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Real-Time Pack Ice Monitoring Systems – Identification of Hazardous Sea Ice Using Upward Looking Sonars for Tactical Support of Offshore Oil and Gas Projects

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Abstract

There is an increasing requirement for real-time detection of sea ice hazards. These hazards include the identification of thick ice keels, large hummocky ice, fast moving ice, rapidly changing ice direction and multi-year ice. Such information is needed in real-time to support tactical applications for safe routing of ships in heavy sea ice concentrations. More recently, a need has emerged for tactical support of offshore oil and gas activities in ice infested waters of the Arctic Ocean and in marginal ice areas such as the Barents Sea, the Sea of Okhotsk, the Caspian Sea, Baffin Bay, the Labrador Sea and East Greenland waters. Reliable upward looking sonar (ULS) instruments, including the ASL Ice Profiler for ice keel measurements and the Acoustic Doppler Current Profiler for Ice Velocity measurements have been widely used in these areas for many years. These instruments, which record data internally, are operated from subsurface moorings that are deployed and recovered by ship during times of minimal sea ice coverage.

Providing real-time measurements from the upward looking sonar measurements operating under heavy ice cover pose new technological challenges. The use of surface buoys to relay data from subsurface instruments to shore facilities or satellites is not possible due to the ice cover itself. A more feasible approach is to transmit the data from each instrument using underwater cables on the sea floor and which link the instruments on the subsurface moorings to a bottom mounted or floating structure. For a floating structure, the use of high performance acoustic modems may be required.

Previous experience with real-time ULS ice measurement systems dates back to operational projects undertaken from 2002 to the present. More challenging requirements for real-time ULS ice measurement systems are being addressed in much deeper and more remote areas of the Arctic Ocean such as the Barents and Beaufort Seas. Conditions in these areas can vary from short episodes of hazardous ice to more prolonged and severe ice conditions. ULS ice systems may be deployed on a year-round basis or used episodically strategically just before hazardous ice episodes begin. The requirements for timely and accurate ice information demand high reliability in support of ship navigation, offshore oil and gas drilling and development applications. The real-time ULS ice measurement system must be capable of operating for multiple years without servicing in conjunction with other metocean sensors packages (e.g. ice radar, satellite, winds). Multiple ULS measurement arrays will be needed over operational areas spanning distances of many kilometers. For these Arctic Ocean applications, cabled ocean observatory technology and advanced underwater acoustic modems become key enabling technologies.

Recent developments of automated detection techniques for deep keels, large hummocky (rubbled) ice, high ice speeds and rapid changes in ice direction derived from data collected from autonomous ULS systems will be described. Robust real-time versions of these algorithms, along with development of automated identification techniques of old-ice using acoustic backscatter data from the Ice Profiling Sonar, will be essential in providing the required tactical ice information.

Ice Information Requirements to Support Oil and Gas Operations in Ice Infested Waters

Offshore oil and gas activities in ice infested waters are being considered at a much expanded level for the present decade than past decades, with ambitious new plans being developed to move exploration activities into deeper waters with more severe ice conditions. Ice management systems for stationary vessel operations in moving pack ice is built on experience dating back to the late 1970's in the Canadian Arctic (1,2) and off the Canadian East Coast (3). As noted by Keinonen and Martin (2), the early ice management systems were experimental, an approach which is no longer acceptable given higher safety and environmental standards. Moreover, costs of Arctic drilling operations have risen considerably which dictate that downtime in operations must be minimized.

Past tactical sea ice information systems, used in support of ice management for stationary vessel operations, relied heavily on information sources including: visual and marine radar detection of sea-ice from the stationary vessel and its support vessels; satellite (radar and radiometric) surveillance; and manual predictive systems of identified hazardous ice features. Examples of earlier ice information systems to support ice management are provided in references (1) and (3).

To address the need for improvements in the safety and efficiency of stationary vessel operations in Arctic waters, new and improved sub-surface ocean technologies are now available. These subsea technologies allow continuous real-time monitoring of the underside of the ice features including the thickness, velocity, shapes and types of sea ice present. The key enabling technologies for this purpose are upward-looking ice sonars operated safely below the sea ice and improved underwater communications fibre-optical cables and acoustic modems which allow data acquisitions over horizontal distances of many kilometers and vertical scales of several hundred meters.

This paper provides an overview of the upward-looking sonar and communications technologies, combined with a high level concept design for a real-time subsea ice information monitoring system.

Sea-Ice Upward Looking Sonars Implemented on Real-Time Systems

Reliable upward looking sonar (ULS) instruments, including the ASL Ice Profiler Sonar (IPS) for ice keel measurements and the Acoustic Doppler Current Profiler (ADCP) for ice velocity measurements have been widely used in ice infested polar and sub-polar waters for many years (Figure 1). These instruments, which record data internally, are operated from subsurface moorings that are deployed and recovered by ship during times of minimal sea ice coverage, usually in late summer.

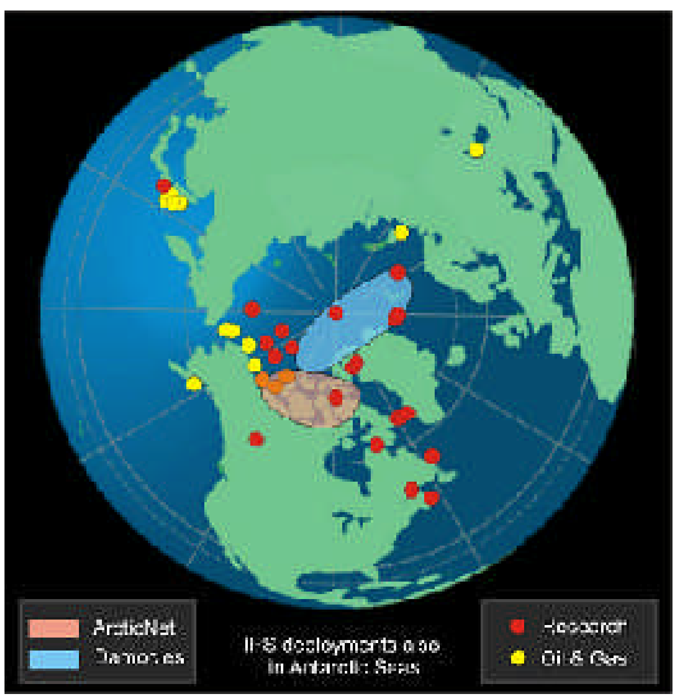


Figure 1: A map showing the locations of Ice Profiler Sonar deployments in the 1990's and 2000's in the Northern Hemisphere.

The upward looking sonar instrumentation, consisting of the Ice Profiler Sonar and the Acoustic Doppler Current Profiler are well suited for deployment at 25 to 60 m below the air water interface using sea floor based moorings with the IPS situated above the ADCP, or in shallower waters from bottom-mounted platforms (Figure 2). As developed in the early 1990's (4) the IPS instrument operates by transmitting and detecting surface returns from frequently transmitted short pulses (pings) of acoustic energy concentrated in narrow beams (less than 2° at half power). Precise measurements of the delay times between ping transmission and reception are converted into ranges separating the instrument's transducer and the ice undersurface.

Simultaneous data from the instrument's very accurate on-board pressure sensor are then combined with atmospheric surface pressure data and estimates of the mean sound speed in the upper water column (obtained from data collected during absences of ice above the instrument) to derive estimates of ice draft from each transmission ping. The IPS instrument transmits pings continuously at user-selectable intervals, typically 1 or 2 seconds.

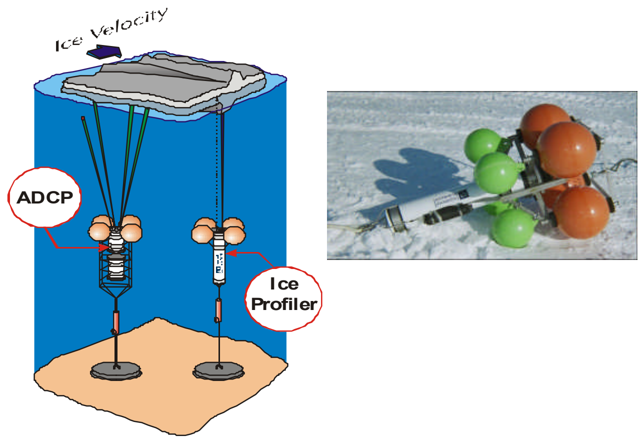


Figure 2: A typical deployment arrangement of IPS and ADCP ice velocity instruments on separate bottom moorings for shallow water applications. In deep waters, the IPS instrument is located above the ADCP instrument on a single taut line mooring.

A new generation of Ice Profiler instruments became available in 2007 (5) which provide enhanced capabilities for sea-ice measurements in the form of more data storage capacity, better resolution and the capability to measure the acoustic backscatter returns beneath and into the ice in addition to the target range to the underside of the sea-ice. The IPS provides ice draft data to a typical accuracy of 0.1 m or better (6).

Ice velocities are obtained with ADCP instruments, which have been used for over twenty years for the measurement of ocean current profiles. Starting in the mid-1990's, the Teledyne RDI ADCP has been configured with a "bottom-tracking" operational mode which can be used to directly measure ice velocities when operated below sea ice. The TRDI ADCP provides ice velocities with an accuracy of typically 0.01-0.03 m/s as computed from ice track ping ensembles at typical measurement intervals of 5 to 20 minutes (6).

When IPS instruments are deployed under moving ice fields and adjacent to, or immediately above, upward-looking ADCP (Acoustic Doppler Current Profiler), the obtained data are used to construct two dimensional cross-sections of the ice cover (Figure 3), in the form of ice draft distance series. With careful processing these products depict detailed variations in the depth of the lower ice surface with a horizontal resolution of about 1-2 m.

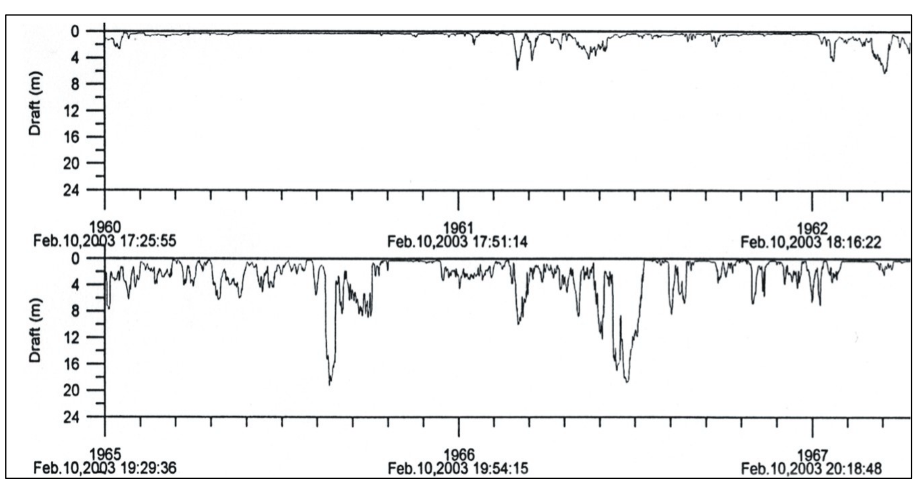


Figure 3: A distance profile of the ice undersurface produced by combining time series ice draft (IPS) and ice speed (ADCP) along a line traced out by all points on the ice which move over the instruments. Large keels of nearly 20m ice draft are evident in this 3 hour data segment.

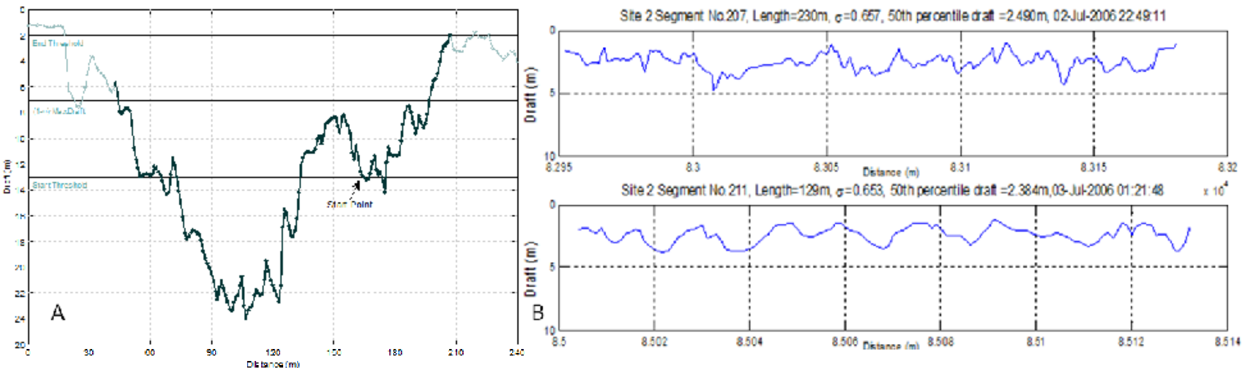
Automated Identification of Ice Hazard Features

Advances in automated detection of potentially hazardous ice features from upward looking sonar data sets have been achieved in recent years. Algorithms for detection of ice hazard features include:

- deep ice keels having ice drafts of 5 to > 20 m and horizontal scales of typically 10 – 200 m;
- large hummocky (rubbled) ice with ice drafts of 4 to > 10 m and horizontal scales of up to several hundred meters;
- high ice speeds and rapid changes in ice velocity

as described in Fissel et al., 2010 (7).

Examples of selected outputs from the automated ice hazard detection algorithms are provided in Figure 4.



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Event Duration (h)	Direction Change during ice turning event 20–60	60–100	100–140	140–180	180–220	220–260	>260	Min. Max. Total
1.0	118	1	2	1				122
2.0	19	15	4	1	1			40
3.0		4	2	3	1			10
4.0			4	3		1		8
5.0				2	3			5
>6						1	1	2
Total	137	20	12	10	5	2	1	187

Figure 4: Examples of ice hazard features as detected with automated software: (a) large ice keel; (b) hummocky (rubbled) ice; and (c) compilation of ice turning events as characterized by direction change over various durations.

An automated algorithm for the detection of old ice (second year and multi-year ice) is presently under development. The occurrences of old ice embedded within Arctic pack-ice are important due to the greater hardness of old ice by comparison to first year ice. Preliminary results for the algorithm under development are that the probability of the presence of old ice can be reliably determined from analysis of ice draft distance series. Verification of the algorithm to positively identify individual old ice feature requires independent simultaneous measurement of the individual old ice floes. High resolution satellite or visual observations are being sought for verification purposes.

Robust real-time versions of these algorithms, along with development of automated identification techniques of old-ice using acoustic backscatter data from the Ice Profiling Sonar, will be essential in providing the required tactical ice information.

Earlier Real-Time Upward Looking Sonar Ice Measurement Systems

Operational real-time ULS ice measurement systems have been developed (8) including:

- a real-time IPS/ADCP system operated in the St. Lawrence Seaway from 2002 to 2007 in support for ship navigation (Figure 5);
- a real-time IPS system operated off the Confederation Bridge in Northumberland Strait in Eastern Canada, 2005-2008; and
- a real-time IPS system in the shallow waters of the NE Caspian Sea, operated from 2009 to the present.

From these systems, data communication protocols and data formats suitable for real-time operations of the IPS and ADCP instruments were developed and automated software for shore- or platform-based computers were developed and tested. The remote software developed for processing and displaying the data (see examples of data displays in Figure 5), as operated over extended periods of time, were refined to provide robust and reliable real-time outputs.

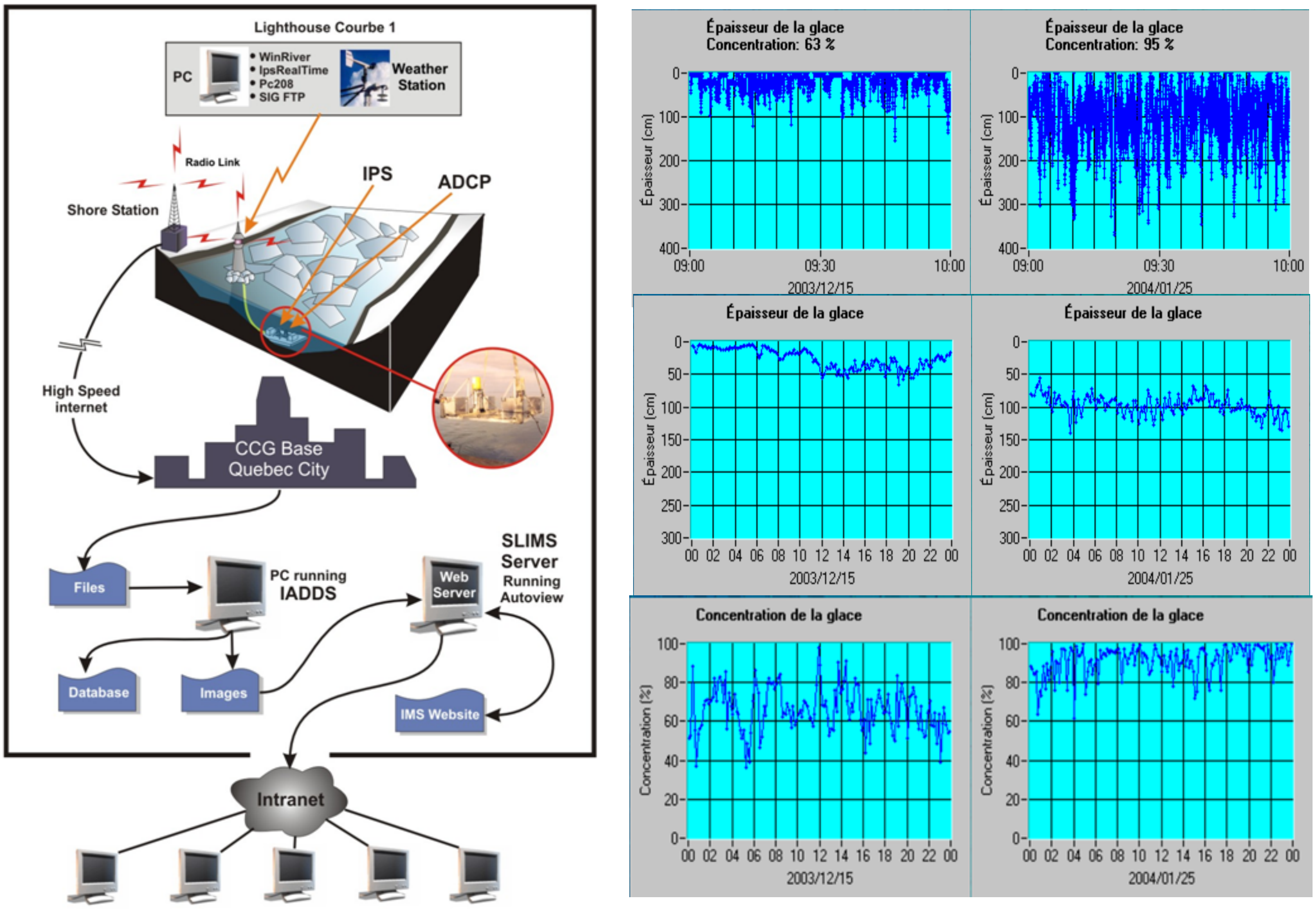

Figure 5: (left) an overview of the components and data flow of the St. Lawrence River ice monitoring system; and (right) examples of data displays including (upper) hourly ice draft, (middle) daily ice draft, and (lower) daily ice concentration.

Future Real-Time Upward Looking Sonar Ice Measurement Systems

More challenging requirements for real-time ULS ice measurement systems are being addressed in much deeper and more remote areas of the Arctic Ocean such as the Barents and Beaufort Seas. Ice conditions in these areas can vary from short episodes of hazardous ice to more prolonged and severe ice conditions. ULS ice systems are expected to be deployed on a year-round basis. The systems will be used operationally during the course of offshore operations when ice is present.

Key system design issues that must be addressed include:

- communication hardware, cables and data protocols to send data from measurements sites to the stationary vessel;
- power sources for self-powered systems (distributed long-life battery systems vs. a much larger central power source);
- the optimal location of the instrument arrays to provide adequate coverage of the area of operations;
- installation and maintenance requirements; and
- the real-time data processing and display software to effectively present information to support tactical ice management purposes

The output of the vessel based software will complement and extend ice information from measurement systems operated above the floating ice cover such as ship-based radar and visual observations and satellite derived information on sea ice cover.

The real-time ULS ice measurement system must be capable of operating for multiple years without servicing, in conjunction with other metocean sensors packages (e.g. ice radar, satellite, winds). Multiple ULS measurement arrays will be needed over operational areas spanning distances of many kilometers. For an application where a stationary drilling vessel will be operated in deep water (> 300 m) in heavy Arctic pack ice (at times), multiple support vessels will be required to break ice floes and pressure ridges into less hazardous objects and/or to deflect the floes away from a collision course with the drill vessel. For the ice breaking support vessels operating at distances of 10-15 km away from the drill vessel, the measurement sites will be distributed over similar distances from the drill vessel. One concept of an array of ULS measurements sites to effectively provide ice information in support of ice management activities is shown in Figure 6.

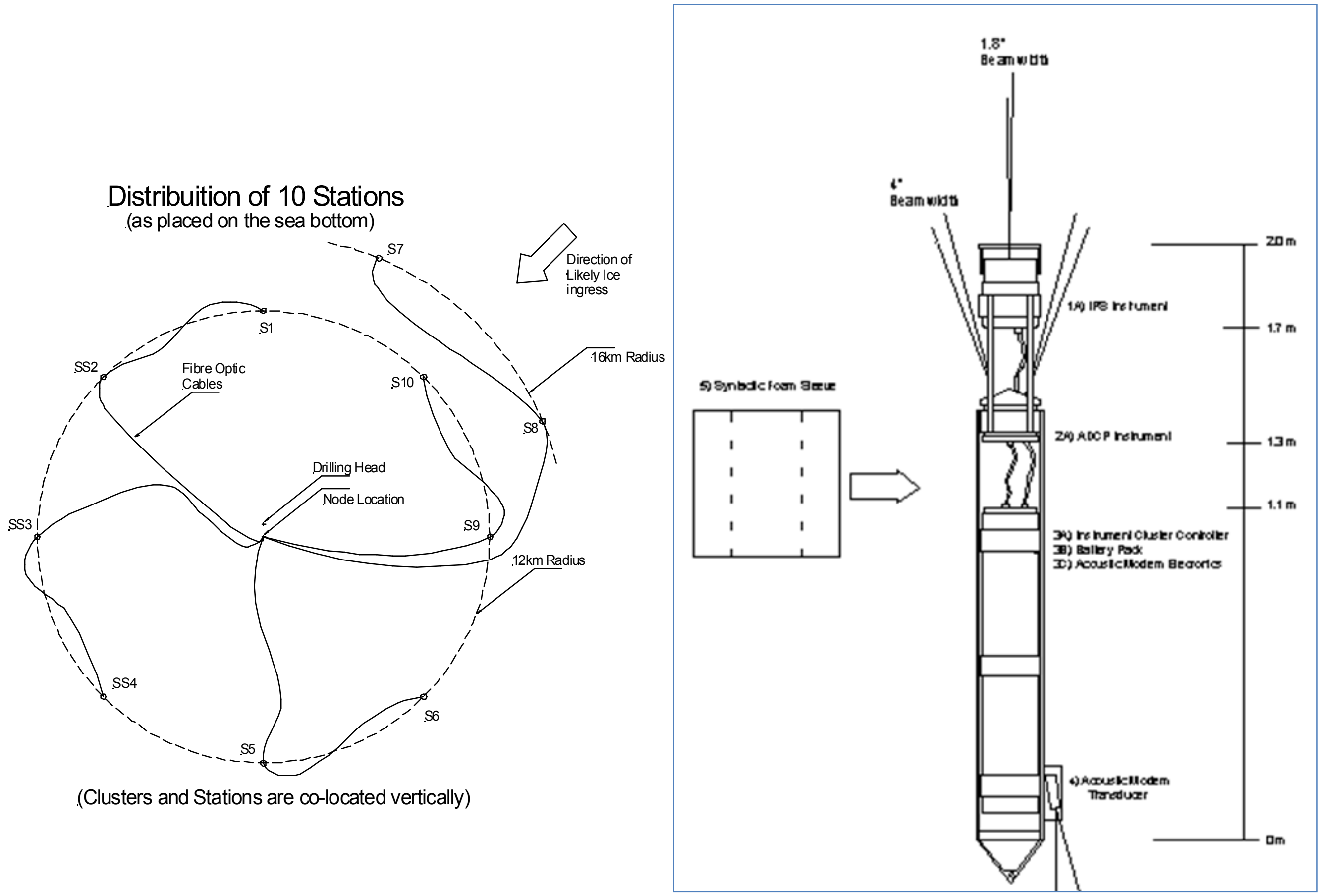

Figure 6: (left panel) An example of a large area (16 km radius) array of ULS measurement sites to support a stationary drilling vessel at the center of the array; and (right panel) the configuration of the IPS (top), ADCP (middle) and battery pack (bottom) instrumentation used at each ULS measurement site.

For horizontal distances spanning many kilometers, the use of underwater fiber optics cables is provides an enabling solution for these applications. In recent years many advances in these technologies have been achieved through the underwater cabled observatory programs funded for real-time ocean observations systems in temperature waters such as the Ocean Network Canada's VENUS and Neptune Canada observatories (9). Application of these advanced technologies to the Arctic requires adaptation for differences in the Arctic environment. In particular, external shore-based power is not readily available in Arctic applications and the ship-based logistics for the deployment of the cabled measurement systems is constrained by the remoteness of the Arctic areas and the presence of sea ice.

In addition to underwater fiber optic cables on the sea-bed, acoustic modems may be used to provide a data link to the instrument clusters, which could be several hundred meters above the sea-bed. Different configurations can be considered for the data links between the instrument clusters to the seabed cables and between the stationary vessel and seabed cables, including acoustic modems, hardwire copper cables or inductive signal transmission through metallic cables (Figure 7). The optimal solution will depend on various factors including the total water depth and the ambient acoustic noise levels at the instrument clusters and in the vicinity of the stationary vessel.

Another key requirement for the real-time ULS ice measurement system, to effectively support ice management, is the real-time data processing and display software operated on the stationary operating vessel. A vessel-based workstation, with purpose designed software, will process the raw IPS and ADCP data obtained in real-time through the subsea system described above. As we have seen, many elements of the software have already been developed through the previous real-time ULS measurement systems operated in the past decade. In addition, development of the algorithms for the detection of hazardous ice features is well advanced. However, the development of fully integrated software system to process and display large quantities of incoming ULS data combined with reliable real-time detection and display of potentially hazardous ice features at each of several measurement sites is a central requirement to the entire ULS ice information support system.

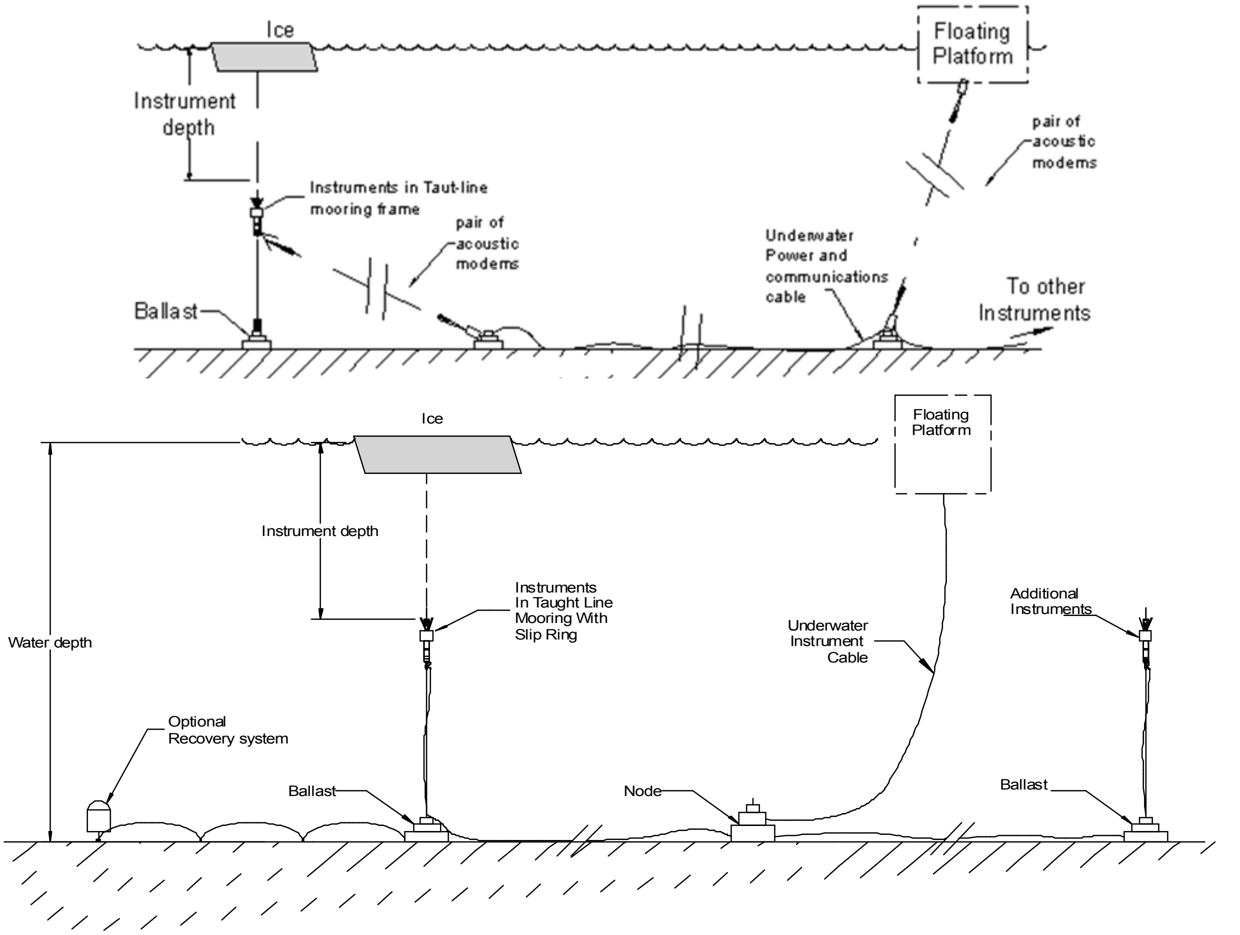

Figure 7: Vertical data communication configurations options include (upper acoustic modems or (lower) hardwire copper cables or inductive modem transmission through metallic cables.

The real-time data acquisition and processing system consists of a number of computer programs running on a computer workstation onboard the vessel platform. The system would be composed of industry standard computers, operating systems, and Database Management Systems (DBS). The display system would incorporate WEB technology to display data and control the systems from an industry standard PC. An overview of the real-time ULS ice information work station software is presented in Figure 8.

Data acquisition programs would control and acquire the IPS and ADCP data from the subsurface system and atmospheric pressure, wind speed and wind direction from a weather station located on the platform. The raw data would be stored as time series data in the DBS. Additional data processing would retrieve and process the raw data in real time to compute oceanographic quantities such as ice draft, water level and water currents and store these quantities in the DBS. The processing system would continually update graphs to display the incoming data from each of the separate station locations.

A second series of processing programs would compute the time series ice data and ice velocity data. From these time series ice data, the ice draft distance series data (see Figure 3) will also be computed. For this real-time application, the ice draft time and distance series will have some uncertainties that will require quality control processes to identify and eliminate outlier ice draft values, and deal with uncertainties in ice velocities that preclude accurate determination of the ice draft distance series, during times of moderate to low ice concentrations. Another ice velocity feature of interest would be very low ice velocities indicative resulting from internal ice stress under high ice concentrations; such occurrences represent a potential ice hazard condition for marine operations.

The third set of processing programs produce additional products to support a decision making system. These products would include the identification and documentation of episodes of large ice keels, large hummocky ice, fast moving ice, rapidly changing ice direction and the probability of the presence of old ice. Examples of the first two types of ice hazards are shown in Figure 9. These data segments with detected episodes of potential ice hazards would be stored in the DBS.

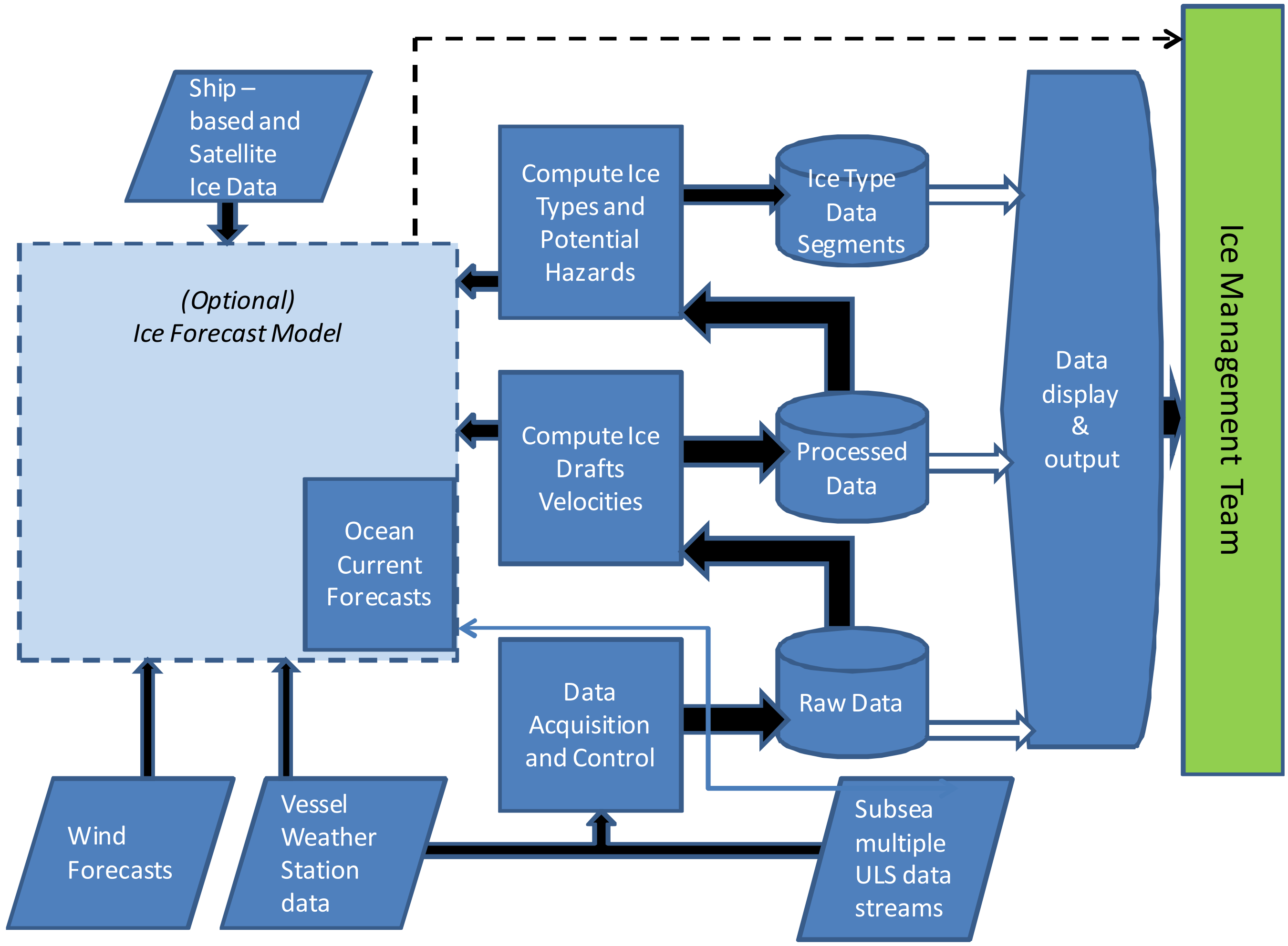

Figure 8: A high level diagram of the real-time vessel-based workstation software for the ULS ice information system. Also shown is an optional ice forecast system and its information feeds from the ULS data and software system modules.

The display and output system will include a clear and highly visible warning functionality providing indicators of potential ice hazards detected at any of the measurement sites. The ice management personnel could then view the detected potential ice hazard and also view selected recent data products obtained for any data processing stage obtained for any of the measurement sites.

The ULS ice information system would be a key input to an optional ice forecast modeling module to support the ice management system. An advanced automated suite of ice and ocean models, incorporating inputs from existing numerical weather prediction models, would forecast ice conditions at the stationary vessel and over an extended operational area using the time series data of ice drafts, ice velocities and ocean currents as well as weather data and forecasts and other sources (surface vessel and satellite) of ice data. The forecasts would be available on the display system with warning systems in place for critical conditions that are forecast to occur based on the data and model outputs.

Summary and Conclusions

To support ice management for stationary vessel operations in the Arctic Ocean, where heavy pack ice conditions occur, a real-time subsea ice monitoring system using upward looking sonars at multiple locations can effectively provide the critical ice information required for ice management. The design of a real-time ULS ice monitoring system will build upon (a) real-time ULS systems which have been successfully operated in other areas over the past decade and (b) on recent advances in algorithms to detect ice types and potential ice hazards from the high resolution ice draft and ice velocities that are measured by ULS instruments. The complementary nature of the subsea ULS measurements, to satellite- and vessel-based data, reduce the risk of safety or environmental problems and increase the operational efficiency of offshore drilling operations.

The two major issues for the real-time ULS ice system design, subsea communications over large operational areas and the real-time software to deal with multiple instrument arrays, have been addressed at a conceptual level as outlined in this paper.

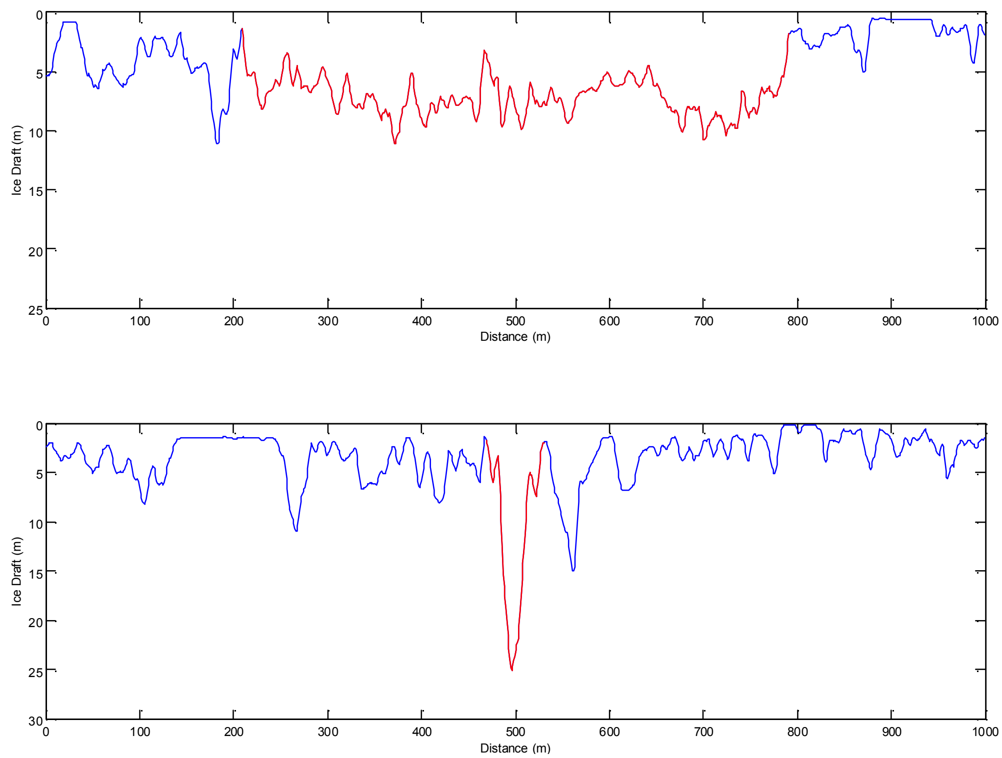

Figure 9: An example of distance ice draft data segments having potential ice hazard conditions (upper: hummocky ice and lower: very large ice keel), as realized by the ice type and potential hazard computing process.

Acknowledgements

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