Testing of Ice Profiler Sonar (IPS) Targets Using a Logarithmic Detector

Ed Ross, Murray Clarke, David B. Fissel, Rene A.J. Chave, Paul Johnston, Jan Buermans and David Lemon

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

***Abstract*— Upward-looking sonar (ULS) instruments have become the primary source of data for high resolution and long duration measurements of sea ice drafts to support engineering requirements for oil and gas exploration projects, along with long-term scientific studies of the underside of the sea-ice canopy in the Arctic and other ice-infested areas. ASL's Ice Profiler Sonar (IPS) has been widely used to provide continuous accurate measurements for ice draft at a horizontal resolution of 1 m, which enables the measurement of ice thickness values over periods from 1-2 seconds up to several years, as well as detailed characterization of many hundreds to thousands of keel shapes and other ice features. In 2014, an important redesign of the IPS instrument was initiated to provide improved performance of the original instrument developed in the 1990s and last upgraded by ASL Environmental Sciences Inc. in 2007- 2008.**

This latest upgrade of the IPS instrument platform is nearing completion with acquisition of a year-long continuous data set from 2014-2015 in the Canadian Beaufort Sea, in order to test the design and implementation of a logarithmic detector module which replaced the previously used linear detector module, which has been used for the past decade in the instrument. The previous linear detector module design dates back to the 1990s and involves the use of an echo sounder detector which generates an analog voltage output from the raw transducer input supplied which is constant, i.e. independent of the time elapsed since the acoustic pulse was originally emitted other than approximate time varying gain (TVG) compensation for different ranges to targets. While this linear detector approach has proven reasonably serviceable, it has the disadvantage that the dynamic range of the instrument is curtailed from the newly designed logarithmic detector module. The larger dynamic range of the log detector vs. linear detector: avoids using the TVG compensation for different ranges to targets; greatly reduces the number of ice target returns that reach the analog-to-digital (A/D) saturation level especially in thin ice; and reduces the need for user-selected discrete threshold values for ice target detection.

In this paper, we report on the outcome of the extended year-long Arctic Ocean testing of the prototype IPS instrument with the logarithmic detector module and derive comparisons of the performance for the new version of the IPS instrument with the previous version using linear detection of targets. The testing for Arctic ice targets revealed that the front end of the logarithmic detector circuitry requires a higher bandwidth to be fully effective with the use of a short pulse width of 68 micro seconds (us). The 68 us pulse width is optimal for ice target detection by comparison to the longer pulse widths which are commonly used for acoustic backscatter applications of the measurement of vertical profiles of multiple scattering such as zooplankton clouds in the water column. The effects for the year-long IPS ice target data set of this attenuation of the measured amplitudes resulting from the effect of the short pulse width relative to the non-optimal bandwidth of the front end of the logarithmic sonar detector module have been simulated. From this transformed data set, the extensive year-long multiple acoustic targets, of up to five for each ping, were analyzed to determine the effects on ice target detection when few, if any ice targets reach A/D saturation levels. In addition, with the greater dynamic range of the logarithmic detector, the capabilities of the sonar instrument were examined with application to discriminating between the representative ice target from: other types of ice scattering off the small scale roughness of the sea ice, especially for thin ice conditions; and for strong backscattering off zooplankton or other types of suspended acoustic scatterers in the water column. Comparisons of the logarithmic IPS sonar results in 30 m water depth vs. the results from a linear IPS sonar operated at the same location two-years earlier are presented for selected episodes of multiple targets and for instances of relatively high levels of acoustic back scattering values within the water column.

I. Ice Profiling Sonar (IPS): Development History

A. Introduction and Principles of Operation

Upward-looking sonar (ULS) instruments have become the primary source of data for high resolution and long duration measurements of sea ice drafts for high resolution scientific studies of the changing ice regime of polar regions. The technology has also been widely used to support engineering requirements for oil and gas exploration projects in Arctic and other ice-infested areas [1]. ULS instruments, in the form of ASL's Ice Profiler Sonar (IPS) continuously collect acoustic data for periods of one year or longer as operated on sub-surface moorings (see Fig. 1). The instruments provide accurate measurements for ice draft on a continuous year-long basis and allow detailed characterization of keel shapes and other ice features. When combined with a companion Acoustic Doppler Current Profiler (ADCP) to measure ice velocities, high resolution ice thicknesses and ice velocities can be obtained along thousands of kilometers of ice which transit over the moored ice profiler location. These measurements provide important data for establishing metocean design criteria related to oil and gas operations in areas with seasonal or year-round ice cover.

The IPS instrument operates by emitting frequent short pulses (pings) of acoustic energy concentrated in narrow beams (1.8° beamwidth) and detecting surface returns [2]. Precise measurements of the delay times between ping emission and reception are converted into distances separating the instrument's transducer and the ice undersurface.

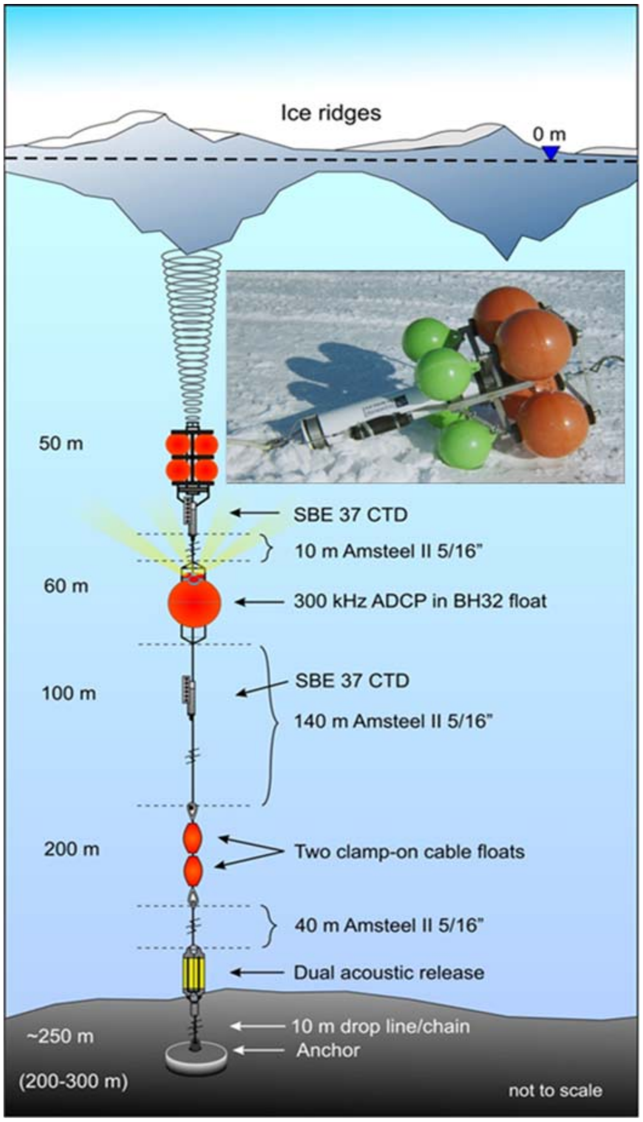

Fig. 1. A typical deployment arrangement of an ice profiler and ADCP ice velocity measuring instrument on a single subsurface mooring.

Contemporary data from the instrument's 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 observations of open water above the instrument) to derive estimates of ice draft from each emitted ping. The IPS can operate continuously for one year at a ping rate of 1 Hz and it provides high precision of approximately ±0.05 m vertical of the underside of the sea ice. When combined with the ADCP instrument located below the IPS instrument, the time series ice draft data can be converted to a quasi-spatial or distances series with a horizontal resolution of approximately 1 m.

B. *Development History*

The ASL IPS is an upward looking sonar device that was purpose-designed for sea ice draft measurements by the Institute of Ocean Sciences (IOS) of the Fisheries and Oceans Canada in the 1990s [3].

The technology was commercialized by ASL in 1996. It was last upgraded by ASL Environmental Sciences Inc. in 2007-2008 through improved instrument design based on more capable microprocessors and more advanced on-board firmware [4]. The additional features of the new IPS5 model as given in Table I included: expansion of the onboard flash data storage from 69 MB to 2GB, then 4 GB and now up to 16 GB; allowing for detection of up to 5 targets per ping rather than the single target detected with the IPS4; increasing the total number of individual sequential sampling selections from 8 to 12; and reduction of overall receiving system gain so that ice targets were not at the saturation limit of the A/D converter. 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.

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	fixed	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

II. IPS LOGARITHMIC DETECTOR: DESIGN OBJECTIVES

An upgrade of the IPS instrument platform was begun in 2014 for the design, testing and implementation of a logarithmic detector module in place of the previously used linear detector module which has been used for the past decade in the instrument.

A. *Present Detector Module*

The existing linear detector module is comprised of three main sections. The first section is an impedance matching pre-amp that provides passive linear gain and bandpass filtering. The second section is a voltage controlled amplifier whose gain is controlled in time relative to the start of the transmitted signal. This Time Varying Gain (TVG) roughly compensates the expected signal loss from attenuation and spreading of the acoustic signal in sea water such that the signal level from identical targets will generate the same DC voltage irrespective of its distance from the instrument. The TVG has four settings, corresponding to different initial gains, with G1 being the lowest and G4 the highest; normally only G1 is used for ice draft measurements. The third section generates an analog DC voltage that is linearly proportional to the peak to peak amplitude of the filtered and gained signal so the 420 kHz echo signal can be digitized by the A/D converter at rates up to 64 kHz.

The effects of the time varying transmission losses are compensated for through a time varying gain (TVG) circuit which only approximately represents the actual transmission losses. While this approach has been successful, it has the limitation of a relatively small "instantaneous" dynamic range at any point in time. This limited dynamic range makes the setup of the instrument more difficult if the user does not want the water-ice and water-air interfaces to be saturated (clipped at the maximum input of the A/D converter). To reduce the clipping problem, the time varying amplifier and the linear detector have been replaced with a "logarithmic" detector that provides a DC voltage for the A/D converter with an instantaneous dynamic range of over 80 dB. The logarithmic detector converts the logarithm of the peak to peak amplitude from the pre-amp/filter into a DC value for the A/D converter. This system was previously developed for the ASL AZFP product line and is now a "proven" technology for delivering high quality sonar data with low power consumption [5]. In addition, the logarithmic sonar detector avoids component obsolescence issues that have been a problem with the older linear detector system and also has manufacturing advantages. The use of the present linear detector module also required the specification of amplitude thresholds for qualifying the detection of targets which were not optimal for short ranges and for very long ranges.

B. Design Objectives and Requirements for the Logarithmic DetectorModule

The log detector has no TVG compensation, instead relying on its large dynamic range to keep the echo signal within the detector's response. In that case, the signal received from a constant strength target will decrease with its range, in accordance with the transmission loss. With the logarithmic sonar detector, the use of discrete user-selected threshold values for detection is avoided and the resulting target detection capability is more robust.

III. Development and Testing of the IPS Log Detector Sonar

The development project involved three principal components: (a) preliminary design and initial construction of a prototype 420 kHz log sonar card; (b) simulations of the response of the IPS log sonar instrument from previous IPS data sets which guided the development of operating firmware for the IPS instrument; and (c) assembly and field testing of a prototype IPS5 unit. The first two components of the development project are summarized in a previous paper [6].

A. Simulation of the IPS5 Log Sonar Detector In Support of the Firmware Development

The development of the operating firmware was started concurrently with the preliminary design phase as described in detail in [6]. Data obtained from many previously collected IPS data sets which had a wide range of signal-to-noise and other types of data attributes were assembled and applied to the firmware development.

These test data from the original IPS instrument digital measurements were converted to the output that would have resulted from the log sonar module (see Fig. 2), through a detailed numerical simulation software system developed for this purpose. These converted profiles were then processed using the new algorithm for target detection with the log sonar module and these targets were then compared to those found by the standard algorithm in the original IPS linear detection module. An example of the output of the software simulation is shown in Fig. 3.

The start and stop amplitudes used in the original data were converted to their logarithmic equivalents (matched at 50 m range), and the same persistence limits were used. For each set of profiles considered for the standard and log versions of the IPS, the number of targets, the difference in the number of targets, and the difference in the index number vs. the profile number were determined. Sample cases where the number of targets detected differed and plots of the signal profile with the start and stop amplitudes are presented in [6].

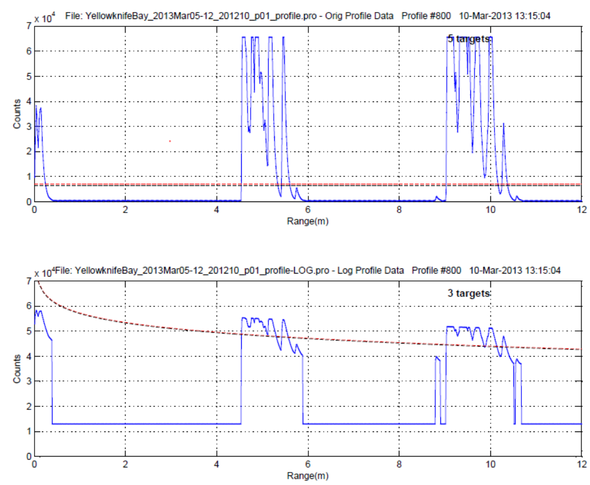

Fig. 2. Converted linear data to log.

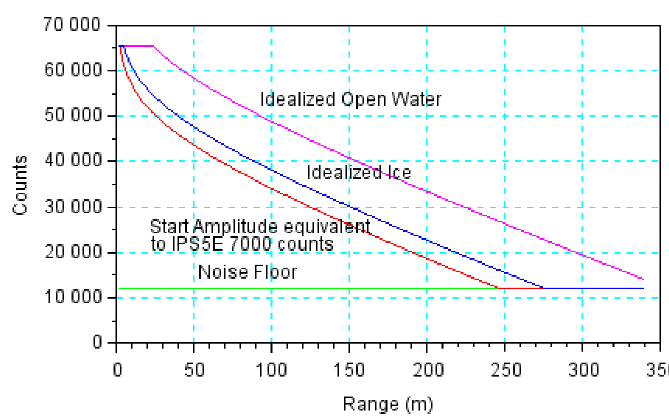

Fig. 3. IPS5L response as a function of range for idealized open water (magenta) and ice (blue). Also shown is the response curve that corresponds to a typical conventional IPS detection threshold of 7000 counts (red) and the IPS5L noise floor (green).

B. Preliminary Field testing of a prototype IPS5- Log Detector unit.

A field test of a prototype version of the IPS5 Log Detector (IPS5L) unit operated alongside a conventional IPS5 (IPS5E) instrumented was conducted in the waters of Saanich Inlet, B.C. Canada near Victoria B.C on June 6, 2014. Detailed results of this preliminary field testing are presented in [6].

In Fig. 3 the response of the IPS5L is shown. The highest estimated returns from the ice are clipped out to just under 20 m while the low returns are out of saturation until the signal drops below the system noise floor out near 270 m. It can also be seen that there is enough dynamic range for returns lower than estimated at the short range and stronger signals at the longer ranges.

IV. EXTENDED FIELD TEST RESULTS, SEPT. 2014 – SEPT. 2015

The next step in the development of the IPS5 log detector sonar was a full year deployment of the IPS5L in the Canadian Beaufort Sea. The IPS5L was operated at a site at which a conventional IPS5 had previously been used, in 2012-2013 during a similar ice season. This allowed extensive comparisons of returns from sea ice of the IPS5L with the conventional IPS5.

This IPS5L instrument was operated over the period Sept. 2014 to Sept. 2015 in the Canadian Beaufort Sea at a site in a total water depth of 30 m. The location of the measurement site is shown in Fig. 4. Ice formation started at the site on 26 October, 2014. Due to shallow water depth and the known occurrence of sea ice keels that can gouge the seabed, the instrument was operated from a near-bottom mooring that was confined to within 5 m of the seabed (see Fig. 5).

Ice formation started at the site on 26 October. Sea ice began to clear from the region in late April/early May. The average ice draft increases to 1.0 m in December and reaches a monthly mean value of 1.6 m in March. The sea ice is heavily deformed with ice drafts of over 16 m for the largest ice keels. As the ice thickens, the motion slows with the ice being fast or immobile for 48 percent of the time in February. As the air temperatures warm and ice growth is much reduced in April, the ice motion becomes continuous as it was in the fall.

The IPS5 data sets were processed using the standard IPS Toolbox software system (www.aslenv.com/toolbox.html). Special data processing was carried out to allow for comparisons to determine the effect of the Log Sonar module on the IPS5 instrument performance in terms of target detectability and dynamic range.

In addition to the acoustic target information (e.g. target range and maximum amplitude) that is determined in firmware for each ping, the IPS instrument can be configured to store the full backscatter amplitude profile for a subset of pings. Fig. 6 shows an example of the amplitude profiles for one month of the IPS5L deployment. Examining the amplitude profiles for both the linear and log IPS datasets enabled: (1) corrections to the recorded amplitude values due to attenuation effects on the IPS5L, (2) corrections to the recorded amplitude values for differences in gain settings used on the two instruments, and (3) consistent target detection algorithm parameters to be applied to both datasets.

The IPS5L was configured to record full backscatter amplitude profiles at a sampling interval of 120 seconds between November 1, 2014 and June 1, 2015 resulting in a total 119,402 recorded profiles. The linear IPS was configured to record full backscatter amplitude profiles at a sampling interval of 120 seconds between November 1, 2012 and May 15, 2013 resulting in a total 139,801recorded profiles.

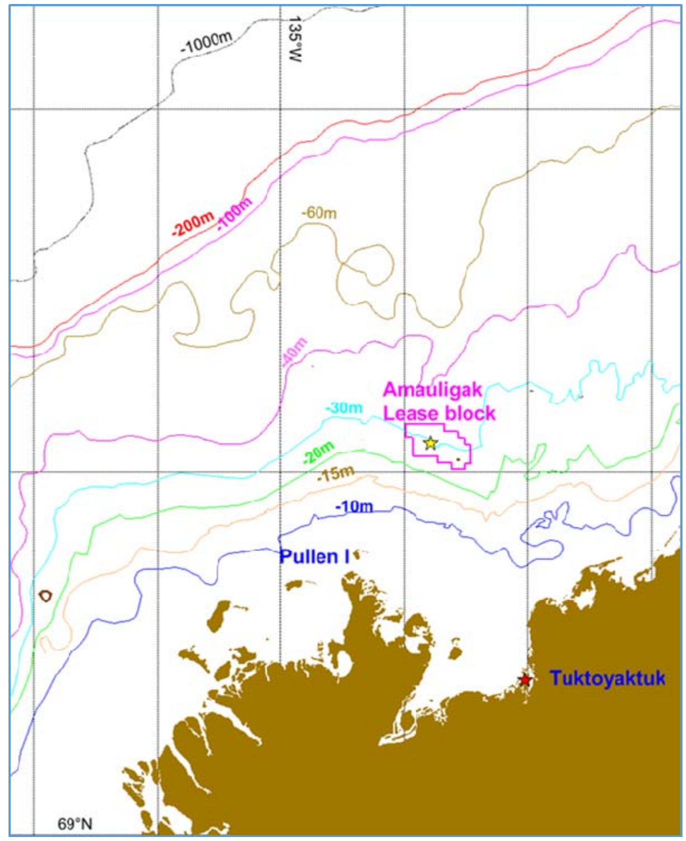

Fig. 4. IPS5L measurement location in the Canadian Beaufort Sea, Sept. 2014 - Sept. 2015.

Fig. 5. Deployment of the IPS5L mooring in the Canadian Beaufort Sea, Sept. 2014 from the CCGS Sir Wlifrid Laurier vessel.

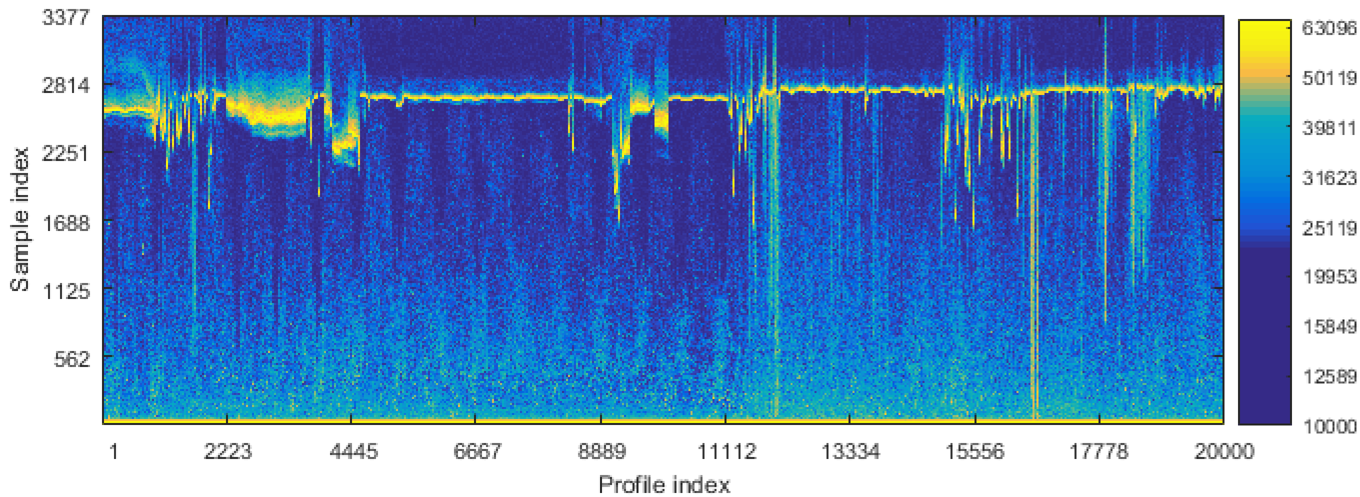

Fig. 6. A segment of the full backscatter amplitude profiles recorded by the IPS5L from February 1, 2015 through March 1, 2015. These profiles were recorded with a sampling interval of 120 seconds throughout the entire deployment. The vertical axis reference is the digitization sample index of the measured backscatter amplitude. This sample index is converted to time since transmission of the acoustic pulse through the digitization rate. These time-of-flight values are then converted to a range using the speed of sound in seawater. The plotted colors represent the backscatter amplitude values and the legend on the right maps the colors to digital counts.

A. Target Detection: Numbers of Valid, False and Null Target Results

Fig. 8 shows the time-series that results from application of the IPS target selection algorithm to the linear and log datasets using target start and stop amplitude thresholds of 10,000 and 9,000, respectively, for the linear IPS and the corresponding start and stop amplitude threshold curves for the IPS5L that were previously determined through simulations of the IPS5L response. The range of all targets (up to 5 for each ping) is plotted and the highest ranked target of each ping is highlighted in red. The IPS5L results show considerably more targets distributed throughout the water column, which is indicative of the increased sensitivity of the IPSL to elevated scattering levels, such as zooplankton targets, within the water column. In contrast, the multiple targets realized by the conventional IPS are highly constrained in range.

In order to further illustrate the difference in capability to detect multiple targets between the IPS5L and conventional IPS, Table II compares the fraction of acoustic pings that realize multiple targets for 0 through 5 targets.

The IPS5L found at least one target in all analyzed pings while 1% of the pings acquired by the conventional IPS were missing targets. Although this typical result for the conventional IPS is satisfactory for the requirements of most applications, the comparison shows an improvement in data completeness achieved by the IPS5L. Reducing null-target gaps in the target time-series can improve ice feature resolution and derived wave parameter accuracy and leads to faster data processing completion times due to fewer steps in the data quality control processes.

The IPS5L consistently acquires more targets across all pings when compared with the conventional IPS. Fig. 7 shows the exceedance curves of pings realizing at least a minimum number of targets from 0 to 5 targets. The IPS5L produced more targets particularly for cases where a single ping lead to 2 or more targets.

TABLE II. COMPARISON OF PERFORMANCE AT DETECTING MULTIPLE TARGETS FOR THE LINEAR AND LOG IPS.

Number of targets	**Fraction of pings realizing multiple targets [%]**	
	Linear IPS	**Log IPS**
0	1.0	0.0
1	80.8	46.3
2	10.6	15.4
3	4.6	8.0
4	1.9	5.7
5	1.1	24.7

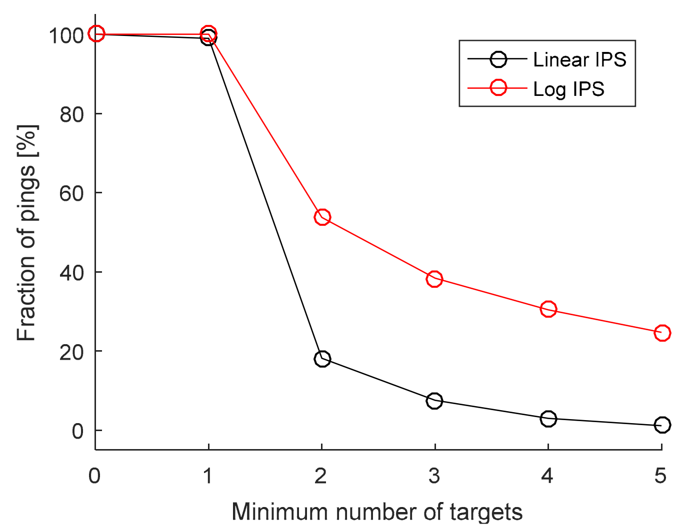

Fig. 7. Exceedance curves of the fraction of acoustic pings that realized a minimum number of targets for the log and linear IPS.

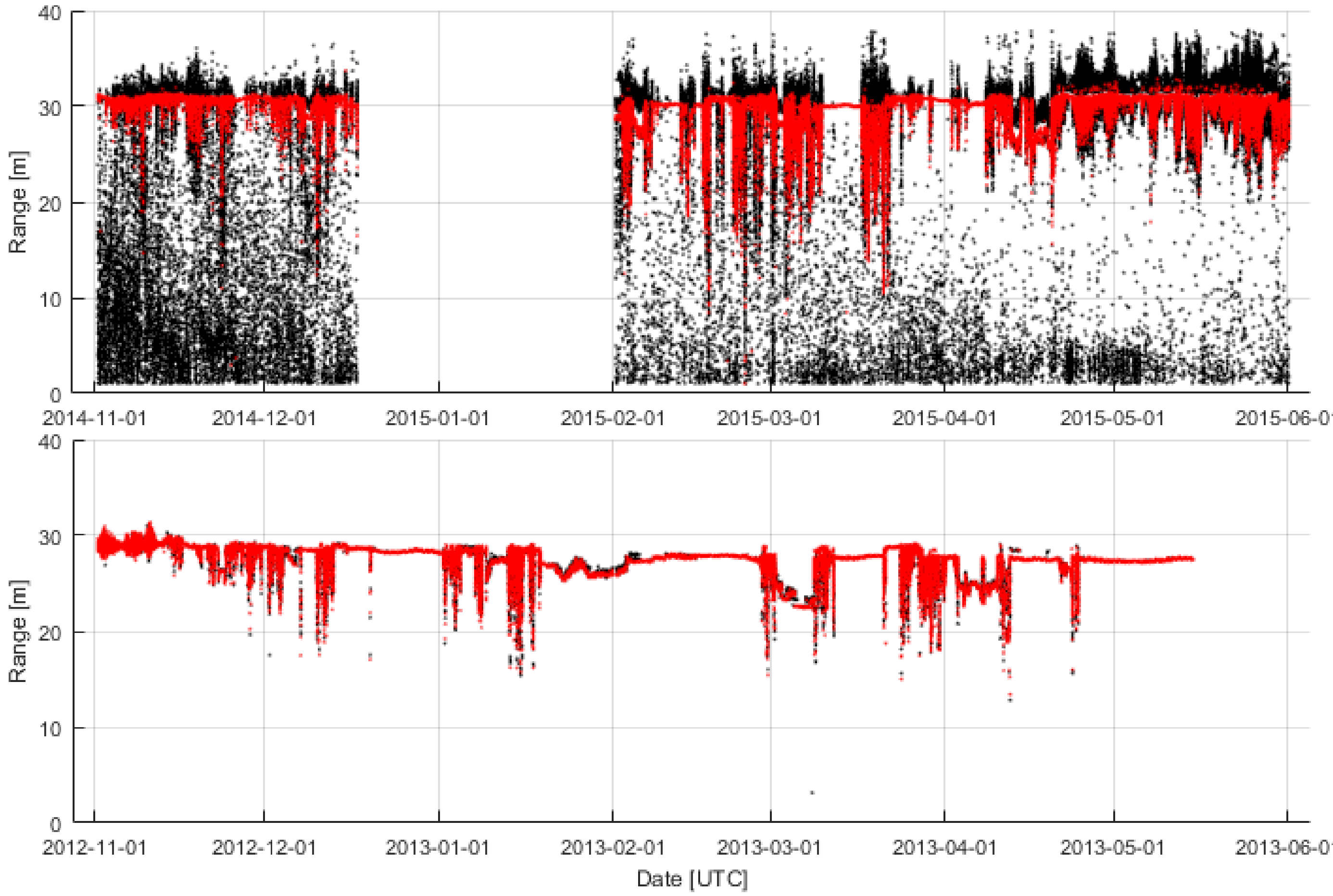

Fig. 8. Time-series of measured target range values for all detected targets for the IPSL (top) and linear IPS (bottom). The range values for the highest ranked targets are highlighted in red. Raw data decoding issues related to the prototype IPS5L lead to a data gap in the backscatter amplitude profiles between December 17, 2014 and February 1, 2015.

B. Sensitivty of the IPS Sonars to Ice and Water Column Back-Scattering Returns

An intended consequence of the greater dynamic range of the IPS5L relative to the conventional IPS is that the fewer acoustic targets have a maximum amplitude that reaches saturation level (Table III). For the subset of acoustic targets that represent the first-ranked target from each ping (the target with the largest persistence above the detection threshold), the smaller dynamic range of the conventional IPS leads to saturation of over 99% of these targets for a representative data set from the same region as the field tests. The large dynamic range of the IPS5L improves this significantly with the majority of targets being unsaturated.

With the majority of target amplitudes from the IPS5L being unsaturated, it is possible to examine the complete acoustic signatures of various types of targets within the amplitude backscatter profiles. We present selected preliminary observations here.

Fig. 9 shows segments of backscatter amplitude profile time-series for thin ice (< 10 cm draft), heavily ridged ice, and open water. The ability to automatically distinguish between these acoustic target types would have several benefits. The range of open water targets are used throughout an IPS dataset to provide an empirical calibration for the time-varying speed of sound in seawater. Identifying open water targets is also important for: (1) masking these targets in an ice draft time-series to prevent the presence of surface waves from contributing to ice draft statistics and identification of ice features and, (2) conversely, selecting open water episodes for derivation of non-directional wave parameters. Open water identification in an IPS target time-series is a time-consuming manual process particularly during the ice shoulder seasons when the ice dynamics and seawater vertical sound speed profiles are highly variable. In order to classify an IPS target as ice or open water, the data analyst depends on supplementary information such as ice charts, local meteorology including air temperature, irradiance and wind speed and direction, in-water temperature and salinity time-series, satellite imagery, and ocean currents and ice velocity time-series. Clearly, an ability for the IPS to classify an individual target as ice or open water based on the acoustic backscatter information only would significantly reduce the data processing and analysis workload and potentially lead to more accurate estimations of ice draft.

There are discerning features between the thin ice and open water backscatter amplitude profile time-series examples in Fig. 9. When surface waves are present during open water, the amplitude profile is approximately symmetric about the air-water interface range. During calm open water conditions, strong amplitude returns from multiple and distinct extended ranges beyond the air-water interface are visible. In contrast, the thin ice profiles are characterized by a steep amplitude gradient in their leading edge, amplitude values that are highly constrained in range about the ice-water interface, and occasionally a strong amplitude return from a single extended range beyond the ice-water interface. Ridged ice presents amplitude profiles with a steep amplitude gradient in their leading edge as with thin ice; however, the amplitude returns beyond the ice-water interface are strong for relatively long range values due to the complex interaction of the acoustic pulse with the highly variable ice undersurface.

Other features are also evident in the IPS5L backscatter amplitude profiles. The first half of the time-series in Fig. 6 appears to show the diurnal cycling of biological acoustic backscatterers vertically through the water column.

Strong backscattering due to bubbles in the open water example of Fig. 9 are evident on the underside of the air-water interface. Identification and characterization of these features and others are potentially of interest for scientific research purposes and as aids in quality controlling the acoustic data when deriving ice draft time-series.

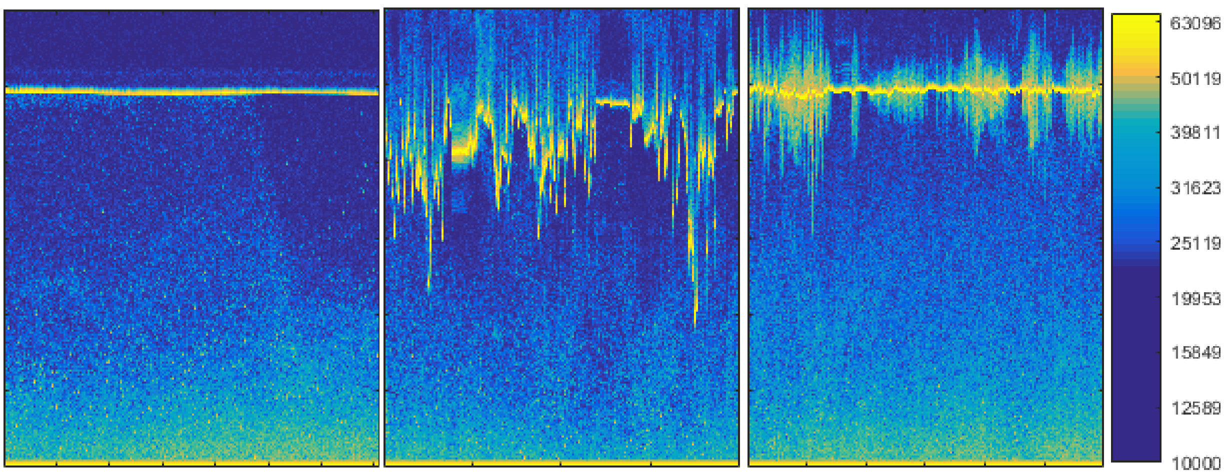

Fig. 9. Backscatter amplitude profile time-series segments for thin-ice (left), heavily ridged ice (center), and open water (right) as measured by the **IPS5L**. The thin ice segment spans from November 2, 2014 05:32 to November 2, 2014 20:12. The heavily ridged ice segment spans from March 17, 2015 22:50 to March 21, 2015 14:16. The open water segment spans from May 14, 2015 04:20 to May 24, 2015 16:34. The vertical scale represents the distance from the IPS5L sonar transducer with the the full scale extending to 38 m range.

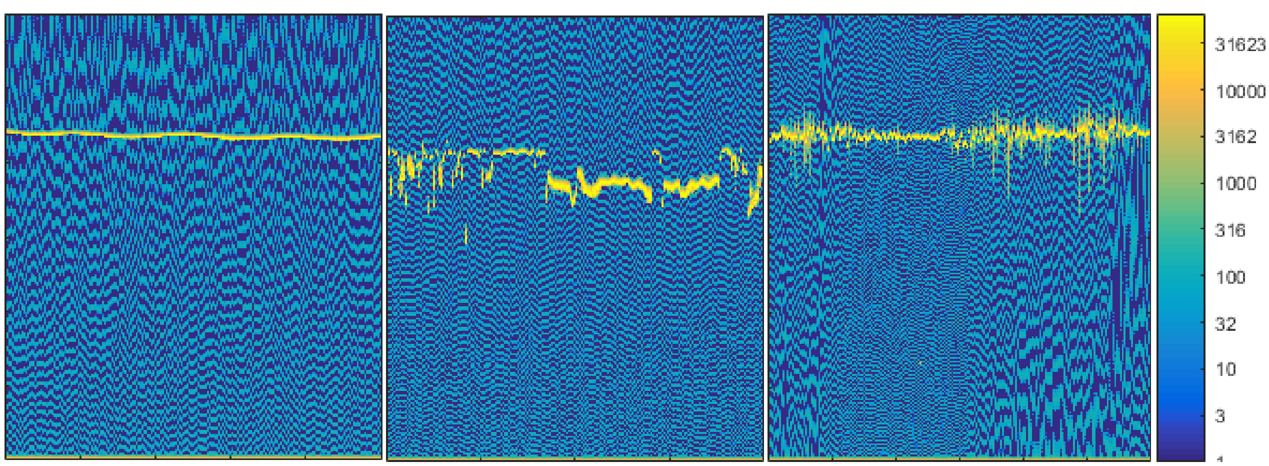

Fig. 10. Backscatter amplitude profile time-series segments for thin-ice (left), heavily ridged ice (center), and open water (right) as measured by the **conventional IPS**. The thin ice segment spans from November 16, 2012 13:16 to November 18, 2012 09:48. The heavily ridged ice segment spans from March 27, 2013 20:20 to April 12, 2013 03:02. The open water segment spans from November 1, 2012 12:00 to November 12, 2012 04:20. The vertical scale represents the distance from the IPS sonar transducer with the the full scale extending to 40 m range.

For comparison to the relatively more constrained dynamic range of the conventional IPS, Fig. 10 shows backscatter amplitude profile time-series for thin ice, ridged ice, and open water. The amplitude features discussed above for the IPS5L are not apparent in the conventional IPS data.

These preliminary observations of the variety in backscatter amplitude profiles from the IPS5L suggest that further examination into automated classification of acoustic targets is possible. Without the increased dynamic range of the IPS5L, this potential for further enhancements of detection of different types of ice and water column targets would not be possible.

C. Noise Floor and Dynamic Range

Using the mean of the minimum measured amplitude from each of the recorded backscatter amplitude profiles acquired by the IPS5L, the instrument noise floor was estimated to be 12400 counts which is in good agreement with the noise floor of 12000 counts as estimated in the earlier simulation work.

With a noise floor of 12400 counts and a maximum possible amplitude of 65535 counts, the dynamic range of the IPS5L instrument is 85 dB.

V. SUMMARY AND CONCLUSIONS

This paper described the final stage of a three-stage project: (a) preliminary design and construction of a prototype 420 kHz log sonar card; (b) development of operating firmware for the IPS instrument; and (c) assembly and field testing of a prototype IPS5 unit. The field test of the prototype IPS5L was performed in the Canadian Beaufort Sea in 30 m water depth from September 2014 through September 2015. Attenuation of the measured backscatter amplitudes by the prototype IPS5L unit due to a short pulse width and non-optimal front-end bandwidth was corrected for prior to analysis of the field data.

The field test of the IPS5L verified the expected noise floor value of 12400 counts and instrument dynamic range of 85 dB.

Through comparison between the IPS5L results against measurements acquired in the same location by a conventional IPS, the expected benefits of the increased sensitivity of the IPS5L were confirmed. The IPS5L realized at least one ice or open water target within every ping; in contrast, a conventional IPS dataset typically has approximately 1% of pings containing no detectable target. The IPS5L consistently acquired a greater number of multiple targets within each ping when compared to the conventional IPS. These multiple targets included more features of the ice undersurface as well as biological backscatterers and near-surface bubbles.

The large dynamic range of the IPS5L resulted in significantly fewer saturated amplitude values for targets. In a conventional IPS dataset, approximately 99% of targets have corresponding maximum amplitude values that are saturated. The majority of the targets in the field test IPS5L dataset had unsaturated maximum amplitudes.

The IPS5L dynamic range should also enable classification of various target types based on their acoustic characteristics that are more fully resolved due to the lack of saturation. Preliminary investigations suggest discernable differences in the acoustic backscatter amplitude profiles of thin ice, open water, heavily ridged ice, and other acoustic targets.

With the increased sensitivity of the IPS5L to multiple targets for each ping, a robust target ranking mechanism is necessary to produce time-series of target range to the desired target type for the user application. Future refinements to ASL's processing software will enable the data analyst to apply refined target ranking algorithms to take advantage of the extended capabilities of the IPS5L.

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