPCMs have been identified including three microwave ones which would complement the existing Sentinels. The HPCMs are subject to change based on a joint decision between the Commission and ESA foreseen to take place in the second half of 2021.

1 CMEMS: Copernicus Marine Environement Monitoring Service; C3S: Copernicus Climate Change Service
CLMS: Copernicus Land Monitoring Service; CMS: Copernicus Maritime service; CEMS Copernicus Emergency Monitoring service; CAMS: Copernicus Atmospheric Monitoring Service.

2 https://op.europa.eu/en/publication-detail/-/publication/3682b-fb3-946b-11e8-8bc1-01aa75ed71a1/language-en/format-PDF/source-search

3 https://op.europa.eu/en/publication-detail/-/publication/25ed00e2-946f-11e8-8bc1-01aa75ed71a1/language-en

To monitor polar regions three HPCMs were identified as most relevant:

- the Copernicus Imaging Microwave Radiometer (CIMR) mission;
- the Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) mission;
- the Radar Observing System for Europe at L-band (ROSE-L) mission.

Since then, detailed definition industrial studies, led by ESA, were initiated in 2018-19 (Preliminary Requirements Review and System Requirements Review[4]) and are still in progress (Preliminary Design Review[5]) with a key decision milestone to proceed to the full development and manufacturing by end 2021. To support these industrial activities, groups of external experts (Mission Advisory Group) were set up and, together with the European Commission, provided Mission Requirement Documents (MRDs) used for these industrial activities.

POLAR EXPERT GROUP III

In 2020, DG DEFIS decided to pursue the PEG activities (with the so-called PEG III) with European and Canadian experts supported by ESA, EUMETSAT, EEA and a major H2020 on-going project, KEPLER (Key Environmental monitoring for Polar Latitudes and European Readiness). This report is the result of six iterations between the Polar Expert Group members throughout the period of July to December 2020/ January 2021.

The scope of the PEG III was to follow-up on the requirements of the previous Polar Expert Groups as well as the requirements of Copernicus services for data from microwave instrumentation[6], with day-and-night and near all-weather[7] observation capability. The assumption is that the Copernicus Space Component will continue to rely on day-and-night and near-all-weather observation capabilities for operational monitoring of the changes in the polar regions. The review and analyses focused also on the complementarity and synergies between the existing Sentinels (mainly Sentinel-1, -3) and the CIMR, CRISTAL and ROSE-L missions, but also on gaps and how to potentially fill these with other data such as third-party missions and/or Sentinels Next Generation.

The generation of detailed and up to date tables describing the existing Copernicus products as well an updated list of PEG observation requirements from all Copernicus services (except CAMS[8]). The observation requirements were expressed in terms of geographical coverage, horizontal resolution, repeat frequency, accuracy (or uncertainty) and data latency. The observation requirements were compared to the specifications of the three microwave HPCMs. This mapping of the requirement compliance per mission made it evident that there is no single mission that can fulfil all PEG observation requirements. Important differences are resulting from the limited duty cycles and geographical coverage/revisit frequencies for SAR instruments on-board S-1 and ROSE-L as opposed to the continuous operation capability (100% duty cycle) of CIMR and CRISTAL. Furthermore, CIMR with a wide swath can provide pan-polar coverage on a daily/sub-daily basis, but at a much lower horizontal resolution compared to ROSE-L and Sentinel-1. The two C- and L-band SAR instruments have narrower swaths and in need of observation planning and trade-off between frequent acquisition of the same targets and extension of acquisition surface coverage. CRISTAL is providing continuous monitoring, but restricted by the ground track location and choice of orbit.

The strengths of the Polar HPCM are not only their uniqueness, but more importantly their complementarity to one another and with the existing Sentinels. The synergies and cross instrument requirements are therefore important for monitoring the polar regions. The geophysical variables addressed by PEG III were therefore compared with the combinations of instruments (Sentinels, third-party missions, HPCMs and Next-Generation Sentinels) needed over time with the year 2020 as a baseline followed by the time period 2021-2027, and the period beyond 2027.

In 2020, third-party PMR - and altimeter data (equivalent to CIMR and CRISTAL) were extensively used by the Copernicus Services (mainly CMEMS, C3S and CLMS) and it is important to ensure continuous provision of these data. CIMR as a response to the PEG II report goes further with instruments allowing multi-frequencies[9]

4 https://artes.esa.int/sites/default/files/ESSB-HB-E-002-Issue1%2821August2013%29.pdf
5 Ibid
6 Some of the requirements might be partially fulfilled by using other sensors and in that case, these are also described
7 Near-all-weather: the precipitation rate impacts effective measurements using Passive Microwave Radiometer instruments.
8 Although CAMS plays an important role in producing value-added products with relevance to the EU Arctic Policy, the various satellite observations of atmospheric composition that the service requires fall outside the range of geophysical variables addressed by the PEG requirements as the main focus is on the microwave instrumentation.
9 C-band (6.9 GHz), X-band (10.6 GHz), Ku-band (18.7 GHz), Ka-band (36.5 GHz), W-band (89 GHz).

as Advanced Microwave Scanning Radiometer (AMSR), but also including additional L-band data as currently provided by ESA Soil Moisture and Ocean Salinity (SMOS) and NASA Soil Moisture Active Passive (SMAP). CIMR is consequently the microwave mission among the Sentinel Expansion Missions that addresses the priority user requirements, as defined in PEG I and II, and can contribute to the highest number of PEG III variables. CRISTAL ensures the continuity of the ESA CryoSat-2 mission (radar altimeter launched in 2010) and NASA ICESat-2 mission (laser altimeter launched in 2018 with a design lifetime of three years) currently used by the Copernicus Services.

Data from CIMR and CRISTAL will be easily integrated in the work of the Copernicus Services. Copernicus currently relies on data from third-party missions to cover the provision of these data and the uncertainty of data availability is addressed as potential gaps for the future. These gaps will impact the following Copernicus products:

- PMR (L-band): Thin sea ice (sea ice thickness < 0.5 meter), sea surface salinity, soil moisture;
- Altimeter (north of 81.5 North/south of 81.5 South): sea ice thickness (> 0.5 meter), sea level anomaly, surface elevation change;
- PMR frequencies covered by AMSR-2 and the follow-up AMSR-3 is planned to be launched in 2023 with a projected lifetime to 2028 (no confirmed plans beyond 2028).

L-band SAR missions were not used by the services in 2020, as operational data were not available for the Copernicus Services, but there is an expressed interest of the Copernicus Services to test these in combination with Sentinel-1. The PEG identified capabilities of L-band SAR also in combination with Sentinel-1 C-band SAR for potentially improving Copernicus Services (identifying the potential improvement of current products and the generation of new products). This is at an early stage and it is currently unclear to what degree this will strengthen Copernicus as a whole, but there is a strong interest from Ice Services to further explore the potentials of combining C- and L-band SAR for precise sea ice mapping.

The identification, through numerous computer simulations of mission combinations, of a preferred orbit configuration scenario involving 3 Sentinel S-1 operating on the same orbit, adequately phased (equally spaced at 0°, 120° and 240 °) together with the 3 Expansion missions. Such a scenario would provide a sub-daily coverage of required geographical areas (e.g. Arctic Ocean, Greenland) and possibility for collocated SAR observations between S-1 and ROSE-L. The complementary SAR coverage could be provided by the Canadian Radarsat constellation.

The confirmation that the ESA multi-mission payload data ground segment architecture will be able to accommodate the additional Expansion missions and develop and integrate the associated new or enhanced mission-specific elements (e.g., processors up to level 1 and 2, dissemination mechanisms, operation planning).

A review, with the support of EEA and the on-going KEPLER project, of the status of in situ data collection platforms in the Arctic. This review identified current gaps and confirmed the need to improve the present situation by increasing the number and quality of platforms and by establishing a closer cooperation and coordination between polar research groups.

As addressed by the KEPLER project, when addressing latency in the sparsely populated polar regions, it is important to consider the time to the users and not to the ground station. Further attention should therefore be paid to the situation of telecommunications in polar regions in order to meet the stringent data delivery and latency requirements (NRT and QRT) of the users.

The report spelled also out ten recommendations for the future activities partially included in the terms of reference for Polar Task Force activities in 2021.

PEG III MAIN RECOMMENDATIONS

- Ensure the long-term continuity of space-based (Sentinels, Expansion missions) and in situ observations as essential pre-requisite to continuously improve Copernicus services and products. This is particularly important for Passive Microwave Radiometer data as well as Radar Altimeter data;
- Further develop the use of Expansion missions in synergy with existing and forthcoming Sentinels to improve existing polar products and generate new innovative polar products;
- Support improvements and of quality and accuracy of existing products; support the generation of additional products required by users and not achievable today;
- Establish an efficient data management system for the in-situ observations in order to improve data accessibility and quality (e.g. formats, standards);
- International cooperation and coordination are strongly recommended with European and non-European organisations (e.g. Japan, China, Korea, Canada, USA, Russia) operating in the Arctic;
- Further continue to develop an end-to-end integrated Polar monitoring system considering and optimising the "complete chain" from space and in situ observations over services up to delivery of appropriate products meeting requirements of intermediate and end-users;
- Ensure the development of synergy-products within Copernicus Services combining the data from different missions to achieve the full benefit
- Continue and further expand user's consultation activities in particular with the private sector and companies;
- Explore and expand the role of industry and, more generally, of private sector for the development, procurement and operation of space systems (tailored micro/nanosatellites developed by SMEs) and services (IT industry, AI sector);
- Ensure continuity of underlying scientific research mandatory for the development of new products, of advanced assimilation techniques and modelling through identification of associated funding sources;
- Ensure the international cooperation need for this global context;
- Further attention should be paid to the situation of telecommunications in polar regions in order to meet the stringent data delivery and latency requirements (NRT/QRT) of user.

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The report is a product based on important contributions from:

- KEPLER Project
- ESA (ESRIN and ESTEC)
- EUMETSAT
- Copernicus in-situ component
- Copernicus Services

TABLE OF CONTENT

LIST OF ACRONYMS

AATSR	Advanced Along Track Scanning Radiometer
ATSR	Along Track Scanning Radiometer
ALOS-PALSAR-2	Advanced Land Observing Satellite- L Band SAR (of JAXA)
AVHRR	Advanced Very High Resolution Radiometer (of NOAA)
BGC	BioGeoChemical
CDR	Climate Data Record
CAMS	Copernicus Atmospheric Monitoring Service
C3S	Copernicus Climate Change Service
CMEMS	Copernicus Marine Environment Monitoring Service
CEMS	Copernicus Emergency Monitoring Service
CLMS	Copernicus Land Monitoring Service
CMS	Copernicus Maritime Service
CSC	Copernicus Space Component
CHIME	Copernicus Hyperspectral Imaging Mission
CIMR	Copernicus Imaging Microwave Radiometer
CO2M	Copernicus CO2 Monitoring Mission
CRISTAL	Copernicus polaR Ice and Snow Topography ALtimeter
COP 21	21st Conference of Parties held in Paris in 2015
CTD	Conductivity, Temperature, Depth sensor
DIAS	Copernicus Data and Information Access System
DINSAR	Differential Interferometry SAR
ECMWF	European Centre for Medium range Weather Forecasts
ECV	Essential Climate Variable
EEA	European Environment Agency
EMSA	European Maritime Safety Agency
EMODNET	European Marine Observation and Data Network
ERAS	C3S Reanalysis (of ECMWF)
ESA	European Space Agency
EUMETSAT	European organisation for the exploitation of Meteorological satellites
EUMETNET	Grouping of 31 European National Meteorological Services
EU-POLARNET	European Network for Polar research
GL	Grounding Line (ice sheet)
GMES	Global Monitoring for Environment and Security
HLOP	High Level Operation Plan
HPCM	Copernicus High Priority Candidate Mission
IOC	Intergovernmental Oceanographic Commission
INSTAC	In Situ Thematic Assembly Centre (of CMEMS)
INTAROS	Integrated Arctic Observation System
IV	Ice Velocity
JRC	Joint Research Centre
KEPLER PROJECT	Key Environmental monitoring for Polar Latitudes and European Readiness
LSTM	Land Surface Temperature Monitoring Mission
MAG	Mission Advisory Group
METOP	Meteorological Operational Satellite - Second Generation
MFC	Monitoring and Forecasting Centre
MRD	Mission Requirement Document
MSG	Meteosat Second Generation
NG	Next Generation (of Sentinels)
NISAR	NASA-ISRO Synthetic Aperture Radar (L+S-band SAR)

NILU	Norwegian Institute for Air Research
NRT	Near Real Time
OSI SAF	Ocean and Sea Ice Satellite Application Facility (of Eumetsat)
PDGS	Payload Data Ground Segment
PMR	Passive Microwave Radiometer
QRT	Quasi Real Time
RCM	Radarsat Constellation Mission
ROSE-L	Copernicus Radar Observing System for Europe at L-band
SAF	Satellite Application Facility (of Eumetsat)
SAR	Synthetic Aperture Radar
SEA DATA NET	Distributed Marine Observation Data Infrastructure
SEVIRI	Spinning Enhanced Visible and Infra-Red Imager
SIC	Sea Ice Concentration
SID	Sea Ice Drift
SIE	Sea Ice Extent
SITY	Sea Ice Type
SIT	Sea Ice Temperature
SIRAL	SAR Interferometer Radar Altimeter
SLSTR	S-3 Sentinel- Sea and Land Surface Temperature Radiometer
S3-OLCI	S-3 Sentinel - Ocean and Land Colour Instrument
SRAL	S-3 Sentinel Ku-Band radar Altimeter
SMMR	Scanning Multi-channel Microwave Radiometer
SSM/I	Special Sensor Microwave/Imager
SMOS	Soil Moisture and Ocean Surface Salinity mission (of ESA)
SP-INSAR	Single pass SAR Interferometry
SWH	Significant Wave Height
SWE	Snow Water Equivalent
SWOT	Surface Water Ocean Topography mission
TAC	Thematic Assembly Centre
VIIRS	Visible Infrared Imaging Radiometer
TERRASAR-X	German Earth-observation satellite (X-band SAR)
TPM	third-party mission
WMO	World Meteorological Organisation

FULL REPORT

1. INTRODUCTION

"The Arctic saw its lowest average October sea ice extent since satellite measurements began in 1979. October 2020 was the fourth consecutive month with ice-free or close to ice-free conditions along the Northern Sea Route. Meanwhile, the Antarctic saw a second month of above average extents, following 48 consecutive months of below average extent."

Sea ice cover for October 2020, Climate Bulletin, Copernicus Climate Change Service[1].

"Notably, during the six-year period between 2013 and 2019, the number of ships entering the Arctic Polar Code area grew by 25 percent. The total distance sailed by ships in this area grew by 75 percent, from 6.51 million nautical miles in 2013 to 9.5 million nautical miles in 2019."

Arctic Shipping Status Report, April 2020, Arctic Council's Protection of the Arctic Marine Environment Working Group[2].

1 Copernicus Climate Change Service (2020)
2 Arctic Council (2020)

1.1 EU ARCTIC AND SPACE POLICY

Copernicus is the EU's Earth Observation and monitoring programme and constitutes a key contribution to meet the objectives of the Union's strategy. It is a civil, user-driven and policy-driven programme under civil control, which builds on the existing national and European capacities and ensures continuity of its activities and achievements.

In the regulation for the EU Space Programme, entering into force in 2021, Polar monitoring is spelled out as a priority. This follows the line of the EU Arctic Policy from 2016[3] that describes the importance of space assets and Earth Observation to collect an evidence base to the monitoring of the rapid changes in the Arctic due to a changing climate. Given the remote and challenging conditions in the Arctic, evidence of change from Earth Observation is fundamental to the development, implementation and monitoring impact of the EU Arctic Policy. The Space Strategy[4] for Europe and the regulation[5] for the EU Space Programme acknowledge the importance of the Arctic and polar regions for the EU. At the same time the EU Arctic Policy acknowledges the importance of space assets as a whole, for communication connectivity, Earth Observation and Navigation in the Arctic (see Figure 1 illustrating the mutual developments). In order to better understand the existing and potential synergies between Copernicus, Galileo and GovSatcom, DG-JRC carried out a study in 2019[6]. The study highlighted the importance to satisfy the user needs for improved infrastructure and platforms across the EU Space Programme today and in the future. In addition, the study highlighted some possible synergies across the different components of the Space Programme.

Figure 1. Arctic policy and Space policy developments in the European Union

The high interest for the Arctic, combined with evolving user needs, is a strong incentive for the Commission to continuously assess needs and requirements for space assets and applications. This approach will continue to allow new services for the Arctic region, benefiting from the integration of space technologies with user-driven applications, services and equipment. This was also highlighted in the Council conclusions on "Space solutions for a sustainable Arctic[7]" from November 2019, which highlights the importance of space assets as enabler in the Arctic, not only combatting climate change, but also ensuring economically, socially and environmentally sustainable growth in this area.

3 EEAS, JOIN(2016) 21 final
4 COM(2016) 705 final
5 COM(2018) 447 final
6 European Commission, (2020), Karen Boniface et al. "Europe's Space capabilities for the benefit of the Arctic"
7 https://data.consilium.europa.eu/doc/document/ST-13996-2019-INIT/en/pdf

Better knowledge and understanding of changes in the Arctic and delivery of fit-for-purpose services that support the Arctic policy requires observing not only the Arctic Ocean, but also other geophysical variables important for the services benefitting the people in the Arctic. Council conclusions also stressed the importance of maintaining a complete overview and system architecture for monitoring the polar regions and providing added value services including the use of all kinds of space capabilities together with possible alternative sources of information or solutions. Research carried out in the framework of Horizon Europe and the evolution of the Copernicus services can therefore be important means to better serve EU Arctic policies and address key issues in the area. The Polar Expert Group III is making use of this research and development (R&D), as addressed in subsequent sections of this report.

In parallel, the EU Arctic Policy is being revised and an update is expected in November 2021. At the time of publishing this report, there have not been any indications of major changes to the three priority areas of the current EU Arctic Policy:

1. Climate Change and Safeguarding the Arctic Environment;
2. Sustainable Development in and around the Arctic;
3. International Cooperation on Arctic Issues.

Climate Change and the importance of international cooperation is equally important for the Antarctic. The impact of climate changes in the Arctic as well as Antarctic has global repercussions. For Copernicus as a global Earth Observation programme, it is therefore important that the Copernicus Sentinel Missions and the Copernicus Services are tailored to both polar regions, and to the Arctic specifically.

1.2 COPERNICUS POLAR ACTIVITIES IN RECENT YEARS

In 2017, the European Commission set up two rounds of a Polar Expert Group (PEG) to define requirements for a Polar mission and observation priorities. The first PEG was composed of representatives of national operational agencies and of Copernicus services and was complemented by staff from ESA and EUMETSAT in PEG II. The first report identifies the critical variables to be observed in polar areas (i.e. floating ice, glaciers, caps and ice sheets, sea level, sea surface temperature, surface albedo, surface fresh water, snow and permafrost). The second report of the PEG indicates that it would not be possible to rely on a single Copernicus High Priority Candidate Mission (HPCM also called Copernicus HPCMs), operated together with the current Copernicus Sentinels (and Copernicus Contributing Missions), that could meet all observation requirements of the critical variables. Consequently, the report focuses on a smaller number of top-operational-priority objectives as based on the inputs from the Polar experts. The priority variables addressed in the PEG II report are:

- Floating ice and in particular sea-ice concentration, the most important parameter for the climate service, for operational navigation and safe maritime operations in sea-ice infested waters;
- Ice sheets, glaciers/ice caps and seasonal 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.

PEG II supported by ESA and EUMETSAT space experts recommended the following microwave instrumentation to best complement the existing Sentinels so as to meet the user requirements:

- An Imaging Passive Microwave Multi-frequency Radiometer (PMR) with ~ 10 km resolution and with frequency channels for sea ice concentration (SIC) and sea surface temperature (SST) retrievals. A swath width that offers at least daily revisits in the polar regions is considered mandatory;
- An advanced SAR Interferometric altimeter (SARIn): A follow-on mission to CryoSat-2, specialised in nadir altimetry in polar regions;.
- A Single Pass Interferometric Synthetic Aperture Radar (SP-InSAR): A SAR that includes single pass interferometric capabilities as demonstrated with Tandem-X. Such capability could be implemented as a passive bistatic follower to Sentinel-1.

Out of the three types of instrumentation, PEG II recommended imaging PMR as the most promising solution to meet the observation requirements for the priority variables.

1.3 COPERNICUS SERVICES

The Copernicus Services play a key role in formulating the needs and requirements to be met by the Copernicus Space Component (CSC), presently and for its future evolution. The Copernicus Services consist of the following:

- Copernicus Atmosphere Monitoring Service (CAMS);
- Copernicus Climate Change Service (C3S);
- Copernicus Marine Environment Monitoring Service (CMEMS);
- Copernicus Land Monitoring Service (CLMS);
- Copernicus Emergency Management Service (CEMS);
- Copernicus Service for Security applications (Maritime, Boarder Surveillance, Copernicus Service in Support to EU External Action).

The Copernicus Services are active for the polar regions, providing relevant data and services to the Copernicus users. An overview of the current Copernicus inventory relevant for the Arctic can be found in Annex 1.

The Arctic Policy highlights the importance of limiting carbon dioxide (CO2) as well as short-lived climate pollutants such as black carbon and methane. CAMS is monitoring the short-lived pollutants and greenhouse gasses, and is preparing to monitor CO2 by making use of the planned Copernicus Carbon Dioxide CO2 Monitoring mission.

Other important aspects raised in the Arctic Policy that are being addressed by the Copernicus Services are:

- Climate change effects on the marine and terrestrial environment;
- Protecting the environment;
- Blue and Green economy;
- Enhanced safety at sea and navigation in the Arctic;
- Accident prevention and environmental control related to oil and gas activities.

The diversity of challenges is significant in the Arctic and so are the interrelations between the various aspects. Coordination between the Copernicus Services is crucial to have a better overall understanding of the challenges and this is an important part of the planned evolution of Copernicus.

1.4 SPACE INFRASTRUCTURE

The Copernicus Space Component (CSC) currently consists of six series of dedicated Earth Observation space-based missions either operational or under development, Sentinels -1 to -6, each series including two to four units to be launched in order to provide data continuity at least through to the mid-2030s. The Sentinels are complemented with Copernicus Contributing Missions (CCMs) making it possible for the Copernicus Services to access data from commercial or national missions.

The Sentinels operating radar, optical and altimetry instrumentation are designed to meet the needs of the Copernicus operational services in the field of environment and security. These services are based on the synergetic use of Sentinels and in-situ data. To date, eight Sentinel satellites have been launched including two Sentinel-1 platforms operating SAR sensors, two Sentinel-2 platforms with high resolution optical sensors, two Sentinel-3 platforms with both altimetry and optical instruments on-board one Sentinel-6 satellite with altimetry onboard, and one S-5 Precursor satellite for monitoring atmospheric parameters.

Consultations between the European Commission and the entrusted entities in charge of the CSC, i.e. ESA and EUMETSAT, have started to focus on the evolution of the CSC. In September 2020, ESA presented to its Programme Board for Earth Observation "The next phase of Copernicus - Copernicus Space Component (CSC) Long Term Scenario" providing a preliminary schematic overview of the CSC evolution to its Member States (see Figure 2). This evolution, on the one hand, aims at providing stability and continuity of current Sentinels with the preparation of the Next Generation missions to be launched in the 2030s and, on the other hand, aims at responding to emerging and urgent user needs with the so called Copernicus High Priority Candidate Missions (HPCMs). The six HPCMs are also known as the Sentinel Expansion missions as they are identified as new potential candidates with planned launches over the period 2025 to 2030.

Among these six candidates, and based on PEG II recommendations, three Copernicus HPCMs focused on microwave instrumentation, with day-and-night, and near-all-weather observation capability, have been identified as most relevant to monitor polar regions, namely:

- the Copernicus Imaging Microwave Radiometer (CIMR) mission;
- the Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) mission;
- the Radar Observing System for Europe at L-band (ROSE-L) mission.

The three other missions may also be relevant to observe parameters in the polar regions:

- Copernicus Anthropogenic CO2 Monitoring (CO2M);
- Copernicus Land Surface Temperature Monitoring (LSTM);
- Copernicus Hyperspectral Imaging Mission for the Environment (CHIME).

Figure 2 below illustrates the evolution of the Sentinel missions from the present generation to the next one, including the Expansion complement[8].

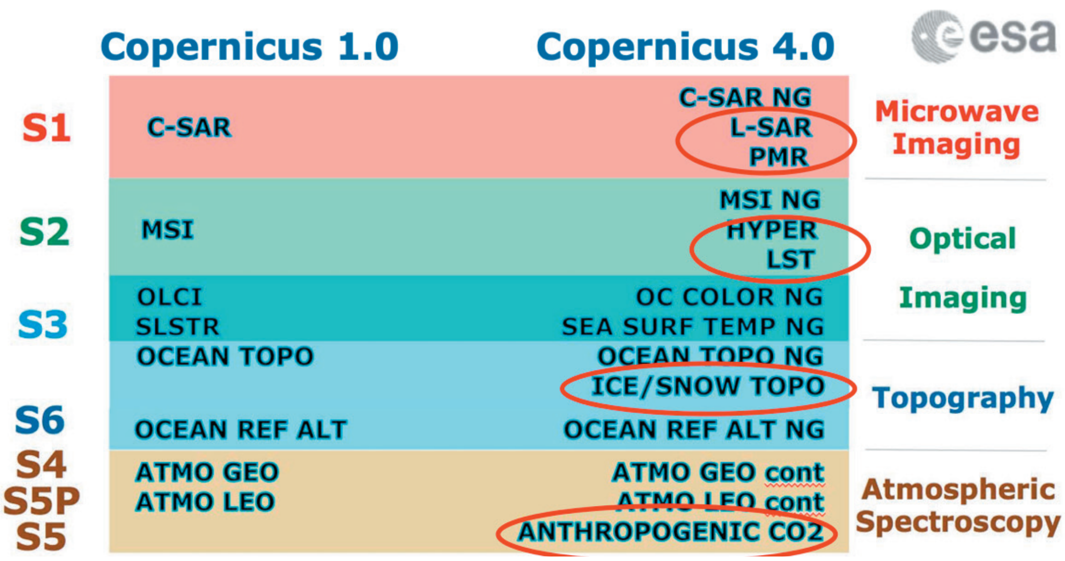


Figure 2. The evolution of the Sentinel missions

8 http://emits.sso.esa.int/emits-doc/ESTEC/News/ESACopernicusIndustryDaysPresentation.pdf

1.5 COPERNICUS HPCM ACTIVITIES

For each of the six Copernicus HPCMs, ESA established Mission Advisory Groups (MAG) mainly composed of experts from various European countries, but also from US, Australia. Japan and other countries.. The MAGs, with participation of the European Commission, supported ESA in issuing the respective Mission Requirement Documents (MRDs) used for the Phase A/B1 (Preliminary Requirements Review and System Requirements Review[9]) performed by industry. These Phase A/B1 studies were completed in mid-2019 and were followed by the preparation of ITTs for industrial Phase B2 (Preliminary Design Review[10]) and subsequent development activities. The negotiation and award of contracts to industry for the 6 HPCMs took place in the second half of 2020.

One should note that the technical specifications (MRDs) for the HPCMs have been settled and translated into System Requirement Documents (SRDs) for the industrial contracts. Therefore, the target[11] technical capabilities of the space component, consisting of the satellite platform, the instrumentation and the ground segment, can now be considered well understood thus allowing a more detailed feasibility assessment and planning of the exploitation capabilities.

Despite the fact that several technical decisions still remain to be taken, and a possible evolution in the timeline, it is now possible to improve the planning of the operations scenario in terms of:

- Orbit configuration of every Sentinel individually and relative to each other and even with respect to other contributing missions for optimizing the ground operations;
- Instrument and instrument-mode operations, where necessary, within the limits of the instrument duty cycle;
- Timeliness of data acquisition, data transmission to ground and processing up to level 1 or 2;
- It is now also possible to start discussions with operators of contributing missions to achieve the best potential synergy with their operations plans.

1.6 SATELLITE ASSET TIMELINE

Earth Observation (EO) activities are increasing globally and a high number of new EO satellites will be launched in the years to come. The fleet of Sentinels is also expanding and is expected to eventually increase from eight Sentinels today to possibly 20 sentinels in orbit in 10 years. This expansion requires a concerted effort for efficient operations and in the event that this is successfully achieved, there is a high potential for even further exploitation of synergies.

An overview of the envisaged Copernicus Space Component deployment schedule for the microwave and topography family, as presented by ESA in the Long-Term Scenario12 (from September 2020), is shown below. The ESA Long Term Scenario (LTS) includes the main elements of the Copernicus space component architecture, which is intended to meet expectations and needs in terms of stability and continuity while increasing the quantity and quality of products and services. The ESA LTS is updated regularly. The description of future Sentinel missions and their target deployment schedule is therefore subject to adjustments. The overview includes also satellite missions from other institutions (including research missions) or commercial actors (also known as Contributing missions or third-party missions - TPMs).

9 https://artes.esa.int/sites/default/files/ESSB-HB-E-002-Issue1%2821August2013%29.pdf
10 Ibid
11 The confirmation of effective capability will only be obtained at the Preliminary Design Review (PDR) or even Critical Design Review (CDR) stage

1.6.1 MICROWAVE FAMILY – EXISTING, PLANNED AND FUTURE MISSIONS

C-BAND SAR

Sentinel-1A and Sentinel-1B were launched in 2014 and 2016. The ESA LTS foresees launches of Sentinel-1C and Sentinel-1D in 2023 and during the period 2024-2027, respectively. Launches of Sentinel-1 NG-A and NG-B would then take place in the first half of the 2030's.

Current Third-party Missions with C-band SAR capabilities are Radarsat-2 launched in 2007 and Radarsat Constellation Mission launched in 2019. Radarsat-2 data is made available to the Copernicus Services as Contributing Mission data.

L-BAND SAR

The ESA LTS from September 2020 foresees a launch of ROSE-L A in 2028 and of ROSE-L B in 2030.

Current Third-party Missions with L-band SAR capabilities are ALOS-2 launched 2014 and the estimated lifetime is until 2024. ALOS-4 is planned for 2022 and with an estimated lifetime of seven years. The SAOCOM constellation is composed of SAOCOM 1A launched in 2018 and SAOCOM 1B with a planned launch in 2021. SAOCOM 2A and 2B are planned for later launches in 2023 and 2024. All SAOCOM have an estimated lifetime of 5 years. The NISAR has a projected launch in 2022 with a baseline mission duration of three years.

PASSIVE MICROWAVE RADIOMETER (PMR)

The ESA LTS (September 2020) foresees a launch of CIMR-A in 2029 and of CIMR-B in 2031.

Current Third-party Missions with PMR instruments used by the Copernicus Services are Advanced Microwave Scanning Radiometer (AMSR), Soil Moisture and Ocean Salinity, SMOS and Soil Moisture Active Passive (SMAP). AMSR is a multi-frequency radiometer covering the C-band (6,9 GHz), X-band (10,6 GHz), Ku-band (18,7 GHz), Ka-band (36,5 GHz) and W-band (89,0 GHz), while SMOS and SMAP are L-band (1,4 GHz) Passive Microwave Radiometer. AMSR-2 was launched in 2014 and the planned lifetime was three years, however AMSR-2 is still providing imagery. AMSR-3 is planned to be launched in 2023 and with an estimated lifetime of five years. SMOS was launched in 2009 with an initial nominal life time of tree years, however SMOS has been extended and is still providing imagery. SMAP was launched in 2015 with a nominal mission duration until 2018, the operations are extended through 2020, and preliminarily, through 2023.

1.6.2 TOPOGRAPHY FAMILY

Sentinel-3 is multi-instrument mission with SAR altimetry instrument on-board. Sentinel-3A and Sentinel-3B were launched in 2016 and 2018.

Sentinel-6 Michael Freilich was launched in 2020 with an expected operational lifetime of 5 years (7 years consumables).

According to the ESA LTS (September 2020), Sentinel-3C and Sentinel-3D are planned to be launched in 2024 and during the period 2025-2028, respectively, while Sentinel-3A NG TOPO and Sentinel-3B NG TOPO are planned to be launched in the first half of the 2030's. Sentinel-6B is planned to be launched in the 2025/2026 timeframe. Similarly, to the above NG families, the ESA LTS foresees launches of Sentinel-6A NG and Sentinel-6B NG in the first half of the 2030's.

The ESA LTS foresees launches of CRISTAL-A and CRISTAL-B in 2028 and 2030, respectively.

Current Third-party Missions with SAR altimetry instruments relevant for the Polar regions are Jason-3, Alti-Ka(SARAL), Cryosat-2, SWOT. Jason-3 was launched in 2016 and nominal operations were initially planned for three years, but extended with two years. AltiKa(SARAL) was launched in 2013, with planned lifetime of 5 years, however still providing imagery.

Cryosat-2 was launched in 2010 and has achieved the design lifetime goal of five and a half years, still providing imagery. HaiYang-2A (also known as HY-2A) was launched in 2011. SWOT is planned to be launched in 2022 and with data collection planned to work nominally for three years.

Current Third-party Missions with laser altimetry instruments. ICESAT-2 was launched in 2018 with a design life time of 3 years, and with consumables for a five-year lifetime (ICESat-1 was operated for 7 years).

1.7 HORIZON 2020 KEPLER PROJECT

The Horizon 2020 KEPLER (Key Environmental monitoring for Polar Latitudes and European Readiness) project is a multi-partner initiative (15 partners), built around the operational European Ice Services and Copernicus Services, to develop a roadmap for Copernicus to deliver an improved European capacity for monitoring and forecasting the polar regions. Its aim is to better respond to the information needs of polar region end-users and stakeholders in the 2020's. The KEPLER project, which started on 1 January 2019 will run until 31 March 2021. KEPLER is an EU Horizon 2020 Coordination and Support Action (CSA) with a budget of €2.9M. The project enabled a comprehensive assessment of:

- existing products and needs for future enhancements based on consultations with stakeholders;
- gaps of in-situ observations in order to improve polar regions monitoring and forecasting capabilities;
- new and novel in-situ and airborne observation sensors and techniques;
- research gaps in terms of space-based capabilities in order to improve the polar regions monitoring and forecasting;
- research gaps in terms of integration/assimilation of space-based and in-situ observations to fill gaps in order to improve polar regions monitoring and forecasting capabilities;
- a "Roadmap" for an "end-to-end" operational system for monitoring the Arctic is being developed.

The material produced by the KEPLER project has been used in the work of the PEG III and is referred to throughout this report.

1.8 THE SCOPE OF THIS REPORT

This report is the result of six iterations between the Polar Expert Group members throughout the period of July to December 2020. The group was supported by ESA, EUMETSAT, EEA and the H2020 KEPLER project. The Polar experts provided expertise in their various fields of work aiming at supporting the European Commission and its programmatic decisions in the years to come.

The scope of this report is to follow-up on the requirements of the previous Polar Expert Groups as well as the requirements of Copernicus services for data from microwave instrumentation, with day-and-night and near-all-weather[12] observation capability. Some of these requirements might be partially fulfilled by using other sensors and in that case, these are also described. The assumption is that the Copernicus Space Component will continue to rely on day-and-night and near-all-weather observation capabilities for monitoring the changes in the polar regions.

The requirements are mapped with corresponding EO space assets over time with the year 2020 as a baseline followed by the time period 2021-2027, the period beyond 2027 including the Copernicus HPCMs and the Next-Generation Sentinels.

12 nesr-all-weather: the precipitation rate impacts effective measurements using Passive Microwave Radiometer instruments.

The report also describes potential synergies across satellite missions, potential gaps, and the needs for non-space assets (in-situ data). The ground segment reflections are also highlighted in order to ensure that all components are well orchestrated in order to fulfil the stringent requirements.

The Polar Expert Group has also proposed objectives to be considered for a future Polar Task Force starting in 2021 with a main focus on the Copernicus Services. The Task Force will also further elaborate on the linkages to the other components in the European Space Programme, meaning the Galileo navigation system and telecommunication systems coordinated by GOVSATCOM.

2. PEG III USER REQUIREMENTS

In the PEG I and II a series of requirements was defined and prioritised. The conclusions of the two reports are considered to remain valid, however over the period 2017-2020 there has been a need to complement the requirements. The drivers to these modifications are changes in policy, outcome of research and the evolution of the Copernicus Services. The major drivers are:

- Policy changes with EU Council Conclusions on "Space solutions for a sustainable Arctic" ensuring economically, socially and environmentally sustainable growth in the area ;
- New evidence of changes in the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) by Intergovernmental Panel on Climate Change (IPCC)[13];
- The UN Sustainable Development Goals;
- Research H2020 projects such as KEPLER ;
- Evolution of the Copernicus Services as the Climate and Land Services are incorporating more products related to the Arctic;
- Copernicus Space segment evolution (Sentinels and third-party missions)?

The complete list of Polar Expert Group III observation requirements can be found in Annex 2 "Requirements and Space Assets" including new geophysical variables from the product list of the Copernicus Services (see Annex 1. "Copernicus inventory").

2.1 SERVICE REQUIREMENTS

The Copernicus end-users are supported by various intermediary users providing various value-adding services, and the intermediary users can be divided into two levels of services:

- The Copernicus core services, are pan-European or global generic services to address core users' needs (needs for public administration and EU agencies to implement, monitor and support policies);
- The downstream services provided by external parties like science, industry, international organisations, and national public authorities with non-policy oriented needs, which use either Sentinel data or Copernicus information products from services to create added-value. Some downstream services (e.g. national ice services) may create separate analysis products that both directly and indirectly feed into the Copernicus core services product catalogue.

The core services are funded by Copernicus, while the downstream services are not. A clear delineation process between the two is in place, protecting business development and national sovereignty and subsidiarity principles.

In terms of requirements, as core service providers, Copernicus services have to ensure at least the continuity of the current service in order to keep the same portfolio and the same level of quality of its products. Current downstream applications and services strongly rely on the continuity of the reference state provided by Copernicus core services' operational capacities.

13 IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, H.-O. Pörtner et al.

Reliable accuracy[14] and uncertainty[15] estimates are almost equally important as the measured quantity; this is particularly valid for the design and implementation of forecasting systems. Observed quantities have to be accompanied by comprehensive uncertainty estimates in order to be correctly interpreted and analysed.

These requirements are phased with future developments of the different core services and consider the gaps identified in the existing core services portfolio (from CMEMS, C3S, CLMS, CEMS, CAMS, CSS-CMS) provided for polar regions.

Space based EO already used in the services and for which continuity is planned in the future Sentinel constellation has a great chance for being implemented with little additional investment. New satellite measurements or improved satellite measurements based on new space technology will need R&D efforts in advance of the satellite mission launch.

Copernicus services monitor the Earth environment, including all polar areas. Even if a dedicated service is not foreseen for Antarctica and its realisation is challenging, space based EO data and information products should have the same quality and reliability in the southern polar regions as in the northern counterpart.

Each service expresses its requirements which are relevant for its own needs. However, there are some commonalities between services in terms not only of observation data (e.g. marine requirements for sea ice, waves and sea level may feed into the monitoring of coastal erosion) but also in terms of physical algorithm development (physical interaction between parameters), data assimilation techniques (statistical approach), product quality estimation (e.g. common or consistent metrics) and service and product calibration and validation (cal/val) approach and tools.

Particular attention will have to be provided in the future to the analysis of service/product cross-fertilization aspects in order to improve the overall benefits of Copernicus core services.

This report has not emphasized the potential cross-cutting opportunities across the Copernicus services.

2.1.1 COPERNICUS MARINE ENVIRONMENT MONITORING SERVICE (CMEMS)

CMEMS requires the near real time availability of high-quality satellite and in-situ data with sufficiently dense spatial and temporal sampling. These observations are required to constrain ocean models through data assimilation and to validate them. The quantity, quality and availability of data sets directly impact the quality of ocean analyses and forecasts and associated services. The service offers reprocessed observations data and reanalysis products to track the vital health signs of the ocean and to provide key reference information on the state of the ocean. The service covers a wide spectrum of spatial and temporal scales ranging from high-resolution all-weather capabilities information to large-scale continuous time series for downstream users' applications. CMEMS is in line with the previous PEG I and II reports and gives top priority for monitoring requirements to floating ice parameters: sea ice extent/concentration/thickness/type/drift velocity, thin sea-ice distribution, iceberg detection/volume change and drift. The main following geophysical variables are also required: sea surface temperature (SST), sea level anomaly, surface current, sea surface salinity (SSS), wave and directional wave spectra, improved geoid, surface wind and ocean colour (OC) which, together with SST and SSS, is essential to monitor and forecast the biogeochemical (BGC) state of the oceans and seas.

14 The closeness of the agreement between the result of a measurement and a true value of the measurand.

15 Non-negative parameter, associated with the result of a measurement, which characterises the dispersion of the values that could reasonably be attributed to the measurand.

2.1.2 COPERNICUS LAND MONITORING SERVICE (CLMS)

CLMS provides a portfolio of bio-geophysical products on the status and evolution of the land surface at global, European, and local scales at high, mid and low spatial resolution. Parameters relevant for polar regions include lake ice extent, lake water level, snow extent and snow water equivalent, soil moisture, seasonal subsidence, and land surface temperature. Some of these parameters are only provided for Europe or Northern Europe in CLMS.

Several of the CLMS products are provided at a high resolution, such as snow extent and condition (wet/dry snow), and ground motion and deformation for Europe. Several of the services are running in near real time which requires a timely availability of the EO data and accessibility by the geophysical processors to generate the products. Additionally, access to EO data archives with full mission life time data of Sentinels and Copernicus Contributing Missions for reprocessing of the products with advanced algorithms is needed.

CLMS also includes several variables related to the state of plants, such as leaf area index, which are based on reflective optical sensors and therefore not covered in this report.

2.1.3 COPERNICUS CLIMATE CHANGE SERVICE (C3S)

C3S provides homogeneous long climate data records for a broad range of Essential Climate Variable (ECV) products across the atmospheric, oceanic and terrestrial domains to support climate change assessments by the scientific community and the development of mitigation and adaptation strategies by policy makers and businesses. The current portfolio of C3S products relevant to the polar regions include air temperature, precipitation, parameters for floating ice (sea ice concentration, thickness, edge[16], and type), ice sheets (ice velocity, surface elevation change, mass balance), glaciers (outlines and ice velocity), ocean surface (sea surface temperature, sea level anomaly), as well as soil moisture. In addition, C3S applies data assimilation to combine observations from satellites and other instruments with numerical weather prediction models to produce global and regional climate reanalyses, which provide valuable information over the polar regions, especially for non- or ill-observed parameters.

To produce ECV data sets, C3S requires the timely availability of consistent and continuous time series of observations of polar regions with full coverage, fast and direct access to EO data archives of Sentinel data and third-party missions, computational resources to enable reprocessing of products with advanced algorithms and methods, as well as access to archives of reference data sets (e.g. in-situ data) for assessing the performance of the products. Although near real-time data availability is a lesser requirement for C3S than for other Copernicus Services such as CMEMS, the C3S reanalysis ERA5[17] is produced with a short delay (typically one day) behind real time and therefore requires the timely availability of certain ECV products used as boundary conditions (SST, sea ice concentration).

16 Sea ice edge (SIE) is a gridded classification of the ocean surface as one water, open ice, and closed ice corresponding to different ranges of estimates of sea ice concentration (SIC). As such, the climate requirements for SIE are closely aligned with those of SIC, which is why it has not been included in the list of PEG requirements. However, one should bear in mind that SIE is not just a mapping of SIC values to ocean surface classes. Although SIC data are used in the SIE classification algorithm (as training data), the algorithm converts satellite brightness temperatures directly to ocean surface classes without going through the intermediate step of generating SIC data.

17 ECMWF reanalysis avilable to users within 5 days

2.1.4 COPERNICUS MARITIME SURVEILLANCE SERVICE (CMS) OF THE COPERNICUS SECURITY SERVICE

CMS offers on-demand image products and value-added products based on two types of Earth Observation data namely radar (SAR) and optical satellite imagery.

CMS require SAR sensors providing all-weather, day and night imaging capability and optical sensors. Depending on the type of monitoring activity, and particularly for detection activities (vessel detection, feature detection, oil spill), different resolution classes is required for SAR and optical imagery varying from very high (VHR) and high (HR) to medium resolution (MR) imagery. Stringent data product latency (in the range of tens of minutes or less) are required for many of the CMS detection applications. The oil spill detection delivered by CMS extends the European CleanSeaNet service to other areas of interest beyond European waters.

2.1.5 COPERNICUS EMERGENCY MANAGEMENT SERVICE (CEMS)

The Copernicus Emergency Management Service (EMS) provides information for disaster management (prevention, preparedness, response and recovery activities). The Copernicus EMS is composed of (1) an on-demand mapping component including the provision of rapid maps for emergency response and risk & recovery maps for prevention and planning and (2) the early warning and monitoring component which includes systems for floods (European Flood Awareness System – Global Flood Awareness System), droughts (European Drought Observatory – Global Drought Observatory), and forest fires (European Forest Fire Information System – Global Wildfire Information System).

Depending on the type and the different phases of the disaster, CEMS requires a wide spectrum of satellite-based data ranging from meteorological weather satellite data to very/high/medium resolution radar (SAR) and optical (visible, infra-red) sensors. Stringent data product latency (in the range of tens of minutes) are required depending on the specific disaster phase considered.

2.1.6 COPERNICUS ATMOSPHERE MONITORING SERVICE (CAMS)

CAMS provides consistent and quality-controlled global information related to air pollution and health, solar energy, greenhouse gases and climate forcing. The service uses satellite and ground-based observations along with data assimilation and numerical weather prediction models to produce near-real-time analyses and forecasts of global atmospheric composition as well as multi-year global reanalyses of atmospheric composition.

Although CAMS plays an important role in producing value-added products with relevance to the EU Arctic Policy (as mentioned in Chapter 1), the various satellite observations of atmospheric composition that the service requires fall outside the range of geophysical variables addressed by the PEG requirements as the main focus is on the microwave instrumentation.

2.2 REQUIREMENTS FOR SPACE BASED EARTH OBSERVATION (EO) SYSTEMS

Space based EO systems for the polar regions are evolving over time. The continuous change of missions is challenging for the users and can lead to periods of gaps, where data is not available. Below follows an overview of microwave instrumentation, with "day-and-night, near-all-weather" EO capabilities over time for the Copernicus Services. However, the requirements that might partially be fulfilled by using other sensors are also described.

2020 is used as the baseline for the EO capabilities and is based on the data used for the Copernicus products (see Copernicus inventory in Annex 1). The evolution over time (2021-2027, Copernicus HPCMs, Next-Generation Sentinels) will consider contributions from the Polar Expert Group and with the participation of some of Copernicus Services also endorsed (CMEMS, C3S). The source behind the evolution over EO capability evolutions are described below.

2.2.1 COPERNICUS MARINE ENVIRONMENT MONITORING SERVICE (CMEMS)

2.2.1.1 EO DATA IN 2020

The oceanographic services currently make use of the Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) sensor for monitoring sea surface temperature (SST) and the Sentinel Ku-Band radar Altimeter (SRAL) sensor to monitor sea level anomaly (SLA).

Various other altimeter missions (Jason-3, HY-2, Saral/AltiKa, CryoSat-2) are used to complement Sentinel-3 data with altimeter data covering the poles. For monitoring SST, Advanced Very-High-Resolution Radiometer (AVHRR) data and C/X-band Passive Microwave Radiometer (PMR) data are used (predominately JAXA AMSR). L-band PMR is also used for sea surface salinity (SSS) with data from third-party missions ESA SMOS and NASA SMAP missions. In addition, the Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) is used for SST monitoring.

For floating ice, Sentinel-1 is used for sea ice concentration (SIC), sea ice drift (SID), ice type-ice stage of development, and icebergs. third-party data from the CryoSat-2 altimeter is used in combination with PMR data from SMOS for observing sea ice thickness (SIT). SIC makes use of several third-party missions providing PMR data (AMSR-2, SSMIS), scatterometer (ASCAT), and SAR data (Radarsat-2, TerraSAR-X, COSMO-SkyMed). For sea ice drift and ice type-ice stage of development Sentinel-1 is used in combination with third-party PMR data (AMSR-2 from Japan, SSMIS from US), and scatterometer data (ASCAT). For icebergs Sentinel-1 is used together with Radarsat data. For sea-ice surface temperature and for SST AVHRR data (VIIRS, MetOp-B) is used.

NB: In addition to CMEMS, as a support downstream Transport/Navigation services SAR and PMR data are supplemented by optical data from VIIRS, MODIS, Sentinel-3 Ocean and Land Colour Instrument (OLCI) and Sentinel-2.

2.2.1.2 EO DATA IN 2021-2027

According to the PEG and CMEMS, the most important changes to the baseline situation for the oceanographic services are the integration of Sentinel-6 replacing Jason-3, and extension of AMSR-3 with C- to W-band replacing AMSR-2[18]. The planned launch of AMSR-3 is 2023 with end of lifetime in 2028. No replacement is foreseen for L-band continuity to SMOS or SMAP research missions at this point in time.

For floating ice, there is an interest in three Sentinel-1 units in orbit and to be coordinated with the Radarsat Constellation Mission (RCM). As CryoSat-2 will retire, ICESat-2 can be an interim alternative until there is a CryoSat-2 follow-on. The change to AMSR-3 is also highly relevant for several floating ice variables. CMEMS is interested in access to data from third-party L-band SAR missions (e.g ALOS-4, SAOCOM and NISAR for Antarctica). ESA is exploring the possibilities for international cooperation for access to ALOS-4 and AMSR-3.

2.2.1.3 COPERNICUS HPCMS

According to the PEG and CMEMS, all three polar-focused HPCMs, namely CIMR, CRISTAL, and ROSE-L, are relevant for CMEMS and described in Annex 3. The use of similar sensors in 2020 and for the period 2021-2027 are:

The monitoring eight of ten of the floating ice and ocean variables (“marine requirements” in Annex 2. Requirements and Space Assets) is based on data from PMR sensors that can be provided by a mission such as CIMR in the future.

Four out of ten the floating ice and ocean variables (“marine requirements”) are based on data from altimeter sensors that can come from a mission such as CRISTAL in the future.

L-Band SAR is currently not used for the floating ice and ocean variables (“marine requirements”) as data have not been available, however this is likely to change in the period 2021-2027 with extended international cooperation.

Out of the ten variables only one variable has requirements that can be fulfilled by one stand-alone HPCM and that is sea level anomaly in the polar regions.

Sea ice thickness (SIT) and sea-ice concentration (SIC) are almost fulfilled, but for SIT and thin ice < 0.5m data need complementary data to CRISTAL will be required such as CIMR. CIMR fulfils the SIC requirements of the oceanographic services <5 km and daily pan-polar coverage, but will need complementary data with 20m resolution in order to fulfil the requirements of the Transport/Navigation services. This means that the horizontal resolution of the current Sentinel-1 constellation is not sufficient. Sentinel-1 is also not offering a daily pan-polar coverage.

These assessments are also valid for downstream ice services.

Other variables that need to operate together with other missions are described in Chapter 2.4.

See further elaborations by the Copernicus Service in Chapter 2.6 (HPCM considerations).

2.2.1.4 NEXT GENERATION SENTINELS

CMEMS requires the data from the following missions:

18 C-band (6.9 GHz), X-band (10.6 GHz), Ku-band (18.7 GHz), Ka-band (36.5 GHz), W-band (89 GHz)

- Next-Generation Sentinel-3 SRAL for sea ice thickness and sea level anomaly.;
- Next-Generation Sentinel-3 SLSTR for surface temperature over ocean and over ice;
- Next-Generation Sentinel-1 (sub-daily coverage) for sea-ice concentration, sea ice drift, ice type-ice stage of development and icebergs.

2.2.2 COPERNICUS LAND MONITORING SERVICE (CLMS)

2.2.2.1 EO DATA IN 2020

CLMS is currently using the following satellite missions:

- Sentinel-1 for producing the following products and services:
  - Soil moisture and the Ground Motion Service (for subsidence; currently being implemented);
  - Wet snow service for Europe (together with Sentinel-2 high resolution snow service).
- Sentinel-2 for high resolution snow extent in Europe.
- Sentinel-3 altimeter (SRAL) and radiometer (SLSTR) data is used for producing the following products:
  - Inland water level, inland water temperature[19], snow extent (by Jan. 2021).
- Third-party data from "day-and-night, all-year and near-all-weather missions" for the following variables soil water index (MetOp ASCAT), inland water level (Jason/Sentinel-6), snow cover extent (VIIRS, MODIS until December 2020, then Sentinel-3 SLSTR), snow water equivalent (SSMI), Lake Ice Extent[20] (by Jan 2021).

Other relevant data for covering the PEG geophysical variables can be found in the "Summary table, Annex 3".

2.2.2.2 EO DATA IN 2021-2027

According to the Polar Expert Group (PEG) it is relevant for CLMS to operate three Sentinel-1 units in orbit, and to be coordinated with the Radarsat Constellation Mission (RCM) in order to improve the frequency of repeat observations. The PEG also underlined the importance of L-band SAR data. Equally important is the use of new altimeter data from the Surface Water and Ocean Topography (SWOT) mission to monitor lake water level.

2.2.2.3 COPERNICUS HPCMS

CIMR, CRISTAL and ROSE-L, are all relevant for the CLMS polar related products. According to the Polar Expert Group (PEG) the following Copernicus HPCMs can provide important data for producing data products for CLMS:

- ROSE-L is relevant for producing high resolution soil moisture, lake ice extent, seasonal subsidence, snow water equivalent (high resolution; for complex terrain);
- CRISTAL is relevant for producing inland water level (lake water level);
- CIMR is relevant for producing low resolution soil moisture, land surface temperature, lake ice extent, snow water equivalent and snow extent (coarse resolution; flat terrain only).

In 2020 and in the period 2021-2027 PMR data will be used for producing snow water equivalent, soil moisture, land surface temperature. For the same time period altimeter data are being used to produce lake water level.

L-Band SAR is currently not used for the "land surface and surface fresh water" variables (see the Summary table in annex 3) as data have not been available. However, this is likely to change in the period 2021-2027 with more international cooperation (e.g. SAR sensors ALOS PALSAR-2, SAOCOM, NISAR).

19 Based on Sentinel-3 SLSTR data and not on "near-all-weather" instrument. Microwave measurements can potentially support.
20 Based on MODIS, Sentinel-3 SLSTR data is foreseen to be used in the future. SAR data can support.

Out of the five "land surface and surface freshwater" variables only one variable has requirements that can be fulfilled by one stand-alone Copernicus HPCM and that is land surface temperature.

Other variables that need to operate together with other missions are described in chapter 2.4.

2.2.2.4 NEXT GENERATION SENTINELS

CLMS requires pan-polar coverage over land for the following missions and variables: Sentinel-1 NG soil moisture and seasonal subsidence, wet snow extent:

- Sentinel-3 NG SRAL lake water level;
- Sentinel-3 NG SLSTR for land surface temperature;
- Sentinel-3 NG SLSTR / OLCI for seasonal snow extent (note: Sentinel-3 NG SLSTR requires additional spectral bands to improve snow / cloud discrimination);
- Sentinels-1, -2, -3 NG (pan-polar) lake ice extent.

2.2.3 COPERNICUS CLIMATE CHANGE SERVICE (C3S)

Although C3S strives to provide as broad a range of ECVs as possible, its current portfolio and what the service expects to be able to provide in 2021-2027 does not include all ECVs considered by the PEG and for which climate requirements exist (e.g. from GCOS). In the following sections, the term "climate applications" or "climate products" will be used in lieu of C3S when discussing ECV products without present or future equivalents in the C3S product range.

2.2.3.1 EO DATA IN 2020

The floating ice and ocean products of C3S rely on a wider range of data than those from CMEMS, owing to their nature of being multi-decadal climate data records:

- Sea ice thickness uses radar altimeter data from Envisat (RA-2) and CryoSat-2 (SIRAL);
- Sea ice concentration (brokered from OSI SAF) and sea ice type use PMR data from SMMR, SSM/I and SSMIS;
- Sea level anomaly uses radar altimeter data from Sentinel-3 (SRAL) in combination with third-party mission data (ERS, Envisat, Jason/S-6, Topex/Poseidon, SARAL, CryoSat-2);
- Sea surface temperature uses Sentinel-3 SLSTR in combination with third-party mission data (AVHRR on NOAA-X and MetOp-A, ATSR/ERS, AATSR/Envisat).

The ice sheets and glacier products of C3S rely on the following data:

- Ice velocity uses Sentinel-1 SAR;
- Glacier outlines uses optical sensor data from Sentinel-2 and Landsat;
- Surface elevation change uses altimeter data from Sentinel-3 SRAL data as well as data from ERS 1/2, Envisat, CryoSat-2.

Land surface and surface freshwater products of C3S rely on the following data:

- Lake water level uses data from Sentinel-3 and third-party data from radar altimeters on TOPEX/POSEIDON, Jason/Sentinel-6, Envisat, SARAL, GeoSat-Follow-On;
- Surface soil moisture is produced using scatterometer data from AMI-WS, ASCAT-A/B and PMR data from SMMR, SMM/IS, TMI, AMSR-2, AMSR-E, WIndSat, SMOS.

2.2.3.2 EO DATA IN 2021-2027

According to the PEG and C3S, the most important changes to the baseline situation for the floating ice and land ice products are as follows.

- With the CryoSat-2 mission approaching its end of life, altimeter data from ICESat-2 for sea ice thickness is planned to be used in combination with PMR data from AMSR-2/AMSR-3/SMAP for sea ice thickness;
- The multifrequency passive microwave radiometer AMSR-3 (expected launch in 2023 with projected lifetime until 2028) is also planned to be used for sea ice concentration, sea ice Drift, ice type-ice stage of development and sea surface temperature at low spatial resolution;
- For Sea ice drift and iceberg (iceberg concentration charts and individual icebergs), climate products would benefit from three Sentinel-1 units in orbit and coordinated with the observation plan of the Radarsat Constellation Mission (RCM);
- For Surface elevation change, C3S plans to make use of ICESat-2, TanDEM-X SP-INSAR DEM, with potential use of the SP-INSAR DEMs from Sentinel-1 C unit flying in formation with the Sentinel-1 A unit;
- For ice velocity and grounding line of ice sheets: potential synergy of Sentinel-1 SAR and upcoming third-party SAR missions (e.g. NISAR) to fill polar gaps in Antarctica and prepare for synergistic use of C- and L-Band SAR (ROSE-L preparation).

2.2.3.3 COPERNICUS HPCMS

All three polar HPCMs (CIMR, CRISTAL and ROSE-L) are relevant for C3S and climate applications. The continuity beyond 2027 of the sensors used in 2020 and during 2021-2027 could be ensured as follows.

Eight out of the 15 climate variables[21] listed under the floating ice, ocean, ice sheets, glaciers and ice caps categories are based on data from PMR sensors that can come from a mission such as CIMR in the future.

Seven out of the 15 climate variables listed under floating ice, ocean, ice sheets, glaciers and ice caps categories are based on data from altimeter sensors that can come from a mission such as CRISTAL in the future.

L-Band SAR data, such as those provided by a mission similar to ROSE-L, are currently not used by C3S as no data are operationally available. For the period of 2021-2027, systematic acquisitions from L-Band SAR from third-party missions could potentially be used, including from SAOCOM A&B, NISAR, and ALOS PALSAR-2 (e.g. in synergy with Sentinel-1 for ice velocity).

Out of the 15 C3S climate variables from the four previously mentioned categories, 7 variables have requirements that can be fulfilled by only one stand-alone Copernicus HPCM (not combinations):

• Sea ice concentration - climate	CIMR
• Iceberg (concentration and individual icebergs) - climate	ROSE-L
• Surface ice velocity of ice sheets and glaciers	ROSE-L
• Surface elevation of ice sheets and glaciers	CRISTAL
• Ice sheet grounding line location	ROSE-L
• Ice margin (extent) of ice sheets	ROSE-L
• Sea level anomaly	CRISTAL

Variables that need to operate in synergy with one or more missions are described in section 2.4. See also further details about how the HPCMs can fulfill C3S requirements in section 2.6 “HPCM considerations.”

2.2.3.4 NEXT GENERATION SENTINELS

C3S requires the data from the following missions:

- Next-Generation Sentinel-3 SRAL for Lake water level and with a pan-polar coverage for floating ice and ice sheets: sea level anomaly, sea ice thickness (SIT), Iceberg (iceberg concentration charts and individual icebergs), surface elevation & change and mass;

21 Variables found both in glaciers and ice caps and in Ice sheets are only counted once. Sea surface salinity is not included in the total count.

- Next-Generation Sentinel-3 SLSTR: sea surface temperature (SST);
- Next-Generation S1 sea-ice concentration (SIC), sea ice drift, iceberg (iceberg concentration charts and individual icebergs), soil moisture and S1 NG SP-InSAR surface elevation & change and mass balance. Sentinel-1 NG SAR at dual polarisation mode should have a better spatial resolution than Sentinel-1 (from $2.5 \text{ m} < x \leq 5 \text{ m}$) and wider swath (towards 400 km) to improve global revisit.

2.2.4 COPERNICUS MARITIME SURVEILLANCE SERVICE (CMS)

2.2.4.1 EO DATA IN 2020

Sentinel-1 data is currently used for oil spill detection delivered by CMS extending the European CleanSeaNet service to other areas of interest beyond European waters. Vessel detection and feature detection is carried out using VHR resolution third-party SAR data (Radarsat, TerraSAR-X, PAZ).

2.2.4.2 EO DATA IN 2021-2027

CMS is interested in operating 3 units of Sentinel-1 in parallel to increase the revisit time globally. In case it is possible to receive Radarsat Constellation Mission (RCM) data with the timeliness needed for CMS they are equally interested in their data. For Vessel Detection and Feature Detection EMSA will continue using third-party SAR data from Radarsat, TerraSAR-X, PAZ.

2.2.4.3 COPERNICUS HPCMS

CMS is interested in additional SAR capacity to increase the revisit time globally. ROSE-L will increase the number of SAR satellites.

2.2.4.4 NEXT GENERATION SENTINELS

CMS is requiring S1-NG Sentinel-1 with a higher horizontal resolution (from $2.5 \text{ m} < x \leq 5 \text{ m}$) globally and if possible, with a data latency of 20 to 30 min. This requirement applies also to the Arctic.

2.2.5 COPERNICUS EMERGENCY MANAGEMENT SERVICE (CEMS)

2.2.5.1 EO DATA IN 2020

Sentinel-1 data is currently (starting 2021) used for the systematic, automated, Sentinel-1 based global flood monitoring product.

2.2.5.2 EO DATA IN 2021-2027

CEMS is interested in 3 units of Sentinel-1 in order to increase the revisit time globally.

2.2.5.3 COPERNICUS HPCMS

CEMS is interested in additional SAR capacity in order to increase the revisit time globally as well as the possibility of making use of the L-band to see water below vegetation (below the canopy cover of trees). ROSE-L will increase the number of SAR satellites and due to the penetration capabilities of L-band radiation, better detection of floods under vegetated areas is expected.

2.2.5.4 NEXT GENERATION SENTINELS

CEMS is requiring S1-NG Sentinel-1 NG globally including the Arctic.

2.3 IN-SITU DATA

In the Summary table in Annex 3 the mentioned in-situ technology and availability to data is mentioned the data is partially based on the KEPLER project, but also provided by the Polar Experts. The content in the table is further elaborated in Chapter 3.

2.4 COMPLEMENTARITY AND SYNERGIES

The Polar Expert Group III analysed, together with ESA and EUMETSAT the synergies and the benefits of cross-sensor observations in order to fulfil the PEG requirements. Below follows an overview of the combinations analysed. The combinations can also be found in the Summary table (in Annex 3) indicating how the combinations are and are planned and how they will be used in the coming years from equivalent missions (third-party data). This is also highlighted in Chapter 4.

2.4.1 CIMR & SENTINEL-1 (AND/OR ROSE-L)

FLOATING ICE

Sea ice concentration for CMEMS: The combination of the CIMR and Sentinel-1 (and/or ROSE-L) will improve the ability to provide reliable automated sea ice-chart-like products (sharpened) for navigational and for high-resolution input to numerical forecasting models.

Sea ice concentration for C3S: The combination of the CIMR and Sentinel-1 (and/or ROSE-L) will provide high-resolution input to numerical forecasting models.

Sea ice drift, ice type-ice stage of development for CMEMS, C3S, and other climate applications: The combination of the CIMR and Sentinel-1 (and/or ROSE-L) will provide high-resolution input to numerical forecasting models for both services.

VIS/IR can complement at intermediate resolution (cloud permitting).

ICE SHEETS

Melt extent of ice sheets for C3S: The combination of the CIMR and Sentinel-1 (and/or ROSE-L) will provide indications for melt extent on ice sheets.

SEASONAL SNOW

Sentinel-1 is used to detect wet snow, for dry snow areas: snow water equivalent from ROSE-L (from INSAR for mountain areas) and snow water equivalent from CIMR (flat terrain). This requires close acquisition between Sentinel-1 and ROSE-L.

2.4.2. SENTINEL-1 & ROSE-L

FLOATING ICE

Sea ice concentration for CMEMS: The combination of C-band Sentinel-1 and L-band ROSE-L will allow the separation of sea ice and ice-free open water leading to more robust and reliable SIC estimates with the potential for automatic ice chart production. A more robust SIC will also make SAR analysis more relevant for assimilation in numerical forecasting models.

Sea-ice drift, ice type-ice stage of development for CMEMS, C3S, and other climate applications: The combination of C-band Sentinel-1 and L-band ROSE-L will provide complementarity/synergy of observations as well as differentiation of sea ice types.

Iceberg concentration charts and individual icebergs for CMEMS, climate applications for C3S and support of the CMS monitoring of activities at sea: The combination of C-band Sentinel-1 and L-band ROSE-L will provide a synergy/complementarity of observations for iceberg detection and provision of improved iceberg concentration charts and detection of individual icebergs.

ICE SHEETS

Grounding line location (GL) for ice sheets (Antarctica, Greenland) for C3S: The combination of C-band Sentinel-1 and L-band ROSE-L (using DInSAR) will provide improved grounding line detection and migration monitoring.

Mass and mass change for ice sheets (Antarctica, Greenland) for C3S: The combination of C-band Sentinel-1 (via DEMs differencing, DEMs being generated by SAR interferometry) will provide the determination of ice sheets mass and mass changes.

Ice margin extent for Ice sheets (Antarctica, Greenland) for C3S: The combination of C-Band Sentinel-1 and L-band ROSE-L will enable the determination of ice margin extent for ice sheets in Antarctica and Greenland at higher temporal frequency.

SEASONAL SNOW

Snow melt extent and snow water equivalent (SWE) for CLMS and climate applications: C-band Sentinel-1 and L-band ROSE-L are combined for improved monitoring of physical snow parameters: Sentinel-1 C-Band SAR is used for detection of wet snow using backscatter data, while for dry snow areas ROSE-L (using repeat pass SAR interferometry - InSAR) will provide SWE.

Snow melt for CLMS and climate applications: The combination of C-band Sentinel-1 and L-band ROSE-L will provide the determination of snow melt based on backscatter change detection.

SEASONAL SUBSIDENCE

Land surface movement/seasonal subsidence for CLMS (e.g. Ground Motion Service) and climate applications: The combination of C-band Sentinel-1 and L-band ROSE-L SAR interferometry will provide stable long-term coherent information on land surface movements due to freezing/thawing of the active layer.

2.4.3. ROSE-L & CRISTAL

Ice sheet grounding line (GL) requirement of the PEG (not a Copernicus product): The combination of ROSE-L and C-band Sentinel-1 (using InSAR) will provide detailed GL mapping and monitoring in synergy with CRISTAL for adjusting vertical displacements in grounding zones and on ice shelves (breaking slope approach).

FLOATING ICE

Retrieval of iceberg properties: For icebergs that are equal or larger than the altimeter footprint, radar altimetry may deliver iceberg height and SAR areal extension (i.e. horizontal dimensions). Lower frequency (L-band) SAR provides better detection of icebergs within sea ice.

Tracking of sea ice thickness and deformation evolution: Sea ice deformation data can be retrieved with lower frequency (L-band) SAR, providing improved deformation mapping capability, radar altimetry data deliver ice thickness profiles.

2.4.4 CIMR & CRISTAL

FLOATING ICE

Global Sea-ice thickness maps (already operational in CMEMS): sea ice thickness (SIT) for CMEMS and C3S: The combination of CIMR and CRISTAL will provide SIT > 1 m and thin sea ice < 0.5 m outside of the melt season:

1) Sea-ice thickness maps for all ranges of thickness can be obtained by merging radar altimetry thick sea- ice thickness and L-band PMR thin sea-ice thickness, and

2) PMR provides the age of sea ice which can either be input to ice thickness calculations or directly approximate ice thickness.

2.4.5 SENTINEL-1, ROSE-L & CIMR

SEASONAL SNOW

Snow water equivalent (SWE) for CLMS and climate applications: The combination of CIMR and ROSE-L (repeat pass InSAR) will provide SWE retrieval of dry snow, ROSE-L for dry snow in mountain areas and CIMR for flat terrain. Sentinel-1 SAR will provide detection of wet snow.

2.4.6 CRISTAL, SENTINEL-1, ROSE-L & CIMR

FLOATING ICE

Ice type separation: CRISTAL is planned as a dual-frequency altimeter system operating at Ku and Ka-band, which provides data along with profiles from which the thickness of sea ice and potentially of the snow layer on the ice can be retrieved with a horizontal resolution of 80m. Ice thickness profiles and indications of the presence of snow on the ice may be used to complement the ice classification based on SAR imagery. Sea ice type information can also be retrieved from PMR by exploiting the difference in emissivity of the different ice types.

The age of sea ice (ice age) can be computed with ice drift from PMR, supplemented with In-situ (buoys) or other satellite sensors including SAR or optical during the melt season, and used as an input to free-board-to-thickness conversion, and to tune and quality control PMR-based sea-ice type information. Sea ice type classification from microwave sensor synergies will work outside of the melt season, but will be reliant on synergy with in-situ data and optical sensors during the melt season.

2.4.7. ROSE-L, CRISTAL & SENTINEL-1

ICE SHEETS

Determine the ice discharge and the mass budget of ice sheets and ice caps for C3S requires the observation of different parameters using different satellites: The combination of ROSE -L and CRISTAL and Sentinel-1 provides ice discharge and mass budget derived from ice velocity (ROSE-L and Sentinel-1 repeat pass), grounding line (ROSE-L/InSAR and CRISTAL), volume/mass change (CRISTAL and Sentinel-1 SP-InSAR), and ice thickness (from surface and bed elevation; ice thickness is measured e.g. from airborne campaigns with ice penetrating radar).

2.4.8 CIMR & SENTINEL-3

LAND SURFACE AND SURFACE FRESH WATER

Land surface temperature for CLMS and climate applications: The combination of CIMR and Sentinel-3 will provide land surface temperature with near-all-weather capability (CIMR) and Sentinel-3/SLTR IR with cloud limitations.

FLOATING ICE

Sea and ice surface temperature (already operational in CMEMS): PMR (with C-band microwave frequency) can measure cold polar SST and IST through clouds. IR radiometers can measure them more accurately, but not through clouds. PMR and IR imagery can be combined to achieve improved SST and IST products, particularly for the coastal zone and over lakes.

SEASONAL SNOW

The combination of the snow water equivalent product in flat areas from CIMR and snow extent from Sentinel-3 SLSTR / OLCI can be used to improve the boundaries of seasonal snow extent (especially for thin snow packs).

2.4.9 CRISTAL & SENTINEL-3

LAND SURFACE AND SURFACE FRESH WATER

Lake water level for C3S and CMLS: The combination of CRISTAL (Ku-Band interferometric SAR) and Sentinel-3 SRAL (Ku and C-band SAR Radar Altimeter) will provide lake water level information.

2.4.10 ROSE-L & SENTINEL-1 & SENTINEL-2 & SENTINEL-3

LAND SURFACE AND SURFACE FRESH WATER

Lake ice extent for CLMS and climate applications: The combination of ROSE-L, Sentinel-1, Sentinel-2 and Sentinel-3 will provide lake ice extent information, with L and C-band SAR being able to distinguish lake ice and water, and Sentinel-2 and Sentinel-3 providing better contrast between water and thin ice as well as between bare lake ice and snow-covered lake ice with limitations (cloud cover periods).

SEASONAL SNOW

Advanced monitoring of seasonal snow parameters can potentially exploit the synergy of several Sentinel data sets: Sentinel-3 SLSTR/OLCI (total snow extent), Sentinel-1 SAR (snow state wet / dry) and ROSE-L (snow water equivalent for dry snow areas in mountains and complex land surface cover). CIMR can be included to get snow water equivalent for flat areas at coarser resolution.

2.4.11 ROSE-L & SENTINEL-1 & SENTINEL-2 & SENTINEL-3 & CHIME

FLOATING ICE

High-resolution sea ice mapping concentration and type mapping to support maritime end users: Improved automatic classification of sea ice concentration and type through a combination of multi-polarimetric SAR at different frequencies. Low frequency (L-band) SAR provides greater penetration into the ice and higher contrast for deformation features.

High spatial resolution of SAR and optical/thermal radiometers are complementary in providing information on sea ice rheology.

2.4.12 ROSE-L & CIMR & CHIME & S1

LAND SURFACE AND SURFACE FRESH WATER

Soil moisture for CLMS and C3S: The combination of PMR and L-&C-band SAR will provide soil moisture retrieval for only non-frozen soil and below the vegetation canopy with a higher soil penetration depth (up to 5 cm) provided at L-band. Improvement of spatial resolution is possible through a combination of CIMR and CHIME or CIMR with ROSE-L or Sentinel-1. Combination with optical data can be used to improve detection of freeze/thaw state.

2.4.13 ROSE-L & CIMR & CHIME

FLOATING ICE

Calibration and validation of PMR data products: The high spatial resolution of SAR and optical/thermal radiometers permits independent verification of data obtained from PMR. A key element is the summer season where sea ice concentration, type, and melt-pond fractions are available from SAR or optical/thermal radiometers but are an ambiguity for PMR. The combination of CIMR and ROSE-L/Sentinel-1 SAR may also be useful for resolving SAR dark/bright returns.Thickness retrieval for thin ice classes: The thickness of thin ice can be retrieved from PMR (L-band), thermal radiometers, and from L-band SAR data. Scales are different: with PMR one obtains the average thickness over areas > 50 km in extension, whereas SAR and thermal radiometers are optimally suited for retrieving changes of thin ice thickness on scales of tens of meters. Mutual comparisons of the thickness retrievals are helpful in judging the reliability and robustness of the individual results.

2.5 REMAINING GAPS

2.5.1 OBSERVATION GAPS PRE-HPCMS FOR POLAR REGIONS

Mission continuity is a general concern for various missions, but most critical for SMOS, AMSR data, and CryoSat-2. Continuity of altimeter data at high polar latitudes (north of 81.5 North) is a critical gap and measures should be taken to ensure observations beyond the life time of the current CryoSat-2 (e.g. CCM data see section 1.6). Continuity of timely SAR data from Radarsat-2 and SP-InSAR DEMs from TanDEM-X is also of concern. However, each mission has different duty cycle and/or revisit and coverage constraints that must also be considered. For example, PMR can provide pan-Polar regions coverage on a daily basis. An altimeter is more restricted to the ground track location and choice of orbit and a SAR system is restricted by swath and duty cycle.

The update frequency is also stressed for several of the geophysical variables and for many variables the frequency of coverage of the southern Arctic is not sufficiently covered. The southern latitudes are especially of interest for sea ice drift and icebergs. Repeat coverage (continuous 6 days) with crossing orbits (ascending and descending) of SAR (C-Band and L-Band) to enable InSAR applications is missing for monitoring of glaciers and ice caps, as well as margins of Greenland and Antarctic ice sheets. The full Greenland ice sheet should be continously covered by crossing orbits, but at least once a year (e.g. during winter campaign) (InSAR ice velocity), and the interior of Antarctica (as covered by Sentinel-1) every 3 to 5 years. Outlet glaciers and margins of ice sheets, ice caps and mountain glaciers should be covered continuously by SP-InSAR to map surface elevation changes.

For glaciers, snow, ice sheets and land surface and surface fresh water a higher revisit time of optical imagery is requested. Additional spectral bands should be added to optical sensors (S3 SLSTR and OLCI, S2 MSI) to allow for a better discrimination of snow and clouds. A task force group including experts from snow, clouds and atmospheric radiative transfer should be initiated to elaborate on the best set of spectral bands for upcoming optical sensors for snow / cloud discrimination and retrieval of physical snow parameters under various illumination conditions.

Coverage of polar gap in Antarctica: determining ice velocity using SAR: requires left looking third-party SAR missions (e.g. NISAR); coverage required every 3 to 5 years.

A data latency <1h is expressed as a gap for sea ice thickness, sea ice concentration, sea ice drift and icebergs.

In-situ data is generally very sparse in the polar regions.

2.5.2 POTENTIAL OBSERVATION GAPS POST-HPCMS

It is difficult to plan accordingly to take into account future (>5 years) gaps of third-party missions as they might be filled. It might be possible to influence the decisions of the owners of third-party missions, but the decision remains with the owner. It is therefore difficult to be clear on the gaps post-HPCMs and the importance of these missions to fulfil the various requirements.

In-situ observations will be required to fill gaps, such as pan-polar Automatic Identification System (AIS) required by The Copernicus Maritime Surveillance) and on-ice buoys with < 1 h sampling.

Timeliness (update frequency and data latency) is identified as a potential gap.

SP-InSAR is needed to monitor all land ice surfaces, ice sheets (focussing on margins and outlet glaciers), mountain glaciers worldwide and for glaciers in complex terrain, and permafrost areas.

2.6 COPERNICUS HPCM CONSIDERATIONS

The “Requirements and Space Assets” table in Annex 2 provides and overview of the various requirements and the completeness per Copernicus HPCM.

2.6.1 COPERNICUS MARINE ENVIRONMENT MONITORING SERVICE (CMEMS)

2.6.1.1 COPERNICUS IMAGING MICROWAVE RADIOMETER (CIMR)

Out of the three missions CIMR, CRISTAL and ROSE-L, CIMR is the mission that meets best the CMEMS commitments (core service) for polar regions with high feasibility in the implementation. Parameters of interest for CMEMS include:

- sea ice concentration (SIC, 1st primary objective), thin sea ice thickness (SIT) (< 0.5 m), sea ice drift, sea ice type, snow depth on sea ice, sea ice surface temperature (SIST);
- sea surface temperature (SST, 2nd primary objective) , sea surface salinity (SSS), surface ocean winds. CIMR is the only planned mission internationally to provide L-band continuity for Sea Surface Salinity and has been specifically designed to address SSS in cold waters;
- making use of synergies is relevant for CMEMS, to make up for the expected loss of capabilities (AMSR-2, SMOS) in measuring SIC, SST, thin-SIT and other sea ice and ocean parameters in 2022-2023 timeframe.

BENEFITS FOR CMEMS

Continuity of the service: SIC, thin SIT, sea ice drift and SST are currently assimilated by CMEMS models. Apart from the thin SIT which only has been recently implemented, SIC, sea ice drift and SST are parameters for which operational systems can be relied on (incl. C3S). SIST is part of the CMEMS portfolio.

Sub-daily coverage in the polar regions and adjacent seas is of particular importance for Copernicus services in their commitments of providing core services for downstream applications.

Measurements of SIC at a spatial resolution of less than 5km will meet the increase of the horizontal resolution (~ 3km) foreseen beyond 2021 in CMEMS operational systems.

The provision of sea surface salinity following after SMOS will also be relevant. The assimilation of SSS in the Arctic MFC system is currently being investigated within the ESA Arctic + Salinity project.

Spatial measurements (SIST/SST) across the ice edge will introduce spatial continuity to the operational systems.

2.6.1.2 COPERNICUS POLAR ICE AND SNOW TOPOGRAPHY ALTIMETER (CRISTAL)

The CRISTAL mission also fulfils CMEMS commitments together with a significant degree of feasibility in the implementation. Main improvements provided by CRISTAL include:

- High resolution Thick SIT (> 1.0m) with better accuracy, sea ice type, snow depth on sea ice, iceberg detection and height;
- Sea level anomaly (ocean currents) (also measured by Sentinel-3 but with less polar coverage) + significant wave height (SWH) + improvements with snow cover on ice;
- No altimetry mission north of 81.5°N and south of 81.5°S by mid-2020's;
- Synergy between ICESat-2 as a laser instrument and CryoSat-2 as a radar altimeter. It is unclear to what extent ICESat-2 can fill the gaps after Cryosat-2, with noticeable differences between these observations, as the laser signals do not penetrate snow on ice sheets.

BENEFITS FOR CMEMS

- Continuity of the service: The sea level anomaly over the open ocean is currently assimilated by CMEMS models. CRISTAL will provide data of thick sea ice thickness following on CryoSat-2; assimilation of this type of measurement is currently operational in the ARC MFC and is underway in the GLO MFC;
- Iceberg detection products will complete the CMEMS portfolio (core service) with measurements made in both hemispheres.

2.6.1.3 RADAR OBSERVING SYSTEM FOR EUROPE AT L-BAND (ROSE-L)

The ROSE-L mission partly fulfils the data needs of the core service provided by CMEMS; ROSE-L has a large potential but major efforts have to be developed in operational systems in order to take full benefit of these measurements, particularly for reliable automated sea-ice chart-like products. It provides limited coverage and very high resolution compared to forecasting systems. Operational (model) systems are currently not designed to implement such information in a multivariate and multi-data framework.

Main improvements offered by ROSE-L:

- L-Band SAR high-resolution (< 100m), ice type (ice charts), iceberg occurrence and areal density, sea ice drift and deformation, sea ice concentration and ice edge position;
- Potential to augment and complement existing Marine services has been demonstrated through case studies: ocean surface vector stress (wind speed & direction, sea state), SWH (wave period, direction and energy spectrum);
- Thin sea ice thickness (<0.5m), snow depth on sea ice, ocean winds;
- Also part of 1st objectives: Copernicus Maritime Surveillance (safety and security): vessels & fisheries monitoring, oil spills and icebergs detection.

MAIN BENEFITS PROVIDED FOR CMEMS:

- Continuity of the service for the provision of Sea ice concentration and ice type at very high resolution in complement to Sentinel-1. These measurements are the core input for the ice charts disseminated in CMEMS.
- Continuity of the service for iceberg detection products currently in the CMEMS portfolio.

2.6.2 COPERNICUS CLIMATE CHANGE SERVICE (C3S)

2.6.2.1 COPERNICUS IMAGING MICROWAVE RADIOMETER (CIMR)

The CIMR mission would fulfil partially C3S requirements for the provision of the following ECVs:

- sea ice concentration (SIC)
- sea ice edge (SIE)
- sea ice type (SITy)
- sea surface temperature (SST)
- Soil Moisture (SM)

BENEFITS FOR C3S:

- Continuity of existing low-resolution Climate Data Records (CDR) of SIC, SIE, and SITy based on the SMMR-SSM/I-SSMIS series. Aside from their importance for assessing long-term changes in sea ice, the SIC CDR provides essential ocean boundary condition for C3S global and regional reanalyses;
- Continuity of the medium-resolution CDR of SIC based on AMSR-E/AMSR-2. This CDR is important to provide boundary conditions for high-resolution Arctic regional reanalyses.

2.6.2.2 COPERNICUS POLAR ICE AND SNOW TOPOGRAPHY ALTIMETER (CRISTAL)

The CRISTAL mission would fulfil C3S requirements for the provision of the following ECVs:

- Ice sheet surface elevation
- Ice sheet surface elevation change
- Sea ice thickness
- Sea level anomaly
- Snow depth on sea ice

BENEFITS FOR C3S:

- Continuity of the SIT Climate Data Record based on CryoSat-2. However, the CryoSat-2 mission has already long extended its nominal lifetime and bridging the gap between CryoSat-2 and CRISTAL will be essential;
- Enhanced spatial coverage of SIT and SLA over the central Arctic Ocean compared to CryoSat-2 and Sentinel-3 (both limited to <81.5°N);.
- Provision of significant wave height data needed for assimilation into global reanalyses.

2.6.2.3 RADAR OBSERVING SYSTEM FOR EUROPE AT L-BAND (ROSE-L)

Although L-band SAR are currently not available for C3S, the ROSE-L mission will highly support the provision by C3S of land ice ECVs, both as a standalone mission and in synergy with other missions such as Sentinel-1 C-band SAR. Such synergy would assume the following configuration:

- Sentinel-1 A/B / (C): 6-d repeat pass; resolution: 5m x 20 m;
- ROSE-L: repeat pass < 6 days, L-band, resolution 5mx10m; continuous acquisition over land and Arctic; operating in close formation with Sentinel-1 platforms (enabling closely speed collocated aquisition of C- and L-Band SAR).

BENEFITS FOR C3S:

Ice velocity for ice sheets and glaciers:

- Methods to be used: Repeat-pass InSAR, Coherent and Incoherent offset-tracking;
- L-band improves significantly ice velocity (IV) retrieval in areas with snow drift and even light surface melt, where S1 C-band fails;
- ROSE-L will provide improved IV retrieval over the interior of ice sheets with missing features and improved coverage (due to better coherence than C-band);
- ROSE-L's higher resolution than S1 will improve IV coverage especially over mountain glaciers.

Grounding line (Antarctica, Greenland):

- Method used: DInSAR -Differential Interferometry Synthetic Aperture Radar;
- L-band shows improved coherence against C-band, which will improve coverage.

ROSE-L will be the primary source for grounding line detection and monitoring migration –(with contribution from Sentinel-1).

2.7 EARTH OBSERVATION REQUIREMENTS – SUMMARY

CONTINUITY

Ensuring access to the existing Sentinels and CCMs is crucial for generating the Copernicus products and services. In the short term there are few enhancements addressed and that is mainly the need to phase in a third S-1 satellite. For the period 2021-2027, the Copernicus Services stressed the importance of having three Sentinel-1 satellites in orbit for observing the geophysical variables addressed by the PEG. The "Summary table" (Annex 3) describes that out of 25 geophysical variables, where S-1 can contribute to the completeness of the PEG requirements, 16 were found to have a need for a phasing in a third S-1 satellite, mainly because of higher revisit time. For the CCM data it is also important to support the Copernicus Services by making data available from Radarsat Constellation Mission as well as data from missions with instruments similarities to the Copernicus HPCMs.

ENHANCED CONTINUITY – COPERNICUS HPCMS FOR THE POLAR REGIONS

The PEG considers that the primary objectives of CIMR, CRISTAL and ROSE-L are to serve the polar regions and applications. Still, even if the number of geophysical variables to be obtained is higher for PEG III compared to the PEG I and II it is also important to take into consideration the secondary objectives of these missions as they are also relevant to observe other variables than the ones identified by the PEG.

Support to the Copernicus services is a priority, ensuring continuity, enhanced continuity and new products:

The analysis is mainly done undertaken on the current product portfolio of the services as a baseline, but also considering the variables addressed by PEG I and II. The Copernicus Services have contributed to the analysis and have ensured that enhanced continuity with better observation, and better discrimination of ice specifics or coverage was correctly addressed:

- The CIMR and CRISTAL missions are obviously addressing extensive needs for the three services CMEMS, C3S and CLMS in terms of providing continuity to existing missions and supporting the continuity of the existing baseline. For both of them, the science is well documented and adaptation by the services should not demand too many resources. However, data from these missions can be further explored and provide new and improved applications;
- ROSE-L is of interest for some parameters, while ROSE-L rather addresses new potential applications or the improvement of existing products. The maturity of the science and algorithms remains to be demonstrated and operationalised by the Copernicus Services with a special interest from CLMS and C3S. The development of ROSE-L should be accompanied with resources for research and development to ensure the full use from the Copernicus Services;
- When considering the primary and secondary objectives to address polar issues and mainly ice, both CIMR and CRISTAL are more critical for the Copernicus Services than ROSE-L. CIMR addresses more variables than CRISTAL.

SPECIFICS OF EACH MISSION:

- CIMR can fly and bring benefit independently from other missions. CIMR addresses in total three domains: floating ice / sea surface temperature and sea surface salinity/soil moisture. PMR is used by three Copernicus services. CIMR is unique for SST and salinity/soil and cannot be replaced by Sentinel-3/SLSTR or MSG/MetOp;
- CRISTAL is critical for ice climatology (including ice mass balance change and monitoring of Greenland and Antarctic ice sheets) and sea level providing altimeter coverage north of 81.5 degrees. However, for ice thickness (< 1 meter) the uncertainty increases the thinner the ice is while for PMR, at L-band, it is almost the opposite as the ice becomes opaque for ice thicker than as above the 50cm, meaning that there is no/limited sensitivity to thickness at any higher thickness. It is therefore important to combine a PMR sensor (SMOS, SMAP or CIMR) with an altimeter and to make synergy products regularly. CRISTAL is therefore less independent. CRISTAL is also of interest for use by three services. CRISTAL is not mandatory for inland water level globally because of

Sentinel-3 and Sentinel-6, but it is mandatory for obtaining sea-level data for higher latitudes north/south of 81.5 degrees North/South;
- ROSE-L is promising in many areas and is being assessed by the C3S, CEMS, CLMS CMEMS and CMS. For many applications it is unclear to what extent the L-band frequency will result in improvements compared to the C-band. Applications related to land and biophysical variables are well documented. CEMS sees an asset in making use L-band SAR for delineating floods under the tree cover in forests, but L-band SAR is also of relevance for subsidence. ROSE-L remains complementary to Sentinel-1 mainly;
- From the analyses of the three missions and by the five services, a common recommendation is also to fly three Sentinel-1 satellites to improve the temporal and spatial coverage of the observations.

COMPLEMENTARITY / COMBINATION WITH OTHER MISSIONS

Many combinations have been investigated in Chapter 2.4 as well as in Chapter 4, but the most important combinations are:

- The combination of CIMR and the existing Sentinels (Sentinel-1, Sentinel-3 and S-6) is described and will be further described in Chapter 4. CIMR, CRISTAL with Sentinel-3 and Sentinel-6 is also of interest, is necessary and easy to implement since this is based on the experience and knowledge of the existing sensors (CryoSat and AMSR). For observing ice specifics, it is key to combine sensors with wide coverage and high revisit frequency as CIMR and CRISTAL with high resolution SAR data from Sentinel-1;
- The combination of ROSE-L and Sentinel-1 is promising, but it is difficult to determine if this combination is simply an added plus or is mandatory to make the ROSE-L sensor beneficial per se (meaning ROSE-L would be less beneficial as a standalone mission). Complex combinations / integrations of ROSE-L with all other Sentinels are elaborated but the maturity and the operationality at short- to mid-term of these approaches remains also to be demonstrated.

All Copernicus HPCMs offer important new and additional data, that would otherwise not exist for the polar services since:

- No such instruments exist or;
- Comparable instrumentation in orbit has exceeded predicted lifetime or;
- Data from comparable instrumentation is not reliably accessible at all (sovereignty, unclear technical programmatic financial planning beyond European influence);
- The CIMR/PMR instrument is needed to ensure the continuity with AMSR-2 and (-3) data of C-band (6.9 GHz), X-band (10.6 GHz), Ku-band (18.7 GHz), Ka-band (36.5 GHz), W-band (89 GHz). AMSR-3 is planned in 2023 with an end of lifetime in 2028 meaning that CIMR/PMR would be needed at least in 2028. So a gap may be realistically avoided before 2028;
- The L-band radiometry of CIMR (1.4 GHz) is the only mission foreseen to ensures the continuity of the SMOS and SMAP mission for salinity (over the poles and globally), soil moisture (water scarcity) and thin sea-ice thickness. This mission launched in 2009 is important in these times of climate change and passed its nominal lifetime in 2012. SMOS is assimilated into models and brought value. The SMAP L-band mission of NASA will fly until 2023. There is clearly a gap in L-band observations, the extent of which will become apparent years before 2028 most probably since SMOS is already more than 11 years old. CIMR would be the first L-band PMR flow in operational context;
- CRISTAL ensures continuity of CryoSat-2 (launched in 2010) and is complementary to ICESat-2 (laser altimeter launched in 2018 with a design lifetime of three years). Discussions are on-going to further extend the operations of the CryoSat-2 mission and the real lifetime of ICESat-2 is unknown as well as the possibility for a follow-up mission to ICESat-2 With the end of operations for CryoSat-2 the Copernicus Services could face a gap. Discussions should start about the possibility to obtain complementary data from Icesat-2;
- ROSE-L complements the current ALOS-2 (end 2024), 2 SAOCOM1 (end 2025), future ALOS-4 (2022-2029), 2 SAOCOM2 (2025-2031) and NISAR (2022-2025) missions.

NEXT GENERATION SENTINEL MISSIONS FOR THE POLAR REGIONS

The Copernicus Services expressed also requirements for Next Generation Sentinels and continuous monitoring of polar regions:

- Next-Generation S1:
  - Pan-polar and sub-daily coverage: for floating ice variables (sea-ice concentration (SIC), Sea ice drift, ice type-ice stage of development and icebergs);
  - For polar land masses S-1 NG was addressed for soil moisture and seasonal subsidence, wet snow extent, lake ice extent, as well as for flood monitoring;
  - Copernicus Maritime Surveillance (CMS) and C3S requires S1-NG Sentinel-1 with a higher horizontal resolution (from 2.5 m $< x \leq$ 5 m) globally;
  - CMS products requires data latency of 20, 30 min;
  - C3S addressed also the need for S1 NG SP-InSAR surface elevation & change and mass balance;
  - Other C3S needs are and wider swath (towards 400 km) to improve global revisit as well as Sentinel-1 NG SAR in dual-polarisation mode.
- Next-Generation Sentinel-3 SRAL:
  - Pan-polar coverage for floating ice and ice sheets for sea ice thickness (SIT), sea level anomaly, sea ice thickness (SIT), Iceberg (iceberg concentration charts and individual icebergs), surface elevation & change and mass;
  - Global coverage: Other variables: Lake water level, lake ice extent.
- Next-Generation Sentinel-3 SLSTR:
  - Surface temperature over ocean (SST) and over ice (IST), seasonal snow extent (requires additional spectral bands to improve snow / cloud discrimination).

3. POLAR IN-SITU OBSERVATIONS

3.1 ROLE AND IMPORTANCE OF POLAR IN-SITU OBSERVATIONS

Continuous monitoring of polar regions, both for scientific environmental research and provision of Copernicus operational services and products, relies largely on the combined use of Earth Observation satellite data and of in-situ observations collected by a variety of platforms (airborne, ship-borne, ocean surface floats and profilers/buoys, etc.). The harsh terrestrial and marine environment of the polar regions (Arctic and Antarctic) makes it difficult and expensive to permanently deploy and maintain sophisticated in-situ observation equipment and platforms, which are essential inputs for the provision of reliable and high-quality Copernicus products.

A majority of Copernicus operational products results from the use of complex “data assimilation models” based on physical or semi-empirical algorithms and generating global/regional/seasonal numerical forecasts, hindcasts and re-analysis products.

In-situ observations play a key role and are crucial and unique for:

- Providing data which cannot be observed from space (e.g. surface pressure, subsurface temperature and salinity profiles in ocean and sea ice);
- Meeting requirements for local, high frequency and high spatial resolution data;
- Testing and calibration of models during the development phase (“to constrain models”) and for product validation/quality evaluation during the operational phase.;
- Use in assimilation schemes in multivariate and multi data frameworks, in conjunction with satellite data.
- Periodical validation of models and their improvements as appropriate;
- Satellite instrumentation calibration and product validation, for in situ data qualified as Fiducial Reference Measurements (FRM) to ensure that the satellite measurements are not degraded or misinterpreted.
- Provision of L2 to L4 in-situ data products to users;
- Provision of concomitant measurements of different quantities used to derive products for many oceanic, weather and climate applications, (e.g. subsurface salinity, together with temperature and pressure and satellite surface observations of SST, SSS and SSH are used to derive ocean velocity, mixed-layer depth, density stratification, sea level and indirect subsurface ocean mixing).

For the calibration of instruments on-board satellites which form the Copernicus Space Component (CSC), operated by ESA and EUMETSAT, there is a need for high quality in-situ measurements together with their uncertainties, also referred to as “Fiducial Reference Measurements” (FRM), i.e. a few points with high precision and well characterized (a typical example being the limited number of ground transponders deployed for SARs and scatterometer calibration).

Geophysical product verification (typically Level 2 products) against in-situ measurements, requires more points but possibly less precision.

3.2 POLAR IN-SITU OBSERVATIONS IN SUPPORT TO COPERNICUS SERVICES

It should be noted that Europe has a dynamic and well-connected polar scientific research community, at a national, European and international level and significant effort has been put to deploy and maintain polar infrastructures, facilities and observation platforms.

The European Environment Agency (EEA) plays a key role and is responsible within the Copernicus programme for the coordination of in-situ observations to be used for relevant Copernicus services. In this context, EEA has initiated several actions/study projects with the objectives to assess the status and availability of polar in-situ observations, to identify access conditions and modalities (i.e. data freely available or subject to restricted availability, limited use or payment) as well as quality level and geographical distribution and gaps.

The following two important studies/projects were initiated in 2019-2020, focussing on the Copernicus and the Arctic, namely:

- The "Arctic In-Situ Data Availability[22]" study with a small consortium led by EuroGOOS (with DMI, NILU, Eumetnet and University of Lund). The study focused mainly on the in-situ for CMEMS, C3S and CAMS. The study is now completed;
- The KEPLER (Key Environmental monitoring for Polar Latitudes and European Readiness) project, a European Union Horizon 2020 project kicked-off in January 2019 and to be completed by the second half of 2021. KEPLER has a wider scope which encompassing not only the in-situ observation requirements but also the research and improvement requirements related to the space component of Copernicus (CSC) for the monitoring and forecasting activities in polar regions. The deliverable named "In situ observation gaps[23]" was here an important asset for this chapter.

In both projects, comprehensive and detailed reviews and analysis of existing environmental data from the Arctic region were performed via a large consultation process involving the European marine and terrestrial research communities. The list of the main sources of data/information consulted include: WMO, INSTAC, EMODnet (incl. its Arctic checkpoint), SAON and AMAP, INTAROS and iCUPE, JCOMMOPS, C3S 311a Inventory Activity, EMEP, EU-PolarNet, IASOA, AERONET, NDACC, WOUDC, NILU, IAGOS, EEA. Workshops with terrestrial and marine infrastructure networks such as INTERACT, a pan-Arctic network of currently 88 terrestrial field bases and European Ice Services, were organised to explore their possible contribution to Copernicus.

At European level, contacts were established with three main organisations/programmes involving a broad range of European-funded polar research namely:

I. The European Polar Board established by the European Science Foundation and focusing on major strategic priorities in the Arctic and Antarctic research;
II. The EU-PolarNet, the world's largest consortium of expertise and infrastructure for polar research with 17 countries represented by 22 of Europe's internationally-renowned multi-disciplinary research institutions;
III. The EU Polar Cluster. As an example, the EU Polar Cluster is a collaboration of large multidisciplinary Arctic and Antarctic projects funded by the European Commission. The EU Polar Cluster (EUPC) currently comprises 15 Horizon 2020 and one Framework Programme FP7 projects including APPLICATE, ARCSAR, ARICE, Beyond EPICA, BLUE-ACTION, EU-PolarNet, FORCeS, ICE-ARC, iCUPE, INTAROS, INTERACT, KEPLER, SO-CHIC, TiPPACS, and NUNATARYUK.

22 Copernicus In-Situ Component, E Buch et al, (2019) Copernicus Arctic In-Situ Availability
23 KEPLER Project, J. Wilkinson et al, (2020), In situ observation gaps

Meetings between KEPLER, the EEA, and INTAROS (Integrated Arctic Observation System- a research and innovation action under the H2020 - running from 2016 to 2021) were organised to discuss possible ways to cooperate, to provide initiatives towards an open and free exchange of data, and to discuss requirements for a sustained Arctic observation network.

Both studies/projects concluded that the present Arctic Observing System - especially the central Arctic - is undersampled.

They, in particular, identified severe gaps and/or shortcomings related to:

- The timely availability and quality of existing observations affected by the lack of reliable data transmission facilities;
- The availability of data from non-European countries;
- The fitness-for-purpose of observation technology;
- The data management structures at data producer level, affecting data exchange;
- The sustainability of existing observing system – many rely on time-limited research funds;

CMEMS example from the report "CMEMS requirements for the evolution of the Copernicus In-Situ Component" (December 2018)[24]: CMEMS has set up a dedicated unit, the In-situ Thematic Assembly Centre "INS-TAC", responsible for collecting in-situ data from data providers (national and international networks such as SeaDataNet and EMODNet), carrying out quality control in a homogeneous manner, and distributing them in near real time. Annex 4 below provides a schematic overview of organisations providing data to the Copernicus Marine Environment Monitoring Services (CMEMS). The data sets provided by these organisations include surface and at depth temperature, salinity and currents as well as sea level, wave, biogeochemical (BGC) parameters (e.g. chlorophyll) and ice properties (thickness and drift). These parameters are measured today by ice-tethered profilers (ITP), acoustic tomography, Argo floats, sea mammals, moorings, drifters, and by research cruises CTD (Conductivity, Temperature and Depth) sensors.

The CMEMS requirements report from 2018 stresses that "a specific effort for the Arctic region is needed as there are severe limitations with measurements over the seasonal ice zone, which is growing broader and none of the platforms available today can collect data there. More ITPs, core and BGC Argo floats are needed. IMB (ice mass balance) buoys are needed to measure ice thickness and snow depth that is critical for remote sensing algorithm calibration and validation".

3.3 SUPPORT TO COPERNICUS SPACE SENSOR CALIBRATION AND PRODUCT VALIDATION

Calibration of satellite sensors and validation of resulting products (typically L2 geophysical parameters) are mandatory activities performed during the "commissioning phase" of space Earth Observation missions (generally of 6 months duration) to confirm the quality of the sensor as well as that of the associated product. These activities are pursued on a regular basis all throughout the lifetime (7-10 years) of the satellite in order to monitor/control the eventual degradation of the sensors and ensure a stable with time and good product quality to users. This is particularly important for all Copernicus products and even more for C3S for which long-term consistent time series (decades) data are required to detect/monitor climate changes. An example of ESA needs for in-situ measurements in the Arctic for Cal/Val is provided in the Table 1 below, based on findings from the KEPLER report "New and novel observation sensors and techniques". The table covers satellite missions of relevance to polar monitoring including:

- Existing (Sentinel-1, Sentinel-2, Sentinel-3) and their respective Next Generation (NG) Sentinels
- Existing Altimetry (CryoSat) and Salinity (SMOS) Earth Explorer missions
- 5 out of 6 future HPCMs (CRISTAL, ROSE-L, CIMR, LSTM, CHIME)
- Earth Explorers SKIM, Steroid

24 Mercator Ocean, EuroGOOS and CMEMS Partners (2018)

Table 1. ESA needs for in-situ measurements in Arctic for Cal/Val[25]

Thematic area/Parameters	Missions	Potential In-situ sensors
Ocean validation		
Sea level (sea surface height)	Sentinel-3, CryoSat, Sentinel-3NG, CRISTAL, SKIM	Tide gauge, Moving vessel profiler (MVP), Gliders, CTD, Argo buoys, Drones
Ocean wave	Sentinel-1, Sentinel-3, CryoSat, Sentinel-3NG, CRISTAL, SKIM	Tide gauge, buoys
Sea surface gradients/current	Sentinel-1, Sentinel-3, CryoSat, Sentinel-3NG, CRISTAL, SKIM, Steroid	Moving vessel profiler (MVP), Gliders, CTD, ADCP, drifting buoys, HF radar, drones
Sea surface temperature	Sentinel-3, Sentinel-3NG, CIMR	SST radiometers, MVP, gliders, CTD
Sea surface salinity	SMOS, CIMR	MVP, gliders, CTD
Ocean colour (CHL, LIGHT, CDOM…)	Sentinel-3	Chlorophyll-fluorescence, light and other optical sensors on BioArgo, gliders, buoys
Sea-Ice validation		
Sea ice thickness	Sentinel-3, CryoSat, Sentinel-3NG, CRISTAL, SMOS, CIMR	Boat and airborne campaigns, submarine data, drifting buoys
Sea ice freeboard	Sentinel-3, CryoSat, Sentinel-3NG, CRISTAL, SMOS, CIMR	Boat and airborne campaigns, submarine data, drifting buoys
Snow depth (+temperature and salinity)	Sentinel-3, CryoSat, Sentinel-3NG, CRISTAL, SMOS, CIMR	Boat and airborne campaigns,
Sea ice drift	Sentinel-3, Sentinel-3NG, SKIM, Sentinel-1, Sentinel-2, Steroid	Boat and airborne campaigns,
Iceberg drift, size and thickness	CryoSat, Sentinel-1, Sentinel-2, Sentinel-3, CRISTAL	Boat and airborne campaigns
Land-Ice validation		
Ice sheet spectral albedo, broad band albedo	Sentinel-3, Sentinel-3-NG	Campaigns, surface-mounted radiometers
Ice sheet snow grain size distribution	Sentinel-3, Sentinel-3-NG, Sentinel-2	Campaigns
Ice sheet surface temperature	Sentinel-3, Sentinel-3-NG, LSTM (Copernicus LST), CIMR	Campaigns, surface-mounted temperature sensors
Ice sheet surface elevation	Sentinel-3, Sentinel-3-NG, CryoSat, CRISTAL, SKIM	Campaigns
Ice sheet surface velocity	Sentinel-1, Sentinel-2	Campaigns, GPS trackers
Ice sheet/shelf calving front location	Sentinel-1, Sentinel-1NG, ROSE-L, CryoSat, CRISTAL	Campaigns
Terrestrial snow depth/density or snow water equivalent	MWI, CHIME, ROSE-L	Campaigns
Soil state freeze and thaw	SMOS	Campaigns
Permafrost active layer seasonal subsidence	Sentinel-1, Sentinel-1NG, ROSE-L	Campaigns

25 M. Drinkwater ESA

Similar requirements for in-situ observations are needed for the validation of Copernicus polar products generated by the 8 TACs (Thematic Assembly Centres), essential components of the CMEMS system. These 8 TACs, geographically distributed all over Europe, include the Sea Ice TAC, the Surface Wind TAC, the Sea Level TAC (Sea Level Satellite Data), the In-Situ TAC (in-situ temperature, salinity, currents and other variables), the Ocean Colour TAC (Ocean Colour Satellite Data), the sea surface temperature TAC, the Wave TAC and the Multi Observations TAC. Annex 4 provides an overview of the current usage of Arctic in-situ data for the TACs as well as the Marine Monitoring and Forecasting Centres (MFCs).

3.4 "CITIZEN SCIENCE" APPROACH AND NEW TECHNOLOGIES

The term Citizen Science (CS) can be defined (ref. KEPLER report "on the gaps in terms of in-situ observations in order to improve polar regions monitoring and forecasting capabilities") as *"Voluntary collaborations in scientific research that is conducted, in whole or in part, by non-professional scientists, whose outcomes both advances scientific knowledge, and increases the public's understanding of science"*. This approach allows us to involve a wide variety of non-space competence but having a valuable in-situ experience especially if this takes the form of "collaborative projects" or "co-created projects". This approach is already partly used today by space agencies, e.g. by NASA with more than 20 projects, and by the ESA CSEOL (Citizen Science Earth Observation Lab) initiative.

A number (5) of CSEOL pilot projects are under implementation e.g. the project "Design of a mobile phone application for sea ice observations", where using the IceWatch App citizen scientists will be mapping sea ice. IceWatch is a programme coordinating routine visual observations of sea-ice, including icebergs and meteorological parameters. The programme has already collected over 5,600 records from numerous ship voyages and is complementary to the Antarctic platform ASPeCt.

The KEPLER project strongly recommends that the CS approach be further developed in support to polar science in general. The contributions of indigenous populations and local authorities would also be very valuable.

A review of new and novel in-situ and airborne observation sensors and techniques was presented, covering a wide spectrum of sensors, including Unmanned Aircraft Systems (UAS), High Altitude Pseudo Satellites (HAPS), other airborne systems (kites, balloons), Autonomous Underwater Vehicles (AUVs), gliders (wave and underwater) and new innovative sensors such as Ground Penetrating Radar (GPR), Ultra Wideband (UWB), hyperspectral imaging, tomographic radar, and Bio-optical sensors. They have varying levels of maturity and costs. Sources of funding for the most promising one(s) should be identified both at national and European levels.

3.5 ANTARCTICA (REF EU-POLARNET WHITE PAPER ON EUROPEAN POLAR INFRASTRUCTURE ACCESS AND INTEROPERABILITY[26]

Previous chapters were focused on the Arctic Ocean, surrounded by developed nations, and of easier and more frequent access through commercial regular maritime traffic routes compared to Antarctica. The geopolitical environment for the Arctic is also different from that of Antarctica where activities (mostly research) are regulated by an international treaty. However, Antarctica is the site of intense research programmes most often carried out on a national and multi-national basis governed by bi- or multi-lateral agreements. One can note a growing activity in connection with the study of climate change (Antarctica as a major "climate indicator") as well as tourist activities (the latter worrying the scientific community). Major infrastructures (e.g. French-Italian Concordia station), observation platforms (32 stations) and equipment have been deployed and still continue today.

Therefore, most of the findings and recommendations made for the Arctic are applicable to Antarctica. Particular attention should be given to improving cooperation and coordination between these various programmes, facilitating transnational research (TNA) and ensuring access to existing infrastructures (Concordia, research vessels through Eurofleets funded by the EC), developing/promoting standardisation and interoperability of deployed facilities, and increasing the deployment of in-situ observation equipment, which is still too sparse today.

3.6 RECOMMENDATIONS

Clear recommendations were made to develop a strategic plan in order to improve the present situation. Key recommendations/actions are as follows:

- Ensure a better cooperation and coordination between the various Arctic projects (the number of 202 projects was mentioned), in particular for a better utilisation of European polar research assets (i.e. stations, ships, aircraft and people) essential for the validation of Copernicus polar products and Cal/Val activities of ESA/EUMETSAT space assets;
- Re-enforce the dialogue of all agencies with responsibilities for the Arctic, which is currently too limited, and the cooperation and coordination between ESA, EUMETSAT and national Arctic projects deploying in-situ observing equipment in polar regions, in-situ data should be coordinated far beyond the scope of validating EO data. Accordingly, the cooperation should be more among the environmental projects and agencies with responsibilities for the Arctic;
- Define modalities for an improved access and exchange, possibly free of charge, of collected in-situ data and usage conditions (free or limited use, financial conditions if applicable, etc.);
- Explore the possibility/feasibility of having a unique access portal for in-situ data;
- Develop international cooperation on design and implementation of sustained observing systems in the Arctic and Antarctica since at the moment the number of in-situ platforms is very limited and not sufficient to monitor the entire regions;
- Define and implement an efficient in-situ data handling management and integration with existing data management systems for space data (e.g. DIAS, ESA PDGS and EUMETSAT SAFs);
- Effort and particular attention should be given to provide access to non-European data in particular Russian data and also from countries expressing an interest in polar research (e.g. China, Japan, Korea);
- Develop standardisation of infrastructure, instruments and protocols, essential to improve interoperability (reference to INSPIRE directives);
- Improve dialogue/communications between space agencies, polar infrastructure operators and relevant national and international organisations (WMO, IOC).

26 Gonçalo V. et al, 2020, White Paper on European Polar Infrastructure Access and Interoperability

- Ensure that a relevant FRM quality subset of measurements is available for satellite calibration and validation work.;
- Improve estimates of uncertainty and uncertainty budgets for in situ measurments;
- Space agencies, and in particular ESA, shall further develop the CS approach in relation with CS associations and expand current CSEOL activities in the Arctic environment.

The KEPLER project stressed also the importance of a clear description of in-situ needs from institutions such as the European Commission or the European Space Agency in order to attract significant national/European financing for in-situ activities in the Arctic. The proposal of placing the needs for in-situ data next to the Polar Expert Group requirements (see the “Summary table” Annex 3) was endorsed by PEG III experts.

4. ORBIT PHASING/CROSS INSTRUMENT OPERATION SCENARIOS AND MERITS

4.1 ORBIT PHASING/CROSS INSTRUMENT REQUIREMENTS

The PEG report I and II and the Mission Requirement Documents of CIMR, CRISTAL and ROSE-L address detailed observation requirements for covering the same geographic areas to support multi-sensor observations and retrievals:

- with the same instrument-family (e.g., various C-and L-band SAR systems, various altimeter systems);
- in synergistic use of different instrument families (e.g., combination of C-band, L-Band SAR, PMR, altimeters).

For some missions this translates into:

- Orbit requirements" e.g. in the case of CIMR and all missions with continuous instrument operations;
- Requirements for the orbit, instrument-/mode scheduling and operations of the data acquisition, e.g. in case of ROSE-L and other missions with limited duty cycle.

4.1.1 SYNERGIES

The KEPLER project describes various instrument synergies for the Copernicus HPCMs. These synergies are already tested experimentally. Synergies for land applications are given in green boxes, light grey boxes indicate ice and sea applications. Operational products in Copernicus phase 1 (2021) are written in red colour. Parameters with high impact for intermediate and end-users are marked in bold[27].

Table 2. Instrument synergies composed by the KEPLER project[28]

Sensors	**PMR (e.g. CIMR)**	**Radar Altimeter (e.g. CRISTAL)**	**Infra-red (e.g.LSTM)**	**Optical (e.g. CHIME)**	**SAR (e.g. ROSE-L)**
PMR		lake ice thickness		**Soil moisture downscaling**	Snow Water Equivalent **Soil moisture**
Radar Altimeter	**SIT1**, **ice type**, snow depth			Phytoplankton groups	
Infra-red	**SIT, ice surface temperature, sea surface temp**	**SIT, ice type**			
Optical	**SIT, ice type**	**ice type,** MPF		**Phytoplankton groups, phytoplankton dynamics**	snow extent snow wetness **snow avalanche** lake ice extent
SAR	**SIC, SIDrift**	sea ice deformation evolution **iceberg properties,** snow depths on sea ice	**ice type**	**SIC, ice type**	

27 KEPLER report, Carolina Gabarró, 2020, "Final report on research gaps of space-based Arctic monitoring - Deliverable D3.3"
28 Ibid

The Polar Expert Group suggests the coordinated operations of different instruments in Chapter 2 as well as in in the "Summary table" in Annex 3. The PEG members highlighted the need for the following instrument synergies:

- For the grounding line detection, synergies between different SAR sensors (C-band with short repeat intervals and L-band) and potentially RA;
- For SP-InSAR opportunities of C-band (or higher frequencies X-, Ku-, Ka-band) SARs for monitoring surface elevation changes;
- For wet-snow and snow-water equivalent in mountain regions integration of C-Band SAR (wet snow detection) and L-band SAR (InSAR SWE retrieval for dry snow only), respectively. L-Band SWE products are complemented by PMR in flat areas. Additionally, snow extent from optical sensors (Sentinel-3 SLSTR) is useful.

The Polar Expert Group describes combinations of several families of instruments (>3), which is challenging and therefore it is not possible to enter them into a two-dimensional table, but inspired by the KEPLER project the PEG summarises the following two-satellite system combinations for the all-weather and day-night Sentinel missions (see Table 3):

Table 3. Two-dimension instrument synergies composed by the PEG (cryosphere variables on land (green) and for floating ice and ocean variables (grey). In bold combinations already operational)

Sensors	**CIMR**	**CRISTAL**	**ROSE-L**	**S-1**	**S-3**
CIMR			Land Ice, Snow Water Equivalent, Soil moisture, Melt extent (ice sheets)		Land Surface Temperature
CRISTAL	**Sea Ice Thickness, Sea Surface Temperature,** Snow depth and snow cover on sea-ice		Mass and mass change (ice sheets), Surface Topography, Grounding line information, Ice margin (ice sheets extent)		**Lake water level**
ROSE-L	**Sea Ice Concentration, Sea Ice Drift,** Sea Ice Type	Iceberg, Sea Ice Thickness		Ice Margin, Snow Water Equivalent, Lake Ice Extent, Snow melt, Seasonal Subsidence, Surface ice velocity, Flood extent	
S-1			Sea Ice Concentration, Sea Ice Drift, Iceberg, Sea Ice Type		
S-3					

4.1.2 CROSS-MISSION REQUIREMENTS

The feasibility to meet the cross-mission combinations described in 4.1.1 in operations will gradually increase with the continuous addition of further Sentinels into the entire data collection scheme, in particular of:

- further Sentinels of the current series (C&D units);
- Expansion Sentinels as from 2027;
- Next Generation (NG) Sentinels as from 2031[29];
- further data access agreements with contributing missions (hese agreements will enhance the revisit frequency of the same instrument families).

29 Phase-0 of these NG missions is completed; different expert groups are currently preparing further assumptions for the Phase-A studies. Reference ESA, (2020) Copernicus long-term scenario.

For the mission operations scenario, PEG experts confirm the need for cross-instrument sensing (e.g. quasi-simultaneous acquisitions of different instruments) over polar regions and adjacent seas and for missions with a limited duty cycle. These leads to the following requirements:

- seek maximum synergy between observations of the same geographical areas from different instruments, e.g. between:
  - C-band/C-band SARs
  - Sentinel-1 SAR /ROSE-L- SARs but also between
  - Sentinel-1 SAR/CIMR and CIMR/MetOp-SG-B
  - Sentinel-1 SAR-, ROSE-L SAR with CIMR
  - ROSE-L SAR / CIMR / CRISTAL
  - Sentinel-3 SLSTR/CIMR
  - Sentinel-3/CRISTAL
  - ROSE-L SAR / CIMR / CRISTAL
  - And other combinations addressed in chapter 2.4.
- planning of instrument-, imaging mode operations, according to the specified needs,
- planning of downlink, data acquisition and processing according to the specified timeliness from sensing.

An initial set of cross-mission requirements are summarised in Table 4 below.

Table 4: Initial set of examples of 'Cross-Mission/Instrument' requirements for Sentinel-1 and -3, HPCMs and related contributing missions

	C-Band SAR			L-Band SAR		Radar Altimeter		PMR	
	S1	S1-NG	CCM	Rose-L	L-Contrib.	Cristal	Contr	CIMR	Contr
S1	daily coverage without gaps ;	Cross-cal, daily (or 6h) coverage without gaps	RCM to complement acquistion gaps	< 6 min (1 min*), align timeliness of Acq&NRT Processing, align acq plan/duty cycle		Sync in processing		<1h	
S1-NG	Cross-cal, daily (or 6h) coverage without gaps								
CCM	Compl. Planning S1/RCM								
Rose-L	< 6 min (1 min*), align timeliness of Acq&NRT Processing, align acq plan/duty cycle				Cross-Cal			<3h	
L-Contr									
Cristal				Overlap/ Repeat Mode alignement			Constellation with S3&S6	<3h	
CR-Contr						S3-RA sync			
CIMR	< 1h			<3h		<3h			Metop-SG-B (1-7-10 min apart)
CIMR Contr								Sync with Metop NG; Contempory;	

(*) Rose-L MRD specifies RoseL behind 1min-1h behind S1, this compromises the revisit.

4.2 RESULTS OF ESA SIMULATIONS

The Mission Requirement Documents of CIMR, CRISTAL and ROSE-L address a series of orbit configurations handling the missions individually, but also considering the cross-mission requirements with already planned mission (e.g. CIMR in the same reference ground track as MetOp-SG(B)). However, the MRDs do not in detail express requirements for orbit configuration supporting the cross-instrument synergies addressed by KEPLER or the PEG.

Still, ESA were very cooperative and supportive to requests from the PEG when requesting cross-instrument analysis. A very comprehensive and detailed set of analysis of different orbit- and instrument operations' scenarios, simulations and options, was presented by ESA to PEG experts as per the table below:

Instrument combination of Existing and Expansion Sentinel missions	Simulations (daylight/ eclipse)	Mean Local Solar Time (MLST[30])				
CIMR,CRISTAL,ROSE-L, Sentinel-1 A/B		06:00	09:00	12:00	15:00	18:00
CIMR,Sentinel-1	Daylight, 2-5 days					
CIMR,Sentinel-3	Daylight, 5 days					
CRISTAL,Sentinel-1	Daylight					
CRISTAL,Sentinel-3	Daylight					
CIMR,MetOp-SG	Daylight/Eclipse, 1 day 1. Arctic view 2. Global view					
CIMR coverage	Daylight 1. Arctic view					

These simulations and the detailed presentations are available for consultation on the publicly accessible server: https://www.copernicus.eu/en/Copernicus-Animations-2021 (or use the QR code).

4.3 VIEWS OF PEG EXPERTS ON THE CROSS-INSTRUMENT ANALYSIS

The differences in duty cycle and/or revisit and coverage for the various instruments are evident in the ESA simulations mentioned above: CIMR with pan-polar coverage on a daily basis, CRISTAL with ground track location/choice of orbit and the SAR systems with restricted swaths and duty cycles. The SAR systems are therefore more demanding for the ground segment in order to make most out of their cross-instrument potentials. Below follow some views of the Polar Experts cross-instrument analysis presented by ESA:

- **3 Sentinel-1 units operated simultaneously** would ensure a sub-daily gap-free coverage of the Arctic region including the southern part of Greenland (see gap in Figure 3 below). *This is the preferred solution of the PEG majority.* The orbit phasing of the 3 Sentinel-1 missions should be 0-120-240 degrees (see Figure 4 below). Until then and also beyond that time, a close cooperation with Radarsat Constellation Mission (RCM) operations[31] and mutual timely data exchange should be sought. It is understood that a 6h-repeat coverage is a goal not yet fully met by the current constellation;

30 Mean Local Solar Time (MLST): The average local time of the descending node of a spacecraft's Sun- synchronous orbit.
31 Canadian Space Agency, (2020), Access to data - Standard coverage maps

Figure 3. Example: Greenland Sentinel-1 coverage gap (mode IW, polarization DH)

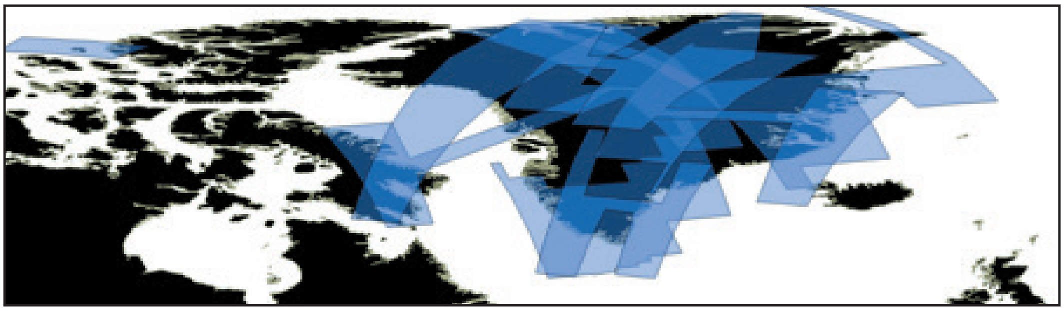
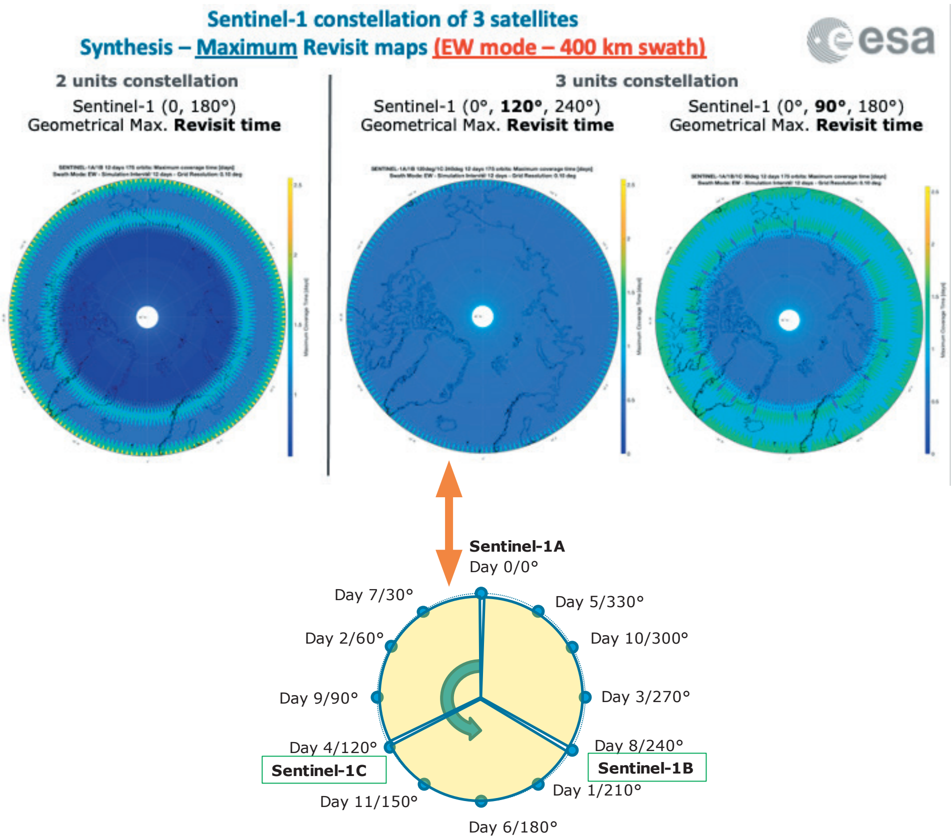


Figure 4. Options for Sentinel-1 constellations
(for further details see ESA Presentation on the publicly accessible server [32])



- **The timeliness requirement for (level L1-2) data products of 1 h from sensing, [33] e.g., for Sentinel-1, ROSE-L and CIMR can be** met in direct station visibility using a pass-through mode and real-time processing at the receiving station[34]. Using an additional satellite data relay function (EDRS), e.g. for S1 and ROSE-L, would further increase the downlink capacity for the operations scenario;
- **The timeliness requirement for a 1-6 minutes max offset from Sentinel-1 C-band to ROSE L-band acquisition** is considered by the PEG as a higher priority than the option to use ROSE-L for gap-filling the C-band coverage. This latter requirement may be met through a cooperation with RCM. Accordingly, the C-L-band mission requirement MR-SYS-090 is confirmed;

32 Presentation prepared by Pierre Potin, ESA, 2020.
33 Both, the PEG-I report and the KEPLER Report D3.3 had already expressed the timeliness requirement <1h for sea-ice monitoring from Sentinel-1, ROSE-L and CIMR.
34 For Sentinel-2 this timeliness is currently not planned.

MR-SYS-090	**The mission shall enable quick successive collocated L-band SAR image acquisitions with Sentinel-1 with a time interval between L-band and C-band acquisitions of 1minute or less.**
	This requirement can be traced to the use of L- and C-band SAR imagery for new enhanced information products for floating sea ice (Sec 3.2.4.2). Sea ice is a dynamic part of the world surface often moves at rates of up to 20cm/second or more. A maximum complementarity between C- and L-band requires near-simultaneous acquisitions for both frequencies, likely in order of 10s of seconds to 1hour. The precise requirement is under study as flying as flying in formation reduces the revisit capabilities of the constellation consisting of ROSE-L and Sentinel-1. A potential additional benefit of very short time intervals between successive acquisitions is the tracking of vessels from one image to another, enabling to derive efficiently their speed.

- **The synergy operations requirement for CIMR with MetOp-SG-B (MRD-030)** has been confirmed and no issues are currently expected;

MRD-030 The separation in time between the ascending node crossing of MetOp-SG(B) and the ascending node crossing of CIMR shall be between 1 and 7 minutes.

Note 1: This requirement is used to set the timeliness of crossovers between CIMR and MetOp-SG(B) in the polar regions within ±10 minutes (CIMR orbit control 'box' parameter). The impact of a time separation of ±10 minutes between many *geophysical products can be, in general, ignored because at a scale of 5-10 km the surface target scene properties of the ocean surface, sea ice and ice sheets will not have changed sufficiently to introduce significant uncertainty into the final products.*

Note 2: However, ±10 minutes is significant with respect to atmospheric state: for example (e.g.,

- CMEMS and other Copernicus Services have been using Landsat data in low sun illumination conditions over the Arctic. An adaptation of the Sentinel-2 acquisition strategy at sun zenith angles reaching a latitude of 85 deg. over certain Arctic regions is requested and already planned;
- The acquisition plans of Sentinels and Copernicus Contributing Missions should be coordinated through arrangements to ensure best revisit and redundancy for all Copernicus user communities and particularly the polar areas;
- **The High Level Operations Plan mechanism (HLOP)** allowing for adaptation of the mission operations scenario shall be transparently used to manage the compromise between the priorities of different user communities. The option of acquisition campaigns, i.e. for certain instrument operations or even orbit scenarios during specific periods shall be considered. The HLOP is regularly updated and discussed with experts.
- **Cross-calibration campaigns** shall be organised for the different instrument synergies. This cross-calibration data shall be made available for science use and for services;
- **Some cross-calibration campaigns are disadvantages** for other applications and goals (e.g. ROSE-L satellite phasing close to S1 satellites, privileging cross-band observations rather than increase coverage and repeat observation frequency);
- **The simulations and plans of the existing Sentinels and HPCMs either confirm fulfilment of PEG requirements or form the basis for further recommendations and decisions**, which also need to account for financial, technical and operational aspects. However, some options/choices on the operations scenario will remain open until and even during operations phase and shall be continuously addressed through a regular consultation with users and experts.

5. OVERALL GROUND SEGMENT OPERATIONS CONSIDERATIONS

5.1 OVERALL GROUND SEGMENT CONCEPT

The ground segment of the Copernicus space infrastructure is based on a modular approach making use of services and facilities common to various Sentinel missions (e.g. acquisition services, data processing/ production, data quality, data distribution, data archive). This multi-mission approach will allow to "plug-in" and integrate mission-specific components or services for new missions such as HPCMs (processors, mission planning, specific auxiliary data etc.). Different elements of the ground segment will contractually and operationally be managed and implemented through ESA and EUMETSAT respectively. The required flexibility to adapt the existing ground segment to the different cross-mission operations is therefore anticipated.

Regarding the downlinks, there are no constraints for the Sentinels overflying the same receiving stations at the same time. For the planned orbit scenarios no issues on interference in the Radio-Frequency (RF) downlink[35] are expected as of today. Therefore within the onboard constraints and within direct station visibility quasi-real-time (QRT) or near-real-time (NRT) data access (either 1h or 3h from sensing to the intermediary users such as the Ice-Services) is technically possible, but RF risks need to be continuously explored. Near-real-time processing and product dissemination with the adequate throughput are part of the Sentinel core ground segment, while this is not the case for QRT product data and information product generation and dissemination. QRT have been implemented by several member states in the framework of Collaborative Ground Segment (CollGS) initiatives.

The ground segment provides a long-term data archiving (LTA) functionality for raw (Level0) data. The LTA service ensures data preservation and integrity as well as the production service for reprocessing campaigns. Mission Performance Clusters (MPC) ensure the evolution of algorithms and updates of cal/ val data and plan reprocessing campaigns as required.

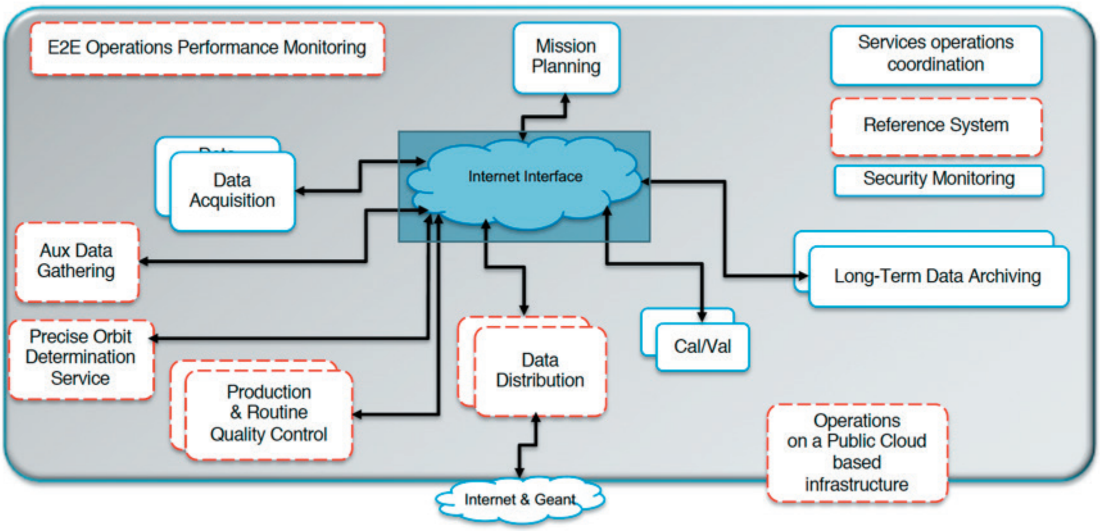


Figure 5. ESA Sentinel Ground Segment Architecture

35 The Sentinel-1 and ROSE-L satellite will follow each other by a few seconds or minutes, however the Sentinel-1 satellites perform RF downlink in X-band, whereas ROSE-L satellites will perform RF downlink in Ka-Band.

The ground segment functions and facilities put in place by EUMETSAT in the framework of Copernicus rely on the evolution of and synergy with its validated multi-mission elements and services.

The ground segment infrastructures put in place by ESA and EUMETSAT for Copernicus are fully compatible. The evolution and compatibility of the ESA and EUMETSAT ground-segment elements are assessed periodically, with the next checkpoint planned for early 2021.

5.2 TECHNICAL AND PROGRAMMATIC CONSIDERATIONS

The final operations concept will be influenced by a number of decisions such as the number of Sentinel satellites to be operated simultaneously (e.g. 2 or 3 Sentinel-1 units), the exact launch dates as a consequence of development cycles, and other programmatic or operational elements (e.g. funding availability, risk of failure of one Sentinel).

Consequently, the planning and preparation of the Copernicus Space segment operations will require adaptation of operations scenarios always aiming at best users' satisfaction within the existing constraints.

5.3 EVOLUTION OF THE OPERATIONS APPROACH

Sentinels – especially the ones with a limited duty cycle [36](Sentinels-1 and -2 and partly Sentinel-3 and Sentinel-5P) - are currently operated, following a High-Level Operations Plan (HLOP). This HLOP is updated on a regular basis, in consultation with the European Commission and Copernicus Services, taking into account the evolution of observation needs by the different users and services, and the system capacity. A recent update of the HLOP addressed e.g., the need from the Copernicus Climate Change Service (C3S) for permanent inner Greenland coverage as illustrated in Figure 6.

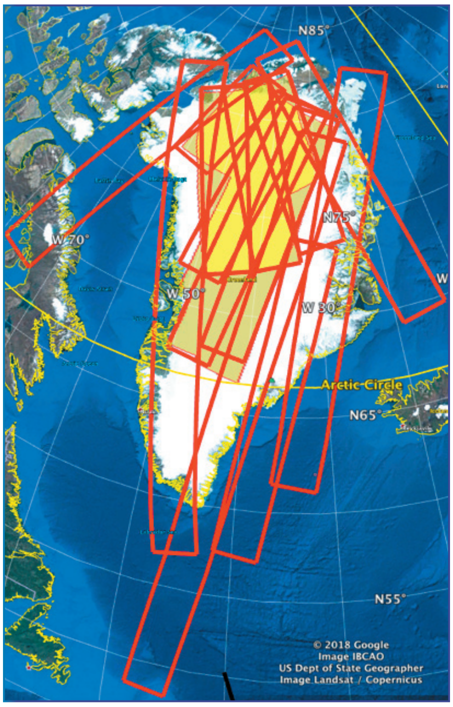
Future versions of the HLOP – always jointly developed by ESA and the European Commission - will additionally address the operations of ROSE-L and other relevant Sentinels.

All Sentinel data from past and future missions are downlinked and processed systematically according to a predefined list of core products within specified timeliness.

For the upcoming Sentinel missions, these Level-1 and Level-2 standard products are still to be specified. The algorithms and quality parameters are being defined/developed with the science and applications user communities.

Data access will rely, in line with the Copernicus data policy, on a suite of openly accessible cloud environment(s) which offer streamlined download interfaces, processing and cooperation environments for the users. This/these cloud environment(s) will have to ensure sufficient redundancy and inter-dependencies (e.g. through federation) for avoiding network traffic issues for the Copernicus Services, public and scientific users. With increasing amount of data, the dissemination capacity needs to be re-assessed regularly.

36 i.e. instruments which can operate only on parts of an orbit or in different modes throughout the orbit



The cross-operations of some missions (e.g. Sentinel-1 and ROSE-L) will require the additional, specific setup of cross-mission elements, such as the mission planning to ensure joint observations. Further enhancements in timeliness, will also require adjustments of the multi-mission ground segment in terms of acquisitions, processing and dissemination.

It should be noted that the space infrastructure ground segment will generate single instrument Level 1 and Level 2 geophysical products. The cross-mission integration and synergetic processing in synergy of these single-mission products are to be planned and prepared by the Copernicus Services. The space infrastructure ground segment shall provide the necessary auxiliary data (orbit information, instrument timing and parameters, etc.) to support the generation of such synergy-products by the Copernicus Services.

Figure 6. Regular Sentinel-1 coverage of the inner part of Greenland, in addition to the specific yearly acquisition campaigns providing a 6-day repeat frequency in both ascending and descending geometry

5.4 GROUND SEGMENT & OPERATIONS SUMMARY

ESA's current analysis confirms that:

- cross-mission coordination and operations are specifically relevant for the constellations of Sentinel-1 and ROSE-L, and require not only the maintenance of a specific orbital configuration, but also the coordinated planning of instrument/mode observations;
- complementarity of the Sentinel observation scenario with relevant contributing missions, such as RCM, and ALOS-4, shall be sought, e.g. to improve revisit over sea-ice areas not daily covered;
- the polar user community is invited to provide input to the regular updates of the high-level operations plans (HLOP);
- CIMR will provide key and frequent observations of polar areas; joint operations of CIMR (which is operated by ESA) and MetOP-SG (which will be operated by EUMETSAT) are planned and specified in the CIMR MRD;
- CRISTAL is foreseen to be operated independently and does not require orbit synchronisation with non-altimetry missions; but concomitant observations with other missions are of interest (see related simulations);
- Sentinel-2 should be further considered by the PEG and Arctic services, especially as observations in low illumination conditions have been recently included in the Sentinel HLOP.

The selection of data from Contributing Missions, being made available through Copernicus to the Services, shall transparently follow the user-priorities:

- Current agreements with the operators of contributing missions will be extended and aligned with the operation concept of the HPCMs;
- New contributing missions will complement the Sentinel data, e.g., RCM will extend the C-band SAR observations provided by Sentinel-1 on relevant Arctic regions in order to further increase the revisit frequency.

Cross-mission operations and synergy aspects at the space- and ground segment need to be:

- complemented by multi-mission products by the Copernicus Services and the related science base;
- supported by inter-calibration and inter-validation activities.

6. STATUS AND EVOLUTION OF COPERNICUS POLAR SERVICES

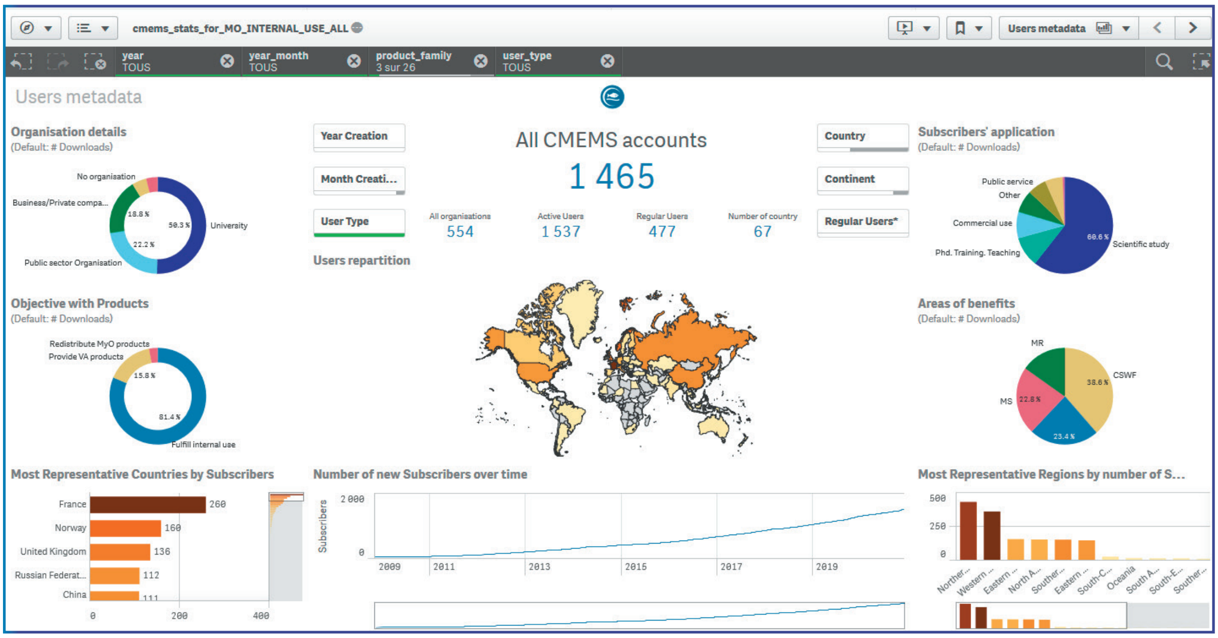
A short summary is provided on the current status of Copernicus services and their evolution with particular attention given to polar relevance.

6.1 CMEMS STATUS AND EVOLUTION

STATUS

The current state of CMEMS polar products users (incl. intermediate and end-users) is regularly established from a statistical analysis. At this date (autumn 2020) and since the opening of the service in 2009 (incl. MyOcean projects), 477 regular users have downloaded polar (Arctic only + sea ice) products all over the world where European countries remain by far the most representative countries. These users are spread within more than 500 different organisations. The number of new subscribers is continuously increasing. Scientific studies are the main subscribers' application within universities and public sector organisations. In terms of areas of benefits, the Climate (ice monitoring), Seasonal and Weather Forecasts is the sector that benefits most from polar CMEMS products; Marine Resources being the less representative area. The NRT products are preferred over the reanalysis products. This is illustrated in Figure 7 below.

Figure 7 CMEMS polar products and users



EVOLUTION

Feedbacks from users is overall positive but indicates the need for improvement of existing products and for new products and new services. This is comprehensively addressed in the KEPLER project and includes, for instance, the need for a more complete portfolio of higher spatial and temporal resolution sea ice products, easier download of products, the availability of additional forecast products (e.g. iceberg forecasts), the need for observations of biogeochemistry parameters and the development of improved models (e.g. improved sea ice model physics).

6.2 CLMS STATUS AND EVOLUTION

STATUS

The Copernicus Land Monitoring Service (CLMS) is divided into three components, namely global, pan-European and local. Priority has been given to the global CLMS product portfolio structured into several themes, among them "Cryosphere" that includes only three variables: lake ice extent, snow cover extent, and snow water equivalent. Snow cover extent and lake ice extent are based only on satellite data, while snow water equivalent assimilates satellite data and in-situ snow measurements. None of the cryosphere products in the current global CLMS product catalogue uses forecasts or reanalysis products derived from data assimilation.

The current state of CLMS cryosphere products is provided on the CLMS portal and states that 94 TB of data were downloaded in the 2nd quarter of 2019. There are 5000 registered users. However, this concerns the whole global CLMS, no details are provided for just the cryosphere products users.

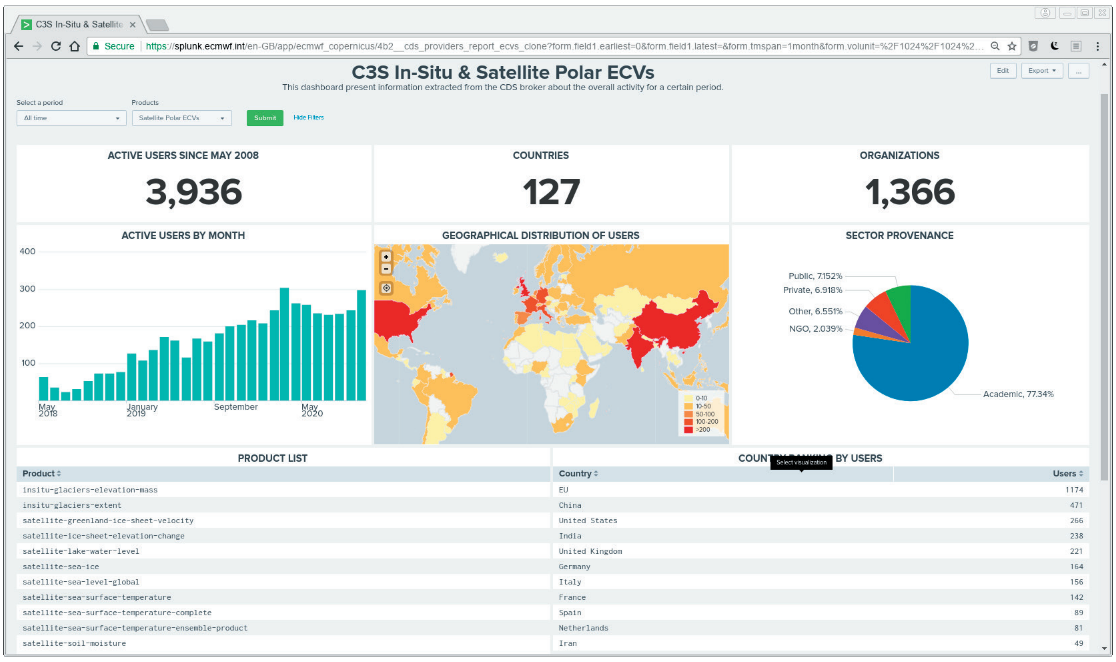
EVOLUTION

Production and delivery of land forecast products should be considered as well as the evolution of the current products (algorithm evolution, adaptation to new sensors) and the generation of validated new products (e.g. permafrost, snow condition (dry/wet)). Further recommendations for potential evolution of the cryospheric product portfolio includes: (i) attachment of a per-pixel uncertainty estimation layer to each product; (ii) continuous quality assessment of products in key region using independent reference data sets (e.g. from high resolution sensors, in-situ data); (iii) homogenization of relevant services; (iv) contribution to international satellite snow product intercomparison and validation exercises (e.g. https://earth.esa.int/eogateway/activities/snowpex).

6.3 C3S STATUS AND EVOLUTION

STATUS

C3S closely monitors data access to its products to assess and improve the service to its user community. As of November 2020, close to 4,000 users had downloaded C3S ECV products relevant to the polar regions through the C3S Climate Data Store since the opening of the service in May 2018. These polar products include both satellite-based products (floating ice variables, ice sheet velocity[37] and elevation change[38], sea surface temperature, sea level anomaly, soil moisture, lake water level) and in-situ products (glacier extent, elevation and mass balance[39]). Users of these products originate from close to 1,400 organisations spread across 127 countries. EU countries represent the main contingent (30%), followed by China, the United States, and India (25% combined). Unlike CMEMS users, C3S users come overwhelmingly from the academic sector (75%). The steady growth in the number of monthly users since 2018 can be attributed both to new user uptake and to the integration of new ECV products in the CDS. This number represents a relatively small fraction of the total number of registered C3S users (>60,000). These polar products include datasets with global coverage such as sea level anomaly or SST, which means that their use is not limited to polar applications. At the same time, global reanalysis products, such as ERA5 and ERA5-land, which can also be used for polar applications.



EVOLUTION

The evolution of C3S is driven by feedback and requirements from users collected through regular user surveys and gathered in a User Requirement Database. In addition to regular extension of its Climate Data Records (CDRs), new CDR versions are also produced periodically to incorporate developments in algorithms, changes in input data, and the need to produce consistent and stable data records. Furthermore, data quality is a central aspect of the C3S service. Building on the work of the C3S Evaluation and Quality Control (EQC) service, a new quality assessment feature was first implemented in October 2020 for selected datasets in the CDS and will be further enhanced and expanded in subsequent months. This new feature is intended to provide guidance to users on the content, quality, and usability of C3S products and relies on independent technical and scientific assessments of the datasets also available to users.

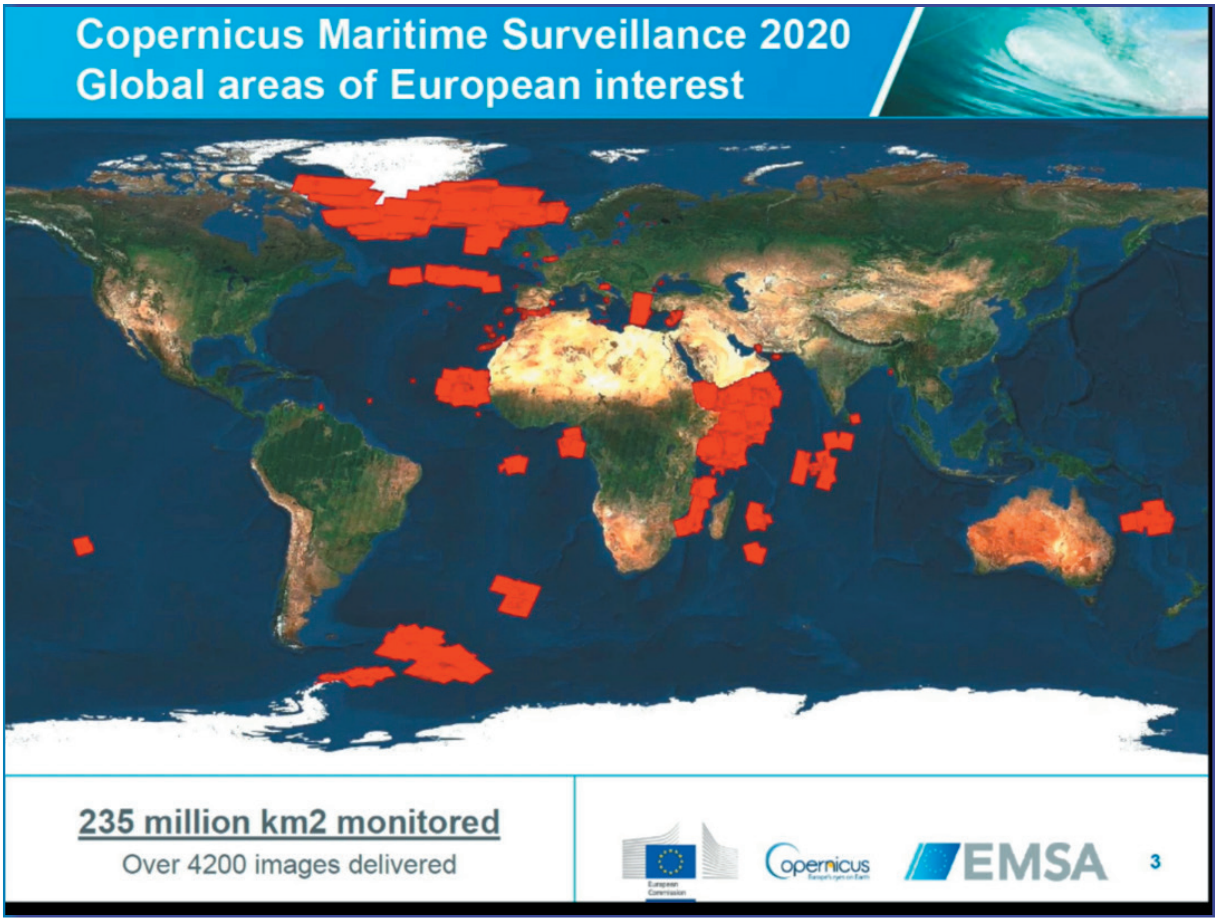
37 product for Greenland - relies on data from Copernicus Sentinel-1
38 product for Greenland and Antarctic – relies on CryoSat-2 and Sentinel-3A
39 product for Greenland, brokered from ESA CCI – will be reliant on the GRACE-FO Mission

6.4 CMS STATUS AND EVOLUTION

STATUS

Operational services are delivered to Member States' national authorities and EU bodies in the function areas of fisheries control, maritime safety and security, law enforcement, customs, marine environment pollution monitoring, and support to international organisations (e.g. United Nations Office of Drugs and Crime (UNODC) and other user communities. Figure 8 below indicates the areas of interest covered by CMS.

Figure 8. Global areas of European interest covered by CMS in 2020



CMS has close to 50 registered user organisations, but there is no readily available statistics for CMS monitoring activities specific for polar regions. CMS is activated by Copernicus Participating Countries in the Arctic from Greenland in the west to Finland in the east. CMS is also activated in the Antarctic and Safety of navigation.

EVOLUTION

The service evolution activities include the identification and validation of technical and operational solutions for future products and services. These activities stem from the requirements of users which are gathered in a variety of contexts such as (i) User Requirement Workshops and Annual User Groups, (ii) User Uptake Meetings, (iii) User questionnaires, and (iv) User feedback forms submitted on completion of an operation. These activities include support to exercises and operations of end-users with the purpose of carrying out operational validation of already existing products in new areas of application (new use, new geographical areas, etc.).

6.5 CEMS STATUS AND EVOLUTION

STATUS

The Copernicus Emergency Management Service (CEMS) is divided into two modules namely Early-warning and monitoring (fires, floods and droughts) and on-demand mapping (Rapid Mapping and Risk & Recovery). The early-warning and monitoring service of interest to polar regions includes EFAS (European Flood Awareness System) and EFFIS (European Forest Fire Information System).

EFAS is designed to support preparatory measures for flood events across Europe, particularly in large transnational river basins. To this end, EFAS relies on a hydrological forecasting chain including meteorological forcing and land surface data and hydrological models. The hydrological model LISFLOOD, developed by JRC, is primarily used for medium- and seasonal-range forecasts, whilst conceptual hydrological algorithms are used for the flash flood indicators. EFAS products are a set of maps and graphs that highlight possible future flood risk from the EFAS forecast simulations. They are produced by comparing the forecasts with reference flood thresholds, and are categorised according to different lead-time:

- Flash flood indicators: they provide indication of risk of flooding from flash floods, up to 5 days;
- Medium-range flood forecasts: they give overview of upcoming flood events for the next 10 days;
- Seasonal hydrological outlooks: they summarise the hydrological situation over the next 8 weeks;
- Flood impact forecasts: they highlight regions with expected impacts in the next 10 days.

EFFIS supports the services in charge of the protection of forests against fires in the EU Member States and provides the European Commission services and the European Parliament with updated and reliable information on wildland fires in Europe. EFFIS is supported by a network of experts from 40 countries in European, the Middle East and North African countries. Main EFFIS modules include fire danger forecast, active fire detection, rapid damage assessment, fire damage assessment, European fire database, seasonal forecast and monthly forecast. Referring to the 2019 EFFIS annual report, EFFIS is widely used by government organisations and citizens with nearly 200,000 users from 188 countries. At present, the EFFIS network constitutes 43 countries including 26 EU Member States, 12 European non-EU countries and 5 MENA (Middle East and North Africa) countries.

Today there are some 6680 registered users with CEMS (Mapping: 32[40], Floods: 6,605, Fires: 43[41] countries):

EFFIS	2019	2020
Burnt Area (ha)	European Union: 333542.12 Other European countries: 199847.03 Middle East and North Africa: 256340.58	European Union: 338263 Other European countries: 54705 Middle East and North Africa: 188161
Number of Fires	European Union: 2282 Other European countries: 1025 Middle East and North Africa: 555	European Union: 1658 Other European countries: 1368 Middle East and North Africa: 698

Country specific statistics are available on the EFFIS website (https://effis.jrc.ec.europa.eu/).

CEMS activities covering the Arctic have increased in recent years with activations from the Civil Protection Authorities monitoring fires and floods in the region.

40 Authorised Users only.
41 One registered user for each country member of EFFIS.

In recent years there has been an increase of activations in the Arctic.

There have been on-demand activations in Greenland for wild fire monitoring in 2017 and 2019, as well as for the large-scale forest fires in Sweden in 2018. In 2020 the high temperatures in Russia resulted in large-scale forest fires of 5,000,000 hectares over the period May-August[42].

On-demand activations for floods have increased for the Scandinavian countries above 60 degrees latitude with activations in Norway, Sweden and Finland for monitoring and delineating the spring floods in 2020.

EVOLUTION

CEMS is recognised for their Rapid Mapping activations, but as the access to satellite data and other data is increasing, new automatic products are being developed allowing continuous detection of fires and monitoring of fires and floods. Upgrading of models and setting up of databases are also in progress for both EFFIS and EFAS:

- EFFIS: Additional EFFIS modules are under development such as the post-fire vegetation regeneration and the post-fire soil erosion risk;
- EFAS: The set-up of the systematic, automated, Sentinel-1 based global flood monitoring product.

42 https://erccportal.jrc.ec.europa.eu/Maps//NEWMAPSPAGE#/maps/3565

7. FINDINGS AND RECOMMENDATIONS

7.1 EU POLICY AND STRATEGY FOR CLIMATE CHANGE ACTIONS

Over the last decade major European policy decisions have been taken in response to the concerns of politicians, decision-makers and the scientific community in relation to climate change consequences and possible mitigations actions. These concerns were expressed at the highest political level in 2015 by the COP 21 Paris Agreement with the objectives of 40% GHGs emission reduction by 2030 and climate neutrality by 2050.

A major component of the complex Earth climate system is the cryosphere as defined in the special 2019 IPCC report entitled "The Ocean and Cryosphere in a Changing Climate", namely: "Volumes of snow, glaciers, land ice, ice sheets, pack ice, icebergs, sea, lake and river ice, and temporarily or permanently frozen soils (permafrost depending on the season)". Understanding and forecasting climate change implies a close and continuous monitoring of the cryosphere and more specifically the Arctic, Antarctica and Greenland. This need was expressed in the EU Arctic Policy ("An integrated European Union Policy for the Arctic", 2016) and in the EU Council conclusions of "Space solutions for a sustainable Arctic" (November 2019).

This was recently further confirmed with the EU Green Deal and its European Climate Pact adopted in 2020 by the EU Council. The relevance of the Arctic Policy was also reiterated in President von der Leyen's Letter of Intent for the State of the Union 2020 and spelled out in the Work Programme 2021 (headline ambition "A stronger Europe in the world"):

"... and present a Communication on the Arctic to update EU policy towards a region particularly exposed to climate change and environmental pressures and its economic and security impact".

The update of the Communication will have to handle and balance the safeguarding of the Arctic, the interests of the local communities in the Arctic and an increased international interest in the resources and the potentials (e.g. natural resources, ship routing) in the region. To sustain peace in the region all developments need to be carefully monitored and Copernicus plays and will play an important role providing data and information for the Arctic.

7.2 COPERNICUS, A MAJOR EUROPEAN CONTRIBUTION TO POLAR REGION MONITORING

With the implementation of the Copernicus programme over the last decade, Europe today has an acknowledged leading position worldwide for the monitoring of the Earth environment and the provision of satellite-based quality services addressing 6 priority thematic domains namely land, marine, atmosphere, climate change, emergency management and security.

Copernicus has deployed 8 major "Sentinel" satellites into orbit. Daily these generate every day tens of terabytes of data, which are freely accessible and provide reliable and high-quality information and data products through Data and Information Access Services (DIAS) to tens of thousands of users from the six priority domains as mentioned above. Users come from a wide spectrum of affiliations from research scientists to local/regional/national government authorities, industry, NGOs and SMEs developing new and innovative space-based applications including commercial businesses.

The polar user community is an important one and is provided with products generated from several Copernicus services as, today, there is no single/stand-alone "Copernicus Polar Service". In practice, "Polar products" are available on an operational basis since 2014/15, provided mostly by CMEMS CAMS, CLMS and C3S but as well by the on-demand services (CEMS and CMS).

7.3 PEG III SUMMARY FINDINGS AND RECOMMENDATIONS

The main PEG III findings and recommendation are summarized in the following subsections.

7.3.1 CONTINUITY OF OBSERVATIONS

CONTINUITY OF OBSERVATIONS BASED ON SPACE ASSETS

Continuity and improved capabilities of satellite observations are crucial for the provision of long-term time series of observations to operational users' entities and to the very active European scientific research community. The current launch schedule and development of space assets will have to be reviewed to ensure a strict continuity of space observations and, in any case, minimise gaps, which may for instance occur for space altimetry data and PMR L-band (1.4 GHz) data. In the case of gaps, partnerships with third party mission operators will have to be concluded to fill these gaps to the maximum extent possible.

As described in Chapter 2 it is of high importance to ensure the availability of the observations that the Copernicus Services are using today (baseline 2020). Sentinel-1 is used for several applications and the need for an increased availability is stressed by the users and especially the Copernicus Services. Copernicus is currently exploring the possibility of phasing in a third satellite of Sentinel-1, -2, -3, and having 3 satellites in orbit. A constellation of 3 satellites in orbit of Sentinel-1 is a priority for the Copernicus Services as this is highlighted for the geophysical variables addressed by the PEG. Complementary data from the Radarsat Constellation Mission (RCM) is also requested by the services that make use of the RADARSAT-2 data today. Access to RCM data was analysed by the PEG and the cooperation and coordination efforts made by ESA together with the Canadian Space Agency on RCM/Sentinel acquisition planning are appreciated.

[REC1: The PEG III recommends that the Copernicus Space Component (CSC) provides C-band SAR data with an improved coverage and higher revisit time in line with the PEG III requirements. This entails:

- Continuously 3 S-1 satellites in orbit (Sentinel-1A to Sentinel-1D);
- RCM data in the Copernicus Contributing Mission portfolio with latency comparable to the RADARSAT-2 data

Passive microwave radiometer (PMR) and altimeter data are currently extensively used by the Copernicus Services (mainly CMEMS, C3S and CLMS) and it is important to ensure continuous provision of these data. A PMR mission was considered as the priority of PEG II as it responded best to the observation requirements for the priority variables: Floating ice (in particular sea-ice concentration), ice sheets, glaciers/ice caps and snow. CIMR as a response to the PEG II report goes further with instruments allowing L-band data to be generated. CIMR is consequently the microwave mission among the Copernicus HPCMs that addresses the priority user requirements, as defined in PEG I and II, and can contribute to the highest number of PEG III variables.

Data from CIMR and CRISTAL will be easily integrated in the work of the Copernicus Services. Copernicus currently relies on data from third-party missions to cover the provision of these data and the uncertainty of data availability is addressed as potential gaps for the future (see "summary table" in Annex 3). These gaps will impact the following Copernicus products:

- PMR (L-band): Thin sea ice (sea ice thickness < 0.5 meter), sea surface salinity, soil moisture;
- Altimeter (north of 81.5 North/south of 81.5 South): sea ice thickness (> 0.5 meter), sea level anomaly, surface elevation change.

PMR frequencies covered by AMSR-2 are still accessible as this instrument is operational despite that the estimated life-time ending in 2021. The CIMR Mission Requirement Document indicates that AMSR-2 will be operational until 2025 meaning that it overlaps with AMSR-3 (planned launch date 2023). AMSR-3 was decided in 2020 by JAXA, which worried the users as there are no identical alternatives. This uncertainty is relevant for various missions where one is dependent on one or few third-party missions and this can potentially also be the case beyond AMSR-3 (projected lifetime to 2028).

[REC2: The PEG III recommends that clear mitigation plans and actions are put in place to reduce the risk of future gaps for altimeter data (north of 81.5 North/south of 81.5 South) and PMR L-band (for the polar regions)[43]].

[REC3: In case a selection procedure between the six Copernicus HPCMs is necessary, then the PEG III recommends that continuity of the Copernicus Services is prioritised and that the vulnerability of being dependent on one or few third-party data providers is considered].

L-band SAR missions are currently not used today (baseline 2020), as operational data are not available for the Copernicus Services, but there is an interest of the Copernicus Services to test these in combination with Sentinel-1. The PEG identified capabilities of L-band SAR also in combination with Sentinel-1 C-band SAR for potentially improving Copernicus Services (identifying the potential improvement of current products and the generation of new products). This is at an early stage and it is currently unclear to what degree this will strengthen Copernicus as a whole, but there is a strong interest from Ice Services to further explore the potentials of combining C- and L-band SAR for precise sea ice mapping.

[REC4: The PEG recommends further efforts to explore the possibilities with L-band SAR data for operations based on the experiences gained from various space agencies worldwide (e.g. Japan, Argentina, USA)].

X-band SAR missions are already available as Contributing Missions and will be further complemented with additional missions in the period 2021-2027 (see also 7.3.7 Role and contribution of Industry).

The requirements for the Next Generation Sentinels 1 and 3 (SRAL, SLSTR) are stringent, requiring continuous pan-polar and sub-daily monitoring of polar regions. For NG-S1, the Copernicus Services have additional requirements for fulfilling the variables that relate to their products, such as as higher horizontal resolution and improved data latency.

43 PEG III focus is only on MW instrumentation, but this is also applicable in general for other types of Copernicus data

CONTINUITY OF OBSERVATIONS BASED ON NON-SPACE ASSETS (IN-SITU)

In-situ data is sparse in the polar regions and there is a clear need for Copernicus to make major efforts to increase the number of observation platforms and equipment in particular for the central Arctic region (this is also applicable to Antarctica and Greenland). Development of international cooperation with Arctic countries is essential, but also with the research community and national investments in order to sustain a repository of in-situ data.

The basis for international cooperation is clearly the needs of the European Space Programme and what this programme can offer in exchange as data and services. In order to clarify the needs, the PEG produced an overview table including the gaps of in-situ data and potential instruments for covering the gaps (see "the summary table" in Annex 3).

7.3.2 EFFICIENT DATA MANAGEMENT FOR IN-SITU DATA

An inventory of existing in-situ observation platforms in the Arctic has identified a variety of in-situ platforms deployed primarily by national/multi-national research projects /programmes but lacking proper coordination and having, for various reasons, a somewhat limited cooperation. Major improvements are required not only to maintain this equipment operating in a harsh environment but also to organise an efficient data management system in order to maximise the use and ease the access to these data and also to ensure the timely delivery of the data. This effort should include in particular the definition of agreed data standards and formats, modalities of access and conditions of utilisation, and possibilities and conditions for exchange of data (some have a restricted access or are available at commercial rates) between the parties concerned. An additional and important aspect is to highlight the need for improved access to non-European in-situ research and operational monitoring data from countries such as Russia (having a long tradition and experience with Arctic activities) and from countries having expressed an interest in operating in the Arctic (e.g. China, Korea, Japan).

[REC5: The PEG recommends continuous[44], stronger international cooperation/coordination (including all EU Member States, WMO and Arctic States) and encouraging national investments/effort to develop and maintain platforms and equipment. In-situ data used for research and operational services, in the polar regions, shall be free and open, following standardised data formats].

[REC6: The PEG recommends that requirements for Fiducial Reference Measurements become an integrated part in the Mission Requirements and consequently in the design phase of new Sentinel missions].

7.3.3 BENEFITS OF THE COPERNICUS HPCMS IN SYNERGY WITH EXISTING AND FORTHCOMING NG SENTINELS

The possibility of having the three Copernicus HPCMs, CIMR, CRISTAL and ROSE-L, used in synergy with existing and forthcoming NG Sentinels will bring unique opportunities for Copernicus services. The major improvements provided in terms of spatial and temporal coverage, horizontal resolution and multi-microwave frequency observations will complement the current Sentinel observations and enable the development of improvement for existing products, for instance, in terms of accuracy of some products (e.g. floating ice products) as well as the development of new innovative products as described in Chapter 2. It should be noted that this is conditional upon the selection and implementation of appropriate orbit configurations and phasing between existing, forthcoming Next Generation, and the 3 HPCMs as described in Chapter 4 "Orbit phasing and Cross-instrument operations".

[REC7: The PEG recommends that the Copernicus Services further consider and describe L3 and L4 cross mission requirements for products and services].

44 Cooperation agreements already exists with the US and Chile, and additional ones are being planned (Canada, Japan, and WMO).

7.3.4 USERS CONSULTATION PROCESS

Copernicus is organising regular workshops and consultations with the user communities and the private industry (industrial workshops). These meetings provide very useful information about the quality of the products and services, and also about the need for new and innovative products. Examples are CMEMS workshops[45], workshops for the Copernicus Arctic Regional Reanalysis Service[46] as well as the Copernicus Polar industry Workshop in late 2018[47]. This process can be further improved by reaching out to the broader private sector, including oil companies, insurance companies, shipping industry, fishing industry, mining companies, IT industry. Further enhanced outreach to decision makers in Europe and worldwide on Arctic environmental policies is also of high importance.

These improvements are challenging due to various reasons, such as national as well as commercial interests. However, Copernicus plays an important role in understanding the environmental changes in the polar regions offering standardised, open and free satellite data and services.

In the last years the activities around the Copernicus Contributing Missions have increased the focus on commercial satellite data providers' interest in supporting Copernicus with data and information products covering various areas including the Arctic. This example of increased involvement of the private sector should be further pursued and integrated in the work of the Copernicus Services.

7.3.5 END-TO-END INTEGRATED POLAR MONITORING SYSTEM

An important part of an end-to-end integrated polar monitoring system is the ground segment. Chapter 5 describes the ESA and EUMETSAT multi-mission ground segment elements currently operating the Sentinel missions and third-party missions as agreed, with data and products made available on a full, free and open basis to all users, through EUMETSAT's Near Real Time dissemination channels EUMETCast/EUMETview, the different Copernicus Online Data Access Hubs and the DIAS.

Operations/planning of multiple missions and generation of NRT geophysical products (up to Level 2) of individual missions are classical ground segment activities. While the synergistic satellite- and instrument operations are scheduled by ESA and EUMETSAT respectively, however, it should be noted as per Chapter 5 that the synergistic cross-mission integration and processing of these single-mission products are to be planned and prepared for by the Copernicus Services. These developments are relevant and should be followed in the possible future work of the Polar Expert Group.

7.3.6 TELECOMMUNICATIONS IN POLAR REGIONS

Timeliness of the services is essential for some operational entities (e.g. operational forecasting, or environmental forecasting, or ocean/atmosphere forecasting safety of maritime traffic, emergency rescue). The data processing and network transmission between the on-board instrument data acquisition and the product delivery to the user segment interface is a critical part of the service quality.

- As addressed by the KEPLER project, when addressing latency in the sparsely populated polar regions, it is important to consider the time to the users and not to the ground station. For the Arctic users on land and sea, this means additional use of space assets in form of communication satellites. This is also addressed in the report of DG-JRC called "Europe's Space capabilities for the benefit of the Arctic"[48] For the European Space Programme, this need should be addressed in the discussions around the GovSatcom capability, now included as a new component of the proposed Space Programme, based on existing, pooled and governmental SatCom resources.

[REC8: The PEG recommends to consolidate Copernicus requirements for telecommunication capacity in the Arctic (and Antarctica[49]) in order to reach the end-users and to share this with GovSatcom].

45 Copernicus Marine Service (2019)), Training Workshop dedicated to the Arctic Sea region
46 Copernicus Climate Change Service (2020), User workshop on Copernicus regional reanalysis for Europe and the European Arctic
47 European Commission (2019) Copernicus Polar Industry Workshop
48 https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/europes-space-capabilities-benefit-arctic
49 Arctic is explicitly mentioned in the EU Space Regulation, but not Antarctica

7.3.7 ROLE AND CONTRIBUTION OF THE PRIVATE SECTOR

The role of the private sector in Europe for Earth Observation was until a few years ago essentially focused on:

- The procurement and manufacturing of space and ground systems (large space companies, specialised SMEs);
- The development of high-performance data processing systems (IT industry).

This situation has evolved over the last years with:

- The manufacturing and operation of EO satellites (with services offered on a commercial basis) by the private sector;
- The advent of high-performance mini and micro satellites in particular, those developed by SMEs and universities. These new missions, contrary to the large multi-purpose missions, have very focused objectives and could offer an interesting complement to the current large systems like Sentinels (e.g. IceEye constellation now entering the Contributing Mission portfolio).

[REC9: The PEG recommends that the rapidly evolving private sector should be continuously explored for the benefit of Copernicus Services, and in particular for the development of polar services. The evolution of the Copernicus Space Component (e.g. Sentinels) should not hamper the private sector, but make room for complementary products and services].

7.3.8 UNDERLYING SCIENTIFIC RESEARCH

Existing services and products improvements as well as development of new products, taking advantage of new missions (e.g. HPCMs) require significant scientific research such as the development of improved physical and biogeochemical algorithms, relevant validation for Level 2 products, and the further development of advanced data assimilation techniques (e.g. Ensemble Kalman Filter, statistical approach). The EU should promote and facilitate effective international scientific cooperation through supporting transnational access to research infrastructure and open data resources to improve political and economic links and maintain good relations with key countries in the region.

The Citizen Science approach already (modestly) used by space agencies should be further developed in support of polar science in general. The contributions of indigenous populations, routine vessels and local authorities would also be very valuable and should be integrated in the research activity (for instance for product validation).

7.3.9 FINANCING REQUIREMENTS AND SOURCES

The financing of scientific research related to development and adaptation of applications based on new space systems for the polar regions is not well defined and funding mechanisms and sources should be identified. This also applies to the development of additional in-situ platforms whilst the continuity of space segment Sentinels seems to be ensured until 2030+, provided the funding for the 4 units planned for each series is confirmed. Unfortunately, the EU MFF covers only the 2021-2027 period. Therefore, it is important to continuously work with and inform the EU, ESA and their Member States about the importance of the continuity of required space assets. As for the scientific research activity new sources/mechanisms should be identified, e.g. the private sector/industry.

[REC10: The PEG recommends that the financing of operations is strengthened making it possible for the Copernicus Services to further develop and integrate new space and non-space data as well as scientific research].

7.3.10 FINAL REMARKS

This report has a main focus on the observations needed in the years to come thereby concentrating on space assets using microwave technologies. The Arctic has been the main focus of the PEG responding to the EU Arctic Policy, however Antarctica is considered in this report but needs to be further assessed in the future work of the PEG. The work of the Services will need to be further explored together with synergies with the other part of the EU Space Programme. This will therefore be the main objective of the next phase of the Polar Expert Group. A draft of the Terms of Reference has been produced and handled by DG-Joint Research Centre. The next phase is to be handled by a Polar Task Force and will start in 2021. 2021 will also be the year of some important decisions regarding the Copernicus HPCMs and this report from the PEG has provided some constructive inputs to this programmatic decision point.

8. GLOSSARY

SATELLITE/INSTRUMENT DATA PROCESSING LEVELS (REFERENCE CEOS – WGISS)

- **Raw data:** Physical telemetry payload data as received from the satellite, i.e. a serial data stream without de-multiplexing;
- **Level 0:** Reconstructed (i.e. with all communications artefacts removed e.g. synchronization frames, communications headers, duplicate data…), unprocessed instrument and payload data from satellite raw data with available supplemental information to be used in subsequent processing (e.g. ephemeris, health and safety) appended;
- **Level 1A:** Unaltered/unprocessed Level 0 instrument data annotated with processed ancillary data and supplemented by auxiliary information (including radiometric and geometric calibration coefficients and geo-referencing parameters e.g. ephemeris) allowing, if appropriate, further processing to Level 1B;
- **Level 1B:** Level 1A instrument data which have been radiometrically calibrated and spatially aligned (co-located) to represent physical units in sensor nominal spatial sampling and viewing geometry, geolocated and supplemented by appropriate ancillary and auxiliary data for further processing to Level 1C;
- **Level 1C:** L1B data orthorectified and re-sampled to a specified geodetic grid;
- **Level 2:** Derived geophysical object properties (e.g. surface reflectance, sea surface temperature, leaf area index, soil moisture) in the same grid (i.e. without spatial resampling) as Level 1 source data;
- **Level 3:** Level 1 or Level 2 data which have been harmonised and combined across one or several platforms and acquisitions to achieve a larger spatial or temporal coverage (the completeness of which usually will be specified in the metadata). Harmonisation and combination may include radiometric and geometric resampling making use of aggregation and/or interpolation.;
- **Level 4:** Model output or results from analyses of lower-level data i.e., variables that are not directly measured by the instruments, but are derived from these measurements; could be derived from multiple instrument measurements.

GEOPHYSICAL VARIABLES (ALSO CALLED PARAMETERS)

Terminology which covers geophysical variables (e.g. sea surface temperature, sea surface salinity, soil moisture) equal to Level 2 data.

PRODUCT

This is an information product delivered to end (or intermediate) users which meets their operational service requirements. It can take the form of an L3/L4 product but also include socio-economical information, statistics, and other information.

COPERNICUS PRODUCT

This is a product based on combined space and in-situ observations, possibly assimilated into models, and tailored to the 6 thematic priority domains selected by the Commission, namely for Marine environment monitoring (CMEMS), Land monitoring (CLMS), Climate Change (C3S), Atmosphere composition (CAMS), Emergency management situations (CEMS) and Security (CSS).

Typically, a Copernicus product is associated with a Product User Manual (PUM) providing a detailed description of the product characteristics, name of production entity/agency, list of space and in-situ observations used, data assimilation techniques/models used, spatial and temporal resolutions, quality information/accuracy estimate, delivery format and mechanisms, update frequency, etc. (when applicable).

Hereafter for illustration purpose, two examples of Copernicus services, CMEMS and C3S, are briefly described.

- **Copernicus Marine Environment Monitoring Services (CMEMS)**

CMEMS provides regular and systematic core reference information on the state of the physical oceans and regional seas. The observations (space and in-situ) and forecasts produced by the service support all marine applications. CMEMS provides two main categories of products: (i) Satellite and in-situ observations for real-time (today) and reprocessed (20 years historic) products and (ii) outputs of ocean numerical models assimilating the above satellite and in-situ data to generate reanalyses (20 years in the past), analyses (today) and 10-day forecasts of the ocean.

CMEMS Product example: Global Ocean 1/12° Physics Analysis and Forecast updated daily (from CMEMS site)

The Operational Mercator global ocean analysis and forecast system at 1/12 degree is providing 10 days of 3D global ocean forecasts updated daily. The time series starts on January 1st, 2016 and is aggregated in time in order to reach a two full years time series sliding window. This product includes daily and monthly mean files of temperature, salinity, currents, sea level, mixed layer depth and ice parameters from the top to the bottom over the global ocean. It also includes hourly mean surface fields for sea level height, temperature and currents. The global ocean output files are displayed with a 1/12 degree horizontal resolution with regular longitude/latitude equirectangular projection. 50 vertical levels are ranging from 0 to 5500 meters. This product also delivers a special dataset for surface current, which also includes wave and tidal drift called SMOC (Surface merged Ocean Current).

- **Copernicus Climate Change climate Services (C3S)**

The Copernicus Climate Change Service (C3S) combines observations of the climate system with the latest science to develop authoritative, quality-assured information about the past, current and future states of the climate in Europe and worldwide. In the context of C3S, operational means that C3S is able to provide quality-assured data and services in a reliable and timely fashion to all its users and stakeholders.

The portfolio of C3S service products includes:

- A Climate Data Store providing access to a broad range of climate datasets, applications, and analysis tools;
- Consistent estimates of multiple Essential Climate Variables;
- Global and regional reanalyses (including for the Arctic region), covering a comprehensive Earth system domain (atmosphere, ocean, land, carbon);
- Products based on conventional and satellite observations alone;
- Multi-model seasonal forecasts;
- Climate projections at global and regional scales;
- Sector-specific climate information and data tailored for businesses and decision-makers.

C3S Product example: sea ice thickness

The C3S sea ice thickness (SIT) Climate Data Record consists of monthly retrievals of sea ice thickness for the Arctic region from October 2002 to present derived from satellite radar altimetry measurements from the Envisat and CryoSat-2 satellites. The dataset is a Level-3 collated product provided on a polar EASE-2 grid with a 25-km resolution. It is updated on a monthly basis with a one-month delay behind real time. Data are currently limited to the winter months of October through April due to retrieval issues during the melting season. Along with SIT data, the files contain estimates of algorithm uncertainty and a quality status flag. Data can be downloaded from the C3S Climate Data Store either through an interactive online form or through a python-based API. Users can also visualise the data and perform various data manipulation operations through the CDS Toolbox.

POLAR REGION OF INTEREST (AS DEFINED FOR PEG)

- Arctic Ocean: > 59-60°N, 0-360° longitude (this includes Iceland, Svalbard, Russian Arctic ice caps, etc.)

- Adjacent Seas (> 50° N as per CIMR MRD) encompassing all seas and major water bodies adjacent to the Arctic (Baltic Sea, Gulf of Botnia, Gulf of Finland, etc.)
- Land areas: > 60° N
- Greenland: > 55° N
- Antarctica: >50° S, 0-360° longitude

ACCURACY OF MEASUREMENT (REFERENCE WMO)

The closeness of the agreement between the result of a measurement and a true value of the measurement.

Notes:

1. "Accuracy" is a qualitative concept. The quantitative measure of the accuracy is expressed in terms of "Uncertainty";
2. The term "precision" should not be used for "accuracy".

ANCILLARY DATA

Data acquired on-board but not obtained from the main instrument itself (usually provided as part of Level 0 data). They have the primary purpose to serve the processing of main instrument data (e.g. orbit position and velocity of platform).

AUXILIARY DATA

Data which enhance processing and utilization of main instrument data. The auxiliary data are usually not captured by the same data collection process as the main instrument data. Auxiliary data include data collected by any other platform or process. Examples are e.g. meteorological data received from ECWMF/Met. Offices. Auxiliary data help in data processing, but are also data sets in their own right.

CALIBRATION DATA

Calibration refers to the process of quantitatively defining the instrument responses to known, controlled signal inputs. It implies the collection of pre-flight and in-flight calibration measurements and ground truth data that is to be used in the data calibration processing routine.

DATA LATENCY

Time delay introduced by automated data processing and network transmission between the on-board instrument data acquisition and the product delivery to the user segment interface. Typically – for meteorological purposes – this is within 3 hours from sensing.

DISSEMINATION

The dissemination function delivers the final product to the user, by means of physical media, electronic distribution (e.g. ftp-push) or electronic server access (e.g. ftp-pull). Therefore, dissemination is concerned with the preparation of the delivery media in case of offline delivery and the management of on-line access.

ESSENTIAL CLIMATE VARIABLES (ECVS)

An ECV is a physical, chemical, or biological variable or a group of linked variables that critically contributes to the characterization of Earth's climate. ECV data sets are needed to understand and predict the evolution of climate, to guide mitigation and adaptation measures, to assess risks and enable attribution of climatic events to underlying causes, and to underpin climate services.

EARTH OBSERVATION (GEO DEFINITION)

Earth Observations are data and information collected about our planet, whether atmospheric, oceanic or terrestrial. This includes space-based or remotely-sensed data, as well as ground-based or in-situ data. Coordinated and open Earth Observations enable decision makers around the world to better understand the issues they face, in order to shape more effective policies.

IN-SITU OBSERVATION

'In-situ' describes observations performed in the same place where an object is located or a phenomenon is occurring, without isolating it from other systems or altering its original conditions. In-situ measurements require either direct physical contact or a distance which has no or negligible impact on the measurement. Measurements not fulfilling these conditions are considered 'Remote Sensing'.

LABORATORY OBSERVATION

Laboratory observations are (usually) in-situ observations in which the object or phenomenon is isolated from other systems or altered in its original conditions.

MEASUREMENTS

Measurements are quantitative observations having the objective of determining the values of a quantity.

MISSION PLANNING

This is a non-conflicting timeline of activities for the space segment payload and for the corresponding reception activities of the stations. The planned activities comprise sensing operations to meet users' requirements, recording, downlink and reception. Planning has to take into account constraints like sensors and platform limitations, capacities and receiving station availabilities. Part of this function is cross-mission reception conflict resolution, e.g. in case of interference between downlinks of different satellites.

NEAR REAL TIME (NRT) DATA/PRODUCTS

NRT data/products are those that have to be made available to users with a specified short latency, which is typically within 3 hours from on-board sensor observation for operational applications (such as meteorology).

QUASI REAL TIME (QRT) DATA/PRODUCT

QRT data/products are those that have to be made available to users with a specified short latency, which is typically less than 1 hour from on-board sensor observation for operational applications such as exceptional emergency events/catastrophe situations. This may be as low as 15 minutes (as specified by EMSA).

OBSERVATION

Observation is the active acquisition of information from a primary source like an object or a phenomenon. Observations can be qualitative, that is, only the absence or presence of a property is noted, or quantitative if a numerical value is attached to the observed phenomenon by counting or measuring.

OPERATIONAL SERVICE

This is the capability offered by an agency/organisation/company to provide a high quality, reliable and on a continuous basis (all throughout the year, 7 days a week if applicable) information products of interest to communities of intermediate and end-users (for example, meteorological weather and marine forecasts).

QUALITY INDICATOR

A quality indicator shall provide sufficient information to allow all users to readily evaluate the "fitness for purpose" of the data or derived product. A Quality Indicator may be a number, set of numbers, graph, uncertainty budget, or a simple "flag".

REMOTE SENSING

Remote sensing is the observation of the property of an object or phenomenon at a significant distance from that object or phenomenon. 'Significant' in this context means that the distance has or may have a non-negligible impact on the measured quantity. The effect of distance is the main distinction criteria between 'remote' and 'in-situ' measurements or observations.

TRACEABILITY

Property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations each contributing to the measurement uncertainty.

UNCERTAINTY (REFERENCE WMO)

Non-negative parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurement. The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

VALIDATION DATA

Validation is the process of assessing, by independent means, the quality of the data products derived from the system outputs. As for the calibration activities, it implies the collection of pre-flight and in-flight measurements as well as ground-based and in-situ data.

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ANNEXES

ANNEX 1. COPERNICUS PRODUCT INVENTORY

Annex 1: Copernicus inventory, specification per product	
Products	Name of Copernicus product
Horisontal coverage	Area of interest to be covered
Horisontal Resolution	The sampling distance of measurements in [m], equal spacing in x and y is assumed
Update frequency	Temporal frequency of the Copernicus products
Latency	Time delay between the on-board instrument data acquisition and the Copernicus product delivery to the user segment interface
Accuracy/Uncertainty	Accuracy: The closeness of the agreement between the result of a measurement and a true value of the measurand. Notes: 1. "Accuracy" is a qualitative concept. The quantitative measure of the accuracy is expressed in terms of "Uncertainty". 2. The term "precision" should not be used for "accuracy" Uncertainty: Non-negative parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand. The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.
Satellites/Sensors used to produce the Copernicus products	Satellites and/or Sensors used to produce the Copernicus products

PRODUCTS	CHARACTERISTICS					
	HORISONTAL COVERAGE	HORISONTAL RESOLUTION	UPDATE FREQUENCY	LATENCY	ACCURACY/ UNCERTAINTY	SATELLITES/SENSORS USED TO PRODUCE THE COPERNICUS PRODUCTS
1. Marine	**Horisontal coverage**					
1.1 Sea ice thickness (SIT)	N. Hemisphere (Obs)	25km	Weekly			Cryosat2, SMOS Merged
	N. Hemisphere (Model)	3km	Daily		1m Sat L4	Assimilation o Cryosat2, SMOS merged only for N. Hem.
	S. Hemisphere (Model	9km				
1.2 Sea-ice concentration (SIC)	Ice charts, Arctic Regional, Svalbard & Greenland (Obs)	1km	Irregular Weekly-mean Irregular Daily			HR Imagery SAR, mainly S1, other SAR missions (Radarsat, COSMO. TerraSAR), MODIS more used than S3, OLCI (twilight acquisition issue). Sometimes S2 (coastal)
	Arctic (Obs)	5km	Daily			AMSR2 brokered from OSI SAF
	Global (Obs)	10km	Daily			SSMIS brokered from OSI SAF
	N. Hemisphere (Model) S. Hemisphere (Model	3km 9km	Daily		18-20% Sat L4	SSMIS, Assimilation of OSI SAF 10km products
1.3 Sea ice drift	Global (Obs)	10km	Irregular Subdaily/Daily			S1A/S1B (has used SAR Envisat RADARSAT)
	Global (Obs)	62.5km	Daily			ASCAT, QuikSCAT, SSM/IS brokered from OSI SAF
	N. Hemisphere (Model) S. Hemisphere (Model	3km 9km	Daily		5-8km/day Sat L4	Assimilation of OSI SAF 62,5km products, only for N. Hem.
1.4 Snow depth and snow cover on sea-ice	N. Hemisphere (Model) S. Hemisphere (Model	3km 9km	Daily		Use of In Situ	Observation R&D exist, many techniques based on PMR, altimetry, SAR…
1.5a Ice type of developement	Global (Obs)	10km	Daily			SSMIS brokered from OSI SAF
	N. Hemisphere (Model)	12,5km	Daily		0.1-0.2 Mkm2	Validation with CMEMS/OSI SAF data but also with ice charts
1.5b Ice age of developement	N. Hemisphere (Model)	12,5km	Daily		Ice Age mtrics to be added shortly	Not measurable with in situ.
1.6 Iceberg (iceberg concentration charts and individual icebergs)	N. Hemisphere, Regional Greenland (Obs)	10km	Irregular Weekly-mean Irregular Daily			S-1
1.7 Sea-ice edge - Existing parameter	Antarctica Regional (Obs)	1km	Irregular			S-1, Radarsat, ASCAT, SSMIS
	Global (Obs)	10km	Daily			SSMIS brokered from OSI SAF
1.8 Sea-ice extent - Existing parameter	N. Hemisphere S. Hemisphere both Model & Obs	Timeseries in km2	Yearly			SSMIS brokered from OSI SAF
1.9 Sea-ice albedo - Existing parameter	N. Hemisphere (Model)	12km	Daily			Observation R&D exist and based on S3-OLCI
1.10 Sea-ice surface temperature - Existing parameter	N. Hemisphere (Obs)	5 km	Daily		Validation with In Situ	Sentinel 3b SLSTR SST, NOAA 20 VIIRS SST and VIIRS_NPP SST/IST
1.11 Sea level anomaly	Global (Obs)	25Km L4 14Km L3 along track	Daily			All altimeters, no data if presence of sea ice
	Global (Model)	9km	Daily		6cm Sat L3	Assimilation of all Altimetry
1.12 Sea Surface Temperature (SST)	Global (Obs)	25km	Daily, Hourly for diurnal skin Temperature			Multi product ensemble using a large number of MW satellite OSTIA diurnal skin temperature
	Global (Obs)	10km, L3	Daily			Multi sensors : NOAA-18 & NOAAA-19/AVHRR, METOP-A/AVHRR, ENVISAT/AATSR, AQUA/AMSRE, TRMM/TMI) and geostationary (MSG/SEVIRI, GOES-11
	Global (Obs)	5km	Daily/Monthly			OSTIA SST; IR and PMW satellite (AVHRR, MSG, NOAA20, S3a,b, AMSR2)
	Global (Model)	9km	Daily		0.6-0.8°C In Situ & Sat (Metop A,B & AVHRR)	Assimilation of SST OSTIA
1.13 Sea Surface Salinity (SSS)	Global (Model)	9km	Daily		0.2 In Situ	No assimilation yet

(*) SAR based value added products : EVS, EFS, WDS, ADS currently under integration tests on EMSA EO Chain (**) These delivery times refer to the standard image size. For images acquired outside EMSA contracted ground stations coverage, using on-board recorders, satellite fly time is added (***) S1 A+B for Oil Spill Detection and VDS only for CleanSeaNet service

PRODUCTS	CHARACTERISTICS					
	HORISONTAL COVERAGE	HORISONTAL RESOLUTION	UPDATE FREQUENCY	LATENCY	ACCURACY/ UNCERTAINTY	SATELLITES/SENSORS USED TO PRODUCE THE COPERNICUS PRODUCTS
2. Land						
2.1 Leaf Area Index, FaPAR, Fcover, NDVI	[-60,80]	300 m, 1 Km	10 d			SPOT VGT, PROBA, S3
2.2 Land Surface Temperature	[-60,70]	5 km	1 h, 10 d	4 hours	3 K (A), 4 K (U)	MSG, GOES, MTSAT, Himawari
2.3 Soil Moisture	Europe	1 Km	1 d - 6 d	1 day	0.04 m3/m3 (A)	S1
2.4 Soil Water Index	Global	0.1 deg (1 km for Europe)	daily			METOP ASCAT, S1
2.5 Land Cover	[-60,78.25]	100 m, 300 m	annually			SPOT VGT, PROBA, S3
2.6 Inland Water Bodies	up to 75N	300 m, 1 km	10 d			SPOT VGT, PROBA, S3, S2
2.7 Inland Water Level	Global	N/A (non-gridded)	10 d	4 d	0.2 m (A)	Jason, S3
2.8 Inland Water Temperature	Global	1 Km	10 d			S3 SLSTR
2.9 Inland Water Quality	Global	300 m, 1 km	10 d			S3, S2
2.10 Lake Ice Extent	Baltic Sea Region	250 m	daily	< 1 day	250 m (A)	MODIS / Sentinel-3 SLSTR
2.11 Snow Cover Extent	N. Hemisphere [25,84]	1 Km (500 m for Europe)	daily	< 1 day		VIIRS / Sentinel-3 SLSTR MODIS / VIIRS
2.12 Snow Water Equivalent (SWE)	N. Hemisphere [35,85]	5 Km	daily	< 2 days		SSMI
2.13 Ground Motion	EEA39	20 m	annual	4 months	0.5 cm (U); geolocation: 15 m (A)	S1
2.14 EEA High Resol. Snow & Ice Service - Snow Exent	EEA39	20 m	daily	< 3 h		S2
2.15 EEA High Resol. Snow & Ice Service - Lake/ River ice	EEA39	20m	daily	< 3 h		S2
2.16 EEA High Resol. Snow & Ice Service - Wet Snow Exent IN IMPLEMENTATION	EEA39	tbc	daily	tbc		S1

(*) SAR based value added products : EVS, EFS, WDS, ADS currently under integration tests on EMSA EO Chain (**) These delivery times refer to the standard image size. For images acquired outside EMSA contracted ground stations coverage, using on-board recorders, satellite fly time is added (***) S1 A+B for Oil Spill Detection and VDS only for CleanSeaNet service

PRODUCTS	CHARACTERISTICS					
	HORISONTAL COVERAGE	HORISONTAL RESOLUTION	UPDATE FREQUENCY	LATENCY	ACCURACY/ UNCERTAINTY	SATELLITES/SENSORS USED TO PRODUCE THE COPERNICUS PRODUCTS
3. Climate						
3. Sea ice concentration	Global (northern and southern polar regions)	25 km grid res (true spatial res: 30-60 km)	Daily (every second day from 1979-1987)	16 days	NH: 6-14 % SH: 10-17 %	SMMR, SSM/I, SSMIS
3.2 Sea ice thickness	Northern Hemisphere	25 km grid res (true spatial res: 1-10 km)	Monthly and for Arctic winter months only (October through April)	1 month	0.4-1 m	RA-2 on Envisat, SIRAL on CryoSat-2
3.3 Sea ice edge	Global (northern and southern polar regions)	12.5 km grid res (true spatial res: 15 km)	Daily (every second day from 1978-1987)	16 days	30-40 km (distance from ice chart edge)	SMMR, SSM/I, SSMIS
3.4 Sea ice type	Northern Hemisphere	25 km grid res (true spatial res: 40-70 km)	Daily (every second day from 1978-1987)	16 days		SMMR, SSM/I, SSMIS
3.5 Sea Level	Global + Mediteranean and Black Seas	- 0.25 x 0.25° for global; - 0.125 x 0.125° for Mediterranean and Black Seas	Daily	6 months		ERS-1/2, Envisat, Jason-1/2/3, Topex/Poseidon, SARAL, Cryosat-2, S-3A
3.6 Sea Surface Tempearture	Global	- 1km x 1km for ATSR and SLSTR Level 2P products; - ~4km x 4km for AVHRR Level 2P products; - 0.05° x 0.05° for Level 3 and Level 4 products	Daily	9-12 months	L4: 0.2-0.3 K vs in situ	- AVHRR on NOAA-X and Metop-A, - ATSR on ERS-1/2, - AATSR on Envisat - SLSTR on S-3A/B
3.7 Maps of Land Cover	Global land	300 m	Yearly			AVHRR, SPOT-VGT, PROBA-V & S3-OLCI
3.8 Albedo	Global land	1/112° (~1 km) for SPOT-VGT and PROBA-V, 1/30° (~4 km) for AVHRR	10 days			AVHRR, SPOT-VGT & PROBA-V
3.9 Leaf Area Index	Global land	1/112° (~1 km) for SPOT-VGT and PROBA-V, 1/30° (~4 km) for AVHRR	10 days			AVHRR, SPOT-VGT & PROBA-V
3.10 Glaciers outlines (distribution)	All glaciers, incl-. Peripherial glaciers in Greenland and Antarctica	30 m (dependent on satellite sensor)	Annualy	Annual (in January)	better than 5% of area	Landsat, (Sentinel-2)
3.11 mass change / elevation change	selected glaciers globally	glacier specific	annual to decadal	Annually	0.2 kg/m2 0.2m/y (TBC)	based on insitu measuremts from WGMS database
3.12 Gravimetric mass balance	Greenland and Antarctic Icesheet -brokered product from ESA CCI	50kmx50km	Monthly (timeseries)	Annual release	attached to the product	Grace
3.13 Ice Velocity	Greenland Icesheet	250 m	Annual IV Maps	Annual Release (in January)	pixelbased uncertainty product attached	Sentinel-1
3.14 Surface Elevation Change	Greenland and Antarctic Icesheet	25kmx25km	monthly (*different moving windows for satellites)	Annual Release (January), monthly upddate of datasets	pixelbased uncertainty attached to the product	ERS-12, ENVISAT, Cryosat-2, Sentinel-3A, Sentinel-3B
3.15 Lake surface water temperature	Global	0.05 x 0.05°	Daily			ERS-2 (ATSR-2), Envisat (AATSR), Metop A & B (AVHRR)
3.16 Lake Water Level	Global	one value per lake per timestep	1 to 10 days			RA on TOPEX/POSEIDON, Jason 1/2/3, Envisat, SARAL, GeoSat-Follow-On, S-3A
3.17 Surface soil moisture	Global land	0.25 x 0.25°	Daily, 10-day and monthly	4 months		Active data: AMI-WS, ASCAT-A & B Passive data: SMMR, SMM/I, TMI, AMSR-E, AMSRE, WIndSat, SMOS

(*) SAR based value added products : EVS, EFS, WDS, ADS currently under integration tests on EMSA EO Chain (**) These delivery times refer to the standard image size. For images acquired outside EMSA contracted ground stations coverage, using on-board recorders, satellite fly time is added (***) S1 A+B for Oil Spill Detection and VDS only for CleanSeaNet service

PRODUCTS	CHARACTERISTICS					
	HORISONTAL COVERAGE	HORISONTAL RESOLUTION	UPDATE FREQUENCY	LATENCY	ACCURACY/ UNCERTAINTY	SATELLITES/SENSORS USED TO PRODUCE THE COPERNICUS PRODUCTS
4. Atmosphere						
4.1 Ozone concentrations		40km spatial resolution and 137 vertical levels	Twice-daily analyses and forecasts			S-5p, GOME-2, MLS, OMI, SBUV-2
4.2 Organic matter aerosol concentrations		40km spatial resolution and 137 vertical levels	Twice-daily analyses and forecasts			MODIS, PMAP, (VIIRS, S-3)
4.3 Black carbon aerosol concentrations		40km spatial resolution and 137 vertical levels	Twice-daily analyses and forecasts			MODIS, PMAP, (VIIRS, S-3)
4.4 PM2.5 concentrations		40km spatial resolution and 137 vertical levels	Twice-daily analyses and forecasts			MODIS, PMAP, (VIIRS, S-3)
4.5 PM10 concentrations		40km spatial resolution and 137 vertical levels	Twice-daily analyses and forecasts			MODIS, PMAP, (VIIRS, S-3)
4.6 Methane concentrations		40km spatial resolution and 137 vertical levels	Twice-daily analyses and forecasts			S-5p, GOSAT, IASI
4.7 UV Index		40km spatial resolution and at surface level	Twice-daily analyses and forecasts			
4.8 Deposition of aerosol and chemical species (under development)		40km spatial resolution and at surface level	Twice-daily analyses and forecasts			

(*) SAR based value added products : EVS, EFS, WDS, ADS currently under integration tests on EMSA EO Chain (**) These delivery times refer to the standard image size. For images acquired outside EMSA contracted ground stations coverage, using on-board recorders, satellite fly time is added (***) S1 A+B for Oil Spill Detection and VDS only for CleanSeaNet service

PRODUCTS	CHARACTERISTICS					
	HORISONTAL COVERAGE	HORISONTAL RESOLUTION	UPDATE FREQUENCY	LATENCY	ACCURACY/ UNCERTAINTY	SATELLITES/SENSORS USED TO PRODUCE THE COPERNICUS PRODUCTS
5. Security						
5.1 Vessel Detection Service (VDS)*	Global	●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;) ●High Resolution HR1 (4 m < x ≤ 10m;) ●High Resolution HR2 (10m < x ≤30m); ●Medium resolution MR (30m < x ≤100m)	On demand	20 min**		Radarsat, S-1 (***), TERRASAR-X, PAZ
5.2 Feature Detection Service (FDS)*	Global	●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m); ●High Resolution HR1 (4 m < x ≤ 10m;)	On demand	20 min**		Radarsat TERRASAR-X, PAZ
5.3 Oil Spill Detection	Global	●High Resolution HR2 (10m < x ≤30m;) ●Medium resolution MR (30m < x ≤100m)	On demand	20 min**		Radarsat, S-1 (***), TERRASAR-X, PAZ
5.4 Enriched Vessel Service (EVS)*	Global	●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;) ●High Resolution HR1 (4 m < x ≤ 10m;)	On demand	30 min**		Radarsat TERRASAR-X, PAZ
5.5 Enriched Feature Service (EFS)* (eg: Fish farms, Debris,..)	Global	●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;) ●High Resolution HR1 (4 m < x ≤ 10m;)	On demand	30 min**		Radarsat TERRASAR-X, PAZ
5.6 Wake Detection Service (WDS)*	Global	●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;) ●High Resolution HR1 (4 m < x ≤ 10m)	On demand	30 min**		Radarsat TERRASAR-X, PAZ
5.7 Activity Detection Service (ADS)* (eg: Fisheries control, Anti-piracy, ...)	Global	●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;)	On demand	30 min**		Radarsat TERRASAR-X, PAZ
6. Emergency Management						
6.1 Automatic Flood Monitoring	Global	20 m	6d			S1
6.2 Burnt Area	Global					
6.3 Active fire maps	Global					

(*) SAR based value added products : EVS, EFS, WDS, ADS currently under integration tests on EMSA EO Chain (**) These delivery times refer to the standard image size. For images acquired outside EMSA contracted ground stations coverage, using on-board recorders, satellite fly time is added (***) S1 A+B for Oil Spill Detection and VDS only for CleanSeaNet service

ANNEX 2. REQUIREMENTS AND SPACE ASSETS

Annex 2: PEG III specification scheme by geophysical variable	
Geophysical variable	Generic designation/terminology which covers geophysical variables (e.g. sea surface temperature/salinity/wind field …) derived via processing algorithms (physical, semi-empirical/empirical …) from satellite/in situ sensors data (similar to L2)
Horisontal coverage	Area of interest to be covered
Horisontal Resolution	The sampling distance of measurements in [m], equal spacing in x and y is assumed
Update frequency	Update (temporal) frequency between the same type of instrument (e.g. S1 A,B,C, D phasing options) for regular measurements and 'on demand' acquisitions
Latency	Time delay introduced by automated data processing and network transmission between the on-board instrument data acquisition and the product delivery to the user segment interface.
Accuracy/Uncertainty	Accuracy: The closeness of the agreement between the result of a measurement and a true value of the measurand. Notes: 1. "Accuracy" is a qualitative concept. The quantitative measure of the accuracy is expressed in terms of "Uncertainty". 2. The term "precision" should not be used for "accuracy" Uncertainty: Non-negative parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand. The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.
Satellites/Sensors used to produce the Copernicus products	Satellites and/or Sensors used to produce the Copernicus products
Requirement Compliance statement per mission for CIMR, CRISTAL, ROSE-L	- Fulfilled (F): The mission fulfils all requirements in Polar regions and Adjacent Seas as a stand-alone mission or in cross-sensor planning with Sentinel missions. - Non-Compliant (no value): The mission does not comply with any or few requirements

GEOPHYSICAL VARIABLES	POLAR EXPERT GROUP REQUIREMENTS					REQUIREMENT COMPLIANCE STATEMENT PER MISSION		
	HORISONTAL COVERAGE	HORISONTAL RESO-LUTION	UPDATE FRE-QUENCY	LATENCY	ACCURACY (A) / UNCERTAINTY (U)	CIMR	CRISTAL	CRISTAL
						FULL (F), NON-COMPLIANT (NO VALUE)		
1. Floating ice								
1.1.1 Sea ice thickness (SIT) - Marine	"1. Global 2. Pan Arctic"	"1. < 5km 2. 80m (20m) "	" 24h"	<1h	"1. Thick ice: < 0.1m; Thin and Freeboard: <0.05m; otherwise <10% of the measured quantity (A). 2. Thick ice: 0.1m (A), Thin ice (<0.5 m): 5% (A)"		1. F (Thick ice)	
1.1.2 Sea ice thickness (SIT) - Climate	Global, Pan Arctic	25 (5) km	24 h	≤24h	<0.1m (A)	"F (Thin ice (<0.5 m): 10% instead of 5%, Resolution <50km"	F (Thick ice)	
1.2.1 Sea-ice concentration (SIC) - Marine	"1. Global 2. Pan Arctic"	"1. <5 km 2.20 m"	<24h(6h)	<1h	"1. < 5% (A) 2. 5% (A)"	1. F (Global)		
1.2.2 Sea-ice concentration (SIC) - Climate	Global, Pan Arctic	15 km (<5) km	24 h	≤24h	<5% (A)	F		
1.3.1 Sea ice drift - Marine	"1. Global 2. Pan Arctic"	"1. < 10km 2.80 (20) m"	≤24h(6h)	<1h	"1. < 2-3km/Day (A) 2.< 100m/Day"			
1.3.2 Sea ice drift - Climate	Pan Arctic	10 km (as SIC if SIC <10km)	24 h	24h	<1km/day (A)			
1.4.1 Snow depth and snow cover on sea-ice - Marine	1. Global	1. < 5 km	24 h		"1. <0.05m or < 10% of the measured quantity (A) 2.?SD: 10mm (A) SC: 10% (A)"			
1.4.2 Snow depth and snow cover on sea-ice - Climate	Global, Pan Arctic	25 (5) km	24 h		"SD: 10mm (A) SC: 10% (A)"	F	F: (5 cm over 25 km)	
1.5.1 Ice type-Ice stage of development - Marine	1-2. Pan-Arctic.	"1. < 10km 2.T80 (20) m"	"<24h 48h (24h) "	<1h	1-2: < 15% (A)			
1.5.2 Ice type-Ice stage of development - Climate	Pan Arctic	10 km (1km)	24h	24h	< 15% (A)			
1.6.1 Iceberg (iceberg concentration charts and individual icebergs) - Marine	"1. Global 2.Greenland and European Arctic"	"1. < 10km 2.as S-1 (20m)"	< 6h	<1h	" 15% (A)"			
1.6.2 Iceberg (iceberg concentration charts and individual icebergs) - Climate	Greenland and European Arctic	10 km		24h				F
1.7.1 Sea-ice surface temperature - Marine	1.Global	1. < 5km	< 24h (6h)	<1h	1. 0.5K for L2 products (A)			
1.7.2 Sea-ice surface temperature - Climate	Pan Arctic	1 km (IR)			0.5K for L2 products (A)			

Continuity(1): Continuity on the service level of 2020
Enhanced Continuity(2): Enhanced continuity in the MFF period post-2021 with the service level of 2020 as baseline
(*) SAR based value added products : EVS, EFS, WDS, ADS currently under integration tests on EMSA EO Chain (**) These delivery times refer to the standard image size.
(*1) Between the same type of instrument (incl S1 A,B,C, D phasing options) (*2) Cross instrument repeat based on combinations of existing, planed and future instruments e.g. SAR C-Band/L-band repeat, SAR C-Band/CIMR/MetOp repeat, SAR CIMR/CRISTAL repeat.

GEOPHYSICAL VARIABLES	POLAR EXPERT GROUP REQUIREMENTS					REQUIREMENT COMPLIANCE STATEMENT PER MISSION		
	HORISONTAL COVERAGE	HORISONTAL RESOLUTION	UPDATE FREQUENCY	LATENCY	ACCURACY (A) / UNCERTAINTY (U)	CIMR	CRISTAL	CRISTAL
						FULL (F), NON-COMPLIANT (NO VALUE)		
2. Glaciers and ice caps								
2.1 Glacier extent	global (areas of permanent snow / ice, including ice caps and peripehrial glaciers of Greenland and Antarctica; excluding ice sheets)	"T: 30 m G: 10 m"	"T: 5 y G: 1 y (end of summer/ablation poeriod)"	not critical	"T: 3% G: 1%"			
2.2 Surface ice velocity		"T: 100 m G: 10 m"	"T: 1 y G: 1 m"	not critical	"T: 5% G: 1%"			F
2.3 Surface elevation & Change and mass balance		"T: 100 m G: 10 m"	"T: 5 y G: 1 y (end of summer/ablation poeriod)"	not critical	"T: 2m G: 0.5 m relative elevation change 0.2 m better than 200 kg/m2/year (glacier wide)"		F	
3. Seasonal snow								
3.1 Snow water equivalent (SWE)	"Global Regional"	"T: 5km; G: 1 km regional/complex Terrain: T: 1 km G: 100m"	24 h	< 1 d	G: 10 mm			
3.2. Snow melt	Global to regional	"T: 500 m G: 100 m (complex terrain: 100m)"	24 h	< 1 d	"T: 10% G: 5% "			
3.3 Snow Extent	"Global regional"	"T: 1 km G: 500 m T: 500 m G: 100 m"	"T: 1 day G: 12 h"	< 1 d	"T: 10% G: 5% "			
3.4 Snow depth on Land-ice								

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(*1) Between the same type of instrument (incl S1 A,B,C, D phasing options) (*2) Cross instrument repeat based on combinations of existing, planed and future instruments e.g. SAR C-Band/L-band repeat, SAR C-Band/CIMR/MetOp repeat, SAR CIMR/CRISTAL repeat.

GEOPHYSICAL VARIABLES	POLAR EXPERT GROUP REQUIREMENTS					REQUIREMENT COMPLIANCE STATEMENT PER MISSION		
	HORISONTAL COVERAGE	HORISONTAL RESOLUTION	UPDATE FREQUENCY	LATENCY	ACCURACY (A) / UNCERTAINTY (U)	CIMR	CRISTAL	CRISTAL
						FULL (F), NON-COMPLIANT (NO VALUE)		
4. Ice sheets								
4.1 Surface Topography	Antarctia, Greenland	"Interior of ice sheets: T : 1 km G: 1 km Outlet Glaciers / Margins: T: 100 m G: 50 m"	"Interior: G: 1y Margins: G: 1 m"	not critical	"Interior: (Relative Change) T: 0.1 m G: 0.1 m Outlet Glaciers: (Relative change Standard dev.) T: 2 m G 0.3 m"		F	
4.2 Surface ice velocity	Antarctia, Greenland	"T: 500 m G 100 m"	"ice sheet wide veloicty : Winter acquisition campaign margins: all year"	not critical	"T: 5 % of velocity G: 2 % of velocity"			F: (All major ice sheets, << 6days)
4.3 Grounding line location	Antarctia, Greenland	"T: 1 km G 100 m"	"T: 5 years G: 1 year for fast changing outlet glaciers / ice streams: G: 1 months"	not critical	1 m			F: (All major ice sheets, << 6days)
4.4 Melt extent	Antarctia, Greenland	"T: 5 km G: 500 m Outlet Glaciers: G: 100 m"	"T: 7 days G: 1 d"	not critical	"T: 10% or area G: 5 % of area TBC"			
4.5 Mass and mass change	Antarctia, Greenland	"50 km drainage basin of outlet glaciers"	"T: 5 y G: 1 y"	"Cristal, ROSE-L/S1 (IOM- method together wih other data)"	not critical			
4.6 Ice margin (Extent)	Antarctia, Greenland	"T: 500 m G: 20 m"	"T: 1 year G: 1m"	"Rose-L, S1 A and/or B and/or C (Amplitude); Cristal (delineation of ice front using DEM) Useful S1 Constellation: S1 A/C Single Pass-IN-SAR, "	not critical		F	F

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(*1) Between the same type of instrument (incl S1 A,B,C, D phasing options) (*2) Cross instrument repeat based on combinations of existing, planed and future instruments e.g. SAR C-Band/L-band repeat, SAR C-Band/CIMR/MetOp repeat, SAR CIMR/CRISTAL repeat.

GEOPHYSICAL VARIABLES	POLAR EXPERT GROUP REQUIREMENTS					REQUIREMENT COMPLIANCE STATEMENT PER MISSION		
	HORISONTAL COVERAGE	HORISONTAL RESO-LUTION	UPDATE FRE-QUENCY	LATENCY	ACCURACY (A) / UNCERTAINTY (U)	CIMR	CRISTAL	CRISTAL
						FULL (F), NON-COMPLIANT (NO VALUE)		
5. Ocean								
5.1 Sea level anomaly	Global	<10km	≤24h	<1h	"3cm for along-track products (A)"		F	
5.2.1 Sea Surface Temperature (SST) - Marine	Global	<5km	<24h (6h for L2)	<1h	"0.1K for L2 products (A)"			
5.2.2 Sea Surface Temperature (SST) - Climate	Pan Arctic	10 km (1 km (IR))	<24h (6h)		0.1K for L2 products (A)			
5.3 Sea surface salinity	Global	<5km (as for SST)	<24h	< 1h	0.2			
6.Land surface and Surface fresh water								
6.1 Soil moisture	Global	1 km	1d	1d	0.04 m3/m3 (A)			
6.2 Lake ice extent	Pan-Arctic, Europe	250 m	1d	1 d	250 m (A); location accuracy 1/3 IFOV			
6.3 Lake water level	Global	N/A (non-gridded, for lake areas > 1km2)	10d	4 d	Threshold: 0.2 m (A) Goal: 5 cm (A)			
6.4 Land Surface Temperature	Global	Threshold: 5 km Goal: 1 km	1d	4 hours	Threshold: 3K(A), 4K(U) Goal: 1K(A), 2K(U)	F		
6.5 Seasonal subsidence	Pan-Arctic, Europe	20 m -100 m (L2)	annual	4 months	0.5 cm (U) L2a 1 cm (U) L2b geolocation: 15 m (A) L2b			
7. Emergency Management								
7.1 Flood extent	Global	20 m	6d					

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(*1) Between the same type of instrument (incl S1 A,B,C, D phasing options) (*2) Cross instrument repeat based on combinations of existing, planed and future instruments e.g. SAR C-Band/L-band repeat, SAR C-Band/CIMR/MetOp repeat, SAR CIMR/CRISTAL repeat.

GEOPHYSICAL VARIABLES	POLAR EXPERT GROUP REQUIREMENTS					REQUIREMENT COMPLIANCE STATEMENT PER MISSION		
	HORISONTAL COVERAGE	HORISONTAL RESO-LUTION	UPDATE FRE-QUENCY	LATENCY	ACCURACY (A) / UNCERTAINTY (U)	CIMR	CRISTAL	CRISTAL
						FULL (F), NON-COMPLIANT (NO VALUE)		
8. Security								
8.1 Vessel Detection Service (VDS)*	Global	" ●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;) ●High Resolution HR1 (4 m < x ≤ 10m;) ●High Resolution HR2 (10m < x ≤30m); ●Medium resolution MR (30m < x ≤100m) "	On demand	20 min**				
8.2 Feature Detection Service (FDS)*	Global	" ●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m); ●High Resolution HR1 (4 m < x ≤ 10m;)"	On demand	20 min**				
8.3 Oil Spill Detection	Global	" ●High Resolution HR2 (10m < x ≤30m;) ●Medium resolution MR (30m < x ≤100m) "	On demand	20 min**				
8.4 Enriched Vessel Service (EVS)*	Global	" ●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;) ●High Resolution HR1 (4 m < x ≤ 10m;)"	On demand	30 min**				
8.5 Enriched Feature Service (EFS)* (eg: Fish farms, Debris,..)	Global	" ●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;) ●High Resolution HR1 (4 m < x ≤ 10m;)"	On demand	30 min**				
8.6 Wake Detection Service (WDS)*	Global	" ●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;) ●High Resolution HR1 (4 m < x ≤ 10m)"	On demand	30 min**				
8.7 Activity Detection Service (ADS)* (eg: Fisheries control, Anti-piracy, …)	Global	" ●Very High Resolution VHR2 (from 2.5 m < x ≤ 4 m;) "	On demand	30 min**				

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(*1) Between the same type of instrument (incl S1 A,B,C, D phasing options) (*2) Cross instrument repeat based on combinations of existing, planed and future instruments e.g. SAR C-Band/L-band repeat, SAR C-Band/CIMR/MetOp repeat, SAR CIMR/CRISTAL repeat.

ANNEX 3. SUMMARY TABLE

Annex 3: PEG III Summary table space and non-space data over time	
Geophysical variable	Generic designation/terminology which covers geophysical variables (e.g. sea surface temperature/salinity/wind field …) derived via processing algorithms (physical, semi-empirical/empirical …) from satellite/in situ sensors data (similar to L2)
Pre-HPCM - Continuity	Continuity on the service level of 2020 (ALT: Altimeter, OPT: Optical, PMR: Passive Microwave, SAR: Synthetic Aperture Radar, SCAT: Scatterometer, GRAV: Gravimeter
Pre-HPCM - Enhanced continuity	Enhanced continuity in the MFF period >2021 with the service level of 2020 as baseline
Post-HPCM	Covering the Sentinel Expansions and other necessary missions/instruments
NG Requirements	Short requirements for the NG Sentinels to ensure enhanced continuity of the exiting Sentinels
Observation gaps Pre-HPCM	Observation gaps important pre-HPCMs (also considering Non-space data)
Potential Observation gaps Post-HPCM	Observation gaps important also existing post-HPCMs (also considering Non-space data)
Synergies/cross-sensor planning	Synergies/cross-sensor planning important to take into consideration in the orbit planning of the HPCMs, existing and Next-Generation Sentinels
Availability of in situ observations	Availability of in situ observations, options are: [0] hardly accessible, [1] irregular measurements available, [2] various sources exist and (non-harmonised) data are made available on a regular basis, [3] international standardised network
Potential in-situ sensors	Not exhaustive list of in situ observations. Source the KEPLER project and Mark Drinkwater (ESA)

GEOPHYSICAL VARIABLES	IDEAL SPACE OBSERVATION ASSETS OVER TIME				OBSERVATION GAPS PRE-HPCM	POTENTIAL OBSERVATION GAPS POST-HPCM	SYNERGIES/ CROSS-SENSOR PLANNING	AVAILABILITY OF IN SITU OBSERVATIONS	POTENTIAL IN-SITU SENSORS
	PRE-HPCM - CONTINUITY(1)	PRE-HPCM - ENHANCED CONTINUITY(2)	POST-HPCM	NG REQUIREMENTS					
1. FLOATING ICE									
1.1.1 Sea ice thickness (SIT) - Marine	• ALT: CryoSat-2 (SIRAL) • PMR: SMOS	• ALT: ICESAT-2 • PMR: SMAP	• ALT: CRISTAL • PMR: CIMR	• ALT: S-3 (Pan-Polar)	• Mission continuity • Bi-daily Pan-Polar coverage • In situ observations • More than <1h Latency	• In situ observations • More than <1h Latency	• ALT and PMR: Combination of SIT >1m and thin Sea ice < 0,5 m	0	Boat and airborne campaigns, submarine data, drifting buoys
1.1.2 Sea ice thickness (SIT) - Climate	• ALT: CryoSat-2 (SIRAL), ERS (RA2)	• ALT: ICESAT-2 • PMR: SMAP	• ALT: CRISTAL • PMR: CIMR	• ALT: S-3 (Pan-Polar)	• Mission continuity • Daily Pan-Polar coverage • In situ observations • More than 24h Latency	• In situ observations	• ALT and PMR: Combination of SIT >1m and thin Sea ice < 0,5 m	0	Boat and airborne campaigns, submarine data, drifting buoys
1.2.1 Sea-ice concentration (SIC) - Marine	• PMR: AMSR-2, SSMIS • SCAT: ASCAT • SAR C-band SAR available via S-1 complemented with CCMEs (C- and X-band). L-band SAR currently not used not in the CCME data offer	• PMR: AMSR-2/-3 • SAR: S-1A+B+C , ev. RCM data L-band SAR available as ALOS-4, SAOCOM and NISAR for Antarctica	• PMR: CIMR • SAR: C-band SAR - S-1 ev. RCM data L-band SAR -ROSE-L	• SAR: S-1 (Pan-Polar) • OPT: S-2, S-3	• Mission continuity • Daily Pan-Arctic coverage • In situ observations • More than <1h Latency	• In situ observations • More than <1h Latency	• PMR and SAR: Reliable automated sea ice-chart-like products (sharpened) for navigational and for high-resolution input to numerical forecasting models • C-Band SAR and L-Band SAR: separate ice and water leading to more robust and reliable SIC estimates with the potential for automatic ice chart production	0	
1.2.2 Sea-ice concentration (SIC) - Climate	• PMR: SMMR, SSM/I, SSMIS	• PMR: AMSR-2/-3	• PMR: CIMR	• SAR: NG-S-1 (Pan-Polar)	• Mission continuity • Daily Pan-Arctic coverage • In situ observations • More than ≤24h Latency	• In situ observations	• PMR and SAR: High-resolution input to numerical forecasting models	0	
1.3.1 Sea ice drift - Marine	• PMR: AMSR-2, • SCAT: ASCAT • SAR: S-1, Radarsat	• PMR: AMSR-2/-3, METOP-SG • SCAT: METOP-SG • SAR: S-1A+B+C, ev. RCM data	• PMR: CIMR, AMSR-3, METOP-SG SCAT: METOP-SG • SAR: S-1, ROSE-L, RCM data.	• SAR: NG-S-1 (Pan-Polar)	• Mission continuity (AMSR-2, AMSR3) • Daily Pan-Arctic coverage (lower latitudes) • In situ observations • More than ≤24h Latency	• In situ observations, on-ice buoys <1h sampling • More than ≤24h Latency	• Pre-HPCM: RCM access or 3*S-1 recommended • with HPCM: increased repetitivity S-1&ROSE-L and C/L-band SAR Synergy • PMR and SAR: High-resolution input to numerical forecasting models	3	Drifting buoys

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For images acquired outside EMSA contracted ground stations coverage, using on-board recorders, satellite fly time is added

GEOPHYSICAL VARIABLES	IDEAL SPACE OBSERVATION ASSETS OVER TIME				OBSERVATION GAPS PRE-HPCM	POTENTIAL OBSERVATION GAPS POST-HPCM	SYNERGIES/ CROSS-SENSOR PLANNING	AVAILABILITY OF IN SITU OBSERVATIONS	POTENTIAL IN-SITU SENSORS
	PRE-HPCM - CONTINUITY(1)	PRE-HPCM - ENHANCED CONTINUITY(2)	POST-HPCM	NG REQUIREMENTS					
1.3.2 Sea ice drift - Climate	• PMR: AMSR-2, • SCAT: ASCAT • SAR: S-1, Radarsat	• PMR: AMSR-2/-3, METOP-SG • SCAT: METOP-SG • SAR: S-1A+B+C, RCM data.	• PMR: CIMR, AMSR-3, METOP-SG • SCAT: METOP-SG • SAR: S-1, ROSE-L, RCM data.	• SAR: NG-S-1 (Pan-Polar	• Mission continuity (AMSR-2, AMSR3) • Daily Pan-Arctic coverage (lower latitudes) • In situ observations • More than ≤24h Latency	• In situ observations, on-ice buoys <1h sampling • More than ≤24h Latency	• Pre-HPCM: RCM access or 3*S-1 recommended • with HPCM: increased repetitivity S-1&ROSE-L and C/L-band SAR Synergy • PMR and SAR: High-resolution input to numerical forecasting models	3	Drifting buoys
1.4.1 Snow depth and snow cover on sea-ice - Marine			• PMR: CIMR, • ALT: CRISTAL		Lack of reliable operational products	• In situ observations	• CIMR and CRISTAL	0	Boat and airborne campaigns
1.4.2 Snow depth and snow cover on sea-ice - Climate			• PMR: CIMR, • ALT: CRISTAL		Lack of reliable operational products	• In situ observations	• CIMR and CRISTAL	0	Boat and airborne campaigns
1.5.1 Ice type-Ice stage of development - Marine	• PMR: AMSR-2, • SCAT: ASCAT • SAR: S-1, Radarsat	• PMR: AMSR-2/3, METOP-SG • SCAT: METOP-SG • SAR: S-1, RCM	• PMR: CIMR, AMSR-3, METOP-SG • SCAT: METOP-SG • SAR: S-1, RCM, ROSE-L	• SAR: S-1-NG	• Mission continuity (AMSR-2, AMSR3 • In situ observations	• In situ observations • More than <24h Latency	• Pre-HPCM: RCM access or 3*S-1 recommended • with HPCM: increased repetitivity S-1&ROSE-L and C/L band Synergy, plus PMR and SAR: input to numerical forecasting models	0	
1.5.2 Ice type-Ice stage of development - Climate	• PMR: AMSR-2, • SCAT: ASCAT	• PMR: AMSR-2/-3, METOP-SG, SSMIS • SCAT: METOP-SG	• PMR: CIMR, AMSR-3, METOP-SG SSMIS • SCAT: METOP-SG		• Mission continuity (AMSR-2, AMSR3) • In situ observation	• In situ observations • More than <24h Latency	• Pre-HPCM: RCM access or 3*S-1 recommended • with HPCM: increased repetitivity S-1&ROSE-L and C/L band SAR Synergy, plus CIMR and SAR: input to numerical forecasting models	0	
1.6.1 Iceberg (iceberg concentration charts and individual icebergs) - Marine	• SAR: S-1, Radarsat	• SAR: S-1, RCM	• SAR: S-1, RCM, ROSE-L	• SAR: S-1-NG	• Mission contínity (RS-2 coverage) • In situ observations • More than <1h Latency	• In situ observations • More than <1h Latency	• Pre-HPCM: RCM access or 3*S-1 recommended • with HPCM: increased repetitivity S-1&ROSE-L and C/L band Synergy plus CRISTAL	0	Boat and airborne campaigns

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GEOPHYSICAL VARIABLES	IDEAL SPACE OBSERVATION ASSETS OVER TIME				OBSERVATION GAPS PRE-HPCM	POTENTIAL OBSERVATION GAPS POST-HPCM	SYNERGIES/ CROSS-SENSOR PLANNING	AVAILABILITY OF IN SITU OBSERVATIONS	POTENTIAL IN-SITU SENSORS
	PRE-HPCM - CONTINUITY(1)	PRE-HPCM - ENHANCED CONTINUITY(2)	POST-HPCM	NG REQUIREMENTS					
1.6.2 Iceberg (iceberg concentration charts and individual icebergs) - Climate	• SAR: S-1, Radarsat	• SAR: S-1, RCM	• SAR: S-1, RCM, ROSE-L	• SAR: S-1-NG	• Some gaps at some days at southern Arctic latitudes in the daily S-1 coverage	• In situ observations • More than <1h Latency	• Pre-HPCM: RCM access or 3*S-1 recommended • with HPCM: increased repetitivity S-1&ROSE-L and C/L band Synergy plus CRISTAL	0	Boat and airborne campaigns
1.7.1 Sea-ice surface temperature - Marine	• OPT: MetOp(AVHRR), VIIRS_NPP	• OPT: MetOp(AVHRR), VIIRS_NPP	• PMR:CIMR • OPT: MetOp(AVHRR), VIIRS_NPP	• OPT: S-3-NG SLSTR				0	Boat and airborne campaigns
1.7.2 Sea-ice surface temperature - Climate	• OPT: MetOp(AVHRR), VIIRS_NPP	• OPT: MetOp(AVHRR), VIIRS_NPP	• PMR:CIMR • OPT: MetOp(AVHRR), VIIRS_NPP	• S-3-NG SLSTR				0	Boat and airborne campaigns
2. GLACIERS AND ICE CAPS									
2.1 Glacier extent	• OPT: S-2, Landsat 8, other optical satellite with resolution < 30 m	• OPT: S-2, Landsat-8 and -9, other optical satellite with resolution < 30 m	• OPT: S-2, Landsat-8 and -9, other optical satellite with resolution < 30 m	• SAR: S-1 NG • OPT: S-2 NG Additional spectral bands to improve Snow/Cloud discrimination required	• Improve repeat coverage for cloud-free images			0	oblique Photos
2.2 Surface ice velocity	• OPT: S-2, Landsat8, • SAR: TSX, S-1,	• OPT: S-2, Landsat- 8 and -9, • SAR: TSX, S-1,	• OPT: S-2, Landsat- 8 and -9, • SAR: S-1	• SAR: S-1-NG • OPT: S-2-NG	• repeat coverage of SAR (continous 6 days; also over ice caps) • acquisitions of crossing orbits for SAR		• SAR ROSE--L, S-1 and OPT: S-2 (ev Landsat)	1	GPS
2.3 Surface elevation & Change and mass balance	• ALT: CryoSat-2, ERS RA, Envisat RA, Icesat-2 • SAR: TandemX SP-INSAR DEMs	• ALT: CryoSat-2, S-3 SRAL, Icesat-2 • SAR: TanDEM-X SPIN-SAR DEM • SAR-Potential: S-1 A+C SP-INSAR DEM	• ALT: CRISTAL • SAR-Potential: S-1 A+C SP-INSAR DEM	• SAR: S-1 NG SP-INSAR • ALT: S-3 SRAL NG (volume change)	• regular coverage of glaciated areas limited to very large glaciers due to resolution of Altimeter (requires SP-INSAR) • Mission continuation of SP-InSAR DEMs (TanDEM-X ; Potentially S-1 A+C)	• CRISTAL will improve coverage for very big glaciers); glaciers with complex topo not covered • Mission continuation of SP-INSAR for TandemX or S-1 A+C SPiNSAR	• CRISTAL and S-1 NG SP-INSAR	1	GPS

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GEOPHYSICAL VARIABLES	IDEAL SPACE OBSERVATION ASSETS OVER TIME				OBSERVATION GAPS PRE-HPCM	POTENTIAL OBSERVATION GAPS POST-HPCM	SYNERGIES/ CROSS-SENSOR PLANNING	AVAILABILITY OF IN SITU OBSERVATIONS	POTENTIAL IN-SITU SENSORS
	PRE-HPCM - CONTINUITY(1)	PRE-HPCM - ENHANCED CONTINUITY(2)	POST-HPCM	NG REQUIREMENTS					
3. SEASONAL SNOW									
3.1 Snow water equivalent (SWE)	• PMR: SSMI, AMSR-2 (Coarse Resolution not for steep mountains) • Mountain regions: not covered	• PMR: SSMI, AMSR-2/-3 (Coarse Resolution not for steep mountains) • SAR-Potential for .Mountain regions: SAOCOM, NISAR with InSAR Synergy with Snow Extent Product	• PMR: CIMR • SAR: Mountain Regions: ROSE-L		• Mission continuity • In situ observations • More than 12h Latency		• Same acquisition time: of ROSE–L, S-1, and CIMR; S-3 SLSTR daily coverage: - S-3: presence of Snow (dry or wet) - Mountain areas: ROSE-L (SWE for dry snow areas) S-1 (Wet snow areas), - Non-Mountain areas: SWE from CIMR	2	Campaigns
3.2. Snow melt	• SAR: regional products S-1 (e.g. Alps)	• SAR: Pan-European S-1A+B+C+ RCM (in synergy with Snow Extent from optical satellite data)	• SAR: S-1 A+B+C	• SAR: S-1 NG	• Daily coverage of snow regions • More than 12h Latency		• S-1 and other C-band Sensors: e.g. RCM	1	Campaigns
3.3 Snow Extent	• OPT: Global: MODIS, VIIRS, Europe: High resolution: S-2	• OPT: Global: MODIS, VIIRS, Europe: High resolution: S-2	• OPT: S-3 SLSTR/OLCI (Global)	• OPT:S-3 NG SLSTR / OLCI: Additional spectral bands to improve Snow/Cloud discrimination required	• Europe: High resolution: Daily Coverage of S-2		• Optical data: daily coverage of S-3	2	
3.4 Snow depth on Land-ice	direcly related to SWE	NA	NA	NA	NA	NA	NA		Campaigns
4. ICE SHEETS									
4.1 Surface Topography	• ALT: CryoSat-2, ERS RA, Envisat RA, Icesat-2	• ALT: S-3 SRAL, Cryo-Sat-2, Icesat-2	ALT: CRISTAL, S-3 SRAL	• ALT: S-3 SRAL NG	• mission continutiy for cryosat • outlet glacier not covered due to resolution ´(SP-INSAR needed)	• Outlet glaciers (complex, steep terrain)	• ALT: CRISTAL and S-1 NG SP-INSAR for Outlet glaciers	1	indirect through AWS (snow temperature)
4.2 Surface ice velocity	• SAR: S-1 A+B, RSAT, • SAR Archived data: ERS, ENVISAT ASAR, Radarsat, TSX • OPT: Landsat8, S-2	• SAR: S-1 A+B+C; Pot. 1day S-1 A+C; NISAR, SAOCOM, ALOS PALSAR-2 • OPT: S-2, Landsat8+9	• SAR: ROSE-L, S-1, NISAR • OPT: S-2, Landsat 9	• ALT: S-1 NG • OPT: S-2 NG: Additional spectral bands to improve Snow/Cloud discrimination required	• areas with low coherence (drift,melt) not covered • polar gap in AIS • crossing orbits for SAR (asc and desc) needed • insitu data in AIS and GIS for validation are sparse	• Crossing orbits (Asc + Des) needed • Polar gap in AIS not covered by ROSE-L and S-1; continuation of NISAR (left looking) ??	• ROSE-L, S-1 - Crossing orbits (Asc and Des)	1	GPS(through Surface elevation change)

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GEOPHYSICAL VARIABLES	IDEAL SPACE OBSERVATION ASSETS OVER TIME				OBSERVATION GAPS PRE-HPCM	POTENTIAL OBSERVATION GAPS POST-HPCM	SYNERGIES/ CROSS-SENSOR PLANNING	AVAILABILITY OF IN SITU OBSERVATIONS	POTENTIAL IN-SITU SENSORS
	PRE-HPCM – CONTINUITY(1)	PRE-HPCM – ENHANCED CONTINUITY(2)	POST-HPCM	NG REQUIREMENTS					
4.3 Grounding line location	• SAR: S-1 A+B 6 days • ALT: CryoSat-2	• SAR: S-1 A+B+C; ev. 1day S-1 A+C; NISAR, SAOCOM, ALOS PALSAR-2 • ALT: CryoSat-2, S-3 SRAL	• SAR: ROSE-L, S-1 • ALT: CRISTAL	• SAR: S-1 NG	• InSAR coherence problems in areas with drift/melt (S-1 6d)	• requires propoer ROSE-L acquisition planning for AIS and GIS	• ROSE-L, S-1; • CRISTAL	0	
4.4 Melt extent	• SAR: S-1, RCM/ Radarsat-2	• SAR: S-1 A+B+C, RCM, Radarsat-2	• SAR: S-1, RCM • PMR: CIMR	• SAR: S-1 NG	• daily coverage with S-1 required	• daily coverage required (S-1)	• S-1, CIMR	0	
4.5 Mass and mass change	• GRAV: Grace FO, • ALT: through Volume change; CryoSat-2, • Through IO-method: - SAR: S-1 A+B, RSAT, Archived data: ERS, ENVISAT ASAR, RSAT, TSX - OPT: Landsat, (S-2 A+B	• GRAV: Grace FO, • ALT: Volume change mezthod; CryoSat-2,S-3 SRAL • IO-method: - S-1 SAR: A+B+C, NISAR, SAOCOM A+B - OPT: S-2 A+B	• GRAV: Grace FO, • ALT: through Volume change; CRISTAL, (S-3 SRAL) • Through IO-method using ice velocity: - SAR: ROSE-L, S-1 A+B+C, - S-2 A+B	• ALT: S-3 SRAL NG (volume change) • SAR: S-1 NG (ice velocity) • OPT: S-2 NG	• Mission continuity for Grace FO • SAR IOM: ice velocity, ice thickness data at grounding line (from other data needed; e.g. airborne) and Surface Mass Balance models	• ice thickness measurments at grounding line needed for IOM (by airborne data)	• ROSE-L, S-1 • CRISTAL	0	
4.6 Ice margin (Extent)	• SAR: S-1 A+B 6 days • ALT: CryoSat-2 • OPT: S-2	• SAR: S-1 A+B 6 days • ALT: S-3 SRAL • OPT: S-2	• SAR: ROSE-L • ALT: CRISTAL	• SAR: S-1 NG SPIN-SAR (Automatic mapping using DEM) • SAR: S-1 NG Amplitude • OPT: S-2 NG, S-3 NG OLCI: additional bands for cloud versus snow/ice detection		• requires continous acquisitions for AIS and GIS for SAR	• ROSE-L, S-1, S-1 NG INSAR, + CRISTAL	0	

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GEOPHYSICAL VARIABLES	IDEAL SPACE OBSERVATION ASSETS OVER TIME				OBSERVATION GAPS PRE-HPCM	POTENTIAL OBSERVATION GAPS POST-HPCM	SYNERGIES/ CROSS-SENSOR PLANNING	AVAILABILITY OF IN SITU OBSERVATIONS	POTENTIAL IN-SITU SENSORS
	PRE-HPCM - CONTINUITY(1)	PRE-HPCM - ENHANCED CONTINUITY(2)	POST-HPCM	NG REQUIREMENTS					
5. OCEAN									
5.1 Sea level anomaly	• ALT: S-3A/B, Jason-3, HY-2A/B, Saral/AltiKa, CryoSat-2	• ALT: S-3, S-6, HY-2, SWOT	• ALT: CRISTAL	• ALT: S-3- NG SRAL	• Mission continuity • In situ observations	• In situ observations		0	Tide gauge, Moving vessel profiler (MVP), Gliders, Conductivity, Temperature, and Depth (CTD), Argo buoys, Drones
5.2.1 Sea Surface Temperature (SST) - Marine	• OPT: MetOp(AVHRR), VIIRS_NPP, S-3A-3B SLSTR, MSG(SEVIRI) • PMR: AMSR-2, SSMIS	• OPT: MetOp(AVHRR), VIIRS_NPP S-3A-3B SLSTR • PMR:AMSR-2/3	• OPT:S-3 SLSTR • PMR:CIMR • ALT:CRISTAL	• OPT: S-3-NG SLSTR	• Mission continuity • In situ observations	• In situ observations	CIMR & S-3-NG	0	SST radiometers, MVP, gliders, CTD
5.2.2 Sea Surface Temperature (SST) - Climate	• OPT: MetOp(AVHRR), VIIRS_NPP, S-3A-3B SLSTR, MetOp(SEVIRI) • PMR: AMSR-2, SSMIS	• OPT: MetOp(AVHRR), VIIRS_NPP, S-3A-3B SLSTR • PMR:AMSR-2/3	• OPT: S-3-NG SLSTR • PMR:CIMR • ALT:CRISTAL	• OPT: S-3-NG SLSTR	• Mission continuity • In situ observations	• In situ observations	CIMR & S-3-NG	0	SST radiometers, MVP, gliders, CTD
5.3 Sea surface salinity	PMR : SMOS, COSSM, SMAP	PMR:SMOS, COSSM, SMAP	PMR:CIMR		• Mission continuity • In situ observations	• In situ observations		0	MVP, gliders, CTD

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GEOPHYSICAL VARIABLES	IDEAL SPACE OBSERVATION ASSETS OVER TIME				OBSERVATION GAPS PRE-HPCM	POTENTIAL OBSERVATION GAPS POST-HPCM	SYNERGIES/ CROSS-SENSOR PLANNING	AVAILABILITY OF IN SITU OBSERVATIONS	POTENTIAL IN-SITU SENSORS
	PRE-HPCM - CONTINUITY(1)	PRE-HPCM - ENHANCED CONTINUITY(2)	POST-HPCM	NG REQUIREMENTS					
6.LAND SURFACE AND SURFACE FRESH WATER									
6.1 Soil moisture	• SAR:S-1 A+B, Radarsat-2 • PMR: SMOS, SMAP, • OPT: MODIS, MetOp(SEVIRI), ASTER, Landsat-7	• SAR:S-1 A+B+C, Radarsat-2 • PMR: SMOS, SMAP, • OPT: MODIS, MetOp(SEVIRI), ASTER, Landsat-7	• SAR: ROSE-L, S-1 • PMR: CIMR • HYP: CHIME	• SAR: S-1 NG (Pan-Polar)	• In CLMS currently only provided for Europe • Detection of freezing/ thawing • Densely vegetated areas and soil penetration depth (for C Band)	• No retrieval outside the growing season • Soil penetration limited to 5 cm	• ROSE-L, S-1, CIMR	2	electrical impedance sensors, dielectric techniques, heat pulse sensors
6.2 Lake ice extent	• SAR: S-1 • OPT: S-2, MODIS, S-3 SLSTR	• SAR: S-1 • OPT: S-2, MODIS, S-3 SLSTR	• SAR: ROSE-L, S-1 • OPT: CHIME, S-2, S-3 SLSTR	• S-1,2,3 NG (Pan-Polar)	• In Copernicus currently only provided for Baltic region • Freeze-up period not included (polar night) • Frequent cloud cover during ice breakup	• Poor contrast between water and thin ice • Backscatter from melting snow on lake ice	• ROSE-L, S-2 • ROSE-L, CHIME • S-1,S-2/3	1	visual inspection
6.3 Lake water level	• ALT: S-3,JASON	• ALT: S-3, S6, SWOT	ALT: CRISTAL, S-3	ALT: S-3 NG SRAL	• only open water lakes (no vegetation)	• only open water lakes (no vegetation)	• CRISTAL, S-3 (GRACE, GRACE-FO)	1	acoustic sensors, pressure sensors
6.4 Land Surface Temperature	• OPT: S-3 SLSTR, MODIS, VIIRS, MSG, GOES, MTSAT/ Himawari, • PMR: SSMI, AMSR-2	• OPT: S-3 SLSTR, MODIS, VIIRS, MSG, GOES, MTSAT/Himawari, • PMR: SSMI, AMSR-2	• OPT: S-3 SLSTR, LSTM • PMR: CIMR	• S-3 NG OLCI/ SLSTR	• Cloudy conditions (for infrared measurements) • Larger error (for microwave measurements)	• Cloudy conditions (for infrared measurements) • Larger error (for microwave measurements)	• CIMR, LSTM • LSTM, S-1/2/3	2	thermal infrared radiometers, thermocouples
6.5 Seasonal subsidence	• SAR: S-1 A+B, Radarsat-2, TerraSAR-X, CosmoSkyMed	• SAR: S-1 A+B+C, Radarsat-2, TerraSAR-X, CosmoSkyMed, NISAR, Tandem-L	• SAR: S-1, ROSE-L	• SAR: S-1 NG (Pan-Polar)	• In Copernicus currently only provided for Europe • Incoherent scattering for water bodies,dense vegetation, changing snow cover (for C and X Band)	• Location uncertainty • Motion component in north/ south direction	• ROSE-L, S-1	1	extensometers, spirit-level surveys
7. EMERGENCY MANAGEMENT									
7.1 Flood extent	• SAR: S-1 A+B	• SAR: S-1 A+B+C	• SAR: ROSE-L, S-1	• SAR: S-1 NG (Pan-Polar)	• Revist time • Incoherent scattering for water bodies,dense vegetation, changing snow cover (for C and X Band)	• Location uncertainty	• ROSE-L, S-1	3	Drones
8. SECURITY									

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GEOPHYSICAL VARIABLES	IDEAL SPACE OBSERVATION ASSETS OVER TIME				OBSERVATION GAPS PRE-HPCM	POTENTIAL OBSERVATION GAPS POST-HPCM	SYNERGIES/ CROSS-SENSOR PLANNING	AVAILABILITY OF IN SITU OBSERVATIONS	POTENTIAL IN-SITU SENSORS
	PRE-HPCM - CONTINUITY(1)	PRE-HPCM - ENHANCED CONTINUITY(2)	POST-HPCM	NG REQUIREMENTS					
8.1 Vessel Detection Service (VDS)*	• SAR: S-1 A+B, Radarsat-2, TERRASAR-X, PAZ	• SAR: S-1 A+B+C, Radarsat-2, RCM TERRASAR-X, PAZ	• SAR: ROSE-L, S-1	• S-1 NG (Pan-Polar) • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• Revist time • Latency • Resolution (from 2.5 m < x ≤ 5 m;)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• ROSE-L, S-1 - observation plan allowing high revisit frequency	• 3 • 2 • 0	• AIS, • RPAS, • Radio Frequency Sensors for the future
8.2 Feature Detection Service (FDS)*	• SAR: Radarsat-2, TERRASAR-X, PAZ	• SAR: S-1 A+B+C, Radarsat-2, RCM TERRASAR-X, PAZ	• SAR: ROSE-L, S-1	• SAR: S-1 NG (Pan-Polar) • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• ROSE-L, S-1 - observation plan allowing high revisit frequency	• 3 • 2 • 0	• AIS, • RPAS, • Radio Frequency Sensors for the future
8.3 Oil Spill Detection	• SAR: S-1 A+B, Radarsat-2, TERRASAR-X, PAZ	• SAR: S-1 A+B+C, Radarsat-2, RCM TERRASAR-X, PAZ	• SAR: ROSE-L, S-1	• SAR: S-1 NG (Pan-Polar) • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• ROSE-L, S-1 - observation plan allowing high revisit frequency	• 3 • 2 • 0	• AIS, • RPAS, • Radio Frequency Sensors for the future
8.4 Enriched Vessel Service (EVS)*	• SAR: Radarsat-2, TERRASAR-X, PAZ	• SAR: S-1 A+B+C, Radarsat-2, RCM TERRASAR-X, PAZ	• SAR: ROSE-L, S-1	• SAR: S-1 NG (Pan-Polar) • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (20 min**)	• ROSE-L, S-1 - observation plan allowing high revisit frequency	• 3 • 2 • 0	• AIS, • RPAS, • Radio Frequency Sensors for the future
8.5 Enriched Feature Service (EFS)* (eg: Fish farms, Debris,..)	• SAR: Radarsat-2, TERRASAR-X, PAZ	• SAR: S-1 A+B+C, Radarsat-2, RCM TERRASAR-X, PAZ	• SAR: ROSE-L, S-1	• SAR: S-1 NG (Pan-Polar) • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• ROSE-L, S-1 - observation plan allowing high revisit frequency	• 3 • 2 • 0	• AIS, • RPAS, • Radio Frequency Sensors for the future
8.6 Wake Detection Service (WDS)*	• SAR: Radarsat-2, TERRASAR-X, PAZ	• SAR: S-1 A+B+C, Radarsat-2, RCM TERRASAR-X, PAZ	• SAR: ROSE-L, S-1	• SAR: S-1 NG (Pan-Polar) • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• ROSE-L, S-1 - observation plan allowing high revisit frequency	• 3 • 2 • 0	• AIS, • RPAS, • Radio Frequency Sensors for the future
8.7 Activity Detection Service (ADS)* (eg: Fisheries control, Anti-piracy, …)	• SAR: Radarsat-2, TERRASAR-X, PAZ	• SAR: S-1 A+B+C, Radarsat-2, RCM TERRASAR-X, PAZ	• SAR: ROSE-L, S-1	• SAR: S-1 NG (Pan-Polar) • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• Revist time • Resolution (from 2.5 m < x ≤ 5 m;) • Latency (30 min**)	• ROSE-L, S-1 - observation plan allowing high revisit frequency	• 3 • 2 • 0	• AIS, • RPAS, • Radio Frequency Sensors for the future

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ANNEX 4. IN-SITU OBSERVATIONS IN CMEMS

Table A4.1: Current use of Arctic in-situ observations in CMEMS Thematic Assembly Centres (TACS)

ARC:Arctic; SL:Sea level; OC:Ocean colour; REP:Reprocessed; BGC:Biogeochemical; PHYS:Physics; INS:In-situ; AD:Algorithm development; CV:Calibration/Validattion;DA:Data assimilation; NRT:Near Real Time; RAN:Reanalysis.

Each CMEMS TAC product is associated with a QuID (Quality Information Document). The analysis of these QuIDs shows that the lack of temporal and spatial in-situ data in the polar regions is affecting the quality of Copernicus products for the polar regions.

The MFCs (Monitoring and Forecasting Centres) of CMEMS also require in-situ observations for the validation of their polar products as illustrated in Table A4.2 below.

CMEMS USERS	CMEMS PRODUCT NAME	CURRENT USAGE OF ARCTIC IN-SITU OBSERVATIONS										
		PURPOSE OF USE			DATA CHARACTERISITICS							
		AD	CV	DA	DATASET NAME	PROVIDER	PARA-METER	NO. OF STATIONS	COVER-AGE	UPDATE_ FREQ.	TIME-LINESS	PERIOD
SL TAC	SEALEVEL_ARC_PHY_L3_NRT_OBSERVATIONS_008_038		√		GLOSS/CLIVAR & PSMSL	UHSLC	Sea level	~10	Arctic	monthly	N/A	N/A
	SEALEVEL_GLO_PHY_L4_NRT_OBSERVATIONS_008_046		√			UHSLC	Sea level	~100	Global	monthly	N/A	N/A
	SEALEVEL_GLO_PHY_L4_REP_OBSERVATIONS_008_047		√		GLOSS/CLIVAR & PSMSL	UHSLC	Sea level	~100	Global	monthly	N/A	N/A
	SEALEVEL_GLO_PHY_L3_REP_OBSERVATIONS_008_045		√			UHSLC	Sea level	~100	Global	monthly	N/A	N/A
OC TAC	OCEANCOLOUR_ARC_CHL_L4_NRT_OBSERVATIONS_009_087		√		No data used	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	OCEANCOLOUR_ARC_CHL_L3_NRT_OBSERVATIONS_009_047 Reprocessed products		√			N/A	N/A	N/A	N/A	N/A	N/A	N/A
SST TAC	SEAICE_ARC_SEAICE_L4_NRT_OBSERVATIONS_011_008; L4_NRT_OBSERVATIONS_011_003; L3_REP_OBSERVATIONS_011_010		√		Drifters	ICOADS	SST	~132	Arctic Ocean	Hourly	NRT	hourly
			√		IMB buoy	DMI	IST	~8		Hourly	offline	2012
			√		Argo T/S	INSTAC	SST	~80		10 days	NRT	10 days
SIC TAC			√		Drifter data	ICOADS	SID	~132	Arctic Ocean	Hourly	NRT	
Wind TAC	WIND_GLO_WIND_L3_NRT_OBSERVATIONS_012_002		√		No data used	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Wave TAC	WAVE_GLO_WAV_L3_SWH_NRT_OBSERVATIONS_014_001		√		No data used	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table A4.2: Current use of in-situ observations in CMEMS Marine Monitoring and Forecasting Centres (MFCs) – Source: Arctic In-situ data availability, Buch et al. 2019.

CMEMS USERS	**CMEMS PRODUCT NAME**	**CURRENT USAGE OF ARCTIC IN-SITU OBSERVATIONS**										
		PURPOSE OF USE			**DATA CHARACTERISTICS**							
		AD	**CV**	**DA**	**DATASET NAME**	**PROVIDER**	**PARA-ME-TER**	**NO. OF STA-TIONS**	**COVER-AGE**	**UPDATE_ FREQ.**	**TIME-LI-NESS**	**PERIOD**
ARC MFC	ARCTIC_ANALYSIS_FORECAST_ PHYS_002_001_A	√	√	√	Argo & R/Vs TS	INSTAC	T/S	~2000/y	Nordic Seas	daily	NRT & offline	2010-
			√		Drifter buoy	INSTAC	SST	~132	Arctic Ocean	hourly	NRT	2012-
			√		Drifter buoy	INSTAC	U,V	~132		hourly	NRT	2012-
		√			Sea ice drift buoy	IABP-SIDFEx	UICE,VICE	~10 at any time		3hourly	NRT	1980-
			√	√	ITP-TS	INSTAC	T/S	~400/y		daily	NRT	2006-
	ARCTIC_ANALYSIS_FORECAST_ BIO_002_004	√			R/V BGC	INSTAC	chl-a, N	~30	Nordic Seas	daily	offline	2007-2008
			√		Bio-Argo	INSTAC	chl-a, O2	~300	Irminger Sea	daily	offline	2015-
	ARCTIC_REANALYSIS_ PHYS_002_003		√	√	Argo, ITP & R/Vs TS	INSTAC	T/S	~3000/y	Arctic Ocean	daily	offline	2003-2017
			√	√	ICES Ocean. Data	ICES	T,S	~1000/y	Nordic Sea	daily	offline	1991-2009
			√	√	R/Vs	AARI, IOPAS, MMBI	T/S	~1000/y	Nordic Sea	daily	offline	1991-2009
			√		IMB buoys	CRREL Portal1	SIT	3	Beaufort Sea	daily	offline	2013-2016
			√		BGEP moorings	WHOI	SIT	4	Beaufort Sea	daily	offline	2013-2016
			√		Drifter buoy	INSTAC	SST	~132	Arctic Ocean	hourly	NRT	1991-
			√		Drifter buoy	INSTAC	U,V	~132		hourly	NRT	1991-
			√		IABP buoys (sea ice)	NSIDC	UICE,VICE	~10 at any time		3hourly	NRT	1980-
			√		Tide Gauges	PSMSL	sea level	42	Arctic Ocean	monthly	offline	1991-2009
	ARCTIC_REANALYSIS_ BIO_002_005		√		R/V data	INSTAC	chl-a, N	~30	Nordic Seas	daily	offline	2007-2008
	ARCTIC_ANALYSIS_FORECAST_ WAV_002_010		√		Platform-Buoy Wave	Met.no	Waves	~26	NOR-offshore	hourly	offline	3-4 months

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