Identifying “Skylites” for AUV Operations under Pack Ice: Insights from Ice-draft Profiling by Moored Sonar

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***Abstract*-The past decade has seen a remarkable evolution of sea-floor-based ice-draft profiling capabilities. Efforts have progressed from an original Beaufort Sea deployment of a single upward-looking acoustic echo sounder to the almost routine present-day positionings of special-purpose profiler units which operate in conjunction with adjacent current profiling and ice drift measurement instruments. These units allow detailed specification of draft statistics and high resolution mapping of moving ice undersurfaces for both on-board storage and, in real time, via cable and VHF connections. The data acquired have been employed for a wide variety of purposes including: monitoring the effects of climate change; characterization of pack ice properties relevant to offshore platform- and facility-design; studies of wave climates inside marginal ice zones; and provision of realtime assistance for navigation and ice management decision-making. Presently, special purpose ice profiling sonars are being incorporated into under-ice science-related missions using autonomous underwater vehicles (AUVs) and on manned submarines**

This presentation begins with a short outline of present profiling capabilities, identifying important characterizations of acoustic scattering by an ice undersurface and outlining the development of the high frequency sampling technique which is an essential element in providing the detail and accuracy required for most modern applications. Quantitative data are provided on key issues determining instrument performance and their implications for optimal use of similar instruments for identifying suitable “skylites” or patches of open water or thin ice suitable for bringing AUVs to the sea surface for recovery or to carry out operational tasks. Two fundamentally different identification approaches, based upon, respectively, echo amplitude and range measurements are discussed and related to typical AUV operating constraints and needs. It is concluded that neither approach will, in itself, meet user needs, necessitating future efforts toward development of a hybrid identification methodology in accord with suggested operating principles.

I. INTRODUCTION

With the recent cancellation of the U.S. Navy SCICEX program and apparent reductions in the frequency of submarine transits of the Arctic Ocean, scientists and others with climate monitoring interests are finding it increasingly necessary to develop alternative methodologies for measuring of the thickness of the Arctic sea ice cover. Thus far, stationary ice profilers, attached to seafloor-based mounts or moorings [1] have been a primary source of alternative draft estimates. These profilers provide periodic measurements of hydrostatic pressure and echo ranges to the ice undersurface. In this approach, draft profiles of the ice cover equivalent to, but usually more accurate than, equivalent upward-looking submarine sonar (ULS) products are acquired from the combined use of ice-draft and -velocity data acquired at fixed monitoring sites. These data are recorded, respectively, by adjacent ice profiling (ranging) and acoustic Doppler current profiler (ADCP) instruments as illustrated in Figure 1 by a typical pairing of ASL Environmental Sciences’ IPS-4 Ice Profiler and an RDI Workhorse ADCP or equivalent instrument with a capability for extracting both ice- and water column current- velocities. IPS-4 range data. In this case range data are obtained from repeated samplings with short 420 kHz, narrow beam, acoustic pulses at frequencies as high as 1 Hz (see Table 1) prior to conversion to draft values using: regional atmospheric- and on-board-recorded hydrostatic-pressures and estimates of the effective sound speed in the overlying water column. The latter estimates are typically obtained from range values associated with patches of local ice-free water.

Operating Frequency	420 kHz
Beam Width	1.8°
Sampling rate	≤ 2Hz
Range	≤ 225 m
Range Precision	0.05 m
Tilt Sensor Range	20°
Tilt sensor accuracy/precision	0.5°/0.01°
Data Storage	64 Mbytes & 128 Mbytes
Typical Deployment (standard battery pack)	40 weeks recording at 1 Hz.
Size	0.17 m (diameter) × 1.0 m
Shipping Weight	37 Kg

Table 1. IPS-4 Ice Profiler System Parameters

The availability of ice drift velocity data (typically sampled at much lower temporal frequencies) allows direct conversion of the resulting ice draft time series into "quasi-spatial" series (Figure 2). The obtained results are analogous to the draft vs. distance profiles which have been generated over past decades from submarine-ranging and navigation data.

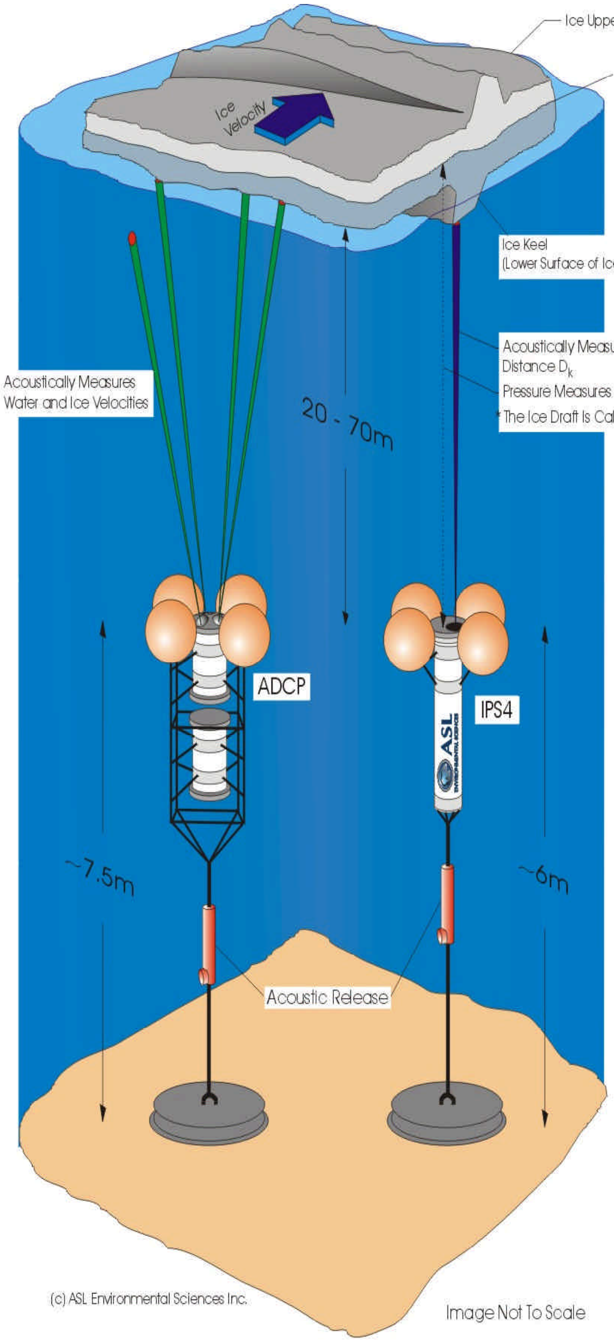

Figure 1. Schematic illustration of typical deployment of ice-profiling and ice-tracking ADCP instrumentation.

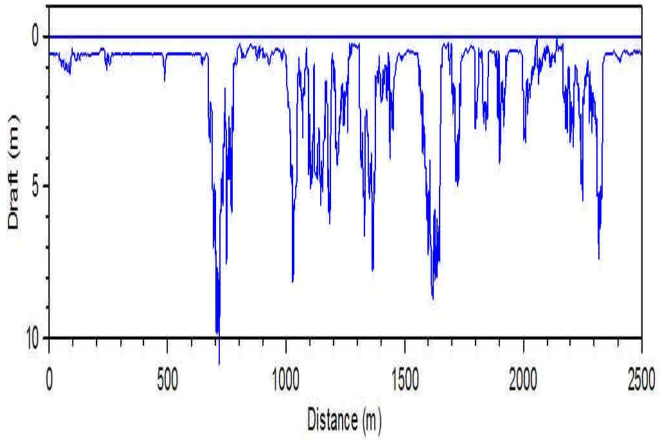

Figure 2. Quasi-Spatial Profile representation of ice draft data, gathered over the northeastern Sakhalin Island shelf, March 20, 1998.

II APPROACHES TO SKYLITE IDENTIFICATION

As it is still important to obtain draft data over designated grids and/or over a wide area within a relatively short time period, alternative mobile ice profiling technologies based upon the use of Autonomous Underwater Vehicles (AUVs) are currently under development. In most instances, ULS instrumentation on such AUVs serves two purposes: 1) to obtain range and, eventually, ice draft data equivalent to that underlying the above-described submarine-based- and stationary–instrument products; and 2) to facilitate periodic data transmissions, navigation updating, surface observations and vehicle recovery by enabling identification of "skylites" [2], comprised of patches of thin ice or open water, suitable for vehicle surfacing.

The present work is directed at the second, application of ice profiling. It specifically draws on data and experience acquired in earlier moored sonar studies to define on-board profiling capabilities compatible with successful, safe AUV data gathering. Relevant data are available from two quite different geographical regions: the Beaufort Sea [3] and the Sea of Okhotsk [4] which are, respectively, representative of the heavy (winter) ice covers characteristic of the High Arctic and the shorter-lived marginal ice zones typically found at sub-Arctic latitudes. In the High Arctic, patches of truly open water and/or containing ice no thicker than 20 cm are usually rare, short-lived, features during the nine months of winter when ice growth is rapid. The slower freezing rates and proximity to ice-free seas, typical of marginal ice zones, provide higher incidences of local open water/thin ice occurrence. Nevertheless, in both instances, profiler characteristics are critical determinants of skylite recognition capabilities.

Two basic approaches have been taken, historically, in achieving these capabilities:

1) recognition based upon return signal amplitude measurements [5]; and
2) recognition based upon direct range measurements [1].

A. The Echo Amplitude Approach

The **amplitude-based** approach relies upon the expectation of significantly larger echo amplitudes from the water/air (open water) interface relative to the water/ice interface. This expectation is based upon the much larger acoustic impedance mismatch at the sea surface as opposed to the water/ice boundary. Quantitative studies [6] of sonar signal returns from calm and wind-disrupted patches of open water and from water covered by ice of various thicknesses have verified this expectation, but only in a statistical sense. Echoes detected with narrow-beam ice-profiling sonar are scattered by small- scale roughness elements distributed across the ice or open water targets. Echoes rarely show evidence of coherent or specular reflection.

The resulting large variability in echo amplitude even from a calm open water surface is illustrated in Figure 3 which shows (Figure 3 a) the envelope of echo amplitudes recorded at various ranges from the surface and (Figure 3 b) the characteristic log normal distribution of echo amplitudes received at a range of about 75 m. Likewise, the range of amplitude variability under a real ice cover and its relatively weak linkage to ice thickness and topographic character are evident in Figure 4. In the latter Figure, the received return signal amplitudes (top panel) are plotted as a function of time coincidently with the corresponding drafts (bottom panel) as derived from the echo return time delays associated with the ice surfaces responsible for the scattering the individual sonar pulses.

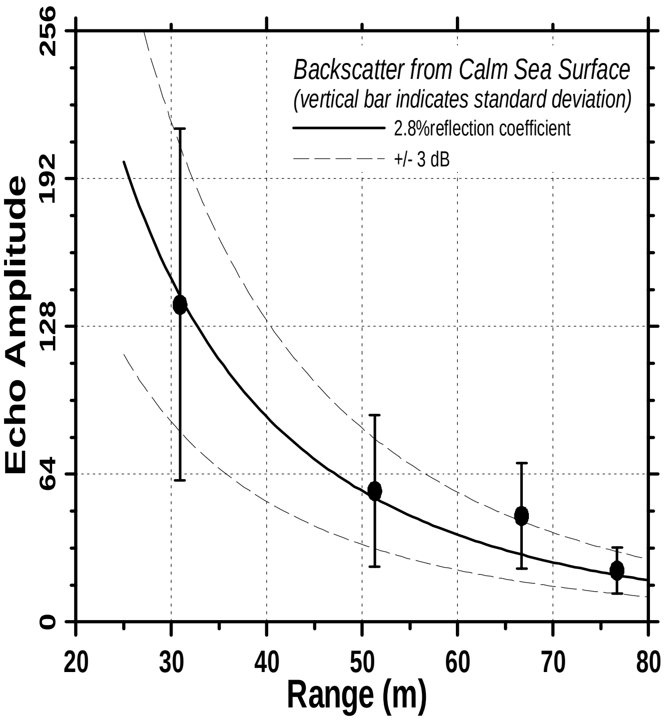

Figure 3a. Mean amplitudes and their standard deviations for echoes backscattered off calm sea surfaces as a function of sonar depth. The heavy line shows the expected range dependence of specularly reflected signals while the broken lines show the envelopes of the +/- 3 dB values of the specular reflections (Adapted from [6]).

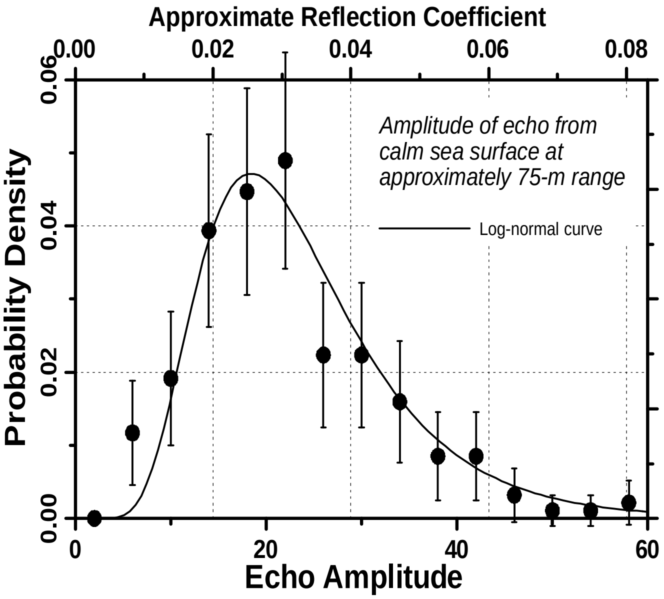

Figure 3 b. Probability density of amplitude echoes and an optimal lognormal fit to echo amplitude data recorded under a calm sea surface at a range of 75 m (Adapted from [6]).

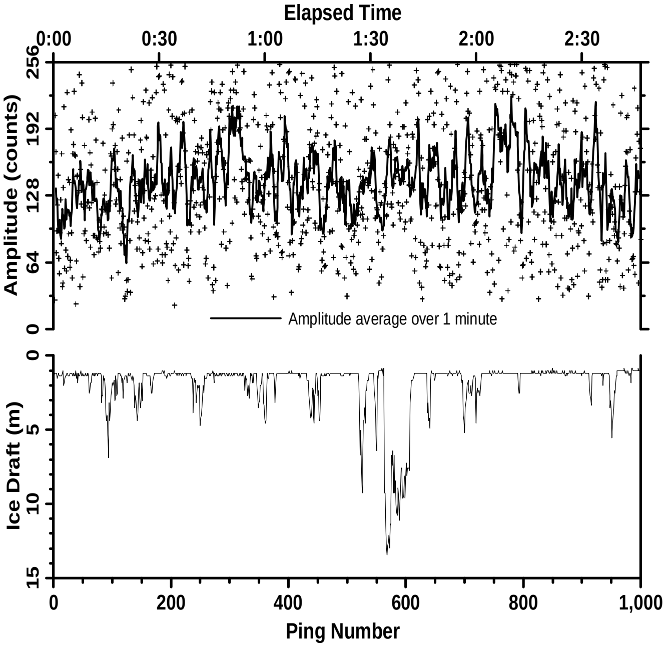

Figure 4. Peak amplitude and range data derived from measurements in the Beaufort Sea in December, 1995 (Adapted from [6]). The top frame shows actual amplitudes (crosses) and their running averages (solid line) over 3 minutes (18 echoes). The bottom plot shows corresponding ice draft values inferred from the corresponding range data during the depicted time interval.

Detailed studies showed that amplitudes of echoes from level ice fluctuate more widely than those from deformed ice. Melling [6] argues that the observed narrower domain of echo probability density associated with deformed ice is a consequence of strong multiple scattering within the complex micro and macro geometrical structure of pressure ridge keels. Moreover, the scattering coefficient of level ice decreases only gradually from open water values as ice thickens to 40 cm. No abrupt change in scattering coefficient is associated with the first appearance of ice on the sea surface. Thus, the median scattering coefficient for ice of 40 cm draft is only 9 dB below the 5th percentile value for a calm open ocean surface. Although receiver saturation in the cited study precluded more definitive estimates, the 95th percentile scattering coefficients for 40 cm draft was approximately equal to the 5th percentile coefficient for calm open water. Since the scattering coefficient of ice is higher at smaller drafts and ocean surface scattering decreases with increasingly rough seas, there is appreciable overlap of the scattering coefficient distributions associated with open water and ice of, say, 20 cm draft.

Further complications arise when wind speeds exceed 10 m/s and begin to generate bubble clouds associated with wave-breaking. Even at relatively high sonar frequencies above 400 kHz, the intensity of scattering from bubbles beneath the sea surface can overlap the range associated with pack ice. Echoes from such bubbles, if infrequently sampled, may be interpreted as scattering by ice of several metres draft.

Recognizing that bubble clouds are unlikely in small patches of ice-free water, amplitude-based skylite identification still must acknowledge the 20 dB difference separating the 5th and 95th percentile values of thin ice scattering coefficients and the proximity of the higher values in this range to values associated with ice-free surfaces. Clearly, a single or even a small number of amplitude measurements are of little use in unambiguously identifying open water and/or ice with drafts less than 20 cm. Instead, multiple, statistically independent, measurements must be averaged to reduce the uncertainty in the mean scattering coefficient to 3 dB or less. This reduction, by the central limit theorem, requires at least 45 independent measurements within the bounds of a prospective skylite feature. If such measurements are made with a narrow-beam (less than 2°) sonar at the one second intervals possible with ASL's IPS-4 (the highest currently available sampling rate in a commercial ice profiling unit), the ping-to-ping variation in scattering coefficients limits the minimum size of a confirmed skylite to 45 m.

Longer range AUVs are typically less than 5 m in length and could easily utilize a confirmed skylite much smaller than 45 m in extent. Thus, the limitation on skylite identification by the echo amplitude approach imposes unnecessarily stringent requirements for recovery, service and communication tasks, particularly in mid-winter High Arctic pack ice. Much longer sampling intervals have been employed in some moored profilers [5, 7] to accommodate power and/or data storage limitations. The resultingly decreased information acquisition rates progressively scale up the minimum detectable skylite dimensions. A similar scaling applies with respect to the tolerances for the mean value of ice draft in an acceptable skylite.

Finally, amplitude-based detection also requires careful calibration of the sonar and a large dynamic receiver range in order to accommodate the full range of echo strengths (at least 60 dB) encountered in the pack ice environment.

B. The Echo Ranging Approach

The second, **range-based**, approach to skylite identification eschews meaningful use of echo amplitude information. In fact, to increase data returns, range measurements are usually extracted using output from a saturated receiver to assure detection of the ice- or sea-surface despite a 100-fold variation in the amplitude of individual returns. The focus here is the accurate measurement of the time delay, ? t, associated with the onset of return signal levels which reach and remain above a pre-determined threshold for a defined acceptable minimum "persistence" time interval. The range, r, from the sonar transducer to the nearest portions of the ice is then given by:

$$r = (c\ ?\ t)/2, \quad (2.1)$$

where c is the speed of sound averaged over the water column above the IPS instrument. Water levels, ?, are then computed relative to the sonar transducer from the on-board measured hydrostatic pressure, P_{ob}, and the estimated sea-level atmospheric pressure, P_{atm}, using the relationship:

$$? = (P_{ob} - P_{atm})/?g - ?D, \quad (2.2)$$

where ? is the average density of water in the upper water column, g is the acceleration of gravity and ? D is the vertical separation of the profiler transducer face and the active crystal of the on-board hydrostatic pressure sensor. Ice drafts, d, are then obtained by combining the range and water level data through:

$$d = ? - ß\, r \cos(?), \quad (2.3)$$

with the quantities ß and ?, respectively, representing a correction factor to account for changes in the assumed average sound speed and denoting the angular deflection of the nominally upward looking sonar beam on the basis of tilt meter data recorded on board the profiling instrument. In stationary monitoring applications, where constantly updated vertical profiles of sound speed are not available, values of ß are determined, whenever possible, throughout a measurement program by assuring that unambiguously recognizable patches of open water or very thin ice yield zero or near-zero values of d. In the AUV application, adjustment of ß values could be calculated on-board using CTD and/or direct sound speed measurements acquired above the cruising depth by the AUV itself during short sorties to the surface.

Again, recognition of thin ice/open water patches by the ranging technique is greatly facilitated by the use of high sampling frequencies. Given an AUV moving at 1 m/s 25 m below the ice, the 1.8° beam width of ASL's IPS-4 profiler allows independent sampling to be carried out at 1 Hz, reducing range- and draft- measurement uncertainties which decrease as the inverse square root of the number of accumulated estimates. Consequently, this approach can enable reliable estimates of mean draft to be made for overlying ice/open water features having linear dimensions as low as 10 m.

The intrinsic measurement accuracy of the sonar-based profiling technique is, presently, a critical and poorly known quantity. Estimates of attainable accuracies ranging between 30 and 50 cm have been made [8] for submarine ULS measurements without further quantification of suspected considerable dependences upon submarine cruise depth, sonar beamwidth and other factors. Equivalent estimates for moored profiler measurements have been based upon assessments of possible error sources both for the high current speed regimes of the Sea of Okhotsk (10-20 cm) [4, 9] and for the slower moving, Beaufort Sea ice regime (5-10 cm) [1, 3].

We have directly evaluated the consistency and, perhaps, the absolute accuracy of mooring-based measurements. This evaluation compared values of mean ice drafts computed from segments of "quasi-spatial" profile data with 50% overlap. These quasi-spatial series results were derived from IPS-4 and ADCP data gathered at two sites (AD1 and AD2) separated across the direction of drift by, approximately, 3 km in 40 m water depths. Data acquisition took place over time periods when both monitoring sites were in the broad (= 150 km in width) flow of compact pack ice which, each winter, moves southward past Sakhalin Island. At no time in the compared records was either site close to the shoreward or offshore ice edges. Under such circumstances, real differences in canonical mean draft between the two sites would have been expected to be very small, particularly when averaging is carried out over long profile segments.

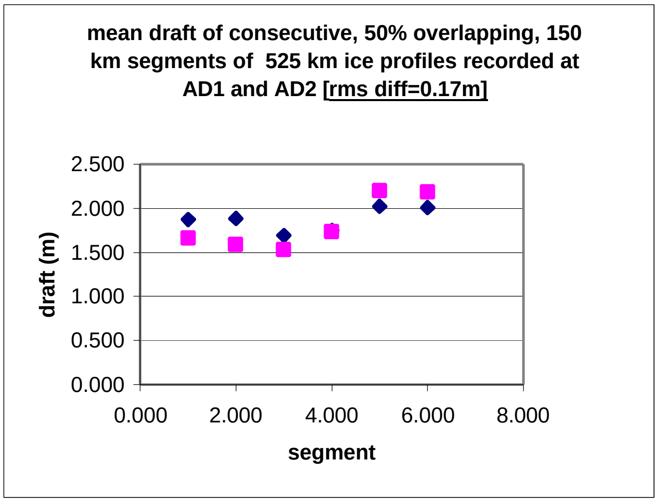

Figure 5. Comparisons of mean drafts derived for consecutive 50% overlapping 150 km long quasi-spatial profile data sets gathered simultaneously in March-April, 1998 at two different sites (AD1 and AD2) separated by approximately 3 km in the cross-stream direction of a southwardly drifting ice pack on the continental shelf off Sakhalin Island.

Comparisons of values over 150 km segments should reveal any systematic under- or over-estimation of draft at the individual sites which could confound attempts to accurately quantify drafts in potential skylites. The results obtained (Figure 5) from total track lengths of 525 km at each site show an overall difference in the site means equal to about 0.07 m and an rms difference between corresponding 150 km means of 0.17 m. These results are consistent with IPS-4 measurement capabilities for stationary moored platforms which are equivalent to an approximate precision of +/- 0.1 m, or of a magnitude similar to the accuracy estimates quoted above [1, 4, 9]. Such estimates would be compatible with reasonably reliable detection of skylites with ice thicknesses of 20 cm or less if attainable from an appropriately stabilized AUV platform.

III CONCLUSIONS

At first glance, the above considerations would appear to suggest that the least restrictive skylite detection methodology based upon currently available technologies is likely to employ both high frequency sampling and the use of conventional ranging techniques similar to those currently employed on moored ice profiler instruments [1]. Difficulties with this approach, however, arise from the real-time processing requirement associated with typical AUV applications. The draft accuracy figures quoted above for the ranging methodology were all obtained using retrospective analyses of the full bodies of required range-, atmospheric pressure-, tilt- and ice velocity-time series data. Assuring access to equivalent data on board an operating AUV is not a trivial task, except, perhaps, for very short period local deployments employing depth-cycled CTD and/or sound speed data acquisition. Critical additional factors include the likely necessity to make range corrections for rapid pitch and roll variations with magnitudes as large as 30° [10] and a need for access to local atmospheric pressure data which, if not available with sufficient accuracy, could introduce errors into realtime draft estimates as large as 50 to 70 cm.

It is clear that development of a hybrid data acquisition and processing scheme is likely to be required for long-range under-ice AUV operations. Such a scheme should retain echo sampling frequencies at least as high as the present 1Hz upper limit associated with moored profilers. This effort is justified since the identification capabilities of both generic skylite identification approaches discussed above increase (in terms of producing decreases in mean draft uncertainties and in minimum detectable skylite dimensions) with increasing sampling rates. The composition and logical structure of the included data acquisition and processing modules will have to facilitate increasing the weighting of echo amplitude- relative to range- data as an inverse function of the quality and/or quantity of key range computation inputs, such as atmospheric pressure, sound speed and AUV attitude.

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