RESULTS OF THE EO SENTINEL CONVOY STUDY ON THE OCEAN & ICE THEME: GAPS, OPPORTUNITIES AND SCIENCE BENEFITS

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ABSTRACT

As part of its Support to Science Element (STSE) programme, the European Space Agency (ESA) is funding three EO-Convoy studies, aimed at 1) identifying scientific and operational objectives and needs which would benefit from additional in-orbit support, and 2) identifying and developing a number of cost-effective mission concepts that would meet these identified objectives and needs.

The first of these studies, dedicated to ocean & ice applications, has now been completed. The present paper highlights the results of this study, in particular the comprehensive user needs analysis which has been derived from Earth science analysis, applications and identification of novel data products. This process has identified a number of areas with gaps and where support measurements from additional satellites would prove valuable. Based on this analysis over ten convoy mission concepts were identified. The science benefits of the three concepts that were selected for further analysis are also presented.

1 INTRODUCTION

Satellite formations, flying and operating in a coordinated manner (e.g., tandems, clusters, or trailing formations) are not a new concept for space technology. In recent years, this concept has gained more attention in the Earth observation sector as an alternative way to accomplish complex scientific objectives exploiting the synergies among different type of missions. Notable examples include the Afternoon Train (A-train), which is operated by multiple agencies e.g. NASA, CNES, JAXA etc., or European national missions such as TerraSAR-X and Cosmo-Skymed.

It can be seen that when data sets from different missions and different sources are collected and combined in a coordinated manner numerous benefits result and many scientific questions can be addressed. These data sets can be integrated together to obtain a more complete and comprehensive picture of the Earth and Earth-System processes which would be beyond the capabilities of a single satellite.

Over the next few years a number of new long-term operational satellites will be launched by Europe, providing long-term stable streams of Earth Observation (EO) data in a reliable way. These missions include:

- The Sentinels – the dedicated space segment of Copernicus (previously known as Global Monitoring for Environmental and Security).
- The meteorology/climatology missions EPS (MetOp) and MetOp second generation (MetOp-SG) (operated by EUMETSAT).
- Copernicus contributing missions (assuming long term continuity).

These operational missions will provide a solid basis from which additional and complementary satellite missions can be designed. From a scientific perspective the possibility of flying additional satellite missions in constellation or formation (e.g. tandem formation, train formation, or some other sorts of specific constellation) with operational missions opens new exciting opportunities: these would provide rich and valuable synergetic observations, novel data products and complementary data sets, able to respond to various scientific requirements and operational needs not (fully) addressed thus far (e.g. observational gaps).

In this context, the objectives of ESA's EO Convoy studies are:

- To review the capabilities of current and future European operational missions, from the standpoint of both scientific and operational users.
- To identify and develop innovative Earth science objectives and novel applications and services that could be made possible by flying additional satellites (possibly of small-class type), in constellation or formation with one or more already deployed or firmly planned European operational missions;
- To perform a scientific analysis and preliminary assessment of a number of mission concepts in close collaboration with the scientific community;
- To select the most promising mission concepts and provide an outline of the resulting scientific requirements, observational principles, preliminary architectures for the selected concepts, in an end-to-end manner;

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- Perform a preliminary assessment of the scientific and technological feasibility and develop scientific and technology roadmaps that may provide the basis for further research and development activities.

In the long-term the project aims at stimulating the development of novel (smaller) mission concepts in Europe which may exploit new and existing European operational capacity in order to address new scientific objectives and applications in a cost effective manner. The ocean and ice analysis was split into three domains: oceans, sea ice and land cryosphere.

The following summarises the findings of the study focusing on the ocean and ice applications, led by Astrium, with the expertise of the NERSC, ENVEO and Polar Imaging Ltd.

2 OCEANS

2.1 Applications and scientific needs

The oceans and their interactions with the atmosphere and land play a major part in driving the global climate through the large amount of heat and mass transported by ocean currents, the evaporative fluxes and momentum exchange. More than 70% of the Earth’s surface is covered by oceans, which absorb more than half of the Earth’s total absorbed solar radiation. Moreover, about 40% of the anthropogenic carbon dioxide emission is absorbed by marine biological processes. Complex ocean–atmosphere interaction and feedback mechanisms occur across a wide range of temporal and spatial scales, including momentum exchange, radiative and turbulent heat fluxes and freshwater fluxes through evaporation, precipitation, sea-ice growth and melt, ablating ice sheets and mountain glaciers and river discharges. In addition, there are exchange processes with the land biosphere as well as oceanic biogeochemical processes invoked by shortwave absorption and scattering, the biological CO_2 pump and the exchange of gases, aerosols, dust and other natural or man-made chemicals. Ocean satellite data (topography and imaging) are today utilised by many user groups ranging from oceanographers and climate researchers, shipping or off-shore technology operators, search and rescue, fisheries, to those that use oceanographic data in coupled ocean-atmosphere models such as weather forecasts and climate studies. In general, global and regional numerical weather prediction models, seasonal to inter-annual forecasts and climate models assimilate ocean observations to generate initial conditions or boundary conditions.

These application areas require regular and sustainable observations of the main geophysical and biological variables listed in Tab. 1.

2.2 Oceans gap analysis

A broad spectrum of phenomena, such as global warming and sea-level rise, decline in fish stocks, seasonal oxygen depletion, acidification, episodic harmful algal blooms and loss of biodiversity, are all now showing troubling trends in their magnitude and frequency in open oceans as well as in many coastal areas. In the context of climate change the challenges of seasonal-to-decadal-to-centennial prediction are further aggravated by the existence of several unresolved key scientific problems, such as the coupling between wind-driven gyres and the thermohaline circulation, the effects of water mass variability on the vertical stratification, the convective overturning and the connection between tropical and extra-tropical disturbances at seasonal to decadal timescales. Moreover, the impact of climate change on ecosystem variability and dynamics remains largely unpredictable.

There are consequently still knowledge gaps regarding our understanding of ocean variability and dynamics, and its coupling and interaction with the biogeochemical state and processes despite significant advances in our understanding of the Earth System from combined use of observations, models and their combination via data assimilation. Typical temporal and spatial scales of variability of the key variables range from days to centuries and local to global, and invoke significant requirements and challenges for the observing systems. Ocean modelling and prediction are hampered by such knowledge gaps and existence of unresolved scientific understanding. Moreover, they hamper the quality and reliability of initial and boundary conditions to constrain the model simulations and predictions.

Variable	Sensor	Existing Satellites	Approved Satellites
Ocean wind (speed, direction)	Scatterometer, passive microwave, SAR, altimeter	MetOp, QuickSat, AMSR-E, Envisat, Jason	Sentinel 1 Sentinel 3
Sea State Parameters	SAR and altimeter	Envisat, Radarsat, Jason	Sentinel 1 Sentinel 3
Sea Level	Altimeter	Envisat, Jason	Sentinel 3
Ocean surface topography	Altimeter, ASAR, gradiometer	Envisat, Jason, GOCE	Sentinel 1 Sentinel 3
Ocean currents	Altimeter, ASAR	Envisat, Jason	Sentinel 1 Sentinel 3
Sea surface temperature (SST)	AATSR, AVHRR, MODIS Passive microwave around C-band	Envisat, NOAA, Aqua, AMSR-E	Sentinel 3
Sea surface salinity (SSS)	Passive microwave L-band frequency	SMOS	Aquarius
Ocean colour / bio-geochemical variables	MERIS MODIS	Envisat Aqua	Sentinel 3 OLCI
Mesoscale fronts and eddies	SAR, altimeter, MODIS, MERIS, AATSR, AVHRR	Envisat, Aqua, Jason, NOAA	Sentinel 1 Sentinel 3

Table 1. Main ocean variables subject to regular and sustainable observations from satellites

To advance the scientific understanding and fill the knowledge gaps the observing system must be sustained and further developed to ensure new and better measurements of essential climate and environmental variables. For instance, measurements of oxygen fluxes and other chemical substances at the air-sea interface are rare, and require specialised, synergetic sensing techniques which as yet have not been fully accomplished. The gaps associated with ocean observations are summarised in Tab. 2.

Ocean parameters and processes	Status	Gap
SST, surface salinity, near-surface vector wind, surface current. High resolution gravity field and geoid	Altimetry, scatterometry, passive microwaves and IR radiometry are the principal sensing methods. They must be sustained. Each sensor needs to be operated on several platforms and must be ensured for long term provision of data. Data collocation and merging needed.	Absolute surface current not yet observed. Cloud cover limit IR radiometry. Lack of precise knowledge of the geoid. Lack of detailed observation of surface salinity. Sea state bias correction still not physical-based.
Gas and heat exchange, aerosol input, E-P	Active and passive microwaves together with IR radiometry are key sensing methods for air-sea interaction observations.	Oxygen and CO_2 fluxes, other chemical exchange processes, aerosol fluxes, role and influence on acidification not understood
Rossby waves, mesoscale processes, eddies, internal waves	Radar altimetry together with Imaging sensing from SAR, IR and spectrometer	Absolute surface current is lacking. Relationship of 2D satellite image expressions with 3D state of the upper ocean is missing.
Erosion, run-off, contaminant and nutrient loading. Surface current, sea level	High resolution SAR, IR radiometry and spectrometry (including hyperspectral) sensing methods are used together with altimetry for land-ocean interaction monitoring in the coastal zones.	These processes occur at high temporal (order of hours) and fine spatial resolution (order 100 m to km) and cannot be adequately resolved by satellite coverage and repeat visit time. Lack of surface current and high resolution wind field. Run-off, contaminant, nutrient loading also not sufficiently observed
Marine ecosystem functioning	Imaging spectrometer used for chlorophyll a and primary productivity estimates. In open ocean it is (almost) operational. In coastal water the method is still insufficient.	CO_2 uptake and transport including influence of biological pump and acidification. Surface current and frontal dynamics (convergence, shear). Colour Dissolved Organic Matter (CDOM) and freshwater relationship is missing.

Table 2. Ocean measurement gaps

3 SEA ICE

3.1 Applications and scientific needs

Sea ice is a part of the cryosphere which interacts continuously with the underlying oceans and the overlaying atmosphere. The growth and decay of sea ice occur on a seasonal cycle at the surface of the ocean at high latitudes. Sea ice plays a crucial role in air-sea interaction in polar regions. The sea ice insulates the ocean from heat exchange with the atmosphere, modulates the thermohaline circulation of the world's oceans through deep-water formation, and insulates the polar oceans from solar radiation by its high albedo. Because the albedo of snow-covered sea ice is high (as much as 98%) relative to that of open water (20%), the presence of sea ice considerably reduces the amount of solar radiation absorbed at the earth's surface, particularly in summer when the insolation is high.

Satellite observations are the only source of continuous information about sea ice extent on global and regional scales, and have underpinned the well-known decline in Summer (September minimum) ice area in the Arctic of 14% per decade from 1979 to 2012 [1]. However, satellites have also proven essential for classification of ice types and estimates of ice drift. Ice thickness data have historically been obtained from in situ and underwater observing systems, but altimeter data from satellites are playing an increasingly important role in providing estimates of ice thickness across the polar oceans. Satellite data can also, in principle, be used to observe and quantify several other sea ice parameters, such as surface temperature, snow cover, ridges, leads, landfast ice, and processes such as ice edge eddies, waves in ice and melting/freezing.

As well as being of strong scientific interest, sea ice is increasingly important to operational users, particularly in the Arctic where there is a growth in human activities linked in large part to the decline in sea ice extent. The range of operational users of ice information is now very large, ranging from oil and gas majors to transportation companies, structural marine engineers, meteorological organisations, cruise operators, fishing fleets and those national agencies interested in maintaining sovereignty in areas that previously were almost impossible to access. Ice and ocean conditions are therefore of practical interest to a range of users who require not only tactical information in support of surveys, transportation and other activities, but also improved forecasts (which themselves require improved satellite observations for model-based data assimilation). This is an urgent need that has resulted in the International Ice Charting Working Group (consisting of operational ice services) publishing a press release in 2007 that draws attention to the dangers of increased activities in the Arctic with their concomitant increases in opportunities for ice-related accidents.

Measurement need	**Status**	**Gap**	**Primary option**	**Other options**
Ice edge	Monitoring using scatterometry, SAR (several bands) and passive microwave.	Young ice biases in passive MW algorithms; insufficient temporal and spatial resolution for scientific studies of the marginal ice zone.	C-band SAR constellation	
Ice concentration, extent, leads, polynyas (coarse resolution)	Coarse resolution from passive microwave, scatterometry, ENVISAT GM data;	Reduced ambiguities required, e.g. for ice concentration at margins and under certain atmospheric conditions (differences between algorithms).	Passive MW observations linked to improved information on atmospheric and surface conditions (coarser resolution)	GPS L band bistatic signals (more speculative, resolution limitations)
Leads and polynyas (Improved resolution)	SAR can detect narrow leads; Lagrangian tracking from SAR to detect openings in the pack with temporal resolution of a few days	Improved sampling from SAR needed for adequate temporal and spatial resolution.	C-band SAR constellation: configuration to minimise ice-water ambiguity (use of dual pol observations?) and sufficient resolution to detect narrow leads	Lagrangian technique for identifying ice openings in pack (as well as convergence)
Ice type classification	Some success at large-scale multi-year, first-year ice type mapping; detailed ice type mapping carried out manually as single sensor mapping ambiguous	Need reduced ice type ambiguity, particularly in marginal ice zone where thin and young ice is not well quantified by other satellite sensors.	SAR constellation: complementary SAR sensors, L + C or X band; dual polarisation (and adequate NESZ)	Manual analysis may still be required Optical imagery when available can help with ambiguities
Ice drift	Coarse resolution from passive microwave, scatterometer, buoys; moderate resolution in archive data (NASA/RGPS and ESA/GlobICE)	Mesoscale dynamics needs improved temporal resolution	C-band SAR constellation: compatible imaging modes for ice tracking, moderate to high resolution	Active + passive SAR for instantaneous ice motion as complementary approach Single pass INSAR? Also Doppler range velocity can provide data on instantaneous ice velocity
Ice thickness and mass	Radar (which penetrates snow cover) and laser (snow surface) measurements available from Cryosat-2 and IceSAT-1. Ice mass conversion uncertainty. In archive: Lagrangian ice tracking from SAR to estimate thickness distributions in the ice pack interior	Near real time, high spatial and temporal resolution products required; Coordinated snow cover information for conversion of freeboard / thickness to ice mass	Coordinated laser + radar altimeter (though sampling is not really adequate for some applications)	Links to time-varying gravity? Single pass INSAR? Imaging altimeter?
Ridge height and concentration	Not observed systematically; observed in some area of operational interest (e.g. Caspian) using data that is not optimised. Methodology for describing these features from EO imagery is not well established.	Need improved information on ridges and deformation zones (deformation type, density, thickness, orientation) in areas of operational interest around fixed structures and pipelines. Also useful for navigation. Links to bathymetry useful in areas of operational interest (basal scouring risk)	L band SAR, which is sensitive to surface roughness, coordinated to C or X band.	Short repeat or single pass INSAR for topography of landfast ice (areas where ice is grounded) – operational interest
Snow cover	Passive microwave is used (AMSR-E) excluding perennial ice; not well tested	Need for reliable product linked to other parameters	Scatterometer and passive microwave sensors near contemporaneous CoRe-H2O for improved resolution	.
Melt onset and duration	Melt onset and freeze-up dates estimated using passive microwave, some work on evolution of SAR signatures from first melt.	Melt stages (melt onset, etc) needed to be observed for operational reasons	C-band SAR constellation with good temporal revisit and complementary frequencies	Vis/NIR/SWIR/TIR is useful when available
Surface characteristics	Clear sky bias in datasets	Need to improve surface temperatures under cloudy conditions. Need coordinated observations giving ice concentrations (cloud and non-cloud) and albedo.	Combine both IR and MW surface temperature measurement Multispectral snow reflectance observations from coordinated sensors	Links to SAR needed to estimate albedo under cloudy conditions
Icebergs	No systematic and routine observations of icebergs smaller than about 1km in dimension, except around Grand Banks. Examples now of tactical ice monitoring to relatively small icebergs using high resolution and dual polarimetric SAR	Need moderate resolution systematic observations in areas of significant flux and/or operational activity. Tactical observations can augment this, but background information will build up knowledge on level of iceberg threat, climatology and behaviour.	SAR constellation: high resolution and cross-polarisation modes	Active + passive SAR also has possibilities

Table 3. Sea ice gaps and options of gap-filler missions.

3.2 Sea ice gap analysis

Although satellites provide essential data on large-scale ice concentration, area and motion, there are several key sea ice parameters where satellite remote sensing is under development. Measurements of the vertical dimension of sea ice (ridges, freeboard, thickness, snow thickness) and thermodynamic properties (temperature, heat flux) is possible by the use of altimeters and infrared / microwave radiometers, but the methods are not yet mature.

Optical properties such as albedo can be observed, but cloud cover and darkness prohibit systematic observations from spaceborne sensors. Many small-scale processes and phenomena can be observed by high-resolution SAR and optical / infrared images, but there are no systematic and long-term observations because the data coverage is insufficient.

Tab. 3 summarises the main gaps in sea ice satellite observations, and options to address them.

4 LAND CRYOSPHERE

4.1 Applications and scientific needs

The terrestrial snow and ice masses (land cryosphere) comprise snow cover, river and lake ice, glaciers, ice caps, ice sheets, permafrost and seasonally frozen ground In terms of extent and temporal variability the seasonal snow cover dominates, jointly with seasonally frozen ground. The main ice masses are stored in the big ice sheets of Antarctica and Greenland. Most of the snow and ice accumulating in Antarctica is routed to floating ice shelves and discharged to the ocean as icebergs. In Greenland mass loss due to surface melt is presently of the same order of magnitude as iceberg calving.

Ice and snow are important components of the global climate system, responding particularly sensitive to climate change, influencing the surface energy and moisture balance, gas and particle fluxes, hydrology, and atmospheric and oceanic circulation. These processes are coupled with the global climate system through complex feedbacks that are not yet well understood. Improved observational data are needed for a better understanding and accurate quantification of the main cryospheric processes and for improved representation of the cryosphere in climate models.

The various components of the cryosphere play different roles within the climate system. The seasonal snow cover, with its large extent but relatively small volume, interacts with the atmosphere at short time scales by changing the radiative and heat transfer on the Earth's surface. Permafrost (perennially frozen ground) controls the soil water content and vegetation cover over continental-scale in northern regions and is very sensitive to atmospheric warming trends.

Due to their rather small area and volume, glaciers and ice caps, as well as river and lake ice, respond rather quickly to climate effects. This jeopardizes water supply for human activities and ecosystems [6]. The large ice sheets of Antarctica and Greenland actively affect the global climate at longer time scales. Nevertheless, recent observations suggest that major mass depletion and associated sea level rise may happen within decadal time scale [7].

Satellite observations are essential for delivering comprehensive and consistent data on global ice and snow masses and processes. The important role of EO satellites for ice and snow observations is well documented in [8]. Sensors providing data of relevance to cryospheric research include altimeters, high and low resolution active microwave sensors, passive microwave imagers, different types of optical imagers, and gravimetry.

4.2 Land ice gap analysis

There are very few satellite sensors specifically dedicated to cryospheric applications, so that significant observational gaps are still existing. Main open issues for cryospheric observations and research are documented in [8] and [2], based on broad consultation of the scientific and Earth observation communities. Open issues and uncertainties for cryosphere monitoring and research are also raised in the Cryosphere section of the IPCC 2007 Report [5]. These three documents provide the background for identifying specific gaps in the observations of cryospheric parameters quoted in Tab. 4. In the table the present status of EO observations and observational gaps are specified for 11 parameters of the cryosphere.

Satellite constellations and sensors to deliver the missing observations are also summarised in Tab. 4. Some of the configurations are able to serve various applications. An important constellation is the passive SAR in formation with Sentinel-1, delivering precise, high resolution topographic data. It is able to close a main gap in observations of glaciers and ice caps (LI-G1) and provides basic data for studies of permafrost (LI-G6). Another powerful option, serving three applications (LI-G4, LI-G5, LI-G7) is the constellation of scatterometer and multi-frequency microwave imager. The combination of microwave altimeter and laser altimeter (LI-G2) offers significant improvements for precise measurement of surface topography on ice sheets. However, the orbit height of 814 km of the Sentinel-3 with the radar altimeter SRAL is challenging.

ID	Cryosphere parameter	Status	Gap	Option 1	Option 2
LI-G1*	Precise surface topography and its temporal change of mountain glaciers, ice caps, and outlet glaciers of ice sheets	Global data bases on surface topography of glaciers: SRTM and ASTER stereo; better accuracy needed for mass balance	Accuracy needs: ≤ 1m for mass balance at regular repeat observations (annual, bi-annual), ≤ 5m for base maps	≤ 3 passive SAR sensors for single pass interferometry associated to Sentinel-1; avoids the problem of temporal decorrelation; multi-baseline interferometry to improve retrieval accuracy	Configuration of two active SARs in close formation (e.g. helix)
LI-G2*	Very precise surface topography (and temporal changes) on ice sheets	Radar altimetry (RA) time series since 1991: ERS-Envisat-Cryosat-2, upcoming Sentinel-3. Lidar: IceSat-1 2003 – 2009, IceSat-2 2015+.	For RA measurements accuracy need ≤ 10 cm (annually) compromised by radar signal penetration and ambiguity in sloping terrain.	Microwave altimeter (Sentinel-3 Ku/C-band Altimeter, SRAL) and laser altimeter in loose formation (leader, follower)	Microwave altimeter and laser altimeter in different orbits (lower orbit for laser altimeter to improve the sensor performance)
LI-G3	Surface velocity fields of glaciers and ice streams	Presently mapping and monitoring of glacier and ice stream motion mainly based on SAR amplitude correlation.	Present repeat-pass InSAR application impaired by temporal decorrelation. Amplitude correlation requires conservative surface features - not applicable in firn areas.	Short-term repeat pass interferometric SAR, preferably 1 day; with the same SAR (S-1) on 2 platforms; preferred mode: interferometric wide swath; orbit configuration similar to ERS Tandem	Choosing the orbit for the 2nd (approved) Sentinel-1 (S-1B) such that 3-day repeat coverage is obtained.
LI-G4	Snow accumulation on ice sheets	Local/regional maps of snow accumulation (experimental) from scatterometer and multi-spectral microwave radiometer (MWR) data	No widely applicable algorithm for snow accumulation available. Synergy of active / passive MW systems promising. Coincident data not available.	Dual-polarized (VV, HH) Ku-band scatterometer and multi-frequency microwave imager (e.g. MWR on Post-EPS) covering similar ground swath within short time delay	Dual-polarized (VV, HH) Ku-band scatterometer &multi-frequency microwave imager in different orbits; time difference ≤ 1 hour in melt areas. Time delay not critical in dry snow zone.
LI-G5*	Snow mass (SWE) on land	Low resolution SWE maps available from MWR.	Ambiguity due to impact of grain size, , saturation over deep snow. spatial resolution in mountains.	Ku-band scatterometer/MWR configuration (as LI-G4), global repeat coverage 1 to 2 days; short time delay (< 30 min) between active - passive	Ku-band scatterometer and MWR measurements separated by several hours; OK only for dry snow cover
LI-G6*	Precise surface topography of permafrost regions	Data base on surface topography in high latitudes: ASTER stereo; std.err. ≥ 10 m	Accuracy needs as LI-G1. (Multi-) annual repeat coverage required.	Cartwheel of ≤ 3 passive SARs, same configuration as LI-G1	Configuration of two active SARs in close formation
LI-G7	Freeze/thaw cycle of soil	Imaging microwave radiometer (MWR) and scatterometer applied in demonstration studies	Improvements by synergy of active/passive MW systems, temporal coincidence needed.	Scatterometer/MWR configuration as for LI-G4 and LI-G5, global repeat coverage 1 to 2 days; with short time delay; thermal IR imager as add-on	Scatterometer and/or MWR imager applied separately; for qualitative analysis (mapping) of freeze/thaw
LI-G8	Snow albedo	Hemispheric snow albedo derived from medium resolution spectral imagers (MERIS, MODIS, …)	Multi-angular measurements for reducing angular effects of surface reflection and impact of atmosphere	Multi-angular, multispectral (0.4 – 1.6 μm) medium resolution imager on one platform; very precise calibration required; spectral resolution not critical	Multispectral medium resolution imager, single view direction (Sentinel-3 OLCI), and similar sensor with oblique view on another platform
LI-G9	Snow microphysical properties	Snow microphysical properties (grain size, metamorphic state) inferred from spectral imaging sensors in the VIS and SWIR (MODIS) - experimental	Multi-angular measurements in VIS and SWIR required for compensating angular effects of surface and atmosphere	Multi-angular, multispectral (0.4 – 1.6 μm) medium resolution imager on one platform; $\Delta\lambda \sim 20$ nm	As LI-G8
LI-G10	Ice sheet thickness and basal properties	Ground-based and airborne RES measurements.	Spaceborne technique required to get complete coverage with adequate spatial and vertical resolution	P band SAR mission; complementary surface elevation (altimetry, no need of formation flight);	No alternatives
LI-G11	Ice sheet internal layer depth	As LI-G10	As LI-G10	As LI-G10	No alternatives

*Table 4. Land Ice measurement gaps and options to fill these. Gaps marked with * correspond to missions of high priority for science and applications.*

	Ocean									Sea ice											Land ice										
	Ocean surface wind	Sea state parameters	Sea level	Ocean topography	Ocean currents (geostrophic & Doppler range)	Sea Surface Temperature	Sea surface salinity	Ocean biogeochemical variables	Mesoscale fronts, eddies, internal waves	ice edge	ice concentration	leads and polynyas	ice type	ice drift	ice thickness	ridge height & concentration	snow cover	melt onset and duration	surface characteristics	icebergs	surface topography glaciers & ice caps	ice sheet topography changes	surface velocity fields of glaciers & ice streams	snow accumulation on ice sheets	snow mass (SWE) on land	surface topography of permafrost	freeze/thaw cycle of soil	snow albedo	snow microphysical properties	ice sheet thickness and basal	internal layer depth
S1 + C-Band SAR (short repeat InSAR)	u	u		u	u				u	u		u	u	u	u	x		u	u	u	u	u	x	u		u					
S1 + Passive SARs	u	u		u	u				u	u		u	u	u	u	u		u	u	u	x	u	u	u		x					
S1 + X/Ku-Band SAR	u	u		u	u				u	u		u	u	u	u	u	x	x	u	u				x	x						
S1 + VIS-NIR-SWIR	u	u		u	u			u	u	u		u	x			u		u	u	u									x		
S1 + TIR	u	u		u	u	u		u	x	u		u			u			u	x								u				
S1 + L-Band SAR	u	u		u	u				u	u		u	x			x		x	u	u											
Ku-Band scatterometer + MWI (+TIR)	u					u					u		u				u	u	u					x	x		x		u		
S3 + Laser altimeter, gradiometer		u	u	u	u				u						x	u	x				u	x									
S1 + PMR (L-band)	u	u		u	u				u				x		u				u												
P-Band SAR					u				u		u			u				u												x	x
S2 + SAR	u	u		u	u			u	u																				x		
ASCAT + PMR SST	u					u					u						x	u	u					u							
S3 (SRAL) + PMR SST		u	u	u	u				u		x																				
S3 (OLCI) + multispectral oblique imager								u	u				u															x	x		
S1 + gravity field mission	u	u		u	u				u																						
MWS + PMR											x						u		u												
S3(OLCI / SLST) + MWI (+ASCAT)																									u				x		

Table 5.Potential missions addressing the ocean and ice identified gaps. An "x" denotes a necessity, while a "u" indicates that the mission would also be useful to address the corresponding gap.

5 PROMISING CONVOY MISSIONS

Based on the gap analyses, which is briefly summarised above, 17 mission concepts were identified to address these gaps (Tab. 5). Out of these, 11 were found to fit within the scope of the EO Convoy study.

Three mission concepts were selected by ESA, based on the recommendations of the study team for further analysis by the study team in the second part of the study. The team's recommendations were based on an assessment methodology adapted from that of the Earth Explorer selection process, but taking into accounts such aspects as operational merits and constraints. The three selected concepts are:

- Passive SAR(s) in formation with Sentinel 1;
- Laser Altimeter in tandem with Sentinel 3;
- Ku-Band Scatterometer in tandem with MetOp-SG

These are briefly presented in the following sections. Further details are available from the study report [9].

5.1 Passive SAR with Sentinel 1

The mission concept employs passive SAR(s) utilising the scene illumination provided by the C-Band SAR on the Sentinel-1 spacecraft. This configuration allows single pass interferometry thus avoiding temporal decorrelation. The aim is for the concept to deliver repeat observations of high accuracy surface topography generated from the across track InSAR, in order to fill identified gaps in land ice and permafrost observations. In the oceanic domain, bistatic SAR can also provide along track InSAR measurements of the surface velocity providing that the baseline is optimized. The aim would be the direct recovery of range directed ocean surface velocities, particularly those associated with major open ocean and coastal currents. For the sea ice domain, topography measurement could potentially be an important application. Depending upon the vertical sensitivity this convoy concept may support the measurement of sea-ice ridges, sea ice deformation features as well as sea ice topography in general. These measurements require good sensitivity in the vertical direction as well as a high spatial resolution.

5.2 Laser Altimeter with Sentinel 3

The proposed baseline is a laser altimeter operating on a separate platform in combination with the Ku/C Radar Altimeter (SRAL) operating on Sentinel-3. A main scientific objective of the mission is the precise measurement of surface topography and topographic change on ice sheets, ice caps and large glaciers. These data are essential for estimating the mass balance and contributions to sea level rise.

The mission concept relies on the combination of radar and laser altimeter measurements, which reduces the measurement uncertainty attributed to the individual sensors. Reducing these uncertainties improves the resulting data products particularly in the ice sheet topography and topographic change domains. The different footprint sizes (of the two instruments) enable sloping / undulating terrain to be characterised e.g. coastal regions. These footprints (of the two sensors) must overlap to enable the individual measurements to be combined. Near-coincident measurements are particularly required for sea-ice retrievals. Therefore, strict control box requirements are a critical element of the system design.

5.3 Ku-Band Scatterometer with MetOp-SG

This mission concept considers a single Ku-band scatterometer flying in a loose leader-follower formation ahead or behind MetOp-SG. The mission concept exploits the scattering and emission properties of snow and ice at different frequencies and polarizations in order to retrieve of snow and ice properties. A main parameter would be snow accumulation on land surfaces and on ice sheets. The backscatter measurements by the Ku-band scatterometer are combined with multi-frequency microwave radiometer measurements from the Microwave Imager instrument (MWI) and optionally also with C-band backscatter data of SCA (ASCAT follow-on), both embarked on MetOp-SG.

Combining passive and active microwave measurements, as proposed in this concept, will help to reduce this ambiguity between snow mass (SWE) and snow morphology. The sensors proposed for this concept have low spatial resolution and cover a wide swath, enabling daily repeat coverage at high latitudes. Due to the rapidly changes in snow and ice state, a high temporal resolution between the two sensors (radar, laser) is required to ensure improved characterisation of the snow and soil freeze-thaw cycle and the mapping of melting snow.

For sea ice, the Ku-band scatterometer data will help improve observations of ice concentrations from the MWR data, notably in terms of first-year vs. multi-year ice. The sensor combination will also help in reliably detecting large-scale melt onset, assessing surface characteristics and estimating snow cover on ice.

6 CONCLUSIONS

Current and future applications and user needs were compared to capabilities of present and future operational missions to identify gaps and opportunities in the systematic remote sensing of oceans and ice. Based on this thorough analysis, potential mission concepts were identified to address these gaps. The three most promising concepts were then analysed in further details, with their scientific objectives briefly introduced.

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