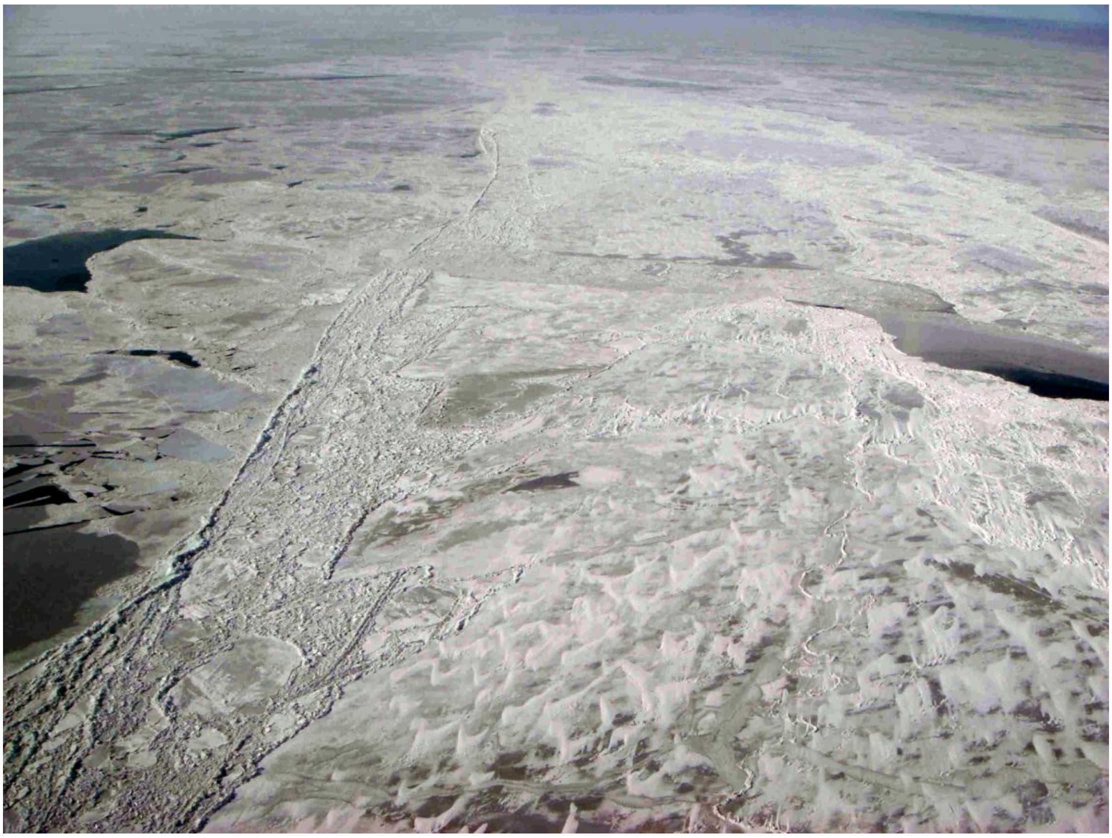
Technical Note on Potential Cryosphere Applications of Wavemill

Provided for Satellite Oceanographic Consultants Ltd



Abstract. This technical note provides a short assessment of the potential of Wavemill satellite mission for supporting cryosphere applications.

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Kim Partington
Polar Imaging Limited

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Polar Imaging

Issuing Authority			
Name	Kim Partington, Managing Director, Polar Imaging Limited		
Address	"Farthings", Stoke Road, Hurstbourne Tarrant, Andover, Hampshire, United Kingdom SP11 0BA		
Telephone	+44 7796 956594		
Fax	+44 870 705 9990		
Email	Kim.partington@polarimaging.co.uk		
Company registration	5919275	Date of incorporation	30 August 2006
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Frontispiece: Photograph of ice river in the Caspian Sea.

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Executive Summary

The cryosphere is an important application for any earth observing technology because it is considered likely to play a critical role in amplification of CO_2-induced global warming and can have a major impact on global sea level. In addition, operational interest in the Arctic is adding to scientific interest as summer sea ice has retreated opening up routes for navigation and resource exploitation. Wavemill offers several potential benefits to the broader earth observing network as follows:

- Novel estimation of high frequency sea ice motion, currently not sampled by any spaceborne sensors;
- Sampling of the thin surface layer of the cryosphere facilitated by the high operating frequency (Ku band), in particular snow cover, which is inadequately sampled by existing spaceborne sensors.
- Observations of poorly sampled dynamic processes, particularly in regard to the marginal sea-ice zone and terrestrial snow cover;
- Complementary observation capabilities to many existing and planned satellite missions, including altimeters and SARs, that would enhance the interpretation of observations from those sensors.
- The ability to observe currents and other oceanographic parameters in polar waters, in polynyas and larger leads, providing insight into ocean-ice interactions within pack ice.
- Speculatively, some interesting possibilities regarding the synergistic use of multiple parameters from Wavemill that could result in innovative products, for example in relation to retrieval of SWE using local slope.

Acronyms

CAFF	Conservation of Arctic Flora and Fauna	MIZ	Marginal ice zone
ECMWF	European Centre for Medium-Range Weather Forecasts	NASA	National Aeronautics and Space Administration
ESA	European Space Agency	NCEP	National Centre for Environmental Prediction
GCM	Global circulation model	NWP	Numerical weather prediction
GCOS	Global Climate Observing System	SAR	Synthetic aperture radar
HH	Horizontal transmit, horizontal receive polarisation	SATOC	Satellite Oceanographic Consultants Ltd
IABP	International Arctic Buoy Program	SWE	Snow water equivalent
IGOS	Integrated Global Observing Strategy	UNEP	United Nations Environment Programme
IICWG	International Ice Charting Working Group	VV	Vertical transmit, vertical receive polarisation
INSAR	Interferometric SAR	VIR	Visible / infra-red

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1. Introduction

Although the cryosphere is generally associated with remote and uninhabited areas of the Earth, there are several reasons why the cryosphere is of interest as a target for satellite monitoring, as follows:

- Global climate models typically show the Arctic as being one of the most sensitive areas of the planet to climate change, in large part because of positive feedbacks associated with the striking contrast in albedo of open water and ice and the role of sea ice in insulating the relatively warm ocean from the cold and dry atmosphere.
- The circulation of the oceans is critically affected by thermohaline processes in the polar regions, associated with the formation and melting of sea ice. It is this circulation pattern which keeps western Europe relatively mild compared, for example, to Labrador in eastern Canada.
- Land ice has the potential to raise sea level by metres, and several ice shelves fringing the polar ice sheets have either collapsed or shown evidence of accelerating discharge in recent years.
- Glaciers and snow cover represent both a resource and a hazard in temperature regions where they can act as a critical source of seasonal water supply and have the potential to create floods and avalanches.
- The Arctic is beginning to play a more prominent role as a source of resources and as an arena for a range of economic activity.


Ice sheets Sea ice Permafrost Seasonal snow Glaciers

Figure 1. Key elements of the cryosphere.

Satellite observations are essential for delivering comprehensive and consistent observations of global ice and snow, in order to support and advance these scientific and economic activities. The important role of satellite observing systems for ice and snow observations is well documented in the Cryosphere Theme Report of the Integrated Global Observing Strategy (IGOS) [1]. Although satellite observations have been crucial in reaching our current level of understanding of the cryosphere, there are still major open issues and challenges which limit the understanding and modelling of important cryosphere processes including the interactions with the oceans and atmosphere. Sensors providing data of relevance to cryospheric research include altimeters, high and low resolution active microwave sensors, passive microwave imagers and different types of optical imagers.

In the following document, cryospheric applications of potential relevance to Wavemill are reviewed briefly, gaps identified and potential benefits of Wavemill discussed and tabulated.

2. Cryosphere Applications

Accurate observations of the various elements of the cryosphere can help to:

- Understand, assess, predict, mitigate, and adapt to climate variability and change;
- Plan and initiate timely actions to cope with adverse effects of sea level rise;
- Help reduce the loss of life and property from natural disasters;
- Improve weather forecasting and hazard warnings;
- Improve the management of energy and water resources;
- Support engineering activities and transportation in high latitudes;
- Support the management of ecosystems and to conserve biodiversity;

The most commonly quoted cryosphere requirements can be divided into distinct categories, including the following:

- Science
    - Climate modelling (representation of ice in global circulation models, feedback processes, mesoscale interactions, etc.)
    - Other (ecosystem assessments, pollution pathways, etc.)
- Numerical weather prediction
    - Global
    - Regional (particularly sub-polar seas incorporating the marginal ice zone)
- Operations
    - Vessel navigation
    - Hazards detection and monitoring (icebergs, avalanches, ice jams, etc)

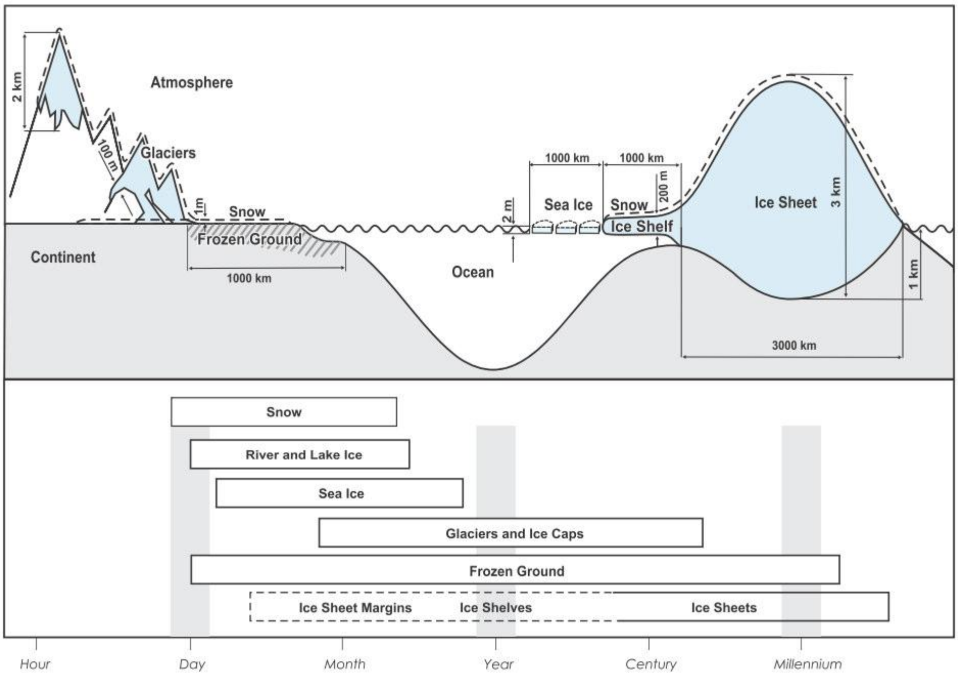


Figure 2. Components of the Cryosphere and their timescales [2].

2.1. Marine Cryosphere

2.1.1. Scientific Applications

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 (Figure 3). As much as 30 million km^2 of the earth's surface can be covered by sea ice. In comparison, the area of Russia is about 17 million km^2.

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. This is most significant in summer, when the insolation, or solar heating, is high.

Sea ice processes also affect oceanic circulation directly by the rejection of salt to the underlying ocean during ice growth. This governs the density of the water directly under the ice, the induced convection and the thermohaline circulation of the ocean. Much of the world oceans' deep and bottom water is believed to be formed in polar latitudes by these mechanisms. Conversely, the input of relatively fresh water to the ocean during ice melt periods tends to increase the stability of the upper layer of the ocean, inhibiting convection. Furthermore, the net equator-ward transport of ice in each hemisphere produces a positive freshwater transport and a negative heat transport.

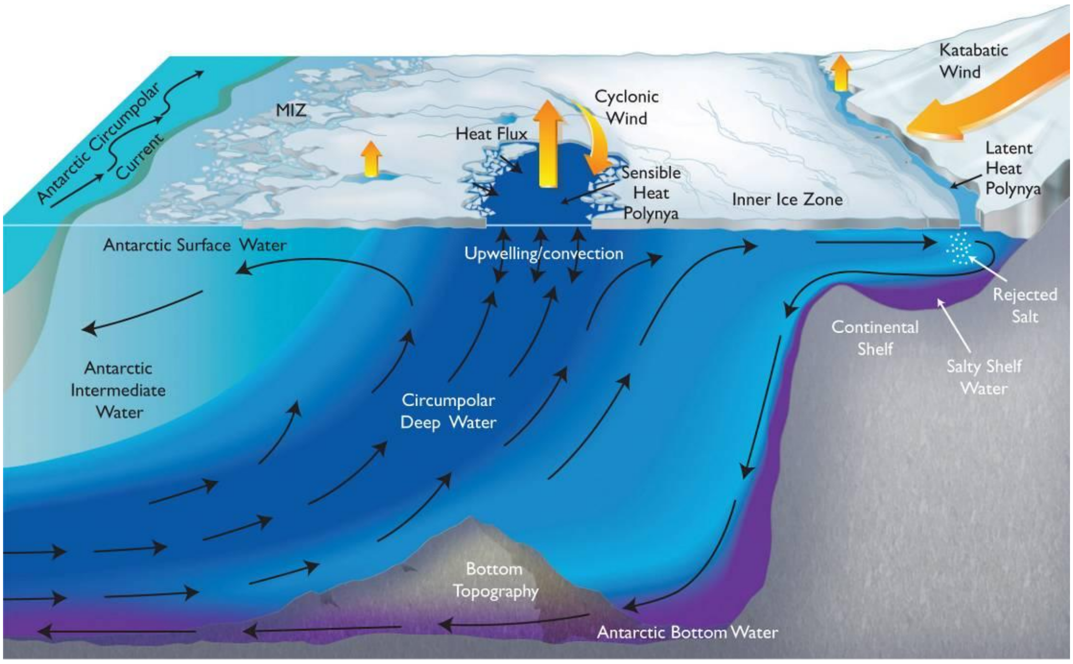


Figure 3. Open water areas within the ice are called polynyas and these are important features for both ocean-atmosphere interaction and for ocean biology [3].

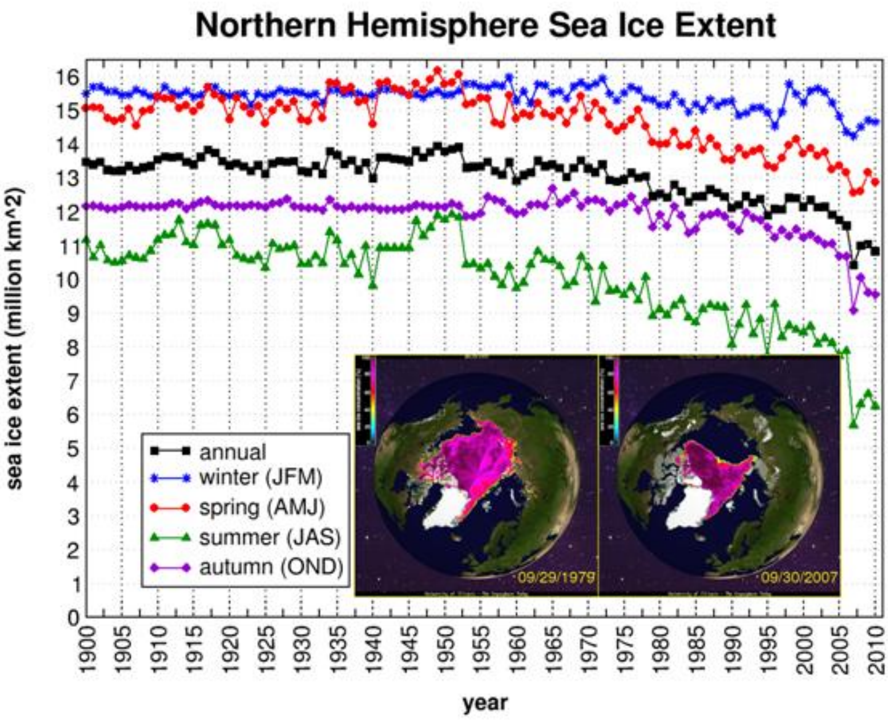
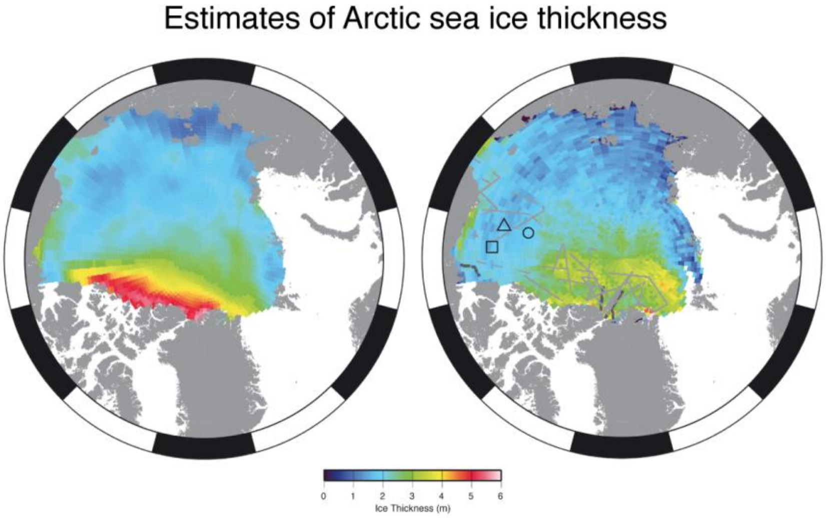


Figure 4: Sea ice extent in the northern hemisphere, 1900-2009, showing dramatic decline during the second half of the twentieth century, particularly in summer [1].

Satellite observations are the only source of continuous information about sea ice extent on global and regional scales. The significant decline of the summer ice area in the Arctic of 8 – 9 % per decade since 1979 is documented by satellite data. Satellite data are also essential for classification of ice types and estimates of ice drift. Ice thickness data have mainly been obtained from in situ and underwater observing systems, but altimeter data from satellites are playing an increasingly important role in obtaining ice thickness data in the polar oceans. Satellite data can also 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.



2004-2008 February/March estimate from ICESat

2012 February/March estimate from CryoSat-2

Figure 5: Estimates of February/March average sea ice thickness for 2004 to 2008 from NASA's ICESat (left) and February/March 2012 from CryoSat-2 (right). Colours indicate ice thickness in metres, with blue indicating 1 metre thick sea ice and red indicating 5 metre thick sea ice. Image courtesy of American Geophysical Union and the National Snow and Ice Data Center, University of Colorado, Boulder.

2.1.2. Operational Applications

Over recent years there has been a significant growth in oil and gas exploration and other activities in the Arctic, driven by the decline in summer sea ice extent. This is leading to a greater need for information on sea ice and related met-ocean conditions. 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). The need is an urgent one 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.

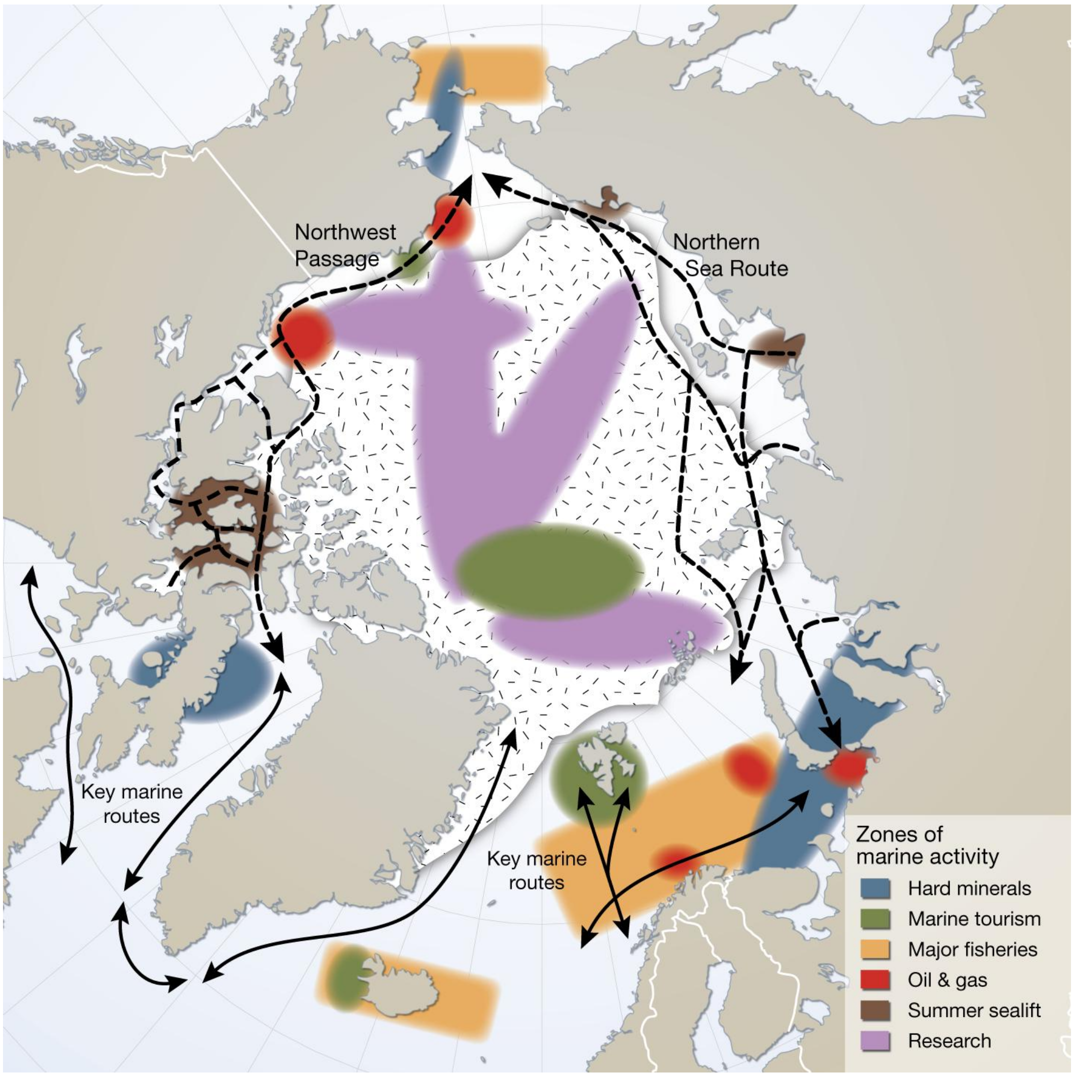


Figure 6. Current marine shipping uses in the Arctic, courtesy Hugo Ahlenius, GRID-Arendal & CAFF [4].

2.2. Land Cryosphere

The terrestrial snow and ice masses (the land cryosphere) comprise snow cover, glaciers, ice sheets, ice caps, lake and river ice, permafrost and seasonally frozen ground. They play a pivotal role in the global climate system, due to their influence on the surface energy and moisture balance, on gas and particle fluxes, precipitation, hydrology, and on atmospheric and oceanic dynamics. The impact of snow and ice is directly evident in polar regions and mid-latitudes. It also provides important feedbacks to the global climate system that are not yet understood. From observations delivered by satellites and conventional observing systems, it is obvious that snow and ice are particularly sensitive to climate change. Key open scientific questions on the role of the land cryosphere in climate are:

- What is the contribution of glaciers, ice caps and ice sheets to changes in the global sea level on decadal-to-century time scales?
- What will be the impact of changes in snow and ice masses on the atmospheric and oceanic circulation (including the question of fresh water supply to the high latitude oceans)?
- What will be the magnitudes, patterns and rates of change in the terrestrial cryosphere on seasonal to century time scales in the 21st century? How will this affect the water cycle, ecology and biodiversity?
- What will be the major socio-economic consequences of changes in the cryosphere?
- What is the likelihood of abrupt or critical climate and/or earth system changes resulting from processes in the cryosphere?

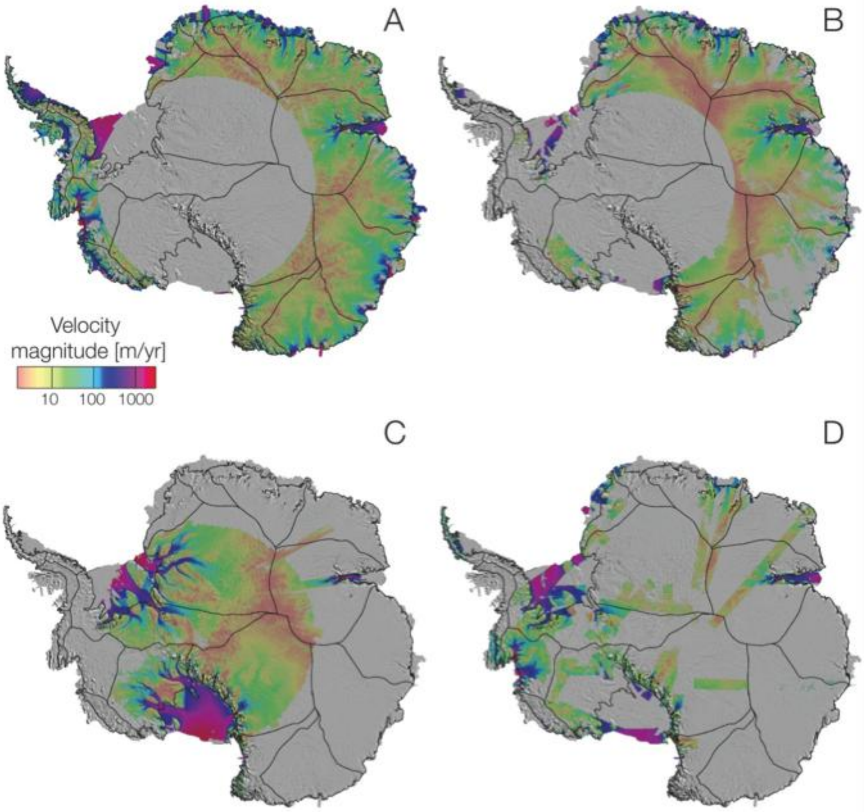
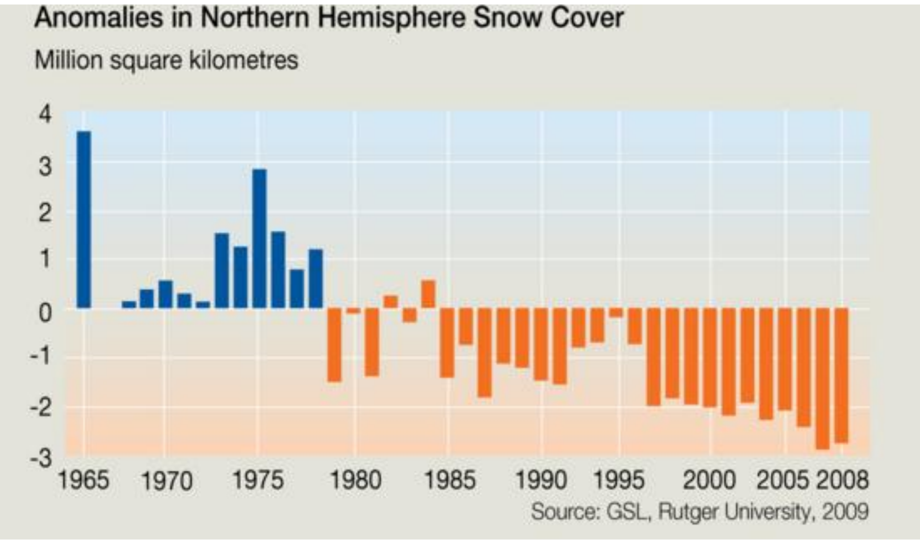


Figure 7. Antarctic ice velocity derived from (A) PALSAR, (B) ASAR, (C) RADARSAT-2, and (D) RADARSAT-1 and ERS-1 and 2 satellite radar interferometry overlaid on a MODIS mosaic of Antarctica. Thick black lines delineate major ice divides. Image/photo courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder from [5].

Earth observation is fully established as the key technology for monitoring the terrestrial ice sheets, and to lesser extent smaller ice caps and glaciers. Altimetry and interferometric SAR are able to provide information on topography, topographic change and ice flux, revealing that complex patterns of dynamic behaviour that were speculation only a few decades ago. Lower frequency radar systems have provided insight into the internal and basal properties of the ice sheets, while passive and active microwave systems have provided some information on the accumulation rates of snow and patterns of seasonal melting and refreezing with the result that estimates of the mass balance of the ice sheets and their contributions to sea level rise are now becoming more usefully precise.

Over land, snow cover, which has very important influences on both climate and water resources, and while it is a challenge to routinely estimate snow water equivalent, large scale changes in snow cover have been observed with both optical and microwave sensors.



Source: GSL, Rutger University, 2009

Figure 8. Decline in northern hemisphere snow cover from 1965 to 2008, courtesy of Riccardo Pravettoni, UNEP/GRID-Arendal [6].

Snow cover and snow water equivalent (SWE) are required for use in land surface process models, atmospheric circulation models, hydrological models, sea ice process models and glacier mass balance models. The spatial scale of many of these models has been decreasing steadily. Land surface models have been moving towards grid sizes below 1 km. Snow cover data for initializing and validating these models at high spatial scale are largely missing [7] and on land this has short term practical application to water resources forecasting.

Accurate description of the land surface, including the terrestrial snow cover, is also of importance for numerical weather forecasting and the assessment and prediction of climate change at global scale. In order to obtain accurate estimates of initial conditions, advanced data assimilation systems and observations are needed. Snow cover is not particularly well represented in the ECMWF four-dimensional variational data assimilation system, for example. As snow cover is heterogeneous on scales smaller than GCM grids, parameterizations have to be used to calculate snow cover fraction. Due to the shortage of reliable measurements of snow extent and mass at high resolutions, these parameterizations lack proper validation [7].

3. Cryosphere Requirements

3.1. Utilization Needs

Cryosphere applications have some key utilisation needs that reflect broad research and operational activities and programmes. Some of these are well established, while others, e.g. the use of earth observation for design of offshore operations and facilities, are relatively new, as follows.

Table 1. Key cryosphere applications for the utilisation of earth observation.

Type	Key utilization need
Climate and Science	**1. Sea level rise** is determined by the mass balance of the large ice sheets and, to a lesser extent, ice caps. It is important to be able to monitor the accumulation of snowfall on ice sheets and the ablation through iceberg discharge and underwater melting of ice shelves.
	2. Sea ice mass balance and freshwater redistribution is required to elucidate thermohaline circulation, which has an important role in climate. The spatial and temporal distribution of the parameters used to generate these fluxes and budgets also need to be available in order to help establish the processes which are driving polar changes. There are also other applications such as pathways for pollutants in the Arctic
	3. Sea ice model development. Present sea ice models, mainly based on viscous-plastic rheology, are useful on the large scale, but are not appropriate on local scale. Model development is essential to support the development of numerical forecasting techniques and is essential to help understand the precise role of sea ice in acting as an interface between the ocean and atmosphere in the climate system.
	4. Surface energy balances. Sea ice acts as an interface between a warm, wet ocean and cold, dry atmosphere, and modulates moisture flux, momentum flux and radiation balances. This needs to be well parameterised in climate models in order to understand just how sensitive the climate system is to sea ice. The role of snow is also very important in this regard. For example, anomalous snow cover across Siberia has been implicated in many northern hemisphere climate conditions.
Operations	**5.** Long records of climatological length need to be developed and maintained in order to **design for infrastructure and operations**, including not only “normal” ice (and other metocean) conditions, but also for extreme events. Construction in areas of permafrost, snow cover and potential floods require statistics related to cryospheric conditions and associated risk assessments.
	6. National ice services generate regular (daily to weekly) wide coverage marine **ice charts** for as a public service, with some custom support for operational and commercial clients.
	7. Hazards and tactical support: monitoring of hazards, vessel navigation, etc. The major increases in operations in polar regions (tourism, leasing of large areas for oil and gas exploration, shipping) lead to a growing requirement to provide an infrastructure that supports safe operations, which translates into a requirement for timely information on hazards (icebergs, ice jams on rivers, stamukha, avalanche threat, etc.).
	8. Water resources. Energy derived from water resources depends in many areas on sources that are impacted by ice jams and the amount of annual snowfall and water storage in glaciers. Melt water is, in many semi-arid areas, essential for the maintenance of viable agriculture. The state of glaciers and seasonal snow cover and any changes are important to determine. Certain ecosystems also depend on the seasonal cycle of freshwater volumes and nutrient inputs.
Numerical weather prediction	**9.** Accurate and robust **regional-scale numerical forecasting** of ice and related metocean conditions is critical to sustainable operational activities in polar and sub-polar regions. Development of effective forecasting implies that regional models (with boundary conditions set by larger models such as ECMWF and NCEP) are developed which assimilate regional scale observations of cryosphere parameters, in particular related to sea ice and snow cover.

3.2. Observation Requirements

These requirements imply a range of temporal and spatial sampling needs and are summarised in Table 1. This report rules out optical-related properties (surface radiative properties, albedo, etc.) because these cannot be observed with a microwave sensor.

Table 2. IGOS 2007 requirements for cryosphere applications.

PARAMETER	Operations: goal (threshold)				Climate: goal (threshold)			
	Spatial resolution	Temporal resolution	Accuracy	Comments	Spatial resolution	Temporal resolution	Accuracy	Comments
SEA ICE								
Ice extent / ice edge	0.1km (10km)	<1d	0.1km (10km)		1-5km (10km)	1d	5km (10km)	GCOS 2011 specifies 7d revisit
ice concentration					10km (15km)	1d	5% (10%)	Some sources specify down to 1km spatial
ice classification					10km (15km)	1d	5% (10%)	
ice thickness	0.5km	1d	10%	Up to 20km spatial resolution cited (SA Sea Ice CCD URD 2012)	25km	1d	0.1m	5km cited by SA Sea Ice
leads / polynyas	0.1km	1d	$0.1km^2$	25m cited for operations (IICWG)	10km	1d	5%	
meltponds (% area)				10% cited (IICWG, NWP and operations)	0.5km	1d	1-5%	
ridge height							1m (2m)	
ice motion	0.1km (25km)	1d	0.5km/d (3km/d)		1km (25km)	1d	1km/d (3km/d)	6hrs (regional NWP) to 7d (GCOS-2011) cited
snow depth on ice					5km (10km)	1d	2cm (5cm)	
melt onset					10km (15km)	1d	1d (2d)	
ICEBERGS								
size					0.001km (0.01km)	1hr (1day)	30%	
position								
draft								
velocity								
FRESHWATER ICE								
river ice edge location								
river ice concentration	30m	1d	5%		30m	1d	5%	
river / lake ice concentration								
river / lake ice thickness								
LAND ICE AND SNOW								
Topography					30m (100m)	1yr (5yr)	1m (5m)	
topographic change					1km (5km)	1yr (5yr)	5cm (10cm)	
surface velocity					20m (100m)	30d (1yr)	10m/yr (5%)	
snow accumulation					1km (25km)	180d (1yr)	1cm/yr	
snow mass on land					100m (500m)	1d (6d)	10% $(20kgm^{-2})$	
permafrost topography					30m (100m)	1yr (5yr)	1m (5m)	
freeze/thaw cycle of soil					0.1km (1km)	0.5d (6d)		

4. Gap Analysis and Potential of Wavemill

Current earth observation technologies collectively cover well many of the requirements identified above, but there are some clear gaps. These are addressed below, along with an initial assessment of how Wavemill can contribute to addressing these gaps.

4.1. Marine Cryosphere

4.1.1. Gaps

Key gaps in relation to monitoring the marine cryosphere (relevant to microwave observations) can be identified as follows:

Mesoscale spatial-temporal sampling. The marginal ice zone is a highly dynamic environment, involving complex interactions and feedbacks between the open ocean, sea ice and the atmosphere. The sampling required to elucidate these complex processes is very demanding, requiring both high spatial resolution and frequent revisit. The marginal ice zone is also increasingly important for operational activities, including tourism, oil and gas exploration and transportation, with a resulting need for more reliable forecasts of both weather and ice conditions and hazards. There is also a requirement for enhanced spatial-temporal sampling, with particularly high spatial resolution, in pack ice where lead formation and destruction is important in determining surface energy balances. Fortunately, polar orbiting satellites have favourable temporal sampling in the polar regions (up to any latitudinal limit of coverage), but some ice-prone areas are well outside extreme latitudes and so do not benefit from this as much as might be expected and daily revisit is the general requirement.

Vertically differentiated sampling. Microwave sensors have the important ability (during freezing conditions) ability to penetrate snow and/or ice to provide information on the depth or other characteristics of the material. However, this depends sensitively on the frequency of the sensor and, to lesser degree, incidence angle and other sensor configuration parameters. However, specific microwave sensors do not measure the sea ice thickness directly, and neither do they “cleanly” sample the overlying snow cover or the underlying sea ice, and so there is a need to use multiple sensors to help ensure that observations are corrected for any biases introduced by imperfect vertical sampling. Radar altimeters are particularly relevant in this regard: it is necessary to estimate snow cover and its impact on the radar signal, as well as vertical density profile, in order to convert radar altimeter elevation measurements into sea ice thickness, thus sensors that can be used to extract information about distinct vertical layers in the sea ice, in particular the snow layer, are very useful to support interpretation of observations from a range of other sensors. In part, it is the mixing of scattering from different components of sea ice and snow that can lead to ambiguities in extraction of key geophysical parameters.

Reliable melt season products. The melt season is associated with the most significant reductions in Arctic sea ice cover in recent decades, and is also when most operational activities take place (including potential transits of the northern sea route, for example). Microwave sensors are subject to more ambiguities in assessing ice conditions during the melt season because melting ice can have some sensing similarities to open water, and the ability to penetrate the surface to sampling underlying ice, or the snow cover itself, is effectively removed. Thus, passive microwave sensors can underestimate sea ice concentration.

Near real time products. For many marine applications, near real time information is needed to support forecasting and operational applications. Improvements to the timeliness of observations on snow cover and ice motion would be very useful, as in particular would ice thickness.

Measurement need	Utilis'n Need	Status	Gap
Ice extent / edge	2,4-7,9	Monitoring using passive microwave and VIR, scatterometry and SAR when available.	Young and wet snow/ice biases in passive microwave algorithms; insufficient temporal and spatial resolution for marginal ice zone
Ice concentration	2,4-7,9	Passive microwave radiometry is used routinely, but inconsistent algorithms.	Reduced ambiguities required, e.g. for ice concentration at margins and under certain atmospheric conditions; notable biases in summer when surface contains free water.
Ice type classification	2-7,9	Carried out manually and routinely for particular areas using skilled ice analysts; SAR with support from optical can be used; automated analysis has proved challenging. Some potential from polarimetry.	Need reduced ice type ambiguity, particularly in marginal ice zone where multiple thin and young ice types have ambiguous signatures; clear demand for robust automated classification if possible.
Ice thickness and mass	2-7,9	Radar (which penetrates snow cover) and laser (snow surface) measurements available which can be used to convert to ice mass using density estimates; in near real time, ice type is a crude proxy. Lagrangian techniques have been used to estimate ice thickness from SAR data (RGPS, Globice), but this is processing intensive and non-near real time..	Near real time estimates required; Coordinated snow cover information for conversion of freeboard / thickness to ice mass; Improved coverage (existing techniques do not provide spatially continuous or routine ice freeboard/thickness)
Leads and polynyas	3,4,6,7,9	SAR can detect narrow leads; Lagrangian tracking from SAR to detect openings in the pack with temporal resolution of a few days; VIR for thermal detection.	Improved sampling needed for adequate temporal and spatial resolution; ice-water ambiguity in radar at certain wind-speed dependent incidence angles
Meltponds	4,6,7,9	Not routinely available. VIR can be useful when available, but not often available (cloud)	Microwave presents ambiguities (meltponds vs. open water).
Ridge height	3-5,7,9	Not observed systematically; observed in some area of operational interest (e.g. Caspian) using high resolution SAR; INSAR being assessed over landfast ice; L band more sensitive than C/X to these features. Quantitative techniques not well developed.	Lack of techniques for generating topography over dynamic ice (landfast ice also challenging, but demonstrated in part with Terrasar-x/tandem-x). Sampling is a challenge (high spatial resolution combined with adequate coverage). Key need is for mapping in critical areas of interest (operational areas, plus key areas of ice export such as Fram Strait).
Ice motion	2-7,9	Coarse resolution from passive microwave, scatterometer, buoys; intermittent use of SAR for high resolution drift vectors. Algorithms well proven.	Mesoscale dynamics needs improved temporal resolution; improved spatial resolution also important to detect dynamic features.
Snow depth on ice	2-7,9	Some experimental products such as from passive microwave (e.g. AMSR-E, first-year ice only); not well tested. Requires high frequency to minimise signal from underlying ice.	Need for reliable product linked to other parameters, notably ice thickness. In Antarctic, most of freeboard can consist of snow cover. Critical is the detection of the snow signal without contamination from ice or atmosphere.
Melt onset and duration	2-7,9	Melt onset and freeze-up dates estimated using passive microwave, some work on evolution of SAR signatures from first melt, but this is in research phase.	Melt onset and freeze-up can be detected fairly reliably from microwave signatures; challenge lies in detecting specific phases of melt (which impacts on general thermodynamic properties of ice and "strength").
Icebergs	2,5-7	No systematic and routine observations of icebergs smaller than about 10km in dimension (scatterometry), except around Grand Banks (using SAR). Examples now of tactical ice monitoring of relatively small icebergs using high resolution and dual polarimetric SAR in areas of operational interest (Arctic, Falklands).	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. Detection of icebergs in sea ice and in rough seas can be challenging.

Table 3. Sea Ice observations status and gaps, with reference to utilisation needs in Table 1.

4.1.2. Elevation estimation: sea ice thickness and topography

Sea ice represents a store of fresh water and its mass balance is therefore an important parameter for the hydrological cycle. Furthermore, it is clear that the extent of sea ice cover has been reducing significantly over the last three decades, but without an estimate of thickness of the ice cover, it is difficult to know whether this change has been compensated or exacerbated by thickness changes. Measuring the freeboard of the sea ice plus snow cover from which sea ice thickness and mass can be estimated is therefore of major value to the science community. Laser measures the sea ice freeboard including the snow cover, whereas radar altimetry measures to a surface which more closely approximates the sea ice – snow interface, so laser altimetry is complementary to radar altimetry. Near real time products would have operational interest in areas of offshore activity; information on surface elevation in leads would have benefits to the oceanographic community; high latitude gravity field may be improved and perhaps even tides (depending on sampling).

If Wavemill had the possibility of generating sea ice topography at a spatial resolution of about 15km, this would be marginally useful for regional scale applications, but would meet the requirement for climate-related applications, so the spatial and temporal sampling of Wavemill would be potentially useful. More critical to the contribution of Wavemill is the potential thickness precision, or sensitivity to sea ice thickness change over time. The requirement for ice thickness appears somewhat insensitive to the scale, being specified in several sources as 10cm (but ranging from about 5cm to 50cm), which can be interpreted from a climate perspective as uncertainty in the monthly mean of absolute ice thickness (Ridley, personal communication, 2014). This is very different from the uncertainty in a single measurement which will be much larger and it is important not to confuse a requirement of 10cm ice thickness uncertainty (over a month and 25km x 25km) with the uncertainty in a single measurement of sea ice freeboard. Any measurement uncertainty associated with a single sea ice freeboard measurement (surface elevation above mean sea level) is amplified in terms of sea ice thickness uncertainty. Uncertainties in the density of the ice and snow contribute to uncertainty in the thickness estimate derived from freeboard under the assumption of hydrostatic equilibrium.

Some assessment of this has been carried out in support of the Cryosat-2 mission. Alexandrov et al. [8] suggest that the error in freeboard (height) measurement is the main uncertainty factor for first-year ice thinner than 0.8 m, while ice density becomes the main error source for thicker first-year ice and all multi-year ice (based on Arctic data). The relationship between freeboard and ice thickness is significantly different for multi-year ice than for first-year ice, because the former approximates (low density) fresh water ice, whereas the latter is (higher density) saline ice. For first year ice, a freeboard uncertainty of 0.03m corresponds to a thickness uncertainty of about 0.5m (close to half the ice thickness), while for multi-year ice, the same freeboard uncertainty corresponds to a thickness uncertainty of about 0.54m (which is a much smaller proportion of the mean ice thickness of close to 3m).

Thus, to achieve the necessary performance it is required to generate enough independent estimates of sea ice elevation within 25km over a month to achieve precision of 10cm in mean ice thickness values. It would be necessary to model the number of independent observations using the orbit configuration of Wavemill to answer this question, along with the spatial resolution of the estimates and the impact of the specific baseline.

There are a number of additional challenges that might apply to Wavemill in its application to sea ice thickness estimation. At Ku band, the ratio between surface and volume scattering depends sensitively on incidence angle. For Ku band altimeters operating at nadir, there is a strong ice-snow interface scattering component with some impact of volume scattering from the overlying snow [9], depending on snow and surface roughness properties. As the incidence angle increases, the snow volume scattering component increases relative to the ice-snow interface component. Given that there is a bias from overlying snow cover for Ku band elevation measurements at nadir such that it is necessary to estimate the snow cover in order to interpret Ku band nadir elevation measurements correctly, at incidence angles of 20°-30° incidence angle, this will be even more important because the impact of the snow cover on the freeboard measurement will be even greater. Therefore a challenge for estimating surface elevation with Wavemill will be to ensure that there is an effective way to account for the snow cover in generating an estimate of sea ice freeboard and then converting to ice thickness. The estimated elevation may indeed be a varying surface somewhere between the snow-air interface and the snow-ice interface. It would be interesting to consider that, if the sensor were able to both estimate the snow depth and the elevation of a surface that is influenced by the snow cover, then the sensor may be able to provide some elevation bias correction of its own, but this is speculative.

It is worth briefly considering the potential of Wavemill for detecting and measuring deformed sea ice. Pressure ridges, rafting, rubble fields and stamukha, contain a significant percentage of the total mass of sea ice in both the Arctic and Antarctic, on average perhaps 40% of the mass in the Arctic, with some keels extending 50m below sea level. Improved sampling of these features would help elucidate ocean-ice-atmosphere interactions in areas such as the role of ridges in increasing sea ice drag coefficients and transferring kinetic energy from the atmosphere to the ice cover. These deformation features are also critical for ice navigation and other operational activities, e.g. potential scouring of shallow bathymetry creating hazards for buried pipelines. The ability to detect and characterise these features would be very valuable and the vertical precision and accuracy is an order of magnitude more lenient for measuring the topography of these features (Table 1). However, the observation of ice deformation features requires spatial resolutions that are in general beyond the capabilities of the proposed configuration of Wavemill. Although, for landfast ice, it is possible to use long baselines to achieve smaller height errors (Lang et al., [10][1]), the required spatial resolution is still orders of magnitude better than that proposed for Wavemill and so Wavemill is unlikely to provide much support for detection and mapping of ice deformation features. At the other end of the thickness spectrum, it is important to note that there is evidence that Ku band backscatter can be correlated with the thickness of thin ice less than about 8cm in thickness [11], so Wavemill could be used to detect, and even estimate the thickness of, thin ice.

Finally, it is important to point out that the measurement of the mean sea surface elevation is important to sea ice thickness mapping. This implies the ability to measure elevation in leads and polynyas as well as around the ice margin. Given the coarse spatial resolution of Wavemill, this may benefit significantly from coordination with altimetric missions that have the spatial resolution to measure sea surface height in open leads. More generally, coordination of Wavemill with altimetric missions would have strong benefits to both in terms of optimising estimates of sea ice thickness and enhanced spatial-temporal sampling, if the former were able to be used for ice thickness estimation.

It is understood that elevation products are no longer envisaged for Wavemill.

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[1] 300m baseline was used to achieve height errors of <1m in the Caspian Sea using TerraSAR-X data, with incidence angles of 30° or greater for adequate coherence

4.1.3. Motion estimation: Sea ice motion

The marginal ice zone is generally defined as the area of ice (and interleaving open water) that is impacted by ocean swell, while polynyas are also areas of open water within the ice cover but that may be maintained by latent or sensible heat processes. Both types of area are important to a wide range of applications, including ocean biology (having extremely high primary productivity, especially in spring) and ocean-ice-atmosphere interactions. There is also growing operational interest in several marginal ice zone areas. These areas can be extremely dynamic, requiring very good temporal and spatial sampling for effective monitoring. Any sensor which is able to elucidate dynamic processes in this area has the potential to provide important insights into interactions between the cryosphere and the rest of the climate system, as well as to provide useful practical information for operational activities.

The sea ice motion requirements can be specified in terms of velocity and direction. Both of these requirements have been taken into account for Wavemill, but in Table 2 it is interesting to note that direction is not included. As direction appears more challenging for Wavemill than velocity, we should not ignore direction in our assessment. The spatial sampling requirement is compatible with Wavemill, being 1km, although this will be impacted by any requirement to increase the number of looks substantially (i.e. in light of the tougher motion accuracy requirements of the application).

The velocity requirements for sea ice motion in Table 2 suggest a requirement of about 2km/d (values in Table 2 extend from 0.5km/d to 4km/d, so the accuracy requirements do not vary hugely across the different applications). This translates into a value of ~2.5 cm/s, which is more stringent than the oceanographic requirement of 10cm/s. However, these accuracy requirements relate to estimation of the ice motion over the required temporal resolution (which is generally daily for most applications). The motion requirements are not for instantaneous sea ice motion, which consists of both a random walk and a mean field.

There are two potential applications of Wavemill with respect to sea ice motion. The first is to estimate the mean field (over the specified temporal resolution). The advantage of more conventional ice motion observations based on repeated observations from between 1 and 6 days, typically (using SAR, scatterometry, etc.) is that the random walk element is averaged out. In order to make use of Wavemill to understand sea ice dynamics, it would be necessary to carry out some analysis to determine the sampling requirements (temporal as well as spatial) for instantaneous measurements of sea ice motion needed to provide an accurate estimation of the mean motion field. This would be seasonal and area-dependent, because the relative contributions of the mean field and the random walk would vary depending on environment, from low concentration sea ice that exhibits free movement with respect to wind and currents, to higher concentration sea ice which is far more constrained. Wavemill has the potential to generate ice motion instantaneously, but in order to achieve the required mean field from observations of instantaneous ice motion, it will be necessary to generate samples of ice motion several times during a day. The ability to achieve such sampling will be easier at high latitudes where there is frequent revisit, but at lower latitudes (i.e. mid-latitude regions of sea ice, such as Caspian Sea), this will be harder.

It may be that Wavemill used in conventional SAR mode would be able to contribute to mapping of the mean sea ice motion field, or alternatively simply that other sensors would cover this application adequately. SAR constellations (e.g. Cosmo-Skymed) are particularly suited to robust and effective mapping of sea ice motion with temporal resolution of the order of daily. Sea ice motion derived from cross-correlating successful SAR images has also been used as the basis for Lagrangian mapping, providing motion updates over the revisit period of the satellite (e.g. in the case of Radarsat-1 from 1996, with revisit interval of 3 or 6 days). The divergence or convergence of the Lagrangian vectors can then be used to identify new leads or areas of pressure ridge formation. If the ice motion is tracked and monitored carefully in a database, and an ice growth model is used along with estimates of freezing degree days, then it is possible, making certain assumptions, to generate estimated sea ice thickness histograms [12]. SAR imaging modes that have contributed to Lagrangian tracking of this nature are generally Scansar with swaths of ~400km or more, providing 3 day coverage of the Arctic. Narrower swaths from single platform missions increase the revisit period, which reduces the value of the application as well as increasing the demands on the algorithm.

A second application which is not identified in the formal requirements in Table 2 is to characterise the random walk component of ice motion as this would provide useful insight into high frequency dynamic processes that can reflect the ice rheology as well as detailed meticeocean interactions. This would be innovative, but again the value of this would depend strongly on temporal-spatial sampling. Currently, buoys provide high frequency (Lagrangian) sampling of ice motion, which can be compared to reanalysis winds to determine if ice model rheology is optimised. Wavemill could be used to augment the International Arctic Buoy Program, and would provide additional coverage in the Southern Ocean also, which is covered by a very limited of buoys. Although no formal requirement has been provided, Ridley (personal communication, 2014) suggests that instantaneous motions at 3 hour intervals would be useful for pack ice (in terms of sampling inertial tidal component of motion as well as convergence and stress), while in the marginal ice zone such an interval would sample synoptic changes (and the marginal ice zone is not sampled well by buoys). Wavemill would not achieve this level of temporal sampling, so its value would largely be in augmenting buoy observations rather than replacing them. It may be that the combination of spatial component of instantaneous motion from Wavemill and the temporal component of near-instantaneous motion from buoys could be combined to elucidate the high frequency behaviour of sea ice, particularly in the Arctic pack.

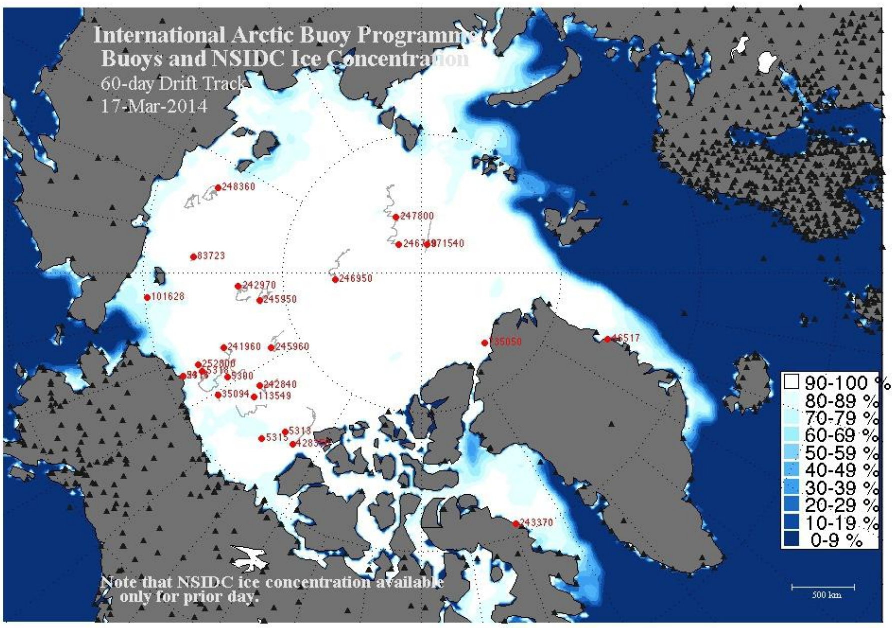

Figure 9. International Arctic Buoy Program 60 day drift tracks from March 2014 ([13]).

It would need to be established if the along-track baseline could be optimised for sea ice motion (the optimum value may be different from that of open ocean), and also whether there would be sufficient precision in the direction (requirements for the latter being curiously absent from some key studies).

4.1.4. Other sea ice parameters

Wavemill may be used as a conventional SAR (single look ~50m resolution), in which case it can contribute additional sampling to more traditional parameter estimations including ice extent, ice concentration, melt onset and ice classification. Passive microwave sensors are a spatial resolution of 6km or coarser have traditionally been used to provide daily updates of ice concentration, with some patchy success in using the same sensors to observe melt onset and ice type (classification) and Ku band scatterometers (NSCAT and Seasat) have also been used to provide information. Typical challenges include ambiguities between water on sea ice, and water between sea ice (biasing ice concentrations), while sensitivity to the snow surface and atmospheric conditions (depending on frequency), act to disturb the ability to generate robust ice classifications (e.g. first-year vs. multi-year ice). For **discriminating between ice and open water** as a conventional SAR, Wavemill will have similar performance to that of lower frequency SAR systems. At 30° incidence angle in particular, it will suffer from ambiguities introduced by open water backscatter variations at different wind speeds. At 20°, there is less ambiguity because most wind speeds will generate higher open water backscatter. Dual HH and VV polarisation would be important in assisting with ice-water discrimination at 30° incidence angle (dual co-cross polarisation would be much more useful). At C band, as the incidence angle increases, the ratio VV/HH is highest for open water [14], with the ratio being particularly useful above about 35° (it may well be different at Ku band)[2]. A similar trend would be expected at Ku band, though the threshold incidence angle is probably different. At 20° incidence angle, there is less need for dual polarisation because of the much reduced ice-water ambiguity.

For **ice type mapping**, Wavemill operating as a conventional imaging SAR at Ku band would have slightly subdued, but still adequate capabilities for discriminating first-year and multi-year sea ice compared to X and C band SAR systems, as demonstrated by Ku band scatterometers and airborne observations. For mapping of more detailed ice types, including young and new ice, it would be worth considering the more sophisticated capabilities of Wavemill, with its combination of dual co-polarisation (and perhaps interferometric coherence) at Ku band, to resolve some of the ambiguities faced by more traditional sensors in discriminating certain basic ice types (e.g. frazil from older ice), although there is little if any information at Ku band. The coherence, for example, might be a discriminator between older and younger ice types. However, this is speculative and would require research. For ice type mapping, there is an advantage to penetration to the ice-snow interface, which is likely to be better at 20° than 30° incidence angle, though it is not clear the extent to which this would be important.

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[2] Much sea ice will have a co-polarisation ratio of approximately 0 dB at C band, while open water has a ratio of 2 dB or higher at incidence angles above 35° [14]

Given the operating frequency and incidence angles of Wavemill, it is expected that it will provide useful information on **snow depth on sea ice** (or SWE). Experimental work, plus modelling, has indicated that Ku band backscatter is sensitive to snow thicknesses on sea ice up to about 5cm, with backscatter being larger for snow-covered rather than bare ice. The processes governing scattering from snow on sea ice are very different from snow on land, as in the case of the former the snow cover insulates the underlying ice with a concomitant impact on temperature and brine content of the surface layer of the sea ice. Thus, the impact of varying absorption through the snow cover as a function of its depth may be subordinate in influence on the backscatter to insulation-related changes in the scattering properties of the snow-ice layer brought about by changes in snow depth. This is not fully understood, but it explains why sensitivity to, and detectable range of, snow depths is different for snow on sea ice from terrestrial snow cover. The sensitivity to snow depth appears to be greatest over smooth sea ice. As in the case of ice type mapping with Wavemill, it could be productive to investigate the extent to which dual polarisation (and perhaps interferometric coherence) could be used to enhance snow depth sensitivity. In any event, a dual polarimetric Ku band SAR mission is likely to be of significant value and unique for mapping snow on sea ice.

A fundamental requirement for **iceberg detection and monitoring** is a spatial resolution of the order of 10m, which rules Wavemill out for routine observations. However, there may be some value to Wavemill in the Southern Ocean where icebergs can be much larger. Icebergs classified as “Very Large” (greater than 200m in dimension) are the largest category defined for the North Atlantic by the International Ice Patrol, and so Wavemill is likely to have limited utility for iceberg detection in the northern hemisphere. In the southern hemisphere, the Australian Antarctic Program has seven categories covering the Southern Ocean which include categories 5 (0.8 to 1.6km in dimension), 6 (1.6 to 3.2km) and 7 (>3.2km). For these largest size categories of icebergs, it may be possible to observe their motion using Wavemill, but the specific trajectories can be observed from repeat observations from a wide range of imaging satellite missions, including Wavemill itself. The very largest tabular icebergs (such as those reported in the press), of some 15km in size or larger, could have mass estimated using Wavemill observations, via their height (their height to draft ratios are typically 1:5) should topographic observations be available from Wavemill. Therefore, Wavemill may have some value for detecting and monitoring the trajectories of large tabular icebergs in the southern hemisphere, which represent a significant component of ablation from the Antarctic ice sheet and which can ultimately spawn large numbers of smaller icebergs well away from the Antarctic continent that may pose a threat to shipping, but for the vast majority of icebergs, its main role is likely to be that of a supporting mission.

It is also important not to overlook the benefits of observing **oceanographic parameters** within, and around, the ice margin, including currents. This would be of particular benefit for helping to understand ice-ocean interaction involved in the formation and maintenance of polynyas, which are biologically very productive areas. This is also important for the marginal ice zone, where monitoring of sea ice is much more valuable if carried out alongside the monitoring of oceanographic parameters.

4.1.5. Summary

Measurement need	Possible Wavemill products	Synergies with other sensors	Preferred configuration						Wavemill Challenges	Potential role of Wavemill
			Polarisation		Incidence angle		Sampling[1]			
			HH or VV	HH+VV	20°	30°	Dual swath 200km (assumed resolution)	Wide swath >>200km (assumed resolution)		
Ice edge and concentration	Ice / open water	Other sensors to help resolve ambiguities and enhance spatial-temporal sampling	✓	✓✓	✓✓	✓	✓ (100m)	✓✓ (<1km)	Open water ambiguities for particular wind speeds; ambiguities in summer and in marginal ice zone	Supporting mission
Leads and polynyas							✓✓ (100m)	✓ (<1km)		
Ice type classification	First-year / multi-year ice	Augment lower frequency SAR sensors	✓	✓✓	✓	✓✓	✓ (100m)	✓✓ (<1km)	Sensitivity to surface roughness; sensitivity to overlying snow cover	Supporting mission
	Thin and young ice detection	All	✓	✓✓	?		✓✓ (100m)	✓ (<1km)	Thin ice is transient; temporal revisit may limit utility	Experimental
Ice motion	Mean motion field	Passive microwave, scatterometry, SAR, radiometry	✓	✓	✓	✓	✓✓ (1km)	✓ (<25km)	Achieving temporal and spatial resolution	Supporting mission
	Near instantaneous ice motion field	Buoys	✓	✓	?		✓✓ (1km)	✓ (<25km)	Number of revisits per day; directional precision	Experimental
Ice thickness	Sea ice freeboard converted to thickness	Altimeters for mean sea surface elevation in leads; passive microwave or Wavemill for snow cover	✓	✓	✓✓	✓	✓✓ (15km)	✓ (<25km)	Sufficient vertical precision over 25km; influence of snow cover	Topographic mode no longer planned
Snow water equivalent	Snow depth	Passive microwave for independent estimates of snow depth	✓	✓✓	✓✓	✓	✓ (1km)	✓✓ (<5km)	Sensitivity to the range of snow depths; influence of underlying ice	Possible primary mission
Melt onset and duration	Melt onset date; ablation state	Other SAR data	✓	✓✓	?		✓ (1km)	✓✓ (<10km)	Ablation state is speculative	Supporting mission
Icebergs	Iceberg freeboard and thickness	Altimetry	✓	✓✓	✓✓	✓	x (15km)	x (>15km)	Spatial resolution rules out all but largest bergs	Topographic mode no longer planned
	Iceberg detection and motion	Other SARs to track major icebergs	✓	✓✓	✓	✓✓	✓ (1km)	x (>>1km)		Supporting mission

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[1] Assumed 100m ≥ 4 looks for image products

Table 4. Potential role of Wavemill in marine ice observations (✓✓✓ = required; ✓✓ = preferred; ✓= adequate; x=insufficient; ? = preference unknown).

4.2. Land Cryosphere

4.2.1. Gaps

Key gaps in relation to monitoring the land cryosphere (relevant to microwave observations) can be identified as follows:

Vertical sampling. Snow is a penetrable medium to radar, but low radar frequencies penetrate more than higher frequencies, so different frequencies are required to sample different depths in the snow and ice. In the case of the ice sheets (and to lesser extent, ice caps and glaciers), different depths correspond to very large differences in the age of the sampled ice and hence cumulative "historical" time period sampling of the sensor. Civilian satellite SAR sensors have to date operated between L and X band; lower frequencies are required to sample deep into the interior of ice sheets while higher frequencies (Ku band in particular) are required to sample the surface layer, including recent snow accumulation on ice sheets and glaciers, and terrestrial snow cover on land.

Spatial-temporal sampling. Terrestrial snow changes in terms of both thickness and extent very quickly, and would benefit from both relatively high spatial resolution and frequent observation updates that can capture these rapid changes. Because current spaceborne sensors are not optimised for snow observations, terrestrial snow cover is not well observed, at least not sufficiently for water resource prediction, nor to connect snow cover well into regional numerical weather prediction.

Figure 10. Snow cover is particularly poorly monitored, yet is a highly dynamic and critical factor in northern hemisphere climate, as well as a range of operational applications.

Table 5. Land Ice observations status and gaps, with reference to utilisation needs (Table 1).

Parameter	Utilis'n Need	Status	Gap
Surface topography (+changes) of mountain & outlet glaciers, ice caps	1,8	Global data bases on surface topography of glaciers: SRTM (only 56°S-60°N; in 2001) and ASTER stereo; std. error > 10 m	Accuracy needs: ≤ 1m (goal), ≤ 5m (threshold), DEM grid 30 m not achieved with present sensors
Surface topography (+changes) of ice sheets	1	Regular repeat observations by radar altimetry (Cryosat-2); laser altimetry also planned (icesat-2)	Accuracy needs ≤ 10 cm (annually) compromised by uncertainty of radar signal penetration changes over time. Significant differences between radar and lidar.
Surface velocity fields of glaciers and ice streams	1,8	Interferometric and feature-tracking techniques well established; mapping of Antarctica and Greenland achieved.	Application of repeat-pass INSAR systems constrained by temporal decorrelation. Amplitude correlation less accurate and requires surface features which only present around the ice sheet margins.
Snow accumulation on ice sheets	1,4,9	Local/regional maps of snow accumulation are produced from scatterometer and multi-spectral microwave radiometer data	Snow accumulation algorithms are required for both the dry snow and percolation zones. Problem of restricting sampling to recent (decadal) accumulation layers.
Snow water equivalent (SWE) on land	4,5,7-9	Low spatial resolution SWE maps available from radiometry, but at comparatively large uncertainty.	Currently, no high frequency (Ku) band SAR mission availability with strong sensitivity to terrestrial snow cover.
Precise surface topography of permafrost regions	5,7	Data base on surface topography at high latitudes: ASTER stereo; std. error > 10 m	Accuracy requirements not achieved with present sensors
Freeze/thaw cycle of soil	4,5,8,9	Radiometry and scatterometer (separately) applied for regional studies	Improvements for freeze/thaw monitoring expected from synergy of active/passive MW systems. Exact temporal coincidence needed
Snow and ice facies distribution	1	SAR and scatterometers have been used on larger ice bodies	Validation is limited

4.2.2. Elevation estimation: land ice elevation

Ice sheets are contributors to global sea level and much recent work has focused on the extent to which the ice sheets are current contributors to sea level rise, and the extent to which they are potentially unstable in the context of a changing climate and therefore a potential cause of a major increase in sea level in the future. Recent work shows increasing concern over the stability of the West Antarctic ice sheet [15], and in Greenland where summer melting has been reaching new elevations. Factors involved include increases in basal melting of ice shelves caused by warmer water circulating beneath, enhanced summer melting percolating to the base of ice and lubricating flow and possibly also changing surface albedo caused by dust.

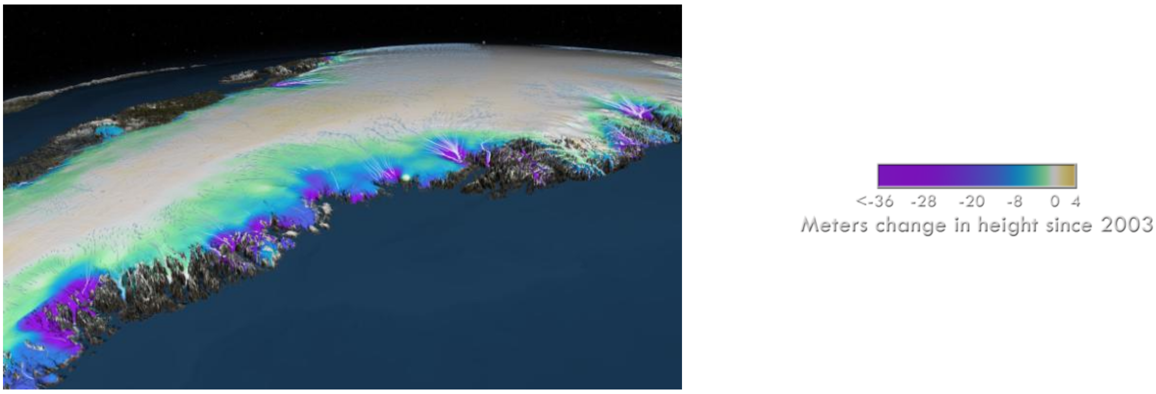

Figure 11. Surface elevation change over the Greenland ice sheet, 2003-2012 (NASA's Goddard Space Flight Center Scientific Visualization Studio).

There is a long heritage of using microwave sensors to monitor **terrestrial ice sheet elevations**. Altimeters (both radar and laser) have been used since Seasat in 1978 to calculate surface elevation change. The record is being continued with Cryosat-2 and (in 2017) Icesat-2. Unfortunately, while Wavemill could potentially contribute to this, the spatial resolution requirements are of the order of 30m (elevation) to 100m (elevation change). Wavemill would require a spatial resolution of this order, at appropriate vertical resolution, to provide some useful support to observations in particular around the highly dynamic peripheral regions of the ice sheets.

It is also useful to obtain elevation information in relation to **seasonally frozen river and lake levels**. Ice cover plays a fundamental role in the biological, chemical, and physical processes of arctic freshwater systems. In particular, freshwater ice is integral to the hydrological cycle of northern systems. The duration and composition of lake ice, for example, controls the seasonal heat budget of lake systems. This in turn determines the magnitude and timing of evaporation from these systems, ranging from small ponds to large lakes; storage levels in the latter also control the flow of some of the major Arctic rivers, such as the Mackenzie. Similarly, river ice has a significant influence on the timing and magnitude of extreme hydrological events, such as low flows and floods. Many of these hydrological events are due more to in-channel ice effects than to landscape runoff processes. The levels of sub-Arctic lakes and rivers will be impacted by changing snow cover, glacier melt and permafrost. If discharges change significantly, then there will be an important change in freshwater input to the Arctic Ocean. Topographic information is also of value for mapping of permafrost topography. This is subject to change as a result of systematic changes in mean air temperatures, which can have repercussions for man-made infrastructure stability. Lake levels, river ice and permafrost all have relatively demanding elevation precision requirements, but in the context of Wavemill, even more demanding horizontal resolutions of the order of tens of metres. Wavemill is now unlikely to provide a topographic measurement mode.

4.2.3. Motion estimation: Glacier and ice sheet motion

The motion of ice from the interior of the ice sheet to the margins, and hence into the ocean, can be highly variable with ice stream fluxes changing over time. Any assessment of the stability of the ice sheets and their current mass balance needs to quantify these fluxes of ice and their variability, and link these to other factors such as changes to backpressure from grounded ice, basal friction, etc. The motion of ice ranges up to about 1km/yr (~0.003 cm/s) so is orders of magnitude slower than sea ice, even in the most dynamic locations.

Wavemill can be used to generate both along track and repeat pass estimates of ice motion, in much the same manner as conventional SAR systems at lower frequency, with the qualification that at Ku band the signal will be more sensitive to the surface roughness, which is subject to influence by wind and solar conditions, which may adversely impact on temporal coherence. The spatial resolution needs to be the order of tens of metres, but if there is some flexibility in the temporal and physical baseline, then it is possible that Wavemill could support other satellite missions and be able to optimise the sampling for the local velocity of the ice. However, the spatial resolution would need to be sufficient to provide the spatial details, particularly in the highly dynamic marginal areas of the ice sheets, and 1km spatial resolution would be limiting in this respect.

4.2.4. Terrestrial snow water equivalent

Terrestrial snow cover is the most rapidly varying cryospheric variable on the surface of the earth. Snowfall and snow cover play key roles with respect to feedback mechanisms within the climate system (albedo, runoff, soil moisture, and vegetation) and are important variables in monitoring climate change. About one third of the Earth's land surface is seasonally snow-covered and seasonal snow melt is a key factor in runoff regimes in middle and high latitudes as well as in many other high altitude locations. Snow depth and snow-cover duration affect the permafrost thermal state, the depth and timing of seasonal soil freeze/thaw /break-up, and the melting of land ice and sea ice. Snow cover represents an important element of the hydrological cycle and has been implicated in many mid to high latitude climate processes. Snow also has more immediately practical importance as a source of freshwater for many semi-arid areas, where spring melt provides an essential resource.

Wavemill, with a Ku band operating frequency, has potential value to snow monitoring, because the penetration depth is reduced significantly over that of lower frequencies, so that for terrestrial snow, there is sensitivity to dry snow cover up to about 2m thick at 30° incidence angle [7]. This has been assessed in some detail in support of the candidate Earth Explorer mission, CORE-H2O [16]. Yueh et al. [17] found a 0.2 to 0.4 dB increase in backscatter for every 1cm SWE accumulation for sage brush and agricultural fields at Ku band. Experiments indicate a strong sensitivity of co-polarisation backscatter coefficient to snow water equivalent up to at least 100mm (extended by use of cross-polarisation), with larger incidence angles providing greater sensitivity (30°+). Dual co-polarisation was not shown to be particularly useful for snow mapping (in contrast to dual co and cross-polarisation, [17]). Relatively high spatial resolution is required to “see” the snow cover through gaps in trees. One of the constraints that CORE-H2O would have to operate under would be bias introduced by topography; local incidence angle has a major impact on apparent snow depth and can bias SWE estimations significantly. If Wavemill was able to combine backscatter (including polarisation ratio) with information on slope, this would help to compensate for slope-induced error in SWE estimations (the local incidence angle being effectively modified by the slope). Ulander [18] suggests a technique whereby INSAR can be used along with backscatter to directly correct for local slope in retrieving snow parameters, which is worth considering in the context of Wavemill.

The main challenge in the application of Wavemill to terrestrial snow mapping lies in the temporal resolution. A temporal sampling of 10 days would be marginal in utility (6 days is specified as the threshold requirement) but would be better than this at higher latitudes due to orbit convergence, where much of the snow cover is found.

4.2.5. Ice sheet snow accumulation

On the terrestrial ice sheets, frequencies lower than Ku band tend to penetrate, in effect, distances that correspond to centuries or millennia of history, rather than more contemporary conditions that are of interest for current ice sheet mass balance. Wavemill could potentially provide information on current climatological snow accumulation rates that are relevant to current global circulation models.

The penetration depth of Ku band over dry polar firn is of the order of 8m, so the majority of backscatter comes from the near surface layer, but the signal is impacted strongly by the diagenetic zone that is being imaged. The dry snow zone does not melt in summer, and so consists of internal layers and compacted snow grains. The percolation zone, at lower altitudes, consists of buried ice pipes and lenses that are formed from refrozen melt water during the summer, and which are strongly reflective at most radar frequencies.

Over the dry snow zone it has been demonstrated that, at Ku band, there is both an influence on the backscatter from surface roughness, and from the internal properties of the snow, with evidence that the former is related to katabatic wind direction in some conditions, while the latter can be related to snow accumulation rate (via influence on internal layer density and snow grain size). Ledroit et al. [19] found, using Ku band scatterometer data, a correlation between surface roughness parameters and backscatter such that it was possible to infer katabatic wind processes from the scatterometer data, but above about 25° the internal properties of the snow also impact on the signal. Despite an influence of surface roughness impacts, the experience from Ku band scatterometry suggests that it should be possible to estimate mean multi-year snow accumulation rates from Wavemill (i.e. integrating across multiple annual snow accumulation layers, equivalent years to decades of snow accumulation, depending on snow accumulation rate), with the added advantage of enhanced spatial resolution, particularly at higher incidence angles. For the percolation zone, annual snow accumulation is likely to be estimated via the influence of the snow cover on the backscatter from the buried pipes and lenses [7]. A multi-sensor approach can assist with generating a more robust inversion process for snow accumulation rate, but the impact of different sensors on different vertical sampling of the snow needs to be taken in account [20]. Nevertheless, there is important value in a Ku band relatively high resolution imaging sensor for estimating snow accumulation over the ice sheets.

4.2.6. Summary

Measurement need	Possible Wavemill products	Synergies with other sensors	Preferred configuration						Wavemill Challenges	Potential role of Wavemill
			Polarisation		Incidence angle		Sampling[1]			
			HH or VV	HH+VV	20°	30°	Dual swath 200km (assumed resolution)	Wide swath >>200km (assumed resolution)		
Precise surface topography (changes) of ice sheets, mountain glaciers, ice caps, and outlet glaciers of ice sheets	Surface elevation Surface elevation change	Radar altimetry, laser altimetry, INSAR	✓	✓	?		x (15km)	x (>15km)	Adequate spatial resolution	Topographic mode no longer planned
Surface velocity fields of glaciers and ice streams	Surface velocity	InSAR, SAR feature tracking	✓	✓✓	?		x (1km)	x (>1km)	Adequate spatial resolution	Supporting mission
Snow accumulation on ice sheets	Snow accumulation in relation to contemporary (decadal) conditions	Scatterometry and passive microwave can be used for longer term accumulation rates	✓	✓✓	✓✓	✓	✓✓ (1km)	✓ (>1km)	Surface-volume scatter ambiguity; definition of depth (~time period) sampling; algorithms for dry zone vs percolation zone	Possible primary mission
Terrestrial snow cover	Snow depth SWE	X band SAR for thicker snow cover; scatterometers and passive microwave for coarser resolution	✓	✓✓	✓	✓✓	✓✓ (100m)	✓ (<500m)	Temporal resolution; vegetation, snow melt, slope impact, covering range of snow depths	Possible primary mission
Permafrost changes	Surface elevation change	Other INSAR missions	✓	✓✓	?		x (1km)	x (>1km)	Insufficient spatial resolution	Topographic mode no longer planned
Freeze/thaw cycle of soil	Surface changes in relation to freeze/thaw	Other SAR missions; optical sensors sensitive to vegetation (NIR)	✓	✓✓	?		✓✓ (100m)	✓ (<500m)	Unproven	Experimental
Snow and ice facies distribution (diagenetic zones)	Snow and ice facies distribution (ice sheets)	Multi-frequency SAR observations may be useful for different depth sampling	✓	✓✓	✓✓	✓	✓✓ (100m)	✓ (<500m)	Insensitive to buried percolation features	Supporting mission

Table 6. Potential role of Wavemill in land ice and snow observations (✓✓✓ = required; ✓✓ = preferred; ✓= adequate; x=insufficient; ? = preference unknown).

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[1] Assumed 100m ≥ 4 looks

5. Conclusions

The cryosphere is an important application for any earth observing technology because it is considered likely to play a critical role in amplification of CO_2-induced global warming and can have a major impact on global sea level. In addition, operational interest in the Arctic is adding to scientific interest as summer sea ice has retreated opening up routes for navigation and resource exploitation. Wavemill offers several potential benefits to the broader earth observing network as follows:

- Novel estimation of high frequency sea ice motion, currently not sampled by any spaceborne sensors;
- Sampling of the thin surface layer of the cryosphere facilitated by the high operating frequency (Ku band), in particular snow cover, which is inadequately sampled by existing spaceborne sensors.
- Observations of poorly sampled dynamic processes, particularly in regard to the marginal sea-ice zone and terrestrial snow cover;
- Complementary observation capabilities to many existing and planned satellite missions, including altimeters and SARs, that would enhance the interpretation of observations from those sensors.
- The ability to observe currents and other oceanographic parameters in polar waters, in polynyas and larger leads, providing insight into ocean-ice interactions within pack ice.
- Speculatively, some interesting possibilities regarding the synergistic use of multiple parameters from Wavemill that could result in innovative products, for example in relation to retrieval of SWE using local slope.

Some key issues for cryosphere applications include the following:

- The temporal sampling is critical for terrestrial snow and sea ice applications and needs to be sufficient to capture dynamic processes, with ~daily revisit requirements for many parameters. In some cases it may be possible to achieve higher revisits by combining missions where Wavemill itself does not achieve the required temporal revisit, but this is not possible for the innovative Wavemill products.
- Work with Core-H2O was important in establishing the potential of Ku band to many cryospheric applications, but focused more on terrestrial than marine applications. This work forms a good staging post for continuation of assessment of how Wavemill may be applied to cryospheric applications, once the design becomes fixed (and assuming that cryospheric applications are not driving the design of the mission).
- For many cryosphere applications at Ku band, there is insufficient data to suggest whether 20° or 30° incidence angle is strongly preferred. Exceptions include terrestrial snow cover, which appears to have greater sensitivity at 30° under freezing conditions, and sea ice - water discrimination, which is less ambiguous at 20°, but which can be compensated to some degree by the availability of dual polarisation at 30° incidence angle.

- Dual polarisation is useful for a number of cryosphere applications, including sea ice water discrimination at higher incidence angles. It is likely to be helpful for most cryosphere applications at 30°, although there is little clear evidence of the degree of utility at Ku band in general because of a lack of data (terrestrial snow has more data at Ku band, but also provides little evidence for additional value from dual polarisation). In any event, dual polarisation is likely to have limited utility at 20° incidence angle.
- Wide swath imaging (>>200km) can enhance the temporal revisit, which may be very important for sea ice and terrestrial snow applications, but in a trade-off with spatial resolution, there is not an obvious advantage to many cryospheric applications. For applications that do not depend on rapid (~daily) revisit (e.g. over land ice), it is more important to retain relatively high spatial resolution. For marine and terrestrial snow applications, having the flexibility of a wide swath mode would be useful in order to adjust to temporal-spatial sampling to particular cryospheric applications and areas, but in general the high spatial resolution is important to retain. Analysis of the Wavemill orbit to provide information on revisits would be very useful in order to confirm the merits or otherwise of a wide swath imaging mode.

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