Advances in Moored Upward Looking Sonar Systems for Long Term Measurement of Arctic Ice and Oceanography

David B. Fissel, Rene A.J. Chave, Murray Clarke,
Paul Johnston, Keath Borg, John R. Marko, Ed Ross,
Jan Buermans and Matthew Stone

ASL Environmental Sciences Inc.
Victoria BC Canada
dfissel@aslenv.com

Abstract—**A major impetus for scientific studies of climate change in the Arctic Ocean has been the reduction in the areal extent and thickness of its sea ice cover which has been experienced at accelerated rates in the past decade. These dramatic changes resulted in major climate science studies being conducted in the Arctic Ocean as well as opening the way for increased shipping and offshore oil and gas activities. An extended measurement record of the horizontal dimensions of this ice cover is available for the full Arctic Ocean Basin based upon a record compiled from nearly 40 years of relatively continuous satellite based measurements. Unfortunately, data accumulations for the ice cover's vertical dimension, i.e. sea ice thickness, as well as full temporal resolution ice velocity and under-ice ocean current profiles tend to be limited to a small number of year-long mooring data sets with durations that are only a few to several years, reflecting underlying greater measurement challenges. Moreover, the longest duration ice thickness data collection efforts, spanning more than 10 years, have been confined only to two specific portions of the Basin, namely, Fram Strait and the Canadian sector of the Beaufort Sea. However, in the past ten years, the available year-long ice and oceanographic mooring data sets have greatly increased in total number and in the number of sites.**

Advanced upward-looking sonar (ULS) instruments operated from subsurface moorings has been and continues to be the primary source of data with volumes and accuracy sufficient for meaningfully monitoring ice thickness, ice velocities, ocean current profiles and other in-situ water properties. The ice thickness, or more properly ice draft (underwater ice thickness) data is measured continuously with temporal resolution of 1 -2 seconds. Technological advances, since ULS instruments were first developed in the 1980's have led to new generations of ice-profiling sonar (IPS), incorporating much expanded on-board data storage capacities (up to 16 Gigabytes) and powerful real-time firmware which now allow unprecedented temporal (ping rates of up to 1 Hz). When combined with ULS Acoustic Doppler Current Profiler (ADCP) instrumentation using a special ice tracking mode (with a temporal resolution of a few minutes), details of the ice topography can be realized to resolutions of better than 0.1 m in the vertical and 1 m in the horizontal. These very high resolution ice draft measurements fully resolve individual ice features including undeformed level ice, brash ice, individual large ice keels including multi-year ice, hummocky ice rubble fields, glacial ice including icebergs and ice islands, and open water interruptions of the ice cover including leads between ice floes. Such continuous highly detailed ice measurements, along with concurrent measurements of ice velocities and ocean current profiles, are essential to understandings of mechanical and thermodynamical aspects of sea ice processes which govern ocean-atmosphere exchanges in polar waters, thereby determining ice extent and thickness parameters. The ice profiler ULS instrument can sample at higher sampling frequencies to measure non-directional ocean wave spectra and parameters (significant and individual maximum wave heights and peak periods) both during the period of mostly open water, often from mid-summer to mid-autumn, and also when ocean waves propagate into the periphery of the Arctic Ocean pack ice. Ocean wave interactions with pack ice are important in understanding the fracturing of sea ice floes and hastening the deterioration and melt of sea ice. The ULS data provide the first detailed measurements of such ocean wave – ice processes.

A major challenge in moored ULS measurement systems is the inaccessibility of the measurement sites to ship logistics due to the very remote areas in the Arctic Ocean and its peripheral seas and the difficulty, resulting in very high logistic costs, of deployment and servicing the moorings due to the sea ice itself. This challenge is being addressed through the development of expanded capacity and more efficient internal power capability and increased onboard data storage, along with very high instrument reliability. With expanded alkaline battery packs, continuous operation for 2 to 3 years is now possible; lithium battery packs are being developed that will extend the in-situ ULS instrument operation to approximately five years.

To provide access to the ULS data between mooring servicing intervals, two different approaches are being developed. In some areas cabled underwater observatory technology can be installed to provide real-time access to the ULS ice measurements in support of navigation and oil and gas exploration activities as previously described in Fissel et al. (2009) for sub-Arctic applications. The first such ocean observatory involving a ULS ice instrument was commissioned at Cambridge Bay in the Canadian Arctic in September 2012. At locations far from shorelines, the challenges become even greater. For offshore oil and gas drilling applications, an array of subsurface ULS moorings spanning distances of tens of kilometers, interconnected via bottom mounted fiber optics cable systems interfaced to the moored ULS instruments and to vessel platforms using acoustic modems, have been designed to provide tactical support for ice management operations in support of drilling activities. An alternative approach to provide yearly access to the multi-year moored ULS data sets is the development of small expendable buoyant "datapods" which store the ULS data on flash cards; during times of open water or very thin ice,

the datapods are released from the mooring to float to the surface and the ULS data is then transmitted via satellite to provide remote access to the scientific users. There are variations on this approach involving aircraft landing on sea ice in the vicinity of the subsurface ULS moorings to access the data via on-command acoustic modem transmission of the data to acoustic receivers operated through ice holes.

Keywords— Arctic Ocean; Sea Ice; Upward Looking Sonars; Ice Profiling Sonar; Acoustic Doppler Current Profiler; Ice Dynamics; Ocean Observatory

I. INTRODUCTION AND BACKGROUND

A. *Impetus for Arctic Ice-Ocean Monitoring Programs*

A major impetus for scientific studies of climate change in the Arctic Ocean has been the reduction in the areal extent and thickness of its sea ice cover which has been experienced at accelerated rates in the past decade [1] as shown in Fig. 1. These dramatic changes resulted in major climate science studies being conducted in the Arctic Ocean as well as opening the way for increased shipping and offshore oil and gas activities.

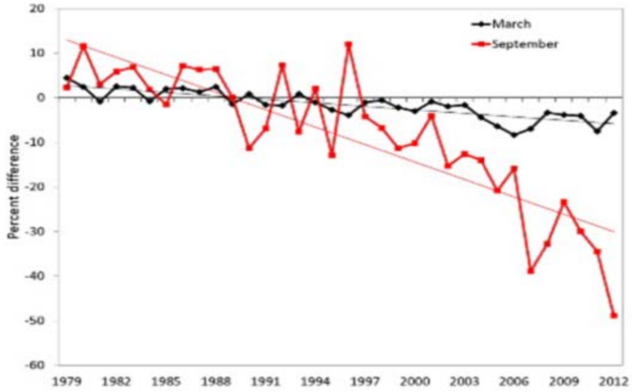


Fig. 1. Time series of the percent difference in Arctic ice extent in March (the month of ice extent maximum) and September (the month of ice extent minimum) relative to the mean values for the period 1979–2000 (Perovich et al., 2012).

B. *Ice Thickness – Long Term Measurements*

An extended measurement record of the horizontal dimensions of this ice cover is available for the full Arctic Ocean Basin based upon a record compiled from nearly 40 years of relatively continuous satellite based measurements [1]. Unfortunately, data accumulations for the ice cover's vertical dimension, i.e. sea ice thickness, as well as full temporal resolution ice velocity and under-ice ocean current profiles tend to be limited to a small number of year-long mooring data sets with durations that are only a few to several years, reflecting underlying greater measurement challenges [2]. Moreover, the longest duration ice thickness data collection efforts, spanning more than 10 years, have been confined only to two specific portions of the Basin, namely, Fram Strait [3] and the Canadian sector of the Beaufort Sea [4]. However, in the past ten years, the available year-long ice and oceanographic mooring data sets have greatly increased in total number and in the number of sites (Fig. 2).

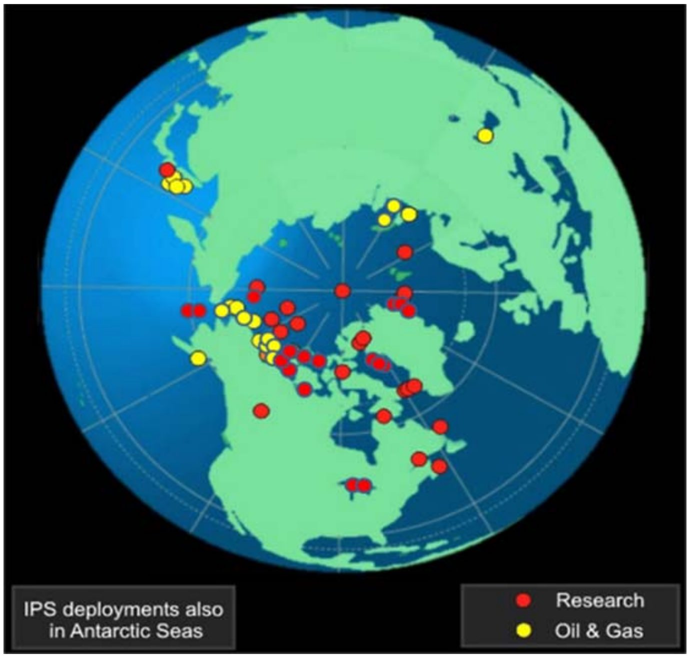


Fig. 2. Locations of marine moored ice profiler deployments in the Northern Hemisphere from 1996 to the present. Ice profiler locations for scientific applications are shown by red symbols while oil and gas locations are shown by yellow symbols.

II. MOORED UPWARD LOOKING SONAR (ULS) MEASUREMENTS

A. *ULS Instrumentation and Moorings for Long-Term Measurements*

Since initial developments in the mid 1970's, advances in ULS technologies have allowed ever more accurate and information-rich extraction of data on the draft, undersurface topography and immediately adjacent water column environment of polar and other marine ice covers. The initial motivation for such developments was to extend ice thickness measurement capabilities beyond ULS sounders mounted on U.S. and British submarines as well as deployments of airborne- sensors such as laser profilometers and electromagnetic (EM) induction instrumentation. Access to submarine platforms became problematic in the mid-1990's. The airborne measurement approaches involve considerable logistical costs and efforts and yet were characterized by intrinsic limitations in accuracy and resolution which significantly degraded data quality from that available using ULS sensors. In the past decade, satellite-based ice thickness measurement capabilities have been developed (e.g. the IceSat and CryoSat programs) although the horizontal resolution is much larger, typically 100-250 m, than for the 1-2 m ULS sensors and the accuracy is reduced especially for thicker ice.

The more modern acoustic profiling technologies were based upon instrumentation designed to be deployed 25 to 50 m below the air water interface from sea floor based moorings or, in shallower water, from bottom-mounted platforms. In its most extensively productive form [5] the instrument operated by emitting and detecting surface returns from frequent short pulses (pings) of acoustic energy concentrated in narrow beams (less than 2° at half power). Precise measurements of the delay times between ping emission and reception were converted into ranges separating the instrument's transducer and the ice undersurface. Contemporary data from the instrument's on-board Paroscientific Digiquartz^{TM} pressure sensor were 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 emitted ping.

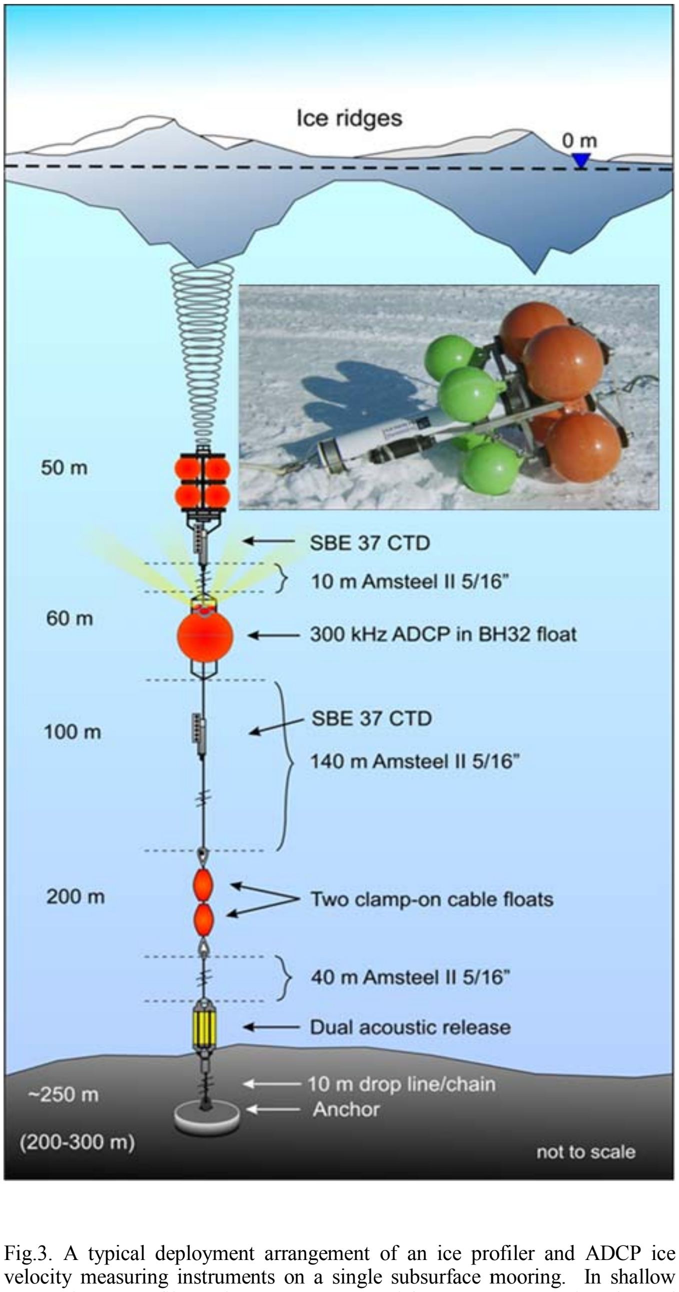


Fig.3. A typical deployment arrangement of an ice profiler and ADCP ice velocity measuring instruments on a single subsurface mooring. In shallow waters the Ice Profiler and ADCP are operated from separate moorings located within 100 m of one another.

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 ocean regions for many years (Fig. 2). These instruments, which record data internally, are operated from subsurface moorings (Fig. 3) that are deployed and recovered by ship during times of minimal sea ice coverage.

The IPS is an existing and proven instrument originally developed by Dr. H. Melling of the Institute of Ocean Sciences (IOS) of the Canadian Dept. of Fisheries and Oceans [5]. Since 1996, the IPS instrumentation has been manufactured by ASL Environmental Sciences Inc., of Victoria BC Canada, first as the model IPS4. The instrument is capable of providing real-time output via a RS-232/422 serial data protocol. The IPS has become the industry standard for upward looking sonar measurements of sea ice keels, and it is has been widely used for one year or longer deployments in the Arctic Ocean and marginal ice zones. Because of the extended deployment periods, the instrument features very low power consumption and operates over one year periods or longer using an internal 8 layer alkaline battery pack

A new generation of Ice Profiler instruments became available in 2008 [6] which provide enhanced capabilities (Table 1) 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 IPS5's 16-bit data resolution, low power consumption and up to 8-Gbyte memory capacity now permit multiple mode (up to 12) operation in which information on up to 5 separate targets can be measured and stored for each ping. Combined with the larger dynamic range, the backscatter returns of ice features were reduced so as to be below the A/D limiting value which makes ice targets more identifiable. Also, the echoes from separately programmed "bursts" of pings can be recorded over the entire water column above the instrument with a vertical resolution of 1.1 cm. These innovations greatly expand the versatility of the IPS technology and permit the collection of data from the upper ocean which significantly augments that gathered from the ice cover itself. Thus, for example, improved accuracies in extracted ice draft values can be expected as a consequence of more confident identification of the zero ice draft targets which are used to determine the time varying average speed of sound in the upper water column.

At the usual ping rate of 1 Hz, and with typical ice velocities of < 0.1 to 0.8 m/s, the instrument can fully resolve ice keel features at a resolution of 2 m or better. With suitable data processing, the accuracy of the 1 Hz ice draft values is 0.1 m. A sample segment of IPS derived ice drafts, spanning less than 3 hours, is shown below in Fig. 4.

TABLE I. The improved features of the Ice Profiler Sonar model IPS5 with comparisons to the model IPS4.

Parameter	**IPS-4**	**IPS-5**
Year Introduced	1996	2008
Sample Rate	up to 1 Hz	up to 2 Hz
Data Storage	68/128 MB	2 to 8 GB
A/D Resolution	8 bits	16 bits
Receiver Gain	standard	variable
Power Consumption	up to 2 years	improved
Multiple Phases	8	12
Targets per Ping	1	up to 5
Full Water Column Profiles	Limited	User selectable
Wave Measurement Mode	Not Available	2 Hz Burst Sampling

B. *Derived Ice-Ocean Parameters*

The very high resolution IPS ice draft measurements fully resolve individual ice features including undeformed level ice, brash ice, individual large ice keels and open water interruptions of the ice cover including leads between ice floes (Fig. 4).

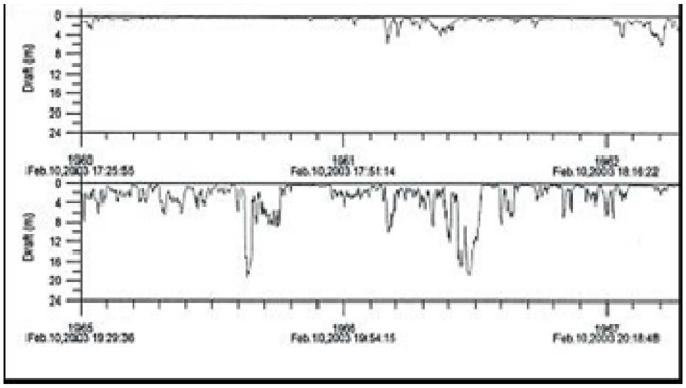


Fig.4. A quasi-spatial profile of an ice cover produced by combining time series draft and ice speed data to produce a product equivalent to the profile of the ice undersurface along a line traced out by all points on the ice which move over the ice profiler instrument during the measurement period. The abscissa is in kilometers, annotated with time of observation.

Characterization of potentially hazardous ice features from the high resolution ice draft measurements can be made [7] for:

- Large individual sea ice keels which can have vertical dimensions of 10 m or more (as shown in the lower panel of Fig. 4);
- multi-year ice which is stronger and generally thicker ice which has survived over at least two consecutive summers. This type of ice feature can be identified through its strong concentrated acoustic returns and its relatively smooth underside profile;
- hummocky ice rubble fields, which is continuous sea ice cover that has a relatively large ice draft, e.g. exceeding 2 m, and which spans large horizontal distance scales of hundreds of metres or more;
- glacial ice including icebergs and ice islands that have formed from tidewater glaciers or ice sheets.

Such continuous highly detailed ice measurements along with concurrent measurements of ice velocities and ocean current profiles, are essential to understandings of mechanical and thermodynamical aspects of sea ice processes which govern ocean-atmosphere exchanges in polar waters, thereby determining ice extent and thickness parameters. Moreover, the measurements of potentially hazardous ice features has proven to be an important data input to the design of offshore platforms and operations, including ice management in support of offshore oil and gas activities in marine ice infested waters.

C. *Ocean Wave Measurements*

The ice profiler ULS instrument can sample at higher sampling frequencies to measure non-directional ocean wave spectra and parameters (significant and individual maximum wave heights and peak periods) both during the period of mostly open water, usually from mid-summer to mid-autumn. An analysis of long-term IPS5 measurements in the Canadian Beaufort Sea starting in 2001 and in the Eastern Alaskan Arctic starting in 2005 [8] reveal a trend towards an increasing duration of episodes of relatively large ocean waves, with considerable year-to-year variability. Wave episodes, exceeding 8 m in significant wave height, exceeded the 25 return period values based on wave model hindcast study results which span the period from the mid-1980's to the mid-2000's, suggesting that there is a trend to larger waves in association with trend towards reduced summer and fall sea ice cover [8].

In addition, the ice profiler instruments provide highly detailed measurements of the propagation of ocean waves into the periphery of the Arctic Ocean pack ice. Ocean wave interactions with pack ice are important in understanding the fracturing of sea ice floes and hastening the deterioration and melt of sea ice. The ULS data provide the first detailed measurements of such ocean wave – ice processes [9].

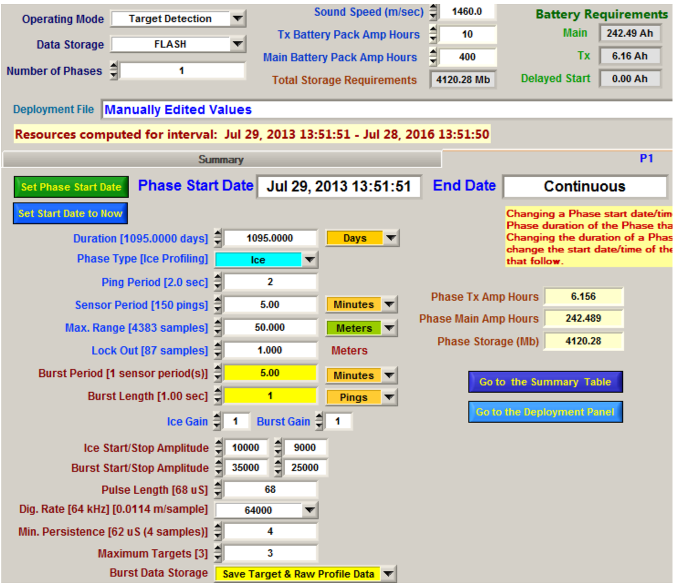
III. ONGONG IMPROVEMENTS TO ADDRESS MEASUREMENT CHALLENGES

Since the release of the IPS5 model in 2008, additional improvements to the technology have been introduced or are presently in development. The most pressing and demanding challenge for ULS moorings is addressing the inaccessibility of the measurement sites to ship logistics due to the increasingly very remote areas in the Arctic Ocean and its peripheral seas and the difficulty, resulting in very high logistic costs, of deployment and servicing the moorings due to the sea ice itself.

A. *Extended Multi-Year Mooring Operations*

This challenge is being addressed through the development of expanded capacity and more efficient internal power capability and increased onboard data storage. In 2012, larger alkaline battery packs were introduced using an extended pressure housing that allows a maximum capacity of 250 Amp

Hour (Ah), up from the maximum battery capacity of 200 Ah with the standard pressure housing. The continuous operation of the IPS5 instrument is now possible for 2 to 3 years, at an instrument depth of 40 m (corresponding to maximum range setting of 50 m), as can be seen in the example of deployment file of Fig. 5. In early 2013, a lithium battery pack kit was developed for the IPS5 in conjunction with an existing Woods Hole Oceanographic Institution (WHOI) lithium battery pack system that provides an even larger battery capacity of 400 Ah at 12 VDC. This battery capacity along with a second transmit battery pack of 20Ah @ 15V (Vtx) provides sufficient battery capacity that should support up to 5 years of continuous operation of an IPS5 instrument operated at 40 m depth and up to four years for an IPS instrument operated at 65 m depth.



Operating Mode: Target Detection
Data Storage: FLASH
Number of Phases: 1
Sound Speed (m/sec): 1460.0
Tx Battery Pack Amp Hours: 10
Main Battery Pack Amp Hours: 400
Total Storage Requirements: 4120.28 Mb

Battery Requirements
Main: 242.49 Ah
Tx: 6.16 Ah
Delayed Start: 0.00 Ah

Deployment File: Manually Edited Values
Resources computed for interval: Jul 29, 2013 13:51:51 - Jul 28, 2016 13:51:50

Phase Start Date: Jul 29, 2013 13:51:51
End Date: Continuous

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that follow.

Duration [1095.0000 days]: 1095.0000 Days
Phase Type [Ice Profiling]: Ice
Ping Period [2.0 sec]: 2
Sensor Period [150 pings]: 5.00 Minutes
Max. Range [4383 samples]: 50.000 Meters
Lock Out [87 samples]: 1.000 Meters
Burst Period [1 sensor period(s)]: 5.00 Minutes
Burst Length [1.00 sec]: 1 Pings
Ice Gain: 1
Burst Gain: 1
Ice Start/Stop Amplitude: 10000 9000
Burst Start/Stop Amplitude: 35000 25000
Pulse Length [68 uS]: 68
Dig. Rate [64 kHz] [0.0114 m/sample]: 64000
Min. Persistence [62 uS (4 samples)]: 4
Maximum Targets [3]: 3
Burst Data Storage: Save Target & Raw Profile Data

Phase Tx Amp Hours: 6.156
Phase Main Amp Hours: 242.489
Phase Storage (Mb): 4120.28

Fig.5. An example of a three year deployment with a 250 Ah rated battery. The IPS5 unit will ping once every two seconds looking for targets up to 50 Meter range. It will sample Temperature, Pressure, Tilt X and Tilt Y as well as store a complete water column profile every 5 minutes. The deployment will acquire a total of 47,304,000 pings.

B. *Near-Real Time Data Access from ULS Moorings*

Extending the mooring operation capacity to multiple years will results in a very long time to access the ULS data sets from the moorings. To provide more timely access to the ULS data between mooring servicing intervals, two different approaches are being developed. In some areas cabled underwater observatory technology can be installed to provide real-time access to the ULS ice measurements in support of navigation and oil and gas exploration activities as previously described in [10] for sub-Arctic applications. The first such ocean observatory involving a ULS ice instrument was commissioned at Cambridge Bay in the Canadian Arctic in September 2012[11]. Plans are in place to operate ULS ice sonars in 2014 on a cabled observatory off Gascoyne Inlet in western Lancaster Sound, as part of the Defense Research and Development Canada Northern Watch system. Other sites for cabled ULS ice sonars are under consideration including one off eastern Baffin Island and another off the Port of Churchill in Hudson Bay.

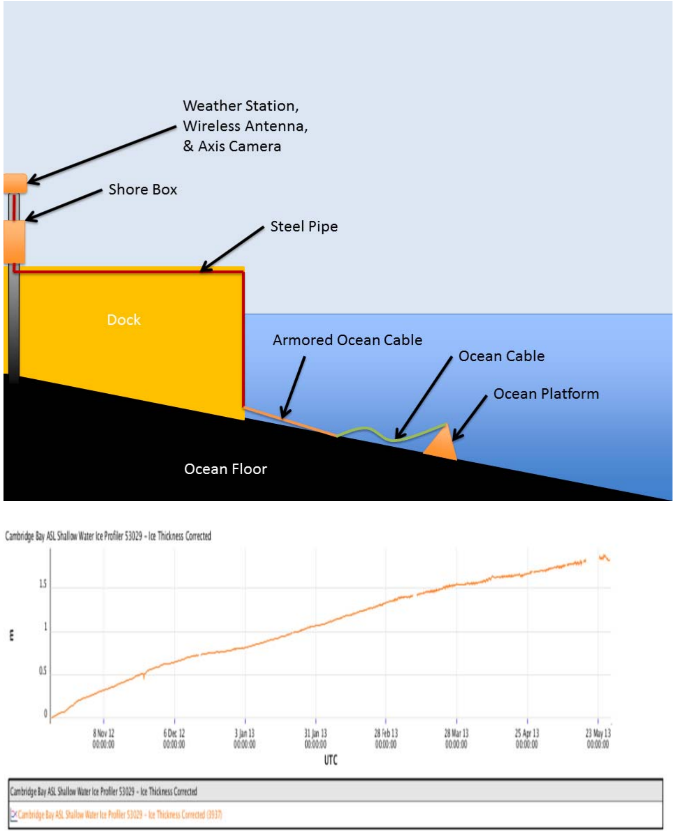

Fig.6. A schematic diagram of the nearshore cabled ocean observatory (upper panel) at Cambridge Bay, NWT Canada [11] which was installed in September 2012. The lower panel displays the real-time ice thickness data obtained from a Shallow Water IPS5 instrument from October 2102 (ice formation) through to May2013.

At locations far from shorelines, the challenges become even greater[12]. For offshore oil and gas drilling applications, an array of subsurface ULS moorings spanning distances of tens of kilometers, interconnected via bottom mounted fiber optics cable systems interfaced to the moored ULS instruments and to vessel platforms using acoustic modems (Fig. 7), have been designed to provide tactical support for ice management operations in support of drilling activities[10, 16].

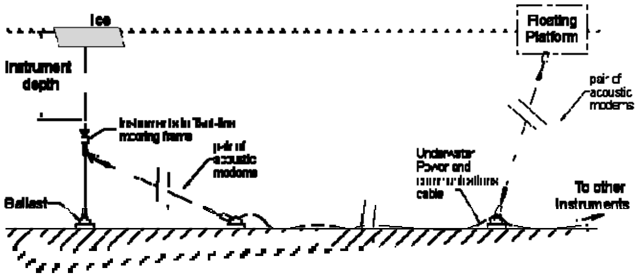

Fig.7. A schematic diagram of a remote real-time deep-water cabled observatory system [16].

An alternative approach to provide yearly access to the multi-year moored ULS data sets is the development of small expendable buoyant “datapods” which store the ULS data on flash cards; during times of open water or very thin ice, the datapods are released from the mooring to float to the surface and the ULS data is then transmitted via satellite to provide remote access to the scientific users. There are variations on this approach involving aircraft landing on sea ice in the vicinity of the subsurface ULS moorings to access the data via on-command acoustic modem transmission of the data to acoustic receivers operated through ice holes. Work on the datapods for ULS moorings is presently at a conceptual design stage and will require considerable development effort to proceed further.

C. Adaptation of ULS Ice Sonars to Autonomous Underwater Vehicles (AUV) platforms

Over the past ten years, the IPS5 instrument has been adapted so as to operate on various AUV platforms to provide near-real time data for sea ice measurement programs. The AUV missions include those of the Monterey Bay Aquarium Research Institute [13, 14], Hokkaido University and the DAMOCLES Project (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies) [15] for sea ice missions and the Memorial University of Newfoundland for underwater profiling of icebergs. Going forward, the AUV platforms provide the capability for detailed near-real time ice measurement programs operated from Arctic-capable vessels or ice camps supported by aircraft logistics.

D. Other Present and Planned Improvements

Other presently planned improvements to the ULS mooring instrumentation include:

- Log Sonar electronics (status: presently underway): the existing linear analog electronics for transducer signal processing will be replaced by logarithmic detector circuitry that provides improved consistency in the output voltages and a larger dynamic range.
- Expanded flash data storage (status: presently underway): testing and firmware changes are being made which will allow the use of 16 Gigabyte flash cards. Further expansion of flash card capacity may be feasible in the future to 32 and 64 Gigabyte capacity.
- Improved calibration of acoustic backscatter returns from IPS5 instrument (status: planned for 2013-2014): when the log sonar analog electronics is in place, improved calibration procedures for the acoustic backscatter returns will be implemented to realize calibrated target strength measurements to better than 2-3 dB.
- Multiple transducer systems for 3 D profiling (status: waiting on market requirements): With the additional battery capacity recently achieved, a multiple transducer configuration can be developed to allow for up to four transducers. One transducer would continue to be operated in the vertical as this provides the greatest accuracy for ice draft measurements. The other three transducers would be operated at 30-40 degrees from the vertical so as to provide three dimensional measurements of ice draft features rather than the present two dimensional ice profiles.

In addition, the IPS Toolbox set of software programs are continuously undergoing updates and the addition of new programs for more advanced sea analyses. The IPS Toolbox software package includes more than 200 individual programs that are available in either Matlab or as standalone executable versions.

IV. SUMMARY AND CONCLUSION

The development of advanced upward looking sonar (ULS) technology for measurements of marine ice has been underway for over 20 years, primarily using subsurface moorings with unattended operation for periods of one year or longer. The ULS technology provides very high accuracy and unprecendented resolution (1 m in the horizontal) for underwater ice thickness using the ASL Ice Profiler Sonar (IPS), as well as providing direct measurements of ice velocities from Acoustic Doppler Current Profilers (ADCP). From the combined ice draft and ice velocity measurements, quasi-spatical ice draft profiles are routinely measured that provide data on thousands of kilometers of the underside of the sea ice cover passing over the mooring measurement site.

These very high resolution ice draft measurements fully resolve individual ice features including undeformed level ice, brash ice, individual large ice keels including multi-year ice, hummocky ice rubble fields, glacial ice including icebergs and ice islands, and open water interruptions of the ice cover including leads between ice floes. Such continuous highly detailed ice measurements, along with concurrent measurements of ice velocities and ocean current profiles, are essential to understandings of mechanical and thermodynamical aspects of sea ice processes which govern ocean-atmosphere exchanges in polar waters, thereby determining ice extent and thickness parameters.

The capabilities of the ULS instrumentation has greatly expanded over the past 20 years, taking advantage of technological advances in miniaturized electronics and computer processor modules, as outlined in this paper.

Further developments are presently underway and planned over the next few years to develop further capabilities. The most pressing issue is the inaccessibility of the measurement sites to ship logistics due to the very remote areas in the Arctic Ocean and its peripheral seas and the difficulty, resulting in very high logistic costs, of deployment and servicing the moorings due to the sea ice itself. This challenge is being addressed through the development of expanded capacity and more efficient internal power capability and increased onboard data storage, along with very high instrument reliability. A related requirement is developing more timely access to the measurements since extending the mooring operation capacity to multiple years' results in a very long time to access the ULS data sets from the moorings. To provide more timely access to the ULS data between mooring servicing intervals, different approaches are being developed: real-time data links from the moored instrumentation via cabled and/or acoustic modem links to shore- or vessel-based platforms having satellite communications; the potential use of small expendable buoyant "datapods" which store the ULS data on flash cards; during times of open water or very thin ice, the datapods are released from the mooring to float to the surface and the ULS data is then transmitted via satellite to provide remote access to the scientific users; and the use of ship or ice-camp based Autonomous Underwater Vehicles (AUVs) equipment with ULS instruments.

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