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SUMMARY OF CURRENT ICE CHARACTERIZATION RESEARCH: NORWAY/RUSSIA/EUROPE

Prepared for the
Technology & Operations Subgroup

On March 27, 2015, the National Petroleum Council (NPC) in approving its report, *Arctic Potential: Realizing the Promise of U.S. Arctic Oil and Gas Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Technology & Operations Subgroup. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 46 such working documents used in the study analyses. Appendix D of the final NPC report provides a complete list of the 46 Topic Papers. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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Topic Paper (Prepared for the National Petroleum Council Study on Research to Facilitate Prudent Arctic Development)		
5-5	**Summary of Current Ice Characterization Research: Norway/Russia/Europe**	
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SUMMARY

The purpose of this paper is to identify research that has been recently / is currently in progress in Europe and Russia that pertains to the measurement and characterization of ice. As some of these results may be bound by confidentiality, a brief overview of program goals and objectives will be provided where possible.

The approach taken in this paper is to identify emerging trends and important new technologies for measuring and characterizing ice rather than simply listing every European research project in progress today. Citations will be provided to support the stated trend where possible but they should only be viewed as representative, not exhaustive.

Characterizing the Ice Environment to Support Drilling

In 2008, the United States Geological Survey (USGS) indicated the potential presence of 30% of the world's undiscovered gas and 13% of the world's undiscovered oil north of the arctic circle, mostly offshore under less than 500 m water depth [Gautier et al., 2009]. These areas include dynamic ice features that need to be effectively managed, mainly through towing for icebergs and floe size reduction for sea ice, in order to protect drilling facilities. With systematic ice / iceberg management typically taking place as close as possible to keep facilities within managed zones (i.e., < 6 hours updrift for seas ice management), any failure of ice management will not provide enough warning time to execute managed suspension of operations and disconnection, which notionally requires about 1 day [Hamilton et al., 2013]. Consequently safe, wide area coverage, reliable, and continuous characterization of the dynamic sea ice environments in the far-field (i.e., >24 hours) is essential for safe and economic floating drilling operations [Haugen et al., 2011]. Given the dynamic nature of ice in the arctic, reliable ice cannot be achieved except through a multi-sensor / multi-platform operation.

An ice characterization system would include space- / air- / ship-borne systems and potentially subsea reconnaissance platforms such Autonomous Underwater Vehicles (AUV), Ice Profiling Sonars (IPS) and Acoustic Doppler Current Profiler (ADCP), as needed. On-ice coring and drilling are mature technologies that will NOT likely be used to support active drilling operation and therefore will not be discussed in detail in this paper.

For sea ice, and in order to reliably characterize an ice environment, information about ice edge, concentration, surface roughness, drift speed, thickness are needed. In addition, ice temperature and salinity provide insight into how manageable an ice feature is.

This paper focuses on presenting examples of recent arctic characterization research activities in Europe and Russia with special focus on tools that are less susceptible to weather constraints (i.e., radar-based rather than optical tools) and can effectively cover large areas. Key areas are:

- Space borne Arctic Characterization
- Airborne Arctic Characterization
- Ship borne Arctic Characterization
- Subsea Arctic Characterization
- Ice drift monitoring and forecasting

It is to be mentioned here that one of the most significant recent arctic research efforts in Europe is the formation of the Sustainable Marine and Coastal Technology Center (SAMCoT) which started in 2011. SAMCoT started with funding from the Research Council of Norway and is headquartered in the Norwegian University of Science and Technology (NTNU) with expectation to operate until 2019. SAMCoT's main focus is conducting research in support of arctic oil and gas development. According to SAMCoT's 2013 annual report, SAMCoT has several partners representing Oil and Gas operators, contractors, universities and governmental agencies.

SAMCoT mainly has six active research areas which are:

1- Data collection and process modeling: focus on sea ice, icebergs, and permafrost data acquisition and analysis.
2- Material modeling: focus on developing constitutive / numerical models to characterize ice properties and drift behaviors.
3- Fixed structures in ice: focus on characterizing sea ice – structure interactions.
4- Floating structures in ice: focus on developing analytical and numerical models to improve the prediction of sea ice and iceberg loads on floating structures.
5- Ice management and design philosophy: focus on enhancing design philosophy considering use of ice management means and disconnection/reconnection capabilities.
6- Coastal technology: focus on developing innovative methods to use local materials for building erosion protection structures.

Since its formation, SAMCoT has been active in conducting comprehensive arctic research to address problems in the above mentioned six areas. Table 1 provides a summary of SAMCoT's 2013 research activities. Further information can be obtained from SAMCoT's webpage.

Table 1. Summary of SAMCOT research activities in 2013

Research Area	2013 Activity
Data collection and process modeling	Data collection of sea ice properties and ice loads on coastal structures in the fjords of Spitsbergen and the central western Barents Sea. Tests included uniaxial compression and flexural strengths tests in addition to mathematical 3D modelling to improve data interpretation. Studies in the Barents Sea included sea ice drift and ridge morphological and strength properties, which contribute to statistics important for structural design.
Material modeling	Ice rubble characterization numerically and experimentally and also frozen soils numerically and theoretically. Experimental field and laboratory studies have been carried out in addition to FEM / DEM simulations to characterize ice rubble's mechanical behavior.
Fixed structures in ice	Initiated work on sloping structures and the estimation of probabilistic ice actions based on measurements and numerical modelling.
Floating structures in ice	Continue to focus on improving sea ice and iceberg load predictions through developing theoretical and numerical models that account for breaking and splitting of ice as well as hydrodynamic interaction. These models have been further enhanced through SAMCoT's field data collected.
Ice management and design philosophy	Stewarded a major research cruise to the Greenland Sea with the icebreaker Oden where focus was monitoring the drift of icebergs in broken ice and thus developing a realistic approach to the modelling of iceberg towing in pack ice. In addition, ice-management trials were carried out supported by several detection technologies.
Coastal technology	Focus was collecting field data from thermistor strings and monitoring erosion processes at Vestpynten (Longyearbyen) in addition to Varandey and Baydaraskaya Bay. Also, coastal erosion protection was studied in using geosynthetics and locally available materials.

Space borne Arctic Characterization

Scope

Satellite remote sensing, especially in the microwave spectrum, has been widely used in ice characterization for decades, since it can collect ice-related data over vast regions in a regular, repetitive, systematic, and cost-effective fashion. With the rapid development and enhancement of remote sensing and satellite technologies, a wide variety of ice associated parameters can be directly or indirectly characterized. Moreover, new assets such as CryoSat-2, TanDEM-X and Sentinel-1A with innovative technologies that are being designed and launched can enhance arctic characterization. The next section will introduce new developments in satellites that can enhance ice characterization.

In addition to the conventional satellite systems, small satellite systems can prove powerful and cost-effective tools to react flexibly to earth observation requirements. The motivation of most small satellite missions is to make remote earth observation more affordable to a customer and to open application-oriented missions.

First, small satellite system can provide good quality and timely geo-referenced information. The spatial and spectral resolution of small satellite data is close or equivalent to that of conventional satellites, while the rich constellations give small satellite systems the unique possibility of observing various dynamic phenomena such as ice monitoring through their ability of increased temporal resolution. On the other hand, most of the small satellite systems utilize off-the-shelf technologies with certain level of modification, which not only significantly reduces the development costs, but makes the missions focused on specific physical phenomena. This feature offers an opportunity for organizations with a modest research budget and little or no experience in space technology to enter the field of space-borne earth observation for specific applications. Therefore, greater involvement of local and small industry has been observed compared to the applications of conventional satellites.

Moreover, the trend to small satellites has been supported by the improvements in diverse fields of technology including optics, electronics, signal processing, and spacecraft launching and controlling. The current capabilities and performances of small satellites have been significantly enhanced, allowing extended applications of both passive optical and active microwave systems. Key applications have been identified on disaster monitoring, forestry, maritime mode, oil spill, and ice monitoring. The following section will introduce several small satellite systems with special emphasis on ice monitoring.

As mentioned above, numerous satellite remote sensing missions with various earth observation purposes have been planned in Europe, some of which have been actually executed. These missions can potentially be beneficial to ice monitoring as they:

1- Provide significant shorter revisiting period over the interested Arctic regions though the rich formation of constellation, such that the improved temporal resolution of image acquisitions will enable continuous monitoring on dynamic ice conditions.
2- Offer high flexibility in choosing desired imagery acquisition modes whose combinations of spatial resolution and swath width are appropriate and optimized for various specific ice monitoring objectives.
3- Enrich the existing satellite remote sensing data services with reduced costs so as to mitigate the conflict and priority issue of imaging requests placed by various industries and parties.

4- Potentially allow the estimate of specific physical features of sea ice and glacier ice such as ice type, ridging, leads, and low resolution thickness estimates through fusion of the data collected in multiple radar frequencies and polarization.

Examples

CryoSat-2

As part of the European Space Agency's (ESA's) Earth Explorer mission, CryoSat-2 was launched in April 2010. This satellite replaces the original CryoSat, which was lost owing to a launch failure in October 2005. The ESA's Earth Explorer mission is dedicated to precise monitoring of the changes in the thickness of sea ice floating in the polar oceans and variations in the thickness of the vast ice sheets that overlie Greenland and Antarctica.

The primary payload of CryoSat-2 is a Ku-band SAR/Interferometric Radar Altimetry (SIRAL) designed to measure the ice-sheet elevation and sea-ice freeboard (Table 2). SIRAL is the first altimeter to operate in SAR and SAR Interferometry (SIN) modes, which generates a burst of radar pulse at much shorter interval less than 50µs. using these two modes simultaneously has proven to significantly reduce the noise level and achieve as accurate as 1.6 cm vertical measurement resolution with 1 month temporal sampling rate over Arctic sea ice.

Table 2. SIRAL characteristics (CryoSAT-2 Handbook)

Operating Frequency	13.575 GHz (single frequency Ku-band Radar)
Pulse Bandwidth	320 MHz (40 MHz for tracking only in SIN mode)
PRF	1.97 KHz in LRM mode 18.181 KHz in SAR and SIN mode Coherent pulse transmission for Doppler processing
Burst Mode PRF	1.97 KHz in LRM 85.7 KHz in SAR 21.4 KHz in SIN
Pulse Duration	44.8 µs
Timing	Regular PRF in LRM mode Burst mode in SAR and SIN mode
RF Peak Power	25 W
Antenna Size	2 reflectors 1.2 x 1.1 m , side by side
Antenna Beamwidth 3(dB)	Along track: 1.08o ; Cross track: 1.2o
Antenna Baseline Length	1167.6 mm

As mentioned, CryoSat-2 measures the ice freeboard, and such measurements have been used to compute sea ice thickness and estimate the ice volume. One year after launch, ESA conducted CryoSat-2 Validation Experiment (CryoVE) in 2011, which aimed to directly validate the performance and measurements from SIRAL radar. Five experiment sites including sea ice and glacier ice conditions were selected, where the ice thickness is estimated from the freeboard measurements acquired by SIRAL. The ice thickness estimates were found generally matching with the Electromagnetic Induction measurements on level sea ice but not on deformed ice. The data set acquired in this campaign was utilized to optimize the CryoSat-2's Level 1b and Level 2 data retrieval algorithms [Skourup et al., 2011]. Moreover, research efforts have been focused on improving the accuracy of thickness estimate by introducing new filters [Giles et al., 2012]. Other potential areas of using CryoSat-2 has been focused on verifying the capability of radar altimetry's penetrating capability into snow covers by comparison to laser altimetry data [Willatt et al., 2011]. Moreover, the CryoSat-2 data in combination with the NASA's ICESat-2 data have been continuously used to monitor the sea ice volume changes.

It is to be emphasized here that thickness estimates using CryoSat-2 may not be beneficial in detecting Potentially Unmanageable ice (PUI) embedded in large floes. The issue of directly measuring ice thickness is discussed in detail later in the paper.

TanDEM-X

As part of the Interferometric SAR mission of German Aerospace Center, TanDEM-X was launched in June 2010. This satellite is an extension of the TerraSAR-X mission, which operates as a second almost identical SAR on X-band (Table 3). Flying these two satellites in a close formation with cross-track distances of 300-500m provides a flexible single-pass interferometry configuration to generate global, consistent, and high-precision Digital Elevation Model (DEM). The current data product can archive 12m posting and 2m relative height accuracy for flat terrain.

One of the mission objectives of TanDEM/TerraSAR-X constellation is to measure ocean currents and detect ice drift. Initial ice mapping using along-track interferometry was tested over the October Revolution Island, Russian Arctic [Lopez et al. 2011]. Another data sample acquired at NE Greenland in August 2010 was analyzed using baseband azimuth scaling algorithm [Scheiber et al. 2011]. This study demonstrates the potential application of interferometric radar constellations for monitoring dynamic sea ice process in the arctic, and it suggests that increased along-track baseline between two satellites will allow more accurate ice drift measurement.

Table 3. Selected parameters of TanDEM-X

System Parameter	Value	System Parameter	Value
Operating Frequency	9.65 GHz	Antenna Size (L x W)	4.8 x 0.7 m
Chirp Bandwidth	100 MHz	Antenna Tapering	Linear phase
Sampling Frequency	110 MHz	Along-track Baseline	< 1 km
Mutual Swath Overlap	> 4 km	Indep. Post Spacing	12 x 12 m
Peak Power	2260 W	Losses (atmosphere…)	3.1 dB
Duty Cycle	18%	Azimuth Processing Loss	< 1.5 dB

Sentinel

In the frame of the ESA's Global Monitoring for Environment and Security (GMES) program, a new family of missions called Sentinel is being developed for the European polar orbit satellite system. Each Sentinel mission is based on a constellation of two satellites to fulfill revisit and coverage requirements and provide robust datasets. These missions carry a range of technologies, such as radar and multi-spectral imaging instruments for land, ocean and atmospheric monitoring to achieve specific objectives (Table 4).

Sentinel-1A, the first satellite of the imaging SAR mission, was launched in April 2014. System design has been driven by the need for continuity of ERS / Envisat with improved revisit, coverage, timelines and reliability of service (Table 5). The Sentinel-1 mission is designed to work following a pre-programmed conflict-free scenario, which means there is no need to make data acquisition requests. The two-satellite constellation offers six days exact repeat based on four main operational modes (Table 6).

Before launch, an airborne campaign was conducted to assess the technical performance of Sentinel-1A SAR instrument on imaging sea ice with a special emphasis on ice type discrimination [Dierking, 2010].

Results indicate that the designed Sentinel-1A SAR instrument is acceptable for operational sea ice mapping using co-polarization imagery, but the noise level at cross-polarization is too high. Moreover, the C-band instrument provides better performance on identifying new level ice and discriminating deformed ice from level ice than L-band.

As for current status, Sentinel-1A is testing its on-orbit operational qualification, and a full operation is expected in the second half of 2014.

Table 4. Description of Sentinel Missions

Mission	Launch Plan	Payload	Description
Sentinel-1	1A: Apr. 2014 1B: 2016	C-SAR	Polar-orbiting, all-weather, day-and-night radar imaging mission for land and ocean services.
Sentinel-2	2A: Apr. 2015 2B: 2017	Multispectral Imager (MSI)	Polar-orbiting, multispectral high-resolution imaging mission for land monitoring. (Designed swath: 290 km; Designed resolution: 10 m, 20 m and 60 m)
Sentinel-3	3A: mid-2015 3B: 2017 3C: Before 2020	OLCI, SLSTR, SIRAL, etc.	Measure sea-surface topography, sea- and land-surface temperature, ocean color and land color with high-end accuracy and reliability.
Sentinel-4	4A: 2017 4B: 2019	UVN, IRS	Geostationary orbiting, atmospheric monitoring mission embarked upon a Meteosat Third Generation-Sounder (MTG-S) satellite.
Sentinel-5	5A: 2016 5B: TBD	UVN, IRS, VII, etc.	Polar-orbiting, monitor the atmosphere

Table 5. Sentinel-1A Technical Characteristics

System Parameter	Value	System Parameter	Value
Center Frequency	5.4505 GHz	Antenna Size (L x W)	12.3 x 0.82 m
RF Peak Power	4.141 kW	Azimuth Beam Width	0.23o
Incidence Angle Range	20o – 46o	Azimuth Beam Steer Range	-0.9o – 0.9o
Look Direction	Right	Elevation Beam Width	3.43o
Max. Range Bandwidth	100 MHz	Elevation Beam Steering Range	-13.0o – 12.3o
PRF range	1000 – 3000 Hz	Polarization Options	Single or Dual

Table 6. Sentinel-1A SAR Instrument Operational Modes

Mode	Access angle (deg)	Single Look Resolution (Range x Azimuth)	Swath width	Polarization
Interferometric Wide Swath	> 25	5 x 20 m	> 250 km	HH+HV or VV+VH
Wave Mode	23 and 36.5	5 x 5 m	>20 x 20 km	HH (23 deg) VV (36.5 deg)
Strip Map	20-45	5 x 5 m	> 80 km	HH+HV or VV+VH
Extra Wide Swath	> 20	20 x 40 m	> 400 km	HH+HV or VV+VH

Other Activities

A new global, operational, high-resolution, combined sea surface temperature (SST) and sea ice analysis system (OSTIA) has been developed in 2007 at the Met Office, UK. OSTIA launched a High Resolution Sea Surface Temperature Pilot Project aiming to provide daily global coverage with combined sea surface temperature and sea ice concentration product at 6 km spatial resolution [Stark et al. 2007]. This system utilizes data from a combination of infrared and microwave satellites as well as in situ measurements (Table 7).

As part of the ESA's SMOS (Soil Moisture and Ocean Salinity) mission, a multi-layer ice salinity model is established to simulate the salinity of the thin FYI based on the observations from L-band data. Since the salinity profile of thin sea ice is correlated to the ice thickness, this model is further utilized to estimate the thin FYI thickness with less than ±15% average errors [Kaleschke et al., 2010]. However, this approach is less reliable on the ice thicker than 0.5m when the surface ice salinity is less correlated to the thickness. Also within the SMOS mission, another approach characterizes the ice thickness based on surface roughness [Toyota et al., 2009]. In this study, the surface roughness is measured by L-band backscattering coefficients. A correlation between surface roughness and thickness of seasonal ice (deformed and undeformed FYI) is found. This is consistent with the fact that the development of ice thickness in the experimental region is controlled by the ridging process. However, this approach is not robust when applied to MYI, because the correlation becomes less prominent due to the refreezing process.

Table 7. OSTIA Source Data

Sensor (Platform)	Sensor Type	Resolution	Data Source	Coverage
AATSA (EnviSat)	Infrared	~1 km (swath)	ESA-Medspiration	Global
AMSR-E (Aqua)	Microwave	~25 km (swath)	Remote Sensing System	Global
AVHRR-LAC (NOAA 17 & 18)	Infrared	~1/10^{o} (gridded)	ESA-Medspiration	North-East Atlantic and Mediterranean
AVHRR-GCA (NOAA 18)	Infrared	~9 km (swath)	JPL PO-DAAC	Global
In situ salinity and temperature	Ship and buoys	In-situ	Global Telecommunication	Global
SSM/I (DMSP)	Microwave	10km	EUMETSAT OSI-SAF	Global
SEVIRI(MSG1)	Infrared	0.1^{o} (gridded)	ESA-Medspiration	Atlantic Sector
TMI (TRMM)	Microwave	~25 km (swath)	Remote Sensing System	Tropics

NovaSAR-S

NovaSAR-S is a joint technology demonstration initiative of Surrey Satellite Technology Ltd (SSTL), UK government, and EADS Astrium Ltd. The NovaSAR-S platform is based on the SSTL-300 avionics which has been implemented on NigeriaSat-2 since the launching in 2011 (Table 8). The S-band SAR instrument is Astruim's new payload design, which will provide medium resolution (6-30 m) imagery ideal for many applications including disaster monitoring, forest monitoring, land use mapping, and ice monitoring. This system can operate in four modes with different combination of resolution and swath width (Table 9).

Table 8. NovaSAR-S Specifications

Operating Frequency	3.2 GHz (S-band)
Design Lifetime	7 years

Mass	400 kg
Optimum Orbit	580 km SSO
RF Peak Power	1.8 kW
Antenna Size	3 x 1 m (Microstrip patch phased array)
Imaging Polarization	Single, Dual, Full
Payload Duty Cycle	At least 2 minutes per cycle (multiple images or single image > 800 km long)
Payload Data Memory	544 GB
Downlink Rate	500 Mbps

Table 9. Details of NovaSAR-S operating modes (based on 580 km orbit)

Modes	Swath Width	Resolution	Incidence angle	Number of looks	Ambiguity ratio
ScanSAR	100 km	20 m	16o – 30o	4	<-20 dB
Maritime Surveillance	750 km	30 m	48o – 73o	1	<-25 dB
Strip Map	15 – 20 km	6 m	16 o – 31 o	4	<-20 dB
ScanSAR Wide	140 km	30 m	14 o – 32 o	4	<-18 dB

The mission is designed to either operate independently or in a constellation to maximize imaging opportunities and data acquisition. A single satellite using the fine resolution strip map mode can revisit the same observing area twice a week, and a constellation of three can provide the data acquisition in same operational mode every 6 hours or less.

Several flight trails simulating and testing the performance of S-band SAR have been conducted over the period of 2007-2010. Since then, Astrium has upgraded the instrument and built the ground prototype of NovaSAR-S payload in 2010. The ground prototype has been tested by producing inverse SAR image of International Space Station in 2011, and by another two flight trails executed in 2012 and 2014, respectively. The previous campaigns focused on testing the performance of the instrument on land, forestry, agriculture and oil spill detection applications. The results indicate that S-band offers a number of advantages over other frequencies, in particular X-band. Especially S-band is less subject to rain shadowing which has been shown to be a problem at X-band and hence can image in areas of high rainfall [Bird, 2012].

As a dedicated system, NovaSAR-S is available for independent ownership and control. The first launching is planned for early 2015, but the SSTL does not yet have a plan for sharing the operational qualification data on the first flight. For the future applications, 15% of the NovaSAR-S imaging capacity will dedicate to UK government, but the detailed method of capacity sharing strategy can be adjusted depending on future partners [Davies et al. 2012].

ICEYE

ICEYE is a planned constellation of small SAR satellites, which is dedicated for Arctic ice surveillance. The design of this system was initialized in 2012 by Aalto University in Finland. An independent entity is currently being formed to finish the system development and execute mission operation. This constellation is designed to be a dedicated commercial system, which aims to provide timely, reliable, and free of priority conflicts arctic image acquisition service.

Similar to NovaSAR-S, the actual configuration of constellation has not been defined, but it has been proposed that with 6 satellites' setting, less than 3 hours revisit period over an area of interest at 70 – 80 latitude can be expected. Within one orbiting period, each ICEYE satellite is able to acquire at maximum 30 seconds data over the Arctic region, and the system switches to charging mode during the rest of the orbiting period. The designed life time of each asset is 2 years.

The main payload of ICEYE is an X-band SAR, operating on a single mode (Table 10). One special feature of this system is the operation in circular polarization. This feature theoretically makes the system less subjective to the rain and fog clutters, but this polarization has not been tested on sea ice monitoring. The ground prototype is being built and a flight trail validating the sensor's imaging performance on sea ice has been planned for early 2015. The first launch of the system has been scheduled in 2016.

Table 10. ICEYE X-band SAR parameters

Parameter	Value
Center Frequency	10.0 GHz
RF power	2 kw
Pulse Bandwidth	15 MHz
PRF	6 kHz
Azimuth Beamwidth	0.9 deg
Range Beamwidth	19 deg
Incidence Angle Range	10 – 55 deg
Resolution	10 x 10 m
Swath Width	200 km
NESZ	-27 dB
Antenna Size (L x W)	2.5 x 0.2 m
Polarization	Circular

PanelSAR

PanelSAR is a small satellite-based SAR instrument developed by a Dutch company, SSBV. The company started this small satellite project in 2011 based on own investment and support from the Netherlands Space Office. The ground prototype is being built as part of ESA's Prodex program, and an airborne trail testing the sensor performance is expected in late 2016. Yet the in space platform has not been selected and the first launching has not been planned.

PanelSAR's antenna takes modular and distributed design based on commercially available 33 x 33 cm slotted waveguide antenna elements. This design allows the payload to be easily scaled for different platforms and applications. Moreover, PanelSAR features an active array antenna with programmable control over each of its active antenna elements, which allows the system to operate in three modes. PanelSAR operates in X-band with continuous Wave Radar Technology (FMCW). One of the advantages of utilizing FMCW in space is that it requires much less peak power compared to widely deployed pulse radars. Selected system specifications are summarized in Table 11. Moreover, the PanelSAR design includes specific RF optimizations to support InSAR for 3D mapping, which can potentially enhance the system's capability of ice monitoring.

Table 11. PanelSAR Specifications

Parameter	Value
Center Frequency	X-band
RF Mode	FMCW
Antenna Size (L x W)	3 x 1 m
Swath width*	Strip Map: 15 km ScanSAR: 65 km Spotlight: 3-4 km
Resolution*	Strip Map: 4 m ScanSAR: 6-10 m Spotlight: 2 m
Designed Lifetime	3 years

* mission/orbit dependent

Airborne Arctic Characterization

Scope

Some of the most operationally challenging aspects of satellite operations are: (1) revisit times to specific Areas of Interest (AOIs), (2) uncertainty in acquisition especially if orders are made on a short notice and (3) lack of control over the satellite acquisition modes and coverage to optimize the results. It is therefore believed that airborne ice reconnaissance has the potential for complementing satellites. This section focuses on presenting the need for acquiring detailed ice information in real time using airborne sensors to evaluate ice-induced hazards on offshore facilities. Specific focus will be given here to all weather / wide swath sensors, mainly radar systems as premier candidates of supporting arctic drilling operations.

With regard to radar systems, it can be observed over the last few years that airborne reconnaissance research efforts in Europe have been focused on developing and testing multi-band / multi-polarization SAR systems. These systems can prove beneficial in the area arctic characterization as they:

1. Feature a reconnaissance approach that balances between high resolution associated with high frequency radar systems such as X-band and lower weather attenuations associated with low frequency radar systems such as P-band.
2. Provide the ability to classify different ice features based on topography using advanced signal processing algorithms of different bands and polarizations.
3. Allow making direct measurements of ice thickness remotely through employing low and high frequency radar bands.
4. In addition, a multi-sensor airborne approach provides some redundancy that can be beneficial if a sensor malfunctions.

In addition to radar systems, Ground Penetrating Radar (GPR) and electromagnetic inductions (EMI), but mainly EMI, have been used mainly to measure sea ice thickness and therefore predict its breakability. Most of the European research efforts in this regard have been undertaken by the Alfred Wegener Institute in Germany. Few EMI examples of these efforts are presented at the end of this section.

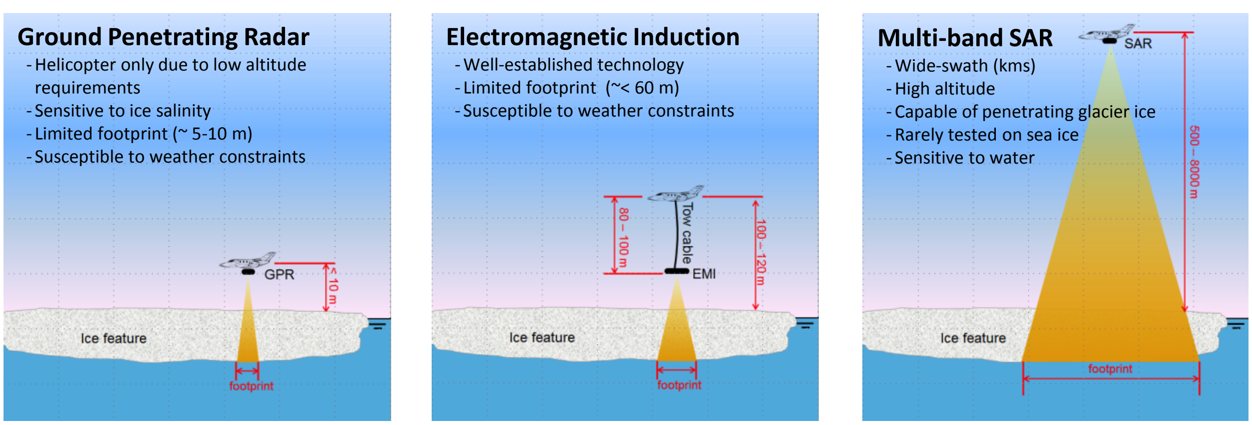

Figure 1. Schematic Diagram of most used ice reconnaissance airborne systems

Also, there is an increasing interest in using Unmanned Aerial Systems (UAS) due to safety and extended endurance advantages as compared to manned aircraft. Recent advances in aerodynamic design, automated control systems and information processing power have greatly enhanced the capabilities of UAS platforms, making them increasingly viable options for non-military applications [Garas et al., 2014]. Based on currently envisioned ice reconnaissance senor needs including multi-band SAR, Garas et al., [2014] concluded that MALE platforms capable of flights up to 24 hours at altitudes of 5,500 to 14,000 m can prove suitable for ice reconnaissance.

Main hurdles to UAS widespread use are mainly regulatory-related, some of these are:

1- UAS sense and avoid technologies to ensure reliable detection of other aircraft and obstacles in its flight environment
2- Possible failures in the command and control operations.
3- Security of data links, remote pilot stations and the UAS vehicles.

As compared to manned platforms of comparable role, UAS typically feature the following advantages:

1- Lower fuel consumption due to lighter aircraft (e.g., a typical Medium Altitude Long Endurance (MALE) UAS carrying about 1,800 kg of fuel is capable of a maximum endurance of 24 hours, whereas a comparable typical turboprop aircraft carrying 2,400 kg of fuel may be capable of a maximum endurance of 10 hours).
2- Lower labor costs associated with fewer UAS operating and support personnel.
3- Safer reconnaissance operations due full-control of the whole mission from the Ground Control Station (GCS).

<u>Examples of Radar Systems</u>

- **EMISAR (Danish Technical Research Council / EU)**

EMISAR is a high-resolution (2 x 2 m), dual frequency (L- and C-band) fully polarimetric SAR that features topographic/elevation mapping capabilities. The EMISAR system is operated on a Gulfstream G3 aircraft (twin engine jet with a 6000 km range). This system nominally operates at an altitude of about 41,000 ft (Table 12) [Christensen et al., 1998].

In 1986, the Electromagnetics Institute of the Technical University of Denmark started the development of a high-resolution airborne C-band SAR. Primary requirements were system calibration, high resolution, and significant flexibility in the acquisition geometry such that the instrument could serve as an under flight instrument for the European Space Agency (ESA) satellite SAR system (ERS-1). The fully polarimetric capability was completed, tested, and calibrated in late 1993 and the later the polarimetric L-band SAR was calibrated in early 1995. Since then, the dual-frequency system has been used for scientific applications.

In azimuth, pre-filtering to 1.5 m sample spacing is normally applied to limit the data rate but a finer sampling is possible if either: (1) only one frequency is recorded; (2) only 2 polarizations are recorded at each frequency; or 3) the swath is reduced. Normally, data are collected on tape with 1.5 m x 1.5 m sample spacing, and the unprocessed slant range swath width is 12 km. In wide swath modes the sample spacing is 3.0 m x 1.5 m or 6.0 m x 1.5 m (range and azimuth), and the corresponding swath widths are 24 km and 48 km. It is to be mentioned that simultaneous L- and C-band polarimetry necessitates the swath to be reduced or the resolution to be degraded.

An example application of using the EMISAR system for ice characterization during the European Multi-sensor Airborne Campaign (EMAC'95) [Guneriussen et al., 1995]. In this study located in Norway, 66^o N, 14^o E, data from the fully polarimetric C- and L-band EMISAR combined with ERS SAR were analyzed in order to determine the capabilities for snow parameter estimation in mountainous areas and the backscatter statistics of EMISAR C-band data from two areas partly covered by wet snow was studied. It was concluded in this study that EMISAR C-band polarization responses from wet snow at 50^o local incidence angle correspond to theoretical responses from rough surfaces while the polarization response of the L-band showed a lower degree of scatter than C-band. One other important conclusion from this study was that an investigation of areas larger areas through averaging radar backscatter may yield better correlations to in situ measurements and / or remote sensing techniques.

Table 12. EMISAR's Key Radar Instrument Parameters

Parameter	Value (C-Band)	Value (L-Band)
Frequency	5.3 GHz	1.25 GHz
Output power	2 kW	6 kW
Polarization	Fully polarimetric	Fully polarimetric
Resolution in slant range	2, 4 or 8 m	2, 4 or 8 m
Resolution in azimuth	2, 4 or 8 m	2, 4 or 8 m
Swath width	12, 24 or 48 km	12, 24 or 48 km
Flight altitude	Typically 41,000 ft	Typically 41,000 ft
Real-time processing	Full resolution	Full resolution
Weight, Equipment inside cabin	600 kg	
Pod	240 kg	
Power: 115 V, 400 Hz	5 kW, 6 kVA	
28 V, DC	1 kW	
Dimensions: Equipment inside cabin	3 x 19" racks, H=1.40 m	
Pod	4.59 x 0.81 x 0.55 m	

- **E-SAR (Microwaves and Radar Institute / German Aerospace Center (DLR))**

E-SAR is DLR's airborne SAR operated by the Microwaves and Radar Institute in cooperation with the DLR flight facilities onboard their Dornier DO228-212 aircraft. DLR developed the system and started operating it in 1988. Since then, there have been continuous upgrades to the system to fit a versatile and reliable workhorse in airborne Earth observation with applications worldwide.

E-SAR operates in X-, C-, L- and P-band (wavelengths from 3 to 85 cm) in both vertical and horizontal polarizations with SAR interferometry operational in X-band, L-band, and P-band. Featuring long wavelengths (i.e., P-band and beyond) gives this system a potential capability of penetrating through ice and obtaining direct measurements of thickness, which is one of the most challenging ice parameters to be measured remotely [Table 13].

Table 13. E-SAR Key Radar Instrument Parameters

Platform	Dornier DO 228-212, modified
Engines	2 turboprop, Garrett TPE 331-5A-252D
Air crew	2 pilots, 1 a/c engineer; 3 radar operators
Ceiling	20 000 ft above mean sea level (FL 200)

Range	600 nautical miles
Endurance	2.5 to 3 hours under IFR conditions
Frequency	X (9.6 GHz), C (5.3 GHz), L (1.3 GHz), P (350 MHz)
Measurement modes	SAR Interferometry, SAR Polarimetry
Slant range resolution	2.3 m (HR) or 4.5 m (MR)
Azimuth resolution	X (0.25 m), C (0.30 m), L (0.40 m), P (1.50 m)
Swath width (on ground)	3 km - 5 km
Scene size (typ.)	Up to 3 x 20 km (NS) or 5 x 20 km (WS)
DEM (Resolution/Posting)	5 m, 5 m, ≤ 1m (N, E, H) / 2.5 and 5 m
DEM (Accuracy)	2 m, 2 m, ≤ 4 m (N, E, H), absolute
Geo-coding	UTM WGS84 (and GK), Posting ≥ 1 m

E-SAR was used in characterizing sea ice in the Barents Sea east of Spitsbergen, (approx. 600 miles from North Pole) during a joint campaign of DLR-HR with the Alfred-Wegener-Institute (AWI), Bremerhaven, Germany in 2005 where both optical and SAR images were acquired during the campaign for the study of sea ice. Utilizing the quad-pol capability and assigning false colors to different polarization prove to be successful in providing insights about ice surface topography and deformations. In addition, the use of longer wavelengths than the typical X-band (i.e., L-band in this case) mitigates atmospheric clutter.

- **F-SAR (Microwaves and Radar Institute / German Aerospace Center (DLR))**

F-SAR is the newer generation of the E-SAR, also operated by The Microwaves and Radar Institute of the German Aerospace Center (DLR). F-SAR is the successor of the E-SAR system, developed to focus on simultaneous data acquisition at different wavelengths and polarizations at very high range resolution, a capability that was limited in the E-SAR. F-SAR also operates on the DLR's Dornier DO228-212 aircraft. F-SAR features X-, C-, S-, L- and P-bands with simultaneous all polarimetric capability. Range resolution is determined by the available system bandwidth. A special antenna mount that holds seven right-looking dual polarized antennae is used (i.e. 3 X-band, 1 C-band, 2 S-band and 1 in L-band. The P-band antenna is mounted under the nose of the aircraft). This mount has the one important advantage that it makes it easy to change antenna configuration [www.elib.dlr.de].

The authors could not find publically available information about the use of this system for arctic characterization, however a system like the F-SAR that features multi-band /quad polarization capabilities can prove to provide significant improvements in small ice feature detection, sea ice classification and making direct measurements of ice thickness, capabilities that do not currently exist in space borne systems.

- **COMPACT-100 SAR (GosNIIAS)**

The COMPACT SAR system was developed be the Russian State Institute of Aviation Systems to provide high resolution surveillance capabilities on either side of a fixed wing aircraft. This system features swath coverage that typically ranges from 25 to 50 km with a spatial resolution ranging between

0.5 and 3.5 m [Table 14]. This system is typically operated with 300 – 2000 m altitude and features onboard data processing and imaging capabilities [www.gosniias.ru].

Publically available information about the system is limited, however authors are aware of specific examples where this system was used for arctic characterization, and specially detecting ice features in open water environments. Information about these applications is yet not released. Authors are also aware of other Russian airborne SAR systems used for arctic characterization but information about these systems are not yet publically released simply because they have been originally developed for military applications.

Table 14. E-SAR Key Radar Instrument Parameters

Parameters	X -band	L-band	P-band	VHF-range
Central carrier frequency	8600 MHz	1310 MHz	430 MHz	140 MHz
The width of the signal	300 MHz	100 MHz	60 MHz	40 MHz
spatial resolution	0.5 x 0.5 m	1.5 x 1.5 m	2.5 m	3.5 x 35 m
locking band	3 km	15 km	5 km	3 km
Working range	10-15 km	15-25 km	15 km	5 km
Antenna size	0.25 x 0.25 m	dia 0.35 m	dia 0.5 m	1.3 x 0.65 m
Pulse power of transmitter	60 W	250 W	200 W	150 W
Power consumption on the network = 27V	< 150 W	< 60 W	< 60 W	< 60 W

- **POLarimetric Airborne Radar Ice Sounder (POLARIS)**

Funded by European Space Agency (ESA), an airborne P-band ice sounding radar, POLARIS, has been developed by the Technical University of Denmark. The development of POLARIS is intended to provide a comprehensive understanding of P-band scattering and propagation through ice sheets and to verify surface clutter suppression techniques in preparation for a potential space-based ice sounding mission. Detailed parameters of the POLARIS are listed in Table 15. POLARIS is a fully polarimetric system, which enables the measurement of internal ice-crystal orientation. Previous studies have shown that the variation in backscatter intensities with polarization can exceed 20 dB [Dall et al., 2007].

A proof-of-concept campaign was carried out in Greenland in May 2008 to test the functionality and technical performance of the POLARIS system. The results of this campaign indicated the penetration depths ranging from 350 – 750 m with the same polarization setting. The analysis of the polarimetric data employed to measure ice anisotropy is not yet released. This system has not been tested yet in sea ice and therefore the penetration capability of P-band sounder on saline ice remains uncertain [Dall, 2008].

Table 15. Key parameters of POLARIS

Center frequency	435 MHz
Bandwidth	85 MHz
Polarization	Quad
Pulse length	50 µs
Peak power	100 W
Pulse Repetition Frequency	20 kHz

(PRF)	
Operating altitude	3500 m

Examples of Other Systems

The EMI sea ice thickness remote sensing approach makes direct ice + snow thickness measurements through using the electrical conductivity contrast between sea ice and seawater, with the latter having orders of magnitude higher conductivity than the former where a primary electromagnetic field penetrates through ice to identify the ice/water interface while another sensor (e.g., laser altimeter) is simultaneously used to measure ice surface elevation.

EMI has been used to obtain direct ice thickness measurements from helicopter and fixed wing platforms [Kovacs and Holladay, 1990; Prinsenberg and Holladay, 1993; Haas et al., 1997, 2009, 2010, 2012; Prinsenberg et al., 2011; Hendricks et al., 2014]. EMI's sensor footprint is typically 3-4 times its altitude above ice surface and is typically maintained about 20 m above the ice surface to limit underestimation of the maximum ice thickness where ridges are present. EMI method for measuring ice thickness is sensitive to certain parameters such as the height and frequency of the sensor in addition to the conductivity and the thickness of the material being sounded. For example, a recent study where drill-hole techniques were used to measure multi-year ice thickness showed that EMI statistically underestimated thickness as compared to drilling results due to EMI footprint averaging and possibly EMI interpreted freshwater ponds on the floe's top surface (i.e., 15 - 24% underestimation). Also, EMI provided no information about ice thicker than about 12 m in this study. While this study showed that EMI, in most case, provided a reasonable estimate of the average thickness, it also concluded some limitations of using EMI data directly to design structures subjected to impacts with multi-year ice and also or predict ice manageability [Johnston and Haas, 2011]. In 2012, a study showed the feasibility of increasing the number of sensors on a relatively small airborne EM instrument to accurately measuring sea-ice thickness, including the thickness of pressure ridges using 2D/3D EM interpretation software [Pfaffhuber et al., 2012].

One of the main elements associated with using the EMI method, is the low flight altitude associated with the required 20 m separation between the EMI sensor and ice surface. This requirement can be achieved either by flying a rotary wing aircraft at this altitude with the EM sensor attached to the fuselage or by towing the sensor from an aircraft (helicopter or fixed wing) flying at a higher altitude. EMI low flight altitude requirement, limits, to some extent, its application in foggy conditions. As such, it is currently envisaged that EMI flight operations will likely be confined to daylight missions [Garas et al., 2014]. One potential way of overcoming this limitation is integrating the sensor with a UAS.

Ship-borne Arctic Characterization

Scope

This section mainly focuses on presenting ship-borne radar systems in Europe that are used to detect and track sea ice and icebergs.

Radar, which is an acronym for Radio Detection and Ranging, is a system that uses electromagnetic waves to identify the range and speed of objects. This section will mainly discuss marine radars, which are used routinely to detect ice hazards, provide good resolution, but their range is limited to the visible horizon (a few miles). The principle of operation of all active microwave systems, such as marine radar, is to transmit a signal and measure the intensity and often polarization and other properties of the returning scattered signal.

The use of marine radar for ice detection and tracking is a major research area, especially in Canada [O'Connell, 2011]. Current research is centered around improving ice tracking capability of slowing moving ice targets and mitigating rain clutter effects on detection potentially through one or more of the following techniques:

- Increasing the sampling rate trough increasing the Pulse Repetition Frequency (PRF) or scan rate.
- Increasing dwell time and thus improving the signal to noise ratio.
- Increasing power level and gain (size).
- Decrease beam width which decrease angular tracking noise.
- Using multiple polarizations.
- Using longer wavelength radar bands than X-band, typically S-band.
- Advanced signal processing such as scan averaging.

Examples

Two advanced marine radar systems that were and are being used for ice characterization have been identified. These are: (1) The Selesmar Selux system developed by Consilium (Sweden) and (2) Rutter Sigma 6 marine radar (Canada). With the focus of this paper being Europe, only the first system will be presented here.

- **Selesmar Selux Marine Radar**

This is the fifth generation radar developed and manufactured by Selesmar Consilium, three of these radars recently replaced old systems on the Hibernia platform offshore East Canada. Depending on the application, X-band and/or S-band, 6 to 12 ft antenna length, 12 to 30 kW power, and 0.7 to 2 degree horizontal beam width can be selected. this system also features:

- Automatic Identification System (AIS) that allows identification of up to 100 targets.
- Automatic Radar Plotting Aid (ARPA) that allows creating tracks and calculate the tracked object's course, and speed, thereby knowing if there is a danger of collision with other ships, ice features, or landmass.
- Manual or automatic acquisition and tracking of up to 40 targets is possible.
- An advanced Guard Zone system has been introduced, which automatically checks all targets around the vessel against the specified minimum safe parameters and provides acoustic and visual warnings when necessary.

It is to be mentioned that for improved radar performance in ice, the signal processing system manufactured by Rutter Technologies (Sigma 6) and described in the next section, should be installed.

Beside marine radar, Thermal Infrared (TIR), on the other hand is a passive remote sensing methodology that has been used for ice detection. TIR technology depends on the fact that every substance with a temperature greater than absolute zero emits some form of electromagnetic radiation, most of which in the infrared region. TIR measurements rely on this emitted radiation, which is a function of the surface temperature and emissivity. One of the limitations of thermal infrared remote sensing is clouds and fog that reflect and emit infrared radiation thus hindering detection of radiation from ice. Also when ice temperature is close to the temperature of the surrounding ocean (e.g., during ice melting period) distinction between infrared signatures of ice and ocean is unlikely.

Subsea Arctic Characterization

Scope

The fourth area of arctic characterization research in the report is subsea. For this area, data is collected below the sea/ice interface. There are two major systems that fall into this category. The first of these is the moored Ice Profiling Sonar. The system, which was developed by ASL, is an off-the-shelf technology with a 96% success rate. This system has been in use for many years and has been an invaluable source of data on ice thickness (or more accurately, keel depths). When deployed with an Acoustic Doppler Current Meter (ADCP), ice velocities/trajectories and ocean currents can be calculated to add a spatial component to the ice drafts. While the measurement technology is mature, interpretation of these data is however the subject of on-going research. Given the draft profile of ice drifting over the sensor location, it is important to be able to classify the record into a collect of ice features e.g. FY/MY ridges, etc. Algorithms have been developed by different organizations that accomplish this task but validation of the results is challenging in the absence of on-ice corings or other defensible measures of ice age.

The second major category is Autonomous Underwater Vehicles (AUV) with sensors mounted on them to measure the ice above. One database of AUVs contained 239 unique configurations of 138 vehicle platforms. The vast majority of these have been developed for non-Arctic applications. Companies that sell AUVs on the international market, include Kongsberg Maritime, Hydroid (now a wholly owned subsidiary of Kongsberg Maritime[12])), Bluefin Robotics, Teledyne Gavia, International Submarine Engineering (ISE) Ltd and Saab.

AUV have been successfully used in a variety of data collection programs and support of operations. They enable close access of sensors to the objects of study and measure draft of ice features, which is very difficult to obtain with other remote sensing technologies. To date the primary application for arctic missions has been bathymetry mapping and data acquisition for Arctic research. In the long range, AUVs could play an important ice measurement in support of ice management operations for exploration and production activities. In order for an AUV to function effectively in Arctic mission, the following requirements must be satisfied:

- Launch and recovery in ice infested waters
- Ability to map the ice profile of large areas e.g. 10's-100's km^2 each day which combines speed, endurance, sensor swath width requirements and quick post-processing of data products
- Under ice navigation which includes route following (geographic and depth below ice) and collision avoidance
- Reliability for day to day operations over extended periods
- Through ice location and recovery of "lost" units

Based on analysis of the 3-D imagery of the underside of ice ridges, Wadhams [2012] observed that "results of high-definition multibeam profiling so far point to a fundamental difference in shape between FY and MY ridges. This is not so much a difference in average ridge slope as a difference in crest continuity, with FY ridges approximating to linear triangular prisms while MY ridges are broken up by the intervention of leads into a sequence of individual ice blocks, sometimes losing all evidence of ridge linearity." If this observation holds true, ice mapping with AUVs could be an important element in ice type classification.

AUVs can survey remote environments that are inaccessible to other submersibles (e.g., ROVs and submarines) and are completely autonomous, which makes them independent of the weather after launch and results in high efficiency through increased survey speed. They can be instrumented with a variety of sensors and provide a very stable and low-noise platform for measurements. Several system manufacturers are working to extend AUV range through improved capacity of batteries or fuel cells, which may also lead to applications of AUVs for inspection, maintenance and repair of subsea installations. Navigation under ice and launch and retrieval systems are also areas being improved. Advances in sensor technology designed specifically for AUVs will allow each mission to carry more extensive measurement programs. Longer-term development plans for the systems involve AUV gliders with a range of thousands of kilometers, AUV deployment from the air, underwater docking systems to mitigate risks associated with launch and recovery operations, and AUV's ability to cooperate thus allowing a team of vehicles to communicate and adapt to changing conditions of the mission.

Examples

HUGIN 1000 (Kongsberg, Norway)

Recent papers by Kongsberg [2011] illustrate several concepts of operations and the capabilities of their HUGIN 1000 Arctic class AUV. The HUGIN 1000 was originally deployed in 1997 and has booked over 300,000 km of line surveys. The arctic class version of this AUV was developed over the last few years. The concept of operation includes the use of satellite SAR images to identify ice features of interest within a large area of interest and then deploy AUVs from a host facility or icebreakers in the field to map the ice profile of those features from below. Key elements of the subject AUV include:

- For ice mapping:
    - GeoSwath Plus 250 kHz for ice mapping – GeoSwath Plus is a wide swath bathymetric sonar system with 100m vertical range and up to 12 x depth swath;.
- For bottom mapping:
    - HISAS 1030 interferometric synthetic aperture sonar and EM 2040 multibeam echo sounder, 200-400 kHz, 0.7° x 0.7° beamwidth, swath 120°-135°. Combined they provide a 400m swath width at 2m/s.
- Vehicle speed is 2-6 knots with 24-78hr endurance
- RF Through-Ice Localization and Communications System (TILACSys) enables a surface vessel, helicopter or UAV to locate HUGIN 1000 under ice at up to 1 km
- Navigation options include use of transponders on seabed tightly integrated with INS and , terrain-based navigation
- Launch and Recovery systems for use in a vessel moonpool or thru an opening in the ice.

Autosub 3 (National Oceanography Centre, UK)

The National Oceanography Center in the UK has developed a number of AUVs over the last twenty years ranging from gliders to the Autosub 6000. Autosub missions were carried out in the Arctic and Antarctic from 1999 until the present, with long missions, beyond 24 hours, operating under sea ice and under the floating ice-tongues of glaciers. During the campaign of 2009 in the Western Antarctic, the Autosub3 operated beneath the 500 m to 1000 m thick floating ice tongue of the Pine Island Glacier, penetrating into the ice cave by up to 60 km. Using upwards and downwards looking mapping sonar, it was able to map out, for the first time, both the ice above and sea bed depths below the AUV track. The Autosub3 has a total displacement 3.6 tons and can travel up to 400 km on a set of batteries. It can dive to a depth of 1600 m.

The Arctic Explorer AUV

Since 1975, International Submarine Engineer (ISE), has built 23 different AUVs. The Arctic Explorer is a derivative of the successful Explorer AUV that was first designed in 2001. ISE has built two Arctic Explorers for Natural Resources Canada to map the sea floor underneath the Arctic ice using the Kongsberg Maritime EM 2040.

In April 2010, one of these vehicles completed over 1000 km of under-ice survey, mapping the sea floor during 10 days of continuous underwater operation. The Arctic Explorer can be launched from a ship or an ice-hole and the modular sections can be separated for transportation.

The Arctic Explorer is the largest of the Explorer AUV class, measuring over 7 m long and weighing over 2000 kg. It is equipped with an extended range capability, making 80 missions covering 450 km possible. The Arctic Explorer has a unique variable ballast system that enables it to park on the sea floor or hold itself on the underside of the ice during the mission. It is rated to 5000 m depth and is designed to remain underwater between missions with all servicing and charging being carried out by a small portable ROV. The base ran of the Arctic Explorer is 120 km at 1.5 m/s with 75-Watt payload. The range can be increased to 240 km with 2nd battery bank and 360 km with 3rd. The maximum speed is 2.5 meters per second.

Ice Drift Monitoring and Forecasting

Scope

The fifth and final area of arctic characterization research in the report is ice drift monitoring and forecasting. Ice drift monitoring and forecasting are key components of an ice management system, because it is crucial to know where the ice is coming from and to estimate where it is going in order to efficiently deploy ice management resources. Ice drift monitoring and forecasting can be classified into two primary regimes; near field and far field. Near field ice drift monitoring and forecasting focus on short term ice and drift motions and are essential components of an ice management system, while far field focuses on regional scale ice motion.

Ice drift monitoring involves tracking the motion of ice as a function of time. Monitoring can be accomplished in several different manners, including; satellite imagery, aerial surveys, enhanced marine radar, and by deployment of beacons directly on floes of interest. Each of these methods has tradeoffs that must be considered when selecting ice monitoring methods. For instance, analysis of successive satellite images or aerial surveys provides estimates of ice motion with coarse temporal resolution over a relatively wide region. In contrast, enhanced marine radar and beacons deployed directly on floes of interest provide high temporal resolution of individual features. The type of ice drift monitoring required will likely depend on the ice concentration during ice management operations: Broad, lower temporal resolution will be needed when operating in high concentration conditions such as in pack ice, while high temporal resolution feature tracking will be needed when operating in low ice concentration conditions characterized by isolated floes along the marginal ice zone (MIZ).

Depending on ice concentration, the physics of ice drift forecasting change. For low concentration conditions, the ice drifts freely, while under heavy concentration conditions, the ice does not drift freely. This can be clearly seen in ice drift records. In low concentration conditions isolated floes tend to show strong inertial motion characterized by cusps and loops in the drift paths. In high concentration conditions, such as found in pack ice, these inertial motions tend not to occur. In order to cover the full range of expected ice conditions, ice drift forecasting must account for the physics of both low concentration and high concentration ice conditions.

Examples

A model developed specifically for modestly deformed free (ice ridges remain within the mixed layer) drifting sea ice has shown skill forecasting isolated ice floes in the Canadian Beaufort Sea [Blunt et al., 2012]. The model is driven primarily by wind stress and the gradient of mean dynamic topography (MDT) with a lesser contribution from the gradient of sea level pressure through the inverse barometer affect. The model, freely run for six days after initialization, was able to accurately replicate the drift of a large ice floe. It has also shown skill with other floes in the Canadian Beaufort, as well as for floes in other regions, as well.

When ice concentration reaches a level such that the ice drift becomes constrained, different models must be employed. One such model is the next generation Arctic Cap Nowcast/Forecast System (ACNFS). The ACNFS is an assimilative coupled sea ice and ocean model that nowcasts and forecasts conditions in all sea ice covered areas in the northern hemisphere poleward of 40°N [Posey et al., 2010]. The ACNFS is a high spatial resolution model (~3.5 km near the North Pole) with a 10 minute time step for the ice model component. ANCFS is forced with 3-hourly wind fields from Navy Operational Global

Atmospheric Prediction System (NOGAPS). The ACNFS has shown skill at forecasting the ice drift, thickness, and concentration on broad scales throughout the arctic.

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