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Review

Gaps Analysis and Requirements Specification for the Evolution of Copernicus System for Polar Regions Monitoring: Addressing the Challenges in the Horizon 2020–2030

Estefany Lancheros [1,*], Adriano Camps [1,*], Hyuk Park [1], Pierre Sicard [2,†], Antoine Mangin [2], Hripsime Matevosyan [3] and Ignasi Lluch [3]

1 Universitat Politècnica Catalunya—BarcelonaTech & IEEC, Campus Nord, 08034 Barcelona, Spain; park.hyuk@tsc.upc.edu
2 ACRI Bâtiment Le Grand Large, Quai de la Douane—2 ème éperon, 29200 Brest, France; psicard@argans.eu (P.S.); antoine.mangin@acri.fr (A.M.)
3 Skolkovo Institute of Science and Technology, Moscow 143026, Russia; hripsime.matevosyan@skolkovotech.ru (H.M.); ignasi.lluchicruz@skolkovotech.ru (I.L.)
* Correspondence: estefany@tsc.upc.edu (E.L.); camps@tsc.upc.edu (A.C.); Tel.: +34-626-94-2616 (E.L.); +34-627-01-6695 (A.C.)
† Current address: ARGANS, 260 routes du Pin Montard, BP234, 06904 Sophia-Antipolis CEDEX, France.

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Abstract: This work was developed as part of the European H2020 ONION (Operational Network of Individual Observation Nodes) project, aiming at identifying the technological opportunity areas to complement the Copernicus space infrastructure in the horizon 2020–2030 for polar region monitoring. The European Earth Observation (EO) infrastructure is assessed through of comprehensive end-user need and data gap analysis. This review was based on the top 10 use cases, identifying 20 measurements with gaps and 13 potential EO technologies to cover the identified gaps. It was found that the top priority is the observation of polar regions to support sustainable and safe commercial activities and the preservation of the environment. Additionally, an analysis of the technological limitations based on measurement requirements was performed. Finally, this analysis was used for the basis of the architecture design of a potential polar mission.

Keywords: Earth Observation (EO); satellite; sensors; platform; microwave radiometer; SAR; GNSS-R; optical sensors; polar; weather; ice; marine

1. Introduction

Copernicus is a program that powers the European Earth Observation (EO) capacity to meet the user needs and be highly competitive globally. Copernicus addresses six thematic services: land, marine, atmosphere, climate change, emergency management and security. Each service relies on a product portfolio that is derived from space and in situ infrastructure. The European Space Agency (ESA) has developed the space segment, a series of missions called the Sentinels, specifically tailored to the operational needs of the Copernicus program. Additionally, the Sentinels' missions are supported by contributing missions, such as the Earth Explorer missions by the ESA and the Meteorological Satellites (EUMETSAT) and include missions from European Union (EU) and non-EU member states.

Sentinel-1 is equipped with a C-band Synthetic Aperture Radar (SAR) for land, ocean and emergency services. This is based on a constellation of two polar orbiting satellites, in the same orbital plane with a 180° orbital phase difference. Currently, Sentinel 1-A and Sentinel 1-B are operational satellites, and Sentinel 1-C and Sentinel-1D are future missions to ensure data continuity. The first Sentinel-1 satellite was Sentinel-1A, and it was launched on 3 April 2014. Sentinel-1B was launched on 25 April 2016. Sentinel-1C will be launched in 2021 and Sentinel-1D in 2023. Each Sentinel-1 is expected to have at least seven years of lifetime.

Sentinel-2 is equipped with a Multi-Spectral Imaging (MSI) sensor, to cover the land and emergency services of Copernicus. Constituted by the A/B/C/D series, at present, there are two satellites in polar orbit (Sentinel-2A and Sentinel-2B). Sentinel 2-A was launched on 23 June 2015, and Sentinel 2-B was launched on 7 March 2017. Planned missions to provide data continuity are Sentinel-2C and Sentinel-2D, which will be launched in 2021 and 2022.

Sentinel-3 is equipped with seven instruments for land- and ocean-monitoring services. The two multispectral sensors are named the Ocean and Land Color Imager (OLCI) and Sea and Land Surface Temperature Radiometer (SLSTR). It also has a Synthetic aperture Radar Altimeter (SRAL) that requires a micro-wave radiometer for water vapor correction, a Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS), a Laser Retro-Reflector (LRR) and a GPS receiver for orbitography correction. It is composed by four satellites series (A/B/C/D), with two operational polar orbit satellites at the present time. Sentinel-3A and Sentinel-3B were launched on 16 February 2016 and 25 April 2018, respectively. The future Sentinel-3C and Sentinel-3D will be launched in 2023 and 2024.

Sentinel-5p, also known as Sentinel-5 Precursor, is equipped with a Tropospheric Monitoring Instrument (TROPOMI). This mission brings support for atmospheric services. It is based on a single satellite in polar orbit, launched on 13 October 2017.

Sentinel-4 and Sentinel-5 are planned as hosted payloads for a mission operated by EUMETSAT, to ensure the atmospheric and climate change services of Copernicus. Sentinel-4 is a spectrometer called the Ultra-violet, Visible and Near-infrared sounder (UVN), which will be onboard the Meteosat Third Generation-Sounder (MTG-S). MTG-S is composed of two series (MTG-S1 and MTG-S2), in geostationary orbit. MTG-S1 and MTG-S2 are scheduled for launch in 2023 and 2031, respectively. Sentinel-5 is a sounder called the Ultra-violet, Visible and Near-infrared Sounder (UVNS) onboard the MetOp-Second Generation (MetOp-SG, with the series A1, A2 and A3), in polar orbit. MetOp-SG A1/A2/A3 will be launched in 2021, 2028 and 2035, respectively.

Sentinel-6, also called the Joint Altimetry Satellite Oceanography Network-Continuity of Service (JASON-CS), will be developed and implemented through a partnership between EUMETSAT, ESA, National Aeronautics and Space Administration (NASA), and National Oceanic and Atmospheric Administration (NOAA). A radar altimeter package like the one in Sentinel-3 will be equipped in two Sun-synchronous series satellites (JASON-CS-A and JASON-CS-B) with a seven-year lifetime each. Currently, the launches of JASON-CS A and B are planned for 2020 and 2025, respectively.

In recent years, European Commission (EC) has led the Horizon 2020 program-supporting mission aligned with major EU policy priorities. In the context of Copernicus, the priorities are to contribute to the evolution of its services and to satisfy the end-user needs. The H2020 ONION (Operational Network of Individual Observation Nodes) project played an important role in defining the technological EO requirements based on the user needs and future measurement gaps of the Copernicus system in the horizon 2020–2030. Each use case is linked to a Copernicus service, and they are integrated by a set of measurements required to fulfil the users' needs. The measurements are the geophysical product estimated from satellite acquisitions. The measurements with gaps are the measurements detected with an observation gap (in terms of spatial resolution, and/or revisit time, and/or accuracy, and/or temporal continuity, and/or data latency) in the Copernicus space infrastructure in the time period from 2020–2030. The main objective of the ONION project was to place the user requirements at the center of the design process, as well as to identify solutions to meet these needs. This project has helped to understand the challenges for the evolution of the new Copernicus missions.

From the knowledge of the end-user needs, this project has provided an important scientific basis to address the measurement requirements, the instrumentation and remote sensing technologies that have to be explored to cover the next decade of the measurement gaps of the Copernicus system, where monitoring of the polar regions is an emerging need, with improved revisit time and latency time for marine weather forecast and sea ice monitoring use cases.

The methodology used in this work is described in Figure 1. First, the top 10 use cases were ranked according to the end-user needs [1], and end-user requirements were defined [2]. Second, a database of the future Copernicus instruments and contributing missions was generated to analyze the measurement gaps in the horizon 2020–2030. The gaps were detected based on the ability of these sensors to monitor each measurement defined in the use cases. Measurement gaps were analyzed in terms of the spatial resolution, revisit time, precision and temporal continuity, as well as the data latency for products requiring near real-time data (Section 2). Based on the results of the gap analysis in the time frame 2020–2030, monitoring of the polar regions arose as the top emerging need. Accordingly, Section 3 describes the importance of observing the polar regions. Section 4 presents the potential instrumentation required to cover the emerging needs, based on the measurement characteristics. Section 5 presents a discussion based on the limitation of current technologies and the challenges addressed to next generation of the sensors, to ensure all the measurements with gaps in the polar region are covered by the Copernicus space segment. Finally, the conclusions are presented.

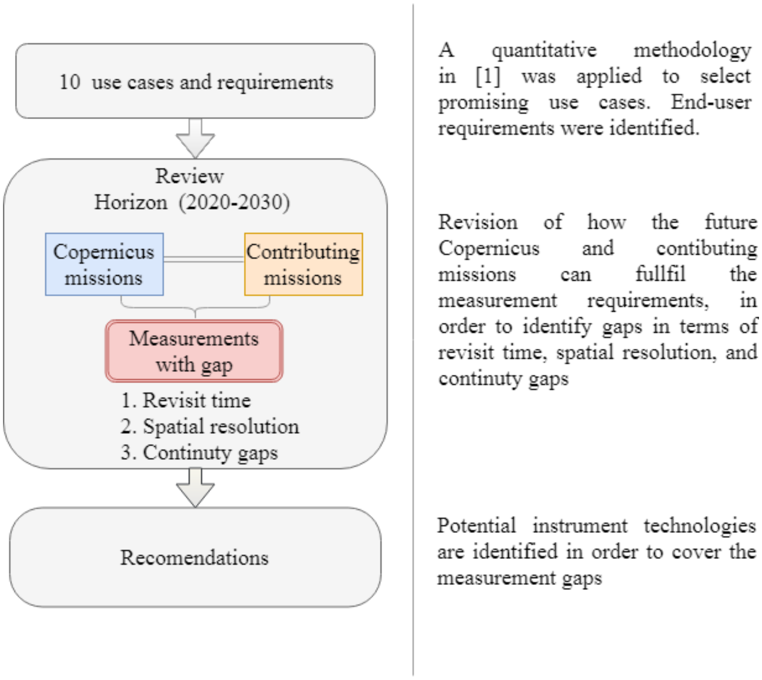

Figure 1. Methodology applied to define the end-user requirements and measurement gaps.

2. Requirements Specifications and Measurements Gaps

This study focuses on the identification of the EO measurements gaps in the time frame from 2020–2030, to complement the Copernicus space infrastructure, based on the top 10 use cases [1]. These use cases are not satisfied by the existing Copernicus infrastructure, and they were generated through a quantitative methodology that involved the prioritization of 38 EO data needs (the complete list of the identified needs with their description is presented in Table 1), 96 products across the six Copernicus services, 63 stakeholders, 131 measurements and 48 uses cases, which were scored. The top 10 use cases were defined as (1) marine weather forecast, (2) sea ice monitoring (extent and thickness), (3) fishing pressure and fish stock assessment, (4) land for infrastructure status assessment, (5) agriculture and forestry (hydric stress), (6) land for mapping (risk assessment), (7) sea ice melting emissions, (8) atmosphere for weather forecast, (9) climate for ozone layer and UV and (10) natural habitat and protected species monitoring.

Table 1. Description of the identified user needs [1].

Need Name	Need Description
Agriculture, Rural Development and Food Security	Estimates of crop production, water satisfaction index, early warning of harvest shortfalls.
Air Quality and Atmospheric Composition	The quality of air that one directly breathes at the surface.
Alerting Service	Alert of an ongoing crisis.
Animal Migration Maps	Track for animal migration.
Assessment of Renewable Energies Potential	Provide meteorological (cloud, water vapor) and atmospheric (aerosol, ozone) data; and solar irradiance maps.
Basic Maps	Base layer information with key geographical features.
Biodiversity Assessment	Vegetation indices, information on habitat deterioration, evolution of vegetation parameters.
Climate Evolution	Assess long-term climate evolution.
Climate Forcing	Monitoring human-forced climate change.
Climate Policy Development	Informing policy development to protect citizens from climate-related hazards such as high-impact weather events.
Communication/Reporting Resources	Context/supporting and justifying operations.
Crisis and Damage Mapping	Updated (24 h) geographical information.
Emission and Surface Flux Assessment	Anthropogenic emissions, greenhouse gases.
Fish Stock Management	Analysis and forecasting of fish stocks.
Forest Resources Assessment	Deforestation rates, forest intactness.
In-Field Data Collection	Locally-sampled information.
Infrastructure Status Assessment	Roads, railroads, buildings, power lines, pipelines and others.
Inland Water Management Maps	Measure quantity, quality (acidity) and track for algae.
Land Degradation and Desertification Assessment	Degradation risk index, degradation hot spots, etc.
Maintenance information	Estimation of the required ship maintenance date
Marine Operations Safety	Oil spill combat, ship routing, weather forecasting, defense, search and rescue
Mining	Focused on information for the mining industry
Mitigation and Adaptation	Improving planning of mitigation and adaptation practices for key human and societal activities.
Ocean Color Maps	Track for algae, bloom, toxicity, "red tide" and acidity.
Oil and Gas Assessment	Focused on information retrieval for the oil and gas industry.
On time operation	Optimized routing and ship speed.
Ozone Layer and UV	Archive and forecast information on ozone layer and UV.
Ports Monitoring	Monitoring of ports and facilitate traffic management.
Refugee Support Mapping	Snapshot of temporary settlements and internally-displaced people.
Ship Positioning Mapping	Monitoring ship positions and information.
Situation Mapping	After crisis mapping.
Solar Radiation	The amount of solar radiation coming to Earth.
Thematic Mapping	Focused on the spatial variation of a theme.
Urban and Regional Development	Monitoring of settlements, land losses or gain.
Water quality	Water quality and pollution both in high seas and coast.
Water Resources	Erosion risk maps, average water available for watershed.
Weather Forecast	Climate monitoring, ice seasonal forecast.

These 10 use cases require 75 measurements. The results of the observation gap in the time frame from 2020–2030 presented 20 measurements with gaps that correspond only to eight use cases (see Table 2). The marine weather forecast use case has six measurements with gaps; sea ice monitoring (extent and thickness) involves 13 measurements with gaps; fishing pressure and fish stock assessment has five measurements with gaps; land for infrastructure status assessment use case will be met by future Copernicus infrastructure and contributing missions (the measurements require high spatial resolution with a long revisit time); the agriculture and forestry (hydric stress) use case implies four measurements with gaps; the land for mapping (risk assessment) use case presents only one measurement with observation gaps (this measurement is associated with the agriculture and forestry (hydric stress) use case); the sea ice melting emission use case involves six measurements with gaps (these measurements are associated with sea ice monitoring (extent and thickness) use case); the atmosphere for weather forecast use case has only one measurement with gaps, and this measurement is associated with the marine weather forecast use case; the climate for ozone layer and UV use case will be satisfied by future Copernicus infrastructure and contributing missions; and natural habitat and protected species monitoring has only one variable with an observation gap (this measurement is associated with the agriculture and forestry (hydric stress) use case).

In most cases, each measurement is associated with different use cases. There are four use cases that involve all the measurements with gaps (marine weather forecast, sea ice monitoring (extent and thickness), fishing pressure and fish stock assessment and agriculture and forestry (hydric stress)). In this way, if only four use cases are addressed, they cover all the 20 measurements with gaps. These four use cases that involve all the measurements are congruent with respect to a recent survey into the state and the health of the European EO services industry [3], where the results indicated that the Copernicus data and services do not fully respond to the customer needs. Principally, it reported that the agriculture, maritime and fishery domains are of major importance for the European EO market. For these reasons, the next sections focus on the analysis of these four use cases.

Marine weather forecast covers measurements such as wave and wind parameters. This information is of predominant importance to a wide variety of activities, from tourism to fishing, oil and gas exploration and exploitation. Results of the measurement gap analysis focused on "marine weather forecast" showed that revisit time gap to be reduced to 3 h and data latency <1 h. Table 2 shows the Copernicus and contributing missions in the time frame from 2020–2030, which are capable of measuring the variables defined for the marine weather forecast use case. These future missions will provide high horizontal spatial resolution for ocean measurements, but the provision of appropriate sea-state products and the adequacy of EO observations in near- or real-time (<1 h) are not satisfied. This translates into a system mission that shall support existing and planned EU infrastructure to reduce the revisit time for "marine weather forecast" use case to 3 h and data latency to less than 1 h.

The use case "sea ice monitoring" covers a wide range of measurements that are of high relevance to marine operations and to understand global climate change. This use case requires providing real-time sea ice data and improving the precision of ice thickness measurements, as well as increasing the operational monitoring capability of polar regions. On the one hand, the Arctic and Antarctic are the parts of the globe with better revisit time statistics as most EO missions are in polar Low Earth Orbits (LEO) and fly over the poles 14–15 times per day. On the other hand, polar regions represent a blind zone for instruments flying in a geostationary orbit and are poorly covered by some narrow-swath nadir-pointing instruments such as radar altimeters (e.g., SRAL/Sentinel-3 and Poseidon-4/Sentinel-6). This means that for instruments in polar LEO orbits (typically Sun-Synchronous Orbits, SSO) with off-side acquisition capacity, the coverage of the polar regions is limited by the swath of the instrument and by the number of satellites considered. The latency of the data is also an issue for near real-time products. Moreover, a very small subset of EU or cooperating missions can provide sea ice thickness, sea ice type, sea ice concentration, sea ice cover, sea ice drift and extent at the resolutions required by end-users. Therefore, sea ice monitoring with a short revisit time, short latency time and high spatial resolution are the main requirements, the mission shall support sea ice products (e.g., sea ice type, cover, extent, drift, thickness and iceberg tracking) with a revisit time <3 h and latency time < 1 h [4].

The use case "fishing pressure and fish stock assessment" promises also new prospects for the system in the maritime domain and would benefit from a reduction in access and revisit times for the provision of appropriate oceanic conditions (e.g., sea surface temperature, ocean chlorophyll concentration) and fishing pressure (e.g., vessel tracking). Ocean chlorophyll concentrations are related to the presence of planktonic life, which is the base of the marine food chain. In this regard, this parameter brings information on the health and productivity of marine ecosystems. Therefore, these data are valuable and help to develop strategies for sustainable and productive commercial fishery. Another important measurement to cover is Sea Surface Temperature (SST) in this time frame.

The SST over polar regions in a global context is essential for climate modeling, weather forecast, as well as for the fishing and maritime industry. Missions with optical instruments (in the visible and infrared domains) provide information on the sea surface composition (e.g., ocean chlorophyll concentration, color dissolved organic matter) and sea surface temperature. One of the main difficulties of these types of techniques is that they are directly impacted by cloud coverage and depend on solar illumination conditions. The current Copernicus infrastructure provides about 24–48 h of latency for those measurements. From the side of contributing missions in geostationary orbits, these provide data every 30 min (shorter revisit time), but with a coarse resolution of 5 km. Geostationary satellites are essential in equatorial and mid-latitude areas, but for high latitudes, image distortion and atmospheric effects are too large for effective use.

In the context of the fishing pressure and fish stock assessment, data on fish farming cages (density) and vessel's identity and location (position, speed and direction) are potentially valuable for emergency and management services. For instance, the provision of these observations will help to improve ship routing services, offshore operations and search and rescue operations, thus contributing to marine safety. This type of data can be provided by using an Automatic Identification System (AIS). The ESA has promoted the use of AIS systems on Satellites (SAT-AIS) [5] through of Advanced Research in Telecommunications Systems (ARTES) program. In the horizon 2020–2030, only the NORSAT-2 and Triton-2 missions carrying AIS have been planned [6].

The "agriculture and forestry (hydric stress)" use case is based on methods enabling precision agriculture, efficient irrigation, fire prevention, forest protection and impacts on hydrological basins, supporting agronomic research and production, assessment of population food security and sovereignty and environmental impact evaluation. Soil moisture is a key parameter for the hydrological cycle, meteorology, climatology and agriculture production. The role of soil moisture for meteorology lies in the global transfer of water and energy between the Earth's surface and the atmosphere. In the agricultural context, the amount of soil moisture is an important element affecting production and plant growth. Surface soil moisture can be estimated with a high spatial resolution by the Advanced Scatterometter (ASCAT) on the meteorological Operational (MetOp) mission and SAR-C on the Sentinel-1. However, the accuracy, revisit time and temporal resolution are insufficient to meet the user requirements. New developments in the miniaturization of cameras in the visible and infrared bands with high-resolution data make new techniques available for remote observation of crops [7,8]. However, for precision agriculture applications, the use of remote sensing can be limited because of inadequate spatial, temporal and thematic products tailored to the needs of farmers. Future satellites carrying sensors in the thermal infrared band present coarse spatial and temporal resolutions and are also limited to clear sky conditions. Due to these limitations, thermal imagery is not useful at the plot scale for precise irrigation monitoring. There is also an emerging need to consider L-band microwave radiometers (with high spatial resolution) to support crop condition monitoring.

Table 2. Gap analysis results over the Copernicus space segment in the horizon 2020–2030.

Measurements	Use Cases	Requirements [2]	(2020–2030)		
			Copernicus Instruments/Mission [9]	**Contributing Instruments/Mission [10]**	**Gap**
Ocean surface currents	1. Marine weather forecast 2. Sea ice monitoring 7. Sea ice melting emissions	Spatial resolution: 1–25 km Revisit time <3 h 0.5 m/s and 10° accuracy	SAR-C/Sentinel-1 SRAL/Sentinel-3 Poseidon-4/Sentinel-6	Karin/SWOT SWIM/CFOSAT SAR-2000 S.G/CSG SAR / HRWS SAR-X / TSX-NG SAR-X/PAZ	Revisit time <3 h Latency time <1 h
Dominant wave direction	1. Marine weather forecast 2. Sea ice monitoring	Spatial resolution: 1–15 km Revisit time <3 h 10° accuracy			Revisit time <3 h Latency time <1 h
Significant wave height	Marine weather forecast Sea ice monitoring	Spatial resolution: 1–25 km Revisit time <3 h 0.1 m accuracy			Revisit time <3 h Latency time <1 h
Wind speed over sea surface (horizontal)	1. Marine weather forecast 2. Sea ice monitoring 8. Atmospheric for weather forecast	Spatial resolution: 1–10 km Revisit time <3 h 0.5 m/s accuracy Latency time <1 h		ASCAT/MetOp SCA/MetOp-SG Karin/SWOT SAR-2000 S.G/CSG SAR/HRWS SAR-X/TSX-NG SAR-X/PAZ	Revisit time <3 h Latency time <1 h
Sea ice type	2. Sea ice monitoring 7. Sea ice melting emissions	Spatial resolution: 10 m Revisit time <3 h 0.25/classes accuracy Latency time <1 h			Revisit time <3 h Latency time <1 h
Iceberg tracking	2. Sea ice monitoring	Spatial resolution: 10 m Revisit time <3 h 5% accuracy Latency time <1 h			Revisit time <3 h Latency time <1 h
Sea ice cover	2. Sea ice monitoring 7. Sea ice melting emissions	Spatial resolution: 12 km–10 m Revisit time <3 h 5% accuracy Latency time <1 h		SAR-2000 S.G/CSG SAR/HRWS SAR-X/TSX-NG SAR-X/PAZ MSI/Earth-CARE FLORIS/FLEX	Revisit time <3 h
Sea ice extent	2. Sea ice monitoring	Spatial resolution: 12 km–10 m Revisit time <3 h 5% accuracy Latency time <1 h			Revisit time <3 h Latency time <1 h
Sea ice drift	2. Sea ice monitoring	Spatial resolution: 10 m Revisit time <3 h 0.5 m/s and 10° accuracy			Revisit time <3 h Latency time <1 h
Sea ice thickness	2. Sea ice monitoring 7. Sea ice melting emissions	Spatial resolution: 1 cm (vertical) Revisit time <3 h 1 cm accuracy Latency time <1 h		KARIN/SWOT SAR-2000 S.G/CSG SAR/HRWS SAR-X/TSX-NG SAR-X/PAZ	Revisit time <3 h Latency time <1 h

Table 2. *Cont.*

Measurements	Use Cases	Requirements [2]	[2020–2030]		
			Copernicus Instruments/Mission [9]	Contributing Instruments/Mission [10]	Gap
Atmospheric pressure over sea surface	1. Marine weather forecast 8. Atmospheric for weather forecast	Spatial resolution: 1–25 km Revisit time <3 h 5% accuracy Latency time <1 h	OLCI/Sentinel-3	CPR/Earth-CARE	Revisit time <3 h Latency time <1 h
Sea surface temperature	1. Marine weather forecast 2. Sea ice monitoring 3. Fishing pressure and and fish stock assessment 7. Sea ice melting emissions	Spatial resolution: 1–10 km Revisit time <3 h 0.3 k accuracy Latency time <1 h	SLSTR/Sentinel 3	SEVERI/MSG MSI/Earth-CARE IASI and AVHRR/MetOp METimage, IASI-NG/MetOp-SG FCI/MTG-I IRS/MTG-S	Revisit time <3 h Latency time <1 h
Ocean chlorophyll concentration	3. Fishing pressure and fish stock assessment	Spatial resolution: 1 km Revisit time <72 h 0.05 mg/m^3 accuracy	OLCI/Sentinel-3	3MI/MetOp-SG METimage/MetOp-SG	Latency time <1 h
Ocean imagery and water leaving radiance	1. Sea ice monitoring 3. Fishing pressure and fish stock assessment	Spatial resolution: 1 km Revisit time <72 h 5% accuracy Latency time <1 h	OLCI/Sentinel-3 SAR-C/Sentinel-1	AVHRR/3/MetOp-A/B/C SAR/RADARSAT-2	Latency time <1 h
Color dissolved organic matter	3. Fishing pressure and and fish stock assessment	Spatial resolution: 1 km Revisit time <72 h 5% accuracy	OLCI/Sentinel-3	3MI /MetOp-SG METimage/MetOp-SG FLORIS/FLEX	Latency time <1 h
Detection of water stress in crops	5. Agriculture and forestry (hydric stress)	Spatial resolution: 2–7 m Revisit time <24 h 5% accuracy Latency time <1 h	SLSTR / Sentinel-3	SEVERI/MSG MSI/Earth-CARE IASI and AVHRR/MetOp METimage, IASI-NG /MetOp-SG FCI/MTG-I IRS/MTG-S	Spatial resolution <7 m Latency time <1 h
Estimation of crop evapotranspiration	5. Agriculture and forestry (hydric stress)	Spatial resolution: 1–10 m Revisit time <24 h			
Soil moisture at the surface	5. Agriculture and forestry (hydric stress) 6. Land for mapping: risk assessment 10. Natural habitat and protected species 2. Sea ice monitoring	Spatial resolution: 10 km Revisit time <24 h 0.01 m^3/m^3 accuracy Latency time <1 h	Sentinel-1	ASCAT/MetOp SAR-2000 SG/CSG SEVERI/MSG SAR-P/BIOMASS FCI/MTG-I MSI/Earth-CARE	Accuracy <0.01 m^3/m^3 Latency time <1 h
Crop growth & condition	5. Agriculture and forestry (hydric stress)	Spatial resolution: 2 km Revisit time <24 h Latency time <1 h	N/A	N/A	Spatial resolution: 2 km Revisit time <24 h Latency time <1 h
Monitoring system—vessels and fish farming cages position tracking	3. Fishing pressure and fish stock assessment	Spatial resolution: 1 km Revisit time <72 h (cloud free) 5% accuracy Latency time <1 h	Sentinel-1	NAIS/NORSAT-2 E-SAIL/Triton-2	from 2025

3. Sea Ice Monitoring and Marine Weather Forecast over Polar Regions as an Emerging Need for Future Copernicus Missions

Over the past few decades, the polar regions have been subjected to significant changes. Total sea ice extent has decreased, and it has thinned [11]. Arctic sea ice melts, and it is increasingly influencing human activities, as some Arctic marine routes have gone from being covered by sea ice to being navigable during part of the year. In this direction, the Arctic and Northern Ocean have been considered as interesting areas to extend the commercial operations related to fishing, oil and gas.

As shown in Table 2, 65% of the measurements with gaps correspond to sea ice monitoring, and marine weather forecasts represent around 30%. Here, there is potential to cover these use cases. The sea ice monitoring (extent and thickness) and marine weather forecast use cases would benefit enormously from the improvement of the latency time, revisit time and accuracy. In response to the end-user needs, instrumentation and remote sensing technologies have to be explored to cover the future measurement gaps of the Copernicus system. In this way, we focus on EO over polar regions, where there is a high priority to monitor the previously-mentioned domains.

New remote sensing opportunities will be explored to provide real time data to ensure navigation safety, to increase the operational monitoring capability on sea ice to understand climate change and for marine weather forecast information to a wide variety of activities such as fishing, oil and gas operation. In this direction, the measurements and requirements to cover are detailed in the next section.

4. Instrumentation and Remote Sensing Technologies Required to Cover the Future Measurement Gaps over Polar Regions

The measurements with gaps that have been detected are of dominant importance to a wide variety of activities, from marine traffic, fishery and the environment. Therefore, in this section, these measurements are analyzed in terms of the available instrument technologies to cover the detected gaps. Additionally, the operational limitations of the potential instruments are identified from the viewpoint of measurement requirements. Table 3 summarizes the technologies identified to ensure that the measurements with gaps are covered. The state of the art of the instrumentation is presented and the technology limitations from the perspective of the measurement requirements.

4.1. Ocean Surface Currents

This variable presents a gap in the required revisit time. The required revisit time is 3 h, and the required spatial resolution is 1–25 km, with a speed accuracy of 5 m/s and 10° in direction. A federation of three missions, Sentinel-3 (radar altimeter SRAL) and a specific combination with a constellation of Global Navigation Satellite Systems-Reflectometry (GNSS-R) instruments [12,13], microwave radiometer, altimeter radar [14] and SAR on small platforms, could improve the accuracy and the revisit time efficiently.

4.2. Dominant Wave Direction and Significant Wave Height

These variables can be measured with radar altimeters and SAR. In the time frame 2020–2030, the instruments capable of measuring these variables are Poseidon-4 (Sentinel-6/JASON), SRAL (Sentinel-3) and SAR-C (Sentinel-1), but the 3-h revisit time is not satisfied. The current Copernicus infrastructure delivers about 24–48 h of latency for the corresponding measurements.

4.3. Wind Speed

This variable presents gaps in the revisit time (<3 h) and latency time (<1 h). The required revisit time is 3 h at 10-km spatial resolution, with an accuracy of 0.5 m/s. Typical resolutions for microwave radiometer winds are about 25 km [15] or 12.5 km [16] over oceans; the measurement range is 0–50 m/s [17], and the accuracy is from about 2–10 m/s (depending on the rain flag) [18].

Microwave radiometers infer wind speed from frequencies near 6.8, 10.7, 19 and 37 GHz. Another technology that can be used to measure wind speed is SAR. The current Copernicus infrastructure has a constellation of two SARs, but the revisit time is between one and two days for high latitudes and the high resolution dataset (1 km) [19]. Another solution is to infer the wind vector using radar scatterometers, with a 10-km spatial resolution over the oceans.

Table 3. Mapping of the potential technologies to cover measurements with gaps. The technology limitations from the perspective of the measurement requirements are presented.

Technology Type	Measurements	Instrument Limitations
GNSS-R	Sea ice thickness [a]	Accuracy (∼20 cm) [12,20]
	Dominant wave direction [b]	Coarse spatial resolution (∼25 km) [21]
	Wind speed over the sea surface (horizontal) [a]	Coarse spatial resolution (∼25 km) Accuracy (2 m /s) [12]
	Significant wave height [b] Sea ice cover [b] ocean surface currents [b]	No specific limitation [22]
Microwave sounder (50–60 GHz)	Atmospheric pressure (over sea surface) [c]	Coarse spatial resolution (20 km, at 400 km altitude) [23]
Microwave radiometer (X-, K-, Ka-, W-bands)	Wind speed over sea surface (horizontal) [b] Sea ice cover [b] Sea ice type [a] Sea ice drift [a] Sea surface temperature [a]	Coarse spatial resolution (∼25 km) [24] Accuracy: (1.5-m/s ocean wind speed) [25] (0.5 K for SST) [25] (from 10%–20% for sea ice data) [26]
L-band microwave radiometer	Sea ice cover [b]	Coarse spatial resolution
	Soil moisture at the surface [c]	Coarse spatial resolution
	Sea ice thickness [a]	Accuracy [27,28]
AIS decoder	Monitoring system: vessels [c]	No specific limitation [5]
Cloud radar (oxygen band)	Atmospheric pressure (over sea surface) [c]	Narrow swath (2 km) [29,30]
Radar scatterometer	Wind speed over sea surface (horizontal) [c] Sea ice type [a] Sea-ice cover [a]	Accuracy: Wind speed (<2 m/s) [31]
Radar altimeter (SAR)	Ocean surface currents[3] Significant wave height [b] Dominant wave direction [b] Sea ice type [b] Sea ice cover [b] Wind speed over sea surface (horizontal) [a]	Narrow coverage (nadir-pointing) Long-term analysis and narrow coverage
SAR	Ocean surface currents [c] Iceberg tracking [c] Sea ice drift [c] Sea ice extent [c] Sea ice type [c] Sea ice cover [c] Dominant wave direction [b] Dominant wave period [b] Significant wave height [b] Sea ice thickness [a] Wind speed over sea surface [a]	Narrow coverage (<600 km) Long-term analysis and narrow coverage [32]
LiDAR	Sea ice thickness [b]	Long-term analyses, narrow coverage, Cloud sensitive
Multispectral radiometer VIS/NIR/TIR	Ocean chlorophyll concentration [c] (λ center: 442.5, 490, 510, 560 nm) Ocean imagery and water leaving radiance [c] (λ Centre: 485, 560, 660, 2100 nm) Color Dissolved Organic Matter (CDOM) [c] (λ center: 442.5, 490, 510, 560, 665 nm) Sea surface temperature [c] (λ center: 3.7, 4.05, 8.55, 11, 12 µm) Sea ice cover [a] (λ center: 640, 1610 nm)	Cloud sensitive, Daylight only
Hyperspectral radiometer (VIS/NIR)	CDOM [c] Sea ice cover [b]	Cloud sensitive, Daylight only
Spectrometer/sounder IR	Sea ice cover [c] Sea surface temperature [c]	Cloud sensitive, Daylight only

[a] Marginal relevance; [b] medium relevance; [c] high relevance .

The use of novel techniques using Signals of Opportunity (SoOp), such as those from Direct Broadcast Satellite (DBS) television signals at the Ku- or X-band [33], can be potentially exploited in the future to measure precipitation and winds over the sea surface at higher revisit times. These signals are potentially sensitive to detecting fluctuations of the sea surface roughness and light precipitation. As compared to GNSS-R systems, the spatial resolution will be better (higher frequency) and the Signal-to-Noise Ratio (SNR) higher as transmitters transmit more power. In this regard, a receiver of signals of opportunity at the Ku- or X-band can provide cost benefits and high quality data, but these techniques have yet to be developed.

4.4. Sea Ice Type

Sea ice type is a critical parameter of marine weather forecast to improve and to understand climate change. The requirement for this measurement is a 3-h revisit time with 10 km as the spatial resolution. Previous experiments demonstrated the sensitivity of microwave scatterometers to discriminate sea ice type [34]. According to the gap detected in the revisit time, this instrument will be evaluated in conjunction with other solutions such as microwave imagers, SAR and SAR altimeters [35].

4.5. Sea Ice Cover

This variable requires a revisit time of 3 h, with a minimum requirement of 12 km of spatial resolution and an accuracy of 5%. In the time frame 2020–2030, Sentinel-1 with a C-band SAR and Sentinel-3 with an SRAL radar altimeter are the Copernicus missions capable of measuring this variable. At high latitudes, Sentinel-1 presents a revisit time <1 day, and its utilization period is from 2014–2030. MetOp is a contributing Copernicus mission that can provide sea ice cover data thanks to the Micro-Wave Imager (MWI, instrument operated by ESA and EUMETSAT), with global coverage once per day and a spatial resolution of 25 km. The utilization period for MWI is from 2022–2043. The Sentinel-1 and MetOp missions do not meet the 3-h revisit time at a 12-km horizontal spatial resolution. In this regard, the formulation of potential technologies to measure sea ice cover is necessary. In this way, microwave radiometers, SAR, SAR altimeters and GNSS-R are technologies capable of measuring this variable.

Microwave radiometers can measure this variable using the 19.35-, 37- and 90-GHz channels (e.g., the Special Sensor Microwave, SSM/I ; the Special Sensor Microwave-imager/sounder, SSMIS, with a spatial resolution of 25 km) [36]; or the 18.7- and 89-GHz ones (the Advanced Microwave Scanning Radiometer for Earth Observation System, AMSR-E, with a spatial resolution of 12.5 km) [37]. However, in order to achieve the high spatial resolution required, the antennae of these instruments should be enlarged. Currently, dual-polarization GNSS-R has emerged as a promising technique to measure sea ice cover and thickness. Experiments with the mission TechDemoSat-1 have demonstrated the capability and high accuracy of this instrument to conduct these types of measurements in [22,38,39].

4.6. Sea Ice Extent

Sea ice extent is an important parameter to understand the global climate. Previous works have shown that Ku-band scatterometer data are able to measure sea ice extent [40,41]. The required revisit time is 3 h with 10 km as minimal spatial resolution and 5% accuracy. Scatterometers have a wide swath and a reduced revisit time, which makes them a valuable technology for this application. However, the main limitation is the coarse resolution of the data generated by this sensor. In this sense, many studies have been conducted to develop algorithms to improve the spatial resolution of the data, combining data from multiple passes of the satellite [42,43] or from different sensors [44] (e.g., microwave imager, SAR and scatterometer).

4.7. Iceberg Tracking

Iceberg monitoring is important for climate studies and for navigation safety. In the time frame 2020–2030, the Copernicus EO infrastructure to support iceberg tracking will be SAR-C/Sentinel-1, SRAL/Sentinel-3 and SRAL/Sentinel-4 (JASON). Contributing Copernicus missions that are capable of this are ASCAT/MetOp and Scaterometer (SCA) on MetOp-SG. However, these missions are not enough to meet the user requirements, as iceberg tracking presents a gap in the revisit time (Table 2). Nowadays, the technologies measuring this parameter are the scatterometer, the SAR and the radar altimeter (in SAR processing). The main limitation of SAR and altimeters is their narrow swath, long revisit time and the long time to analyze the data (long latency). Scatterometer data are also valuable due to their coverage, but they present a coarse spatial resolution. The instruments that will be studied to cover the gaps in this measurement are SAR, SAR altimeters and microwave scatterometers.

4.8. Sea Ice Drift

Nowadays, the Copernicus Marine Environment Monitoring Service offers daily sea ice drift data over the Arctic and Antarctic from active (Sentinel-1, ASCAT) and passive microwave sensors (SSM/I, AMSR-E) and optical passive (the Advanced Very High Resolution Radiometer /3, AVHRR/3). With the data combined from different sensors, a global dataset of the sea ice drift is obtained with a spatial resolution of 10 km. The data latency is 5 h. In this regard, the data latency has to be improved down to <1 h and the revisit time down to <3 h. Potential sensing technologies are: microwave radiometers, SAR, multispectral optical and microwave scatterometers.

4.9. Sea Ice Thickness

In the time frame from 2020–2030, the sea ice thickness variable presents a gap in the revisit time (24 h) and in the vertical spatial resolution of 1 cm with 0.1-cm accuracy [2]. Ice thickness maps with a resolution of 50 km and up to 50–60 cm in thickness are produced with the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS), L-band microwave radiometer onboard the Soil Moisture and Ocean Salinity (SMOS) mission of the ESA, with an accuracy mission of 0.5–6 cm [45]. Another technology is the LiDAR altimeter, but its narrow swath and high cost do not compensate its benefits in terms of the variables with a gap. GNSS-R [39] and SAR [46] technologies also are capable of measuring this variable.

4.10. Atmospheric Pressure over the Sea Surface

Atmospheric pressure oscillations produce SST variations, and its monitoring provides a better understanding of the factors disturbing climate variations, contributing to accurate marine weather forecasts. Microwave radiometers can infer this measurement using several channels in the 50–60-GHz frequency bands. Among these, future microwave sounders in the time frame from 2020–2030 to measure the atmospheric pressure over the sea surface are: the Advanced Microwave Sounding Unit-A (AMSU-A), the Advanced Technology Microwave Sounder (ATMS) and nanosatellites, such as the Microwave Radiometer Technology Acceleration (MiRaTA) [23], and the Earth Observation Nanosatellite–MicroWave (EON-MW) missions [23]. AMSU-A is a whisk broom line scanner instrument in a SSO, with a global coverage of twice per day. It has 14 channels in the oxygen band (50–60 GHz). It is operated by NOAA, NASA and EUMETSAT, and the utilization period is from 2006–2024 on MetOp. ATMS on the Join Polar Satellite System (JPSS) is a cross-track scanning microwave sounder in a Sun-synchronous orbit, with a global coverage of twice per day. It is able to measure atmospheric pressure (over the sea surface). Its utilization period is from 2018–2021. It is also operated by NASA, NOAA and EUMETSAT. ATMS is the functional equivalent to AMSU-A with improved coverage thanks to a swath of 2600 km. The EON-MW mission has been proposed by MIT Lincoln Laboratory to extend the JPSS. It aims at demonstrating ATMS quality on a low-cost CubeSat platform in order to mitigate the gaps in weather observations. This mission is scheduled for launch in 2018–2019. The Infrared (IR) sounder/spectrometer also can measure this variable. The IR sounder on a CubeSat is feasible (6U). A good example of the compact from of this type of sensor is the Earth Observation Nanosatellite Infrared (EON-IR) on the CIRAS (CubeSat Infrared Atmospheric Sounder) mission [47]. In this regard, a constellation of microwave sounders or IR sounders as the payload could be considered, in order to cover the low revisit time (<3 h). These data will be complementary to those obtained by sensors onboard large platforms.

4.11. Sea Surface Temperature

The SST can be measured by microwave radiometer imagers [48] and infrared sounders [47]. Microwave radiometer imagers at frequencies of 6–7 and/or 11 GHz with coarse spatial resolution can also provide global SST data. Currently, a spatial resolution of 25 km can be achieved using the microwave imagers' (Tropical Rainfall Measuring Mission Microwave Imager, or TMI; Wind Microwave Radiometer, WindSAT; Global precipitation measurement Microwave Imager, GMI; AMSR-E; and AMSR-2) data fusion technique [24]. Infrared radiometers are capable of measuring this variable over cloud-free areas with high spatial resolution (1–4 km) using wavelength in the 10–12 μm range. Microwave radiometers can improve the coverage in polar regions because microwave signals penetrate the clouds. The challenge is an achievement of a relatively small footprint (<10 km) at low frequency bands (6.8 GHz).

4.12. Surface Soil Moisture

The soil moisture is a key parameter to understand the water cycle, and in cryosphere regions, it provides information about the freeze-thaw cycles. Several remote sensing technologies have been proposed to estimate soil moisture. Two criteria were selected to perform the technology categorization. The first one is related to the region of the spectrum (optical or microwave). Optical instruments acquire soil moisture measurements using the Thermal Infrared (TIR). Microwave instruments use signals in the L-, S- and C-bands. L-band is the main frequency band to acquire soil moisture due to its large sensitivity and its direct relationship with the soil water content [49]. The second criterion is related to the way of measuring: passive vs. active microwave instruments.

Microwave sensors do not rely on Sun illumination and are able to work in all weather and illumination conditions. This particular characteristic is especially important in polar regions that have long dark periods in winter and where it is cloudy most of the time. This feature also makes microwave sensors more suitable than optical sensors in this region. Several missions have been launched with active microwave instruments, which can be grouped into two main families: SAR and radar scatterometers. Current SAR instruments for the C-band are Sentinel-1A and Sentinel-1B, RADARSAT-2, the Radar Imaging Satellite-1 (RISAT-1)and Gao Fen-3 (GF-3). They provide dual polarization and multi-polarization data. Soil moisture estimation by Sentinel-1 is derived from the Advanced Synthetic Aperture Radar (ASAR) algorithm [50]. Operational SAR sensors in the S-band are HJ-1A/B/C and in the L-band the one on the Advanced Land Observing Satellite-2 (ALOS-2). The main limitations of these instruments are: the narrow swath, the dependence on the vegetation cover and the surface roughness and the speckle noise that makes SAR images appear very noisy. The main limitation of the SAR system for soil moisture is also the lower accuracy, as compared to passive microwave data.

The SMOS mission of the ESA was the first satellite dedicated to providing global soil moisture data [51,52]. SMOS-derived soil moisture products have an accuracy of 0.04 m^3/m^3 at a spatial resolution ranging from 35–50 km, as well as a revisit time of 1–3 days. Before SMOS, soil moisture measurements were performed using passive microwave radiometers [53] at 7 and 10 GHz (AMSR; AMSR-2; AMSR-E; the Multi-frequency Scanning Microwave Radiometer, MSMR). However, at these frequencies, soil moisture measurements are more affected by the vegetation cover. On the other hand, the L-band offers additional advantages such as less atmospheric attenuation than at higher frequencies and additional smaller water content effects (up to at least 5 kg/m). GNSS-reflectometry is another potential technology, so far having modest accuracy, that can be implemented even in CubeSats for soil moisture measurements. Data fusion between microwave radiometry, optical and SAR can improve the spatial resolution and accuracy of soil moisture measurements, as has been demonstrated in the SMOS and the Soil Moisture Active-Passive (SMAP) missions [54].

4.13. Monitoring System: Vessel and Fish Farming Cage Position Tracking

Norsat-2 and Triton-2 are contributing missions under the Advanced Research in Telecommunications Systems (ARTES) program by ESA. Spaceborne SAR and AIS can also be considered complementary systems to improve the security and surveillance services for maritime navigation.

5. Discussion

The aim of this section is to establish the promising technologies and to address the technological challenges, to ensure they satisfy the measurement requirements for the observation gaps detected in the Copernicus space segment. As shown in Table 3, the measurements with gaps detected in this study can be monitored by different types of sensors. According to the state of the art of the potential payloads to cover the gaps of the Copernicus space infrastructure in 2020–2030, the next generation of instruments require overcoming challenges and new technological developments in order to meet the end-user requirements.

GNSS-R is a promising technology to detect surface currents, significant wave height, sea ice cover, horizontal wind speed, dominant wave direction and sea ice thickness. The advantage of this technology is that it can process data in real time and onboard, through the use of Delay-Doppler Mapping (DDM); in this way, the latency time can be improved. However, the next generation of GNSS-R sensors should improve the spatial resolution to <10 km and the accuracy to <1 cm and <0.5 m/s, in order to meet the end-user requirements. In this regard, a precise clock module is required to reduce the errors in the retrieval computation.

For the passive microwave, a spatial resolution of <25 km is feasible by increasing the size of the antenna and would be suitable on CubeSats, as well as meet the spatial resolution requirement for atmospheric pressure over the sea surface. Microwave radiometers on small platforms demand the use of inflatable antennas in order to improve the spatial resolution and meet the end-user requirements, covering a variety of measurements between sea ice parameters, ocean conditions and sea surface temperature.

Future cloud radar, radar altimeters, LiDAR and SAR are required to improve the coverage and adopt the use of a new concept to allow a wide-swath. For the the next generation of scatterometer, it is imperative to improve the accuracy for horizontal wind speed over the sea surface <0.5 m/s with a spatial resolution <10 km, in order to meet the user requirements.

Optical sensors (such multispectral, hyperspectral radiometers and spectrometers) can monitor many variables with gaps, but the data can only be acquired in daylight and clear sky, a limiting factor for observing polar regions, where it is very often cloudy and the dark period is long. However, they are a good complement to microwave sensors, where the fusion of data could result in better products in terms of spatial resolution and accuracy.

6. Conclusions

This work is the first study reviewing the instrument requirements based on the end-users needs. The gaps of the future European EO spaceborne infrastructure were identified to select the potential technological areas for complementing and refining the Copernicus infrastructure. The exploration of the requirements and future European EO technology led to detecting and identifying the measurements with gaps and the emerging need to monitor the polar regions. Based on these results, future instruments, services and technology areas to upgrade were identified. Some of the most important characteristics, from which all the Copernicus services can benefit, are latency time and lower revisit time. Specifically, reductions of both revisit time from 24 h to 3 h and product delivery in the marine services from 24–48-h to 1 h would support, e.g., marine services, enabling polar navigation, enhanced marine real-time weather forecast, oil and gas exploration and oil spill remediation.

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