Copernicus Imaging Microwave Radiometer (CIMR) Mission Requirements Document
Approval

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Change Log

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1 INTRODUCTION

This document is the formal Mission Requirements Document (MRD) for the Copernicus Imaging Microwave Radiometry (CIMR) Mission.

The CIMR High Priority Copernicus Mission (HPCM) considers the inclusion of global multi-frequency imaging microwave radiometry, with a focus on high-latitude regions in support of the Integrated European Union (EU) Policy for the Arctic (see https://eeas.europa.eu/arctic-policy/eu-arctic-policy_en). It is part of the evolution of the current Copernicus Space Component (CSC) capabilities described in the CSC Long Term Scenario (LTS, ESA, 2019) to address the User Requirements expressed by the European Commission (EC).

The CIMR Mission Requirements Document (MRD) provides guidance and serves as an input to the European Space Agency (ESA) preparatory phase (Phase A/B1) study activities started in 2018, and for the implementation phase (Phase B2/C/D/E) initiated in 2020. It is managed by the CIMR Mission Scientist according to the ESA Quality Management System (QMS) procedure for Mission Requirements Management (QMS-PR-MMAN-2050-EOP) and Mission Implementation and Operations (ESA-EOP-QMS-PR-2100).
2 BACKGROUND AND JUSTIFICATION

Copernicus [http://www.copernicus.eu/] is a European system for monitoring the Earth in support of European policy. It includes Earth Observation satellites (notably the Sentinel series developed by ESA), ground-based measurements and, services to processes data to provide users with reliable and up-to-date information through a set of Copernicus operational services related to environmental and security issues. These include:

- Copernicus Marine Environmental Monitoring Service (CMEMS [http://marine.copernicus.eu]),
- Copernicus Land Monitoring Service (CLMS [http://land.copernicus.eu/]),
- Copernicus Atmospheric Monitoring Service (CAMS [https://atmosphere.copernicus.eu/]),
- Copernicus Emergency Management Service (CEMS) [http://emergency.copernicus.eu/] and
- Copernicus Climate Change Service (C3S) [http://climate.copernicus.eu].

Copernicus services provide critical information to support a wide range of applications, including environment protection, management of urban areas, regional and local planning, agriculture, forestry, fisheries, health, transport, climate change, sustainable development, civil protection and tourism. Copernicus satellite missions are designed to provide ‘upstream’ inputs to all Copernicus Services as systematic measurements of Earth’s oceans, land, ice and atmosphere to monitor and understand large-scale global dynamics. The primary users of Copernicus services are policymakers and public authorities that need information to develop environmental legislation and policies or to take critical decisions in the event of an emergency, such as a natural disaster or a humanitarian crisis. The Copernicus programme is coordinated and managed by the European Commission. The development of the observation infrastructure is performed under the aegis of the European Space Agency (ESA) for the space component and of the European Environment Agency (EEA) and the Member States for a separate, but important, in-situ measurement component.

As set out in the ESA Program Board for Earth Observation (PBEO) paper (ESA/PB-EO(2017)31 Paris, 5 September 2017), the Copernicus Space Component (CSC) has been established as the largest and most proficient Earth Observation infrastructure in the world. With seven high-performance satellites in orbit and more than 200,000 registered Sentinel data users on the ESA/EC Copernicus data portal as well as numerous sophisticated operational services, the system has evolved at a breath-taking pace. In order to preserve the momentum in fulfilling user needs, the future evolution of the CSC needs to be initiated now in close cooperation with all stakeholders.

According to the Copernicus Regulation (EU Regulation No. 377/2014 dated 3 April 2014), ESA has been mandated by the EU Council and European Parliament to define “the overall system architecture for the Copernicus space component and its evolution on the basis of user requirements, coordinated by the Commission”. Following this rationale ESA, in close interaction with the EC, EUMETSAT and Member States, has identified key components of a Long-Term Scenario.
2.1 Copernicus Evolution

The intense use and increased awareness for the potential of Copernicus have generated great expectations for an evolved Copernicus system. There is now a large set of concrete needs and requirements for the future configuration of the CSC. User and observation requirements have been identified, structured and prioritized in a continuous reflection process led by the EC. Results from EU policy analyses, consultation of Services and Member States, as well as various workshops, gap analyses, studies and task forces now provide the rationale for the LTS. Clearly, a resolute approach is needed to achieve the time-critical objectives of new policies, such as the Integrated European Union Policy for the Arctic, Climate Change, the Sustainable Development Goals of the UN or European EO Data Commercialization.

Two distinct sets of expectations have emerged from the user consultation process:

1. Stability and continuity, while increasing the quantity and quality of CSC products and services, lead to one set of requirements. These requirements are addressed by an Extension of the current Sentinel 1 to 6 satellite capability by providing enhanced continuity of baseline Copernicus observations.

2. Emerging and urgent needs for new types of observations constitute a second distinct set of requirements. They are addressed by a timely Expansion of the current Sentinel satellite fleet. Both sets of expectations have been systematically reflected and integrated by ESA (as the CSC System Evolution Architect) in response to formal documented EC requirements.

The ‘Extension’ and the ‘Expansion’ components are organised around broad observation domains. The distinction between ‘Expansion’ and ‘Extension’ components is not schedule-based. The ‘Expansion’ component corresponds to the enlargement of the present measurements through the introduction of new missions to answer emerging and urgent user requirements. The ‘Extension’ component corresponds to a more progressive improvement of the current measurement capabilities, mostly by means of new generation of similar instrumentation compared to the ones currently deployed by Copernicus today.

The “CSC Expansion” programme includes new High Priority Copernicus Missions (HPCM) that have been identified by the European Commission (EC) as priorities for implementation in the coming years by providing new capabilities in support of current emerging user needs. Three priorities have been identified:

- **Priority 1:**
  - Greenhouse gas monitoring, specifically on anthropogenic CO2 emissions for which currently no European satellite observations are available

- **Priority 2:**
  - Monitoring Polar regions, specifically concerning polar/Arctic observations, namely sea ice/floating ice concentration and surface elevation
  - Monitoring Agriculture, specifically on parameters which potentially could be addressed through thermal infrared and hyperspectral observations

- **Priority 3:**
  - Mining, biodiversity, soil moisture and other parameters, requiring observations in additional bands, currently not available
The following missions have been identified to address these prioritised needs:

- **Anthropogenic CO2 monitoring mission**: this mission aims to analyse through the use of CO2 satellite imagers the man-made CO2 emissions and overall CO2 budget at country and regional/megacity scales and assess the effectiveness of the relevant COP21 decisions. This require the capability to provide satellite accurate and consistent quantification of anthropogenic CO2 emission and their trends.

- **Passive Microwave Imaging Mission** (Microwave Radiometer Imaging Mission): Microwave Imaging Multi-Spectral Radiometers uniquely observe a wide range of floating sea ice parameters, in particular sea ice concentration, and serve operational systems in non-precipitating atmosphere conditions, day and night. This mission, called the Copernicus Imaging Microwave Radiometer (CIMR), will provide improved continuity of missions monitoring floating sea ice parameters, notably in terms of spatial resolution (~5 km), temporal resolution (sub-daily) and geophysical accuracy. Additional measurement of Sea Surface Temperature and other parameters having global coverage, but with a focus in the polar regions, will also be included.

- **Polar Ice and Snow Topographic Mission**: this mission shall provide enhanced measurements of land ice elevation and sea ice thickness implementing higher spatial resolution for improved lead detection and additional capability to determine snow loading on sea ice.

- **High Spatio-Temporal Resolution Land Surface Temperature (LST) Monitoring Mission**: this mission shall be able to complement the current visible (VIS) and near-infrared (NIR) Copernicus observations with high spatio-temporal resolution Thermal Infrared observations over land and coastal regions in support of agriculture management services and possibly a range of additional services.

- **HyperSpectral Imaging Mission**: this mission aims to augment the Copernicus space component with precise spectroscopic measurements to derive quantitative surface characteristics supporting the monitoring, implementation and improvement of a range of policies in the domain of raw materials, agriculture, soils, food security, biodiversity, environmental degradation and hazards, inland and coastal waters, snow, forestry and the urban environment.

- **L-Band SAR Mission**: this mission is responding to the requirements expressed by both the Land Monitoring and the Emergency Management services. Its target applications are: soil moisture, crop type discrimination, forest type/forest cover (in support to biomass estimation), food security and precision farming. In addition, the mission will contribute to the monitoring of ice extent in the polar region. Other emerging applications will be possible by the synergetic and complementary observations with C band and X band SAR systems.

While the long-term consolidation of current CSC capabilities is the utmost priority, no hierarchy is established at this point among the proposed HPCM, which are all backed by strong priority user needs and must all be considered an integral part of the evolving Copernicus system.
2.2 The Integrated European Union Policy for the Arctic.

The Arctic Ocean is changing dramatically responding to significant global atmospheric warming by pan-Arctic sea-ice retreat and thinning (e.g. Meier et al., 2014; Werner et al., 2016). The rise in Arctic near-surface air temperatures has been almost twice as large as the global average in recent decade (e.g. Serreze and Francis, 2006) that is called ‘Arctic amplification’ (Kellog, 1975) although the underlying causes of Arctic amplification remain uncertain (e.g. Screen and Simmonds, 2010). Arctic amplification is the outcome of many complex and interrelated feedback mechanisms (e.g. ice retreat/albedo, surface/lower troposphere air temperatures, synoptic weather patterns, ocean-atmosphere fluxes, cloud, amongst others) and is poorly reproduced in climate models: other feedback mechanisms may emerge in the future complicating the situation even further.

Measurements of geophysical and societal change provide the evidence to underpin the establishment, implementation and monitoring of policy, policy decisions and their impact, not just in Europe, but across the world. In the Arctic region, several extreme concerns have been recently raised by the International Panel for Climate Change (IPCC, 2018):

- Warming greater than the global annual average is being experienced in many land regions and seasons, including two to three times higher in the Arctic with warming generally higher over land than over the ocean.

- Climate related risks for natural and human systems are higher for global warming of 1.5°C than at present. These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options.

- There is high confidence that the probability of a sea-ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5°C when compared to 2°C. With1.5°C of global warming, one sea ice-free Arctic summer is projected per century. This likelihood is increased to at least one per decade with 2°C global warming. Effects of a temperature overshoot are reversible for Arctic sea ice cover on decadal time scales.

- Populations at disproportionately higher risk of adverse consequences of global warming of 1.5°C and beyond include disadvantaged and vulnerable populations, some indigenous peoples, and local communities’ dependent on agricultural or coastal livelihoods. Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small-island developing states, and least developed countries. Poverty and disadvantages are expected to increase in some populations as global warming increases; limiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050.

- Limiting global warming to 1.5°C compared to 2°C is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels. Consequently, limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm water coral reef ecosystems.
These changes may lead to dramatic consequences as discussed by Stephen (2018) who describes the societal impacts of a rapidly changing Arctic. Climate change and globalisation are the dominant drivers of societal impacts in the Arctic. As the climate changes access to the Arctic is improving and, through globalisation and new economic development, a rapid transformation of the environmental and geo-political environment of the region is in progress. While there is a strong desire for sustainable development of the fragile Arctic environment at both the national and international level, significant societal impacts are inevitable. Oil and gas industries prospect for potentially lucrative deposits in the Arctic Ocean. The north-east/north-west polar ocean shipping routes are gaining popularity. Tourism is rapidly expanding with new very large cruise ships dedicated to more adventurous activities reaching deep into the Arctic environment.

Consequently, the demands on highly specialised - but limited - international search and rescue service capacity are growing enormously. As the Arctic climate changes, uncertainty surrounds fisheries that are under pressure in terms of ecological change (i.e. species composition, invasive species, changes in ocean temperature and salinity) with large potential impact on fish stocks. Furthermore, as new prospectors increase activities in the Arctic region using modern techniques, the sustainability of fisheries is a critical question for the indigenous population that rely on the ocean as the major source of protein. Permafrost change is leading to loss of land and unpredictable infrastructure stability – a remarkable observation in a time when investment and further development are increasing.

Arctic climate change can also lead to decreasing access, movement, and living options across the region. Permafrost thaw, extreme weather events, flooding, diminishing sea and land ice, and coastal erosion (exacerbated by sea level rise) result in unreliable ice roads, damage to houses, pipelines, railroads, airports, ports and harbours, unreliable energy and water supply. These may conspire in some regions leading to such a burden that relocation of entire communities may be required. This in turn, may result in the abandonment of lifestyles and cultural traditions that have been established over thousands of years (Stephen, 2018). The often-cited concept of a ‘Global Arctic’ highlights the inextricable linkages between Arctic and global processes and systems and the entangled fate of the Arctic region and the world as a whole (ibid). In this evolving complex setting, while increasingly engaged in rights-holder issues and as active participants in governance, law, politics, and research, Arctic indigenous peoples remain vulnerable. As an increasing number of national and international stakeholders place increasing demands on the Arctic region, political tensions and insecurity across the region as a whole are increasing.

The societal impacts of a rapidly changing Arctic are thus complex, uncertain and ambiguous. In response, the European Commission and the High Representative of the Union for Foreign Affairs and Security Policy issued to the European Parliament and the Council, on 27 April 2016, a joint communication that proposed "An integrated European Union policy for the Arctic". The communication highlights the strategic, environmental and socio-economic importance of the Arctic region, including the Arctic Ocean and adjacent seas. The Arctic’s fragile environment is also a direct and key indicator of the climate change, which requires specific mitigation and adaptation actions, as agreed at the COP-21 held in Paris in December 2015.

To this end, the "integrated EU Arctic policy" has identified and is addressing three priority areas:
1. Climate Change and Safeguarding the Arctic Environment (livelihoods of indigenous peoples, Arctic environment).

2. Sustainable Development in and around the Arctic (exploitation of natural resources e.g. fish, minerals, oil and gas), “Blue economy”, safe and reliable navigation (e.g. the Arctic Northern Sea Route).

3. International Cooperation on Arctic Issues (scientific research, EU and bilateral cooperation projects, fisheries management/ecosystems protection, commercial fishing).

Continuously monitoring the vast and harsh Arctic environment in such a changing world with Earth observation, navigation and communication satellites (considering the sparse population and the lack of transport links) is considered essential to the successful implementation and effective management of the Integrated EU Arctic Policy. The existing Copernicus programme already offers operational thematic services in the fields of atmosphere monitoring, marine environment monitoring, land monitoring, climate change, emergency management and security. For example, the CMEMS Arctic – Monitoring Forecasting Centre (ARC MFC) provides accurate forecast and reanalysis products for sea ice, ocean, biology and surface waves in the whole Arctic. The system is based on a numerical ocean model assimilating in situ and satellite data. The Copernicus Atmospheric Service provides information products about atmospheric composition and solar radiation. Several products are of interest for the Arctic region including: monitoring and assessing the impact of emissions from fires at high latitudes (Canada, Siberia) and transport of the corresponding plumes of gases and aerosol affecting atmospheric composition in the Arctic region and monitoring and forecasting of the ozone layer, including Arctic “mini-holes” events. The Copernicus Climate Service is developing new approaches to provide high-resolution regional climate-quality reanalysis over the Arctic and production of sea-ice Essential Climate Variables. In addition, Economic Sectoral analyses of Arctic shipping addresses the impact of climate change on ship routing issues.

2.3 A High-Priority Copernicus Mission to support the Integrated EU Policy for the Arctic: The Copernicus Imaging Microwave Radiometer (CIMR).

New High-Priority requirements from key Arctic users’ communities have recently emerged within Copernicus that highlight the need for new satellite measurements not available as part of the current Copernicus satellite fleet. The new requirements were reviewed at a Polar Ice and Snow workshop held in June 2016, organised by DG GROW involving relevant European Commission (EC) Directorate General (DGs). The workshop gathered inputs from 70 attendees across EU Member States working in various domains. A strong interest for a Polar Ice and Snow Mission was further reinforced when discussed in a wider international context that considered UN Conventions and pan-Arctic cooperation activities. This situation led DG GROW to set up a new group of European Polar Experts Group (PEG) in spring 2017. The mandate of PEG was to update and/or complete the review and analysis of the Users’ needs, thus allowing the Commission to assess the relevance of the development of a "Copernicus expansion mission" dedicated to Polar and Snow monitoring.

and “Polar expert group, Phase 2 report on Users’ requirements” (31 July, 2017). The Phase-I report provided a detailed inventory of user requirements that were consolidated and prioritised in the Phase-II report. This report highlighted the fragile future continuity of low-frequency satellite microwave radiometers and the need for high spatial resolution. Notably, at the end of the JAXA GCOM-2 mission (e.g. Kasahara et al. 2012) there is a definite gap in capability as shown in Figure 1.

Based on an assessment of Users needs and the likely gap in capability, the PEG recommended, as first priority [AD-2], an Imaging Microwave Radiometry Mission that meets the Joint EC Communication high priorities, in particular the provision of operational sea-ice services that are of prime importance for navigation safety in the Arctic and adjacent seas with at least daily revisit in Polar regions [AD-2].

Figure MRD-2.3.1. Timeline of past, present and future microwave satellite radiometer missions relevant for sea ice concentration mapping for the period 1980s to 2030s highlighting a gap in capability and the use of Chinese missions to bridge the gap. However, these missions do not include the low-frequency channels or high-spatial resolution offered by CIMR. Directly responding to the Integrated European Policy for the Arctic, CIMR will be a unique mission providing low frequency and high-spatial resolution measurements: a game changer for Arctic monitoring.

In addition, and in an independent manner, the Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu) has reviewed its own requirements for the evolution of the CSC. The service is targeted around four main areas of benefits: Maritime Safety, Coastal and Marine Environment, Marine Resources, and
Weather, Seasonal Forecasting and Climate activities. CMEMS provides regular and systematic core reference information on the state of the global ocean and regional seas – including the Global Ocean (including all Antarctic/Arctic sea ice), the Arctic Ocean and the Baltic Sea. The analyses and forecasts produced by the service support any user requesting generic information on the state of the ocean and sea ice, and especially downstream service providers who use the information as an input to their own value-added services to end-users. CMEMS operates the "Sea Ice Thematic Assembly Centre (SI-TAC) providing Sea Ice products for Arctic and Antarctic Oceans based on microwaves, infrared and SAR satellite observations and the “Sea Surface Temperature Thematic Assembly Centre” (SST-TAC) providing multi-sensor temperature observation products for the global ocean and European regional based on multi-sensors Infrared and microwave SST satellite data. These data are regularly distributed to the more than 200,000 registered users for data download directly at the EU/ESA Sentinel Data Hubs and assimilated to the CMEMS modelling components which provides regular forecasts of the Arctic Ocean, Baltic Sea regions as well as the global ocean and all the other European Seas.

CMEMS requires a sustainable European operational provision of medium-resolution (5-10 km) multi-frequency and multi-polarization microwave radiometer observations delivering Sea Ice Concentration (SIC), sea ice area, sea ice extent and Sea Surface Temperature (SST) [AD-3] overlapping with the requirements of PEG [AD-2]. The need to make measurements in cloudy conditions (where infrared measurements are precluded) was noted.

Beyond the provision of key polar ice and snow parameters, the microwave radiometer mission, through the selection of well stable, well-calibrated and validated set of channels will also be of high interest for the observation of non-polar regions in particular for the oceans (SST), a potential for continuity of current ocean surface salinity (SSS) capability and, for land applications such as hydrology, snow-cover extent, snow water equivalent, large scale soil characteristics (moisture), large scale vegetation extent monitoring and biomass, land surface temperature, flooding extent, amongst others [AD-2], depending on the final mission configuration.

The development of an advanced microwave radiometer mission in Europe will offer many advantages/benefits including:

- Security in the availability of microwave radiometer data for scientific and operational applications in polar and non-polar regions.

- European autonomy and independence from non-European sources (USA, Japan, China, Russia) for the provision of satellite microwave radiometer data meeting Copernicus and EC Arctic Policy objectives.

- Evolution of European space industry technical capacity and skill, complementing the existing experience acquired for the development of active microwave (Synthetic Aperture Radar (SAR), Altimeter, Scatterometer) and optical imagers (Visible (VIS), Infrared (IR), Hyper-spectral etc.).

- It is well understood that the CIMR mission will not address the full set of requirements set out by [AD-1], [AD-2] and [AD-3]. It is also understood that the

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Next Generation Copernicus missions will result in a sustained monitoring architecture with operational continuity that will consider any remaining requirements [AD-2].

2.4 Established user needs for the CIMR mission

The EC has built up a repository of prioritized requirements and needs based on the following independent considerations and interactions:

- EU policies priorities,
- Member States input,
- Needs of the existing Services,
- Needs identified in thematic Workshops,
- Climate Change (11 March 2016),
- Polar and Snow Cover Applications (23 June 2016),
- Raw Materials (5 September 2016),
- Security – Support to External Action and applications for EEA (5 April 2017),
- Cultural Heritage (24 April 2017),
- European Environmental Protection Agencies (7 June 2017),
- Coastal Areas (29 June 2017),
- Energy Sector (12 Oct 2017),
- User Requirements Studies,
- Task Forces and Expert Groups focusing on the four domains of EU policy priority,
- Polar Regions Industry Workshop (7 Nov 2018).

EC consultations also included various exchanges in the Copernicus Committee and User Forum. On 9th of June 2017, an extraordinary joint meeting of the Copernicus Committee and ESA PB-EO delegates took place to present the current status of the requirements process and thoughts on the CSC evolution. The feedback was subsequently included in further discussions in the frame of a Joint Working Group (EC, ESA and EUMETSAT), which met regularly to reflect on the emerging requirements and to consolidate the LTS. Feedback from the four Task Forces/Expert Groups to the Joint Working Group (EC, ESA and EUMETSAT), held on 27th of July, confirmed a high degree of correspondence in terms of overall observation priorities for the expansion of the CSC. The User needs for the CIMR mission are set out in reports from EC-led Polar Expert Group (PEG) user consultation processes, which are supplemented by a single document expressing CMEMS recommendations. They are:

2. Polar expert group, Phase 2 report on Users’ requirements (31 July, 2017) and,

CMEMS has responsibility for monitoring the Global ocean and European regional seas including sea ice parameters in the Antarctic, Arctic Ocean and Baltic Sea which is why [AD-3] is also an applicable document for a Polar Ice and Snow satellite mission. While today many “polar parameters/products” already exist (e.g. CMEMS Arctic products: http://marine.copernicus.eu) and are available on an operational or quasi-operational basis, users often look for improved performances and quality (e.g. spatial and temporal resolution, accuracies, timeliness etc.) [AD-1].

Moreover, these products rely on non-European research satellite missions delivering microwave radiometer data sets (e.g. from JAXA AMSR-2) and are therefore not secure in the long-term operational context of Copernicus. Furthermore, such data sets do not address the high spatial resolution, dedicated low-frequency channels and radiometric fidelity requirements requested by Copernicus services.

![Figure MRD-2.4.1. comparison of Thermal Infrared satellite measurements (taken from Copernicus Marine Environmental Services (CMEMS) data production) and microwave radiometer SST coverage in the Arctic, September 2012. (left) Data coverage of one (MetOp-A) satellite, (centre) all available infrared satellites and (right) simulated Copernicus Microwave Imaging Radiometer (CIMR) coverage during the sea ice minimum in September 2012. It is clear that IR satellites have severe limitations in the cloud covered Arctic and that CIMR is needed.](image-url)
Floating ice parameters (including concentration/sea ice extent/thickness/type/drift, thin sea ice distribution, iceberg detection/volume change and drift, ice shelf thickness and extent) are key to operational services in the Polar-regions (i.e. for navigation, marine operations, safety of life at sea) as well as for climate monitoring and modelling [AD-1]. However, high-resolution (~1 km) optical satellite measurements of the earth surface, including the thermal infrared region, are confounded by the presence of clouds (see Figure MRD-2.4.1 and MRD-2.4.2) and the polar night so they cannot provide the necessary coverage (e.g. Drüe and Heinemann, 2004). There are significant gaps in coverage and revisit particularly in areas with persistent cloud cover including the polar-regions [AD-2][AD-3].

Microwave Synthetic Aperture Radar (SAR) including Sentinel-1 operating with varied polarisation and C-band frequency provide coverage at a high spatial resolution except in precipitating atmospheres and with ice discrimination capability although the accuracy of SAR sea ice concentration is still an active field of research and ice-water discrimination still can be challenging under certain conditions (e.g. Karvonen, 2014). However, due to the characteristics of the Sentinel-1 missions with limited swath coverage, sub-daily revisit and coverage is not presently available. In contrast, wide-swath microwave imaging multispectral radiometers uniquely observe a wide range of parameters, including Sea Ice Concentration and Sea Surface Temperature that serve operational systems in non-precipitating atmospheric conditions, day and night [AD-2], with excellent revisit and coverage characteristics.
2.4.1 Sea Ice Concentration (Sea Ice Fraction)

Sea Ice Concentration (SIC, or sea ice surface fraction) is the most important parameter for operational navigation in sea-ice infested waters and for climate services [AD-2]. SIC describes the relative amount of area covered by ice, compared to a reference area. For example, SIC could describe how large a fraction of a 25.0 x 25.0 km area is covered by sea ice (typically expressed in %). Sea ice area (SIA) of a region, e.g., the complete Arctic, is calculated by multiplying SIC with the grid cell areas and integrating over the region.

Sea Ice Extent (SIE) is a related parameter and preferred by some organisations (e.g. National Snow and Ice Data Centre (NSIDC)). SIE is typically mapped by taking any grid cell with a SIC of ≥15 % and labelling that cell as ice (typically expressed in km²). Compared to SIA, SIE is much less affected by systematic sea ice algorithm biases caused by sea ice emissivity anomalies during summer and winter. The uncertainty (systematic or random) at high SICs (due to uncertainty in sea-ice and snow emissivity and melt-ponds) ranges from 2-3% SIC in winter to, ~10-15% SIC in summer. This noise has little influence on SIE since the threshold for SIE is low (15%). It is common that datasets that compare well in terms of SIE, do less so in terms of SIA and SIC (because the thresholding of SIE removes a large part of the noise). However, SIE is affected by atmospheric noise and spatial resolution issues along the ice edge. SIE is more easily comparable to other sea ice information datasets (ice charts, SAR imagery...) because the measure is not linked to a specific SIC algorithm. On the other hand, SIE is grid cell size dependent (coarser grid resolutions will result in larger SIE because of the 15% SIC criterion for SIE), which can complicate comparisons. During summer a microwave radiometer will measure the sea ice surface fraction meaning that open melt ponds and leads in between the floes are measured as open water - even if melt ponds are located on top of the ice floe. This is an important consideration when using the data for computing the fluxes between the ocean and the atmosphere in ice covered waters during summer.

Microwave radiometer data are available at coarse resolution and are used to derive SIC, e.g. as available from CMEMs’ catalogue (e.g. see http://marine.copernicus.eu/). The expected increase in operational model resolution and time availability of products from operational systems will require sub-daily observations and resolution < 10 km in the future. Synergy with Sentinel-1 SAR data would be useful particularly in the Marginal Ice Zone (MIZ). However, radar backscattering of sea ice is a highly non-linear process where surface features and roughness elements can totally dominate the total backscatter magnitude. Furthermore, SAR ice and water backscatter signatures are not unique which means that it is not possible to determine an unambiguous surface classification - especially at sub-pixel level.

[AD-1] states the requirement for SIC as follows:
[AD-2] states the prioritised operational requirement as:

SIC in sea ice charts is typically determined manually using either synthetic aperture radar (SAR) instruments providing high resolution estimates of SIC (e.g. Grenfell et al., 1992) and/or polarised multi-spectral microwave radiometer measurements including different combinations of 6, 19, 37, 89 GHz frequencies depending on the algorithm used (e.g. Comiso et al., 2003; Spreen et al., 2008; Ivanova et al., 2015). A critical aspect is to ensure spectral diversity with sensitivity to sea ice and open water (see Figure 3a) and high spatial resolution to determine the presence of sea ice.

For climate data record (CDR) applications, channels near 19 and 37 GHz are used by the most widespread algorithms for SIC retrievals (e.g. Andersen et al., 2006; Lavergne et al., 2019) providing spectral diversity but at relatively poor spatial resolution. 19 and 37 GHz channels have been available from an unbroken series of satellites since the 1970’s and they are therefore attractive for Climate Data Records (CDR). Some algorithms utilise 89 GHz frequency measurements (e.g. Spreen et al., 2008, see Figure MRD-2.4.1.1). While this channel provides a very attractive high spatial resolution (e.g. 3 x 5 km iFoV for AMSR-2) that reduces the sensitivity of algorithms to surface inhomogeneity, data are more sensitive to atmospheric emission and scattering effects. Consequently, a radiative transfer model and meteorological forecast model are required to compensate for these effects (e.g. Lu et al., 2018; Meier et al., 2017) significantly complicating the use of this channel. For
example, the EUMETSAT OSISAF is using atmospheric correction both operationally and for CDR generation. This approach requires algorithm tie-points that are calibrated after the correction step and before the computation of the SIC (Tonboe et al., 2016; Lavergne et al., 2019). In general, while offering a high spatial resolution, the use of 89 GHz channels is considered very complex (it also requires accurate NWP data to compensate for atmospheric scattering). Should high spatial resolution channels at lower frequencies be available, a more robust approach would be possible.

Figure MRD-2.4.1.1. Average top of atmosphere brightness temperatures (Tb) and standard deviations of Arctic open water, first-year and multiyear sea ice at typical imaging frequencies between L-band (1.4 GHz) and W-band (89 GHz). Data highlight the spectral separation of sea ice signatures in the 1.4-36.5 GHz region of the spectrum compared to 89 GHz. FYI= First Year Ice, MYI=Multi-year Ice, OW=Open Water. Solid lines indicate vertical polarisation, dashed lines indicate horizontal polarization. 1.4 GHz data from SMOS 40°-50° incidence angle averaged. Data based on Round Robin Data Package of ESA Sea Ice CCI project (Pedersen et al., 2018). See also Spreen et al. (2008) and Eppler et al. (1992) for a similar plot. (Lu, Junshen; Heygster, Georg (2018): AMSR-E/2 and SMOS Brightness Temperatures of Surface Types. figshare. Figure. https://doi.org/10.6084/m9.figshare.7370261.v2)

Ivanova et al. (2015) present a review of SIC algorithms and performance noting that the best performing algorithm uses 6.9 GHz data of all available channels from historical and contemporary sensors (Figure MRD-2.4.1.2). At this frequency, the atmosphere has little impact (except in precipitating conditions) and there is a large diversity of spectral signature between ice and water (e.g. Eppler et al., 1992 and shown in Figure 3) which is a significant asset for SIC algorithms. However, this channel is severely limited in performance due to the large spatial resolution (e.g. AMSR-2 has a 64 x 32 km field of view at 6.9 GHz) that has been offered by all sensors to date (and those currently planned in the future). Improving the spatial resolution of polarized at 6 GHz measurements could provide a significant improvement in SIC retrievals. For tactical applications (e.g. ice breaking, navigation, maritime operations in the Arctic etc.) high-resolution microwave radiometry can be used in synergy with other data characterised by very high spatial resolution e.g. C-band SAR measurements (e.g. Karvonen, 2014; 2017)
or satellite altimetry estimates of Sea Ice thickness if those missions have sufficient revisit and coverage.

Figure MRD-2.4.1.2. Evaluation of 40+ Sea Ice Concentration algorithms against independent ground truth: ice charts for 0% ice (SIC0) and SAR-drift convergence areas for 100% ice (SIC1). The algorithms with best skills are to the left (low standard deviation, thus high accuracy). The best algorithms use 6GHz and/or optimized combinations of Ku and Ka-band. Results from the ESA CCI Sea Ice projects.

Importantly, current estimates of SIC that use 6-11 GHz channels within ~100 km of any shoreline or the marginal ice zone are not possible with the present and future microwave radiometer satellite mission’s due to the large field of view being contaminated by land or ice. **This is a second important driver to significantly improve the spatial resolution of these channels.**

Radio Frequency Interference (RFI) must be detected and mitigated when using low frequency (i.e. L-, C- and X-band) channels in geophysical retrieval algorithms (e.g., Maeda et al., 2011; Soldo et al., 2017). However, this needs to be managed with care as it is known that mitigation will impact the NEdT of each channel since spectral RFI filtering (where specific sub-bands are flagged as RFI contaminated and removed from the signal) results in a reduction in the available channel bandwidth. Other implications include discarding excessively polluted data or incorrectly flagged data.

In the absence of atmospheric precipitation, microwave radiometer retrievals of SIC suffer from two discrepancies that are not resolved: (1) uncertainties in retrievals of the summer period caused by higher variability in sea ice emissivity due to the increase in surface wetness (snow melt) and presence of melt ponds of water (e.g. Comiso and Kwok, 1996). Virtually all SIC algorithms based on microwave radiometer channels are very sensitive to
presence of melt water on the ice. Melt ponds may exhibit a diurnal cycle with interchanging periods of open water and thin ice. This further complicates SIC retrieval using satellite microwave radiometry during summer and increases the level of uncertainty (e.g. Ivanova et al., 2015; Kern et al., 2016). (2) There will most likely be some underestimation of the concentration of smooth thin ice because such a surface has lower emissivity at all frequencies. Thus, retrieved ice concentration is influenced by the thickness of thin sea ice (e.g. Heygster et al., 2014).

Table MRD-1. MetOp-SG (B) MWI bands and AMSR-2 bands (shown in grey boxes) for comparison.

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>MWI</th>
<th>AMSR-2</th>
<th>MWI</th>
<th>AMSR-2</th>
<th>MWI</th>
<th>AMSR-2</th>
<th>MWI</th>
<th>AMSR-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.7</td>
<td>18.7</td>
<td>23.8</td>
<td>23.8</td>
<td>31.4</td>
<td>36.5</td>
<td>89</td>
<td>89</td>
<td></td>
</tr>
<tr>
<td>Polarisation</td>
<td>Vertical and Horizontal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth [MHz]</td>
<td>200</td>
<td>200</td>
<td>400</td>
<td>400</td>
<td>200</td>
<td>1000</td>
<td>4000</td>
<td>3000</td>
</tr>
<tr>
<td>Swath width [km]</td>
<td>≥1400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Footprint corresponding to -3dB beam width [km]</td>
<td>35 x 65</td>
<td>14 x 22</td>
<td>35 x 65</td>
<td>14 x 22</td>
<td>23 x 37</td>
<td>7 x 12</td>
<td>8 x 12</td>
<td>3 x 5</td>
</tr>
<tr>
<td>Observation Zenith Angle [deg]</td>
<td>53.0</td>
<td>[55.0 for AMSR-2]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiometric resolution (NEAT).</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tref is: MWI 1σ at 280 K [K]</td>
<td>0.7</td>
<td>≤0.7</td>
<td>0.6</td>
<td>≤0.6</td>
<td>0.8</td>
<td>≤0.7</td>
<td>0.8</td>
<td>≤1.2</td>
</tr>
<tr>
<td>AMSR-2 1σ at 150 K [K]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Application (SIC = Sea Ice Concentration, SST = Sea Surface Temperature, SIT = Sea Ice thickness, SSS= Sea Surface Salinity, WS = Wind speed, TWV = Total Water Vapour, TCWV = Total Cloud-liquid Water Vapour, SD = Snow Depth, SM = Soil Moisture, SWE = Snow Water Equivalent, SID = Sea Ice Drift, PCP=precipitation)</td>
<td>TWV, TCWV, PCP, SIC, SD, SM, SID</td>
<td>TWV, TCWV, PCP, SST, SIC, WS, SD, SM, SID</td>
<td>TWV, TCWV, PCP, SST, SIC, WS, SD, SM, SID</td>
<td>PCP, SIC, SD, SID, SM</td>
<td></td>
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</tr>
</tbody>
</table>

Additional co-located and near-contemporaneous measurements of thin sea ice thickness (e.g. from L-band radiometer measurements), thermal/visible optical, C/L-band SAR imagers, and scatterometer measurements can resolve melt water ponds to some extent and would help resolve these two issues. The combination of both active-microwave Sentinel-1 C-band SAR sea ice texture measurements (especially using vertical, horizontal and cross-polarisation) in synergy with microwave radiometry from AMSR-2 delivers a more reliable and accurate estimate of SIC (e.g. Karvonen, 2017). The resulting combined SIC estimates are “sharpened” and include many details not visible in the lower spatial resolution AMSR-2 products alone including much more detail at challenging boundaries such as the marginal ice zone.

SIC is required for the “Polar Regions” (encompassing the pan-Arctic domain (>55°N, 0-360° longitude), all adjacent Seas (>55° North latitude), and Antarctica (>58°S, 0-360° longitude)) with at least a daily revisit and an effective spatial resolution of 25 km.
(addressing climate aspects) with a goal resolution of \( \leq 5 \) km and every 6 hours [AD-1] that is prioritised at “sub-daily” coverage in [AD-2] (addressing operational sea ice monitoring aspects) depending on the channels used [AD-2].

Accuracy in the small ice concentration range (Marginal Ice Zone and near the ice edge) should be improved by an order of magnitude [AD-2].

While the Microwave Imager (MWI) on the MetOp-SG(B) satellite will eventually secure continuation of the Special Sensor Microwave Imager (SSM/I) series, it will not fulfil the requirement for medium resolution (<10 km) measurements as currently available on AMSR-2 [AD-2] – see Table MRD-1. A continuation of multi-spectral microwave radiometer measurements with a high spatial resolution (no less than those provided by the AMSR-2 instrument) is requested in [AD-2].

![Figure MRD-2.4.1.3. Theoretical retrieval error standard deviation on SIC from the information content analysis equation (5) with different combinations of Copernicus Imaging Microwave Radiometer channels. SIC = sea ice concentration (Kilic et al., 2018).](image)

Kilik et al. (2018) estimate the SIC performance for CIMR using the same specifications as set out in this MRD. An information content analysis approach was used to estimate theoretical retrieval uncertainties for SIC. Figure MRD-2.4.1.3 shows the SIC retrieval error standard deviation as a function of SIC, first for each frequency, using both vertical and horizontal polarizations. The calculations use the winter part of the ESA Sea Ice Climate Change Project Round Robin data set, as is usually done for model developments. The combined use of the 6.9-, 10.65-, 18.7-, and 36.5-GHz channels together improves the retrieval, with a SIC theoretical retrieval error standard deviation between 2% and 3%. A 5 km multi-channel retrieval is shown which will be refined in the future.

### 2.4.2 Sea Surface Temperature (SST)

SST in non-precipitating atmospheric conditions (e.g. Chelton et al., 2005; Donlon et al., 2012) is one of the top priorities in [AD-1] and the fourth priority in [AD-2]. SST
in non-precipitating atmospheric conditions is required [AD-2] for climate modelling, mesoscale analysis, oceanic predictions and as climate change indicator [AD-1]. Sub-daily sampling to sample diurnal cycle (e.g. Donlon et al., 2009) is requested [AD-2]. Microwave radiometer SST observations are very important in the global ocean as well as in polar-regions [AD-3] and these data are assimilated in oceanic and meteorological forecast systems [AD-2]. From the merging of Sea Surface Temperature and altimetry data improved global surface currents can be derived. It has been shown that the level of accuracy obtained by combining altimeter velocities based on a two-satellite configuration and microwave SST data is equivalent or higher to the one from a four-altimeter constellation in western boundary currents (Rio et al. 2018).

[AD-1] states the requirement as follows:

SST accuracy of 0.1 K at a spatial resolution of 1 km is an extremely demanding target even for the best available HgCdTe cryo-cooled detectors in the infrared. To reach an SST accuracy of 0.1 K using a microwave radiometer at 1 km spatial resolution with current (2019) technology (even using an extremely large antenna) and the best on-board calibration systems available today is considered unfeasible.

[AD-2] states the prioritised operational requirement as:

The subskin temperature of the sea surface (SSTsubskin) represents the temperature at the base of the thermally conductive laminar sub-layer of the ocean surface (see Donlon et al., 2009). For practical purposes, SSTsubskin can be well approximated to the measurement of surface temperature by a microwave radiometer operating in the 6-11 GHz frequency range (see Wentz, 1997; Wentz and Meissner, 2000; 2006; 2016) but the relationship is
indirect and is not invariant to changing physical conditions or to the specific geometry of the microwave measurements.

However, 6.9-10.6 GHz channels are severely limited in performance due to the large spatial resolution that has been offered by all sensors to date (and those currently planned in the future). Improving the spatial resolution of polarised measurements at 6-10 GHz could provide a significant improvement in SST retrievals and their information content for global SST and regional analysis systems. An improvement in real-aperture spatial resolution is important because this means that CIMR data could be included in the SST analyses of semi-enclosed seas (e.g. Mediterranean, Baltic) and monitor the coastal areas – which is currently not possible using existing microwave imagers.

An accurate SST retrieval (e.g. Gentemann et al., 2010) requires an estimate of sea surface emissivity that depends on wind-induced surface ocean roughness (e.g. Meissner and Wentz, 2002; 2012) that can be derived from microwave radiometer observations at 10 to 36 GHz (Prigent et al., 2013; Kilic et al., 2018) or scatterometer measurement of sigma-zero (e.g. from MetOp-SG B). A second order correction for a weak SST dependency on sea surface salinity (SSS) is also required (e.g. Meissner and Wentz, 2002; 2012). When rain is not present, attenuation by the atmosphere is very small at 6-11 GHz, with 97% of the radiation emitted at the sea surface reaching the top of the atmosphere. Using channels at 6.9 to 37 GHz, the Wentz et al. (2000) SST retrieval algorithm precisely estimates the 3% attenuation due to oxygen, water vapour, and clouds. A full radiative transfer model can be used with microwave radiometer observations to estimate the surface roughness. In addition, the polarization ratio (horizontal versus vertical) of the measurements can be used to estimate sea surface roughness to first order (a better solution would utilise more direct surface roughness measurements such as those from scatterometry). The spatial resolution of the SST retrieval is limited by the ratio of the radiation wavelength to the antenna diameter and by the satellite altitude (Wentz et al., 2000) and hence a large antenna is required to have a high spatial resolution: for a resolution of ~10 km at X-band an antenna of ~6m is required).

Recently a detailed analysis of optimal channels for SST retrievals using AMSR-2 data has been performed (Pearson et al., 2018). This suggests that an optimal combination of five channels (6.9V, 6.9H, 7.3V, 10.7V and 36.5H) yields the best SST retrieval using their optimal estimation retrieval framework. The 36.5 H measurements provide information on the total column water vapour content while the others account for SST, and the effect of surface roughness and SSS within the retrieval framework. However, the Wentz et al. (2000) forward model shows significantly different Tb/Emissivity dependencies with respect to salinity and wind speed. In addition, regression models show larger retrieval errors, using these channels only, compared to using all channels and further optimisation studies are required.

Currently, estimates of SST within 100 km of any shoreline or the marginal ice zone are not possible with the present and future microwave radiometer satellite mission’s due to the large field of view (e.g. AMSR-2 has a 64 x 32 km field of view at 6.925 GHz) being contaminated by land or ice. Significant improvement in the spatial resolution of these channels is required to obtain SST to within ~15 km of these transitions.

Radio Frequency Interference (RFI) must be mitigated when using low frequency (i.e. L-, C- and X-band) channels in geophysical retrieval algorithms (e.g. Maeda et al., 2011; Soldo
et al., 2017). Nielsen et al. (2018), show that an Optimal Estimation retrieval is very efficient to filter out RFI effects in C and X band channels.

MetOp-SG(A) METimage is a multi-spectral (visible and IR) imaging passive radiometer which will provide detailed information on clouds, wind, aerosols and surface properties which are essential for meteorological and climate applications. METimage will provide continuity to the AVHRR (Advanced Very High Resolution Radiometer) series on board the MetOp and NOAA satellites, and VIIRS on board NOAA satellites. METimage is expected to have a great improvement with respect to AVHRR and comparable performance with respect to VIIRS. The primary objective of the mission is to provide high quality imagery data for global and regional Numerical Weather Prediction, nowcasting, and climate monitoring through the provision of:

- High horizontal resolution cloud products including microphysical analysis
- Sea surface temperature
- Vegetation, snow coverage, and fire monitoring products
- Aerosol products
- Polar atmospheric motion vectors

Compared to its predecessor AVHRR, METimage will have many more channels for the benefit of measuring far more geophysical variables. This combined with on-board radiometric calibration of solar channels and the enhanced spatial sampling (500 m compared to 1 km at nadir) will provide a breakthrough in several application areas: numerical weather forecast, very short-range forecast and now-casting, oceanography, hydrology, land-surface applications, and climate monitoring. The imaging radiometer measures the thermal radiance emitted by the earth and solar backscattered radiation. It, thus, covers a broad spectral range in 20 spectral bands from 443 to 13.345 µm. Due to the presence of clouds preventing measurements of the Earth surface, MetImage alone cannot meet the needs of CMEMS.

![Figure MRD-2.4.2.1. The SST theoretical retrieval error standard deviation estimated with the Copernicus Imaging Microwave Radiometer specifications (solid lines) and the Advanced Microwave Scanning Radiometer 2 specifications (dotted lines) for different OWSs (left), TCWVs (middle), and TCLW (right). SST = sea surface temperature; OWS = ocean wind speed; SSS = sea surface salinity; TCWV = Total Column Water Vapor; TCLW = Total Column Liquid Water (from Kilic et al, 2019).](image-url)
The MWI on the MetOp-SG(B) satellite will not fulfil the requirement for medium resolution (<10 km) SST measurements as currently available on AMSR-2 [AD-2] because the low-frequency 6.9-10 GHz channels required for SST retrieval are not included in the instrument design – see Table MRD-1. Furthermore, a significant gap exists in continuity of 6-7 GHz channels beyond 2021/22 (see Section 5.1.1). Continuity of SST in non-precipitating atmospheric conditions is at least required (i.e. that derived from AMSR-2) [AD-1] with at least a daily revisit and a spatial resolution of 10 km [AD-2]. Ideally to address emerging CMEMS needs, a spatial resolution of ~5 km is required.

Building on the previous work of Prigent et al. (2013) and as part of CIMR science support studies based on information content analysis, Kilic et al. (2018) derive a mean global SST uncertainty of ~0.2 K (the retrieval uncertainty varies between 0.15 and 0.45 K with higher uncertainty in cold waters) using the CIMR channel specifications set out in this MRD. Figure MRD-2.4.2.1 shows a comparison for theoretically retrieved SST using the CIMR channel specifications set out in this MRD compared to those of AMSR2. The impact of CIMR on SST performance is obvious. While very challenging it is clear that an uncertainty of ~0.2 K is considered feasible for a spatial resolution of ~15 km.

2.4.3 Sea Ice Thickness (SIT)

Sea Ice Thickness (units of meters) is the thickness of a sea ice layer measured from sea ice surface to the underside of a specified sea ice extent. For ice > ~1 m thick, SIT is typically and successfully measured using satellite altimeters (e.g. Guerreiro et al., 2017; Laxon et al., 2013). For thin SIT, microwave radiometry provides a useful complement (e.g. Heygster et al., 2014; Kaleschke et al., 2010, 2016). Sea ice modellers (e.g. Sakov et al., 2012) and operational ice services (WMO, 2017) consistently rank improved measurement of sea ice thickness distribution as their top priority [AD-1]. Assimilation of thin (<0.5 m) sea ice thickness data derived from L-band (1.4 GHz) satellite missions into dynamic sea ice models results in more accurate forecasts (e.g. Xie et al., 2016; Richter et al., 2018) [AD-2]. However, a high spatial resolution thin sea ice thickness product for navigation purposes does not exist for the Arctic Ocean [AD-2]. The complete daily coverage and the near real-time availability of thin sea ice thickness data are crucial for operational applications [AD-1]. Following the highly successful suite of measurements from the ESA Soil Moisture and Ocean Salinity (SMOS) and United States Soil Moisture Active/Passive (SMAP) missions from which thin sea ice thickness is currently derived (see Pațilea et al. (2017) for combined SMAP/SMOS SIT retrievals) it is important to secure continuity of L-band measurements in an operational context. Techniques exist that use thermal optical imager data (e.g. Maekynen et al., 2013) although this is confounded by the presence of clouds.

The CMEMS position paper presented at the “Polar and Snow Cover Applications – User Requirements Workshop” for future Sentinels (23 June 2016, Brussels) states [AD-1]: “Sea ice thickness is a very important indicator of climate change in the Arctic. In view of the uncertainty in the freeboard to sea ice thickness inversion, a CryoSat type mission is an attractive option, preferably in combination with a laser altimeter. However, for operational sea ice monitoring, input to sea ice models and sea ice charting, satellite

* Calculated for a theoretical retrieval as the mode value of daily global ocean average discrepancies assuming no uncertainty in the validation data set.
measurements of the thin sea ice below 0.5 m (i.e. L-band microwave radiometry) is also required.” [AD-1].

Figure MRD-2.4.3.1. Vertically (left), horizontally (right) polarized brightness temperatures as function of sea ice thickness for various frequencies (from Heygster et al., 2014). The best performing frequency for thin sea ice determination is 1.4 GHz.

For thin sea ice (<0.5 m thick) microwave radiometry operating at 1.4 GHz frequencies provides a viable solution as shown in Figure MRD-2.4.3.1 (e.g. Grenfell et al. (1992, 1998); Heygster et al. 2014; Naoki et al. 2008; Kaleschke et al. 2010, Kaleschke et al. 2016). Note that 6.9 GHz vertically polarised measurements are able to determine SIT up to a thickness of ~20 cm whereas 1.4 GHz measurements are able to determine thin SIT up to a depth of ~0.5 m (e.g. Naoki et al. 2008).

[AD-1] states the requirement as follows:

<table>
<thead>
<tr>
<th>THM</th>
<th>DOM</th>
<th>Parameter</th>
<th>AOI</th>
<th>Resolution</th>
<th>TOY</th>
<th>Frequency</th>
<th>Leadtime</th>
<th>TL</th>
<th>Unit</th>
<th>Range</th>
<th>Accuracy</th>
<th>I</th>
<th>S</th>
<th>C</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>CL</td>
<td></td>
<td>1</td>
<td>T. 10 km</td>
<td>0</td>
<td>1 dy</td>
<td>n/a</td>
<td>0</td>
<td>0 [m]</td>
<td>(0, 0.5)</td>
<td>5%</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>OC</td>
<td>Thin sea ice</td>
<td>0</td>
<td>T. 9 km</td>
<td>0</td>
<td>T. 8 hr</td>
<td>n/a</td>
<td>2</td>
<td>0 [%]</td>
<td>(0, 100)</td>
<td>5%</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>SI</td>
<td>TR</td>
<td></td>
<td>0</td>
<td>T. 2.5 m</td>
<td>0</td>
<td>T. 2 d</td>
<td>24 h</td>
<td>1</td>
<td>0 [m]</td>
<td>(0, 0.3)</td>
<td>T. 0.05</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

The spatial resolution requirement of 10 km cannot be met for thin SIT above ~20 cm thick using available L-band microwave radiometer technologies.

[AD-2] states the operational requirement as:
[AD-2] states the climate requirement as:

<table>
<thead>
<tr>
<th>Sea ice thickness (freeboard) (including summer ice and thin ice)</th>
<th>Pan-Arctic data does not exist presently in the CMEMS catalogue. Assimilation of sea ice thickness data (SMOS-like one) is underway in operational systems. High resolution product for navigation purposes does not exist for the Arctic Ocean.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryosat-2 for thick ice (medium resolution, 25 km) and SMOS estimates of thin (&lt;0.5 - 1 m) sea ice</td>
<td>Cryosat estimates are too uncertain in the melt season (due to melt pond effects). Complete coverage of the Arctic is only available at the expense of the time resolution (monthly means). SMOS estimates are limited to small thickness ranges (&lt;1 m). Revisit and resolution should be similar as described by the climate community. Uncertainty due to snow cover in CS2 ice thickness estimates must be reduced</td>
</tr>
</tbody>
</table>

Note that in [AD-2] Table 2 notes that a secondary mission objective for the microwave radiometer is “Topography”. Clearly a microwave radiometer cannot make “Sea ice topography” measurements and this entry is considered a direct reference to “thin sea ice thickness” typically derived from a 1.4135 GHz channel. Such a capability complements the proposed topography SARIn altimeter mission measurements of sea ice freeboard because an altimeter is unable to provide meaningful ice thickness measurements much below 1 m. Furthermore, the CIMR mission will provide complementary information on snow loading ("snow depth on sea ice") to assist the topography mission measurement of sea ice thickness derived from sea ice freeboard estimates. In this sense CIMR and the proposed Topography mission are highly complementary. **Continuity of thin (<0.5 m depth)** sea ice measurements using L-band microwave radiometry with daily coverage of the Marginal Ice Zone in the pan-Arctic and adjacent Seas (>55° North latitude), and Antarctica regions is requested [AD-1][AD-2][AD-3]. Kaleschke et al (2016) note that an uncertainty of <30% is possible based on SMOS tSIT measurements although validation remains a challenge using aircraft and in situ data sets.

2.4.4 **Sea Ice Drift**

Sea ice drift measures the displacement of sea ice for a given location and time period. It does not describe the trajectory of ice within the measurement period. Sea ice drift has been derived from optical imagery, synthetic aperture radar imagers, hi-resolution multi-frequency microwave radiometry and scatterometry based on feature recognition and maximum cross-correlation techniques (e.g. Emery et al., 1997; Girad-Ardhuin et al.,
Sea ice drift products are available from CMEMS catalogue (http://marine.copernicus.eu) and from the EUMETSAT Ocean and Sea Ice Satellite Applications Facility (OSI-SAF) at coarse resolution and currently use a number of dedicated channels including AMSR-2 36.5 GHz and SSM/I/S at 91.0 GHz (e.g. Lavergne et al., 2010; 2016a; 2016b). Note that other channels (e.g. 6.9-18.7 GHz) provide better spectral diversity and could potentially provide a better SID result if the spatial resolution is significantly improved. 18.7 GHz AMSR-2 (14 x 22 km spatial resolution) data are being used to provide 2-day global sea ice drift estimates during summer, but much better spatial resolution / spectral feature resolution is required (≤5 km). The CMEMS Arctic Modelling and Forecast Centre (MFC) is assimilating sea ice drift and products are available from CMEMS catalogue at coarse resolution. Summer sea ice drift is also derived from Sentinel-1 SAR data, but daily full coverage in the Polar Regions cannot be reached using this approach alone: an optimal combination is the use of SAR and microwave radiometry in synergy.

The resolution of gridded sea ice drift products is currently poor and products deteriorate near the ice edge or in summer [AD-2]. In order to better constrain the high sea ice drift variability and better understand its response to high frequency forcing (tides, wind), an increase of the spatial resolution and frequency of the currently available data is required [AD-1]. Results from a recent ESA CCI Sea Ice algorithm study indicate that the accuracy of sea ice drift products from microwave radiometer imagery are mainly influenced by 1) the resolution of the instrument, 2) the presence of stable sea ice emissivity patterns to be tracked between images, 3) the geo-location accuracy, and 4) a see-through atmosphere. Accuracy targets of sea ice drift products put additional requirement on the spatial resolution, but also geo-location accuracy. The lower frequencies (C and X) might not have stable enough emissivity patterns to be tracked compared to those at Ku and Ka band. Near-90 GHz channels suffers from the complicating effect of atmospheric absorption and scattering that must be corrected.

[AD-2] states the prioritised operational requirement as:

| Sea Ice drift | CMEMS’ operational systems assimilate pan-Arctic coarse resolution (60km) and 3 day/lag datasets. Currently CMEMS provide a pan Arctic high resolution ice drift product based on Sentinel-1 data in HH polarisation that meets the current high-priority requirements. | It will be likely that increase in resolution and time availability of products from operational systems will require higher resolution and frequency. Higher resolution could be used to increase the drift resolution. For planning of a next generation of S1 this should be taken into consideration. | Coverage: Pan Arctic Temporal resolution: At least daily Spatial resolution: Corresponding to Sentinel-1 |

[AD-2] states the prioritised climate requirement as:

| Sea Ice drift | Pan-Arctic coarse resolution (25-60 km) (combination of active and passive sensors) gridded datasets. High resolution lagrangian products deduced from processed SAR images (ex: RADARSAT GPS) are also extremely useful for process studies on sea ice mechanics as well as validation of drift/ deformation fields produced by sea ice models. | Resolution of gridded products is too low. Products deteriorate near the ice edge or in summer. SAR data do not provide global coverage: improve on the use of these data. | Pan-Arctic Frequency: daily Resolution: 10 km, as for SIC |
Sea ice drift products are required with daily coverage in the pan-Arctic and adjacent Seas (>58° North latitude), and Antarctica regions and a spatial resolution of 10 km [AD-2].

2.4.5 Snow Depth on Sea Ice.

Snow is a critically important and rapidly changing feature of the Arctic. However, snow-cover and snowpack conditions change through time and pose challenges for measuring and prediction of snow. Plausible scenarios of how Arctic snow cover will respond to changing Arctic climate are important for impact assessments and adaptation strategies (Bokhorst et al., 2016). Merkouriadi et al. (2017) discuss the critical role of snow on sea ice growth in the Atlantic sector of the Arctic Ocean. Snow lying on top of sea ice modulates the growth and decay of sea ice (Maykut, 1978; Sturm and Massom, 2010). Snow has a high albedo (Perovich et al., 2017) and even when limited snowfall occurs on sea ice in spring conditions (high insolation) it may reduce significantly surface melt. In winter conditions, when high Arctic sea ice grows in the absence of solar insolation snow has two roles: (1) it insulates the sea ice surface from cold air temperatures, hindering thermodynamic growth of sea ice (Ledley, 1991; Maykut, 1978) thus reduces the heat transfer from ocean to atmosphere, influences the sea ice growth below and thereby the sea ice mass balance. (2) snow contribute to the sea ice mass balance through the formation of snow-ice (e.g., Leppäranta, 1983). Snow-ice forms when seawater floods and refreezes at the ice/snow interface, due to excessive snow load that pushes the ice surface below sea level. Snow-ice is a common process in seasonally ice-covered seas but has not been prevalent in the Arctic, where thick perennial sea ice has dominated (Sturm and Massom, 2010). Due to its high friction, information about snow depth is also important for shipping operations (e.g. Huang et al, 2018) in the ice-infested regions such as the northern polar route.

The main limitation of using microwave radiometers is the coarse resolution (i.e. tens of kilometres), whereas radars lack the appropriate frequencies (Bokhorst et al., 2016). Monitoring of snow depth on sea ice is clearly a significant parameter to monitor by CIMR due to the relatively high spatial resolution of this mission. Snow cover on sea ice influences the Earth’s climate and biology in the ocean. The only current snow-depth-on-sea ice algorithm that uses satellite data is based on microwave radiometer observations (Cavalieri et al. 2012; Brucker and Markus 2013).

Snow depth measurements (e.g. Warren et al., 1999; Maass et al., 2015; Zheng et al., 2017) over sea ice are needed for an accurate determination of the sea ice freeboard when used together with satellite altimeter measurements (e.g. Kern et al., 2015; Kurtz et al., 2013) [AD-2]. Snow depth can be estimated from microwave radiometry using a combination of AMSR-E or AMSR-2 brightness temperatures (e.g. 18.7 and 36.5, GHz) using a spectral gradient approach (e.g. Markus et al., 2006; Comiso et al., 2003). Although the method is confounded in the presence of snow melt water and sensitive to the ice roughness below, potentially this can allow direct snow measurements to replace the Warren snow climatology. Recently, the use of neural network approaches has shown promising improvements (e.g. Brackmann-Folgmann and Donlon, 2019) although more work is required to develop this approach further.
[AD-1] states the requirement as follows:

[AD-2] states the prioritised operational requirement as: “Snow depth measurements are needed to best measure sea ice freeboard. The specification should follow the ice thickness specifications in terms of resolution and time sampling”.

[AD-2] states the prioritised climate requirement as:

[AD-2] notes that snow depth on sea ice measurements are needed to best measure sea ice freeboard. The specification should follow the ice thickness specifications in terms of resolution and time sampling.

### 2.4.6 Ice type/Ice stage of development

Sea ice includes any form of ice found at sea which has originated from the freezing of seawater (e.g. Eppler et al., 1992). It can be broadly described in terms of Ice Type/Stage of Development using the following classification: new ice, young ice, first/second-year ice and multi-year ice (e.g. Walker et al., 2006). These categories broadly reflect the age of the ice and include different forms and thicknesses of ice at various stages of development.

[AD-2] states that sea ice type is key to operational services (navigation, marine operations) as well as to climate modelling. At present, sea ice type information is needed for converting sea ice freeboard (from satellite radar altimeter measurements) to sea ice thickness;

Ice-type is typically derived from scatterometers (e.g. MetOp ASCAT) in combination with AMSR-2 or SSMI microwave radiometry measurements, e.g. as in the current operational OSI-SAF and CMEMS catalogue. Historically, ice type from microwave radiometry alone has used Ka-band (31 or 36 GHz), but some sensitivity also exists at lower frequencies (e.g. Lee et al., 2017). Because of the many types of sea ice and its dynamic nature, scattering from sea ice is very complex. The general approach is to create feature vectors with either fixed reference vectors, dynamically- selected reference vectors, or automated clustering techniques to classify the observed scattering characteristics for each pixel to a particular ice type (e.g. Long, 2017, Ye et al. 2015, 2016). The combination of microwave radiometry and scatterometry (and optical data when available) to provide sea ice type in non-

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Copernicus Imaging Microwave Radiometer (CIMR) Mission Requirements Document
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precipitating atmospheric conditions offers a powerful synergy for sea ice parameters including ice classification.

[AD-1] states the requirement as follows:

<table>
<thead>
<tr>
<th>THM</th>
<th>DOM</th>
<th>Parameter</th>
<th>AOI</th>
<th>Resolution</th>
<th>TOV</th>
<th>Frequency</th>
<th>Leadtime</th>
<th>TL</th>
<th>Unit</th>
<th>Range</th>
<th>Accuracy</th>
<th>I</th>
<th>S</th>
<th>C</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>TR</td>
<td>Ice Type</td>
<td>0</td>
<td>T: 20m G: 2m</td>
<td>0</td>
<td>T: 2d G: 1d</td>
<td>24h</td>
<td>1</td>
<td>1</td>
<td></td>
<td>T: 95%, G: 95%</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>TR</td>
<td>Ice Type</td>
<td>0</td>
<td>T: 40m G: 25m</td>
<td>0</td>
<td>T: 16y G: 6hr</td>
<td>n/a</td>
<td>2</td>
<td>1</td>
<td></td>
<td>T: 95%, G: 95%</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>ME, OC</td>
<td>Ice Type</td>
<td>0</td>
<td>T: 1.3km G: 1km</td>
<td>0</td>
<td>T: 16y G: 12hr</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
<td>T: 95%, G: 95%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[AD-2] states the prioritised operational requirement as:

<table>
<thead>
<tr>
<th>Stage of development / Ice type</th>
<th>Ice services are making a visual interpretation based on the SAR backscatter values.</th>
<th>Automatic products should be available.</th>
<th>Accuracy: Fractions of deformed ice has to be measured with an accuracy of 10%.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fully polarimetric SAR observations are required in order to enable automation of product generation.</td>
<td>Dynamic topography products are required at high spatial and temporal resolutions. These can be provided by single pass interferometric SAR.</td>
<td>Coverage: pan-arctic (G), areas near shipping routes and marginal ice zone (T).</td>
</tr>
<tr>
<td></td>
<td>Spatial resolution: 20m(G), 80m(T).</td>
<td></td>
<td>Frequency: 1 day(G), 2 days(T).</td>
</tr>
</tbody>
</table>

[AD-2] states the prioritised climate requirement as:

<table>
<thead>
<tr>
<th>Ice type</th>
<th>Multiyear ice concentration is available from PMW. Distinction of deformed/levelled ice is available via scatterometer data.</th>
<th>Continuity of the PMW brightness temperature at different polarizations.</th>
<th>Accuracy: Fractions of deformed ice has to be measured with an accuracy of 10%.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full polarimetric SAR observations are required in order to enable automation of product generation.</td>
<td>Dynamic topography products are required at high spatial and temporal resolutions. These can be provided by single pass interferometric SAR.</td>
<td>Coverage: pan-arctic (G), areas near shipping routes and marginal ice zone (T).</td>
</tr>
<tr>
<td></td>
<td>Spatial resolution: 20m(G), 80m(T).</td>
<td></td>
<td>Frequency: 1 day(G), 2 days(T).</td>
</tr>
</tbody>
</table>

Continuity of ice-type in non-precipitating atmospheric conditions is at least required [AD-1] with at least a daily revisit and an effective (gridded) resolution of <5 km [AD-2].

2.4.7 Ice Surface Temperature (IST)

IST is typically retrieved using thermal infrared (TIR) measurements that are confounded by the presence of clouds (e.g. Scott et al., 2014).

Microwave radiometry has potential to retrieve the ice surface temperature using 6.9 GHz AMSR-E and AMSR-2 data (e.g. Comiso et al., 2003) in combination with other microwave channels and thermal infrared satellite data when available (cloud cover remains a challenge in the Polar Regions). At ~6 GHz an effective temperature ($T_{eff}$) of the
emitting layer due to the finite emission depth at this frequency is retrieved. $T_{\text{eff}}$ is more representative of the snow-ice interface temperature rather than the IST derived by TIR measurements. Figure 5 provides an example of the differences between IST (derived from a TIR radiometer) and the temperature at different depths in the snow-pack and at the ice/snow interface.

Recent developments using satellite microwave radiometer data at 6.9, 18.6 and 35.5 GHz with empirical algorithms (Kilic et al., 2018b, shown in Figure MRD-2.4.7.1) suggest that the snow-ice interface temperature, the effective temperature, and the snow depth in terms of brightness temperature can be retrieved (OSISAF, 2017). IST is potentially as important as SST in terms of assimilation for vertical heat diffusion. IST is a CMEMS product derived from MetOp AVHRR and provided daily with 5 km resolution for the Arctic domain (> 58°N) [AD-1].

[AD-1] states the requirement as:

![Figure MRD-2.4.7.1. IST temperatures at DMI Automatic Weather Station IR120 highlighting the significant differences between the temperature at the snow/ice interface (bottom of the snow layer) and the skin IST as measured by an infrared radiometer.](credit: Kilic et al., 2018b).

[AD-2] states the prioritised climate requirement as:

<table>
<thead>
<tr>
<th>THM</th>
<th>DOM</th>
<th>Parameter</th>
<th>AOI</th>
<th>Resolution</th>
<th>TOY</th>
<th>Frequency</th>
<th>Leadtime</th>
<th>TL</th>
<th>Unit</th>
<th>Range</th>
<th>Accuracy</th>
<th>I</th>
<th>S</th>
<th>B</th>
<th>C</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>CC</td>
<td>IST</td>
<td>0</td>
<td>T: 9 km</td>
<td>0</td>
<td>8 hr</td>
<td>n/a</td>
<td>2</td>
<td>$K$</td>
<td>[10,29]</td>
<td>0.5K</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>TR</td>
<td></td>
<td>0</td>
<td>T: 15 km</td>
<td>G: 50 km</td>
<td>0</td>
<td>T: 24 h G: 16 h</td>
<td>24 h</td>
<td>1</td>
<td>$K$</td>
<td>[137,37]</td>
<td>0.1K</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>IS</td>
<td>CL</td>
<td>ME</td>
<td>0</td>
<td>T: 10 km</td>
<td>G: 10 km</td>
<td>0</td>
<td>T: 1 yr G: 1 mo</td>
<td>n/a</td>
<td>0</td>
<td>$K$</td>
<td>[170,279]</td>
<td>1K</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Continuity of IST in non-precipitating atmospheric conditions is required (i.e. that derived from AMSR-2) [AD-1] with at least a daily revisit [AD-2].
2.4.8 Terrestrial Snow Cover: Snow Area and Snow Water Equivalent.

[AD-1] notes that seasonal snow is a main element of the global water cycle and climate system. Due to its strong influence on the radiation and energy balance, changes in snow extent tend to amplify climate fluctuations. Terrestrial snow covers up to 50 million km² of the Northern Hemisphere in winter and is characterized by high spatial and temporal variability. Seasonal snow is an important resource, supplying major parts of Europe but also many other regions in the world with water for human consumption, agriculture, hydropower generation, support of geotechnical and construction planning activities, management of water supply for agricultural industry, and other economic activities. Seasonal snow is also important for hydrological forecasting in the context of flood prevention [AD-1].

High priority parameters needed to monitor the seasonal snow are snow water equivalent (snow mass: SWE), snow extent / fraction, and the snow melt extent (presence of liquid water in the snow pack). Among those parameters **SWE is the most needed parameter of the seasonal snow** [AD-1]. For many applications (e.g. in hydrology, climate, meteorology, water resource management, etc.) high resolution SWE is required with improved accuracy and appropriate spatial resolution for complex terrains and forests. Seasonal snow is a main element of the global water cycle and climate system. SWE is an emerging product of the Copernicus Land Monitoring Service (http://land.copernicus.eu/global/products/swe) based on SSM/I and optical satellite data.

Snow Water Equivalent (SWE) is one of the most useful parameters to monitor seasonal snow and [AD-1] states the requirement as follows:

<table>
<thead>
<tr>
<th>THM</th>
<th>DO</th>
<th>Parameter</th>
<th>ADI</th>
<th>Resolution</th>
<th>TOY</th>
<th>Frequency</th>
<th>Leadtime</th>
<th>TL</th>
<th>Unit</th>
<th>Range</th>
<th>Accuracy</th>
<th>I</th>
<th>S</th>
<th>C</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN</td>
<td>CL ME</td>
<td>T. Northern Hemisphere</td>
<td>G. Global</td>
<td>T: 10km G: 1km</td>
<td>0</td>
<td>T: 5ly G: 1ly</td>
<td>nia</td>
<td>1</td>
<td>[mm (kg/m³)]</td>
<td>(0.500)</td>
<td>For SWE &lt; 200 mm: T: 40 mm; G: 20 mm</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>SN</td>
<td>HY EN ME</td>
<td>Snow Water Equivalent</td>
<td>T. North, Hemis, G. Global</td>
<td>T: 1km G: 200m</td>
<td>0</td>
<td>T: 5ly G: 1ly</td>
<td>nia</td>
<td>1</td>
<td>[mm (kg/m³)]</td>
<td>(0.500)</td>
<td>For SWE &lt; 200 mm: T: 10% G: 10%</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>SN</td>
<td>GEN PF</td>
<td>Snow Water Equivalent</td>
<td>G. Mountain regions, perennial, G. Global</td>
<td>T: 50m G: 10m</td>
<td>1 snow covered period</td>
<td>T: 5ly G: 1ly</td>
<td>nia</td>
<td>1</td>
<td>[mm (kg/m³)]</td>
<td>(0.500)</td>
<td>For SWE &lt; 200 mm: T: 40 mm; G: 20 mm</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

It is feasible to measure SWE from space (e.g. Pulliainen et al., 2001) using empirical spectral and polarization difference algorithms that are driven by microwave radiometer brightness temperatures. Empirical methods exist based on SMMR and SSM/I microwave radiometer brightness temperatures (e.g. 37 GHz and either 18 or 10.7 GHz, e.g. Hallikainen and Joma, 1992; Tsutsui and Maeda, 2017). Both AMSR-E and AMSR-2 have SWE algorithms based on 18.7 and 36.5 GHz channels (e.g. Cho et al., 2017) [AD-2]. Snow water equivalent (SWE) SWE is observed by current satellite microwave radiometer systems on-board of Defence Meteorological Satellite Program (DMSP) SSM/I satellites at coarse spatial resolution (a few tens of km), but retrieval algorithms are saturated for deep snow and are not capable of measuring SWE in complex terrain. The availability of microwave radiometer sensors on-board of DMSP satellites is uncertain. Observations by MetOp-SG MWI will not improve spatial resolution or retrieval skill [AD-1].
Snow Extent is an important parameter for climate change assessment, but also important for water management, hydrology and meteorology. Snow extent (binary and fractional) is monitored by means of multi-spectral, medium resolution optical sensors like AVHRR, MODIS, ATSR-2/ AATSR, and monitoring is continued by Sentinel-3 SLSTR and OLCI, providing improved spectral properties and spatial resolution. Long time series of satellite data are available since the beginning of 1980s [AD-1].

The extent of the Snow Melt is important for hydrology, water management, and snow melt flood forecasting. At coarse resolution, microwave radiometer and scatterometer measurements are used that are continued by sensors on-board MetOp-SG. Sentinel-1 Interferometric Wide Swath (IWS) and the Extended Wide Swath (EWS) modes are suitable to map the melt snow extent, but this approach requires a suitable acquisition planning [AD-1].

[AD-2] requests the following:

<table>
<thead>
<tr>
<th>SEASONAL SNOW</th>
<th>Status</th>
<th>Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Snow Area</td>
<td>VIS, NIR &amp; TIR imager, some problems with cloud / snow discrimination; available products show significant differences.</td>
<td>Higher resolution required for complex terrain (mountains); cloudiness / polar night; in some products filled with coarse IMWR.</td>
</tr>
<tr>
<td>Snow Mass (SWE) on land</td>
<td>Low spatial resolution SWE maps available from IMWR, but at comparatively large uncertainty. Operational products available (GlobSnow, etc.), continuity of PMW on METOP.</td>
<td>IMWR SWE: accuracy needs to be improved; problems with spatial resolution in complex terrain, forests, saturation over deep snow. High resolution product needed, not covered by current sensors.</td>
</tr>
<tr>
<td>Snow Melt Extent</td>
<td>C Band SAR (S1, ERS, ENVISAT) provide snapshot, algorithms mature for mountain regions.</td>
<td>Problems in forests. Melt extent depends on acquisition time;</td>
</tr>
</tbody>
</table>

### 2.4.9 Sea Surface Salinity (SSS)

Salinity refers to the mass of dissolved salts in a kilogram of seawater. It is a dimensionless ratio (quantity of conductivity), expressed according to the Practical Salinity Scale. While a challenging measurement to make from space (e.g. Yueh et al., 2001), for warmer waters great progress has been made using 1.4135 GHz measurements from the ESA SMOS (e.g. Reul et al., 2012a) and NASA Aquarius (e.g. Yueh et al., 2014) and SMAP missions (e.g. Meissner and Wentz, 2016). Radio Frequency Interference (RFI) must be mitigated when using low-frequency L-X band channels, in geophysical retrieval algorithms (e.g. Soldo et al., 2017; Mohammed et al., 2016). New algorithms, recently developed at the Barcelona Expert Centre (BEC) to improve the quality of L-band measurements show that for the first time cold-water SSS maps from SMOS data can be derived (Olmedo et al., 2017; Garcia-Eidell et al., 2017) to observe the variability of the SSS in the higher north Atlantic and the Arctic Ocean. Also, BEC has proposed a methodology to mitigate systematic errors produced by the contamination of the land over the sea that allows obtaining SMOS SSS fields over enclosed seas such as the Mediterranean (Olmedo et al., 2018). Buongiorno Nardelli et al, 2012 and 2016 demonstrated that SST can be used together with SSS data to produce L4 SSS products with higher resolution and improved accuracy and to directly estimates the sea surface density (SSD) fields. This method is now adopted by CMEMS to produce global reanalysis of SSS and SSD (1993-2016) at ¼° spatial resolution available...
from the CMEMS catalogue since April 2018 (Droghei et al. 2016, Droghei et al. 2018). The NRT SSS and SSD production is planned for end of 2018.

SSS is a very important variable for CMEMS [AD-3] and first results of assimilating SMOS SSS indicate positive skill (ESA SMOS-NINO15 Project). New Global L4 SSS and SSD datasets including satellite SSS from multiple satellite sensors (SMOS, Aquarius, SMAP...) is planned be developed and produced in the future. However, there are no planned missions to secure continuity of L-band (1.4GHz) measurements following SMOS or SMAP missions from which sea surface salinity is best derived. Actions should be developed to advance our capabilities to observe SSS from space [AD-3].

[AD-3] requests that there is a further advance in Copernicus capabilities to observe sea surface salinity over the global ocean from space. During recent workshops (Cesbio, Nov 2017; ECMWF, Dec 2017, LOCEAN 2018) the need for L-band radiometer continuity was discussed. It was identified that any future sensor must provide L2 measurements with the same spatial resolution as currently orbiting systems (SMOS and SMAP), i.e., ~40-50 km. The following requirements for future SSS observations from Space as function of oceanographic processes were determined as shown in Table-MRD-SSS.

Table-MRD-SSS. Requirements for future SSS observations from Space as function of oceanographic processes. S=Spatial resolution, T=Temporal resolution, A=Accuracy, SRL: Scientific Readiness Level, ARL: Application Readiness Level, y=year, m=month, w=week, d=day, hr=hour. N.B. Accuracies are given in pss and correspond to the accuracies of the SSS at the corresponding temporal and spatial scales

<table>
<thead>
<tr>
<th>Oceanographic Processes</th>
<th>Useful(^3)</th>
<th>Required</th>
<th>Optimal</th>
<th>SRL</th>
<th>ARL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S</td>
<td>T</td>
<td>A</td>
<td>S</td>
<td>T</td>
</tr>
<tr>
<td>SSS long-term change (&gt;10 years)</td>
<td>10(^\circ)</td>
<td>1 y</td>
<td>0.01</td>
<td>5(^\circ)</td>
<td>1 y</td>
</tr>
<tr>
<td>Barrier layer and vertical compensated layers</td>
<td>1.5(^\circ)</td>
<td>1 m</td>
<td>0.1</td>
<td>0.5(^\circ)</td>
<td>1 w</td>
</tr>
<tr>
<td>Density compensation on horizontal</td>
<td>0.5(^\circ)</td>
<td>1 m</td>
<td>0.3</td>
<td>0.25(^\circ)</td>
<td>8d</td>
</tr>
<tr>
<td>ENSO/IOD SSS anomalies</td>
<td>10(^\circ)</td>
<td>1 m</td>
<td>0.2</td>
<td>1(^\circ)</td>
<td>8d</td>
</tr>
<tr>
<td>Mesoscale/eddy propagation</td>
<td>1(^\circ)</td>
<td>1 m</td>
<td>0.2</td>
<td>0.5(^\circ)</td>
<td>1w</td>
</tr>
<tr>
<td>Tropical Instability Waves</td>
<td>1(^\circ)</td>
<td>8d</td>
<td>0.2</td>
<td>0.5(^\circ)</td>
<td>8d</td>
</tr>
</tbody>
</table>

\(^3\) Indicates Spatial, Temporal and Accuracy Required. Useful, Required and Optimal Requirements respectively (useful means that below this threshold data is of very little impact, required is the value which people want, optimal is the day dreaming value)
### 2.4.10 Wind speed over the ocean and extreme winds in Polar regions

Multi-channel microwave radiometers have been used to measure ocean surface winds for several decades. As discussed by Wentz (1992), wind induced roughness of the sea surface reduces the polarisation of sea surface emissions at microwave frequencies (except at incidence angles above 60° for which the vertically polarized emission decreases). Surface waves having wavelengths long compared to the radiation wavelength mix the horizontal and vertical polarization states and change the local incidence angle. Foam at the sea surface (a mixture of air and water) increases in the emissivity for both polarizations. Sea surface emissivity depends on wind-induced surface ocean roughness (e.g. Meissner and Wentz, 2002; 2012) that can be derived from microwave radiometer observations at 10 to 36 GHz (Prigent et al., 2013, Kilic et al., 2018). These estimates are then used to derive an estimate of the surface wind over the ocean. The technique is mature and validated data sets are available from SSM/I, AMSR/E/2 amongst others. CIMR will derive wind speed estimates by combining, X- with C- and L-band channels.

The first fully polarimetric satellite microwave radiometer, CORIOLIS WindSat (Gaiser et al., 2004), was launched in January 2003. The mission was developed to evaluate the potential of polarimetric microwave radiometry to retrieve ocean surface wind vectors. The polarization properties of an electromagnetic wave can be fully characterized by measuring the modified Stokes vector. The modified Stokes vector includes the vertical and horizontal polarizations and the third and fourth Stokes parameters that provides sufficient information to retrieve an estimate of the ocean surface wind vector. Because the wind direction dependence differs for the 4 Stokes parameters it is possible to resolve the vector wind ambiguities without the use of an ancillary numerical weather prediction field. Nonlinear iterative retrieval algorithms for wind vector retrievals from WindSat data have been developed (e.g. Bettenhausen et al., 2006). Bourassa et al (2019) review the current capability of ocean wind measurements from space. At wind speeds below 6m s\(^{-1}\), the wind direction signal from microwave radiometry is small in all polarizations leading to noisy wind direction estimates. At 6m s\(^{-1}\), the uncertainty of WindSat wind direction is 20° (Hilburn et al., 2016). Above 8m s\(^{-1}\), the uncertainty is 10°-15° and is similar to that derived from scatterometers (Ricciardulli et al., 2012; Hilburn et al., 2016).
(above 10 m s⁻¹) the wind direction signal derived from microwave radiometry is strong in all 4 Stokes parameters.

The combined use of both CIMR full Stokes measurements and MetOp-SG(B) active microwave sea surface wind estimates will provide an unprecedented wind speed/vector data set at high spatial and temporal resolution for application in Copernicus.

CIMR also provides L-band measurements that have been recently used to determine extreme wind speeds over the ocean. The application of L-band measurements to measure extreme wind speed over the ocean has been pioneered by Reul et al. (2017). Estimates of storm intensity and sizes are being produced in near-real time from SMOS (www.smosstorm.org) and SMAP (www.remss.com) for operational applications at the US Navy and the Joint Typhoon Warning Center have started to ingest this information into their Automated Tropical Cyclone Forecasting Systems (Sampson and Schrader, 2000; Bender et al. 2017, Knaff et al. 2018). Considering the Arctic, Polar Lows (PL) are intense mesoscale cyclones that are associated with cold air outbreaks and form pole ward of the main baroclinic zone. Sometimes referred to as Arctic hurricanes, polar lows are short-lived (the mean lifetime is ~15 h) and small-scale cyclones (diameters ranging from 200 to 600 km), unlike their tropical counterparts (Smirnova et al., 2015). What they do have in common is strong surface winds: at least gale force is required for a polar low (Rasmussen and Turner 2003).

Early detection and evaluation of PL parameters are extremely important to ensure the safety of navigation, fishing and oil industry, and expanding construction on the Arctic shelf. These extreme storms, characterized by strong and rapidly changing winds, are known to enhance vertical mixing processes. This can affect the cold halocline layer, possibly leading to a positive feedback to impact sea-ice formation. Because of the sparse network of weather stations and irregular meteorological observations at the sea, fast movement and short life cycle of PLs, the phenomena are not always identified in the pressure fields on the surface weather maps. That is why satellite data remain the basic source of information on PLs.

Polar lows can be identified in integrated Water Vapor Content (WVC) fields (Smirnova et al., 2016), but in some regions (Chukchi Sea, Laptev Sea and the East Siberian), they are associated with extremely low WVC values which make their detection from high-frequency radiometers (e.g., SSM/I) difficult (Zabolotskikh et al., 2016). Efficient masking of the areas over the oceans, where geophysical parameter retrievals are objectively impossible due to non-transparent atmosphere, is still an important issue for satellite radiometer measurements working at frequency higher or equal than C-band. As demonstrated for Tropical cyclones (Reul et al., 2012b, 2016, 2017, Meissner et al., 2017) L-band radiometer data can provide a direct way to probe surface wind speed in extreme weather events, being almost transparent to the atmosphere. Estimation of the total atmospheric absorption can be also done from the ~10 GHz channel with high accuracy due to the weak influence of liquid water and especially water vapour (Zabolotskikh et al., 2013). This helps to refine a new filter to considerably reduce masking ocean areas in e.g., AMSR2 radiometer data for severe weather systems such as PL, characterized by high wind speeds and moderate atmospheric absorption. Combining, X- with C- and L-band channels, a methodology can be proposed to jointly retrieve sea surface wind speed and sea surface temperature in PL.
The combined usage of both CIMR passive and MetOp-SG(B) active microwave sea surface wind estimates will demonstrate the potential of the highest spatial and temporal resolution in the investigation of PL intensity. The ability to better measure warm SST PLs wakes thanks to X/C band combination for SST and L-band wind retrievals will also help in better characterizing feedbacks of PLs to impact sea-ice formation.

2.4.11 Other parameters that can be derived from CIMR

A variety of parameters can be derived from a multi-frequency conical scanning microwave radiometer such as CIMR including the following.

2.4.11.1 Soil Moisture (SM)

Soil moisture is a primary state variable of hydrology and the water cycle over land either as an initial condition or a boundary condition of relevant hydrologic models (NASA, 2014). Applications that require accurate maps of high-resolution soil moisture and its spatial and -temporal evolution include: weather forecasting, modelling and prediction of climate variability and change, agricultural productivity, water resource management, drought prediction, flood area mapping, and ecosystem health monitoring all require information on the status of soil moisture. See Dorigo et al. (2017) for a full review. Satellite surface soil moisture, up to 5cm soil depth, is recognized as an Essential Climate Variable by the Global Climate Observing System (GCOS), alongside subsidiary variables freeze/thaw state, vegetation optical depth, surface inundation and root-zone soil moisture. The Copernicus Land service provides estimates of Soil Moisture (in development) and a Soil Water Index (Albergel et al., 2008; Wagner et al., 1999) that quantifies the moisture condition at various depths in the soil. It is mainly driven by the precipitation via the process of infiltration. Soil moisture is a very heterogeneous variable and varies on small scales with soil properties and drainage patterns. Satellite measurements integrate over relative large-scale areas, with the presence of vegetation adding complexity to the interpretation.

Microwave observations are sensitive to soil moisture because moisture affects the dielectric constant of the surface and thus the emissivity soil surfaces. Vegetation and surface roughness reduce the microwave sensitivity to soil moisture and are more pronounced as microwave frequency increases. At L-band frequencies the soil moisture emission originates from deeper in the soil (a few centimetres), giving a more representative measurement of conditions below the surface crust or skin layer. Measurements at C-band range are sensitive to soil moisture, but primarily in regions of low vegetation but the attenuation by vegetation and the shallow sensing depth of ~1 cm for bare soil impose limitations on the retrieval of soil moisture. See Njoku et al. (2003) for information on the application of AMRE for Soil Moisture retrieval. The CIMR channel at 1.4315 GHz is ideally suited to soil moisture measurements complemented by the primary channel at 6.9 GHz.

2.4.11.2 Land Surface Temperature (LST)

The Copernicus Land Service provides estimates of LST defined as the radiative skin temperature of the land surface, as measured in the direction of the remote sensor. It is estimated from Top-of-Atmosphere brightness temperatures from the infrared spectral channels of a constellation of geostationary satellites (Meteosat Second Generation, GOES, MTSAT/Himawari). Its estimation further depends on the albedo, the vegetation cover and
the soil moisture. LST is a mixture of vegetation and bare soil temperatures. Because both respond rapidly to changes in incoming solar radiation due to cloud cover and aerosol load modifications and diurnal variation of illumination, the LST displays quick variations too. In turn, the LST influences the partition of energy between ground and vegetation, and determines the surface air temperature. The Global Land Service provides the following LST-based products (see Freitas et al., 2013):

- **LST**: hourly LST from instantaneous observations
- **LST10-DC**: 10-day Land Surface Temperature with Daily Cycle
- **LST10-TCI**: Thermal Condition Index with a 10-day composite of Land Surface Temperature

A significant challenge for LST when retrieved from TIR measurements is the presence of clouds that preclude the retrieval. Microwave observations between 10 and 36 GHz can overcome this primary difficulty and have been successfully used to retrieve LST (e.g., Aires et al., 2001, Holmes et al., 2000, Prigent et al., 2016). The errors on these LSTs are slightly larger than for their infrared counter parts, but the estimates are available ~90% of the time (compared to less than ~40% of the time with the infrared estimates).

### 2.4.11.3 Irrigation applications.

Low frequency (< 10 GHz) microwave radiometer systems like CIMR are very well suited to monitor soil moisture (e.g. Enthekabí et al., 2010; Kerr et al., 2012;) which makes them an attractive resource for several agricultural applications. For example, a farmer can use soil moisture information to optimize its irrigation practices which could lead to an improvement in water use efficiency. Remotely sensed soil moisture has proved a valuable resource for estimating irrigation water use at the continental scale (Brocca et al, 2018, Zaussinger et al., 2019) and as such can be used to estimate and optimise water use efficiency globally.

However, the coarse gridded resolution of ~25 km from current missions (e.g. SMOS/SMAP) providing soil moisture products limits the applicability for this sector. With the recent advances in downscaling, this situation has improved and we are now also able to capture local variability caused by irrigation. For example, in 2016, Gevaert et al. (2016) revealed a clear irrigation signal in Australia when C-band soil moisture retrievals from AMSR-E where enhanced with Ka-band observations. Escorihuela and Quintana Sequi (2016) showed an irrigation signal in Spain when the SMOS signal was downscaled with LST observations.

These irrigation signals were all derived from existing microwave radiometer systems. With the proposed improvement in spatial resolution and continuity of historical capability by CIMR, it is expected that the possibilities within the agriculture sector will further expand.

### 2.4.11.4 Vegetation Water Content

Vegetation Optical Depth (VOD) describes the attenuation of microwave radiation by the vegetation canopy layer and, hence, is closely related to vegetation water content and biomass. VOD is simultaneously derived with soil moisture from microwave radiometer observations at low to mid-frequencies (1 - 20 GHz; Owe et al., 2001), where each frequency shows a unique sensitivity to different parts of the canopy: while lower
frequencies are more strongly related stems and branches (Rodriguez-Fernandez et al., 2018), the higher frequencies appear to be more sensitive to leaf material and crops and therefore a powerful indicator of plant production (Teubner et al., 2018; Andela et al., 2014) complementary to traditional indicators from optical remote sensing like Normalised Difference Vegetation Index (NDVI) and leaf area index. The multi-frequency capability of CMIR will, for the first time, allow for a complete characterisation from a single platform of the water contained in the vegetation, including stems, branches, leaves, and buds. Furthermore, the proposed improvement in spatial resolution of CIMR will allow for a purer characterisation of vegetation types, which is crucial for agricultural applications.

VOD observations from various radiometer missions have been combined into climate data records up to 30 years in length (Liu et al., 2015; Moesinger et al., 2019). These Climate Data Records (CDR) allow studying the variability and trends in vegetation activity and biomass, both due to climate forcing and human intervention (e.g. deforestation, grazing; Liu et al., 2013). The envisaged long-term commitment of the CMIR mission will allow to extend these CDRs up to more than half a century in length, which are crucial for monitoring the impact of climate change and anthropogenic forcing on natural and agricultural ecosystems. This long data coverage will complement more dedicated vegetation microwave missions like ESA Biomass.

2.4.11.5 Cloud Liquid Water over Ocean

Atmospheric water vapour is a major greenhouse gas. In its vapour and liquid states, it is a key parameter in the global hydrological cycle, a component of climate change and ocean–atmosphere energy exchange studies. Water vapour changes in the Arctic are poorly described because of a lack of direct observations and large sea ice cover over which atmospheric water retrievals are either complicated or impossible (e.g. Vihma, 2014). Regular long-term observations of water vapour over the open sea-water are provided by satellite microwave radiometer instruments. Both atmospheric total water vapour content (WVC) and total cloud liquid water content (CLW) have been successfully retrieved from AMSR-E measurements (e.g. Kazumori, 2012) and more recently from AMSR2 (e.g. Zabolotskikh and Chapron, 2017). CIMR does not have a water vapor channel centred at ~22 GHz and it is likely that CIMR will not provide any additional information with respect to the a priori information from ECMWF and other instruments.

However, cloud liquid water content can be retrieved from CIMR (e.g. Greenwald et al., 2018) typically at the same time as precipitation estimates are made (to reduce the risk of inconsistency).

2.4.11.6 Precipitation Rate Over Ocean

Precipitation is a key hydrological and climate variable and includes both the liquid (rain) and solid (snow and ice) forms. Precipitation occurs when a particle formed by the condensation of water vapour becomes heavy enough to fall under the force of gravity. Precipitation rate estimates are a fundamental component of the water cycle characterization. The physical basis for retrieving precipitation from microwave radiometer measurements depends on distinguishing the radiation from Earth’s surface from the radiation emitted from precipitation (e.g. Hilburton and Wentz, 2008). Microwave emission from the ocean surface is strongly polarized, while the emission from rain drops is un-polarized. Thus, precipitation can be accurately distinguished from the underlying ocean surface using measurements of the vertically and horizontally polarized
radiation (see examples at [http://www.remss.com/measurements/rain-rate/](http://www.remss.com/measurements/rain-rate/)). CIMR will be able to provide estimates of precipitation rate, although further algorithm development is required, in particular to exploit forward and backwards views together.

### 2.4.11.7 Continental Surface Water Extent

Surface water extent and dynamics have been estimated with passive microwaves, using essentially at 18 and 36 GHz from SSMI and SSMIS. Monthly mean estimates have been calculated since 1992, at a spatial resolution of ~25 km, including the surface water under dense vegetation ([Prigent et al., 2001, 2012, 2019](http://www.remss.com/measurements/rain-rate/)). These estimates have been widely used to model Earth hydrological and biochemical cycles. They complement the optical estimates (Landsat or MODIS) that can only detect open waters. The inter-annual variability of the surface water extent derived from passive microwaves partly explain the variability of the atmospheric methane emission. Recent works used L-band observations, with some success ([Parrens et al., 2017, Du et al., 2018](http://www.remss.com/measurements/rain-rate/)).

### 2.4.11.8 Other applications

A Joint Cryosphere-Ocean-Land-Ecosystems CIMR Science Workshop was held in Arcadia, California from August 13-15, 2019. The objective of the workshop was to document the potential utility of the CIMR mission for NASA earth science programs. Four panels, Cryosphere, Oceanography, Terrestrial Hydrology, and Terrestrial Ecology reviewed the CIMR mission and its potential in each application domain. Based on the discussions at this meeting, notable additions to the previous paragraphs include:

- CIMR measurements will significantly enhance the understanding of air-sea interaction processes in the Polar regions and global ocean;
- The higher temporal resolution of SSS & SST together with simultaneous measurements of SST, SSS, and wind improves studies of ocean response to synoptic weather and can better constrain coupled modelling for hurricanes as well as tropical/extratropical cyclones, including forecast and impact studies;
- CIMR’s ability to extend the satellite SSS record to cover multiple ENSO events can thus improve ENSO forecast capabilities in climate prediction centres;
- Daily simultaneous measurements of SSS and winds from the CIMR will also enhance the research on processes associated with the dispersal of river-plume induced freshwater as well as the associated redistributions of nutrients and contaminants;
- Simultaneous measurements of soil moisture, surface inundation, SSS will also improve the assessment of flooding impacts across the land-sea interface;
- The simultaneous measurements of SST and SSS will also improve the tracking of horizontal surface density fronts and the related studies of ocean dynamics on mesoscales. Ocean circulation at horizontal density fronts on scales of tens of kilometres is considered to be responsible for transporting much of the heat and carbon from the ocean surface to deeper layers;
CIMR's higher resolution and lower noise SST estimates (compared to past C-band MW radiometers), combined with the dense temporal sampling at high latitudes, should allow a new capability to estimate daily gridded upper ocean vector currents;

CIMR will enable estimation of a number of confounding factors that are essential to accurate soil moisture retrieval from space. These factors include land surface temperature, fractional surface water inundation extent, and vegetation contributions (microwave scattering, absorption, and emission). The availability of these coincident estimates reduces the dependence, latency, and uncertainty of external static and dynamic ancillary data, leading to a faster and more robust operational delivery of soil moisture data to the end users;

The boost in revisit frequency compared with SMAP or SMOS will allow CIMR adequate temporal resolution to capture rapid dynamic soil moisture processes previously unattainable by existing L-band sensors. The corresponding CIMR soil moisture retrievals will allow assessments of rapid dry-downs from storm events when much of the drainage and runoff occurs. The daily fidelity of CIMR observations will improve the characterization of soil moisture preconditions and wetting from severe rainfall events, which are key variables affecting soil water storage capacity and flood risk;

The CIMR observations at L-, C- and X-bands enable derivation of vegetation information that 1) can be used for improving the CIMR soil moisture retrieval, and 2) is critical for answering important ecological, eco-hydrological and hydrologic science questions;

CIMR dual polarized L-band measurements, and also C- and X-band measurements, can be used to retrieve vegetation opacity. Vegetation opacity information obtained simultaneously with the soil moisture retrieval can improve the soil moisture retrieval. The microwave vegetation opacity can be related to other important vegetation characteristics such as vegetation water content (VWC) and above-ground biomass;

The CIMR mission will potentially provide enabling observations to improve process understanding, monitoring and model predictions of environmental change. CIMR's multi-frequency observations are sensitive to variations in water content across multiple layers of the vegetation canopy, and in the surface soil. Since different plant components take up and lose water at different rates, they differ in water status at any given time. CIMR’s simultaneous, single-platform measurements would potentially for the first time enable mapping of plant water content variations along the entire soil-plant-atmosphere continuum;

The Multi-layer soil and plant water content retrievals from CIMR would enable major advances in understanding ecosystem responses to water stress, particularly if linked with synergistic canopy structural information from other satellites.
including Lidar or Radar and foliar chemistry and trait information from hyperspectral optical sensors;

- CIMR’s multifrequency capabilities will improve the delineation of freeze-thaw conditions in soil and vegetation, which are key environmental constraints to water mobility and energy and carbon exchange in seasonally frozen environments.
3 CIMR MISSION AIM AND OBJECTIVES

3.1 CIMR Mission Aim

Considering the User needs expressed in [AD-1], [AD-2] and [AD-3] and concisely articulated in the previous sections, the aim of a Copernicus Imaging Microwave Radiometer (CIMR) Mission is to:

*Provide high-spatial resolution microwave imaging radiometry measurements and derived products with global coverage and sub-daily revisit in the Polar regions and adjacent Seas to address Copernicus user needs.*

3.2 CIMR Mission Objectives

Objectives are split into:

- Primary Objectives (PRI-OBJ-XX) that are mandatory for the success of the mission and
- Secondary Objectives (SEC-OBJ-XX) that shall not drive the system design.

Mission requirements are then derived from Mission Objectives. In this context, the primary objectives of the CIMR mission are to:

**PRI-OBJ-1.** Measure **Sea Ice Concentration** (SIC) and **Sea Ice Extent** (SIE) in non-precipitating atmospheres at a spatial resolution of ≤54 km, with a total standard uncertainty of ≤5%57, and **sub-daily coverage** of the Polar Regions6 and daily coverage of Adjacent Seas7 [AD-1], [AD-2] and [AD-3].

**PRI-OBJ-2.** Measure **Sea Surface Temperature** (SST) in non-precipitating atmospheres at an effective spatial resolution of ≤15 km, with a total standard uncertainty of ≤0.28 ±0.1 K with a focus on **sub-daily coverage** of Polar Regions and daily coverage of Adjacent Seas [AD-1], [AD-2] and [AD-3].

**PRI-OBJ-3.** Ensure European **continuity of an AMSR-type capability** in synergy with other missions [AD-2] (e.g. MetOp-SG(B)).

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*54 km spatial resolution is a critical specification.*

*5 Averaged over all seasons.*

*6 See definition of Polar Regions.*

*7 See definition of Adjacent Seas.*

*8 Calculated for a theoretical retrieval as the mode value of daily ocean average discrepancies assuming no uncertainty in the validation data set and varying between 0.15 K to 0.45 K for cold waters.*
The **secondary objectives**\(^9\) of the CIMR mission are to:

**SEC-OBJ-1.** Measure **Sea Surface Temperature** (SST) in non-precipitating atmospheres at an effective **spatial resolution of <15 km**, with a total standard uncertainty of \(\leq 0.210\) K with daily coverage of the **global ocean and inland Seas** [AD-1], [AD-2] and [AD-3].

**SEC-OBJ-2.** Measure **Thin Sea Ice (<0.5 m depth)** in non-precipitating atmospheres and freezing conditions at an effective spatial resolution of <60 km, with a total standard **uncertainty of <20\%**\(^11\) (goal: <10%) with **daily coverage** of the Marginal Ice Zone in the Polar Regions and Adjacent Seas [AD-1], [AD-2] and [AD-3].

**SEC-OBJ-3.** Measure **Sea Ice Drift** in non-precipitating atmospheres at an effective spatial resolution of \(\leq 25\) km with a standard uncertainty of \(3^{12}\) cm s\(^{-1}\) [AD-1], [AD-2] with daily coverage in the Polar Regions and Adjacent Seas [AD-1], [AD-2] and [AD-3].

**SEC-OBJ-4.** Measure **Ice type/Stage of development** in non-precipitating atmospheres and freezing conditions [AD-1], [AD-2] in combination with other satellite data including scatterometer and SAR measurements with daily coverage in the Polar Regions and Adjacent Seas [AD-1], [AD-2] and [AD-3].

**SEC-OBJ-5.** Measure **Snow depth on sea ice** in non-precipitating atmospheres and freezing conditions with an effective spatial resolution of \(\leq 15\) km and standard uncertainty of 10 cm [AD-1], [AD-2] with daily coverage in the Polar Regions and Adjacent Seas [AD-1], [AD-2] and [AD-3].

**SEC-OBJ-6.** Measure terrestrial **Total Snow Area** with an effective spatial resolution of \(\leq 15\) km and standard uncertainty of \(\leq 10\%\) with daily coverage in the Polar Regions and Adjacent Seas [AD-1], [AD-2] and [AD-3].

**SEC-OBJ-7.** Measure terrestrial **Snow Water Equivalent (SWE)** with an effective spatial resolution of \(\leq 15\) km and standard uncertainty of < 40mm with daily coverage in the Polar Regions and Adjacent Seas [AD-1], [AD-2] and [AD-3].

**SEC-OBJ-8.** Measure **Ice Surface Temperature (IST)** in freezing conditions with an effective spatial resolution of \(\leq 15\) km standard uncertainty of 1.0 K [AD-1], [AD-2] and [AD-3] in combination with other satellite data including thermal infrared imagery in the Polar Regions and Adjacent Seas [AD-1], [AD-2] and [AD-3].

---

\(^9\)Secondary objectives shall not drive the system design

\(^10\)Calculated for a theoretical retrieval as the mode value of daily global ocean average discrepancies assuming no uncertainty in the validation data set and varying between 0.15 K to 0.45 K for cold waters.

\(^11\)Assuming uniform, level ice within the footprint. If a mixture of ice types and open water prevail in the footprint the uncertainty is expected to be higher. Kaleschke et al (2016) note that an uncertainty of <30% is possible based on SMOS tSIT measurements although validation remains a challenge using aircraft and in situ data sets.

\(^12\)OSI-SAFS product http://osisaf.met.no/p/ice/index.html#lrdrift. CMEMS also has an all year Sentinel-1 SAR based sea ice drift product at 10 km resolution. This product has gaps in coverage due to missing S1 coverage of some polar regions. The microwave radiometer product has a 62.5 km resolution but complete coverage of 2-day sea-ice drift. The 62.5 km could potentially be improved to 25 km with CIMR.
SEC-OBJ-9. Measure **Sea Surface Salinity (SSS)** over the global ocean from space [AD-3] with a target gridded spatial resolution of 40 km and uncertainty ≤0.3 ppt over monthly time-scales [AD-3].

SEC-OBJ-10. Measure wind speed over ocean, soil moisture, land surface temperature, cloud liquid water over ocean, precipitation over ocean, terrestrial surface water extent.

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13 See definition of sea surface salinity
4 MISSION REQUIREMENTS

Mission requirements are derived from the CIMR mission Objectives. Definitions are presented in Appendix I. Traceability to documented user needs is provided in Appendix-II (Major Policies) and Appendix-III (Requirements Traceability Matrix).

4.1 General Mission Requirements

**MRD-010** The CIMR mission shall embark a conically scanning multi-frequency imaging microwave radiometer payload to measure the brightness temperature of the upwelling microwave radiation at different frequencies.

*Note 1: This is the fundamental CIMR mission payload.*

*Note 2: A conically-scanning microwave radiometer is assumed based on [AD-2] conclusions.*

*Note 3: The payload should be supported by adequate infrastructure to address orbital knowledge requirements.*

Since Copernicus is an operational system, two satellites may be deployed on-orbit at the same time to ensure operational redundancy.

**MRD-020** The CIMR mission shall include one or more identical satellites on orbit.

*Note 1: Following the nomenclature of Copernicus, the first CIMR will be called CIMR-A with subsequent satellites called CIMR-B.*

4.1.1 CIMR Tandem Flight

A key requirement for CIMR is to provide fundamental measurements to support the Integrated European Strategy for the Arctic of which a core pillar is addressing climate change. If a new satellite is added to the CIMR mission resulting in more than one satellite on-orbit at the same time, a tandem flight phase is required to ensure that the calibration of the CIMR series is both understood and homogenised.

A key commitment in the United Nations Framework Convention on Climate Change (UNFCCC) concerns systematic observation and development of data archives related to the climate system. The Global Climate Observing System (GCOS, established 1992) has, on behalf of UNFCCC, established a list of ‘Essential Climate Variables’ (ECVs) that have high impact. In 2006 it identified specific requirements for satellite data products related to these ECVs. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2014) states that “human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented”. The importance of climate change has been recognised by Copernicus and the Copernicus Climate Change Service (C3S) will provide key indicators on climate change drivers to support European adaptation and mitigation policies in a number of sectors (see...
https://climate.copernicus.eu/about-c3s). Other Copernicus services will conduct their own reanalysis activities to provide the best Climate Data Records (CDR under their domains).

As noted by the National Research Council (NRC) of the USA (NRC, 2004) “Validation and overlap of successive satellite missions is critical for developing consistent CDRs over time. Satellite measurements are by their very nature “remote” and thus in situ observations are needed to validate remotely sensed data and monitor sensor degradation, while overlap is needed to reduce satellite biases”.

As stated by the Global Climate Observing System (GCOS, 2016) “Observations remain crucial for monitoring, understanding and predicting the variations and changes of the climate system. They need to be collected over substantial timescales with a high degree of accuracy and consistency to observe directly long-term trends in climate. Informed decisions can only be made on prevention, mitigation, and adaptation strategies based on sustained, local and comparable observations”. GCOS has established a set of Climate Monitoring Principles (GCMP) that is reproduced as Annex-1 to this TN that include dedicated principles for satellite operators and systems. The need to fully understand biases between satellite missions is firmly highlighted in the GCMP most notably:

“Take steps to make radiance calibration, calibration-monitoring and satellite-to-satellite cross-calibration of the full operational constellation a part of the operational satellite system”

and

“A suitable period of overlap for new and old satellite systems should be ensured for a period adequate to determine inter-satellite biases and maintain the homogeneity and consistency of time-series observations”

ESA established its own Climate Change Initiative (CCI) programme in 2006 as a response to the UNFCCC. The aim is to realise the full potential of the long-term global Earth Observation archives that ESA together with its Member states have established over the last thirty years, as a significant and timely contribution to the ECV databases required by the UNFCCC. The ESA CCI has been a significant challenge demanding a significant investment to produce a long-term data record, involving a series of satellites from different Space Agencies, different sensors, each with different performance characteristics, most notably, different spatial and temporal sampling, different time extents, and different stability, but with overlaps and calibrations sufficient to allow the generation of homogeneous and well characterised global products that are accurate and stable enough for climate monitoring.

Finally, EUMETSAT operates a Climate Satellite Application Facility (CM-SAF, http://www.cmsaf.eu/EN/Home/home_node.html). The CM-SAF contributes relevant data sets for climate monitoring and research, improves understanding of the climate system by supporting process studies, climate trend and variability analysis and contributes to the improvement of climate models by providing data sets for validation purposes.

Properly characterising bias between a number of CIMR satellite instruments is critical to the success of GCOS ECV activities and in turn the activities of the Copernicus Climate change Service.
Recognising that, even though CIMR satellites would be identical in design, it is expected that differences in performance of payload instruments will exist due to subtle differences and tolerances of materials, manufacture and pre-flight characterisation. Furthermore, as demonstrated by the very successful Copernicus Sentinel-3 Tandem flight there are enormous benefits to conducting a Tandem flight in terms of in-flight calibrations, calibration and validation activities that will significantly enhance the early application of CIMR data and the mission robustness. Noting the discussion above, it is essential that relative biases between CIMR satellites are properly characterised for CDR construction and the success of the entire CIMR mission.

The main challenge is to reduce uncertainties when comparing data from different CIMR satellite missions that form a time series. When data are obtained from two satellites at different times but at the same location, there is significant correlated uncertainty:

- Uncertainty due to ocean geophysical space and time variability that complicates inter-comparison, especially in regions dominated by mesoscale structure (1-10 days, <10-50 km), which are particularly lucrative to understand inter-satellite bias;
- Uncertainty due to atmospheric space and time variability.

Both issues introduce uncertainty to the direct inter-calibration of CIMR instruments.

However, if a new satellite is added to the CIMR mission resulting in more than one satellite on-orbit at the same time, by flying CIMR satellites in tandem separated by ~30-60s seconds on the same ground track the correlation between these uncertainties is maximized so that for all practical purposes they can be ignored: the difference between two satellite measurements is solely due to instrumental aspects. Thus, when appropriate, information learned from the commissioning and calibration of one satellite may be transferred to a second with confidence.

**MRD-030** If a new satellite is added to the CIMR mission resulting in more than one satellite on-orbit at the same time, a tandem flight, composed of a drift phase towards a tandem configuration, followed by a tandem phase and completed by a last drift phase towards a nominal operational position, shall be flown as soon as practically possible.

*Note 1: This implies that the tandem phase is flown during the Phase E1 commissioning and PDGS ramp-up phase activities.*

*Note 2: For example, Sentinel-3 has implemented a highly successful Tandem phase. Sentinel-6 will conduct a 12 month Tandem phase building on the previous heritage of the Jason missions.*

**MRD-040** The separation of CIMR satellites if configured in a tandem phase shall be nominally 30 (TBC) seconds or shorter.

*Note 1: The shortest possible separation mitigates the uncertainty due to ocean geophysical space and time variability that complicates inter-comparison and inter-satellite bias; and uncertainty due to atmospheric space and time variability.*

**MRD-050** Detected.
MRD-060 Drift between satellite separation can be tolerated up to a maximum separation between the satellites of 60 (TBC) seconds. Knowledge of the separation drift is required.

An optimal duration for a tandem flight is 12 months as requested by GCOS (2016) and required by the European Integrated Policy for the Arctic (climate pillar). However, for a satellite system observing both the north and south hemisphere (and therefore a holistic view of seasonal aspects) a 6-month duration is appropriate. This excludes the additional time required for the satellite to drift towards the tandem position and towards a nominal phasing position ($180^\circ$) after the tandem phase.

MRD-070 The duration of a CIMR tandem phase shall be a minimum of 6 (TBC) months from the point at which a Tandem flight configuration is reached.

*Note 1:* Ideally a 12 month tandem phase would allow a full analysis of seasonal uncertainties at a global level as requested by GCOS (2016) and the Integrated European Policy for the Arctic (climate pillar).

*Note 2:* A 6-month tandem phase is considered a minimum duration based on the assumption that uncertainties can be identified over a full seasonal cycle by using north and south hemisphere measurements.

MRD-080 There is no requirement for near real time data feeds from the satellite being commissioned. However, data shall be made available to commissioning teams from both satellites operating in Tandem.

*Note 1:* There are no commitments to Copernicus user services during Phase E-1.

MRD-090 The existing on-orbit satellite shall maintain normal operations throughout a tandem phase (i.e. any manoeuvres for maintaining a tandem configuration shall be performed by the new units).

*Note 1:* Normal operations are required by operational satellites during the Tandem phase.

MRD-100 Data shall be acquired continuously in normal acquisition mode from all payload instruments on all satellites throughout the Tandem mission. It is anticipated that new CIMR satellite commissioning activities and on-orbit CIMR manoeuvres may occur and these shall take precedence over Tandem operations.

*Note 1:* The principle is to assemble a dataset for analysis and establish differences between CIMR instruments that can be used to inter-calibrate CIMR measurements. This is best achieved by maintaining normal operations.

*Note 2:* The data collected will be used to transfer calibration and characterisation data collected by operational satellite(s) and using that information to understand
4.1.2 Orbit Requirements

The orbit of CIMR is to be placed in a dawn-dusk orbit. This orbit will minimise daily eclipse periods to mitigate the impact of thermoelastic distortion, maximise power generation and minimise the complexity and size of the solar array. Bearing in mind the strong desire to fly in synergy with MetOp-SG(B) and MetOp-SG(A) take full advantage the SCA, MWI, ICI, 3MI and MetImage instruments, the orbit characteristics of CIMR are chosen to maximise the colocation between CIMR measurements and MetOp-SG(B) within ±10 minutes in the polar regions. In this configuration:

- SST measurements will return an estimate the Sea Surface Foundation Temperature (pre-dawn) for a large portion of the Earth ocean surface. This is preferred by Numerical Weather and Ocean Prediction centres. Should a JAXA AMSR3 instrument fly (potentially in a ~13:00 orbit), CIMR and AMSR3 would be highly complementary in terms of sampling the Diurnal Cycle of SST although the reduced spatial resolution of AMSR would limit its utility in the proximity of coastal regions and inland Seas.

- L-band measurements from SMOS and SMAP are made in a dawn-dusk 06:00/18:00 orbit when Total Electron Content (TEC) is minimal. CIMR will provide continuity of this orbit. In addition, sun-glint over the ocean would also be minimized for better SSS retrieval and would also satisfy some tertiary soil moisture applications (e.g. aid in determining the presence of dew on crop canopy).

- Over 25 years, a large range of geophysical products are derived from the SSMI / SSMIS collection using frequencies that are also available on CIMR. These instruments have a 06:00 / 18:00 orbit. CIMR will provide continuity of this orbit.

MRD-110 The CIMR reference orbit shall be:

<table>
<thead>
<tr>
<th>CIMR reference orbit definition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeat cycle</td>
<td>29 days</td>
</tr>
<tr>
<td>Cycle Length</td>
<td>412 Orbits</td>
</tr>
<tr>
<td>Inclination</td>
<td>Sun-synchronous</td>
</tr>
<tr>
<td>MLST at descending node</td>
<td>6 h 00 min ±10 min</td>
</tr>
<tr>
<td>Eccentricity vector</td>
<td>Frozen</td>
</tr>
<tr>
<td>Longitude of 1st Ascending node</td>
<td>Same as MetOp-SG(B) see note 2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CIMR Mean Keplerian Parameters (ToD)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis</td>
<td>7195.605 km</td>
</tr>
</tbody>
</table>
### Eccentricity
0.0011441

### Inclination
98.702°

### Arg. Of Perigee
90°

### MLST at descending node
6h 00 min ±10 min

### Longitude of 1st Ascending node
Same as MetOp-SG(B) see note 2

---

**Note 1:** For information, the corresponding mean Keplerian parameters in the True of Date reference system are provided. The calculation of these parameters depends on the model used to derive the orbit that fulfils the orbit definition stated above. However, these differences should not exceed a few (tens) meters.

**Note 2:** The current MetOp-SG(B) longitude of the ascending node of the first ground track at equator is 0° E.

### MRD-120
If a new satellite is added to the CIMR mission resulting in more than one satellite on-orbit at the same time it shall occupy the same orbit placed 180° out of phase (TBD) to the on-orbit satellite to maximise coverage and revisit.

### MRD-130
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., onset, variation in intensity and vertical position of precipitation; movement of atmospheric field/clouds/rain-bands at 14 m/s corresponds to ~5 km and is possible in that time). But (i) the implications for primary products are small, (ii) background knowledge of atmospheric flow can inform algorithms to help mitigate impact on products, and (iii) potentially contaminated data for which mitigation algorithms are inadequate must be flagged.

**Note 3:** By flying in synergy with MetOp-SG (B) co-located and near-contemporaneous measurements from MWI channels at frequencies >10.65 GHz MetOp MWI data provide a means to satisfy an AMSR-2-like capability and augment CIMR data products. This implies that implementation of similar bands and channels on CIMR may not be required except for improved spatial resolution and/or redundancy. Relevant MWI bands for the CIMR “mission” are summarised in Table MRD-1 that together with the proposed CIMR “instrument” bands specified in Table MRD-2.

**Note 4:** There is no obligation to manage detailed spacecraft operations that maintain a strict separation or follow all maneuvers of either spacecraft if properly defined orbit control boxes are specified.
Note 5: MetOp-SG(1B) SCA scatterometer data are extremely valuable to independently verify the ocean surface roughness from CIMR data, for sea ice type classification and SIC melt pond detection amongst other applications in synergy with CIMR.

Note 6: The instrument suite of MetOp-SG (1A) provides a powerful means to validate SIC, SST and other products in cloud free conditions using independent data as well as input to geophysical retrieval algorithms e.g. IST.

---

**MRD-140**  
The CIMR ground track shall be maintained to be within ±2.0 km of the reference ground track at the pole defined at the sub-satellite point at nadir.

*Note 1:* This requirement is used to ensure MRD-070 “no hole at the Pole” is always met.  
*Note 2:* The reference ground track of CIMR is the same as MetOp-SG(B).  
*Note 3:* The meaning is that CIMR will remain within a corridor of 2.0 km either side of the nominal ground track of MetOp-SG(B).  
*Note 4:* See also MRD-070.

---

**MRD-150**  
The CIMR ground track shall be maintained to be within ±5.0 km of the reference ground track at the equator defined at the sub-satellite point at nadir.

*Note 1:* This requirement is used to minimise the differences view geometry between MetOp-SG(B) and CIMR.  
*Note 2:* MetOp-SG(B) has a requirement of ±5.0 km over the whole orbit which means that the maximum across track distance between geometries (with respect to the sub-satellite point) can be up to 10 km.  
*Note 3:* This requirement controls the along track variation of CIMR with respect to the reference orbit that is relevant to the implementation of MRD-030.

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**MRD-160**  
Orbital manoeuvres shall not result in data loss for the primary mission objectives.

*Note 1:* As the CIMR mission is focused on ocean and sea ice applications, where feasible, all orbital manoeuvres should ideally take place over land surfaces.  
*Note 2:* Large lakes where the largest distance to land exceeds 25 km are an exception to this requirement and include the following Lakes: Caspian sea, lake Victoria, lake Superior, lake Huron, lake Michigan, lake Ladoga, Garabogazkol basin, Aral sea, lake Erie, Great Slave lake, lake Winnipeg, Great Bear lake, lake Ontario, lake Malawi/Nyasa/Niassa, lake Tanganyika, lake Baykal/Baikal, Ozero Khanka, Uvs lake, Issyk Kul, lago Mar Chiquita, lake Balqhash and lake Onega.  
*Note 3:* See also MRD-110.

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### 4.1.3 Coverage Requirements.

Complete mapping of the Earth surface is required with a focus on Polar Regions which implies a wide swath.
MRD-170  CIMR shall have a swath width that is >1900 km.

*Note 1: A large swath width optimises coverage and revisit specified by MRD-070, MRD-080 and MRD-090.*

---

MRD-180  The CIMR mission shall provide contiguous and complete (i.e. no “hole at the poles”) coverage of the Polar Regions by all channels [AD-2].

*Note 1: This is a strong requirement that acknowledges a primary focus of the CIMR mission on the Polar Regions.*

*Note 2: See definition of “Polar Regions”.*

*Note 3: Even if the focus of the CIMR mission is focused on the Arctic, measurements must be provided in the Antarctic region with the same characteristics [AD-2].*

---

MRD-190  The CIMR mission shall be capable of >95% global coverage [AD-3] of all Earth surfaces every day using a single satellite and complete coverage in ≤2 days.

*Note 1: This requirement excludes outages for spacecraft manoeuvres.*

*Note 2: Given the constraint of the OZA (MRD-160) it is anticipated that a large swath is provided by CIMR (MRD-060) resulting in ~95% global coverage per day using one satellite.*

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![Polar coverage of CIMR (Arctic)](image1)

![Coverage of CIMR (global)](image2)

Figure MRD-4.1.2.1. Example plots showing a simulation of the expected CIMR global coverage and over the Arctic using a single satellite highlighting the number of revisits each day with no hole at the pole. Daily coverage of the Copernicus Imaging Microwave Radiometer mission in the Arctic regions. The colormap shows the number of revisit overpasses in a 24 hours period. The CIMR mission is specifically designed to ensure sub-daily coverage in all the Arctic region. Particularly, CIMR will achieve full sub-daily coverage of the Arctic region (i.e. "no hole at the pole" requirement). By symmetry, the coverage is also excellent in the Antarctic region. Over 95% of the globe will be covered on a daily basis (Lavergne, T., Pinol Sole, M. and Donlon, C.: Daily coverage of CIMR (Arctic, Antarctic, and Global views), figshare, doi:10.6084/m9.figshare.7749284.v1, 2019).
4.1.4 Temporal Resolution (Revisit) Requirements

MRD-200 The CIMR mission shall provide daily revisit of the Polar Regions and Adjacent Seas [AD-2].

*Note 1:* Daily revisit is a primary requirement.
*Note 2:* See definition of “Polar Regions” and “Adjacent Seas”.

MRD-210 The CIMR mission shall be capable of sub-daily revisit of the Polar Regions [AD-2] >55°N and >55°S latitude.

*Note 1:* See definition of “Polar Regions”.
*Note 2:* Sub-daily implies at least two measurements are available in a 24-hour period.

4.2 Level-1 Observation Requirements

4.2.1 General Requirements

MRD-220 The CIMR mission shall continuously acquire measurement data in all channels over all Earth surfaces except during spacecraft manoeuvres.

*Note 1:* This requirement implies that the instrument provides a “carpet mapping” approach.

MRD-230 On-board calibration measurements shall be used to maintain the calibration of all CIMR channels within requirements at any time during measurement operations.

*Note 1:* This requirement is to ensure full calibration of CIMR measurement data at all times.
*Note 2:* The calibration of the CIMR radiometer will drift as the instrument temperature drifts around the orbit.
*Note 3:* The task is to design a radiometer that does not change temperature rapidly (e.g. with appropriate thermal design) and then to acquire sufficient calibration data from calibration reference measurements that are able to account for calibration drift.
*Note 4:* As calibration measurements are inherently noisy, sufficient measurements are required to obtain a smooth estimate of the calibration gain and offset (e.g. every scan).
4.2.2 Frequency Band Requirements

The choice of CIMR frequency bands is based on the following criteria:

1. Frequency sensitivity to geophysical parameters of interest,
2. Historical perspective (continuity of measurement for the climate record),
3. Technical feasibility,
4. ITU regulatory framework.

Wilheit (1978) analysed the sensitivity of microwave emissivity of open seawater to a variety of geophysical variables including sea surface temperature, atmospheric water vapour, wind speed, and salinity as a function of frequency (as shown in figure MRD-4.2.2.1).

The frequency allocations to the Earth Exploration Satellite Service (EESS) passive are defined in Article 5 of the International Telecommunications Union (ITU) Radio Regulations (RR) (ITU, 2016). For the allocation of frequencies the world has been divided into three Regions and specific regulations and allocations apply to each: as Earth Observation is global, the regulations for all Regions (i.e. worldwide) must be considered. In bands used for satellite passive remote sensing, the required minimum availability of sensor data for each band, and the permissible interference level is defined in Recommendation ITU-R RS.2017. “Active Services” are defined in ITU Radio Regulations Article 5 (ITU, 2016) operating either in adjacent bands or in the same band as
EESS(passive) allocations must comply with the regulatory constraints of the RR. Cases of harmful interference to passive sensors have to be reported for resolution by the Administration responsible for the active station causing the RFI (See Recommendation ITU-R RS.2106). ITU RR indicate that the receivers should use equipment with appropriate selectivity (RR No 3.12), and this is particularly important for passive sensors in order to increase robustness against active services operating in adjacent bands. CIMR must be able to detect data polluted by RFI and take steps taken to mitigate their impact. The selectivity of CIMR channels within EESS(passive) bands shall consider the RFI environment, as otherwise it may result in undesirable increased risk of Radio Frequency Interference from adjacent bands. It is important to note that when using for passive sensing frequency bands with no allocation to the EESS(passive), implies that no protection can be claimed from potential interferers. Figure MRD-4.2.2.1 shows the EESS Passive and Active frequency allocations showing the location of proposed CIMR bands.

The fundamental characteristics of CIMR bands are set out in Table MRD-2:

**Table MRD-2. Band specifications for CIMR instrument – see specific numbered requirements for detailed specifications.**

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mission Priority</td>
<td>Addressing CIMR Objectives</td>
<td>ITU EESS (passive) allocated band and band centre frequency (MHz)</td>
<td>Channel centre frequency [GHz]</td>
<td>Maximum channel bandwidth [MHz]</td>
<td>Footprint Size [km] (see definition)</td>
<td>Radiometric resolution [K] NEΔT for zero mean, 1-sigma at 150 K</td>
<td>Dynamic Range [K]</td>
</tr>
<tr>
<td>ID-080-1-1</td>
<td>Mission Priority</td>
<td>All</td>
<td>1.4 ~ 1.427</td>
<td>1.4135</td>
<td>1.4135</td>
<td>27</td>
<td>≤0.3</td>
<td></td>
</tr>
<tr>
<td>ID-080-1-14</td>
<td>(MRD-250)</td>
<td>Primary</td>
<td>6.425 ~ 7.250</td>
<td>6.8375</td>
<td>6.925</td>
<td>825 15</td>
<td>≤0.2</td>
<td></td>
</tr>
<tr>
<td>ID-080-1-2</td>
<td>(MRD-240)</td>
<td>Primary</td>
<td>10.6 ~ 10.7</td>
<td>10.65</td>
<td>10.65</td>
<td>100</td>
<td>≤0.3</td>
<td></td>
</tr>
<tr>
<td>ID-080-1-3</td>
<td>(MRD-380)</td>
<td>Primary</td>
<td>18.6 ~ 18.8</td>
<td>18.7</td>
<td>18.7</td>
<td>200</td>
<td>≤0.4</td>
<td></td>
</tr>
<tr>
<td>ID-080-1-4</td>
<td>(MRD-300)</td>
<td>Primary</td>
<td>36.5</td>
<td>36.5</td>
<td>1000</td>
<td>&lt;5 (goal=4)</td>
<td>≤0.7</td>
<td></td>
</tr>
<tr>
<td>ID-080-1-5</td>
<td>(MRD-420)</td>
<td>Primary</td>
<td>36-37</td>
<td>36-37</td>
<td>&lt;60 16</td>
<td>≤5-5</td>
<td>Kmin=2.7, Kmax=340</td>
<td></td>
</tr>
<tr>
<td>ID-080-1-6</td>
<td>(MRD-430)</td>
<td>Primary</td>
<td>ALL</td>
<td>ALL</td>
<td>≤15</td>
<td>≤5 (goal=4)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

14 The channel center frequency is not necessarily the same as the ITU EESS (passive) allocated band centre frequency.

15 ITU RR footnote No.5458 indicates that when planning future active systems, the Administrations “should bear in mind” the needs of EESS(passive) in the band 6.425 to 7.250 GHz (6.8375 GHz centre frequency, 825 MHz bandwidth). For the band 6.425-7.075 GHz (650 MHz), this footnote indicates that “passive microwave sensors measurements are carried out over the oceans” and for the band 7.075-7.250 GHz (175 MHz) the remote sensing measurements acknowledged in general. Use of this full bandwidth may bring advantages for radiometric accuracy.

16 While the native 1.4135 GHz channel footprint is <60 km, 40 km gridded L2 products shall be produced.
ID-080-1-7 (MRD-440, MRD-450, MRD-460)  | Radiometric Total Standard Uncertainty\(^7\) [K, zero mean, 1-sigma]) | ≤0.5 | ≤0.5 (goal ≤0.4) | ≤0.5 (goal: ≤0.45) | ≤0.6 (goal: ≤0.5) | ≤0.8
---|---|---|---|---|---|---
ID-080-1-8 (MRD-550, MRD-560, MRD-570)  | Polarisation | Acquisition in Vertical and Horizontal with provision of Full Stokes based on computation.
ID-080-1-9 (MRD-170)  | Swath width [km] | >1900
ID-080-1-10 (MRD-270)  | Observation Zenith Angle [deg] | 55.0 ±1.5
ID-080-1-11 (MRD-470)  | Radiometric stability over lifetime [K, zero mean, 1-sigma] | ≤0.2 | ≤0.2 | ≤0.2 | ≤0.2 | ≤0.2
ID-080-1-12 (MRD-480, MRD-490)  | Radiometric stability over orbit [K, zero mean, 1-sigma] | ≤0.2 | ≤0.15 (goal=0.1) | ≤0.15 (goal=0.1) | ≤0.2 | ≤0.2
ID-090-1-13 (MRD-520)  | Geolocation uncertainty [km] | ≤1/10 of the footprint size
Application (SIC = Sea Ice Concentration, SST = Sea Surface Temperature, SIT = Sea Ice thickness, SSS = Sea Surface Salinity, WS = Wind speed, TWV = Total Water Vapour, TCWV = Total Cloud-liquid Water Vapour, SD = Snow Depth, SM = Soil Moisture, SWE = Snow Water Equivalent, SID = Sea Ice Drift, PCP = precipitation)  | SIT, SIC, SSS, WS, SM, SD | SIC, SST, SIT, WS, SID, SM, SD | SST, PCP, WS, SD, SM | TWV, TCWV, PCP, SIC, SD, SM, SID | SIC, SST, TWV, TCWV, PCP, SIC, SWE, SD

MRD-240 The CIMR mission shall measure top of the atmosphere brightness temperature using channels centred on frequencies specified in Table MRD-2 ID-080-1-2.

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**Note 1:** Thus, there are a minimum of two CIMR instrument measurement channels (H and V) for each CIMR instrument band e.g. 18.7V and 18.7H and four computed outputs that are available on ground corresponding to the full Stoke Vector.

**Note 2:** See MRD-550 that requests the provision of Full Stokes Vector outputs (e.g. as part of on-board radio-frequency interference processing) as these measurements can be used to support L2 retrievals (e.g. Faraday rotation correction, wind vector measurements). Provision of HV and VH outputs must not drive the mission design.

**Note 3:** An optimal combination of channels is needed for operational and climate SIC SIE, and SST L2 algorithms that use different combinations of channels to derive a product.

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\(^7\) For CIMR Absolute Radiometric Accuracy (ARA) is not used in the traditional manner but instead we calculate the Total Standard Uncertainty (which is a “zero mean, 1-sigma” total uncertainty). It is noted that this approach, while consistent with international agreements on uncertainty specification (JCGM, 2008), is different compared to other formulations (e.g. as for the MetOp-SG(B) MWI) that do not include NEΔT as part of the absolute radiometric accuracy definition.
Note 4: MetOp-SG (B) MWI alone does not provide low frequency channels, nor a sufficient spatial resolution in the channels it carries to address all CIMR objectives (see Table MRD-1).

Note 5: The 7.3 GHz band of AMSR-2 was introduced for radio frequency interference (RFI) mitigation. MWI has on-board RFI mitigation technologies that could also be used by the CIMR instrument: therefore, this channel is not included.

Note 6: The 1.415 GHz band is required to satisfy CIMR secondary mission objectives (notably thin sea ice thickness, sea surface salinity and other products for Copernicus Services) but should not drive the instrument design. As an additional benefit, this band will allow sea surface salinity and soil moisture measurements to be retrieved.

Note 7: The 36.5 GHz channel is required for SIC and SST algorithms and in addition TWV, TCWV, PCP, SIC, SWE, SD. This was confirmed at the CIMR MAG #01, ESTEC, April 12-13th 2018.

Note 8: A goal for the 36.5 GHz channel is a footprint size of 4 km. This was confirmed at the CIMR MAG #01, ESTEC, April 12-13th 2018.

Note 9: Recent experience with L-band measurements of extreme wind speed over the ocean has been shown to be extremely useful to oceanographic and atmospheric forecasting systems/teams (e.g. Reul et al. 2012b; Meissner et al., 2017) providing an additional benefit.

Note 10: A recent study on Arctic sea ice signatures strongly recommends the assimilation of microwave radiometer measurements from 6 to 37 GHz simultaneously with 1.415 GHz to constrain fractional sea ice coverage and thickness consistently at the same time (Richer et al. 2018).

Note 11: See figure MRD 4.2.2.1.

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MRD-250 The CIMR mission shall be compliant with the ITU Radio Regulations for the EESS (passive) service as specified in Table MRD-2 ID-080-1-14.

Note 1: “Passive Services” are defined in ITU Radio Regulations Article 5 (ITU, 2016).

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MRD-260 All CIMR channels shall include protective measures for unwanted RFI emissions from active services allocated in adjacent bands.

Note 1: “Active Services” are defined in ITU Radio Regulations Article 5 (ITU, 2016).

Note 2: This requirement acknowledges that the use of the full bandwidth allocated to the EESS (passive) as defined by ITU Radio Regulations (ITU, 2016) for a given channel results in increased risk of Radio Frequency Interference from active services operating adjacent bands. In case of poor channel selectivity, CIMR will not be able to claim protection from the active services even in the case of having EESS (passive) a primary allocation in the band.
4.2.3 Observation Zenith Angle Requirements

Using a high OZA also increases the swath width and therefore allows coverage and revisit requirements to be improved. However, the price to pay is that there is reduction of spatial resolution at higher OZA: resolution is decreased by ~2%/°OZA in the 50-55° range for an orbit similar to MetOp-SG. At C-band the sensitivity of the surface TB (assuming V-pol) to SST increases with OZA. At the same time, the sensitivity to wind speed of the V-pol (which acts as a noise source) decreases with increasing OZA. Ignoring secondary issues related to small increases in atmospheric path length, this favours a large OZA. This is also true for SSS. For high wind conditions (L-band, C-band), H-pol data are preferred in the retrieval and the sensitivity is also larger at high OZA.

For comparison, the OZA of AMSR-2 and AMSRE is 55°, for SSMI it is 53° and for WindSat at 18 GHz it is 55.6°. For CMIS (one of the proposed payloads for NPOESS although not developed) an OZA of 58.13° was proposed for one of the channels. A higher OZA is preferred from a radiative transfer modelling point of view as it increases sensitivity and thus reduces retrieval error.

MRD-270 All CIMR imaging microwave radiometer measurements shall view the surface of the Earth at a constant observation zenith angle of 55°±1.5° consistent with ID-080-1-10 in Table MRD-2.

Note 1: Accurate knowledge of the Observation Zenith angle (OZA) is required for accurate determination of surface emissivity and retrieval of geophysical products – see Wentz and Meissner, 2000; 2007 and Meissner and Wentz, 2012.
Note 2: An OZA of \( -55^\circ \) is required to prevent a hole at the pole (MRD-070) while minimizing the size of measurement footprint size.

Note 3: Emissivity of the target source is a function of OZA, band frequency and channel polarisation. It is influenced by surface properties (e.g. wind induced isotropic roughness (waves, capillary diffraction waves, foam, ice/snow surface properties) and by subsurface properties (dielectric coefficient and scatter-size of the target material).

Note 4: For an increasingly rough sea surface, microwave emission increases and polarization differences decrease. At OZA > 55° and a rough sea surface, the vertical polarisation emission begins to decrease. See Wentz and Meissner, 2000; 2007 and Meissner and Wentz, 2012.

Note 5: The OZA may vary from band to band depending on the feed horn accommodation hence a tolerance of \( \pm 1.5^\circ \) is provided.

Note 6: The allocation of the OZA to the feed horn/antenna design should consider high beam efficiency. The nominal OZA should be designed for average distance from spacecraft to ground.

Note 7: Knowledge of the OZA around the orbit is required for L2 algorithms as specified by geo-location requirements (Section 4.2.16).

Note 8: The OZA has implications for the spatial resolution by about 2.0 - 2.5% per deg. around 53° assuming a MetOp-SG orbit.

Note 9: For sea ice concentration mapping the V and H polarization difference is important for both ice and water. The H and V polarisation difference is a function of OZA.

4.2.4 CIMR Scanning Requirements

CIMR shall provide continuous measurements along the scan arc in the flight direction (“forward scan”) and along the scan arc in the opposite direction (“backward scan”).

Note 1: Assuming a satellite altitude of 820 km, with OZA=55°, the forward and backward views along the satellite ground track are separated by ~1880 km. Assuming a satellite velocity of 7.2 km/s, the time separation between each view of the surface is ~260s. During this time, the surface conditions of either the SIC at 5 km resolution or SST at <15 km resolution are not expected to change significantly. However, the atmosphere may change from a non-precipitating to a precipitating state.

Note 2: It is assumed that two measurement scan arcs will be necessary to allow for accommodation of calibration data acquisition and potential blinding by the spacecraft solar array.

Note 3: Using both a forward and a backward view of the same scene separated by ~260 s it is expected that significant noise reduction of up to 29% (factor of \( 1/\sqrt{2} \)) could be gained in L2 data processing by using two views of the same area. This applies to geophysical products where the state change in ~260s is negligible which includes SST and sea ice concentration in non-precipitating atmospheric conditions.

Note 4: For some circumstances where surface characteristics have view angle dependence (e.g. roughness, scattering) independent information may be retrievable from each view. For example, the dual view can also help recover from Sun glint effects.
Note 5: For some secondary variables, particularly precipitation, the state and location can change in a non-negligible manner in ~260s at CIMR channel resolutions. In such cases, having two views provides two temporal samples, improving robustness of measurements.

Note 6: See Figure MRD-4.2.4 that provides a schematic overview of the OZA.

Figure MRD-4.2.4 Schematic overview of CIMR scanning approach and geometry (Donlon, Craig; Vanin, Felice (2019): Scanning Geometry of the CIMR instrument. Figshare https://doi.org/10.6084/m9.figshare.7749398.v1)

MRD-290 Forward scan and backward scan measurements shall be provided as separate data image arrays within the same L1b product.

Note 1: This requirement allows data from each view to be treated independently from the other during ground processing and facilitates the use of data by standard image processing tools.

Note 2: It is expected that while forward scan and backward scan measurements are separate, they will be provided in a single L1b data product (i.e. as separate image arrays).

4.2.5 Spatial Resolution Requirements

A number of measurement samples (see MRD-230) are acquired as the CIMR antenna pattern projected to the ground (the Footprint or Instantaneous Field of View, IFoV) scans across the swath and the satellite flies forward for the duration of the integration time. The ability of each measurement to resolve features on the ground is linked to the -3dB half-power beam width.
As the antenna scans the, IFoV (footprint) is ‘smeared’ over an area leading to an *Effective Field Of View (eFoV)* for that sample. The spatial resolution of a CIMR *measurement at L1b* corresponds to the combination of all samples at L1b. To provide flexibility of processing by different applications (e.g. smaller EFoV for SIC discrimination), the L1b product also contains all samples and the L1b measurement that combines all samples to reach performance requirements as specified in Table MRD-2.

![Diagram showing how CIMR samples a scene using Ka band as an example.](image)

Figure MRD-4.2.5-1 Schematic diagram showing how CIMR samples a scene using Ka band as an example. Lower part highlights how the time integrated power from the footprint ellipse is a function of the distance along scan. The half power beam width provides the spatial resolution for a L1b a measurement.

For comparison, Figure MRD-4.2.5.2 compares the CIMR IFoV footprint size to the MetOp-SG(B) MWI, GCOM-W AMSR2, ESA SMOS (L-band only) and NASA SMAP (L-band only) missions. It must be recalled that SMOS has a range of spatial resolution 35 to 60 km depending on the position of the pixel (incidence angle) in question. SMAP (following the same definition of spatial resolution as CIMR) has a constant instantaneous spatial resolution of ~41 km (-3dB footprint is 36 x 47 km). CIMR has a constant resolution of <60 km but will provide L-band products (after data processing) at 40 km spatial resolution by exploiting the large oversampling characteristics of this channel.
Figure MRD-4.2.5-2. Illustration of the frequency channels of the CIMR mission, and their targeted spatial resolutions. CIMR is also compared to two other similar Passive Microwave Radiometers (PMR): the Japanese AMSR2 in orbit since 2012, and the MWI to fly on-board the European EPS-SG satellites from ~2023 (MWI-SG). SMOS has a variable footprint resolution depending on the OZA shown in white starting as close to circular and increasing as an ellipse at higher OZA (Lavergne, Thomas (2019): CIMR compared to other PMRs: Channels and Spatial resolution. Figshare. https://doi.org/10.6084/m9.figshare.7177730.v1)

MRD-300 The spatial resolution of a CIMR measurement at L1b shall comply with ID-080-1-4 in Table MRD-2 and is computed by combining a number of measurement samples (specified in MRD-340) acquired during the measurement integration time.

Note 1: The spatial resolution of a CIMR measurement at L1b is translated for implementation into the footprint size that considers the instantaneous field of view and the natural behaviour of the instrument (smearing) -see Figure MRD-4.2.5.1.

Note 2: This implies a high-resolution instrument real aperture instantaneous field of view with low side-lobe characteristics (i.e. good beam formation) and measurement oversampling.

Note 3: See MRD-200 - in addition to the L1b measurement, L1b products will include all measurement samples made during a measurement integration time according to MRD-340.

Note 4: See definition of footprint size.

Note 5: See definition of integration time.

Note 6: It is anticipated that resampling/gridding techniques will be employed in L2 processing to achieve an L-band gridded spatial resolution of < 50 km (goal: 40 km, commensurate with SMOS/SMAP) in all L2 and higher products.
Note 7: Other CIMR channels may be used in synergy with the L-band channel to sharpen geophysical products at L2.

MRD-310 L1b products shall include all measurement samples acquired during a measurement integration time according to MRD-340.

Note 1: In addition to the L1b measurement (computed over the full integration time), L1b products should include all measurement samples made during a measurement integration time according to MRD-340.

Note 2: In applications over complex terrain (e.g. SIC determination in the marginal ice zone), users may work with samples that have a higher noise but smaller EFoV.

4.2.6 Sampling Requirements

The footprint size of each CIMR frequency band is different (limited to first order by the size of the antenna reflector). In addition, the Earth location of a footprint centre for each frequency corresponding to the same sample time and scan number may differ by several km (depending on the final location of individual feed horns on the focal plane that necessarily have a slightly different focus on the rotating reflector). The effective spatial resolution of a footprint is determined by the antenna gain pattern and the measurement integration period. The antenna pattern acts as a non-ideal low-pass spatial filter of the surface brightness distribution, limiting the primary surface contribution to the observed radiance to approximately 3-dB beam width, although the measured value includes contributions from the much larger wide-beam and full beam patterns (Long, 2016).

The antenna gain pattern is particularly important for the construction of L1b measurement data as it is used to compensate for unwanted but significant contributions from outside the main -3dB footprint measurements. L1b processing typically starts from L1a data products, remains in instrument geometry and includes amongst other aspects):

- Application of all calibration data;
- Removal of feed horn spill-over effects;
- Removal of antenna reflector self-emission;
- Removal of cross-polarised contamination;
- Correction for OZA variation around the orbit;
- Removal of other contributions (e.g. from the instrument structure or cold space);
- Removal of antenna shape aspects (e.g. grating lobe contributions caused by reflector faceting effects if present);
- Removal of sidelobe contributions from the antenna pattern;
- Computation of geolocation parameters for each measurement;
- Computation of fractional land area inside the main lobe for each measurement;
- Computation of standard total uncertainty for each measurement.
Accurate characterisation of the antenna gain pattern (e.g. including side-lobe and grating lobe patterns if present) for each channel is required by the application community.

**MRD-320** Fully characterised antenna gain pattern data shall be determined for each channel and each feed and provided to all users.

*Note 1: This information is fundamental for the proper production of L1b measurement data from L1a data.*

*Note 2: Users may choose to apply different methods to L1b data product production depending on the specific application.*

*Note 3: This information is derived from on-ground characterisation.*

**MRD-330** The antenna gain pattern outside of the wide beam shall be characterised and all significant lobes (e.g. side-lobes, grating lobes) shall be known.

*Note 1: This information is fundamental for the proper production of L1b measurement data from L1a data because the energy from side lobe locations must be: (1) determined from the CIMR measurements and (2) used in a correction algorithm to adjust the calculated brightness temperature to compensate for these additional out of field radiance sources.*

*Note 3: For MetOp-(SG) MWI significant side lobes equated to those with a power greater than -60 dBc.*

*Note 4: See MRD-430, MRD-440, MRD-450, MRD-460 and MRD-470 where this information is applied in L1b processing.*

In a conically scanning radiometer design, the antenna is scanning during the integration period, and the effective antenna gain is a smeared version of the antenna pattern. The performance of the CIMR mission TOA radiances for each channel footprint requires an excellent Antenna Pattern Correction (APC) - including significant lobe contributions outside the main beam - to meet Mission Requirements in terms of spatial resolution and radiometry at L1b.

It should also be noted that, for a conically scanning radiometer, the spacing between each scan will vary around the orbit due to *(Ashcroft and Wentz, 2000):*

- The elliptical satellite orbit will cause variations in the inter-scan distance.
- The oblateness of the Earth superimposes further variations with a relative phase determined by the orientation of the major axis of the satellite orbit relative to the Earth axis.
- The inter-scan distance is generally greater when measured at the centre of the swath in the flight direction compared to at the edges where multiple scans overlap.
- Earth rotation causes an asymmetry between the inter-scan distance measured at the first observation of each scan, and that measured at the last observation of each scan.
Antenna pattern matching algorithms are used to transform native L1a/B swath to L1R re-gridded products that demand a trade-off between noise, spatial and temporal resolution (e.g. Long, 2016). Conventional “drop-in-the-bucket” (DIB) approaches result in low-noise low-resolution products (Long, 2016). For higher resolution products (with potentially higher noise) image reconstruction techniques such as Backus–Gilbert (Backus and Gilbert, 1967; 1968) or the less computationally intensive radiometer form of the Scatterometer Image Reconstruction (SIR) algorithm (e.g. Long and Daum, 1998) are useful. However, Ashcroft and Wentz (2000) note that although the Backus-Gilbert method could in principle be used to construct effective observations corresponding to gain patterns either larger or smaller than those of the actual observations, the noise amplification for construction of smaller gain patterns (deconvolution) was deemed unacceptable. The OI method (e.g. Stogryn, 1978; Poe, 1990; Meissner et al. 2012) can be used to resample individual radiometer observations onto Composite Field Of View (CFOV) cells. The CFOV of all channels are shifted to a common location. In this approach, measurements are resampled around the main beam of interest defined by the -3dB footprint area of channels with lower frequencies (see definition of L1bR product (section 4.3.5). Adjusted radiance can then be derived for each L1 product for every channel. This approach averages multiple finely sampled high-resolution measurements to lower resolution CFOV footprints with less noise. As a general rule, the finer the sampling of the measurement data, the more effective the OI method can be in finding a solution with lower noise.

All methods rely on very good instrument radiometric performance because deconvolution techniques imply an amplification of the associated radiometric noise (e.g. Poe, 1990; Stogryn, 1978; Bauer and Bennartz, 1998). The balance between resolution enhancement and increased noise must be evaluated by simulation and in-flight performance to obtain a satisfactory balance.

In addition, all of these techniques require sufficient overlap of adjacent measurements so that neighbouring pixels can contribute to the increase of the spatial resolution of the centre pixel of interest for the algorithm being applied. Following Miesner et al. (2011), for an antenna that is taking spatial samples at a rate that is at least twice the spatial frequency response (Nyquist rate) where the spatial frequency response is characterized by L, (the 3-dB footprint size in km), then samples need to be taken every \( L/2 \) km or more. For the GMI instrument only channels 1-7 (10.7 – 37.0 GHz) are at least Nyquist sampled. The AMSR-E and AMSR/2 instruments record measurements at equal intervals of 10 km (5 km for the 89 GHz channels) along the scan to satisfy the Nyquist criteria. However, there remain gaps in the 89 GHz antenna patterns (Maeda et al, 2016) preventing contiguous sampling between scans at the 89GHz frequency (i.e. no overlap). The SMAP radiometer makes an along-scan sample every 11 km, which is faster than the 20-km Nyquist criterion (L=40 km). With the spacecraft moving at 6.8 km/s speed over ground, the across scan sampling at centre of swath is 28 km—slightly slower than the 24-km Nyquist criterion (Piepmeier et al., 2016).

When the Nyquist criterion is not met spatial aliasing occurs and signals from individual footprints become indistinguishable from each other when combined resulting in artificial artefacts and distortion. Kemppinmen and Hallikainen, (1992) set out an approach to determine the ideal scanning method for a scanning radiometer and suggest an overlap of ~30% was required in the MIMR case. The approach of AMSR, AMSR/2 and SSM/I was a
compromise to ensure contiguity of the highest frequency band(s) measurements in the flight direction.

The CIMR situation to satisfy the Nyquist sampling criteria $L/2$ is as follows:

<table>
<thead>
<tr>
<th>Beam centre frequency (GHz)</th>
<th>Beam Target resolution, $L$ (km)</th>
<th>Nyquist sampling criteria, $L/2$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4135</td>
<td>60</td>
<td>30</td>
</tr>
<tr>
<td>6.9</td>
<td>15</td>
<td>7.5</td>
</tr>
<tr>
<td>10.65</td>
<td>15</td>
<td>7.5</td>
</tr>
<tr>
<td>18.7</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>36.5</td>
<td>5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

In the case of CIMR, an overlap in the cross-scan direction is required for all channels. In particular, lower frequency CIMR bands (1.4 to 10.65 GHz) must be strongly oversampled to allow interpolation schemes used in higher-level processing schemes to work most effectively. Furthermore, lower frequency bands are expected to have the most demanding antenna pattern corrections as beam efficiency falls due to the limited size of the CIMR reflector with respect to 1.4 and 6.9 GHz: oversampling will help reduce this aspect.

MRD-340 The CIMR radiometer shall provide at least five equi-spaced samples during the L1b measurement integration time.

- **Note 1:** It is anticipated that oversampling in the along scan direction will be $\geq 5$ samples depending on the reflector rotation speed and will satisfy the Nyquist sampling criteria and minimise aliasing when reconstructing gridded fields.

- **Note 2:** For specific applications (e.g., SIC) access to higher noise and more frequent sampling can be beneficial. To limit smearing and the size of an EFoV, the number of samples may be increased at the cost of a higher $\text{NEdT}$.  

- **Note 3:** $\text{NEdT}$ is computed for the L1b measurement full integration time. Individual samples are likely to have a higher $\text{NEdT}$ and may be computed separately.

- **Note 4:** In addition, the intra-measurement noise characteristics can be monitored.

- **Note 5:** For the 36.5 GHz channel this results in minimum separation of samples at 1.25 km and for the 6.9GHz channel a separation between samples of 3.75 km.

- **Note 6:** Given that oversampling is highly desirable for the lower frequency channels, adopting a standard sampling strategy where all channels are sampled at 1.25 km would be useful.

- **Note 7:** A suitable arrangement of the radiometer feed horns/array will be required due to the different beam size of each channel.

MRD-350 The CIMR radiometer shall sample the target scene in the across-scan direction and the along-scan direction by overlapping footprints by $\geq 20\%$ for all channels.

- **Note 1:** The approach of AMSR, AMSR/2 and SSM/I ensured at least contiguity (i.e. limited or no overlap) of the highest frequency band in the flight direction was attained.
Note 2: It is essential that a significant overlap in the across-scan direction is achieved for all channels below 18.7 GHz in order to allow satisfactory noise reduction when interpolating low-spatial resolution data to high spatial resolution data. Kemppinen and Hallikainen, (1992) suggest an overlap in the across scan direction of 30% although this is particularly challenging.

Note 3: for X band marginal compliance to oversampling may be permissible.

Note 4: A suitable arrangement of the radiometer feed horns/array will be required due to the different beam size of each channel.

Note 5: This requirement applies at the centre point of the forward and backwards swath. Due to the conical scanning principle the remainder of the swath will be automatically oversampled.

MRD-360 The CIMR radiometer may sample the target scene with contiguous footprints for 18.7 GHz channels.

Note 1: The approach of AMSR, AMSR/2 and SSM/I ensured at least contiguity (i.e. limited or no overlap) of the highest frequency band in the flight direction was attained.

Note 2: At Ku band the key scientific driver is high spatial resolution of 5 km. In this case, a compromise configuration could foresee a contiguous footprint arrangement with no overlap of beams but with the major axis of each footprint at least tangential with the next in all parts of the forward and backward scan.

Note 3: This requirement applies at the centre point of the forward and backwards swath. Due to the conical scanning principle the remainder of the swath will be automatically oversampled.

MRD-370 The CIMR radiometer shall sample the target scene with contiguous footprints for 36.5 GHz channels. Discontinuities may be permissible ≤1 km in the along track direction.

Note 1: The approach of AMSR, AMSR/2 and SSM/I ensured at least contiguity (i.e. limited or no overlap) of the highest frequency band in the flight direction was attained.

Note 2: At Ka band the key scientific driver is high spatial resolution of 4 - 5 km. In this case, a compromise configuration could foresee a near-contiguous footprint arrangement with no overlap of beams but with the major axis of each footprint tangential with the next for the majority of the forward and backward scan. In this arrangement, small discontinuities (e.g. ≤1 km) in an angular sector in around the along track direction in the forward and backward scan could be permissible.

Note 3: This requirement applies at the centre point of the forward and backwards swath. Due to the conical scanning principle the remainder of the swath will be automatically oversampled.
4.2.7 **CIMR Spectral Performance Requirements**

**MRD-380** The maximum CIMR channel bandwidth shall be within the limits set by ID-080-1-3 in Table MRD-2.

*Note 1:* CIMR channel bandwidth shall be defined together with the frequency stability, \( \Delta f_o \), as each channel must comply with the EESS(passive) frequency allocations in the ITU radio-regulations.

*Note 2:* Channel bandwidths set within the limits of ID-080-1-3 in Table MRD-2 and will correspond to -30dB-power bandwidths, unless justified. If the full allocated band is not used then the -30dB will apply at the edge of the band as a minimum.

*Note 3:* CIMR channel central frequency, \( f_{\text{channel}} \), depends on the selected channel bandwidth and is not necessarily the same as the centre of the EESS(passive) allocated band.

*Note 4:* ITU note that for C-band, the passive frequency allocation is 6.425 to 7.250 GHz (6.8375 GHz centre frequency, 825 MHz bandwidth) with footnote 5.458 that states: "6.425-7.075 GHz: acknowledged for use over the oceans" and "7.075-7.250 GHz: there is an acknowledgement of use everywhere". Use of this full bandwidth may bring advantages for radiometric accuracy.

*Note 5:* The overall RFI contamination in the passive band 1400-1427 MHz is a significant challenge. Different types of RFI sources have been identified by SMOS and SMAP radiometers and typically these are detected as individual RFI sources. Three main categories: (1) excessive unwanted emissions from radars in adjacent band, (2) unauthorised equipment (e.g. radiolinks, surveillance cameras, etc.) operating in-band and (3) malfunctioning equipment in adjacent bands (e.g. IM or harmonics, frequency shifts, etc). In addition, since Oct 2011 it is observed over Japan and extended RFI over urban areas (aggregated impact of hundreds of individual RFI sources). The cause found is due to poor shielding in IF circuits (L-Band) of 12 GHz Home-TV Satellite Receivers. ESA has been able to report and claim protection for SMOS thanks to the excellent selectivity of the SMOS radiometer (\( f_o = 1413.5 \) MHz, \( B_{\text{3dB}} \) limited to 20 MHz, and more than 30 dB rejection at the edges of the allocated band: 1400 MHz and 1427 MHz). It is strongly recommended that the same approach is used for CIMR.

*Note 6:* There is a trade-off between the bandwidth of the 36.5 GHz channel and the end-to-end performance of the channel especially in terms of the reflectivity of the antenna mesh. The current specification uses that of AMSR-2.

**MRD-390** CIMR channel out-of-band (OOB) rejection shall be > -30 dB at the edges of the allocated bandwidth per channel.

*Note 1:* The OOB rejection refers to the complete chain from the antenna aperture to the instrument output.

**MRD-400** CIMR channel out-of-band rejection, specified at the receiver input shall ensure protection and non-destructive impact from high power transmitters (mainly radars) in adjacent or near-by bands.
Note 1: The purpose of this requirement is to make sure that the receiver is able to withstand very high power radars in adjacent bands that could cause damage or stress.

MRD-410 CIMR channel receiver shall be able to withstand in-band very high-power signals within band.

Note 1: this requires evaluation of signal levels as in the case of SMOS withstanding high-power radars in band that blinded the instrument for a few seconds.

4.2.8 Radiometric resolution (NEΔT) Requirements

In cold polar regions NEΔT is a limiting factor for L-band measurements of SSS and is a fundamental requirement. For SST, C-band and X-band NEΔT is a fundamental requirement in order to satisfy Copernicus SST performance requirements. For sea ice concentration at Ka/Ku band, NEΔT is more relaxed since the operational algorithms employed employ difference ratios.

MRD-420 The NEΔT of each CIMR channel in a L1b product shall comply with ID-080-1-5 in Table MRD-2.

Note 1: CIMR is focussed on Polar Regions where sea ice has a typical (frequency dependent) dynamic range of e.g. <100 to ~260 K @18.7 GHz. Therefore, radiometric resolution (NEΔT) is specified as 1σ at a reference temperature (T_{ref}) of 150 K as for AMSR-2.

Note 2: See definition of NEΔT.

Note 3: NEΔT is a significant performance specification.

Note 4: NEΔT is computed using all samples acquired according to MRD-190 and MRD-230.

4.2.9 Dynamic Range Requirements

MRD-430 The dynamic range of each CIMR channel shall comply with ID-080-1-6 in Table MRD-2.

Note 1: K_{min} allows a view of deep space (cold sky) for absolute calibration purposes.

Note 2: K_{max} allows a view of the largest Sea Surface Temperature values plus a margin of ~10 K headroom for RFI processing.

Note 3: The large dynamic range has implications for the calibration approach. Ideally the reference calibration sources should span the expected range of Earth scene brightness temperatures in order to constrain the calibration appropriately and minimise uncertainties introduced due to non-linearity of derived calibration parameters.
4.2.10 Radiometric Accuracy and Stability Requirements.

From Bell (1999) accuracy (or rather inaccuracy) is not the same as uncertainty. Unfortunately, usage of these words is often confused. Correctly speaking, ‘accuracy’ is a qualitative term (e.g. one could say that a measurement was ‘accurate’ or ‘not accurate’). Uncertainty is quantitative. When a ‘plus or minus’ figure is quoted, it may be called an uncertainty, but not an accuracy.

For CIMR Absolute Radiometric Accuracy (ARA) is not used in the traditional manner but instead we calculate the Total Standard Uncertainty (which is a “zero mean, 1-sigma” total uncertainty). The strength of this approach is that each component of the total standard uncertainty can be validated (which is not the case for ARA which implies a reference of “truth”). It is noted that this approach, while consistent with international agreements on uncertainty specification (JCGM, 2008), is different compared to other formulations (e.g. as for the MetOp-SG(B) MWI) that do not include NEΔT as part of the absolute radiometric accuracy definition.

The Total Standard Uncertainty is comprised of components having individual requirements: NEΔT (MRD-280), end-to-end lifetime radiometric stability (MRD-330) and orbital stability (MRD-340 and MRD-350) and a bias (e.g. associated with pre-launch characterisation uncertainty).

The total standard uncertainty for a single measurement (in one channel) is the combination of uncertainty from random and systematic effects. These correctly combine in quadrature:

\[ u_{total} = \sqrt{u_{random}^2 + u_{systematic}^2} \]  
(Eqn. 4.2.10.1)

Channel NEΔT addresses the uncertainty from random effects in the instrument.

The stability requirements limit the excursions of the calibration from “truth” on slower timescales: the orbit stability requirement constrains the drift of the calibration on orbital timescales; the lifetime stability constrains the degree of drift of calibration over the mission lifetime; and one further component is required to obtain the total standard uncertainty, namely the beginning of life uncertainty of pre-launch calibration knowledge (upl-cal) e.g. derived from ground characterisation). In particular, the uncertainties associated with pre-flight calibration (from unit to instrument level), upl-cal, imply a rigorous pre-launch characterisation of the CIMR instrument (and thus links to the CIMR calibration and validation plans). This is consistent with the definition of all quantities as zero-mean, 1-sigma standard deviations in the MRD requirements. Therefore, the requirements adhere to the formulation of Total Standard Uncertainty:

\[ u_{total}^2 \cong u_{NEΔT}^2 + u_{orbit-stability}^2 + u_{lifetime-stability}^2 + u_{pl-cal}^2 \]  
(Eqn. 4.2.10.2)
For CIMR (using the data in Table MRD-2) these evaluate as (at zero mean, 1-sigma) for the goal values in Table MRD-2:

<table>
<thead>
<tr>
<th>GHz</th>
<th>$u_{\text{total}}$</th>
<th>$u_{\text{NEAT}}$</th>
<th>$u_{\text{orbit-stability}}$</th>
<th>$u_{\text{lifetime-stability}}$</th>
<th>$u_{\text{pl-cal}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4135</td>
<td>0.5</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>6.9</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>10.65</td>
<td>0.45</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>18.7</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>36.5</td>
<td>0.8</td>
<td>0.7</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

MRD-440 CIMR 1.4135, 6.9, and 10.65 brightness temperature measurements in a L1b product shall ensure a total standard uncertainty of ≤0.5 K (zero mean, 1-sigma).

Note 1: This implies an accurate representation of the antenna gain pattern for all feeds is convolved with the measurement data set to correct for side-lobe and other aspects (e.g. grating lobes) contributions to the measurement of interest.

Note 2: This requirement applies to scientific measurements at top of atmosphere.

Note 3: This implies that the calibration subsystem is performing to specification.

Note 4: L1b product corrections should be pursued to maintain the performance of CIMR as close to radiometric discontinuities (e.g. land sea transitions etc).

Note 5: See definition of total standard uncertainty.

Note 6: Vicarious calibration targets are not traceable to SI and are not suitable as reference measurements.

Note 7: This requirement implies that calibration reference target(s) used to validate this requirement are part of the CIMR on-board calibration system and have been thoroughly characterised and are traceable before flight to SI.

MRD-450 CIMR 18.7 GHz brightness temperature measurements in a L1b product shall ensure a total standard uncertainty of ≤0.6 K (zero mean, 1-sigma).

Note 1: This implies an accurate representation of the antenna gain pattern for all feeds is convolved with the measurement data set to correct for side-lobe and other aspects (e.g. grating lobes) contributions to the measurement of interest.

Note 2: This requirement applies to scientific measurements over at top of atmosphere.

Note 3: This implies that the calibration subsystem is performing to specification.

Note 4: L1b product corrections should be pursued to maintain the performance of CIMR as close to radiometric discontinuities (e.g. land sea transitions etc).

Note 5: See definition of total standard uncertainty.

Note 6: Vicarious calibration targets are not traceable to SI and are not suitable targets as reference measurements.
Note 7: This requirement implies that reference target(s) used to validate this requirement are part of the CIMR on-board calibration system and have been thoroughly characterised and are traceable before flight to SI.

MRD-460  CIR 36.5 GHz brightness temperature measurements in a L1b product shall ensure a total standard uncertainty of ≤0.8 K (zero mean, 1-sigma).

Note 1: This implies an accurate representation of the antenna gain pattern for all feeds is convolved with the measurement data set to correct for side-lobe and other aspects (e.g. grating lobes) contributions to the measurement of interest.

Note 2: This requirement applies to scientific measurements at top of atmosphere.

Note 3: This implies that the calibration subsystem is performing to specification.

Note 4: L1b product corrections should be pursued to maintain the performance of CIMR as close to radiometric discontinuities (e.g. land sea transitions etc).

Note 5: See definition of total standard uncertainty.

Note 6: Vicarious calibration targets are not traceable to SI and are not suitable targets as reference measurements.

Note 7: This requirement implies that reference target(s) used to validate this requirement are part of the CIMR on-board calibration system and have been thoroughly characterised and are traceable before flight to SI.

MRD-470  The CIMR radiometer shall demonstrate instrument end-to-end (i.e. following full-calibration) radiometric stability to ≤0.2 K (zero mean, 1-sigma) for all channels over the lifetime of the mission.

Note 1: This requirement is fundamental to the utility of the data in the context of any long-term multi-satellite record.

Note 2: The overall radiometric stability of the instrument is also dependent on the stability of the end-to-end calibrated system (i.e. reflector, calibration reference sources, detector, A/D etc.).

Note 3: The minimum lifetime of the mission is 7 years after a commissioning period of 6 months.

MRD-480  The CIMR radiometer shall demonstrate instrument end-to-end (i.e. following full-calibration) radiometric stability to ≤0.2 K (zero mean, 1-sigma) for 1.4315, 18.7 and 36.5 GHz channels for each orbit.

Note 1: To deal with any bias adequately in flight in retrieving geophysical parameters adequate radiometric stability around an orbit, driven by the geophysical parameter is required. In order not to compromise the geophysical uncertainty, this stability needs to be, order-of-magnitude, half of the geophysical uncertainty value in the channels used. This is not averaged down by using both forward and backward scans. In order not to compromise the SST uncertainty, this stability needs to be, order-of-magnitude, half of the SST uncertainty value in the SST channels. This is not averaged down by using both fore and aft, so the factor is ~ emissivity.
Note 2: The overall radiometric stability of the instrument is also dependent on the stability of the end-to-end calibrated system (i.e. reflector, calibration reference sources, detector, A/D etc.).

MRD-490  The CIMR radiometer shall demonstrate instrument end-to-end (i.e. following full-calibration) radiometric stability to ≤0.15 K (zero mean, 1-sigma) with a goal of ≤0.1 K for 6.9 and 10.65 GHz channels for each orbit.

Note 1: To deal with any bias adequately in flight in retrieving geophysical parameters adequate radiometric stability around an orbit, driven by the geophysical parameter is required. In order not to compromise the geophysical uncertainty, this stability needs to be, order-of-magnitude, half of the geophysical uncertainty value in the channels used. This is not averaged down by using both forward and backward scans. In order not to compromise the SST uncertainty, this stability needs to be, order-of-magnitude, half of the SST uncertainty value in the SST channels. This is not averaged down by using both fore and aft, so the factor is ~ emissivity.

Note 2: The radiometric stability of the instrument is also dependent on the stability of the end-to-end calibrated system (i.e. reflector, calibration reference sources, detector, A/D etc.).

4.2.11 Calibration System Requirements

MRD-500  The calibration of L1b brightness temperature in all channels shall be maintained during science measurement acquisition using an on-board calibration system with at least two reference values that are traceable to SI.

Note 1: Options to provide reference values include hot and cold load sources (including active cold loads and noise diodes).

Note 2: The means that for all CIMR on-board calibration reference value temperatures should be reference to the International Temperature scale 1990 (ITS 1990) – see Preston-Thomas (1990)

Note 3: More than two calibration points could be used to account for non-linearity if needed to constrain the CIMR calibration.

Note 4: The reflector characteristics must be known and the reflector temperature monitored in flight (e.g. using a thermal infrared camera and/or reference thermistors).

Note 5: Vicarious calibration targets are not traceable to SI. Therefore, the CIMR on-board calibration system must be thoroughly characterised before flight and a strategy developed to periodically check calibration

MRD-510  The CIMR radiometer shall be capable of viewing deep space as a cold calibration reference target.

Note 1: This implies that specific manoeuvres are required.
Note 2: the number of deep space views is a function of the calibration system implementation and must be derived during the Phase A/B1.

MRD-520 All on-board calibration data and supporting engineering data required to recalibrate CIMR science measurements shall be sent to ground.

Note 1: Access to engineering data such as thermistor values, instrument state, scan position etc is essential to monitor the performance of the CIMR calibration systems and to re-calibrate the instrument on-ground if required as part of reanalysis.

Note 2: Supporting engineering data includes any on-board information considered necessary to reconstruct the calibration of CIMR and is specific to the implementation of the on-board calibration system e.g. thermistor values, scan position, feed temperature etc.

4.2.12 Inter-channel calibration.

The consistency of brightness temperature retrievals from CIMR bands and CIMR channels is important as L2 algorithms will use a combination of channels to derive geophysical products. The following requirements are designed to ensure that there is consistency both within a channel (regardless of the implementation used e.g. multiple feed chains) and between different bands referred to as inter-channel and inter-band differences.

MRD-530 Brightness temperature differences for the same target area measured at different frequencies (bands) and polarisations (channels) by any combination of two footprints shall be ≤0.2 K when compared to the theoretical brightness temperature derived using the Raleigh-Jeans approximation of for an infinite uniform target scene represented as a perfect blackbody at a temperature of 290 K.

Note 1: This requirement addresses the fact that L2 geophysical retrievals will use a combination of different channel data and consistency of performance between channel data must be guaranteed.

Note 2: 290 K is used as a blackbody physical temperature to facilitate on ground testing.

Note 3: It is assumed that this requirement is to verified prior to launch by analysis and testing.

MRD-540 Brightness temperature differences for the same target area measured at the same frequency (band) and polarisation (channel) by any combination of two footprints shall be ≤0.1 K when compared to the theoretical brightness temperature derived using the Raleigh-Jeans approximation of for an infinite uniform target scene represented as a perfect blackbody at a temperature of 290 K.

Note 1: The requirement addresses the fact that multiple feeds are required to meet sampling requirements and each feed chain (reflector, feed-horn, back end electronics, calibration etc.) may be slightly different. However, from a user perspective, these differences should be minimised so that data within a given channel, regardless of the feed chain used, are essentially uniform.
4.2.13 Polarisation Requirements.

Polarisation is an important quantity for CIMR since channel polarisation differences and ratios are used in retrieval algorithms.

**MRD-550** All CIMR bands shall acquire data in two channels: one with a vertical linear polarisation (V) and a second with a horizontal linear polarisation (H).

*Note 1:* Thus, there is a minimum of two CIMR instrument measurement channels (H and V) for each CIMR instrument band e.g. 18.7V and 18.7H and four computed outputs in a L1b product that are available on ground corresponding to the full Stokes Vector.

*Note 2:* Vertical Polarisation (V) is defined as the electric field being parallel to the plane of incidence.

*Note 3:* Full Stokes Vector is requested in MRD-510.

**MRD-560** All CIMR bands shall have cross polarisation levels $\leq$2%.

*Note 1:* CIMR L2 geophysical retrievals exploit channel polarisation differences and cross-polarisation levels must therefore be low and well characterised.

The degree of polarisation is extremely useful in CIMR L1 (e.g. correction for Faraday Rotation) and L2 (e.g. potential retrieval of wind vector over the ocean) processing and is conveniently expressed in the full Stokes Vector. In principle, with appropriate hardware, this can be derived as an output from the radiometer feeds or as part of the RFI processing system.

**MRD-570** CIMR shall estimate the Full Stokes Vector for each frequency band and send these data to ground if computed on-board.

*Note 1:* The provision of full Stokes Vector channel outputs (e.g. as part of on-board radio-frequency interference processing) should be explored as these measurements can be used to support L2 retrievals (e.g. Faraday rotation correction, wind vector measurements).
4.2.14 Antenna main beam requirements.

Following Kaefer and Harrington (1983), the main-beam efficiency of a microwave radiometer specifies the integral of power over the main beam divided by the integral over the complete antenna pattern. For reference the beam width are used by the AMSR-2 sensor are shown in Table 4.2.14.1.

Table 4.2.14.1. AMSR2 beam characteristics and sampling specification (from Imaoka et al., 2010).

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Beam width (3dB, deg.)</th>
<th>Spatial resolution (km)</th>
<th>Sampling interval (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.9</td>
<td>1.8</td>
<td>35 x 62</td>
<td>10</td>
</tr>
<tr>
<td>10.65</td>
<td>1.2</td>
<td>24 x 42</td>
<td>10</td>
</tr>
<tr>
<td>18.7</td>
<td>0.65</td>
<td>14 x 22</td>
<td>10</td>
</tr>
<tr>
<td>36.5</td>
<td>0.35</td>
<td>7 x 12</td>
<td>10</td>
</tr>
</tbody>
</table>

In the case of CIMR, the main beam is defined as 2.5 x -3dB footprint contour. It represents the fraction of the power received through the main beam if the antenna was in an isothermal enclosure. In the case of CIMR we consider sources within the wide beam defined as 3 x -3dB footprint contour. The fraction of power received from all angles other than the wide beam, 1 – ε, originates from sources other than the scene being observed and, in general, is not accurately known. The effective antenna temperature, $T_a$, then consists of two parts:

$$T_a = \varepsilon T_{\text{scene}} + (1 - \varepsilon) T_{\text{other}}$$

The second term must be removed by assuming a temperature distribution for $T_{\text{other}}$ and integrating over all the side lobes, back lobes and e.g. grating lobes. This process is simple if most of the power is in the first side lobe and the scene is homogeneous, such as an ocean scene. But, for example, if the wide beam is viewing the ocean and the side lobes and e.g. grating lobes, back lobes, spillover etc, are partially viewing land or sea ice, it may be impossible to make the correction to the required accuracy if knowledge of the antenna characteristics is poor and/or the target scene is extremely heterogeneous Kaefer and Harrington (1983). The use of properly computed uncertainty estimates at L1b will be necessary to capture the quality of an individual measurement in challenging conditions. Nevertheless, the larger the beam efficiency, the easier it is to correct for the unwanted received radiation.

The required beam efficiency is highly dependent on the required measurement accuracy, side-lobe structure, and scene heterogeneity. It is possible to obtain wide beam efficiencies $\varepsilon \approx 98\%$ with certain types of horn antennas for a uniformly illuminated reflector antenna (e.g. Gaiser et al., 2004). Since the required wide-beam efficiency is dependent on the particular observation, it is difficult to specify a general requirement on $\varepsilon$ for a broad range of measurements other than to say that $\varepsilon$ should be as high as possible.

One approach is to investigate the impact of main beam contamination using radiative transfer modelling. Simulated SST Level-2 retrievals (using only channels at 6.925, 10.65 and 18.7 GHz) using a radiative transfer model following the approach of Pearson et al. (2018) have been performed to quantify the impact of an additional bias induced by side-
lobe contamination in steps of 0.1 K for a 50 x 50 km area and a straight boundary. In this simulation, the same bias is applied to all the retrievals and all channels. To limit the impact on SST bias to 0.2 K the Tb contributions from side-lobes and grating-lobes must be ~0.1 K. The estimated impact of a 0.5 K side-lobe and grating lobe contribution on SST bias is ~0.8 K.

Practically, the impact of side-lobe and e.g. grating lobe contamination at L1b can be estimated and mitigated by analysing the contribution of power from the full beam (including side and other lobes) compared to the -3dB footprint ellipse using accurate antenna gain patterns and knowledge of the brightness temperature characteristics of surrounding CIMR measurements. This requires that accurate antenna gain and grating-lobe patterns are available for each channel and a L1a to L1b data processing approach is used to adjust the -3dB measurement and compensate for side-lobe contamination.

As CIMR is focussed on the Polar Regions, the following requirements are specified for transitions between open water to first year ice in horizontal polarisation although each requirement provides an additional specification for Land and Ocean surfaces. The approach to be used to address each requirement is summarised in Figure MRD-4.2.14.1.

As a guide to assessing the performance of MRD-430 to MRD-470, and as part of the CIMR total standard uncertainty assessment (Eqn. 4.2.10.2) MRD-300 to MRD-320, a synthetic scene provides a powerful means to control the assumptions used (both geometrically and radiometrically) when performing an assessment. An example scene is provided in Figure 4.2.14.2 as a starting point from which a viable test scene can be appropriately tailored.
The impact of radiometric discontinuities (e.g. thermal ocean fronts, at a coastal boundary, sea ice edge [AD-2] or ice shelf edge etc) on 6.9 GHz L1b horizontally polarised brightness temperature measurements shall not be ≥0.5 K at 1 footprint from a hypothetical and infinite high contrast target scene, with top of the atmosphere brightness temperatures of 75 K and 250 K at each side of a straight boundary.

Note 1: As CIMR is focused on the Polar Regions, the following requirements are specified for transitions between open water to first year ice but it should be recalled that because CIMR has a high spatial resolution it may “see” lakes close to hot land surfaces.

Note 2: Over land surfaces at C-band Tmin= 200 K, Tmax= 300 K.

Note 3: Over ocean surfaces at C-band Tmin= 75 K, Tmax= 150 K).

Note 3: In terms of open-water (OW) to first-year ice (FYI) sea-ice transition cases that are the most common cases (OW to Multi-Year Ice (MYI) transitions are less common) the Tb contrasts in H-polarization (that are always larger than the contrast in V-pol) Tmin(Hpol) = 75K and Tmax(Hpol) = 250K. These are average “realistic” transitions that also consider the variability of conditions around the mean SIC algorithm tie-points.

Note 4: This requirement is designed to ensure that side-lobe and e.g. grating lobe corrections, when applied, result in useful measurements allowing accurate computation of geophysical parameters.

Note 5: This requirement implies a well-formed antenna beam and well characterised antenna side lobes and grating lobe patterns to be used in L1b processing.

Note 6: This requirement implies that a suitable algorithm is used to compensate for side-lobe and e.g. grating lobe contamination at L1b.
Note 7: This requirement will be assessed theoretically by analysis.

Note 8: It is expected that the “worst case” will be in the coastal zones where there are large radiometric discontinuities (temperature, emissivity, varied terrain and elevation etc).

Note 9: See Figure MRD-4.2.14.1

MRD-590 The impact of radiometric discontinuities (e.g. thermal ocean fronts, at a coastal boundary, sea ice edge [AD-2] or ice shelf edge etc) on 10.65 GHz L1b horizontally polarised brightness temperature measurements shall not be ≥0.5 K at 1 footprint from a hypothetical and infinite high contrast target scene, with top of the atmosphere brightness temperatures of 80 K and 250 K at each side of a straight boundary.

Note 1: As CIMR is focused on the Polar Regions, the following requirements are specified for transitions between open water to first year ice but it should be recalled that because CIMR has a high spatial resolution it may “see” lakes close to hot land surfaces.

Note 2: The distribution of GPM-GMI (having an incidence angle of 53.5° similar to CIMR at 55°) data over land surface within the METEOSAT disk (i.e. no polar regions) for both H and V polarization averaged over 6 days per month for a year (2015) is provided as a guide to more realistic scenarios below.

\[
\begin{align*}
T_{\text{min(Vpol)}} &= 240 \text{ K}, \\
T_{\text{max(Vpol)}} &= 320 \text{ K}, \\
T_{\text{min(Hpol)}} &= 220 \text{ K}, \\
T_{\text{max(Hpol)}} &= 300 \text{ K},
\end{align*}
\]

Note 3: The distribution of GPM-GMI (having an incidence angle of 53.5° similar to CIMR at 55°) data over ocean surface within the METEOSAT disk (i.e. no polar regions) for both H and V polarization averaged over 6 days per month for a year (2015) is provided as a guide to more realistic scenarios below.

\[
\begin{align*}
T_{\text{min(Vpol)}} &= 150 \text{ K}, \\
T_{\text{max(Vpol)}} &= 240 \text{ K}, \\
T_{\text{min(Hpol)}} &= 80 \text{ K}, \\
T_{\text{max(Hpol)}} &= 140 \text{ K}.
\end{align*}
\]

Note 4: In terms of open-water (OW) to first-year ice (FYI) sea-ice transition cases that are the most common cases (OW to Multi-Year Ice (MYI) transitions are less common) the TB contrasts in H-polarisation (that are always larger than the contrast in V-pol) \(T_{\text{min(Hpol)}} = 80 \text{ K}\) and \(T_{\text{max(Hpol)}} = 250 \text{ K}\). These are
average "realistic" transitions that also consider the variability of conditions around the mean SIC algorithm tie-points.

Note 5: This requirement is designed to ensure that side-lobe and e.g. grating lobe corrections, when applied, result in useful measurements allowing accurate computation of geophysical parameters.

Note 6: This requirement implies a well-formed antenna beam and well characterised antenna side lobes and grating lobe patterns to be used in L1b processing.

Note 7: This requirement implies that a suitable algorithm is used to compensate for side-lobe and e.g. grating lobe contamination at L1b.

Note 8: This requirement will be assessed theoretically by analysis.

Note 9: It is expected that the “worst case” will be in the coastal zones where there are large radiometric discontinuities (temperature, emissivity, varied terrain and elevation etc).

Note 10: See Figure MRD-4.2.14.1

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MRD-600

The impact of radiometric discontinuities (e.g. thermal ocean fronts, at a coastal boundary, sea ice edge [AD-2] or ice shelf edge etc) on 18.7 GHz L1b horizontally polarised brightness temperature measurements shall not be ≥0.5 K at 1 footprint from a hypothetical and infinite high contrast target scene, with top of the atmosphere brightness temperatures of 100 K and 250 K at each side of a straight boundary.

Note 1: As CIMR is focused on the Polar Regions, the following requirements are specified for transitions between open water to first year ice but it should be recalled that because CIMR has a high spatial resolution it may “see” lakes close to hot land surfaces.

Note 2: The distribution of GPM-GMI (having an incidence angle of 53.5° similar to CIMR at 55°) data over land surface within the METEOSAT disk (i.e. no polar regions) for both H and V polarization averaged over 6 days per month for a year (2015) is provided as a guide to more realistic scenarios below.

\[
\begin{align*}
T_{min}(Vpol) &= 240 \text{ K}, T_{max}(Vpol) = 320 \text{ K}, \\
T_{min}(Hpol) &= 220 \text{ K}, T_{max}(Hpol) = 310 \text{ K}.
\end{align*}
\]

Note 3: The distribution of GPM-GMI (having an incidence angle of 53.5° similar to CIMR at 55°) data over ocean surface within the METEOSAT disk (i.e. no polar regions) for both H and V polarization averaged over 6 days per month for a year (2015) is provided as a guide to more realistic scenarios below.

\[
\begin{align*}
T_{min}(Vpol) &= 170 \text{ K}, T_{max}(Vpol) = 250 \text{ K}, \\
T_{min}(Hpol) &= 100 \text{ K}, T_{max}(Hpol) = 250 \text{ K}.
\end{align*}
\]
Note 4: In terms of open-water (OW) to first-year ice (FYI) sea-ice transition cases that are the most common cases (OW to Multi-Year Ice (MYI) transitions are less common) the $T_B$ contrasts in H-polarization (that are always larger than the contrast in V-pol) $T_{min}(Hpol) = 100K$ and $T_{max}(Hpol) = 250K$. These are average "realistic" transitions that also consider the variability of conditions around the mean SIC algorithm tie-points.

Note 5: This requirement is designed to ensure that side-lobe and e.g. grating lobe corrections, when applied, result in useful measurements allowing accurate computation of geophysical parameters.

Note 6: This requirement implies a well-formed antenna beam and well characterised antenna side lobes and grating lobe patterns to be used in L1b processing.

Note 7: This requirement implies that a suitable algorithm is used to compensate for side-lobe and e.g. grating lobe contamination at L1b.

Note 8: This requirement will be assessed theoretically by analysis.

Note 9: It is expected that the “worst case” will be in the coastal zones where there are large radiometric discontinuities (temperature, emissivity, varied terrain and elevation etc).

Note 10: See Figure MRD-4.2.14.1

MRD-610 The impact of radiometric discontinuities (e.g. thermal ocean fronts, at a coastal boundary, sea ice edge [AD-2] or ice shelf edge etc) on 36.5 GHz L1b horizontally polarised brightness temperature measurements shall not be $\leq 0.5$ K at 1 footprint from a hypothetical and infinite high contrast target scene, with top of the atmosphere brightness temperatures of 135 K and 250 K at each side of a straight boundary.

Note 1: As CIMR is focused on the Polar Regions, the following requirements are specified for transitions between open water to first year ice but it should be recalled that because CIMR has a high spatial resolution it may “see” lakes close to hot land surfaces.

Note 2: The distribution of GPM-GMI (having an incidence angle of 53.5° similar to CIMR at 55°) data over land surface within the METEOSAT disk (i.e. no polar regions) for both H and V polarization for averaged over 6 days per month for a year (2015) is provided as a guide to more realistic scenarios below.

$T_{min}(Vpol) = 240 K$, $T_{max}(Vpol) = 320 K$, $T_{min}(Hpol) = 220 K$, $T_{max}(Hpol) = 310 K$
**Note 3:** The distribution of GPM-GMI (having an incidence angle of 53.5° similar to CIMR at 55°) data over ocean surface within the METEOSAT disk (i.e. no polar regions) for both H and V polarization for averaged over 6 days per month for a year (2015) is provided as a guide to more realistic scenarios below.

\[
T_{\text{min}}(\text{Vpol}) = 200 \text{ K}, \quad T_{\text{max}}(\text{Vpol}) = 260 \text{ K}, \quad T_{\text{min}}(\text{Hpol}) = 130 \text{ K}, \quad T_{\text{max}}(\text{Hpol}) = 250 \text{ K}.
\]

**Note 4:** In terms of open-water (OW) to first-year ice (FYI) sea-ice transition cases that are the most common cases (OW to Multi-Year Ice (MYI) transitions are less common) the TB contrasts in H-polarization (that are always larger than the contrast in V-pol) \(T_{\text{min}}(\text{Hpol}) = 135\text{K}\) and \(T_{\text{max}}(\text{Hpol}) = 250\text{K}\). These are average "realistic" transitions that also consider the variability of conditions around the mean SIC algorithm tie-points.

**Note 5:** This requirement is designed to ensure that side-lobe and e.g. grating lobe corrections, when applied, result in useful measurements allowing accurate computation of geophysical parameters.

**Note 6:** This requirement implies a well-formed antenna beam and well characterised antenna side lobes and grating lobe patterns to be used in L1b processing.

**Note 7:** This requirement implies that a suitable algorithm is used to compensate for side-lobe and e.g. grating lobe contamination at L1b.

**Note 8:** This requirement will be assessed theoretically by analysis.

**Note 9:** It is expected that the “worst case” will be in the coastal zones where there are large radiometric discontinuities (temperature, emissivity, varied terrain and elevation etc).

**Note 10:** See Figure MRD-4.2.14.1

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**MRD-620** The impact of radiometric discontinuities (e.g. thermal ocean fronts, at a coastal boundary, sea ice edge [AD-2] or ice shelf edge etc) on 1.4315 GHz L1b horizontally polarised brightness temperature measurements shall not be \(\geq 0.5\) K at 1 footprint from a hypothetical and infinite high contrast target scene, with top of the atmosphere brightness temperatures of 70 K and 230 K at each side of a straight boundary.

**Note 1:** As CIMR is focused on the Polar Regions, the following requirements are specified for transitions between open water to first year ice but it should be recalled that because CIMR has a high spatial resolution it may “see” lakes close to hot land surfaces.

**Note 2:** Over land surfaces at L-band \(T_{\text{min}} = 250 \text{ K} \) (Amazon Rainforest), \(T_{\text{max}} = 300 \text{ K} \) (Sahara Desert).
Note 3: Over ocean surfaces at L-band Tmin = 70 K, Tmax = 130 K.

Note 4: In terms of open-water (OW) to first-year ice (FYI) sea-ice transition cases that are the most common cases (OW to Multi-Year Ice (MYI) transitions are less common) the T\textsubscript{b} contrasts in H-polarization (that are always larger than the contrast in V-polar) Tmin(Hpol) = 70K and Tmax(Hpol) = 230K. These are average "realistic" transitions that also consider the variability of conditions around the mean SIC algorithm tie-points.

Note 5: This requirement is designed to ensure that side-lobe and e.g. grating lobe corrections, when applied, result in useful measurements allowing accurate computation of geophysical parameters.

Note 6: This requirement implies a well-formed antenna beam and well characterised antenna side lobes and grating lobe patterns to be used in L1b processing.

Note 7: This requirement implies that a suitable algorithm is used to compensate for side-lobe and e.g. grating lobe contamination at L1b.

Note 8: This requirement will be assessed theoretically by analysis.

Note 9: It is expected that the “worst case” will be in the coastal zones where there are large radiometric discontinuities (temperature, emissivity, varied terrain and elevation etc).

Note 10: See Figure MRD-4.2.14.1

4.2.15 Radio Frequency Interference (RFI) Mitigation Requirements.

MRD-630 The CIMR mission shall detect and mitigate Radio Frequency Interference (RFI) on board the spacecraft for all channels.

Note 1: RFI is a source of significant uncertainty in L1 products and must be clearly identified and mitigated from the measurement data if they are to be scientifically useful by the operational user community.

MRD-640 When Radio Frequency Interference (RFI) of a measurement is detected and mitigated by on-board processing, both the original measurement data (i.e. that unprocessed by the RFI system) and the RFI mitigated measurement shall be sent to ground.

Note 1: This requirement allows the performance of RFI filtering on-board to be assessed by the scientific and operational user community.

Note 2: In case of on-board RFI processor failure, access to original data for further on-ground processing will be required to continue the mission.

MRD-650 When Radio Frequency Interference (RFI) of a measurement is detected and mitigated by on-board processing, relevant data generated by the RFI processor shall be sent to ground for the affected measurement.
Note 1: This requirement allows the performance of RFI filtering on-board to be assessed by the scientific and operational user community.

Note 2: “relevant data” in this requirement would include all data samples computed and used in a time-frequency assessment matrix, kurtosis etc.

Note 3: Data compression approaches may be used to minimise the volume of data (e.g. selecting specific data of use for re-computation of NEΔT, re-filtering or identifying RFI sources).

Note 4: RFI sources may be used as a validation source for geolocation – see note in MRD-520.

4.2.16 Geo-location Requirements.

Geo-location accuracy is driven by the need to ensure that the location of CIMR measurements is correct with reference to the WGS-84 ellipsoid and for co-registration with MetOp-SG(B1) MWI and SCA data. Over the open ocean where no reference ground targets are available, geo-location relies on knowledge gained from instrument and platform pointing. The spatial resolution of MetOp-SG(B1) MWI measurements at the highest resolution are 10 km. The geolocation accuracy is set at < 2.5 km (1σ, zero-mean). The nominal spatial resolution of MetOp-SG(B1) SCA is 25 km gridded cells although 12.5 km gridded products will be available. The geolocation accuracy is set at < 1 km (1σ, zero-mean see Rostan et al. 2016).

One of the most important downstream application of CIMR SIC is the merging with high-resolution data from other sources and (mainly Sentinel-1 SAR, L-band SAR or altimeter data) information to allow automatic ice charting. The focus will be on locating the sharp gradient regions (MIZ). This places strong constraints on an accurate geolocation for all channels. Furthermore, a km-scale geolocation error is likely too poor for Sea Ice Drift retrievals. The impact of geolocation error on Sea Ice Drift retrievals strongly depends if it is a “noise” (random) or a systematic error (e.g. along-track).

MRD-660 The geo-location accuracy of CIMR L1b measurements shall be ≤1/10 of the footprint size (zero mean, 1-sigma) for each channel as specified in Table MRD-2.

Note 1: AMSR-E geolocation studied by Wiebe et al. (2008) demonstrates that accuracy varies with frequency (6 to 89 GHz) from 1500 to 250 m.

Note 2: Geolocation applies to all samples at all frequencies and all polarisations.

Note 3: This requirement is to be met at L1b.

Note 4: Accurate positioning of RFI sources (especially via potential processing of grating lobe signals) is extremely useful to report RFI at the international level (SMOS is better than 5 km after post processing). It is expected that CIMR should be able to locate RFI sources to within +/- 5 km.

Geolocation is inextricably linked to Absolute Performance Error (APE) of the instrument pointing accuracy (attitude) and the uncertainty of this parameter expressed as an Absolute Knowledge Error (AKE, see ESSB-HB-E-003, 2011). These parameters are important inputs to the L1R and L2 scientific processing systems. In addition, application of polarized data (e.g. for L2 wind vector measurements, use for surface roughness
calculations etc.) are typically derived from very small differences in polarization pairs (e.g. Gaiser et al., 2004). Therefore, pointing errors have a large impact on the validity of the derived geophysical parameters, primarily because of the impact of OZA variations on the brightness temperature and polarization rotation angle variations on the cross-polarization coupling.

**MRD-670** The CIMR Observation Zenith Angle shall be known with an Absolute Knowledge Error (AKE) of <0.05° per axis.

*Note 1:* Accurate knowledge of the OZA is required for accurate determination of surface emissivity and retrieval of geophysical products – see Wentz and Meissner, 2000; 2007 and Meissner and Wentz, 2012.

*Note 2:* Emissivity of the target source is a function of OZA, frequency and polarisation. It is influenced by surface properties (e.g. wind induced isotropic roughness (waves, capillary diffraction waves, foam, ice/snow surface roughness and scattering properties) and by subsurface properties (dielectric coefficient of the target material). For an increasingly rough sea surface, microwave emission increases and polarization differences decrease. At OZA > 55° and a rough sea surface, the vertical polarisation emission begins to decrease. See Wentz and Meissner, 2000; 2007 and Meissner and Wentz, 2012.

**MRD-680** The combined CIMR platform and instrument pointing shall be known with an Absolute Knowledge Error (AKE) of <0.01°.

*Note 1:* The 18.7 GHz channel is considered as the pointing reference channel.

*Note 2:* AKE on relative pointing for AMSR-E was < 0.07 (Wiebe et al. 2008). For WindSat this was split into Coriolis/WindSat was designed to provide knowledge errors of ±0.05° bias and ±0.05° random components in each OZA and Polarisation Rotation Angle (Gaiser et al 2006).

*Note 3:* the combined pointing AKE is composed of a fixed bias component that could be verified at land/ocean crossing points and a variable component that must be estimated.

*Note 4:* A key aspect is to ensure stability of pointing during extended periods where no ground verification is possible.

**MRD-690** Individual unprocessed attitude sensor data (e.g. from each star-tracker) shall be available on ground in addition to any on-board AOCS solution.

*Note 1:* Due to the stringent pointing requirements for the CIMR mission and large rotating reflector, star tracker, angular position of the antenna and other relevant data will be required to precisely reconstitute CIMR pointing and as input to L2 retrieval algorithms applied by the user community.

### 4.3 Product Requirements.

The CIMR mission product specification is focussed on providing the maximum flexibility to operational users while preserving the radiometric integrity of data.
4.3.1 CIMR Product types

An important aspect for a conically scanning radiometer such as CIMR is to recognise that the most efficient way to manage CIMR products is to manipulate data in the native instrument scan geometry. This is why L1a and L1b products are specified in native instrument scan geometry, while L1bR and L2A products in scan geometry, but generally not at the same locations than the original measurements. L2B products are also provided to ease uptake by downstream services (including the Copernicus services) and users.

Figure MRD-4.3.1.1. Schematic overview of the main data products for the CIMR mission.

4.3.1.1 Un-gridded products

Un-gridded products preserve the native conical scan geometry of the CIMR design. L1a and L1b products are un-gridded products that contain footprints in the native CIMR scan geometry. All data are retained on the original instrument frame of reference, arranged by scan and footprint indices. Thus, there is a direct correspondence between the contents of a product record and the contents of a CIMR instrument scan. Footprints have not been re-gridded or resampled but geolocation is computed and associated with each footprint. When displaying a native un-gridded image, any geophysical features will appear distorted due to the conical scanning geometry of the instrument. However, the advantages of this approach are:

- Radiometric data are retained in their original, time ordered coordinate frame.
- It is a simple process to re-grid to form an image using scan, footprint and channel information.
- Product size is reduced since there are no additional cosmetic pixels or orphan pixel data to store (which is the case for image grid products).
- No unfilled pixels at the edges of the image swath will be generated.
- L1 processing can easily be split into time-sliced segments.
- The transformation from un-gridded to gridded products is a relatively simple operation.
4.3.1.2 Gridded products

Gridded products contain geolocated images. Geolocation derives the Earth-locations of the acquired footprints and maps these onto an appropriate grid defined using the Equal-Area Scalable Earth (EASE, https://nsidc.org/data/ease/ease_grid2.html) grids. These grids were originally conceived at the US NSIDC and have been used to archive several satellite instrument data sets including SMMR, SSM/I, SSMIS and AMSR-E. It is also the grids adopted by the SMAP mission, and several ESA CCI data records. Using this same grid system for CIMR provides user convenience, facilitates continuity of historical data grid formats, and enables re-use of heritage gridding and extraction software tools developed for EASE grid. Because they are equal area grids, visualization and inter-comparison operations are greatly simplified and analysis is more convenient.

CIMR L1c and L2 products are Gridded products ideally using the EASE2 projections.

4.3.2 L0 Products

L0 data products contain native packet data downlinked from the spacecraft. They are not available to end-users and are not discussed further in this MRD.

4.3.3 L1a Un-gridded Products

CIMR products at L1 will be provided in native instrument geometry (sometimes called “swath” products) with no convolution applied (i.e. preserving the “pure” radiometric content of the measurements) so that every sample and footprint measurement acquired is available to users. Because the instrument configuration in terms of feed horn locations, measurements for each CIMR band within L1a and L1b data products will view different Earth locations with different footprint sizes at a given sample time. The mismatch in spatial resolution becomes a critical consideration when observations at different frequencies must be combined to retrieve geophysical parameters (sea ice, SST, etc.) that are not generally homogeneous over such large dimensions (Robinson et al., 1992).

Temporal differences are expected to be very small and are not discussed further: the notable exception is the temporal difference between the forward and backward scan data. Forward and backward scan data are to be provided as separate data streams for users to manipulate according to the application requirements.

L1a is the foundation CIMR product that carries all information from CIMR with all calibration and geolocation data available but not applied (i.e. the data remain in counts and instrument scan geometry and very close to a L0 product). The intention is to provide a L1a data product that could be used as the starting point for re-processing activities while deep archiving L0 data.

<table>
<thead>
<tr>
<th>Product</th>
<th>Description</th>
</tr>
</thead>
</table>
| CIMR L1a | Observed sensor engineering data for each channel in instrument geometry at native channel resolution. L1a data are derived from L0 data that have been reconstructed and ordered into orbit files. 
Data are unprocessed instrument data (counts) at full resolution (i.e. all samples, from all feeds, in all polarisations), time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients (e.g. thermistor counts etc.) and geo-referencing parameters (e.g., platform ephemeris) and auxiliary information (e.g. relevant solar angles etc) computed and appended. No |
calibration or instrument corrections are applied to L1a data: it is designed as the starting point for all ground processing and reanalysis. See JAXA (2005), Aqua AMSR-E Level 1 Product Format Description Document, MAS-100045A as an example.

MRD-700 L1a data products shall be produced and made available to all users.

Note 1: This essential requirement provides flexibility for the ground processors and end user community because L1a products maintain data in native scan geometry with pure radiometry.

Note 2: See definition of product levels.

A NetCDF like format has been chosen for the CIMR data products (https://www.unidata.ucar.edu/software/netcdf/). However, as cloud processing and new IT technologies are emerging at a rapid rate, alternative file formats may be more widely used at the time of CIMR that may provide a more useful format and cannot be dismissed.

MRD-710 L1a files should be formatted in a NetCDF like format, following accepted conventions such as the Climate and Forecast (CF) Convention and latest Attribute Convention for Data Discovery (ACDD) discovery metadata convention.

Note 1: Network common Data format (NetCDF) see https://www.unidata.ucar.edu/software/netcdf/

Note 2: Climate and Forecast (CF) Convention should be version 1.7 or above – see http://cfconventions.org/

Note 3: Attribute Convention for Data Discovery (ACDD) discovery metadata convention version 1.3 or above – see http://wiki.esipfed.org/index.php/Category:Attribute_Conventions_Dataset_Discovery

MRD-720 CIMR L1a data products shall remain in instrument swath geometry with calibration and geolocation available as part of the product but not applied to the data.

Note 1: This is a foundation product that is as close to a Level-0 product as possible implying that a significant amount of engineering/calibration data is also part of the product.

MRD-730 A CIMR L1a data product shall contain the following variables (to be defined during Phase B2/C/D).

Note 1: The exact content of L1a data products depends on the final implementation of CIMR.
4.3.4 L1b Un-gridded Products

L1b data are derived from L1a data to form footprint measurements that are calibrated and geolocated although these remain in a swath geometry. All engineering corrections and calibration parameter (e.g. side-lobe and grating lobe contributions, geolocation adjustment if required) are applied. L1b products remain in native instrument geometry and footprint resolution (i.e. no gridding or mapping projections are implemented). Both the samples and the eFoV footprint observations are available in the L1b files. Importantly no resampling or interpolation of data will be performed to reach this product level. The intention is to provide measurement data with minimum data processing so that the L1b represents the purest calibrated top-of-atmosphere radiometry in native footprint resolution in instrument geometry.

<table>
<thead>
<tr>
<th>Product</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIMR L1b</td>
<td>Top of the atmosphere calibrated brightness temperature for each channel in instrument geometry at native channel resolution. L1b data include all measurement samples in addition to a single L1b measurement (MRD-340) L1b data include all RFI (MRD-640 and MRD-650). All engineering (e.g. corrections for side-lobes and grating lobes, geolocation adjustment) corrections have been applied to each sample, radiometric calibration parameters have been applied to each sample to output top-of-atmosphere spectral brightness temperatures (Tb) in units of Kelvin. Geometric information is computed and appended to each sample (i.e. there is no reprojection or resampling to a gridded product). Samples are aggregated into footprints. Preliminary pixel classification (e.g. land/ocean/ice etc) is included in the product, as well as uncertainty information, and sub-footprint land area fraction. See JAXA (2005), Aqua AMSR-E Level 1 Product Format Description Document, MAS-100045A as an example.</td>
</tr>
</tbody>
</table>

MRD-740 L1b top of the atmosphere brightness temperature measurement data products shall be produced by processing corresponding L1a products in the instrument swath geometry and made available to all users.

Note 1: L1b products are the starting point for further L2 processors.
Note 2: There must be a direct mapping from L1a products to corresponding L1b products.
Note 3: L1b products require that a suitable algorithm is used to calibrate data, correct for antenna spill over, antenna gain patterns, other contributions in wide beam (e.g. grating lobes), attitude and pointing errors, to compute and provide geolocation information etc. Ancillary and auxiliary data sets will be required as input to the L1b algorithm.
Note 4: L1b data products remain in the native instrument conical scan geometry.
Note 5: L1b products include all samples for a given L1b acquisition within the product.
MRD-750 Each measurement sample from each feed horn in all polarisations shall be provided in L1b products together with the L1b measurement instrument swath geometry.

Note 1: L1b data may include low-level data processing choices that may result in a change of the pure radiometric signals (e.g. averaging of samples over footprint size to reduce noise, resampling etc.) that may not easily be reversible.

Note 2: Different users may wish to combine data using different approaches and resolutions depending on the application.

Note 3: This requirement ensures that the purest radiometric measurement data at L1b from the CIMR instrument are available to users.

MRD-760 L1b files should be formatted in a NetCDF like format, following accepted conventions such as the Climate and Forecast (CF) Convention and latest Attribute Convention for Data Discovery (ACDD) discovery metadata convention.

Note 1: Network common Data format (NetCDF) see https://www.unidata.ucar.edu/software/netcdf/

Note 2: Climate and Forecast (CF) Convention should be version 1.7 or above – see http://cfconventions.org/

Note 3: Attribute Convention for Data Discovery (ACDD) discovery metadata convention version 1.3 or above – see http://wiki.esipfed.org/index.php/Category:Attribute_Conventions_Dataset_Disc

MRD-770 A CIMR L1b data product shall contain the following variables (to be consolidated during Phase B2/C/D).

Note 1: The exact content of L1b data products depends on the final implementation of CIMR.

Note 2: The following parameters are expected: the time of measurement; calibrated brightness temperatures for each channel in native instrument geometry at a resolution of 0.01K; the Earth-fixed location of each measurement at the centre of each footprint; earth incidence angle, earth azimuth angle, solar zenith angle, solar azimuth angle, land/ocean fraction for effective(integrated) footprint, Ionosphere, Moon and Galaxy relevant parameters; uncertainty estimates for each measurement; calibration parameters applied to the data.

Note 3: L1b files use netCDF4 Groups to structure the information.

Note 4: NetCDF global Attributes:

<table>
<thead>
<tr>
<th>title</th>
<th>“CIMR L1b product”</th>
</tr>
</thead>
<tbody>
<tr>
<td>disposition_mode</td>
<td>(“Test”</td>
</tr>
<tr>
<td>product_ID</td>
<td>Unique identification of the product</td>
</tr>
<tr>
<td>processing_level</td>
<td>(“L1a”</td>
</tr>
<tr>
<td>reprocessing_ID</td>
<td>Unique identification of the reprocessing run</td>
</tr>
<tr>
<td><strong>production_date</strong></td>
<td>Product creation date (UTC) e.g. 2025-07-29T07:14:29.000Z</td>
</tr>
<tr>
<td>---------------------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>sensing_start_time_utc</strong></td>
<td>UTC time of start of sensing data formatted in CF date and time format with millisecond precision</td>
</tr>
<tr>
<td><strong>sensing_end_time_utc</strong></td>
<td>UTC time of end of sensing data formatted in CF date and time format with millisecond precision</td>
</tr>
<tr>
<td><strong>orbit_start</strong></td>
<td>Absolute orbit number at sensing_start_time_utc</td>
</tr>
<tr>
<td><strong>orbit_end</strong></td>
<td>Absolute orbit number at sensing_end_time_utc</td>
</tr>
<tr>
<td><strong>processing_centre</strong></td>
<td>Data processing centre</td>
</tr>
<tr>
<td><strong>contact_id</strong></td>
<td>Name (e.g. European Space Agency)</td>
</tr>
<tr>
<td><strong>processor_flag_description</strong></td>
<td>Explanation of processor data flags</td>
</tr>
<tr>
<td><strong>quality_flag_description</strong></td>
<td>Explanation of quality data flags</td>
</tr>
<tr>
<td><strong>science_flag_description</strong></td>
<td>Explanation of science data flags</td>
</tr>
<tr>
<td><strong>netcdf_version</strong></td>
<td>Version of NETCDF used</td>
</tr>
<tr>
<td><strong>CF_version</strong></td>
<td>Version of CF convention used</td>
</tr>
<tr>
<td><strong>ACDD_version</strong></td>
<td>Version of ACDD used</td>
</tr>
<tr>
<td><strong>TBD</strong></td>
<td>TBD</td>
</tr>
</tbody>
</table>

**Note 5: NetCDF Group: Satellite (all orbital values)**

| **orbit parameters:** | • Epoch time in UTC of the orbital elements,  
| | • Semi major axis of the orbit at epoch time,  
| | • Eccentricity of the orbit  
| | • Inclination of the orbit  
| | • Argument of perigee of the orbit  
| | • Right ascension of the orbit |
| **Location Summary** | • Latitude and longitude of subsatellite point at start of the product  
| | • Latitude and longitude of subsatellite point at end of the product |
| **State Vector and Attitude (all in Earth Fixed Reference Frame)** | • Time of the state vector and attitude items  
| | • X,Y,Z position of the state vector  
| | • X,Y,Z velocity of the state vector  
| | • Yaw, Roll, Pitch attitude error |
| **Leap Second Information** | • Time and “direction” of leap second event if one occurs during the product. |
| **Manoeuvre Information** | • Number of manoeuvres during the product  
| | • Time of start and end of each Manoeuvre |

**Note 6: NetCDF Group: Processing**
<table>
<thead>
<tr>
<th>processor_name</th>
<th>“CIMR_L1b”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Versions</td>
<td>Versions of the processor software, of the file format, of the input parameters (if any), of the ATBD describing the processor, etc...</td>
</tr>
<tr>
<td>processing_mode</td>
<td>NRT, reprocessing, backlog.</td>
</tr>
<tr>
<td>upstream_source</td>
<td>name of the upstream file (typically L1a file)</td>
</tr>
<tr>
<td>creation time</td>
<td>time when the processor is run to generate this product</td>
</tr>
</tbody>
</table>

**Note 7: NetCDF Group: Calibration Data (to be adapted to CIMR calibration strategy)**

<table>
<thead>
<tr>
<th>NeDT parameters</th>
<th>NeDT at calibration loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>offset</td>
<td>gain, non-linear parameters</td>
</tr>
<tr>
<td>counts</td>
<td>“counts” at the calibration loads</td>
</tr>
<tr>
<td>temperatures</td>
<td>temperature readings relevant for calibration</td>
</tr>
<tr>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

**Note 8: NetCDF Group: Navigation Data (one for each forward and backward scan)**

<table>
<thead>
<tr>
<th>time</th>
<th>time for each observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>observation position and geometry</td>
<td>The Earth-fixed location of each measurement; (at the centre of integrated footprint); - earth incidence angle, earth azimuth angle, solar zenith angle, solar azimuth angle, land/ocean fraction for effective (integrated) footprint, terrain elevation, sun glint angle, parallax latitude and longitude shift,</td>
</tr>
<tr>
<td>RFI information</td>
<td>RFI glint angle, RFI flag, all information from the on-board RFI processor (e.g. number of sub-bands discarded...)</td>
</tr>
<tr>
<td>Other parameters</td>
<td>Ionosphere, Moon and Galaxy relevant parameters.</td>
</tr>
<tr>
<td>Platform information at the time of each observation</td>
<td>Orbit angle, spacecraft altitude, sub-satellite lat/lon,</td>
</tr>
<tr>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

**Note 9: NetCDF Group: Measurement Data (one for each forward and backward scan)**
<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>brightness temperatures</td>
<td>Tb for each feed (with at least 1/100K precision), for all feeds, frequency channels (h+v), (Full Stokes Vector is a goal)</td>
</tr>
<tr>
<td>Uncertainty</td>
<td>Standard total uncertainties for all Tbs</td>
</tr>
<tr>
<td>lobe corrections</td>
<td>side and other lobes (e.g. grating lobes) corrections</td>
</tr>
<tr>
<td>Bt_difference</td>
<td>Difference between forward scan and backward scan Bt [K]</td>
</tr>
<tr>
<td>Faraday rotation</td>
<td>Estimated Faraday rotation</td>
</tr>
<tr>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

**Note 10: NetCDF Group: Flags (one for each forward and backward scan)**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality flags</td>
<td>Per channel, per scan. Concerning Tbs, geolocation, calibration, navigation</td>
</tr>
<tr>
<td>Surface Type</td>
<td>A first-guess of surface type (open ocean, sea-ice, land, lake,...)</td>
</tr>
<tr>
<td>Processing flags</td>
<td>Issues/warning raised during processing</td>
</tr>
<tr>
<td>General quality</td>
<td>Summarized of the quality of the product (missing chunks, etc...)</td>
</tr>
<tr>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

**MRD-780** Standard total uncertainties shall be delivered together with all CIMR measurements for all L1b data products.

*Note 1: This is critical for the L2 processor design and for application of higher L2 products that are used by data assimilation systems [AD-2].*

**MRD-790** The methods used to generate and propagate uncertainties shall be coherent across product levels, and documented for users for all L1b data products.

*Note 1: This is critical for the L2 processor design and for application of higher L2 products that are used by data assimilation systems [AD-2].*

*Note 2: Uncertainty estimates in higher-level products need to reflect uncertainty propagated from lower levels, if significant.*

### 4.3.5 L1c Gridded Products

L1b products are further processed to generate more user-friendly remapped products called CIMR L1c products. L1c products have the same content as L1b (brightness...
temperatures and associated quantities), but the centre points of all channels are matched to location (and resolution) of a target-frequency channel. All other L1b data are synthesized by interpolation to the footprint of the target-frequency channels.

**L1c** products contain geolocated images. Geolocation derives the Earth-locations of the acquired footprints and maps these onto an appropriate grid defined using the Equal-Area Scalable Earth (EASE, [https://nsidc.org/data/ease/ease_grid2.html](https://nsidc.org/data/ease/ease_grid2.html)). The EASE Grids (Brodzik et al., 2012; 2014) utilize an equal-area projection because that minimizes the amount of distortion over the poles, using the Northern and Southern Hemisphere projections, and on other key areas of the globe, using the temperate and global projections. Since areas don’t change between grid cells, visualization and inter-comparison operations are greatly simplified and analysis is more convenient. EASE2 grids are intended to be versatile formats for global-scale gridded data, including remotely sensed data. Data can be expressed as a digital array with one of many possible grid resolutions, which are defined in relation to one of four possible projections: Northern / Southern Hemispheres (Lambert’s equal-area, azimuthal), temperate zones (cylindrical, equal-area), or global (cylindrical, equal-area).

Four EASE Grid projections comprise two polar azimuthal equal-area projections for the Northern and Southern hemispheres, a global cylindrical equal-area projection, and a temperate zone cylindrical equal-area projection (Figure 4.3.5.1); the temperate projection is a subset of the global projection with different latitudinal bounds.

![Figure 4.3.5.1. EASE-Grid map projections: The Northern Hemisphere Azimuthal (top left), the Southern Hemisphere Azimuthal (top right), the Global Cylindrical (bottom), and the Temperate Cylindrical (bottom, excluding the area shaded in grey). Note, the temperate projection covers the same longitudinal extent as the global projection but excludes the areas north and south of approximately 67° latitude; the global projection extends to approximately 84° N and S (from https://nsidc.org/ease/ease-grid-projection-gt)](image)

The EASE grid has a flexible formulation. By adjusting one scaling parameter it is possible to generate a family of multi-resolution EASE grids that “nest” within one another. The nesting can be made “perfect” in that smaller grid cells can be tessellated to form larger...
grid cells. This feature provides CIMR data products with a convenient common projection for various observations. Figure 4.3.5.2 illustrates the different resolutions for the 3-, 9-, 18- and 36-km EASE grids (which is the same scheme used by the SMAP mission).

![Diagram of EASE grids](image)

**Figure MRD-4.3.5.2.** Perfect nesting in EASE2 grids – smaller grid cells can be tessellated to form larger grid cells.

L1c products make full use of the perfect tessellation capabilities of the EASE2 grid. Individual L1b product files shall be remapped to the three EASE2 grids (two polar, one temperate) thus for 1 L1b product file, there are 3 L1c product files.

The exact spacing of the tessellated grids holding the various CIMR T_B channels and their resolution-matched versions is not firmly specified as these will depend on the final characteristics of CIMR, e.g. of the number of samples per L1b footprints (see MRD-230).

Within EASE-2 the correspondence between a footprint and the CIMR instrument scan from which it originated has now been lost. L1b footprint data are copied from the instrument grid to the image grid by means of a re-gridding and re-mapping algorithm.

The L1c product will be helpful for retrievals using geophysical products combining observations at different frequencies. In the L1b product, they have different footprints, that see different regions on surface, potentially introducing noise in the retrieval product.

As these products are mapped products, the standard total uncertainties that accompany each grid cell must include the additional uncertainty associated with re-mapping. Furthermore, NEΔT values may be better represented for a given grid cell rather than per beam in L1bR products to account for under-sampling of high-frequency channels compared to the low frequency channels.

<table>
<thead>
<tr>
<th>Product</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIMR L1c</td>
<td>Gridded Top of the atmosphere calibrated brightness temperature for each channel derived from CIMR L1b data files. All parameters of a L1b file are included in the corresponding L1c file. Additional parameters relating to the gridding process and the implications of the gridding process(e.g. uncertainty, NeDT are likely to be different compared to native L1b etc.) will be included in a L1c file.</td>
</tr>
</tbody>
</table>

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Issue Date: 30/09/2019, Ref: ESA-EOPSM-CIMR-MRD-3236, Version 3.0 ISSUED
L1c are geolocated images. Geolocation derives the Earth-locations of the acquired footprints and maps these onto an appropriate grid defined using the Equal-Area Scalable Earth (EASE, https://nsidc.org/data/ease/ease_grid2.html). The EASE Grids (Brodzik et al., 2012; 2014) utilize an equal-area projection because that minimizes the amount of distortion over the poles, using the Northern and Southern Hemisphere projections, and on other key areas of the globe, using the temperate and global projections.

MRD-800 L1c data products shall be defined from a corresponding L1b file and contain all L1b parameters that have been geolocated and gridded to form an image grid for each channel.

*Note 1: The exact specification and content of L1c products is TBC.*

MRD-810 L1c files should be in EASE2 formant and follow the latest Climate and Forecast (CF) Convention and latest Attribute Convention for Data Discovery (ACDD) discovery metadata convention.

*Note 1: EASE2 see https://nsidc.org/data/ease/ease_grid2.html*

*Note 2: Climate and Forecast (CF) Convention should be version 1.7 or above – see http://cfconventions.org/*

*Note 3: Attribute Convention for Data Discovery (ACDD) discovery metadata convention version 1.3 or above – see http://wiki.esipfed.org/index.php/Category:Attribute_Conventions_Dataset_Discovery*

MRD-820 CIMR L1c data products shall be produced and made available to all users containing the following variables (to be defined during Phase B2/C/D).

*Note 1: The exact content of L1c data products depends on the final implementation of CIMR.*

MRD-830 Standard total uncertainties shall be delivered together with all CIMR measurements for all L1c data products.

*Note 1: This is critical for the L2 processor design and for application of higher L2 products that are used by data assimilation systems [AD-2].*

MRD-840 The methods used to generate and propagate uncertainties shall be coherent across product levels, and documented for users for all L1c data products.

*Note 1: This is critical for the L2 processor design and for application of higher L2 products that are used by data assimilation systems [AD-2].*

*Note 2: Uncertainty estimates in higher-level products need to reflect uncertainty propagated from lower levels, if significant.*
4.3.6 L2 Products

L2 products are generated from L1b or L1c data products using appropriate retrieval algorithms. The output data set is a field of geophysical parameter, with associated uncertainties and processing flags.

MRD-850  L2 geophysical data products shall be produced and made available to all users.

Note 1: L2a products are those that are used to validate the performance of the mission.
Note 2: See definition of product levels.

MRD-860  L2 files should be NetCDF/EASE2 like format, following the latest Climate and Forecast (CF) Convention and latest Attribute Convention for Data Discovery (ACDD) discovery metadata convention.

Note 1: CIMR L2 products are Gridded Products on relevant EASE2 grids.
Note 2: Network common Data format (NetCDF) see https://www.unidata.ucar.edu/software/netcdf/
Note 3: EASE2 see https://nsidc.org/data/ease/ease_grid2.html
Note 4: Climate and Forecast (CF) Convention should be version 1.7 or above – see http://cfconventions.org/
Note 5: Attribute Convention for Data Discovery (ACDD) discovery metadata convention version 1.3 or above – see http://wiki.esipfed.org/index.php/Category:Attribute_Conventions_Data_set_Discovery.

MRD-870  Standard total uncertainties shall be delivered together with all CIMR measurements for all L2 data products.

Note 1: This is critical for the L2 processor design and for uptake of L2 products by data assimilation systems [AD-2].
Note 2: Standard Total Uncertainties are expected to be propagated from L1 to L2A.

MRD-880  The methods used to generate and propagate uncertainties shall be coherent across product levels, and documented for users for all L2 data products.

Note 1: This is critical for the L2 processor design and for uptake of L2 products by data assimilation systems [AD-2].
Note 2: Uncertainty estimates in higher-level products need to reflect uncertainty propagated from lower levels, if significant.
CIMR shall generate L2 sea ice concentration (SIC) and Sea Ice Extent (SIE) [AD-1], [AD-2] products at a spatial resolution of ≤5 km and a standard total uncertainty of ≤5% with sub-daily coverage of the Polar Regions and daily coverage of Adjacent Seas.

Note 1: This requirement addresses PRI-OBJ-1 as requested by [AD-1], [AD-2] and [AD-3].

Note 2: The target standard total uncertainty of ≤5% is realistic for homogeneous scenes, and non-melting surface conditions. In regions of high gradient (e.g. the marginal ice zone) and under surface melt conditions, the standard total uncertainty will be larger.

Note 3: SIE is derived from SIC.

Note 4: With a significant enhancement of spatial resolution compared to current and planned missions, a 6.925 GHz channel in combination with a high resolution 5 km channel at 18.7 and 36.5 GHz is an optimal channel for sea ice concentration measurements (e.g. Ivanova et al., 2015).

Note 5: The best performance SIC products will be obtained when CIMR data are used together with other satellite measurements including scatterometer, SAR and optical data to help e.g. resolve melt water ponds during summer amongst other issues.

CIMR shall generate L2 Sea Surface Temperature (SST) [AD-1], [AD-2] products at a resolution of 15 km in the open ocean, with a standard total uncertainty of 0.2 K for 95% global coverage and sub-daily coverage in the Polar Regions and Adjacent Seas.

Note 1: This requirement addresses PRI-OBJ-2 as requested by [AD-1], [AD-2] and [AD-3].

Note 2: The native footprint for 6.9 GHz channels is <15 km. This requirement implies image-processing and analysis techniques are used to achieve a gridded resolution of 5 km.

Note 3: SEC-OBJ-1 requests SST with daily coverage of the global ocean and inland seas.

Note 4: The achievable geophysical accuracy of SST products is linked to the specific retrieval algorithm used and the final CIMR instrument specification (e.g. NEAT and channel selection).

Note 5: Calculated for a theoretical retrieval as the mode value of daily ocean average discrepancies assuming no uncertainty in the validation data set and varying between 0.15 K to 0.45 K for cold waters (Kilic et al, 2018).

Note 6: 0.2 K SST target needs to be appraised for high latitudes in particular as it is unlikely to be met in a single retrieval sense. The SST retrieval must be considered in a 2-d sense including forward and backward views, including implications of over-sampling on noise reduction and including potential noise reduction from separation of scales, where applicable.

Note 7: The PEG accuracy is stated as 0.1 K (and is not uncertainty, but “accuracy”) and is given in context of climate – without an indication of frequency; whereas the oceanography requirement in PEG is for 6 hourly and without an uncertainty number. Both permit a degree of temporal (multi-orbit) averaging in the specification of the SST uncertainty – i.e., the 0.2 K need not necessarily be a single-pass uncertainty to be within spirit of PEG. Whether multi-pass methods
significantly reduce the uncertainty crucially depends on the instrumental sources of error and their correlation properties. Practically speaking, an uncertainty of 0.2 K in a daily average SST (to be met where SST is not changing significantly within the day) would be a significant advance relative to present state of the art (particularly in the high latitudes).

**MRD-910**

CIMR shall generate thin (≤0.5 m) sea ice thickness [AD-1], [AD-2] L2 data products in freezing conditions at a spatial resolution of <60 km, with a thickness standard total uncertainty goal of 10% and daily coverage of the Marginal Ice Zone in the Polar Regions and Adjacent Seas.

*Note 1:* This requirement addresses SEC-OBJ-2 as requested by [AD-1], [AD-2] and [AD-3]. The requirement is relevant to freezing conditions.

*Note 2:* There is a need to significantly oversample L-band measurements in the across-scan and flight direction and make use of additional channels to sharpen L-band products.

*Note 3:* Channels that can measure thin sea ice thickness up to a depth of ~0.5 m include 1.4315 GHz.

*Note 4:* Channels that can measure thin sea ice thickness up to a depth of ~0.2 m include 6.9 GHz.

*Note 5:* Standard uncertainty assumes uniform, level ice within the measurement FoV. If a mixture of ice types and open water prevail in the FoV the uncertainty is expected to be higher.

*Note 6:* Assuming uniform, level ice within the FoV. If a mixture of ice types and open water prevail in the FoV the uncertainty is expected to be higher. Kaleschke et al (2016) note that an uncertainty of <30% is possible based on SMOS sSIT measurements although validation remains a challenge using aircraft and in situ data sets.

*Note 7:* As a Secondary Objective, this requirement does not drive the instrument design.

**MRD-920**

CIMR shall generate daily sea ice drift [AD-1], [AD-2] L2 products with a standard total uncertainty of ≤3 cm/s at a spatial resolution of ≤25 km with daily coverage of the Polar Regions and Adjacent Seas.

*Note 1:* This requirement addresses SEC-OBJ-3 as requested by [AD-1], [AD-2] and [AD-3].

*Note 2:* As a secondary objective, this requirement does not drive the instrument design.

*Note 3:* OSI-SAF product http://osisaf.met.no/p/ice/index.html#lrdrift. CMEMS also has an all year Sentinel-1 SAR based sea ice drift product at 10 km resolution. This product has gaps in coverage due to missing S1 coverage of some polar regions. The microwave radiometer product has a 62.5 km resolution but complete coverage of 2-day sea-ice drift. The current 62.5 km could potentially be improved to better than 25 km with CIMR. Best accuracy, spatial, and temporal resolution would be achieved by merging CIMR sea-ice drift with SAR (Sentinel-1) drifts.
MRD-930  CIMR shall generate L2 Ice stage of development/Ice type [AD-1], [AD-2] and [AD-3] products at a spatial resolution of <15 km with daily coverage of the Polar Regions and Adjacent Seas.

Note 1: This requirement addresses SEC-OBJ-5 as requested by [AD-1] and [AD-2].
Note 2: As a secondary objective, this requirement does not drive the instrument design.
Note 3: Ice type is provided as a number of defined categories (typically new ice, first year ice, second year ice, multi-year ice, fast ice) according to specific spectral signatures.
Note 4: This requirement will benefit from a combination of microwave radiometer data with scatterometer and SAR data from other satellite missions.

MRD-940  CIMR shall generate snow depth on sea ice [AD-1], [AD-2] L2 products in freezing conditions with a standard total uncertainty of ≤10 cm at a spatial resolution of ≤15 km with daily coverage of the Polar Regions and Adjacent Seas.

Note 1: This requirement addresses SEC-OBJ-6 as requested by [AD-1], [AD-2] and [AD-3]. The requirement is relevant to freezing conditions.
Note 2: As a secondary objective, this requirement does not drive the instrument design.

MRD-950  CIMR shall generate L2 products of terrestrial total snow area [AD-1], [AD-2] with a standard total uncertainty of ≤ 10 % at a spatial resolution of ≤15 km with daily coverage of the Polar Regions.

Note 1: This requirement addresses SEC-OBJ-7 as requested by [AD-1], [AD-2] and [AD-3].
Note 2: As a secondary objective, this requirement does not drive the instrument design.

MRD-960  CIMR shall generate L2 products of terrestrial snow water equivalent (SWE) [AD-1], [AD-2] with a standard total uncertainty of < 40 mm at a spatial resolution of ≤15 km with daily coverage of the Polar Regions.

Note 1: This requirement addresses SEC-OBJ-8 as requested by [AD-1], [AD-2] and [AD-3].
Note 2: As a secondary objective, this requirement does not drive the instrument design.

MRD-970  CIMR shall generate L2 products of Ice Surface Temperature (IST) [AD-1], [AD-2] and [AD-3] in freezing conditions with a standard total uncertainty of ≤1.0 K at an effective spatial resolution of ≤15 km with daily coverage of the Polar Regions and Adjacent Seas.

Note 1: This requirement addresses SEC-OBJ-9 as requested by [AD-1], [AD-2] and [AD-3]. The requirement is relevant to freezing conditions.
Note 2: As a secondary objective, this requirement does not drive the instrument design.
Note 3: For IST measurements, 6.925 GHz channels with significant enhancement of spatial resolution compared to current and planned missions, in combination with thermal infrared imagery, is required.

Note 4: IST is typically retrieved using thermal infrared (TIR) measurements that are confounded by the presence of clouds. At microwave frequencies, an effective temperature \( T_{\text{eff}} \) of the emitting layer due to the finite emission depth at a given frequency is retrieved. At 6.925 GHz (for example) this is more representative of the snow-ice interface temperature than the snow surface temperature in contact with the atmosphere.

Note 5: Additional thermal infrared satellite imagery will be required to achieve a true IST.

MRD-980 CIMR shall generate daily L2 products of sea surface salinity (SSS) [AD-3] over the 95% global ocean from at a resolution of <60 km and a standard total uncertainty of ≤0.3 pss. over monthly timescales.

Note 1: Salinity is a ratio and has no units - see definition of sea surface salinity
Note 2: This requirement addresses SEC-OBJ-9.
Note 3: As a secondary objective, this requirement does not drive the instrument design.
Note 4: A primary band for sea surface salinity measurement is 1.4315 GHz. However other CIMR bands should be used to sharpen the native L-band spatial resolution of SSS products.
Note 5: There is a co-dependency of SSS with SST measurements. SSS has a strong dependency on SST at L-band.
Note 6: Successful SSS retrievals require a measurement of ocean surface roughness ideally from CIMR itself and from co-located and contemporaneous measurements from, for example, scatterometer data such as MetOp-SG (B) SCA.

MRD-990 CIMR shall generate daily L2 products of wind speed and direction over 95% global ocean from at a resolution of <40 (TBC) km and a standard total uncertainty of ≤2 ms\(^{-1}\).

Note 1: The modified Stokes vector includes the vertical and horizontal polarizations and the third and fourth Stokes parameters that provides sufficient information to retrieve an estimate of the ocean surface wind vector. Because the wind direction dependence differs for the 4 Stokes parameters it is possible to resolve the vector wind ambiguities without the use of an ancillary numerical weather prediction field.
Note 2: At wind speeds below 6 m s\(^{-1}\), the wind direction signal from microwave radiometry is small in all polarizations leading to noisy wind direction estimates. At 6 m s\(^{-1}\), the uncertainty of WindSat wind direction is 20° (Hilburn et al., 2016). Above 8 m s\(^{-1}\), the uncertainty is 10°−15° and is similar to that derived from scatterometers (Ricciardulli et al., 2012; Hilburn et al., 2016). At high winds (above 10 m s\(^{-1}\)) the wind direction signal derived from microwave radiometry is strong in all 4 Stokes parameters.
4.3.7 Product Delivery Latency

The EC Polar Expert Group timeliness requirements call for timeliness of 1 hour for SIC and Thickness of thin-ice, and 6 hours for SST as well as Sea Ice type/stage, and Ice Surface Temperature. In keeping with the existing Copernicus ground segment for the first-generation Sentinel series, a near real time timeliness of \( \leq 3 \) hours is specified.

**MRD-1000** The CIMR mission shall deliver all L1a, L1b, L1c and L2 products in Near Real Time (NRT) expressed as \( \leq 3 \) hours of measurement acquisition at the user point of pickup.

*Note 1:* For navigational needs in the Polar Regions, a more stringent timeliness requirement may be required which is covered by MRD-880.

*Note 2:* See definition of Near Real Time.

*Note 3:* This requirement implies that L1 products are available not later than 2 hours after satellite measurement acquisition.

*Note 4:* This is consistent with the timeliness requirements of the Copernicus system.

Given that CIMR is focused on the timely delivery of data to support activities in the Arctic Ocean, including operational aspects associated with shipping, exploration, general operations, and other applications requiring real-time access to information, a more stringent timeliness requirement of \(< 1\) hour is anticipated by European ice services. Such a timeliness enables the services to combine CIMR data with Sentinel-1 (and other) SAR imagery in support of tactical navigation needs. Automated ice charting systems are in active development with participation of the Finnish, Danish/Greenlandic and Norwegian Ice Services as well as their research departments. The current generation of automatic processing systems use a combination of Sentinel-1 SAR and AMSR2 data and minimize the latency from acquisition of data to delivery to end users. In the future CIMR would replace AMSR2.

The ice service requirement for Sentinel-1 is delivery of L1 SAR data \(< 1\) hour after acquisition (for their main areas of interest, which is the Baltic and the European/Atlantic sector of the Arctic and subarctic). Other Ice Services such as the Canadian, Russian and the USA would certainly appreciate a similar low latency. It is important to realize that the value of ice observations in the dynamic regions of the North Atlantic/Arctic for tactical navigation decreases exponentially with time. Considering a target 5 km resolution, it is worth noting that in dynamic cases, sea ice may move 1-2 km each hour. From reception of satellite data at the ice services to delivery of the automatic products to the end user, the ice service timeliness is \(< 15\) minutes. Finally, it should be noted that communication in the Polar Regions remains a challenge with limited coverage for data delivery using conventional approaches.

A direct broadcast capability for data the CIMR mission in the Polar Regions has been considered but due to the expected challenges in data processing (e.g. compensation for grating lobes and side-lobes if a mesh antenna is implemented) this would require an extensive on-board processing capability. A better solution is to focus on the improvement of on-ground data processing and employ a system that can downlink and process polar region data in the most efficient manner. DMI expressed support for this approach noting...
that “acquiring CIMR data at the DMI receiving station in Kangerlussuaq could be of benefit users in Greenland and future plans for the DMI Ice Service”.

**MRD-1010** In support of Arctic polar navigational applications, specific CIMR SIC and other products (TBC) shall be available at the user point of data pickup within \( \leq 1 \) hour of measurement acquisition at the baselined ground station(s).

*Note 1:* Communication in the Polar Regions remains a challenge with limited coverage for data delivery using conventional approaches. Given that CIMR is focussed on the timely delivery of data to support activities in the Arctic Ocean, including operational aspects associated with shipping, exploration, general operations, and other applications requiring real-time access to information enhanced timeliness in the polar regions is highly desirable.

*Note 2:* Several ice service providers (also providing ice charts to CMEMS) state that a major advantage of an operational high-resolution microwave radiometer is in the synergy with Sentinel-1 for which the requirement is \(<60\) minutes from sensing. This synergy can involve artificial intelligence (AI) techniques, for combining the active and passive data.

*Note 3:* In ice charting the validity and utility of data decrease exponentially with the delay from sensing since ice is dynamic. Therefore, data should be made available to users less than 90 minutes after sensing (preferably less than 60 minutes).

*Note 4:* Implementation options could include the use of a pass-through downlink transmitting acquired data to a core ground station while the data is being recorded (as used by Sentinel-1), use of additional ground stations, use of dedicated ground networks etc.

*Note 5:* Users in other Polar regions and adjacent Seas may have similar requirements that are to be confirmed.

*Note 6:* It is assumed that the baseline ground station is Svalbard. However, additional ground stations may be used if required in which case this requirement must be assessed on a case-by-case basis.

### 4.4 User Service Requirements

#### 4.4.1 Routine Processing Requirements

**MRD-1020** The users shall have access to all mission data products and all relevant information to allow the mission data products exploitation, including auxiliary data: including the following (content TBC during Phase B/C/D):

*Note 1:* This includes e.g. data quality information, system anomalies, planning for upcoming operations, production performance, product descriptions, changes in production baseline (processor update/reprocessing campaign) etc. This includes also offering a catalogue of the mission data products.

*Note 2:* The User Service should provide Users with adequate planning of any significant activities or events in the forthcoming period.

*Note 3:* Any change in the data generation or processing should be communicated to all data users in a timely manner. A timely manner means when a chance is known...
it is communicated well in advance of that change. For more immediate changes (e.g. Reactive decisions were required) communication should be immediate (e.g. via email list).

Note 4: The User Service should produce regular reports to Users on the status of data services including any significant operational events.

Note 5: A data product Archival and Retrieval Service should be accessible to Users via at least one data network.

Note 6: A catalogue of all CIMR mission data product files should be maintained, storing all relevant identification information and be available to all users. This is essential to services and users in the operational domain that wish to perform reanalyses.

Note 7: It should be possible for users to retrieve mission data products stored in the Archive, either interactively or by submission of an order for their periodic transmission.

Note 8: An Archival and Retrieval User Service is required to provide an archive for all mission data products and a corresponding catalogue of products and means for retrieving them. The service may also be extended to mission products from sources other than the Mission that support product generation, calibration and validation activities.

Note 9: The Archival and Retrieval Service will be available to all Mission Users, however extent and level of service may differ, depending on the User’s category. A basic form of access to the catalogue should be available on a free and unrestricted basis.

MRD-1030 The user shall be able to search for mission data products using various search criteria and be able visualize their contents with a response time sufficiently rapid to enable interactive usage.

Note 1: This could be a web-based service.
Note 2: The criteria, such as e.g. time window, area of interest are TBD in a later phase

MRD-1040 The User Service shall inform Users of all significant activities or events planned with a lead time of at least 4 weeks.

Note 1: This is essential to services and users in the operational domain.
Note 2: For more immediate changes (e.g. Reactive decisions were required) communication should be immediate (e.g. via email list)

MRD-1050 Any change in the data generation or processing shall be communicated to all data users with a lead time of at least 8 weeks.

Note 1: This is essential to services and users in the operational domain.
Note 2: For more immediate changes (e.g. Reactive decisions were required) communication should be immediate (e.g. via email list)
MRD-1060  The User Support service shall produce, maintain and disseminate one or more User Guides to provide information about the mission and guidance for exploitation of the data products.

Note 1: This could be a web-based service.

MRD-1070  The User Service shall produce regular reports to Users on the status of data services including any significant operational events.

Note 1: This is essential to services and users in the operational domain.
Note 2: Documentation of operational events (and planning) should be accessible via web interface to all users.
Note 3: Regular reports implies a monthly timescale as provided from the current generation of Sentinel satellites.

MRD-1080  A data product Archival and Retrieval Service shall be accessible to Users via at least one operational data network.

Note 1: This is essential to services and users in the operational domain that wish to perform reanalyses.

MRD-1090  It shall be possible for users to retrieve mission data products stored in the Archive, either interactively or by submission of an order for their periodic transmission. This service should allow temporal, geographical, and product-type sub-setting.

Note 1: This could be a web-based service.

4.4.2 Reprocessing Requirements

MRD-1100  The User Services shall provide a Reprocessing Service to generate data products at Levels 1a, L1b, L1c, and L2.

Note 1: Reprocessing is a fundamental part of the CIMR mission.

MRD-1110  The Reprocessing Service shall be sized such that it can reprocess up to 7 years (TBC) of data from Level 0 to Level 2.

Note 1: This is essential if meaningful reprocessing is to be achievable.

MRD-1120  All data acquired during Phase-E1 of the mission shall be reprocessed into Level 2 products after completion of Phase E1.
4.5 Calibration and Validation Requirements

Calibration and validation will, principally, be carried out during the commissioning and verification phases. **Calibration** addresses aspects of the measurement system, which need to be addressed in the generation of the level 1b data products. Since they are concerned with the conversion from the instruments’ measurement quantities into standard physical units, they may be addressed by many techniques. The geolocation accuracy is to be quantified and -if possible- improved as part of the Calibration step. **Validation**, is a term used in the context of the conversion of these instrument measurements into the geophysical quantities. Validation is exclusively concerned with the characterisation of uncertainty in the level 2 parameters. Commonly, this is achieved by suitable analysis of the level 2 data themselves, often in combination with **Fiducial Reference Measurements**.

**MRD-1140** All the contributing sources of uncertainty in L1a, L1b, L1c and L2 data products shall be identified in a Scientific Calibration and Validation Concept Document.

*Note 1: The Calibration and Validation Concept document provides the framework upon which the activities defined in a Calibration and Validation Plan are based.*

*Note 2: The Calibration and Validation Concept document includes the sources of uncertainty in the geo-location of level 1b data products.*

**MRD-1150** A technique for the quantification and propagation of each of the contributing sources of uncertainty in the L1a, L1b, L1c and L2 data products shall be identified in the Scientific Calibration and Validation Concept Document.

*Note 1: For example, techniques may include validation campaigns using dedicated ships/aircraft, use of existing fiducial Reference Measurements, or comparison with other satellite data.*

*Note 2: In designing such techniques and associated methods, care needs to be taken with the spatial and temporal scales and correlation of the uncertainties.*

*Note 3: Techniques to quantify and -if possible improve- the geo-location accuracy should be identified as well (e.g. against land contours, Wiebe et al. 2008).*
MRD-1160 A Scientific Calibration and Validation Plan shall be established that describes how all measurements and techniques identified as necessary in the Scientific Calibration and Validation Concept will be implemented.

**Note 1:** The Scientific Calibration and Validation Plan should identify responsible entities for all calibration and validation measurements and techniques.

**Note 2:** The Calibration and Validation Plan should identify the schedule for all activities planned.

MRD-1170 A Scientific Calibration and Validation Team (CIMR-VT) shall be established to assist in the implementation of the Scientific Calibration and Validation Plan.

**Note 1:** The Scientific Calibration and Validation team should be linked to existing infrastructure and that can perform long-term (i.e. beyond Phase E1) calibration and validation activities according to the Scientific Calibration and Validation Plan.

### 4.6 Software Requirements

MRD-1180 A community, open source, modular library software shall be made available (and maintained through the life time of the mission) to simulate CIMR brightness temperature observations (at L1B) from gridded fields at Earth’s surface, providing a satellite simulator for CIMR. A Radiative Transfer Model (RTM) is included to simulate TOA brightness temperature from the gridded geo-physical quantities.

**Note 1:** The satellite simulator is to support Copernicus Services and Weather Prediction Centres, in the task of directly assimilating CIMR TB observations into geophysical models. It should thus be designed so that it allows comparison of simulated vs measured CIMR data in swath projection.

**Note 2:** As a limit case (by bypassing the RTM), the satellite simulator is limited to a geometric operator that aggregates geo-reference surface gridded fields (e.g. TB, T2m from a NWP model,...) to any L1a, L1b sample and field-of-view.

**Note 3:** The most common geographic projections must be supported as input (including but not limited to: EASE2, polar stereographic, rotated lat/lon,...).

**Note 4:** The satellite simulator should, as much as possible, re-use existing open source libraries.

**Note 5:** “modular” means the interfaces of the software implementing the various stages of the simulator are well defined and documented, so that a user can change parts of the simulator (e.g. the RTM) or access intermediate data.

**Note 6:** the accurate simulation of the L1B observations may require that L1A footprints are simulated (including contribution by side- and grating-lobes) and the L1A-L1B side-grating-lobe correction algorithm (as used in the operational processing chain) be applied. The need for this should be assessed with reference to the case of simulating sea-land boundaries.

**Note 7:** the same software module (or part of) can be used to support the development of CIMR L2 algorithms, by easing the task of collocating auxiliary fields (e.g. NWP and Ocean re-analysis and forecasts fields) with the L1b observations.
5 PRELIMINARY SYSTEM CONCEPT(S) AND CHARACTERISTICS

5.1 CIMR mission preliminary system characteristics

Working exclusively from the User requirements set out in [AD-1], [AD-2] and [AD-3] the following CIMR mission characteristics are established:

- The mission will take advantage of the long-standing experience of Microwave Radiometer development and data utilisation in Europe (starting with science team contributions to the Scanning Multi-frequency Microwave Radiometer (SMMR) on Nimbus-7 in 1978) [AD-2], the ESA Multichannel Imaging Microwave Radiometer (MIMR) studied for the USA EOS-PM Polar Platform18 and MetOp preparatory programme, the EPS-SG system, the Sentinel-3 Microwave Radiometer (MWR), the ESA Microwat activity (2010-2015) and related ESA activities on large antenna technologies.

- A multi-frequency microwave instrument with a wide swath is considered the only possibility to address sub-daily revisit requirements in the Polar Regions [AD-2] with a spatial resolution and dedicated spectral channels for SIC (~5 km) and SST retrievals (~15 km) [AD-2].

- A swath width that offers at least daily revisits in the Polar Regions and Adjacent Seas to observe the associated geophysical parameters with the required spatial and temporal resolutions and coverage requirements is needed [AD-2].

- The mission must offer the best solution from technical, scientific and operational viewpoints (operational daily observations of polar regions and Adjacent Seas in non-precipitating atmospheric conditions, day and night) [AD-2].

- A high degree of synergy with measurements provided by sensors flying on other satellites may be highly advantageous. More generally, the use of a microwave radiometry mission in synergy with active microwave sensors (e.g. wind scatterometer, radar altimeter, SAR imagers) and with optical VIS/IR sensors (e.g. MetOp-SG(A) MetImage) is expected to provide powerful tools/techniques/synergy improve geophysical products and their accuracy for the cryosphere, ocean, land and atmosphere domains. Ice services already make use of AMSR-2 data as a prerequisite for automation of Sentinel-1 SAR SIC retrievals.

- The MetOp-SG (1B) Microwave Imager (MWI) and SCA Scatterometer [AD-2] could be used in synergy with CIMR with the additional benefit of enhanced multi-satellite products (note that AMSR-E and AMSR-2 fly in the NASA A-train (https://atrain.nasa.gov/) to derive similar synergy benefit).

18 Post-EPS Mission Requirements Document, EUM/PEPS/REQ/06/0043, v2D Draft, 2009 included requirements for a Microwave Radiometer with channels centred at 6.9 and 10.65 GHz.
• The MetOp-SG (1A) MetImage sensor could be used in synergy with CIMR with the additional benefit of enhanced multi-satellite thermal infrared and microwave radiometer products.

• The end-to-end mission concept must ensure enhanced continuity of an AMSR-type instrument (specifically of AMSR-2 data on GCOM-W1 that is now close to end of life) [AD-2].

• An L-Band channel is required to address secondary objectives - specifically to retrieve thin (< 0.5m) SIT and SSS and provide continuity to SMOS and SMAP type L-band capability.

• The mission must include a C-band channel (6.9 GHz) with significantly improved spatial resolution to ensure enhanced continuity of AMSR-2 measurements. This frequency, if a resolution of ~15 km can be achieved, offers accurate measurement of SIC and SST in combination with other high spatial-resolution channel data (e.g. a 5 km channel at 18.7 GHz). Furthermore, with the addition of a C-band channel, SST can be measured in the Polar Regions and Adjacent Seas (note that at higher X-band frequencies, the brightness temperature is insufficiently sensitive to changes in SST below ~290 K (Gentemann et al., 2010) [AD-2]).

• The Arctic policy document is a baseline driver for a Polar Ice and Snow mission with the Antarctic being more related to Climate Change when considered together with Arctic. However, a focus is given to the Arctic, related areas and adjacent seas with observations over the Antarctic considered as much as possible [AD-2].

• The mission will be operated in parallel with the Sentinel constellation currently under deployment and/or in operations. In this context, it is assumed that for new missions the same operating paradigm as to the current Sentinel constellation will be applied. The global architecture (Payload Data Ground Segment and its operations) should follow the same standards as the current Sentinel constellation [AD-2].

• This Copernicus mission will not include on-demand rapid tasking of the satellite.

5.2 CIMR mission preliminary system concept
A preliminary mission concept is focused on the provision of one or more multi-frequency conical scanning microwave radiometers using a large antenna flying in synergy with the MetOp-SG(B) and MetOp-SG(A) satellites in the polar regions. The MetOp-SG(B) MicroWave Imager (MWI) offers frequency bands and channels that are similar to AMSR-2 (in particular the high-frequency channels). In addition, co-located and near-contemporaneous measurements from the MetOp-SG(B)SCA scatterometer will be possible. Scatterometer data are ideal to estimate the surface roughness of the ocean and are used in conventional retrievals of SIC, SST, SSS, sea ice type classification, amongst others. MetOp-SG(A) Spatial resolution, radiometric performance and revisit have significantly limited previous and currently planned missions for the primary applications of CIMR. To address this concern, the mission will provide enhanced continuity of AMSR-2-type capability including mandatory band frequencies and spatial resolution of 6.925 (~10-15 km), 10.65 (~10-15 km), 18.7 (~5 km) and 36.5 GHz (<5km). By taking advantage of MWI, the CIMR instrument can focus on improving the spatial resolution and
radiometric fidelity of low frequency (≤18.7 GHz) channels that are best suited to the primary objectives for the mission (SIC and SST).

Compliance to the requirement for SST is based primarily on the performance of vertically and horizontally polarised channels at 6.925 and 10.65 GHz but with a much higher (~10-15 km) spatial resolution than other missions. Furthermore, polarised channels located at 6.925 GHz, provide the best spectral separation between open water and sea ice in SIC retrieval algorithms - but only if a higher spatial resolution can be attained. Using these channels together with polarised channels at 18.7 GHz having a spatial resolution of ≤ 5 km, Europe will be able to provide a superior solution to heritage measurements of SIC and SST without the need for an 89 GHz channel as flown by AMSR-2. The 89 GHz channel, in any case, is compromised by atmospheric attenuation and scattering requiring additional manipulation.

Based on an analysis of Copernicus observational needs, high-level Mission Requirements are derived and articulated for the CIMR mission. Secondary parameters requested by PEG-II and CMEMS, will also make full use of the low frequency channels at high resolution with optimal performance and enlarge the range of ice parameters in non-precipitating atmospheric conditions of interest to Copernicus. The implementation of an additional channel at 1.4315 GHz (L-band) to address secondary requirements for thin sea ice thickness and sea surface salinity products, expressed by PEG and CMEMS, is proposed.
6 DATA PRODUCTS AND USAGE

6.1 Level-0 data products

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIMR L0</td>
<td>Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artefacts (e.g., synchronization frames, communications headers, duplicate data) removed.</td>
</tr>
</tbody>
</table>

6.2 Level-1 data products

<table>
<thead>
<tr>
<th>Product ID</th>
<th>Description</th>
<th>Coverage</th>
<th>Spatial Resolution (km)</th>
<th>Uncertainty</th>
<th>Revisit</th>
<th>Auxiliary data</th>
<th>Ancillary data</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1a (global, instrument geometry, swath based)</td>
<td>Observed sensor engineering data for each channel in instrument geometry at native channel resolution. L1a data are derived from L0 data that have been reconstructed and ordered into orbit files. Data are unprocessed instrument data (counts) at full resolution (i.e. all samples, from all feeds, in all polarisations), time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients (e.g. thermistor counts etc.) and geo-referencing.</td>
<td>Global coverage. Data provided is individual orbit files.</td>
<td>Defined by feedhorn</td>
<td>N/A</td>
<td>Swath based</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>
### L1b (global, instrument geometry, swath based)

| Top of the atmosphere calibrated brightness temperature for each channel in instrument geometry at native channel resolution, derived from a corresponding L1a file. All engineering (e.g. corrections for side-lobes and e.g. grating lobes) corrections have been applied to each sample, radiometric calibration parameters have been applied to each sample to output top-of-atmosphere spectral brightness temperatures (Tb) in units of Kelvin. Geometric information is computed and appended to each sample. | Global coverage. Data provided is individual orbit files linked to corresponding L1a file. | Variable, defined by channel | Variable, defined by channel | Daily | Optional MWI Channels mapped and regridded to CIMR Swath. | 18.7 GHz | 23.8 GHz | 31.4 GHz | 89.0 GHz | TBD |

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6.3 Level-2 data products

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIMR L2</td>
<td>L2 Gridded products are generated from L1b or L1c data products using appropriate retrieval algorithms. The output data set is a field of geophysical parameter, with associated uncertainties and processing flags. The output product stays in swath projection, but the location and spacing of the observations within the L2 file depends on the geophysical product (mostly driven by which L1b or L1c measurements are combined).</td>
</tr>
</tbody>
</table>

The following L2 products are foreseen from the CIMR mission:

<table>
<thead>
<tr>
<th>Product ID</th>
<th>Description</th>
<th>Coverage</th>
<th>Spatial Resolution (km)</th>
<th>Uncertainty</th>
<th>Revisit</th>
<th>Auxiliary data</th>
<th>Algorithm ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIC-R</td>
<td>Sea Ice Concentration</td>
<td>Polar Regions and Adjacent Seas</td>
<td>≤5 km</td>
<td>≤5%</td>
<td>Sub-daily in Polar Regions, Daily in</td>
<td>Optional SCAT sigma-0</td>
<td>SIC-R</td>
</tr>
<tr>
<td>Parameter</td>
<td>Product</td>
<td>Category</td>
<td>Spatial Resolution</td>
<td>Temporal Resolution</td>
<td>Source Parameters</td>
<td>Static Parameters</td>
<td>Areas</td>
</tr>
<tr>
<td>-----------</td>
<td>---------</td>
<td>----------</td>
<td>-------------------</td>
<td>--------------------</td>
<td>-------------------</td>
<td>------------------</td>
<td>-------</td>
</tr>
<tr>
<td>Sea Ice Extent</td>
<td>SIE-R (primary product)</td>
<td>Polar Regions and Adjacent Seas</td>
<td>≤5 km</td>
<td>≤5%</td>
<td>Sub-daily in Polar Regions, Daily in Adjacent Seas</td>
<td>Optional SCAT σ₀ MWR Channels (TBD)</td>
<td>Adjacent Seas</td>
</tr>
<tr>
<td>Global Sea Surface Temperature</td>
<td>SST-G (primary product)</td>
<td>Global ocean and Seas</td>
<td>≤15 km</td>
<td>0.2 ±0.1</td>
<td>Daily (sub-daily in polar regions)</td>
<td>NWP 10m wind, NWP water vapor and temperature profiles, cloud liquid water, MWR Channels (TBD)</td>
<td>SST-G</td>
</tr>
<tr>
<td>Global thin Sea Ice Thickness</td>
<td>SIT-G</td>
<td>Polar Regions and Adjacent Seas</td>
<td>&lt;60 km</td>
<td>≤10%</td>
<td>Daily</td>
<td>Optional SCAT σ₀ MWR Channels (TBD)</td>
<td>SIT-G</td>
</tr>
<tr>
<td>Regional Ice Type/stage of Development</td>
<td>ITY-R</td>
<td>Polar Regions and Adjacent Seas</td>
<td>≤15 km</td>
<td>-</td>
<td>Daily</td>
<td>TBD</td>
<td>ITY-R</td>
</tr>
<tr>
<td>Snow Depth on Sea Ice</td>
<td>SND-R</td>
<td>Polar Regions and Adjacent Seas</td>
<td>≤15 km</td>
<td>&lt; 10 cm</td>
<td>Daily</td>
<td>TBD</td>
<td>SND-R</td>
</tr>
<tr>
<td>Terrestrial Snow Area</td>
<td>TSA-G</td>
<td>Global – Focus on Polar Regions and Adjacent Seas</td>
<td>≤15 km</td>
<td>10%</td>
<td>Daily</td>
<td>TBD</td>
<td>TSA-G</td>
</tr>
<tr>
<td>Terrestrial Snow Water Equivalent</td>
<td>SWE-G</td>
<td>Global – Focus on Polar Regions and Adjacent Seas</td>
<td>≤15 km</td>
<td>&lt; 40 mm</td>
<td>Daily</td>
<td>TBD</td>
<td>SWE-G</td>
</tr>
<tr>
<td>Sea Ice Surface Temperature</td>
<td>IST-R</td>
<td>Polar Regions and Adjacent Seas</td>
<td>≤15 km</td>
<td>≤1.0 K</td>
<td>Daily</td>
<td>TBD</td>
<td>IST-R</td>
</tr>
<tr>
<td>Regional Sea Ice Drift</td>
<td>SID-R</td>
<td>Polar Regions and Adjacent Seas</td>
<td>≤25 km</td>
<td>≤3 cm/s</td>
<td>Daily</td>
<td>TBD</td>
<td>SID-R</td>
</tr>
<tr>
<td>Global Sea Surface Salinity</td>
<td>SSS-G</td>
<td>Global ocean and all inland Seas</td>
<td>≤40 km</td>
<td>≤0.3 pss</td>
<td>Daily</td>
<td>SCAT σ₀ (TBD)</td>
<td>SSS-G</td>
</tr>
</tbody>
</table>
### NWP 10m wind

<table>
<thead>
<tr>
<th>OWS-G</th>
<th>Ocean surface Wind Speed</th>
<th>Global</th>
<th>&lt;15 km</th>
<th>TBC</th>
<th>Daily</th>
<th>TBD</th>
<th>TBD</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOWS-G</td>
<td>High Ocean Surface Wind Speed</td>
<td>Global</td>
<td>&lt;60 km</td>
<td>TBC</td>
<td>Daily</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>CLW-GO</td>
<td>Cloud liquid water (over ocean)</td>
<td>Global ocean</td>
<td>≤15 km</td>
<td>TBC</td>
<td>Daily</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>PCP-GO</td>
<td>Precipitation (over ocean)</td>
<td>Global ocean</td>
<td>&lt;15 km</td>
<td>TBC</td>
<td>Daily</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>SM-G</td>
<td>Soil Moisture</td>
<td>Global</td>
<td>&lt;60 km</td>
<td>TBC</td>
<td>Daily</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>LST-G</td>
<td>Land Surface Temperature</td>
<td>Global</td>
<td>5 km</td>
<td>3K</td>
<td>Daily</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>SWE-GL</td>
<td>Continental surface water extent</td>
<td>Global land</td>
<td>5 km</td>
<td>10%</td>
<td>Daily</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>VI-G</td>
<td>Vegetation Information</td>
<td>Global</td>
<td>&lt;60 km</td>
<td>TBC</td>
<td>Daily</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

From an end user perspective, separate multi-parameter products would be extremely useful. For example a product that include all ocean parameters, one including all sea ice parameters, one for Land products and one for atmospheric products. This should be studied.

### 6.3.1 Polar Sea Ice Concentration algorithm

A large number of SIC retrieval algorithms from microwave radiometer observations exist, using most of the available frequency channels.

Algorithms combining Ka-band (~19 GHz) and Ku-band (~37 GHz) frequency channels are by far the most common because of long time availability (SMMR, SSM/I, SSMIS, AMSR-E/2), relative moderate noise levels compared to near 90 GHz algorithms, and spatial resolution. Examples are the *Comiso*, (1995) Bootstrap algorithm, the NASA Team algorithm (*Cavalieri*, 1991), the Bristol algorithm (*Smith*, 1996), the OSISAF algorithm (*Andersen* et al., 2006), the SICCI2 algorithms (*Lavergne* et al., 2018), mostly developed for SSM/I and being applied to SMMR, SSM/I, SSMIS, and AMSR-E and AMSR2 data. These algorithms are used operationally at many processing centres, such as EUMETSAT OSISAF (feeding into CMEMS), U.S. NSIDC, JAXA, CMA, etc. These SIC products are used to initialize operational global and regional model forecasts, e.g. at ECMWF, at CMEMS and at national meteorological and marine forecasting centre.
Having Ka-band (18.7GHz) and Ku-band (36.5GHz) on board CIMR ensures that this type of algorithms can be used to derive SIC at a high accuracy (<5%) and higher resolution (<5 km) than before. A generic form for a SIC algorithm is expressed by:

\[
C(T) = \frac{\Sigma C(T)}{\Sigma W - <TW>}
\]

where \(C(T)\) is the sea-ice concentration computed from \(T\) (an n-dim vector of L1b Tbs, for example \(T=\{T_{18.7V}, T_{36.5V}, T_{36.5H}\}\) triplet for a 3D algorithm like Bristol or SICCI2). \(<TW>\) and \(<TF>\) are respectively the open water and consolidated sea-ice mean signature, i.e. the water and ice tie-points. \(\phi\) is a unit vector holding the coefficients of the algorithms.

Today’s state-of-the-art SIC algorithms include dynamic tuning of the algorithm coefficients (dynamic tie-points, and dynamic weather filters). This is a key feature to implement as it provides algorithms that are more robust to 1) inter-seasonal and inter-annual changes of open water and sea-ice emissivity, 2) update of channel calibration, 3) changes in auxiliary data. Because tie-points and weather filter thresholds are derived dynamically, the coefficient values entering the algorithms (including the \(<TW>\), \(<TF>\), and \(\phi\) above) cannot be pre-computed (although good pre-launch first-guess and fail-over values can be made).

Today’s state-of-the-art SIC algorithms include RTM-based correction for atmospheric and surface noise contributions. This requires additional auxiliary information from NWP analysis and forecast such as those from ECMWF. At present, air temperature at 2m height (T2m), wind-speed, and Water Vapour fields are routinely used in operational processing chains (e.g. at EUMETSAT OSI SAF).

L2 uncertainties have (at least) two components: the algorithm uncertainty and the smearing uncertainty, that are combined (in terms of variance) into a total uncertainty by:

\[
\sigma^2_{total} = \sigma^2_{algorithm} + \sigma^2_{smear}
\]

Algorithm uncertainty \(\sigma_{algorithm}\) are propagated from those at Level-1B (the NeDTs) but are dominated by the variability of the Water and Sea Ice tie-points:

\[
\Sigma C = \frac{1}{\phi \cdot (\phi \cdot <TW>)} \left[ \Sigma T \phi \Sigma T + (1 - C)^2 \times \phi \Sigma W \phi T + C^2 \times \phi \Sigma I \phi T \right]
\]

where \(\Sigma C\) is \(\sigma^2_{algo}\) and \(\Sigma T\), \(\Sigma W\) and \(\Sigma I\) are covariance matrices for the L1b uncertainty, the Water signature variability, and the Ice signature variability.

The smearing uncertainty \(\sigma_{smear}\) expresses the additional uncertainty arising from combining frequency channels with different locations and/or resolution. It is difficult to express analytically and is typically computed via proxies.

The development of SIC algorithms from microwave radiometer data is an active field of research, and by the time CIMR flies other approaches might have matured further. One of these is multi-variate optimal estimation (OE) that combines more frequency channels, and relies less on ancillary input.
6.3.2 Global and Polar Sea Surface Temperature algorithm

SST retrievals from microwave radiometer measurements have been tested early, as soon as 1978, with dual polarization channels at 6.6, 10.7, 18, 21, 37 GHz from SMMR. It was followed by TMI on board TRMM with better calibrated instruments and spatial resolution (~50 km spatial resolution for the SST estimate) although limited to latitudes of ~40º N/S. Since 2002, AMSR-E and now AMSR-2 also measure using 6.9 GHz.

Many SST studies, from TMI or from AMSR, are derived from retrievals from Wentz and colleagues (e.g., Wentz et al., 2000). The algorithms are based on radiative transfer simulations on a large data set of atmospheric/ocean conditions. The resulting simulated brightness temperatures are typically used to train multi-regression algorithms. Operational AMSR2-based SSTs are provided by Remote Sensing Systems (RSS). Prigent et al. (2013) tested a Neural Network inversion on different subsets of frequencies from AMSR-E, at global scale, with results comparable to the previous algorithm for the full set of AMSR-E channels. An optimal estimation technique has been developed within the European Space Agency Climate Change Initiative (ESA-CCI) at DMI to retrieve SST from AMSR-E. A comprehensive matchup database with drifting buoy observations is used to develop and test the algorithm setup (Nielsen-Englyst et al., 2018). Pearson et al. (2018) also tested an optimal estimation method to prioritize the different window channels from 6 to 36 GHz for SST retrievals. The colder the water, the more important the role of the 6.9 GHz frequency. Outside polar and high-latitude regions, the sensitivity to SST becomes strong enough at 10.7 GHz so that this higher frequency can be given a more prominent role. This can be used to provide higher resolution SSTs outside the high-latitude regions and justify a separate global SST product.

A detailed analysis of CIMR capability to derive SST is provided in Kılıç et al. (2018) who analyse the performances of the CIMR mission in terms of theoretical retrieval precision.
and spatial resolution on the SST, SSS, and SIC products based on the CIMR instrument specification set out in this MRD. A careful information content analysis (see Prigent et al., 2013) is conducted and the derived CIMR performances are compared with the Advanced Microwave Scanning Radiometer 2 and the Soil Moisture Active Passive current missions. Maps of the retrieval precision based on realistic conditions are computed. CIMR will provide SST, SSS, and SIC with a spatial resolution of 15, 55, and 5 km and a precision of 0.2 K, 0.3 pss, and 5%, respectively (see Figure MRD-6.3.2.2). The SST and SIC will be retrieved at better than 30 km from the coast. The figure above provides an estimate of theoretical retrieval errors for CIMR SST compared to AMSR2 SST.

Figure MRD-6.3.2.2. The theoretical retrieval error SD on SST for 1 day (15 June 2008) at global scale, estimated from radiative transfer simulations and realistic ocean and atmospheric fields, with the instrument specifications of CIMR (top) and of AMSR2 (bottom). SST = sea surface temperature; CIMR = Copernicus Imaging Microwave Radiometer; AMSR2 = Advanced Microwave Scanning Radiometer 2; SD = standard deviation (from Kilic et al., 2018).
For the ice-free ocean, consistent retrievals of SST, OWS, SSS, and HOWS, along with the cloud and precipitation retrieval are highly desirable.

### 6.3.3 Polar Thin Sea Ice Thickness algorithm

Operational products of thin sea ice thickness (up to 0.5–1.0 m maximum thickness) retrieved from SMOS observations (since 2010) are today available from two independent retrieval procedures based on observations at different incidence angle ranges. While the procedure by Kaleschke et al. (2010) (algorithm baseline in Tian-Kunze et al., 2014) uses intensity at incidence angle below 40°, the procedure by Huntemann et al. (2014) relies on intensity and polarization difference between 40° to 50° (https://seaice.uni-bremen.de/thin-ice-thickness). Currently, the SMOS SIT retrieval is being transferred to the L band sensor SMAP launched in 2015 (Patilee et al., 2018; Schmitt and Kaleschke, 2018).

The retrieval of thickness of thin sea-ice works only during the cold season (~October to ~April in the Arctic), and have been routinely demonstrated only in the Arctic.

### 6.3.4 Polar Sea Ice Type / Stage of Development algorithm

Ice-type is typically derived from scatterometers (e.g. MetOp ASCAT) in combination with microwave radiometry measurements (e.g. AMSR-2 or SSMI), e.g. as in the current operational OSI-SAF and CMEMS catalogue. Historically, the 19 and 37 GHz gradient has been used for ice type classification into first- and multiyear ice types (Swift and Cavalieri, 1985).

A retrieval method specifically for the multiyear ice (MYI) concentration first uses input data from active and passive microwave instruments (radar scatterometer and radiometer, respectively) as well as distributions of typical brightness temperatures and radar backscatter coefficients for the ice types and open water and then retrieves the concentration of each ice type by a constrained optimisation method. The frequencies used are Ku band or C band for the scatterometer, and 18 and 37 GHz, H and V polarisation for the radiometer. Next, it applies several correction schemes on the MYI concentration to account for the effect of melt-refreeze processes, snow metamorphosis and sea ice drift on...
the sea ice type retrieval, which has proven to eliminate unphysical behaviour of MYI as retrieved from active and/or passive microwave instrument data (Ye et al., 2016a, b).

Using radiometry and scatterometry limit the retrieval period to the cold season (~October to ~April in the Arctic) although post-processing and filtering tests such as those of Ye et al. (2016 a, b) can extend the period to mid-September (onset of freezing) to mid-May (onset of surface melt-ponding).

Because of the many types of sea ice and the dynamic nature of their radiometric signature, state-of-the-art algorithms dynamically adapt their coefficients to cope with inter-seasonal and interannual variability.

![Diagram of Thin Sea Ice Thickness Algorithm](image)

**Figure MRD-6.3.3.1 Prototype CIMR L2 Thin Sea Ice thickness algorithm overview.**

### 6.3.5 Polar Sea Ice Drift algorithm

The vast majority of satellite-based sea-ice drift algorithms work by analysing a pair of satellite images and attempting to explain the change in intensity patterns between the images by two-dimensional shifts of small blocks of pixels. There is no limitation as to what the type of imager is used (active/passive), the type of wavelength (visible, microwave, etc...) nor the actual property that is imaged (snow, ice type, ocean in leads, melt pond patterns, ...). This leads to the same algorithms being easily applied to several types of sea ice images, with adaptations that are often driven by the need for better processing speed when using finer resolution images (typically SAR).

Algorithms for sea-ice drift are mature (e.g. Lavergne et al., 2010), and used operationally on a wide variety of instruments and channels. The most basic algorithms are even integrated in popular of-the-shelf software packages (motion detection is a field of computer vision).

One of the limitations of the sea-ice drift products available from AMSR-2 and SSMIS from OSISAF is that they are “L3C” products, generated only once a day, from daily averaged...
maps of brightness temperature. This reduces the accuracy of the drift vectors, wastes geographical coverage (several vectors a day could be retrieved at many locations, instead of just one), and greatly reduces timeliness (daily averaged maps must be built before a product is generated). CIMR, with its increased spatial resolution and repeat cycle, will provide the possibility to produce so-called “L3U” drift products, that is computing vectors from pairs of swaths, instead of pairs of daily-averaged maps.

In addition to the “L3U” processing approach, the increased resolution of CIMR grants higher resolution (~25x25 km) and better accuracy. Note that high-resolution 18.7 GHz channels have the potential to provide year-round sea-ice drift vectors (Ka-band and above are challenged by surface melt and atmospheric noise during the melt season).

6.3.6 Polar Snow Depth on Sea Ice Type algorithm

SD can be estimated using a combination of AMSR-E or AMSR-2 brightness temperatures (e.g. using 18.7 and 36.5 GHz) using a spectral gradient approach (e.g. Markus et al., 2006; Comiso et al., 2003). Although the method is confounded in the presence of snow melt water and sensitive to the ice roughness below, potentially this can allow direct snow measurements to replace the Warren snow climatology (Warren et al., 1999). Several studies investigated the uncertainties bounds of the microwave SD retrieval in the Arctic and Antarctic (e.g. Markus et al., 2006; Stroeve et al., 2006) and the current retrieval methods have a Scientific Readiness Level (SRL) of 4 or higher. In the Arctic, the traditional 19/37 GHz gradient ratio retrieval, however, is limited to first-year ice. Recently, the method was extended to work over multiyear ice in spring and more reliable over first-year ice by inclusion of the 6.9 GHz channels (Rostosky et al., 2018).

Maass et al. (2013, 2015) and Zhou et al, (2018) proposed the use of L-band radiometer data for snow depth retrieval over thicker Arctic sea ice, where the sensitivity of L-band measurements towards ice thickness shift to snow depth. Similarly, it was demonstrated by Rostosky et al. (2018) that the use of C-band in combination with Ku-band has retrieval skills over thicker old ice.

The performance and uncertainty of the SD retrieval is well quantified by several studies (e.g., Markus et al., 2006; Stroeve et al., 2006; Rostosky et al., 2018). This the method can be considered mature. However, due to the high variability of snow properties (e.g., layering, ice lenses, liquid water content, salinity) and the underlying sea ice (e.g., roughness, salinity) conceptually there are significant uncertainties (RMSD approx. 10 cm) for the retrieved SD.

6.3.7 Polar Sea Ice Surface Temperature algorithm

The Snow/Ice Interface Temperature (SIIT) can be estimated using the 6 GHz radiometer measurements. Snow is mostly transparent at 6 GHz and the sea ice have a very stable emissivity. The vertical snow and sea ice description in models is now advancing and requires information on the vertical temperature profile (Tonboe et al. 2011).

Recent developments using satellite microwave radiometer data at 6.9, 18.6 and 36.5 GHz with empirical algorithms suggest that the snow-ice interface temperature, the effective temperature, and the snow depth in terms of brightness temperature can be retrieved (Kilic et al., 2018b).

Another field of progress which is currently limited by the low resolution of existing 6 GHz sensors will be the simultaneous retrieval of atmospheric and surface parameters from
microwave radiometer observations at higher frequencies using an optimal estimation method. This has been a standard for open-ocean for many years and is subject to ongoing research over sea ice (Melsheimer et al. 2008, Scarlat et al. 2017).

6.3.8 **Global Terrestrial Snow Area algorithm**

Terrestrial snow cover can be detected using a combination of 19 and 36.5 GHz. There are a number of well-established snow cover and snow-melt estimation algorithms that work on hemispherical and Global scales (e.g. Hall et al. 2002, Kelly et al. 2003, Takala et al. 2009, Li and Kelly 2017). In addition to detecting the extent of snow cover, detection of wet snow and snow-melt is straightforward and reliable. There are several operational services providing daily snow extent and wet snow information on regional and hemispherical scales (e.g. EU METSAT H SAF). The methodologies for Snow area estimation can be considered mature.

6.3.9 **Global Terrestrial Snow Water Equivalent algorithm**

From the available set of observed frequencies, the algorithms for retrieval of SWE employ a 36-37 GHz (or 31.4 GHz) and a 18-19 GHz channel in combination. These being the key required frequencies, allowing for SWE retrieval, without the 37GHz (or 31.4GHz) channel the retrieval is in practice not feasible. The scattering of a 19 GHz signal in snow is notably smaller when compared to 37 GHz, while the emissivity of frozen soil and snow is estimated to be largely similar at both frequencies. Observing the brightness temperature difference of the two channels allows to establish a relation with the detected signal and snow depth, with the additional benefit that the effect of variations in physical temperature on the measured brightness temperature is reduced. Similarly, observing a channel difference reduces or even cancels out systematic errors of the observation, provided that the errors in the two observations are similar (e.g. due to using common calibration targets on a space-borne sensor). Typically, the vertically polarized channel is preferred due to the inherent decreased sensitivity to snow layering (e.g. Rees et al., 2010).

The existing globally operational snow mass retrieval algorithms are currently based on microwave radiometer sensors (e.g. Kelly, 2009; Takala et al., 2011). Applying microwave radiometers for snow cover detection is appealing in particular due to the availability of a daily time series with global coverage, extending back almost 40 years to 1979. While the detection of certain snow cover characteristics, such as snow extent and snow melt-off (Takala et al., 2009), is relatively straightforward, estimation of SWE in particular is more challenging. The main challenges hampering retrieval skill are related to the separation of the effect of increasing snow mass from other varying structural properties of the snowpack, and on the other hand, mitigating for mixed pixel effects in the coarse scale microwave radiometer observations over heterogeneous landscapes.

The underlying principle in all microwave radiometer algorithms for retrieval of SWE is based on observing the effect of snow cover on the naturally emitted brightness temperature from the ground surface. Ground brightness temperature is scattered and absorbed by the overlying snow medium, resulting in decreasing brightness temperature with increasing snow mass, up to a frequency-dependent point of saturation when self-emission from the snow itself matches the rate of extinction of the ground radiation (e.g. Mätzler et al., 1982). The rate of extinction can be approximated by dividing extinction into absorption and scattering mechanisms following the radiative transfer theory. The rates of absorption and scattering depend on the wavelength, the amount of snow in the
signal path, and the dielectric and structural properties of the snow cover. Scattering intensity increases as the wavelength approaches the size of the scattering particles. Considering that individual snow particles are measured in millimetres, high microwave frequencies (short wavelengths) will be scattered more than low frequencies (long wavelengths). The intensity of absorption can be related to the dielectric properties of snow, with snow density largely defining the permittivity for dry snow.

Several retrieval algorithms have been proposed in literature, and implemented in an operational context. Studies by Kelly et al. (2003) and Kelly (2009) form the basis of the current NASA AMSR-E SWE product ('NASA SWE Standard' algorithm), as well as the JAXA AMSR2 SWE product. A recent adjustment to the algorithm ('NASA SWE Prototype' algorithm) has been presented by Tedesco and Jeyaratnam (2016). An approach introduced by Pulliainen (2006) and Takala et al. (2011), based on numerical inversion of a snow emission model and assimilation of in situ data, is applied in the Copernicus Global Land Monitoring Service (https://land.copernicus.eu/) and ESA GlobSnow (www.globsnow.info). The in-situ data regulates the retrieval by both calibrating the forward model at sites where in situ data on snow depth are available, and finally through providing a first guess value for SWE through Kriging interpolated background fields of snow depth.

Applying physical models in SWE retrieval requires a robust forward modelling scheme capable of reproducing the emission signatures from snow-covered landscapes. Available snow emission models are mostly based on radiative transfer analysis, treating the snowpack as a scattering medium with varying degrees of complexity (e.g. Tsang et al., 1985; Tsang et al., 2000; Wiesmann et al., 1999; Pulliainen et al., 1999; Picard et al., 2013). Forward models for vegetation and other features can also be applied to mitigate the effects of heterogeneous land cover (Kruopis et al., 1999; Langlois et al., 2011; Lemmetyinen et al., 2011; Roy et al., 2012; Kontu et al., 2014; Cohen et al., 2015). However, actual retrieval schemes are forcibly limited to relatively simple emission models, in particular due to the lack of detailed ancillary input parameters (e.g. snow stratification; detailed vegetation information; lake ice properties) on a global scale.

Microwave radiometer retrievals of SWE have a long history, but regardless of efforts retrieval skill remains a limitation in the current products (e.g. Larue et al., 2016 and Hajnsek et al., 2017). While fairly good results have been achieved using the GlobSnow approach (Takala et al., 2011), the overall accuracy of satellite radiometer-based SWE estimates are slightly better or on par with current land surface model capabilities (e.g. Brun et al., 2013). A known challenge with the usability of the GlobSnow approach is the fact that the final SWE product is reliant on surface observations, and cannot thus be considered as an independent observation for merging with e.g. meteorological reanalysis data. As was found in the ESA SnowPex study, standalone SWE retrievals from microwave radiometer sensors exhibit even larger errors, limiting their usability for most applications.

In general, microwave radiometer retrievals at current frequencies are limited to snow depth between approximately 0.05 m – 1.00 m in thickness, and only under dry snow conditions. Depths of less than 0.05 m cannot be detected as detected brightness temperature difference between the 19 and 37 GHz frequencies used falls below the 1-2 K radiometric resolution of space borne instruments. With snow depths greater than about 1 m, the brightness temperature signal at 37 GHz saturates. Moreover, even a relatively small amount of liquid water will contaminate the detected signal making detection of SWE impossible. Separating the effects of extinction efficiency and of the total amount of
snow also remains an issue in the interpretation of microwave radiometer observations of
snow cover, in particular for stand-alone approaches.

The coarse spatial resolution of microwave radiometer sensors in space remains a serious
handicap for observations over heterogeneous land surfaces and mountain regions, as
spatial resolutions at frequencies relevant for snow parameter retrieval are on the order of
tens of kilometres, an improved resolution of about 5km would improve the situation
notably. Currently, mixed pixel effects from vegetation, topography and subnivean
conditions complicate the microwave signal. The natural variability of snow cover itself is
also notable, as the distribution of snow is strongly affected by meteorological conditions,
interaction with vegetation, and changes in surface topography and land cover. As a result,
in addition to snow height and SWE, properties such as stratigraphy and snow
microstructure change both spatially and over time, affecting the microwave signature and
adding an additional challenge for SWE retrieval.

The methodologies for SWE retrieval from 19GHz and 37GHz is mature and being
conducted in operational fashion within (e.g. Copernicus Global Land Service and
EUMETSAT H SAF services), the improved resolution of the proposed mission would be a
game changer for operational SWE monitoring and would benefit a large array of
downstream services.

6.3.10 Global Sea Surface Salinity algorithm

The brightness temperature measurement at L-band 1.4 GHz is proportional to the surface
skin temperature (SST) and to the sea emissivity, which depends strongly on the salinity
(SSS) at this frequency and to a lesser extent to the OWS. In practice, however, numerous
additional external factors (galactic noise contamination, ionosphere) also contribute to
the signal and must be accounted for. The 1.4 GHz brightness temperature sensitivity in
SSS is ~0.5 K/pss, which is rather weak given that spatial and temporal variability of SSS
does not exceed several pss. The algorithms are based on the reasonable knowledge of the
emissivity radiative transfer at this frequency. Reul et al. (2012) describe the initial SMOS
algorithm and evaluate the products, and Brucker et al. (2014) present the developments
for the Aquarius mission.

While a challenging measurement to make from space (e.g. Yueh et al., 2001), for warmer
waters great progress has been made using 1.4315 GHz measurements from the ESA SMOS
(e.g. Reul et al., 2012a) and NASA Aquarius (e.g. Yueh et al., 2014) and SMAP missions
(e.g. Meissner and Wentz, 2016). Radio Frequency Interference (RFI) must be mitigated
when using low-frequency L-X band channels, in geophysical retrieval algorithms (e.g.
Soldo et al., 2017; Mohammed et al., 2016). New algorithms, recently developed at the
Barcelona Expert Centre (BEC) to improve the quality of L-band measurements show that
for the first time cold-water SSS maps from SMOS data can be derived (Olmedo et al., 2017;
Garcia-Eidell et al., 2017) to observe the variability of the SSS in the higher north Atlantic
and the Arctic Ocean. Also, BEC has proposed a methodology to mitigate systematic errors
produced by the contamination of the land over the sea that allows obtaining SMOS SSS
fields over enclosed seas such as the Mediterranean (Olmedo et al., 2018). Buongiorno
Nardelli et al., 2012 and 2016 demonstrated that SST can be used together with SSS data to
produce L4 SSS products with higher resolution and improved accuracy and to directly
estimates the sea surface density (SSD) fields. This method is now adopted by CMEMS to
produce global reanalysis of SSS and SSD (1993-2016) at ¼° spatial resolution available
from the CMEMS catalogue since April 2018 (Droghei et al. 2016, Droghei et al. 2018). The NRT SSS and SSD production is planned for end of 2018.

6.3.11 Global Soil Moisture algorithm

Microwave observations are sensitive to soil moisture because moisture affects the dielectric constant of the surface and thus the emissivity soil surfaces. Vegetation and surface roughness reduce the microwave sensitivity to soil moisture and are more pronounced as microwave frequency increases. At L-band frequencies the soil moisture emission originates from deeper in the soil (a few centimetres), giving a more representative measurement of conditions below the surface crust or skin layer. Measurements at C-band range are sensitive to soil moisture, but primarily in regions of low vegetation but the attenuation by vegetation and the shallow sensing depth of ~1 cm for bare soil impose limitations on the retrieval of soil moisture. See Njoku et al. (2003) for information on the application of AMRE for Soil Moisture retrieval. The CIMR channel at 1.4315 GHz is ideally suited to soil moisture measurements complemented by the primary channel at 6.9 GHz.

6.3.12 Global Precipitation (rain rate) algorithm

Precipitation is a key hydrological and climate variable and includes both the liquid (rain) and solid (snow and ice) forms. Precipitation occurs when a particle formed by the condensation of water vapour becomes heavy enough to fall under the force of gravity. Precipitation rate estimates are a fundamental component of the water cycle characterization. The physical basis for retrieving precipitation from microwave radiometer measurements depends on distinguishing the radiation from Earth’s surface from the radiation emitted from precipitation (e.g. Hilburton and Wentz, 2008). Microwave emission from the ocean surface is strongly polarized, while the emission from rain drops is un-polarized. Thus, precipitation can be accurately distinguished from the underlying ocean surface using measurements of the vertically and horizontally polarized radiation (see examples at http://www.remss.com/measurements/rain-rate/). CIMR will be able to provide estimates of precipitation rate, although further algorithm development is required, in particular to exploit forward and backwards views together.

6.3.13 Global Ocean Surface Wind Speed algorithm

Multi-channel microwave radiometers have been used to measure ocean surface winds for several decades. Bourassa et al (2019) review the current capability of ocean wind measurements from space. At wind speeds below 6m s\(^{-1}\), the wind direction signal from microwave radiometry is small in all polarizations leading to noisy wind direction estimates. At 6m s\(^{-1}\), the uncertainty of WindSat wind direction is 20\(^\circ\) (Hilburn et al., 2016). Above 8m s\(^{-1}\), the uncertainty is 10\(^\circ\)-15\(^\circ\) and is similar to that derived from scatterometers (Ricciardulli et al., 2012; Hilburn et al., 2016). At high winds (above 10m s\(^{-1}\)) the wind direction signal derived from microwave radiometry is strong in all 4 Stokes parameters.

The application of L-band measurements to measure extreme wind speed over the ocean has been pioneered by Reul et al. (2017). Efficient masking of the areas over the oceans, where geophysical parameter retrievals are objectively impossible due to non-transparent atmosphere, is still an important issue for satellite radiometer measurements working at frequency higher or equal than C-band. As demonstrated for Tropical cyclones (Reul et al.,
L-band radiometer data can provide a direct way to probe surface wind speed in extreme weather events, being almost transparent to the atmosphere. Estimation of the total atmospheric absorption can be also done from the ~10 GHz channel with high accuracy due to the weak influence of liquid water and especially water vapour (Zabolotskikh et al., 2013). This helps to refine a new filter to considerably reduce masking ocean areas in e.g., AMSR2 radiometer data for severe weather systems such as PL, characterized by high wind speeds and moderate atmospheric absorption. Combining, X- with C- and L-band channels, a methodology can be proposed to jointly retrieve sea surface wind speed and sea surface temperature in PL.

The combined use of both CIMR multi-channel, full Stokes measurements and MetOp-SG(B) active microwave sea surface wind estimates will provide an unprecedented wind speed/vector data set at high spatial and temporal resolution for application in Copernicus.

The combined usage of both CIMR passive and MetOp-SG(B) active microwave sea surface wind estimates will demonstrate the potential of the highest spatial and temporal resolution in the investigation of PL intensity. The ability to better measure warm SST PLs wakes thanks to X/C band combination for SST and L-band wind retrievals will also help in better characterizing feedbacks of PLs to impact sea-ice formation.

6.3.14 Global Cloud Liquid Water algorithm

Atmospheric water vapour is a major greenhouse gas. In its vapour and liquid states, it is a key parameter in the global hydrological cycle, a component of climate change and ocean–atmosphere energy exchange studies. Water vapour changes in the Arctic are poorly described because of a lack of direct observations and large sea ice cover over which atmospheric water retrievals are either complicated or impossible (e.g. Vihma, 2014). Regular long-term observations of water vapour over the open sea-water are provided by satellite microwave radiometer instruments. Both atmospheric total water vapour content (WVC) and total cloud liquid water content (CLW) have been successfully retrieved from AMSR-E measurements (e.g. Kazumori, 2012) and more recently from AMSR2 (e.g. Zabolotskikh and Chapron, 2017). The using water-vapour sensitive channels (18.7 and 36.5 GHz) CIMR mission will be able to provide although further algorithm development is required.

6.3.15 Global Land Surface Temperature algorithm

A significant challenge for LST when retrieved from TIR measurements is the presence of clouds that preclude the retrieval. Microwave radiometer data operating in the 6-37 GHz frequency range can overcome this primary difficulty and have been successfully used to retrieve LST. An efficient methodology has been developed to estimate LST at the global scale using microwave radiometer observations between 18 and 37 GHz from SSM/I, SSMIS, AMSR-E or AMSR-2 (Prigent et al., 2016, Jimenez et al., 2017, Ermida et al., 2017). It is based on a neural network scheme, using pre-calculated land surface emissivity atlases at the same frequencies. The method is currently applied for the ESA LST CCI project. The errors on these LSTs are slightly larger than for their infrared counter parts, but the estimates are available ~90% of the time (compared to less than ~40% of the time with the infrared estimates). Another example of LST retrieval is based on AMSR-E data together with estimates of vegetation in an optimal estimation framework (Zhao et al., 2017). The CIMR mission will be able to estimate LST using a priori estimates of vegetation coverage.
6.4 Example European Operational Users

6.4.1 COPERNICUS CMEMS

The Copernicus Marine Environment Monitoring Service (CMEMS) has been designed to respond to issues emerging in the environmental, business and scientific sectors. Using information from both satellite and in situ observations, it provides state-of-the-art analyses and forecasts daily, which offer an unprecedented capability to observe, understand and anticipate marine environment events. The CMEMS provides regular and systematic core reference information on the state of the physical oceans and regional seas. The observations and forecasts produced by the service support all marine applications. In addition, CMEMS hosts regularly updated Ocean Monitoring Indicators (e.g. Sea Ice Extent, Ocean Heat Content, Sea Level Rise etc.) based on state-of-the-art re-analyses (both model and satellite products). CMEMS experts author yearly an Ocean State Report.

CMEMS covers the whole ocean, and thus has some focus on the polar regions. The Global Marine Forecasting Centre (GLO MFC) issues forecasts and re-analyses for the global ocean including both polar regions. The Arctic MFC covers the Arctic Ocean and adjacent seas. Satellite observations covering the polar regions are processed at various Thematic Assembly Centres (TACs). The Sea Ice TAC, Sea Surface Temperature TAC and Multi-Observations TAC are those who would benefit most from the CIMR mission (see e.g. Appendix III CIMR Requirements Traceability Matrix).

The Sea Ice TAC (SI TAC) is responsible for the collection, processing, qualification and distribution of sea ice (SI) data products derived from radiometers (microwave and infra-red), scatterometers, Synthetic Aperture Radar (SAR), and altimeter satellite missions. The SI TAC is in charge of the near-real time (NRT) and delayed mode (REP) processing of Sea Ice observations, (regionally and globally), required for CMEMS modelling and data assimilation and as input to downstream applications. Geophysical variables include Sea Ice Concentration, Sea Ice Type, Sea Ice Edge, Sea Ice Drift, Sea Ice Thickness (merging L-band and radar altimeter data), and Sea Ice Surface Temperature. Sea ice products and services have been strongly improved thanks to the Sentinel-1 A&B constellation, but are also very dependent on the availability of third-party missions, including microwave radiometer (currently AMSR2 and SSMIS, SMOS is used) and meteorological missions (e.g. MetOp AVHRR, NOAA VIIRS, etc.). At time of writing, the SI TAC is led by MET Norway, and includes contribution from the Danish Meteorological Institute, the Technical University of Denmark, the Finnish Meteorological Institute, the French Research Institute for Exploitation of the Sea (IFREMER), the British Antarctic Survey, and the Nansen Environmental and Remote Sensing Centre.

The SST TAC provides Near-Real-Time and Multi-Year (MY) Level 3 and Level 4 observational SST products derived from multiple upstream satellite earth observation L2 data, at global scale and at the regional scales of the European seas. The SST TAC is led by CNR with five production centres (Meteo-France, The National Research Council of Italy, Danish Meteorological Institute, the French Research Institute for Exploitation of the Sea (IFREMER), the British Antarctic Survey, and the Nansen Environmental and Remote Sensing Centre involved in the processing of SST data and MET Norway responsible for the service desk.
The Multi-observation TAC (MOB TAC) provides qualified, global ocean multi observation products (satellite and in-situ) via data-fusion techniques. One of these are the Sea Surface Salinity and Density, merging satellite and in-situ observations including C-band based SSTs (AMSR2) and L-band based SSS (SMOS) (Droghei et al., 2018).

### 6.4.2 EUMETSAT OSI-SAF:

Utilising specialist expertise from the EUMETSAT Member States, Satellite Application Facilities (SAFs) are dedicated centres of excellence for processing satellite data. They form an integral part of the distributed EUMETSAT Application Ground Segment. SAFs develop, generate and distribute operational satellite products including long-term data records.

SAF products are designed to serve operational users: primarily Meteorological Services and other operational services in the member states and international organisations (Copernicus, ECMWF). The OSI SAF develops, processes and distributes, in near real-time, products related to key parameters of the ocean-atmosphere interface. The OSI SAF team focuses on Sea Surface Temperature (SST) and Sea Ice Surface Temperature (IST), scatterometer winds (and soon microwave winds from MetOp-SG(B) MWI), radiative fluxes: Solar Surface Irradiance (SSI) and Downward Longwave Irradiance (DLI), sea ice concentration, edge, type, emissivity, drift. See also [http://www.osi-saf.org](http://www.osi-saf.org).

### 6.4.3 FMI – Finnish Meteorological Institute

The Finnish Meteorological Institute (FMI) is a research and service agency under the Ministry of Transport and Communications. The main objective of the Finnish Meteorological Institute is to provide the Finnish nation with the best possible information about the atmosphere above and around Finland, for ensuring public safety relating to atmospheric and airborne hazards and for satisfying requirements for specialized meteorological products. The Finnish Meteorological Institute offers various services on the Baltic Sea and other seas and oceans also.

The services include real time observations, forecasts and expert analyses. The most common services are the ice service, wave and sea level services. The detailed Finish Ice Report including ice charts for the whole Baltic Sea is published in the autumn twice a week and daily when the amount of ice increases until ice break-up in spring. It represents the
current ice situation and traffic restrictions in the Baltic Sea. More info at http://en.ilmatieteenlaitos.fi/ice-conditions

6.4.4 DMI - Denmark Meteorological Institute

DMI provides meteorological services in the Commonwealth of the Realm of Denmark, the Faroe Islands, Greenland, and surrounding waters and airspace. Meteorological services include forecasting and warnings and monitoring of weather, climate and related environmental conditions in the atmosphere, on land and at sea. Purpose of all activities is to safeguard human life and property. DMI’s many activities also act as background knowledge in terms of planning and decision-making in economic and environment sectors - especially within transport and industry businesses. DMI collects and processes meteorological, climatological and oceanographic measurements/observations, and measures, collects and compiles related geophysical parameters throughout the Realm. Conducting research and development within its area of expertise, DMI ensures efficient operations and state-of-the-art quality in all productions while monitoring and conducting research on global warming and the stratospheric ozone balance.

The DMI’s ocean forecast products for Danish waters include several parameters visualised as strength fields and direction fields, see http://www.dmi.dk/en/hav/#danmark. Ice maps are produced at DMI/Lyngbyvej in Denmark in cooperation with the ice monitoring station in Greenland based on satellite information and observations collected locally.

6.4.5 Met.no – Norwegian Meteorological Institute

The Norwegian Meteorological Institute forecasts weather, monitors the climate and conducts research. Since the institute was established, Norwegian meteorologists have figured prominently in the development of the discipline. The Norwegian Meteorological Institute is today a leading international centre of expertise. The forecasting service in the High North is extensive and ranges from forecasting the extent and thickness of the ice, to warning of icing on vessels. Since 2015 the Norwegian Meteorological Institute together with the Nansen Environmental and Remote Sensing Centre and the Institute of Marine Research, have had the responsibility of monitoring and
measuring the ocean and sea ice conditions in the High North and the Arctic, including in the CMEMS Arctic MFC. See also http://polarview.met.no/

MET Norway leads the high-latitude node of the EUMETSAT OSI SAF (see Sec. 6.4.2) and the Sea Ice Thematic Assembly Centre (SI TAC) of the CMEMS (see Sec. 6.4.1). MET Norway is also involved in the Copernicus Climate Change project (C3S) and the Copernicus Atmosphere Monitoring Service (CAMS).

6.4.6 SMHI – Swedish Meteorological and Hydrological Institute

SMHI, the Swedish Meteorological and Hydrological Institute, is an expert agency under the Ministry of the Environment and Energy. Through unique expertise in meteorology, hydrology, oceanography and climatology, SMHI contributes towards greater public welfare, increased safety and a sustainable society. More info at https://www.smhi.se/en/about-smhi

SMHI provides daily forecasts to the general public and societal functions and issues warnings when faced with severe weather and water events. SMHI also offers products and services that function as vital support in the decision-making of, for example, Swedish authorities, organisations and municipalities. SMHI produce operational sea surface temperature and sea ice concentration services at https://www.smhi.se/en/weather/sweden-weather/marine-coastal-weather/q/Skarphagen/Norrk%C3%B6ping/2678060#ws=wpt-a,proxy=wpt-a,parameter=ice

6.4.7 MetOffice – United Kingdom Meteorological Office

The MetOffice provides global services for weather, operational oceanography and climate. It provides weather and climate-related services to the Armed Forces, government departments, the public, civil aviation, shipping, industry, agriculture and commerce. The MetOffice runs an operational oceanography system and develops operational short-range forecast configurations of community models driven by atmospheric forcing from the Unified Model, and where appropriate using marine data assimilation. Applied research supports users of the models and develops decision tools for marine operations based on model outputs. The MetOffice is a core contributor to the CMES system maintaining and operating a global CMEMS ocean forecasting system model and a number of regional models for CMEMS. Both SST and SIC are fundamental variables used in all aspects of its operations.

6.4.8 ECMWF – European Centre for Medium Range Weather Forecasting

ECMWF is an independent intergovernmental organisation founded in 1975 and supported by 34 states. It produces global numerical weather forecasts for users worldwide. ECMWF produces operational ensemble-based analyses and predictions that
describe the range of possible scenarios and their likelihood of occurrence. ECMWF’s forecasts cover time frames ranging from medium-range, to monthly and seasonal, and up to a year ahead. ECMWF provides current forecasts, climate reanalyses, and specific datasets. These are available to the Member and Co-operating States, as well as through licensing to the World Meteorological Organization (WMO) and the academic and commercial sectors. All forecast systems at ECMWF are coupled to an ocean model. The ensemble and seasonal forecast systems use a coupled atmosphere-ocean model, which includes a simulation of the general circulation of the ocean and the associated coupled feedback processes that exist.

The current operational ensemble forecast systems model sea ice dynamically using the LIM2 model within NEMO ocean model to represent the dynamic and thermodynamic evolution of sea ice within the coupled forecast system.

ECMWF uses the community ocean model NEMO (Nucleus for European Modelling of the Ocean) as part of the IFS. The NEMO model provides the dynamic ocean model used in the ensemble prediction system and the seasonal forecast system (S4). The ensemble prediction system of the medium and monthly range forecasts runs the ocean model at 0.25-degree horizontal resolution with 75 levels in the vertical and is initialised with the NEMOVAR (3D variational assimilation system) OCEAN5. The seasonal forecast system (S4) uses a 1-degree horizontal resolution with 42 levels in the vertical and is initialised with NEMOVAR OCEAN4. Since 2013 the ensemble forecasts have coupled the atmosphere-wave-ocean model from the start of the forecast. This is important to allow capturing the two-way feedback between the atmosphere and the sea surface temperatures, for example when a tropical cyclone is slow moving it can cool the sea surface. Since November 2014 the ensemble forecasts have been run with 0.25-degree horizontal resolution with the sea ice model active. Both sea ice and SST data sets are required for use in ECMWF operations.

7 SYNERGIES AND INTERNATIONAL CONTEXT

A summary of historical and contemporary microwave imaging radiometers is provided in Table 2, which is derived from the extensive information provided within the World Meteorological Organisation (WMO Observing Systems Capability analysis and Review Tool (OSCAR, https://www.wmo-sat.info/oscar/). It is clear from this Table that there is a long heritage of missions carrying a variety of microwave radiometer channels that are suitable for Polar sea ice and ocean monitoring applications.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full name</th>
<th>Channels GHz</th>
<th>Space Agency</th>
<th>Satellites</th>
<th>Usage from</th>
<th>Usage to</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHF</td>
<td>MW Radiometer</td>
<td>7.5 (V&amp;H), 19.4 (V&amp;H), 22.22 (V&amp;H)</td>
<td>Roscosmos</td>
<td>Meteor-P1 Meteor-P2 Meteor-P3 Meteor-P6</td>
<td>1974</td>
<td>1983</td>
</tr>
<tr>
<td>Mission</td>
<td>Description</td>
<td>Frequency Bands</td>
<td>Agency</td>
<td>System</td>
<td>Launch Dates</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
<td>----------------------------------------</td>
<td>----------</td>
<td>-------------------</td>
<td>--------------------</td>
<td></td>
</tr>
<tr>
<td>ESMR</td>
<td>Electrically Scanning Microwave Radiometer</td>
<td>19.0 (H) 37.0 (V&amp;H)</td>
<td>NASA</td>
<td>NIMBUS 5</td>
<td>1972/1975 1977/1983</td>
<td></td>
</tr>
<tr>
<td>SMMR</td>
<td>Scanning Multichannel Microwave Radiometer)</td>
<td>6.6 GHz (V&amp;H) 10.7 GHz (V&amp;H) 18 GHz (V&amp;H) 21 GHz (V&amp;H) 37.0 (V&amp;H)</td>
<td>NASA</td>
<td>Nimbus-7</td>
<td>1978 1987</td>
<td></td>
</tr>
<tr>
<td>SSM/I</td>
<td>Special Sensor Microwave - Imager</td>
<td>19.35 (V&amp;H) 22.23 (V) 37.0 (V&amp;H) 85.5 (V&amp;H)</td>
<td>DoD</td>
<td>DMSP-F08 DMSP-F10 DMSP-F11 DMSP-F12 DMSP-F13 DMSP-F14 DMSP-F15</td>
<td>1987 2017</td>
<td></td>
</tr>
<tr>
<td>TMI</td>
<td>TRMM Microwave Imager</td>
<td>10.65 (V&amp;H) 19.35 (V&amp;H) 21.3 (V) 37.0 (V&amp;H) 85.5 (V&amp;H)</td>
<td>NASA</td>
<td>TRMM</td>
<td>1997 2015</td>
<td></td>
</tr>
<tr>
<td>Delta-2D</td>
<td>Scanning Microwave Radiometer</td>
<td>6.9 (V&amp;H) 13.0 (V&amp;H) 22.3 (V&amp;H) and 37.5 (V&amp;H)</td>
<td>Roscosmos</td>
<td>Okean-O-1</td>
<td>1999 2000</td>
<td></td>
</tr>
<tr>
<td>MSMR</td>
<td>Multi-frequency Scanning Microwave Radiometer</td>
<td>6.6 (V&amp;H) 10.65 (V&amp;H) 18.0 (V&amp;H) and 21.0 (V&amp;H)</td>
<td>ISRO</td>
<td>OceanSat-1 (IRS-P4)</td>
<td>1999 2010</td>
<td></td>
</tr>
<tr>
<td>MTVZA</td>
<td>Imaging/Sounding Microwave Radiometer</td>
<td>20-frequency, band 18.7 - 183</td>
<td>Roscosmos</td>
<td>Meteor-3M</td>
<td>2001 2006</td>
<td></td>
</tr>
<tr>
<td>AMSR</td>
<td>Advanced Microwave Scanning Radiometer</td>
<td>6.925 (V&amp;H) 10.65 (V&amp;H) 23.8 (V&amp;H) 36.5 V&amp;H 50.2 (V&amp;H)</td>
<td>JAXA</td>
<td>ADEOS-2</td>
<td>2002 2003</td>
<td></td>
</tr>
<tr>
<td>Instrument</td>
<td>Frequency Details</td>
<td>Operator(s)</td>
<td>Start Year</td>
<td>End Year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------------------------------------------------------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>AMSR-E</td>
<td>Advanced Microwave Scanning Radiometer for EOS</td>
<td>JAXA</td>
<td>2002</td>
<td>2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSMIS</td>
<td>Special Sensor Microwave Imager/Sounder</td>
<td>DoD</td>
<td>2003</td>
<td>2025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WindSat</td>
<td>WindSat</td>
<td>DoD</td>
<td>2003</td>
<td>2017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTVZA-OK (MW)</td>
<td>Combined Microwave-Optical Imaging/Sounding Radiometer (MW component)</td>
<td>NSAU/Roscosmos/RosHydroMet</td>
<td>2004</td>
<td>2006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MWRI</td>
<td>Micro-Wave Radiation Imager</td>
<td>CMA</td>
<td>2008</td>
<td>2026</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTVZA-GY</td>
<td>Imaging/Sounding Microwave Radiometer - improved</td>
<td>Roscosmos</td>
<td>2009</td>
<td>2028</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIRAS</td>
<td>Microwave Imaging Radiometer</td>
<td>ESA</td>
<td>2009</td>
<td>TBD On-orbit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mission</td>
<td>Sensor Type</td>
<td>Frequencies (GHz)</td>
<td>Agency/Provider</td>
<td>Satellite(s)</td>
<td>Start</td>
<td>End</td>
</tr>
<tr>
<td>-----------</td>
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<td>-------</td>
</tr>
<tr>
<td>MADRAS</td>
<td>Microwave Analysis &amp; Detection of Rain &amp; Atmospheric Structures</td>
<td>18.7 (V&amp;H), 23.8 (V), 36.5 (V&amp;H), 89.0 (V&amp;H), 157.0 (V&amp;H)</td>
<td>ISRO</td>
<td>Megha-Tropiques</td>
<td>2011</td>
<td>2017</td>
</tr>
<tr>
<td>MWI</td>
<td>Microwave Radiometer</td>
<td>6.6 (V&amp;H), 10.7 (V&amp;H), 18.7 (V&amp;H), 23.8 (V), 37.0 (V&amp;H)</td>
<td>NSOAS</td>
<td>HY-2A</td>
<td>2011</td>
<td>2016</td>
</tr>
<tr>
<td>Aquarius</td>
<td>Pushbroom L-band sensor</td>
<td>1.4 full polarisation</td>
<td>CONAE, INPE, BASA</td>
<td>Aquarius</td>
<td>2011</td>
<td>2015</td>
</tr>
<tr>
<td>AMSR-2</td>
<td>Advanced Microwave Scanning Radiometer-2</td>
<td>6.925 (V&amp;H), 7.3 (V&amp;H), 10.65 (V&amp;H), 18.7 (V&amp;H), 23.8 (V&amp;H), 36.5 (V&amp;H) and 89.0 (V&amp;H)</td>
<td>JAXA</td>
<td>GCOM-W1</td>
<td>2012</td>
<td>2025</td>
</tr>
<tr>
<td>GMI</td>
<td>GPM Microwave Imager</td>
<td>10.65 (V&amp;H), 18.7 (V&amp;H), 23.8 (V), 36.5 (V&amp;H), 89.0 (V&amp;H), 166.0 (V&amp;H) and 183.3 (V)</td>
<td>NASA</td>
<td>GPM Core Observatory</td>
<td>2014</td>
<td>2017</td>
</tr>
<tr>
<td>SMAP</td>
<td>Soil Moisture Active-Passive radiometer</td>
<td>1.4 full polarisation</td>
<td>NASA</td>
<td>SMAP</td>
<td>2015</td>
<td>2018</td>
</tr>
<tr>
<td>MWI</td>
<td>Microwave Radiometer</td>
<td>6.6 (V&amp;H), 10.7 (V&amp;H), 18.7 (V&amp;H), 23.8 (V), 37.0 (V&amp;H)</td>
<td>NSOAS</td>
<td>HY-2B</td>
<td>2018</td>
<td>2023</td>
</tr>
<tr>
<td>COWVR</td>
<td>Compact Ocean Wind Vector Radiometer</td>
<td>18.7 (Full), 23.8 (Full), 33.9 (Full)</td>
<td>NASA, US DoD</td>
<td>ORS-6</td>
<td>2018+</td>
<td>?</td>
</tr>
<tr>
<td>MWRI</td>
<td>Conical scanning microwave radiometer</td>
<td>10.65 (V&amp;H), 18.7 (V&amp;H), 23.8 (V&amp;H), 36.5 (V&amp;H), 89.0 (V&amp;H)</td>
<td>CMA, NRSCC</td>
<td>FY-3F, FY-3G</td>
<td>2019+ &gt;2021</td>
<td>2024+ &gt;2026</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Channels</td>
<td>Provider/Agency</td>
<td>Satellites</td>
<td>Start Year</td>
<td>End Year</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------</td>
<td>----------------------------------------</td>
<td>------------</td>
<td>------------</td>
<td>----------</td>
</tr>
<tr>
<td>MWI</td>
<td>Conical scanning microwave radiometer</td>
<td>18.7 (V&amp;H), 23.8 (V&amp;H), 31.4 (V&amp;H), 50.3 (V&amp;H), 52.61 (V&amp;H), 53.24 (V&amp;H), 53.75 (V&amp;H), 89.0 (V&amp;H), 118.75 (V), 166.9 (V), 183.31 (V)</td>
<td>ESA/EUMETSAT</td>
<td>MetOp-SG (B1, B2 and B3)</td>
<td>2022</td>
<td>2043</td>
</tr>
<tr>
<td>FPIR</td>
<td>Full-polarized Interferometric synthetic aperture microwave radiometer</td>
<td>1.4135, 2.695, 6.9 all full polarisation</td>
<td>CAS</td>
<td>WCOM</td>
<td>2021+</td>
<td>?</td>
</tr>
<tr>
<td>PMI</td>
<td>Passive Microwave Imager</td>
<td>6.8 (V&amp;H), 10.7 (Full), 18.7 (Full), 23.8 (V&amp;H), 37.0 (Full), 89.0 (V&amp;H)</td>
<td>CAS</td>
<td>WCOM</td>
<td>2021+</td>
<td>?</td>
</tr>
</tbody>
</table>

Table 2 reveals that more channels, with multiple polarisation, are provided toward the contemporary era of satellite imaging microwave radiometers. However, the provision of lower frequency channels (<18.7 GHz) is sporadic and variable likely due to the challenges of finding a single antenna technology that can accommodate the wide range of frequencies at an affordable mass with an appropriate instantaneous field of view (IFOV). In terms of application in the Polar-regions and global oceans, the limited use of low frequency channels is largely due to the poor spatial resolution of these channels rather than the information content (see the SIC and SST discussions in sections above).

In terms of continuity, bands above 10.65 GHz are well provisioned by the international constellation (missions from Russia, China USA, and Europe). The Chinese National Ocean Satellite Application Centre (NSOAS) HY2 series of satellites carry a Microwave Imager (MWI) with 6.6 (V&H), 10.7 (V&H), 18.7 (V&H), 23.8 (V&H) and 37.0 V&H) channels but with a very large instantaneous field of view (6.6 GHz is 80 x 120 km). The WMO OSCAR database suggests that there are no plans to continue the HY-series MWI instrument beyond HY-2B (i.e. loss of capability in ~2023).

The future European Microwave Imager (MWI) on the MetOp-SG satellites developed for the EPS-SG EUMETSAT programme will eventually secure continuation of the United States Special Sensor Microwave Imager (SSM/I) series of coarse resolution radiometry for climate monitoring, but will not fulfil the requirements for medium resolution (~10 km) sea ice concentration which is needed in the near future by operational ice/ocean models [AD-2]. The MWI instrument on MetOp-SG does not provide access to frequencies below 18.7 GHz and therefore cannot provide continuity of AMSR-2 measurements of SST alone [AD-2], nor can it provide an equivalent spatial resolution in other channels.
The CMA/NRSCC MWRI instrument does carry a 10.65 GHz channel to ~2026 (FY-3F and FY-3G) but this is insufficient for SST and SIC monitoring in the Polar regions and Adjacent Seas as the spatial resolution is too large (the antenna is ~1.8m in diameter) and the fact that a poor sensitivity to SST at water temperatures less than ~290 K (e.g. Gentemann et al., 2010) means that a useful SST cannot be retrieved.

Extensive capability is offered by the Windsat, SMOS and SMAP missions. Windsat allows a retrieval of ocean vector winds over the ocean using a fully polarimetric capability (but there is no follow-on mission) and the L-band missions retrieve sea surface salinity, sea ice thickness and high wind speeds over the ocean. But beyond SMOS and SMAP there are no microwave radiometry imaging missions planned that will provide access to the 1.4 GHz frequency delivering thin sea ice thickness and sea surface salinity (e.g. Olmedo et al., 2017) in the Polar Regions. Copernicus services (i.e. CMEMS in the polar ocean case) cannot solely rely on non-European contributing missions to maintain the current quality of its service [AD-3].

Critically, there is no approved mission to replace AMSR-2 and it is not clear how long the instrument will maintain its current performance. The rotating joint for the antenna scan mechanism of the predecessor instrument (AMSR-E) degraded within ~9.5 years of launch. The design lifetime of AMSR2 was 5 years and clearly a replacement is urgently needed. JAXA is seeking for opportunities to fly an AMSR-3 instrument, but it will be of the same type as AMSR-2, thus not fulfilling the joint requirements of resolution and accuracy for polar SIC and SST ([AD-1]).

It is clear that there is loss of capability of 1.4 and 6 GHz bands in 2022/2023. Without acting, the long-term continuity of microwave space observations at these frequencies will be broken by a data gap in European and non-European satellite missions that provide a unique capability for SIC, SST, thin-SIT and other sea ice parameters in non-precipitating atmospheric conditions is required by Copernicus Services [AD-1][AD-2].

Complementarity of the CIMR mission in the Arctic under the Carbon and hydrologic cycles is very strong. The CIMR mission is relevant considering the complex interplay between the hydrological cycle and the carbon cycle in the atmosphere and in the ocean. The presence of sea-ice can prevent CO2-rich water from releasing its CO2 to the atmosphere (Roberts et al. 2016). Moreover, the atmospheric CO2 uptake into the ocean depends not only from its partial pressure, but also on the physical conditions of the air/sea interface, namely sea surface temperature, sea state (surface roughness) and ocean circulation. As a further example a simplified representation of the global thermohaline circulation is shown in the figure below. Near-surface currents (red lines) flow towards three main deep-water formation regions at high latitudes — which act as atmospheric carbon sinks — (northern North Atlantic, the Ross Sea and the Weddell Sea) and recirculate at depth (deep currents shown in blue). This implies that there are several feedback loops between the hydrologic and carbon cycles, e.g. driven by the sea ice formation and melting, and sea surface temperature in the polar regions.
8 REFERENCES

8.1 Applicable Documents

<table>
<thead>
<tr>
<th>Label</th>
<th>Identifier</th>
<th>Title</th>
<th>Published</th>
</tr>
</thead>
<tbody>
<tr>
<td>[AD-1]</td>
<td>PEG-I</td>
<td>User requirements for a Copernicus polar mission, Step 1 report, Polar expert group.</td>
<td>12th June 2017</td>
</tr>
<tr>
<td>[AD-2]</td>
<td>PEG-II</td>
<td>Polar expert group, Phase 2 report on Users’ requirements.</td>
<td>31st July 2017</td>
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</tbody>
</table>

8.2 Reference Documents


Hilburton, H and F. J. Wentz, (2008), Inter-calibrated Passive Microwave Rain Products from the Unified Microwave Ocean Retrieval Algorithm (UMORA), J. Applied Met. And Climatology, 778-794, DOI: 10.1175/2007JAMC1635.1


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9 APPENDIX I. DEFINITION OF TERMS

**Absolute Performance Error (APE):** difference between an actual parameter (e.g. attitude, geolocation etc.) and the known (measured or estimated) parameter in a specified reference frame (ESSB-HB-E-003, 2011).

**Absolute Knowledge Error (AKE):** difference between the target (commanded) parameter (e.g. attitude, geolocation etc) and the actual parameter in a specified reference frame (ESSB-HB-E-003, 2011).

**Absolute Radiometric Accuracy (ARA):** see Total Standard Uncertainty.

**Across scan direction:** direction normal to the along direction.

**Across track direction:** direction normal to the along track direction in the tangent plane to the Earth at the geodetic sub-satellite position (See Observation Zenith Angle that shows a figure).

**Adjacent Seas:** encompass all Seas and water bodies adjacent to the Arctic including Gulf of Bothnia, Gulf of Finland, Baltic Sea, Caspian Sea, Sea of Azov, Bering Sea, Sea of Okhotsk, Yellow Sea, Bohai Sea, Baikal Lake, Labrador Sea, Gulf of St Lawrence, American Great Lakes, Gulf of Alaska,

**Along track direction:** direction parallel to the projection of the spacecraft velocity on the tangent plane to the Earth at the geodetic sub-satellite position (See Observation Zenith Angle that shows a figure).

**Along scan direction:** direction parallel to the projection of the spacecraft velocity on the tangent plane to the Earth at the geodetic sub-satellite position.

**Altitude:** the satellite altitude is the shortest distance from the satellite centre of mass to the Earth surface.

NOTE: The reference altitude is defined here as the difference between the mean semi-major axis of a circular orbit having the orbital period specified by the repeat cycle and the Earth’s equatorial radius. The satellite altitude differs from the reference altitude, depending on the satellite’s location along its orbit.

**Ancillary Data:** data acquired on-board in support of the observation data, both for the instrument and the platform, such as calibration and timing data.

**Instrument Ancillary data:** data generated on-board by the instrument in support of the observation data, such as calibration, timing for each line acquisition, compression ratio, data validity flag (e.g. nominal detector temperature), needed to process the measurement data on ground.

**Platform Ancillary data:** data acquired on-board by the platform in support of the observation data, such as orbit position, velocity and time, attitude (generated by the AOCS sensors) needed to process measurement data on ground. Depending on timing constraints (NRT product or not), these data will be post-processed on-ground to improve the accuracy of orbit and attitude restitution.

**Azimuth (angle):** the angle in the xy plane from -y axis to the projection of the pointing direction in the xy plane; the angle direction is taken from -y axis to -x axis (see figure in definition of Elevation angle and also Figure MRD-4.2.4(b).
**Bandwidth**: difference between the upper and lower frequencies in a continuous set of frequencies.

**Beam Efficiency ($\eta_{be}$)**: the ratio between the received power (including co- and x-polar radiation) in the main beam and the total received power (including co- and x-polar radiation) over the full sphere:

$$
\eta_{be} = \frac{\int_{0}^{2\pi} \int_{0}^{\theta_{1}} (|E_{co}(\theta,\varphi)|^2 + |E_{x}(\theta,\varphi)|^2) \sin \theta d\theta d\varphi}{\int_{0}^{2\pi} \int_{0}^{\pi} (|E_{co}(\theta,\varphi)|^2 + |E_{x}(\theta,\varphi)|^2) \sin \theta d\theta d\varphi}
$$

where $\theta_{1}$ equal to $2.5 \times \theta_{3dB}$ footprint are the electric field co-polar and cross-polar components.

**Calibration Mode**: mode of operation defined to support the in-flight characterisation of the payload.

**Calibration key data**: required for processing the Level-0 to Level-1b data. Since the characteristics of the instrument can (and will) change over the mission, the calibration key data will change along with it. At launch, the calibration key data will consist of the data that is derived from on-ground calibration. During the mission the calibration key data will be updated with in-flight calibration data and adapted to match new insights in the instrument’s performance.

**Calibration key data set**: a set of data products that contains the calibration key data for a given orbit. The calibration key data set can consist of several files containing the actual data, for example in HDF or NetCDF format, and a descriptive file, for example in XML, that specifies, which parameter can be found in which data file.

**Channel**: polarised measurement (HH, VV, HV or VH) for a given band.

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\[Note 1: \text{Thus, there are a minimum of two CIMR instrument channels (HH and VV) for each CIMR instrument band e.g. 18.7V and 18.7H.}\]

**Characterisation**: the direct measurement, or analytical derivation from measurement, of a set of technical and functional parameters, over a range of conditions (e.g. temperature) to provide data necessary for calibration, ground processor initialisation and verification.

\[Note 1: \text{Characterisation can be performed either before launch on-ground and/or in-flight. In-flight, at least all those parameters have to be determined that may have varied since on-ground characterisation or which have not been measurable on-ground. In-flight characterisation may be based either on data derived from facilities built into the instrument (internal calibration) and/or on external sources (external calibration).}\]

**Commissioning**: verification and validation activities conducted after the launch and before the entry in operational service either on the space segment only or on the overall system (including the ground segment).

**Coverage**: geographical area systematically acquired, disregarding cloud cover, sun glint and OZA conditions.
Cross-Polarisation: radiation orthogonal to the desired polarisation (e.g. the cross-polarisation of a vertically polarised antenna is the horizontally polarised field).

Note 1: Cross-polarisation power refers to the total power received in cross-polarisation in the main beam of the antenna, divided by the total power received by the antenna (in co- and cross-polarisations).

Data Latency: the time interval from data acquisition by the instrument to delivery as Level 1b data product at the user segment interface.

Dynamic range: range of brightness temperatures within which requirements are to be met.

Dwell Time: time period required to acquire a spectral channel for a given spatial sample.

Earth: ellipsoid as defined in the WGS-84 geodetic datum.

Effective Coverage time: the time required to perform systematic acquisition of a given area with precipitation below a specified threshold and possibly under different observation conditions (in particular varying OZA or SZA).

Effective Revisit time: represents the period for systematic acquisition of the same area with precipitation below a specified threshold and under the same observation conditions (in particular same OZA).

Effective field of View (EFOV): area swept by the antenna beam during the integration time for a L1b measurement.

Elevation (angle): the angle between the instrument boresight and the satellite velocity direction.

NOTE: the complementary angle to elevation, theta (θ), is defined as θ = 90 – elevation

End Of Life (EOL): this event occurs at the end of the system in-orbit lifetime.

Fiducial Reference Measurement (FRM): the suite of independent ground measurements that provide the maximum Scientific Utility and Return On Investment for a satellite mission by delivering, to users, the required confidence in data products, in the form of independent validation results and satellite measurement uncertainty estimation, over the duration of the mission. The defining mandatory characteristics of an FRM are:

- Have documented evidence of SI traceability via inter-comparison of instruments under operational-like conditions.
- Are independent from the satellite retrieval process.
- Include an uncertainty budget for all FRM instruments and derived measurements is available and maintained, traceable where appropriate to SI ideally directly through an NMI
- Are collected using measurement protocols and community-wide management practices (measurement, processing, archive, documents etc.) are defined and adhered to.
• FRM uncertainties should be fit for purpose (i.e. be of a magnitude that is relevant to the application e.g. “Validation of satellite derived TSCV 0.1 ms⁻¹ or better”).

**Footprint:** instantaneous intersection of a single antenna pattern at half the maximum power level along the instrument bore sight with the Earth’s surface represented by the WGS-84 ellipsoid. (See Full beam for schematic)

**Footprint Ellipse:** elliptical footprint contour (see Footprint)

---

Note 1 For conically scanning radiometers, in the ideal case where the antenna pattern contour at half power level is circular, the 3dB footprint contour is elliptical. The ellipse representing the 3dB footprint contour is defined as in the following:

- The major axis is defined by the straight-line segment connecting the two points at maximum distance lying on the footprint contour;
- The minor axis is a segment, orthogonal to the major axis, and passing through the centre of the major axis. Its length is the maximum distance between any two points lying on the footprint contour along the direction orthogonal to the major axis.

---

**Footprint Centre:** centre of the Footprint Ellipse (see Footprint definition).

**Footprint Size:** arithmetic mean of the two major and minor axes of the Footprint Ellipse (see Footprint).

**Full Beam:** angular region described by the antenna pattern including all side lobes.

**Gain:** see System Gain.

**Geo-location:** worst-case pixel localisation (to zero mean 1-sigma knowledge error) knowledge expressed in geodetic coordinates within a Level 1B image product.

**Geo-location Accuracy:** difference between the estimated barycentre position of any spatial sample and its true position projected onto the WGS84 reference Earth ellipsoid.

**Geometrical Coverage time:** represents the time required to perform systematic acquisition of a given area disregarding precipitation and possibly under different observation conditions (in particular varying OZA or SZA).

**Geometrical Revisit time:** represents the period for systematic acquisition of the same area disregarding precipitation and under the same observation conditions (in particular same OZA).

**Goal:** a non-mandatory but highly desirable requirement, the implementation of which shall be studied to allow for an assessment of the system impacts. The implementation or not of the goal requirements will be decided by the Agency after analysis of the implications.

**Half Power Beam-width (HPBW):** angle at which the antenna's power radiation pattern is at half its maximum value.

**Horizontal Polarisation (H):** electric field is perpendicular to the plane of incidence.

**Housekeeping Telemetry:** refers to all non-science TM that is generated on-board, either on a periodic basis (Periodic Housekeeping TM) or as on-board events, or on request (report of parameters and tables, dump of memories, dump of data, etc.)
**Image**: ensemble of data acquired over a two-dimensional scene with equal number of spatial samples in the cross and along track direction. The number of spatial samples in cross track is defined by the instrument swath and spatial sampling interval.

**Image Navigation**: the knowledge of the relationship between a spatial sample in instrument coordinates and the corresponding point on the Earth, given by latitude and longitude coordinates. In general, Image navigation refers to the methods employed to obtain that knowledge. Image navigation accuracy is a measure of how well that relationship is known. Image registration is an indication as to how well that navigation knowledge is maintained and controlled over time.

**Image swath**: maximum distance on ground between the positions of two spatial samples belonging to the scan line or row.

**In-Orbit Lifetime**: period of time between the beginning of the in-orbit commissioning and the end of the delivery of data by the satellite.

**Integration time**: time it takes for the instrument scan mechanism to scan across the angular distance corresponding to the footprint ellipse minor axis.

**Instrument Field of View (FOV)**: the angle subtended at the satellite nadir point between the most extreme position on the left-hand part of the instrument swath and the most extreme position on the right-hand part of the instrument swath. See Figure MRD-4.2.4(b)

**Instantaneous Field of View (IFOV)**: see definition of footprint.

**Inter-channel spatial co-registration**: maximum equivalent ground distance between the positions of all pairs of spatial samples acquired in two channels and related to the same target on Earth.

**Inter-channel temporal co-registration**: maximum time interval between the acquisitions of channels related to the same target on Earth.

**Inter-channel radiometric accuracy**: unknown bias error (difference between measured value and true value) of the ratio of radiances measured in two channels and associated to the same target on Earth. The inter-channel radiometric accuracy shall be demonstrated by averaging a sufficiently large number of samples such that the residual temporal variation does not dominate the calculation.

**Main Beam**: angular region within 2.5 times the ellipse representing the 3dB angular contour of the antenna pattern (see Full Beam for schematic). This ellipse is referred to as the “3dB contour Ellipse”.

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**NOTE** The ellipse representing the 3dB angular contour of the antenna pattern is defined as in the following:

The major axis is defined by the straight-line segment connecting the two points at maximum distance lying on the 3dB contour;

The minor axis is a segment, orthogonal to the major axis, and passing through the centre of the major axis. Its length is the maximum distance between any two points lying on the 3dB contour along the direction orthogonal to the major axis.

**Nadir**: nadir direction is defined as the line from the centre of the satellite reference frame that is perpendicular to the reference ellipsoid tangent.
Near Real-Time (NRT): product delivered in less than 3 hours to the point of user pickup after data acquisition by the satellite. NRT products are used for operational applications such as sea ice services, operational oceanography and meteorology.

Nominal Operational Lifetime: the time in orbit over which the performance has to be met with a given satellite availability and excluding the time necessary for the execution of LEOP and commissioning.

Observation zenith angle (OZA): angle between the satellite viewing direction and the local zenith defined in the surface target reference frame (i.e., zenith – target – satellite) as shown in the figure below.

Payload: see instrument

Payload Data Ground Segment (PDGS): elements of the ground segment that perform the functions of data processing, archiving and distribution to the users. They normally also perform the long-term calibration and control the quality and status of the instrument(s) and data products.

Platform: parts of the satellite that provide the functionalities and resources required to operate the instrument and to control and monitor the satellite.

Polar Regions: encompass:

- The pan-Arctic domain (>55°N latitude, 0-360° longitude) and,
- Antarctic (>50°S latitude, 0-360° longitude).

Polarisation sensitivity: assuming measurement of a stable, spatially uniform, linearly polarized scene, the polarization sensitivity is defined as:

\[ P = \frac{S_{\text{max}} - S_{\text{min}}}{S_{\text{max}} + S_{\text{min}}} \]

where \( S_{\text{max}} \) and \( S_{\text{min}} \) are the maximum and minimum sample values obtained when the polarization is gradually rotated over 180 deg.
**Position of sample:** geographic location of the barycentre of the footprint.

**Precipitation threshold:** the maximum acceptable precipitation rate (determined from CIMR measurements) to be considered for the computation of the effective revisit/coverage/accessibility time is 15% per elementary image.

**Precision:** difference between one result and the mean of several results obtained by the same method, ie. reproducibility (includes random uncertainties only).

NOTE: Precision describes the spread of these measurements when repeated. A measurement that has high precision has good repeatability. The statistical standard deviation derived from a number of repeated measurements may serve as a measure of precision.

**Product level definitions:** the concept of product levels, and the definitions thereof, have been codified by CEOS (Committee on Earth Observation Satellites). The CEOS definitions are the basis for the product levels defined in these requirements, with appropriate modifications since the original definitions were formulated with imaging sensors in mind. Data downlinked from the satellite consist of a serial stream of data bits embedded within a framework of transfer frames appropriate for the purpose. This level of data, which may be temporarily archived at the reception station, is not readable by a general-purpose computer and not included in the set of product level definitions.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artefacts (e.g., synchronization frames, communications headers, duplicate data) removed.</td>
</tr>
<tr>
<td>L1a</td>
<td>L0 data reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and geo-referencing parameters (e.g., platform ephemeris) computed and appended but not applied to the data.</td>
</tr>
<tr>
<td>L1b</td>
<td>Level 1a data that have been quality controlled and reformatted but not resampled All radiometric and spectral calibration have been applied to provide top-of-atmosphere spectral brightness temperatures (T_b) in units of Kelvin. Geometric information is computed, appended but not applied. Preliminary pixel classification is included in the product.</td>
</tr>
<tr>
<td>L2</td>
<td>Derived geophysical variables at the same resolution and location as Level 1 source data.</td>
</tr>
<tr>
<td>L3</td>
<td>Variables mapped on uniform space-time grid scales, usually with some completeness and consistency. L3U (Uncollated) product are from gridded individual satellite swath data. L3C (generally referred to as L3) collate several swaths from an instrument (e.g. daily composite).</td>
</tr>
<tr>
<td>L4</td>
<td>Results from analyses of lower-level data (e.g., variables derived from multiple measurements) typically using an analysis technique (e.g. optimal estimation) or a model.</td>
</tr>
</tbody>
</table>

Within these general definitions several distinct products may be defined at each level, containing different levels of detail in the parameters provided.

**Radiometric accuracy:** see Absolute radiometric accuracy.
Radiometric resolution: smallest change of radiometric sensitivity that can be measured.

Radiometric Sensitivity (NEΔT): smallest value of input brightness temperature or radiance that can be detected in the system output for an integration time that is compliant with each individual CIMR footprint along the conical scan direction.

NOTE: The sensitivity requirement applies to calibrated radiances and is applicable throughout the dynamic range. System noise, gain variations and calibration noise shall be taken into account when calculating the sensitivity. In case of multiple beams for single channel the definition and the associated requirements for NEΔT applies to each individual footprint and related integration time. The following formula shall be used:

\[ NEΔT = \left( T_{SYS} + T_{scene} \right) \left( \frac{1}{8\tau} + \left( \frac{\Delta G}{G} \right)^2 + \left( \frac{1}{BN\tau_c} \right) \right) \]

where \( T_{SYS} \) is the receiver noise temperature (including antenna losses), \( T_{scene} \) is the scene temperature, \( B \) is the bandwidth, \( \tau \) is the integration time \( \Delta G/G \) is the receiver gain variation, \( \tau_c \) is the calibration target integration time and \( N \) is the number of calibration cycles averaged.

Radiometric Stability: degree to which radiometric accuracy remains constant over time.

NOTE: Changes in radiometric stability, also known as drift, can be due to components aging, decrease in sensitivity of components, and/or a change in the signal to noise ratio, etc. Radiometric stability is quantified as the standard deviation of measurement differences when viewing an invariant and homogeneous calibration target(s) over a defined period of time and of such magnitude that NEΔT is insignificant, with the system operating within its dynamic range.

Relative Pointing Error (RPE): angular separation between the instantaneous pointing direction and the short-time average pointing direction at a given period.

Revisit time: time between two consecutive possible observations of a same target within the specified incidence angle range.

Sample: measurement made during a fraction of the integration time.

Satellite or Spacecraft: refers to each one of the independently flying elements of the space segment. It comprises all hardware to be placed into Earth orbit with the exception of the launch vehicle. The satellite is composed of the platform and the instrument.

Sea Surface Salinity: Sea Surface Salinity (SSS) is expressed according to the Practical Salinity Scale (UNESCO, 1985) defined as conductivity ratio: a seawater sample of Practical Salinity 35 has a conductivity ratio of 1.0 at 15°C and 1 atmosphere pressure, using a potassium chloride (KCl) standard solution containing a mass of 32.4356 grams of KCl per Kg of solution. Thus SSS is ratio quantity and has no physical units. The use of PSU or PSS as a physical unit for SSS is incorrect. However, the use of PSS to indicate that the PSS scale has been used is appropriate.

Side Lobe: lobes of local maxima in the far field radiation pattern that are not the main beam (see Full beam for schematic).
NOTE: Multiple side lobes may exist in any given antenna gain pattern and the peak side lobe is the largest magnitude side lobe.

Signal to Noise Ratio: ratio of signal power to the noise power.

Spatial Resolution: see Footprint.

Spatial Sampling Distance (SSD): distance between the centre of adjacent footprint samples on the Earth’s surface.

Sub-Satellite Point (SSP): the point on the Earth’s reference ellipsoid that intersects the nadir direction.

Swath width: the across-track ground which is imaged and over which the performance requirements are met.

System Gain: the overall gain of the instrument channel (from the antenna aperture to the instrument output).

Total Standard Uncertainty: For CIMR ARA is not used in the traditional manner but instead we calculate the Total Standard Uncertainty (which is a zero mean “1-sigma” total uncertainty). The strength of this approach is that each component of the total standard uncertainty can be validated (which is not the case for ARA which implies a reference of “truth”). It is noted that this approach, while consistent with international agreements on uncertainty specification (JCGM, 2008), it is different compared to other formulations (e.g. as for the MetOp-SG(B) MWI) that do not include NEΔT as part of the absolute radiometric accuracy definition. Four components of Total Standard Uncertainty are: NEAT, Lifetime radiometric stability, orbital stability and beginning of life uncertainty. The total standard uncertainty for a single measurement (in one channel) is the combination of uncertainty from random and systematic effects. These correctly combine in quadrature:

\[ u_{\text{total}} = \sqrt{u_{\text{random}}^2 + u_{\text{systematic}}^2} \]  

(Eqn. 4.2.10.1)

Channel NEΔT addresses the uncertainty from random effects in the instrument.

The stability requirements limit the excursions of the calibration from “truth” on slower timescales: the orbit stability requirement constrains the drift of the calibration on orbital timescales; the lifetime stability constrains the degree of drift of calibration over the mission lifetime; and one further component is required to obtain the total standard uncertainty, namely the beginning of life uncertainty of pre-launch calibration knowledge \( u_{\text{pl-cal}} \) e.g. derived from ground characterisation). In particular, \( u_{\text{pl-cal}} \) implies a rigorous pre-launch characterisation of the CIMR instrument (and thus links to the CIMR calibration and validation plans). This is consistent with the definition of all quantities as zero mean 1-sigma standard deviations in the MRD requirements. Therefore, the requirements adhere to the formulation of Total Standard Uncertainty:

\[ u_{\text{total}}^2 \equiv u_{\text{NEΔT}}^2 + u_{\text{orbit-stability}}^2 + u_{\text{lifetime-stability}}^2 + u_{\text{pl-cal}}^2 \]  

(Eqn. 4.2.10.2)

Interpretation of total standard uncertainty, NEΔT, orbital stability and the lifetime stability as uncertainty components is consistent with the definition of all of them as zero mean 1-sigma standard deviations in the MRD requirements.
Uncertainty: the closeness of agreement between the result of a measurement and a true value of a measurand as follows:

- **Uncertainty (of measurement):** parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

- **Standard Uncertainty:** uncertainty of the result of a measurement expressed as a standard deviation

- **Type A evaluation (of uncertainty):** method of evaluation of uncertainty by the statistical analysis of series of observations

- **Type B evaluation (of uncertainty):** method of evaluation of uncertainty by means other than the statistical analysis of series of observations

- **Combined standard uncertainty:** standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, the terms being the variances or covariances of these other quantities

Validation: confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.

**NOTE:** CEOS definition is the process of assessing by independent means the quality of the data products (the results) derived from the system outputs.

Verification: confirmation, through the provision of objective evidence, that the specified requirements have been fulfilled.

**Vertical Polarisation (V):** electric field is parallel to the plane of incidence.

**Wide Beam:** angular region 3.0 times the ellipse representing the 3dB angular contour described by the antenna pattern (see Full Beam for schematic).

**Wide Beam Efficiency:** the ratio of total (cross- and co-polarised) power received by an antenna within its wide beam to the total power received from the full sphere, assuming isotropic and unpolarised illumination of broadband noise such as thermal radiation.
APPENDIX II MAJOR POLICIES AND EO APPLICATIONS SUPPORTED BY THE CIMR MISSION

Table AII-1: Summary major policies and EO applications supported by the CIMR mission.

<table>
<thead>
<tr>
<th>Policies Directives</th>
<th>Applications</th>
<th>User Requirements</th>
<th>User entities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EU Integrated Policy on the Arctic</strong></td>
<td>Climate Change and the Arctic Environment, sustainable development in the Arctic, International cooperation on Arctic matters,</td>
<td>Monitoring of floating sea ice and ocean surface parameters with high spatial resolution to support sustainable development and environmental security, cooperation and long-term monitoring of societal impacts in the Arctic Environment. Enhance the safety of navigation in the Arctic.</td>
<td>Arctic States, EC, ESIF(^{19}), UN, UNCLOS(^{20}), ECGFF(^{21}), ACGF(^{22}), TEN-T(^{23}), OSPAR, GEOCRI.</td>
</tr>
<tr>
<td><strong>EU Water Framework Directive</strong></td>
<td>Water rights management, Water pricing, Ground water abstraction limits, Protection of inland and coastal water surfaces</td>
<td>Monitoring of water use from field scale to irrigation system level for enforcing sustainable water abstraction for agricultural production</td>
<td>EEA; national and river basin management authorities</td>
</tr>
<tr>
<td><strong>UN Sustainable Development Goals</strong></td>
<td>Water use efficiency and management, Sustainable agricultural production</td>
<td>Reporting on the SDG 6.4 for increase water-use efficiency across all sectors and ensure sustainable withdrawals.</td>
<td>National statistical offices, UNEP, UN Statistics</td>
</tr>
<tr>
<td><strong>UN Framework Convention on Climate Change</strong></td>
<td>Risk management and climate change adaptation</td>
<td>Mitigating water scarcity impacts related to climate change or extreme weather calamities</td>
<td>Insurance providers; farmers; national water authorities</td>
</tr>
</tbody>
</table>

\(^{19}\) European Structural and Investment Funds  
\(^{20}\) UN Convention on the Law of the Sea (UNCLOS)  
\(^{21}\) European Coast Guard Functions Forum (ECGFF)  
\(^{22}\) Arctic Coast Guard Forum (ACGF)  
\(^{23}\) trans-European Network for Transport (TEN-T)
| Convention for the Protection of the Marine Environment of the North-East Atlantic (the ‘OSPAR Convention’) | OSPAR work areas: biological diversity & ecosystems, hazardous substances & eutrophication, human activities, offshore industry, radioactive substances, cross cutting issues. https://www.ospar.org/about | Marine biodiversity indicator remote sensing, need for higher accuracy of measurements and classification, continuity of data sources | OSPAR contracting parties, Users of nautical charts and sailing directions in high risk/prohibited areas, more general users of the coastline, Fishermen etc. |
| Geo Cold Regions Initiative (GEOCRI) | Biodiversity and ecosystem sustainability, disaster resilience, energy and mineral resource management, food security and sustainable agriculture, infrastructure and transportation management, public health surveillance (weather extremes, water-related illness etc.) water resources management, The GEOCRI mission is to develop a user-driven approach for Cold Regions information services to complement the mainly current science-driven efforts, which will strengthen synergies between the environmental, climate, and cryosphere research efforts and foster the collaboration for improved earth observations and information on a global scale. https://www.earthobservations.org/activity.php?id=114 | There is the need to provide coordinated Earth observations and information services across a range of stakeholders to facilitate well-informed decisions and support the sustainable development of the cold regions globally. | Users from both the public and private sectors, including managers and policy makers in the targeted societal benefit areas, scientific researchers and engineers, governmental and non-governmental organizations, and international bodies |
| EU-PolarNet initiative | Supports a EU-wide consortium of expertise and infrastructure for polar research to better assimilate Europe’s scientific and operational capabilities in the Polar regions. http://www.eu-polarnet.eu/ | Improved coordination of data and infrastructure between EU member polar research institutions. | EC, EU member polar research institutions, public, private organizations, universities and research centres |
| Northern Dimension policy framework | Thematic partnerships related to environment (NDEP), public health and social well-being | Arctic coastal zone monitoring, satellite hydrographic monitoring and | Regional and sub-regional organizations and commissions in the Baltic and Barents area, the sub-national |
The Northern Dimension policy aims at providing a common framework for the promotion of dialogue and cooperation, strengthening stability, well being and intensified economic cooperation, promotion of economic integration and competitiveness and sustainable development in Northern Europe. https://eeas.europa.eu/diplomatic-network/northern-dimension_en

**European Maritime Transport Policy**

Maritime Safety and Security; Digitalisation and Administrative Simplification; Environmental Sustainability and Decarbonisation; Raising the Profile and Qualifications of Seafarers and Maritime Professions and; EU Shipping: A stronger global player. https://ec.europa.eu/transport/themes/strategies/2018_maritime_transport_strategy_en

Floating sea ice and ocean surface parameters to be monitored with high spatial resolution.

**IMO International Code for ships operating in polar waters (Polar Code)**

The Polar Code is intended to cover the full range of shipping-related matters relevant to navigation in waters surrounding the two poles – ship design, construction and equipment; operational and training concerns; search and rescue; and, equally important, the protection of the unique environment and eco-systems of the polar regions. http://www.imo.org/en/MediaCentre/HotTopics/polar/Pages/default.aspx

Improved knowledge on sea ice and other hazards for polar navigation.

In particular sea ice thickness and concentration forecasting.

<table>
<thead>
<tr>
<th>European Maritime Transport Policy</th>
<th>Floating sea ice and ocean surface parameters to be monitored with high spatial resolution.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMO International Code for ships operating in polar waters (Polar Code)</td>
<td>Improved knowledge on sea ice and other hazards for polar navigation. In particular sea ice thickness and concentration forecasting.</td>
</tr>
</tbody>
</table>

24 Cruise Lines International Association (CLIA)
25 European Boatmen’s Association (EBA)
26 European Community Shipowners’ Association (ESCA)
27 European Maritime Pilots Association (EMPA)
28 European Transport Workers’ Federation (ETF)
29 World Shipping Council (WSC)
APPENDIX III CIMR REQUIREMENTS TRACEABILITY MATRIX.

Copernicus is a user-driven programme. User Requirements are critical to steer and to adjust the future evolution of the Copernicus programme in particular in the frame of the next Multi-annual Financial Framework of the European Union (2021-2028):

- The evolution of the Copernicus data and information products and the related services;
- The definition of the next generation of Sentinels (expected type of observation and performances);
- The requirements for additional data that could be complementary to the Sentinels and necessary for the purpose of services.

To prepare this evolution, the Commission has undertaken the collection of User Requirements, the establishment of possible Copernicus service evolution and the elaboration of Observation Requirements that should best fulfil both users’ requirements with direct observations or enhanced Copernicus information services.

The following tables are taken from AD1, AD2 and AD3 and summarise the link of the user requirements to the mission requirements.

Some of the products cannot be satisfied with this mission.

Table AIII-1 Abbreviations used in parameter specification tables

<table>
<thead>
<tr>
<th>THEMES (THM)</th>
<th>DOMAINS (DOM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT</td>
<td>ME</td>
</tr>
<tr>
<td>OC</td>
<td>CL</td>
</tr>
<tr>
<td>FW</td>
<td>HY</td>
</tr>
<tr>
<td>SN</td>
<td>OC</td>
</tr>
<tr>
<td>GL</td>
<td>EC</td>
</tr>
<tr>
<td>IS</td>
<td>HZ</td>
</tr>
<tr>
<td>SI</td>
<td>EM</td>
</tr>
<tr>
<td>LA</td>
<td>EN</td>
</tr>
<tr>
<td>PF</td>
<td>TR</td>
</tr>
<tr>
<td></td>
<td>OI</td>
</tr>
<tr>
<td></td>
<td>SE</td>
</tr>
<tr>
<td></td>
<td>GE</td>
</tr>
<tr>
<td></td>
<td>N</td>
</tr>
</tbody>
</table>
Table AIII-2 Parameter specification scheme used in PEG survey

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOI (coverage)</td>
<td>Area Of Interest to be covered, options are: [0] global, [1] high latitude (&gt;60), [2] regional - in this case provide details (bounding box, shapefile) or map (raster mask at 10-100km resolution)</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>the sampling distance of measurements in [m], equal spacing in x and y is assumed</td>
</tr>
<tr>
<td>TOY (seasonality)</td>
<td>Time Of Year for measurements, options are: [0] year round, [1] seasonal - in this case provide the time window for measurements (months)</td>
</tr>
<tr>
<td>Frequency</td>
<td>temporal frequency, options are: [0] 'on demand' acquisitions - estimate nr of acquisitions per year, [1] regular measurements - provide repetition rate in [mn, hr, dy, mo, yr]</td>
</tr>
<tr>
<td>Leadtime</td>
<td>in case of 'on demand', what should be the minimum lead time for an acquisition to be scheduled in [hr]</td>
</tr>
<tr>
<td>Timeliness</td>
<td>how long after acquisition should the product be available, options are: [0] non time critical, [1] NRT within 6hr [2] QRT within 1hr</td>
</tr>
<tr>
<td>Unit</td>
<td>how is the variable assessed: [0] as continuous scale, in this case give (physical) units (SI) [1] in different categorical classes - in this case provide reference</td>
</tr>
<tr>
<td>Range</td>
<td>dynamic range of measurements in physical units or number (and name) of categories</td>
</tr>
<tr>
<td>Accuracy</td>
<td>95% confidence interval for uncertainty (continuous scale variable) or commission and omission errors (categorical variable)</td>
</tr>
<tr>
<td>In-Situ (I)</td>
<td>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</td>
</tr>
<tr>
<td>Status (S)</td>
<td>is variable currently monitored by means of EO: [0] no [1] experimental research ongoing, [2] operational service, (ATBDs available); for [1] and [2] provide references</td>
</tr>
<tr>
<td>Gaps</td>
<td>If variable is currently observed, give actual specs if different from requirements listed under 1-8 above</td>
</tr>
<tr>
<td>Continuity (C)</td>
<td>what are the expectations with respect to future availability of this variable: [0] current status of EO and IS ensured or likely to</td>
</tr>
<tr>
<td>Priority (P)</td>
<td>[0] low, nice to have, dispensable, models and/or proxies available [1] low, but continuity must be guaranteed [2] high, improvements are essential for progress in the domain</td>
</tr>
<tr>
<td>-------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>

**Copernicus Imaging Microwave Radiometer (CIMR) Mission Requirements Document**

**Issue Date:** 30/09/2019, **Ref:** ESA-EOPSM-CIMR-MRD-3236, **Version 3.0 ISSUED**
### 11.1.1 Sea Ice Concentration (Sea Ice Fraction)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CMEMS Recommendation</th>
<th>Mission Requirement</th>
<th>Compliance statement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sea Ice Concentration (Sea Ice Fraction)</strong></td>
<td>[AD-3] recommends to fly a European microwave mission for high spatial resolution (&lt; 10 km) ocean surface temperature and sea ice concentration and sustainable operation of multi-frequency and -polarization passive microwave observations of SST, sea ice lead fraction and sea ice concentration.</td>
<td>MRD-750 and MRD-760</td>
<td>F</td>
</tr>
</tbody>
</table>
### 11.1.2 Sea Surface Temperature (SST)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CMEMS Recommendation</th>
<th>Mission Requirement MRD</th>
<th>Compliance statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Surface Temperature SST</td>
<td>[AD-3] states that sustainable passive microwave SST observations are also very important in the global ocean as well as in polar regions. Such observations are available in all weather conditions, while infra-red SST observations are available in cloud free conditions only. SST from PMW is a crucial contribution providing input to weather forecasting and CMEMS ocean and analysis and forecasting models. The future for PMW SSTs is very uncertain and as, of today, CMEMS cannot solely rely on USA or Japan contributing missions.</td>
<td>MRD-760</td>
<td>Full F, Non Compliant NC, Partial P</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AOI</th>
<th>Resolution</th>
<th>TOY</th>
<th>Frequency</th>
<th>Leadtime</th>
<th>TL</th>
<th>Unit</th>
<th>Range</th>
<th>Accuracy</th>
<th>I</th>
<th>S</th>
<th>C</th>
<th>P</th>
<th>Mission Requirement</th>
<th>Compliance statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST</td>
<td>OC</td>
<td>CL</td>
<td>T: 10km</td>
<td>G: 1km</td>
<td>n/a</td>
<td>0</td>
<td>°K</td>
<td>[271,283]</td>
<td>0.1K</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td>MRD-760</td>
<td>P (Accuracy 0.1 K not attainable)</td>
</tr>
<tr>
<td>SST</td>
<td>OC</td>
<td>OC</td>
<td>0</td>
<td>T: 5km</td>
<td>n/a</td>
<td>6hr</td>
<td>°K</td>
<td>0</td>
<td></td>
<td>0</td>
<td>2</td>
<td>1</td>
<td></td>
<td>MRD-760</td>
<td>P (95% global coverage using 1 satellite)</td>
</tr>
</tbody>
</table>
### 11.1.3 Sea Ice Thickness (SIT)

<table>
<thead>
<tr>
<th>THM</th>
<th>DOM</th>
<th>Parameter</th>
<th>AOI</th>
<th>Resolution</th>
<th>TOY</th>
<th>Frequency</th>
<th>Leadtime</th>
<th>TL</th>
<th>Unit</th>
<th>Range</th>
<th>Accuracy</th>
<th>I</th>
<th>S</th>
<th>C</th>
<th>P</th>
<th>Mission Requirement</th>
<th>Compliant statement</th>
<th>Full F</th>
<th>Non Compliant</th>
<th>Partial</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>CL</td>
<td>Thin sea ice</td>
<td>1</td>
<td>T: 10km</td>
<td>0</td>
<td>1dy</td>
<td>n/a</td>
<td>0</td>
<td>0: [m]</td>
<td>[0, 0.5]</td>
<td>5%</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
<td>MRD-770</td>
<td>Partially compliant</td>
<td>10% instead of 5%,</td>
<td>&lt;60km instead of 10km</td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>OC</td>
<td>Snow depth</td>
<td>0</td>
<td>T: 5km</td>
<td>0</td>
<td>T: 6hr</td>
<td>n/a</td>
<td>2</td>
<td>0: [%]</td>
<td>[0, 100]</td>
<td>5%</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>TR</td>
<td>Snow depth and density</td>
<td>0</td>
<td>T: 20m</td>
<td>0</td>
<td>T: 2d</td>
<td>24h</td>
<td>1</td>
<td>0: [m]</td>
<td>[0, 0.3] T: 0.03 G: 0.01</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 11.1.4 Snow Depth on Sea Ice

<table>
<thead>
<tr>
<th>THM</th>
<th>DOM</th>
<th>Parameter</th>
<th>AOI</th>
<th>Resolution</th>
<th>TOY</th>
<th>Frequency</th>
<th>Leadtime</th>
<th>TL</th>
<th>Unit</th>
<th>Range</th>
<th>Accuracy</th>
<th>I</th>
<th>S</th>
<th>C</th>
<th>P</th>
<th>Mission Requirement</th>
<th>Compliant statement</th>
<th>Full F</th>
<th>Non Compliant</th>
<th>Partial</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>OC</td>
<td>snow depth and density</td>
<td>0</td>
<td>&lt;5km</td>
<td>0</td>
<td>1dy</td>
<td>n/a</td>
<td>1</td>
<td>0: [m]</td>
<td>[0,10]</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td></td>
<td>MRD-800</td>
<td>P, Resolution &lt;15km, Uncertainty ±10 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>CL</td>
<td>1-10 km</td>
<td>1</td>
<td>1-10 km</td>
<td>0</td>
<td>1dy</td>
<td>n/a</td>
<td>0</td>
<td>0: [m]</td>
<td>[0,1] 0,01 m</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
<td>MRD-800</td>
<td>P, Resolution &lt;15km, Uncertainty ±10 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>TR</td>
<td>25m</td>
<td>0</td>
<td>25m</td>
<td>0</td>
<td>T: 1dy</td>
<td>G: 12hr</td>
<td>n/a</td>
<td>2</td>
<td>0: [m]</td>
<td>[0,10] 0,1m</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 11.1.5 Ice type/Ice stage of development

<table>
<thead>
<tr>
<th>TIME</th>
<th>DOM</th>
<th>Parameter</th>
<th>AOI</th>
<th>Resolution</th>
<th>TOY</th>
<th>Frequency</th>
<th>Leadtime</th>
<th>TL</th>
<th>Unit</th>
<th>Range</th>
<th>Accuracy</th>
<th>I</th>
<th>S</th>
<th>C</th>
<th>P</th>
<th>Mission Requirement</th>
<th>Compliance statement</th>
<th>Fail F</th>
<th>Non Compliant</th>
<th>NC</th>
<th>Partial P</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>TR</td>
<td>Ice Type</td>
<td>o</td>
<td>T: 20m G: 2m</td>
<td>o</td>
<td>T: 2d G: 1d</td>
<td>24h</td>
<td>1</td>
<td>1</td>
<td>[New Ice, Nilas/Level Ice, Rafted Ice, Ridged Ice, Hummocked Ice, Brash Ice]</td>
<td>T: 85%, G: 95%</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>MRD-790</td>
<td>P: Resolution &lt;15km, Uncertainty ≤10 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>TR</td>
<td>Ice Type</td>
<td>o</td>
<td>T: 40m G: 25m</td>
<td>o</td>
<td>T: 1dy G: 6hr</td>
<td>n/a</td>
<td>2</td>
<td>1</td>
<td>FY/MY</td>
<td>New Ice</td>
<td>T: 85%, G: 95%</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>ME, OC</td>
<td>Ice Type</td>
<td>o</td>
<td>T: 3 km G: 1 km</td>
<td>o</td>
<td>T: 1dy G: 12hr</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>FY/MY</td>
<td></td>
<td>T: 85%, G: 95%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MRD-790</td>
<td>P: resolution 15 km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 11.1.6 Ice Surface Temperature (IST)

<table>
<thead>
<tr>
<th>THM</th>
<th>DOM</th>
<th>Parameter</th>
<th>AOI</th>
<th>Resolution</th>
<th>TOY</th>
<th>Frequency</th>
<th>Leadtime</th>
<th>TL</th>
<th>Unit</th>
<th>Range</th>
<th>Accuracy</th>
<th>I</th>
<th>S</th>
<th>C</th>
<th>P</th>
<th>Mission Requirement</th>
<th>Compliance statement</th>
<th>Full</th>
<th>Non</th>
<th>Partial</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI</td>
<td>OC</td>
<td>0</td>
<td>T: 5km</td>
<td>o</td>
<td>6hr</td>
<td>n/a</td>
<td>2</td>
<td>0</td>
<td>°K</td>
<td>[210,290]</td>
<td>0.5K</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>MRD-830</td>
<td>P: Uncertainty &lt;1K Resolution ≤15 km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SI</td>
<td>TR</td>
<td>0</td>
<td>T: 150m G: 50m</td>
<td>T: 2dy G: 1dy</td>
<td>24h</td>
<td>1</td>
<td>0</td>
<td>°K</td>
<td>[173,278]</td>
<td>1K</td>
<td>0.25K</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td></td>
<td>MRD-830</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IS</td>
<td>CL ME HY</td>
<td>2 Antarctica Greenland</td>
<td>10 km</td>
<td>o</td>
<td>1 yr G: 1 mo</td>
<td>n/a</td>
<td>0</td>
<td>°K</td>
<td>[178-278]</td>
<td>1K</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td>MRD-830</td>
<td>P: Uncertainty &lt;1K Resolution ≤15 km</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 11.1.7 Snow Melt and Total Snow Area (dry) on Ice Sheets and Glaciers.
### SN GEN ME
Snow Water Equivalent

<table>
<thead>
<tr>
<th>SN</th>
<th>GEN ME</th>
<th>SN HY ME</th>
<th>SN PF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T: Northern Hemisphere; G: Global</td>
<td>T: 10km G: 1km</td>
<td>T: 50m G: 10m</td>
</tr>
<tr>
<td></td>
<td>T: 5dy G: 1dy</td>
<td>n/a</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>[mm (kg/m²)]</td>
<td>[0,500]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For SWE &lt; 200 mm: T: 40 mm, G: 20 mm</td>
<td>For SWE &gt; 200 mm: T: 20%, G: 10%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

### SN GEN CL ME
T: Northern Hemisphere; G: Global

<table>
<thead>
<tr>
<th>SN</th>
<th>GEN ME</th>
<th>SN HY ME</th>
<th>SN PF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T: 1km G: 200m</td>
<td>T: 5dy G: 1dy</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>[mm (kg/m²)]</td>
<td>[0,500]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For SWE &lt; 200 mm: T: 40 mm, G: 20 mm</td>
<td>For SWE &gt; 200 mm: T: 20%, G: 10%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

### SN GEN CL ME
T: 1km G: 200m

<table>
<thead>
<tr>
<th>SN</th>
<th>GEN ME</th>
<th>SN HY ME</th>
<th>SN PF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T: 1km G: 200m</td>
<td>T: 5dy G: 1dy</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>[mm (kg/m²)]</td>
<td>[0,500]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>For SWE &lt; 200 mm: T: 40 mm, G: 20 mm</td>
<td>For SWE &gt; 200 mm: T: 20%, G: 10%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

### SEASONAL SNOW

<table>
<thead>
<tr>
<th>SEASONAL SNOW</th>
<th>Status</th>
<th>Gaps</th>
<th>Mission Requirement MRD</th>
<th>Compliance statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Snow Area</td>
<td>VIS, NIR &amp; TIR imager, some problems with cloud / snow</td>
<td>Higher resolution required for complex terrain (mountains); cloudiness / polar</td>
<td>MRD-810</td>
<td>F</td>
</tr>
</tbody>
</table>
### 11.1.8 Sea Surface Salinity (SSS)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CMEMS Recommendation</th>
<th>Mission Requirement MRD</th>
<th>Compliance statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea Surface Salinity SSS</td>
<td>[AD-3] requests that there is a further advance in Copernicus capabilities to observe sea surface salinity over the global ocean from space. During recent workshops (Cesbio, Nov 2017; ECMWF, Dec 2017) the need for L-band radiometer continuity was discussed. It was identified that any future sensor shall at least provide observations with the same spatial resolution than currently orbiting systems (SMOS and SMAP), i.e., ~40-50 km and an accuracy of ≤0.2 (TBC)</td>
<td>MRD-840</td>
<td>F</td>
</tr>
</tbody>
</table>

**Snow Mass (SWE) on land**
- Low spatial resolution SWE maps available from IMWR, but at comparatively large uncertainty. Operational products available (GlobSnow, etc.), continuity of PMW on METOP.
- IMWR SWE: accuracy needs to be improved; problems with spatial resolution in complex terrain, forests, saturation over deep snow. High resolution product needed, not covered by current sensors.

**Snow Melt Extent**
- C Band SAR (S1, ERS, ENVISAT) provide snapshot, algorithms mature for mountain regions.
- Problems in forests. Melt extent depends on acquisition time;
[AD-2] Climate Requirements:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Existing products</th>
<th>Gaps</th>
<th>AOI / temporal and spatial resolution</th>
<th>Mission Requirement MRD</th>
<th>Compliance statement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sea ice concentration</strong></td>
<td>Core resolution ~25km&lt;br&gt;Resolution of 6km (12 km) are provided by AMSR (SSM/I) products in case they use radiometric measurements in the 89 GHz (85 GHz) channels&lt;br&gt;Sea ice concentration is the most important sea ice variable for climate studies as it provides the longest satellite time series available to assess the sea ice variability. It is also the parameter now predicted by all climate models and routinely assimilated in ocean and atmosphere reanalyses</td>
<td>MWI on MetOp SG will eventually secure continuation of the SSMI(S) serie, but will not fulfil a requirement for medium resolution (&lt;10km) as currently available on AMSR-2. A continuation of AMSR-2 like sensor is highly uncertain.&lt;br&gt;Accuracy in the small concentration range (MIZ and near the ice edge) should be improved by an order of magnitude. This will require in-situ infrastructure as well as space infrastructure.&lt;br&gt;A PMW with &lt;10km resolution could have been an important contribution for an high resolution concentration product for operational navigation. (See separate table for operational needs)</td>
<td>Area: Pan Arctic&lt;br&gt;Frequency: At least daily&lt;br&gt;Resolution: 25km with a goal of &lt;5km (depending on the channel used).</td>
<td>MRD-750</td>
<td>F</td>
</tr>
<tr>
<td><strong>Sea ice thickness</strong>&lt;br&gt;(freeboard)&lt;br&gt;(including summer ice and thin ice)</td>
<td>Cryosat-2 for thick ice (medium resolution, 25 km?) and SMOS estimates of thin (&lt;0.5 -1 m) sea ice</td>
<td>Cryosat estimates are too uncertain in the melt season (due to melt pond effects). Complete coverage of the Arctic is only available at the expense of the time resolution (monthly means). SMOS estimates</td>
<td>The threshold requirements in terms of revisit, coverage and precision are the same as those specified for Cryosat-2. The goal requirements would also</td>
<td>MRD-770</td>
<td>P: 10% instead of 5%, &lt;60km instead of 10km</td>
</tr>
</tbody>
</table>
| **Sea Ice drift** | Pan-Arctic coarse resolution (25-60 km) (combination of active and passive sensors) gridded datasets. High resolution lagrangian products deduced from processed SAR images (e.g., RADARSAT GPS) are also extremely useful for process studies on sea ice mechanics as well as validation of drift/deformation fields produced by sea ice models. | Resolution of gridded products is too low. Products deteriorate near the ice edge or in summer. SAR data do not provide global coverage. Improve on the use of these data. | **Area:** Pan Arctic  
**Frequency:** daily  
**Resolution:** 10 km, as for SIC | **MRD-780** | **F** |
| **Snow depth and density on sea ice** | Empirical method exist based on PMW brightness temperatures measured at different frequencies for SSM/I or AMSR-E. | The current estimates of snow over ice are empirical and medium resolution. They do not work for thick snow cover. | Snow depth measurements are needed to better assess snow loading and altimeter freeboard measurements, as well as the role of snow in the evolution of the sea ice cover. The specification should follow the ice thickness specifications in terms of resolution and time sampling. | **MRD-800** | **F** |
| Ice type | Multiyear ice concentration are available from PMW. Distinction of deformed/leveled ice is available via scatterometer data. | Continuity of the PMW brightness temperature at different polarizations. | Accuracy: Fractions of deformed ice has to be measured with an accuracy of 10%. Coverage: pan-arctic Frequency: daily (for monitoring of ice kinematics) Spatial resolution: same as for ice drift (order 10 km), ultimate goal would be 1 km. | MRD-790 | F |
| All weather SST/IST | All weather SST/IST are available at low resolution based on PMW. High resolution, weather dependent IR products are available at 1 km resolution | High resolution (1 km) IST are useful to estimate heat transfer through sea ice and sea ice growth rates but are hardly available in cloudy high latitudes. | Continuity of the PMW retrieved SST/IST is required together with high resolution weather dependent SST/IST as this parameter is crucial for climate studies and model validation | MRD-760 | F |
### [AD-2] Operational Requirements:

<p>| Sea ice concentration | Sea ice concentration is the most important variable for operational oceanography. Passive Microwave products are currently assimilated in CMEM’s operational systems. High resolution concentration from the manually derived ice charts. These products are mainly based on Sentinel-1 in Extra Wide Swath Dual polarisation but also on corresponding data from Copernicus Contributing Missions. | The future availability of multifrequency microwave radiometry (AMSR-2) is uncertain and reason for concern. The future MWI in MetOp SG will eventually secure continuation of the SSMI(S) series of coarse resolution radiometry for climate monitoring, but will not fulfil the requirements for medium resolution (&lt; 10 km). Reliable automated sea ice-chart-like products that can be delivered in NRT for navigational aid and for high-resolution input to numerical forecasting models are needed. Such product will probably need a multisensor approach where SAR will be the core input in combination with PMW. | Actual PMW data from CMEM’s catalogue are available at coarse resolution. It will be likely that increase in resolution and time availability of products from operational systems will require sub-daily and resolution less than 10km in the future with at least a continuation of observations with a spatial resolution no less than those provided by the AMSR-2 instrument (threshold). Area: pan-Arctic, frequency: at least daily, threshold resolution &lt; 10km/. SAR requirements: Area: Pan Arctic; Frequency: At least daily or 2-4 times in key areas. Resolution: 20m or at least no less than those provided by Sentinel-1 |
| All weather SST | SST is a key variable for short term forecasts but also seasonal forecast applications. These data also are likely the oldest variables being assimilated in oceanic systems. MWI also lack the necessary frequencies to measure all weather SST. A potential future C-band microwave radiometer (EE-10 suggestion) could fulfil the SST requirements, but resolution better than 5km at frequencies below 40 GHz is not foreseen and still will be needed. Other Status of Pathfinder instruments ? | A continuity is at least required. Infrared ice surface temperature is also required. Area : Pan-Arctic Frequency: At least daily; Sub-daily sampling shall be monitored to sample diurnal cycle. | MRD-750 | F for PMW references |</p>
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
<th>Resolution: for gridded data:</th>
<th>Area: Pan Arctic</th>
<th>Temporal resolution: 1 day (G), 2 days (T)</th>
<th>Coverage: pan-arctic</th>
<th>Spatial resolution: 20m (G), 80m (T)</th>
<th>MRD-770</th>
<th>F (for SMOS like after re-gridding)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global daily ocean SST (L4) from Pathfinder AVHRR and (A)ASTR instrument is a CMEMS' product given at 1/20° horizontal resolution (~5km) in NRT and presently assimilated</td>
<td>There is a gap in operational Sentinel-3 products where no SLSTR IST product is foreseen over sea ice.</td>
<td>&lt; 5km</td>
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<tr>
<td>Ice surface temperature (IST) is a CMEMS' product.</td>
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<td>There is a gap in operational Sentinel-3 products where no SLSTR IST product is foreseen over sea ice.</td>
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<tr>
<td>Resolution: for gridded data: 1/20° horizontal resolution (~5km)</td>
<td>Area: Pan Arctic</td>
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<td>Area: Pan Arctic</td>
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<tr>
<td>Sea ice thickness (freeboard) (including summer ice and thin ice) Pan-Arctic data does not exist presently in the CMEM's catalogue. Assimilation of sea ice thickness data (SMOS-like one) is underway in operational systems. High resolution product for navigation purposes does not exist for the Arctic Ocean.</td>
<td>A need to solve the knowledge gap in snow depth estimation over sea ice. For operational navigation purposes it is difficult to utilize Cryosat data due to its temporal and spatial resolution and too large uncertainty. It is noted that the spatial and temporal resolution requirements needed may not be achievable with today's technology. However, some studies have shown a potential of using ice type as a proxy to derive ice thickness. This will need to be investigated further. Requirements related to ice type are included below.</td>
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<tr>
<td>Sea Ice drift CMEMS' operational systems assimilate pan-Arctic coarse resolution (60km) and 3 day-lag datasets.</td>
<td>It will be likely that increase in resolution and time availability of products from operational systems will require higher resolution and frequency.</td>
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<tr>
<td>Coverage: Pan Arctic</td>
<td>Temporal resolution: At least daily</td>
<td>Spatial resolution: Corresponding to Sentinel-1</td>
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<tr>
<td>MRD-780</td>
<td>F for PMW capability</td>
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</tbody>
</table>
Currently CMEMS provide a pan Arctic high resolution ice drift product based on Sentinel-1 data in HH polarisation that meets the current high-priority requirements.

Higher resolution could be used to increase the drift resolution. For planning of a next generation of S1 this should be taken into consideration.

<p>| Stage of development / Ice type | Ice services are making a visual interpretation based on the SAR backscatter values. | Automatic products should be available. Fully polarimetric SAR observations are required in order to enable automation of product generation. Dynamic topography products are required at high spatial and temporal resolutions. These can be provided by single pass interferometric SAR (bistatic SAR). | Accuracy: Fractions of deformed ice has to be measured with an accuracy of 10%. Coverage: pan-arctic (G), areas near shipping routes and marginal ice zone (T) Frequency: 1 day (G), 2 days (T) Spatial resolution: 20m (G), 80m (T) | MRD-790 | F: 15 km resolution |</p>
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AIV</td>
<td>Assembly, Integration and Verification</td>
</tr>
<tr>
<td>(A)ATSR</td>
<td>Advanced Along Track Scanning Radiometer [of ESA]</td>
</tr>
<tr>
<td>AMSR</td>
<td>Advanced Microwave Scanning Radiometer [of JAXA]</td>
</tr>
<tr>
<td>AMOC</td>
<td>Atlantic Meridional Overturning Circulation</td>
</tr>
<tr>
<td>APC</td>
<td>Antenna Pattern correction</td>
</tr>
<tr>
<td>APKE</td>
<td>Absolute Pointing Knowledge Error</td>
</tr>
<tr>
<td>ARA</td>
<td>Absolute Radiometric Accuracy</td>
</tr>
<tr>
<td>ASCAT</td>
<td>Advanced Scatterometer [of MetOp]</td>
</tr>
<tr>
<td>AOCS</td>
<td>Attitude and Orbit Control Subsystem</td>
</tr>
<tr>
<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer [of NOAA]</td>
</tr>
<tr>
<td>BEC</td>
<td>Barcelona Expert Center</td>
</tr>
<tr>
<td>BOL</td>
<td>Beginning Of Life</td>
</tr>
<tr>
<td>3CS</td>
<td>Copernicus Climate Change Service</td>
</tr>
<tr>
<td>CAMS</td>
<td>Copernicus Atmospheric Monitoring Service</td>
</tr>
<tr>
<td>CCDB</td>
<td>Characterisation and Calibration Database</td>
</tr>
<tr>
<td>CCI</td>
<td>Climate Change Initiative [of ESA]</td>
</tr>
<tr>
<td>CCSDS</td>
<td>Consultative Committee for Space Data Systems</td>
</tr>
<tr>
<td>CDR</td>
<td>Climate Data Record</td>
</tr>
<tr>
<td>CEMS</td>
<td>Copernicus Emergency Management Service</td>
</tr>
<tr>
<td>CEOS</td>
<td>Committee on Earth Observation Satellites</td>
</tr>
<tr>
<td>CFOV</td>
<td>Composite Field Of View [gridding scheme]</td>
</tr>
<tr>
<td>CGLS</td>
<td>Coerpernicus Global Land Service</td>
</tr>
<tr>
<td>CIMR</td>
<td>Coerpernicus Imaging Microwave Radiometer</td>
</tr>
<tr>
<td>CLW</td>
<td>Cloud Liquid Water Content</td>
</tr>
<tr>
<td>CMEMS</td>
<td>Copernicus Marine Environmental Monitoring System</td>
</tr>
<tr>
<td>COP</td>
<td>Conference of the Parties [of IPCC]</td>
</tr>
<tr>
<td>CSC</td>
<td>Coerpernicus Space Component</td>
</tr>
<tr>
<td>dB</td>
<td>deciBel [unit]</td>
</tr>
<tr>
<td>DIB</td>
<td>Drop In Bucket [processing scheme]</td>
</tr>
<tr>
<td>DMI</td>
<td>Danish Meterological Institute</td>
</tr>
<tr>
<td>DMSP</td>
<td>Defense Meteorological Satellite Program</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium Range Weather Forecasting</td>
</tr>
<tr>
<td>ECSS</td>
<td>European Cooperation for Space Standardization</td>
</tr>
<tr>
<td>EEA</td>
<td>European Environment Agency</td>
</tr>
<tr>
<td>ENSO</td>
<td>El Nino Southern Oscillation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>EOL</td>
<td>End Of Life</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>EUMETSAT</td>
<td>European Organisation for the Exploitation of Meteorological Satellites</td>
</tr>
<tr>
<td>FOS</td>
<td>Flight Operations Segment</td>
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<tr>
<td>FOV</td>
<td>Field Of View</td>
</tr>
<tr>
<td>FYI</td>
<td>First Year Ice</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>G</td>
<td>Goal</td>
</tr>
<tr>
<td>GCOM</td>
<td>Global Climate Observation Mission [of JAXA]</td>
</tr>
<tr>
<td>GCOS</td>
<td>Global Climate Observing System</td>
</tr>
<tr>
<td>GMI</td>
<td>Global Monitoring Imager [of JAXA]</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPP</td>
<td>Ground Processor Prototype</td>
</tr>
<tr>
<td>GS</td>
<td>Ground Segment</td>
</tr>
<tr>
<td>HEO</td>
<td>Highly elliptic Orbit</td>
</tr>
<tr>
<td>HF</td>
<td>High Frequency</td>
</tr>
<tr>
<td>HKTM</td>
<td>House Keeping Telemetry</td>
</tr>
<tr>
<td>HPCM</td>
<td>High Priority Copernicus Mission</td>
</tr>
<tr>
<td>IFOV</td>
<td>Instantaneous Field Of View</td>
</tr>
<tr>
<td>IOD</td>
<td>Indian Ocean Dipole</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>IPCC</td>
<td>International Panel for Climate Change</td>
</tr>
<tr>
<td>IST</td>
<td>Ice Surface Temperature</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunications Union</td>
</tr>
<tr>
<td>IWS</td>
<td>Interferometric Wide Swath [radar mode of Sentinel-1]</td>
</tr>
<tr>
<td>JAXA</td>
<td>Japan Aerospace Exploration Agency</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>LEOP</td>
<td>Launch and Early Orbit Phase</td>
</tr>
<tr>
<td>LF</td>
<td>Low Frequency</td>
</tr>
<tr>
<td>LST</td>
<td>Land Surface Temperature</td>
</tr>
<tr>
<td>LTS</td>
<td>Long Term Scenario</td>
</tr>
<tr>
<td>MAG</td>
<td>Mission Advisory Group</td>
</tr>
<tr>
<td>MERIS</td>
<td>Medium-spectral Resolution Imaging Spectrometer [of ESA]</td>
</tr>
<tr>
<td>MFC</td>
<td>Modelling and Forecast Centre [of CMEMS]</td>
</tr>
<tr>
<td>MIZ</td>
<td>Marginal Ice Zone</td>
</tr>
<tr>
<td>MLST</td>
<td>Mean Local Solar Time</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>---------</td>
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</tr>
<tr>
<td>MODIS</td>
<td>MODerate resolution Imaging Spectrometer [of NASA]</td>
</tr>
<tr>
<td>MRD</td>
<td>Mission Requirement Document</td>
</tr>
<tr>
<td>MYI</td>
<td>Multi Year Ice</td>
</tr>
<tr>
<td>MWI</td>
<td>Microwave Imager [of MetOp-SG(B)]</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration [of the USA]</td>
</tr>
<tr>
<td>NEdT</td>
<td>Noise Equivalent difference Temperature</td>
</tr>
<tr>
<td>NEMO</td>
<td>Nucleus for European Modelling of the Ocean</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infrared</td>
</tr>
<tr>
<td>NRT</td>
<td>Near Real Time</td>
</tr>
<tr>
<td>NSIDC</td>
<td>National Snow and Ice Data Center [of the USA]</td>
</tr>
<tr>
<td>OI</td>
<td>Optimal Interpolation</td>
</tr>
<tr>
<td>OPSI</td>
<td>Observation Performance SImulator</td>
</tr>
<tr>
<td>OSCAR</td>
<td>Observing Systems Capability analysis and Review Tool [of WMO]</td>
</tr>
<tr>
<td>OSISAF</td>
<td>Ocean and Sea Ice Satellite Applications Facility [of EUMETSAT]</td>
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<tr>
<td>OTS</td>
<td>Off-The-Shelf</td>
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<tr>
<td>OZA</td>
<td>Observation Zenith Angle</td>
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<tr>
<td>OW</td>
<td>Open Water</td>
</tr>
<tr>
<td>PBEO</td>
<td>Program Board for Earth Observations [of ESA]</td>
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<tr>
<td>PCP</td>
<td>Precipitation</td>
</tr>
<tr>
<td>PDGS</td>
<td>Payload Data Ground Segment</td>
</tr>
<tr>
<td>PEG</td>
<td>Polar Expert Group [of the EC]</td>
</tr>
<tr>
<td>PL</td>
<td>Polar Low</td>
</tr>
<tr>
<td>PSF</td>
<td>Point Spread Function</td>
</tr>
<tr>
<td>QMS</td>
<td>Quality Management system</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFC</td>
<td>Radio Frequency Compatibility</td>
</tr>
<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
</tr>
<tr>
<td>RPKE</td>
<td>Relative Pointing Knowledge Error</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
</tr>
</tbody>
</table>
| SD      | 1. Standard Deviation  
  2. Snow Depth |
| SI      | 1. Sea Ice  
  2. Systeme Internationale [of meteorology units] |
| SIC     | 1. Sea Ice Concentration  
  2. Sea Ice Thickness |
<p>| SID     | Sea Ice Drift |
| SIE     | Sea Ice Extent |</p>
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>SIR</td>
<td>Scatterometer Image Reconstruction [algorithm]</td>
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<tr>
<td>SM</td>
<td>Soil Moisture</td>
</tr>
<tr>
<td>SMAP</td>
<td>Soil Moisture Active Passive [mission of NASA]</td>
</tr>
<tr>
<td>SMOS</td>
<td>Soil Moisture and Ocean Salinity [mission of ESA]</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SPF</td>
<td>Single Point Failure</td>
</tr>
<tr>
<td>SRD</td>
<td>System Requirements Document</td>
</tr>
</tbody>
</table>
| SSD     | 1. Spatial Sampling Distance  
2. Sea Surface Density |
| SSM/I   | Special Sensor Microwave Imager [of DMSP] |
| SSP     | Sub Satellite Point |
| SSS     | Sea Surface Salinity |
| SST     | Sea Surface Temperature |
| SWE     | Snow Water Equivalent |
| TBC     | To Be Confirmed (by ESA) |
| TBD     | To Be Defined (by ESA) |
| TBS     | To Be Specified |
| TC      | TeleCommand |
| TCWV    | Total Column Water Vapour |
| TEC     | Total Electron Content |
| TIR     | Thermal Infrared |
| TM      | TeleMetry |
| TMI     | TRIMM Microwave Imager |
| TOA     | Top Of Atmosphere |
| TRIMM   | Tropical Rainfall Imaging Microwave Radiometer [of JAXA] |
| TRP     | Temperature Reference Point |
| VIS     | Visible wavelength |
| VEGA    | Vettore Europeo di Generazione Avanzata |
| WMO     | World Meteorological Organisation |
| WS      | Wind Speed |
| WVC     | Water Vapour Content |

[End of Document]