Upward Looking Ice Profiler Sonar Instruments for Ice Thickness and Topography Measurements

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***Abstract-* Scientific and engineering studies in polar and marginal ice zones require detailed information on sea ice thickness and topography. Until recently, vertical ice dimension data have been largely inferred from aerial and satellite remote-sensing sensors. The capabilities of these sensors are still very limited for establishing accurate ice thicknesses and do not address details of ice topography. Alternative under-ice measurement methodologies continue to be major sources of accurate sea ice thickness and topography data for basic ice-covered ocean studies and, increasingly, for addressing important navigation, offshore structure design/safety and climate change issues. Upward-looking sonar (ULS) methods characteristically provide under-ice topography data with high horizontal and vertical spatial resolution. Originally, the great bulk of data of this type was acquired from ULS sensors mounted on polar-traversing submarines during the cold war era. Unfortunately, much of the collected information was, and remains, hard to access. Consequently, the development of sea-floor based moored upward looking sonar (ULS) instrumentation, or ice profilers, over the past decade has begun to yield large, high quality, databases on ice undersurface topography and ice draft/thickness for scientific, engineering and operational users. Recent applications of such data include regional oceanographic studies, force-on-structure analyses, real-time ice jam detection, and tactical AUV operations. Over 100 deployments of moored and AUV-mounted ice profiler sonars, associated with an overall data recovery rate of 94%, are briefly reviewed. Prospective new applications of the technology will be presented and related to likely directions of future developments in profiler hardware and software.**

I. INTRODUCTION

Offshore development, navigation, monitoring and assessing anticipated effects of climate change in ice covered marine regions have all placed a premium on access to data on ice thickness and topography. Until fairly recently, such data have been obtained from tedious, costly and often dangerous on-ice manual sampling programs which naturally tended to bias results toward conditions attained in “drillable”, stable, portions of ice packs. Improvements in this situation first became available a few decades ago through access to data collected by upward-looking sonar mounted on military submarines. The resulting data sets provided the first real picture of spatial variability in, particularly, the Arctic Basin ice cover.

Nevertheless, the spatial and temporal limitations of submarine-derived data sets combined with additional information needs created by increased development in ice infested regions motivated further advances in airborne- and satellite-based thickness estimation as well as alternative moored upward-looking sonar technologies [1]. Airborne electromagnetic-induction- and laser-based methodologies, in particular, have shown some promise in these respects in spite of intrinsic uncertainties associated with sensitivity to the physical properties of ice at both the sub-aerial and sub-aqueous interfaces. Satellite imagers, on the other hand, have, thus far, yielded data primarily on the horizontal extents of ice covers (Fig. 1), leaving information on the third, vertical, ice dimension, critical to most climatic, operational and design/safety issues, to be obtained by other means.

Fig. 1. A NOAA AVHRR Image of the seasonal ice cover east of Sakhalin Island in the Sea of Okhotsk.

A forthcoming effort to obtain such data from a radar altimeter aboard the soon to be launched Cryosat satellite is directed at providing vertical dimension data albeit on a relatively coarse horizontal scale and with vertical resolutions which are unlikely to meet the requirements of many applications. This shortfall in applicability reflects the inherent restriction of the Cryosat sensor to estimating the elevation of the much smaller, sub-aerial, ice cover portion of the ice cover, leaving estimates of overall thickness to be obtained using less than robust [2][3][4] assumptions of isostasy. Applications requiring more accurate data include: monitoring climate change in thin, marginal ice packs; providing input and verification data for basin scale- and regional-ice models; providing databases for designing offshore platform structures and terminals for oil- and gas-related activities and for defining related operational windows; and for assisting navigation through ice-infested channels and seaways.

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II. MOORED ICE PROFILING METHODOLOGY

The moored upward-looking sonar methodology to be discussed in the present paper, has been providing information for the above-noted and other applications for more than a decade. This methodology, typically, provides data in the form of linear profiles, referred to as "quasi spatial profiles" (QSPs) representing the drafts of closely spaced points along imaginary linear tracks on ice pack undersurfaces (Fig. 2).

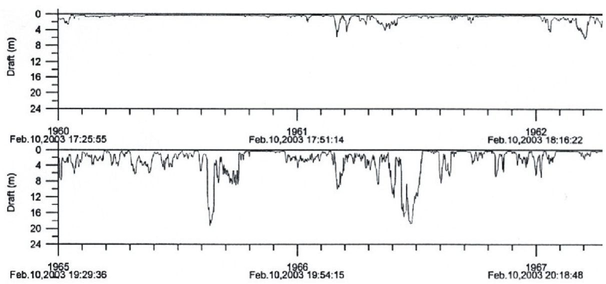

Fig.2. Quasi-spatial profiles of the underwater portions of the Sea of Okhotsk ice cover. Draft values are plotted as a function of along track distance in km.

Data of this type are obtained from a pair of adjacent moored ice (IPS-) and current profiling (ADCP-) acoustic instruments (Fig.3).

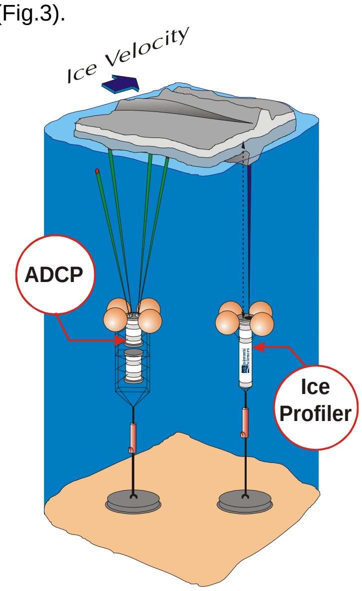

Fig. 3. A typical moored ULS Ice Profiling installations illustrating usage of the single beam ASL IPS4 Ice profiler and the four diverging beams of an adjacent ADCP instrument.

The IPS Ice Profiler is a purpose-built sounder which employs a narrow , 1.8°, high frequency (420 kHz) acoustic beam and rapid sampling (up to 2Hz) to obtain high spatial resolution time series of the range to the nearest (to the sonar sensor) portion of the ice underface. This information is combined with on-board recorded hydrostatic pressure and instrument tilt data as well as regional-scale sea level atmospheric pressure data to provide time series representations of the ice draft above the monitoring site. Such time series are converted into the quasi-spatial profile products represented in Fig. 2 through coincident use of periodically sampled ice velocity data provided by the adjacent ADCP instrument through its built-in "bottom-tracking" capability.

A critical feature of state of the art moored ULS ice profiling is its high sampling rate which facilitates detection and accurate measurement of operationally and environmentally important features such as deep ridge keels and also enables reliable processing and interpretation of data recorded in the presence of typical confounding factors such as bubble clouds, zooplankton concentrations and large amplitude ocean waves. This capability is dependent upon the IPS4's low power consumption which facilitates year-long or longer deployments and its high data storage capacity (64 and 128 MB).

Actual accurate extraction of ice drafts from the recorded data sets requires intensive and careful processing efforts as outlined in Fig. 4 in terms of the linkages which have to be established to between measured ranges, r, the inferred acoustic sensor depth, η, and the ice draft, d. The key relationship in this draft extraction is:

$$d = \eta - \beta r \cos\theta \qquad (1.1)$$

where β is a to-be determined factor which accounts for changes over time in the mean sound speed in the upper water column and θ is the measured tilt angle of the IPS4 instrument. The acoustic sensor depth, η, itself, is established from the hydrostatic pressure measured in the instrument, P_{btm} and the atmospheric pressure, P_{atm}, through:

$$\eta = (P_{btm} - P_{atm})/\rho g - \Delta D \qquad (1.2)$$

where ΔD is the physical separation in the vertical direction between the deployed acoustic and hydrostatic pressure sensors, and ρ and g, respectively, denote the density of sea water and the acceleration of gravity.

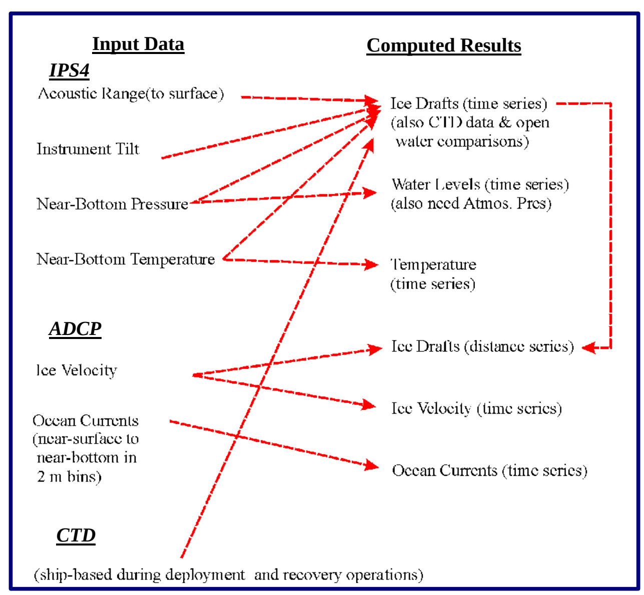

Fig. 4. Linkages between the various data sets collected at an ice profiling site and usage in draft extraction.

The critical, accuracy limiting factor in ice profiling is knowledge of the mean sound speed. This quantity can be accurately established at the start and end of a deployment through direct measurements of CTD profiles and use of established relationships between sound speed and water property parameters. For intermediate times, however, speed estimates must be obtained as an integral part of the data processing/analysis program by establishing values of β which correctly yield zero draft values from Eq. 1.1 using range, r, and sensor depth, η, values acquired from portions of the data record associated with the unambiguous presence of open water above the ice profiling instrument. A typical time series of the correction factor used in processing a Sea of Okhotsk data set is displayed in Fig. 5 along with underlying manual estimates made for individual occurrences of open water conditions and expectations based upon water temperature measurements made on board the deployed instruments. Clearly, the accuracy of measurements made during a long, seasonal, deployment will be governed by the frequency with which open-water re-calibrations can be carried out. This frequency, in turn, is strongly determined by the frequency of range-sampling. Use of low sampling frequencies dictates that only very large patches of open water will be detected and recognized for recalibration purposes, essentially precluding significant probabilities for recalibration during the winter season in most active ice packs. With the 1-2 Hz sampling frequencies associated with ASL's IPS4 instruments, such recalibrations have usually proved to be feasible for a dozen or more distinct intervals during heavy ice seasons at most tested locations. Overall, typical accuracy figures for returned draft data have ranged between 5 and 20 cm for Arctic and Northern hemisphere marginal ice zones depending upon ancillary data availability and levels of effort given to data processing.

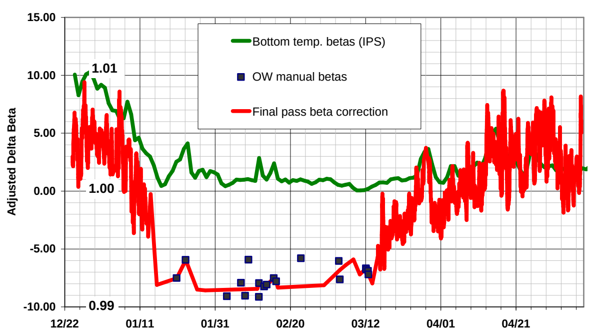

Fig. 5. A plot of correction factors, β, applied in draft data extractions as a function of time over a typical deployment period. The plot includes individual estimates of β for individual periods of open water and expectations from on-board temperature data.

III. APPLICATIONS

Review of Past Deployments

More than 100 separate deployments of IPS4 profilers have been carried out to date, encompassing both hemispheres and a wide variety of ice-covered marine environments (Fig. 6). Given the severity of operating conditions in most of these environments, recovery statistics in excess of 95% for both data and instruments are consistent with a relatively mature state of the measurement technology. Antarctic deployments have been particularly impressive in this respect in that individual moored instruments have been struck as many as eight times and forced to depths as great as 300 m without interruptions of data recording.

Deployments have been directed at a wide range of scientific, engineering design and operational problems. A prominent example in the first category has included more than a decade of monitoring of ice draft in the western Arctic Ocean.

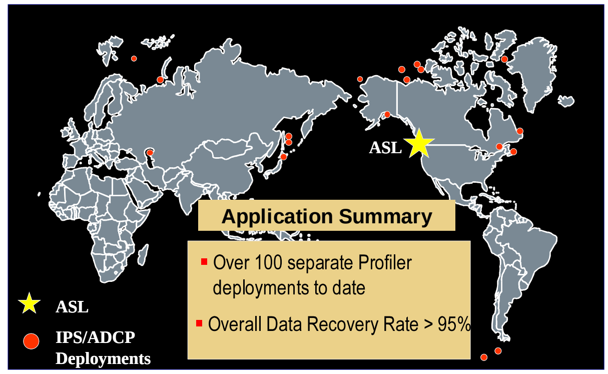

Fig. 6. Locations of IPS4 Ice profiler deployments.

Scientific Climatic Variability Applications

Results from a portion of the data gathered in the latter effort are reproduced in Fig. 7 in the form of annual variations in the monthly mean thicknesses showing, at least in the studied area (the southeastern Beaufort Sea) little definitive evidence of a thinning trend inferred [5] in other portions of the Arctic Basin over a similar period.

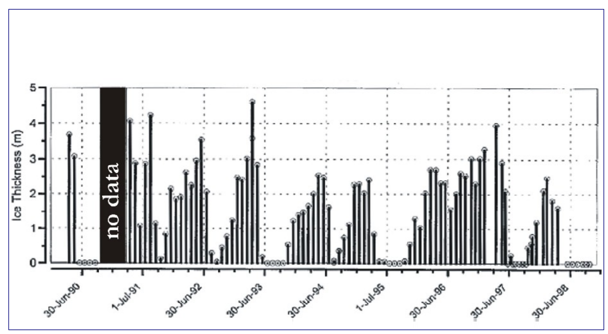

Fig. 7. Monthly mean ice thicknesses as measured at IPS4 sites in the southeastern Beaufort Sea between 1990 and 1998.

Oil and Gas Industry Applications

Other efforts sponsored by the oil and gas extraction industry have focused attention on characterization of individual, particularly large, ridged ice features (Fig. 8) which pose potential dangers to offshore structures, associated pipelines and other underwater infrastructure.

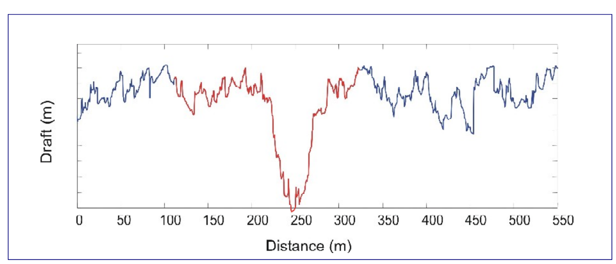

Fig. 8. Profile data recorded beneath a large ice ridge keel in the Sea of Okhotsk.

The large volumes of data which have been gathered in such programs have played a prominent role in improving and developing profiling technology and elucidating previously unrecognized differences in ice topographies. For example, data (Fig. 9) acquired at two equivalent sites 3km apart in a direction transverse to moving pack ice showed mean draft values for multiple corresponding, simultaneously recorded, 50 km segments differed on average by 17 cm. Such differences are closely compatible with the, roughly, 20 cm measurement uncertainty previously estimated to be associated with the measurements,

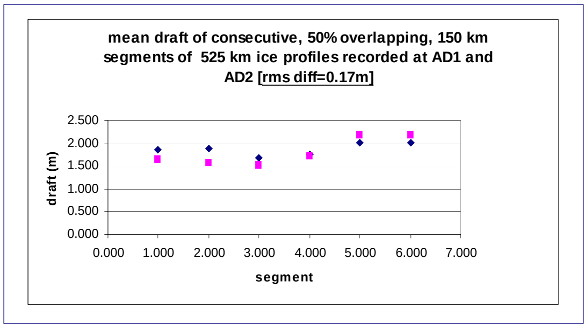

Fig. 9. Plots of mean draft for consecutive 50 km ice segments as profiled while moving over two adjacent sites in the Sea of Okhotsk.

Data from the latter sites and other nearby measurement location also provide the basis for recognizing and distinguishing an "anomalous bright ice" type from the more typically seen "mottled" variety, where these designations were derived from the radar image signatures of the two ice types. The statistics on ice draft obtained from corresponding profiling (Fig. 10) showed the former ice type to be associated with roughened, thick ice which was essentially devoid of the extreme small and large thickness tails associated with the other, more conventional, ice form.

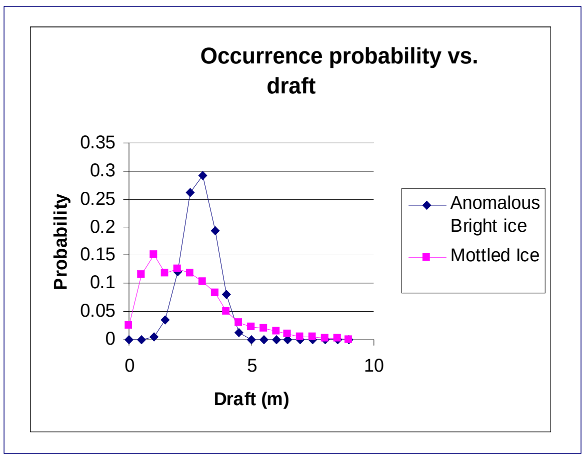

Fig. 10. Draft statistics for two ice types identified in the Sea of Okhotsk.

Other Applications

Still yet other categories of profiling usage has involved operational applications such as:

- providing real-time inputs for Canadian Coast Guard icebreaker and ice management in the St. Lawrence Seaway. A description of the operational IADDS system used in this work is provided in a separate paper in the Oceans'2004 conference [6].
- providing ice draft data to AUV as part of both the vehicle scientific plan and to facilitate finding "skylights" of thin ice/open water areas suitable for vehicle surfacing to carry out data relay and servicing functions. Such an application has already been successfully tested in Arctic waters on an MBARI (Monterey Bay Aquarium and Research Institute) AUV and a similar deployment is planned in the near future by Dr. Fukamachi of Hokkaido University.

III. FUTURE DIRECTIONS OF MOORED ICE PROFILING

Technological advances and experience accumulated with the present generation of profilers are likely to significantly augment the current profiling technology while also addressing the major practical drawbacks of the existing technology.

Augmentation is likely to, most immediately, implement technical advances to increase on-board data storage capacities enabling retention of reflected signal amplitude information and use of larger dynamic ranges to facilitate capabilities for rejection of false target. These advances and improved understandings of the acoustic problems involved could also enable capabilities for obtaining information on the properties of ice interface- and internal ice-features which are of engineering-/design-related interest.

The notable drawbacks of present-day profilers include the one-dimensional nature of the returned data and the considerable expense, efforts and time delays usually involved in obtaining data from typically remote deployment locations. The first of these problems has already been initially addressed at the Institute of Ocean Sciences with the development of a prototype profiler which employs a revolving acoustic beam to azimuthally scan the ice undersurface, eventually enabling production of two-dimensional representation of ice draft. Issues of data cost and access are likely to be addressed on a number of fronts. One promising approach, well underway, requires further progress in the use of AUVs for under ice data-taking. The above-noted applications of this technology suggest this approach could provide a significant and very flexible source of ice topography and thickness data in the relatively near future. A second approach, currently under investigation, is the development of methodologies for periodic downloading of remotely acquired data during either annual open water seasons and/or during shorter ice free periods detected by "smart" data relay systems. Such capabilities would enable long duration deployments of monitoring instrumentation without the long data droughts and risks of unrecognized instrument malfunctioning usually associated with such deployments.

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