The Detection of Multi-Year Ice Using Upward Looking Sonar Data

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ABSTRACT

Upward looking sonar (ULS) instruments on year-long sub-surface moorings are widely used in support of oil and gas exploration programs. The analysis results are used to provide key inputs to the engineering of offshore platform design and ship-based ice management. Detection of the older and harder multi-year sea ice is particularly important for engineering and ice management applications. Here, we analyze multi-year ULS measurements of sea ice in the Beaufort Sea and off Northeast Greenland. The detectability and characterization of multi-year ice is derived from two independent analysis methods. The first method uses the backscattered acoustic pulse shape received by the sonar instrument while the second method involves the degree of the smoothness of the underside of the ice keels away from the leading and trailing edges. Both methods demonstrate skill in detecting multi-year sea ice as distinct from first year sea ice. The two methods are shown to be complementary in that some multi-year ice floes cannot always be clearly categorized by one method alone.

KEY WORDS: sonars; sea-ice, multi-year ice; acoustic; backscatter.

INTRODUCTION

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 in Arctic and other ice-infested areas. The data sets provide typical accuracies of 0.05 m for ice draft on a continuous year-long basis; these data attributes allow detailed characterization of keel shapes and other ice features (Fissel et al., 2008). ULS instruments, in the form of ASL's Ice Profiler, have the data capacity for unattended operation for continuous measurement periods of two years, with three year operations possible under some circumstances. When combined with a companion Acoustic Doppler Current Profiler (ADCP) to measure ice velocities, the combined data sets provide horizontal resolution of 1 m or better. The combined ice thicknesses and ice velocities, measured along thousands of kilometers of ice which typically move over each moored ice profiler location, provide important data for establishing metocean design criteria related to oil and gas operations in areas with seasonal or year-round ice cover.

The early versions of ULS instruments for sea ice measurements were developed in the early 1990's (Melling et al., 1995) for scientific studies of Arctic sea ice. In 1996, the first ULS sea ice oil and gas application was conducted in the Sakhalin exploration area using the ASL Ice Profiler, which was purpose designed for this application by ASL Environmental Sciences Inc. (ASL) and the Institute of Ocean Sciences (IOS) of the Canadian Department of Fisheries and Oceans through a Joint Industry Program funded by Exxon Neftegas and Sakhalin Energy Investment Co. Since then, hundreds of year-long ULS deployments for oil and gas applications have been conducted with these instruments in the ice infested areas of the northern and southern hemispheres.

The capabilities of the instruments for detailed and accurate representation of the thousands of kilometers of sea ice passing over the moored ULS measurement sites are well established. The processing and analysis of these very large data sets are routinely undertaken using an extensive library of purpose designed software. For oil and gas engineering requirements there is a particular need the detection and characterization of potentially hazardous sea ice features. These can be derived from these very large ULS data sets, for different types of potentially hazardous ice, including (a) the deepest ice keels extending to depths of 20 m or more; (b) continuous rubbled and hummocky ice features with horizontal scales of hundreds of meters; and (c) old or multi-year ice floes. The present capability to derive such information on potentially hazardous ice types was presented by Fissel et al. (2012).

In this paper, we report on advances in the detection and characterization of multi-year ice features building on the results in Fissel et al. (2012). Multi-year ULS measurements of sea ice are analysed in the Beaufort Sea and off Northeast Greenland to detect multi-year ice and to provide comparative results on the frequency of occurrence and statistical summaries of the geometrical characteristics (horizontal and vertical distances and the cross-sectional areas of detected multi-year ice features). The detectability and characterization of multi-year ice is derived from two independent analysis methods. The first method uses the backscattered acoustic pulse shape received by the sonar instrument while the second method involves the degree of the smoothness of the underside of the ice keels away from the leading and trailing edges. Both methods demonstrate skill in detecting multi-year sea ice as distinct from first year sea ice. The two methods are shown to be complementary in that some multi-year ice floes cannot always be clearly categorized by one method alone, so the additional method provides supplementary information on determining the likelihood that the floe is multi-year ice. The frequency of occurrence of multi-year ice, as distinct from first year ice, is presented for each region and by season.

UPWARD LOOKING SONAR INSTRUMENTS

Instruments

The upward looking sonar instrumentation, consisting of the Ice Profiler Sonar (IPS) and the Acoustic Doppler Current Profiler (ADCP) are designed to be deployed 25 to 60 m below the air water interface from sea floor based moorings (Figure 1) or, in shallower water, from bottom-mounted platforms. The instrument operates by emitting and detecting surface returns from frequent short pulses (pings) of acoustic energy concentrated in narrow beams (less than 2°). 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 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.

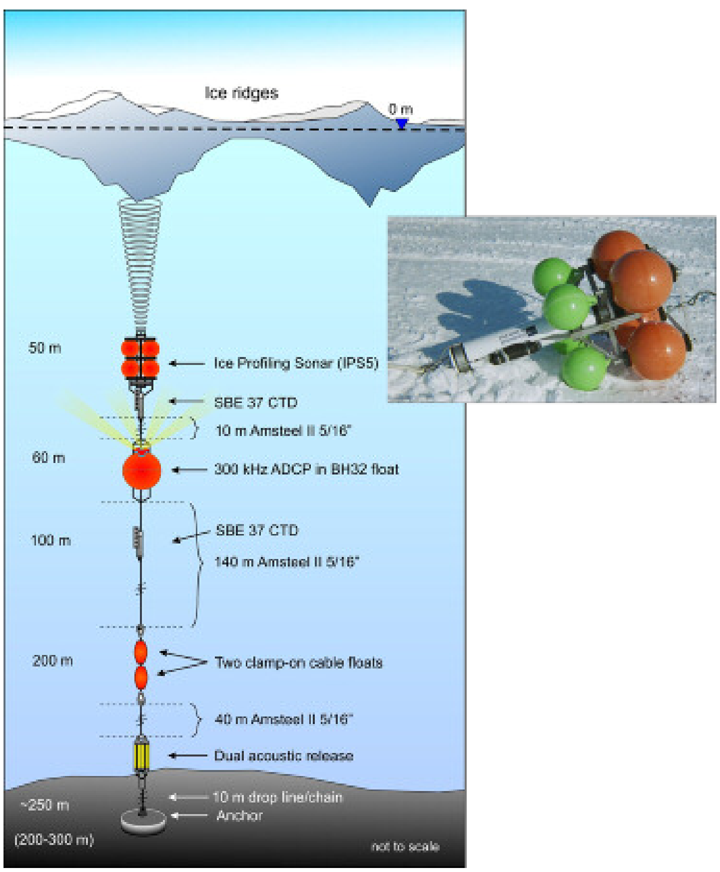

Figure 1. A typical deployment arrangement of an ice profiler and ADCP ice velocity measuring instruments on a single subsurface mooring.

Ice Draft Data

When IPS instruments are deployed under moving ice fields and adjacent to upward-looking ADCP (Acoustic Doppler Current Profiler) instruments (Figure 1) with capabilities for extracting ice drift velocity, the obtained data are used to construct two dimensional cross-sections of the ice cover (Figure 2), designated as quasi-spatial profiles (or ice distance series). With careful processing these products depict detailed variations in the depth of the lower ice surface with a horizontal resolution of about 1 m and an accuracy in the vertical of 5-10 cm. Keys to the utility of the technique are its on-board data storage capacity and capabilities for reliable long term un-attended operation in the hostile environments usually associated with ice covered waters. Until recently, principal users of this technology have been polar ocean scientists with interests and concerns regarding climate change (Fissel et al., 2008b) and, increasingly, international oil and gas producers with deployments throughout the Arctic Ocean and in sub-polar seas (Figure 3).

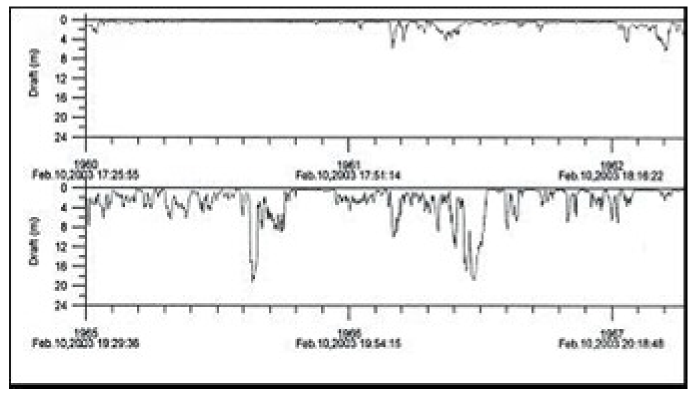

Figure 2. A quasi-spatial profile of an ice cover produced by combining time series draft and ice speed data to derive a product equivalent to the profile of the ice undersurface. The abscissa is in kilometers, annotated with time of observation.

METHODOLOGY

While first year ice is the dominant ice type in the Arctic Ocean, some of the sea ice is older having survived at least one summer. Old ice has two categories: second year ice and multi-year ice. As sea ice ages from year to year, its physical properties change (Wadhams, 2000). The salinity is reduced as the brine channels are evacuated and frozen over. The hardness of the ice increases and it yields less to external objects such as ships making passage through the ice, leading to the more hazardous nature of encounters with this multi-year ice. The topography of the ice also changes as it tends to becomes smoother on its top and bottom sides due to partial melting in summer leading to smoothing of its rough topographic features.

Detection of old (second- or multi-year) ice from upward looking sonar data sets is challenging. There are two basic approaches that have been considered:

1. Analysis of the shape of the leading edge of the acoustic backscatter return realized from the ice return on each individual acoustic ping.
2. Determination of the roughness scales of the underside of the sea-ice to differentiate between the smoother old ice from the rougher first year ice which involves analysis of ice drafts from several successive pings to determine a bottom roughness scale.

These methods were first introduced by Fissel et al. (2012) and have since been enhanced.

Method 1 – Acoustic Pulse Leading Edge

The profile ping returns over the water column were used for the leading edge analysis. To ensure that the profiles examined were representative of the underside of the sea ice feature rather than along steep sides, the profiles selected were qualified as follows. First, the profiles had to have a draft of at least 3 meters. In addition, the distance ice draft series was windowed to those values occurring within the sonar beam of the IPS5 instrument. The window size is $2d\cdot\tan(\theta)$, where θ is the beam angle of the IPS5, nominally 1.8 degrees, and d is the instrument depth below the underside of the ice. A linear regression of the windowed draft series was taken, and profiles were further selected by the slope of this regression. A maximum absolute slope of 0.1 (Δdraft / distance) was required. Finally, any profile where the difference between the maximum and minimum draft in the selected window was greater than 0.4m, was rejected. The conditions were designed to include only ice of sufficient draft, with relatively “flat” features.

An example of a portion of the acoustic backscatter return profile that corresponds to an ice target is shown in Figure 3. The rise of the sampled backscatter amplitude above a threshold (Start threshold) indicates the earliest acoustic returns realized from the insonification of an ice target via a single ping. The target is considered to end when the signal drops below an amplitude threshold (Stop threshold). The persistence is defined to be the timespan over which the target remains above the Start and Stop thresholds. The maximum amplitude that occurs within a target is also recorded. The system noise level can be seen to be less than 100 counts in amplitude.

The fairly linear portion of the leading edge of a target is characterized by approximating the instantaneous slope at the inflection point of the leading edge curve (red line in Figure 3). The inflection point is found by determining the point at which a sign change occurs in the series of second-difference values computed from the amplitude profile. The slope at this point is then approximated using the amplitude and sample index values of its’ two neighbouring points.

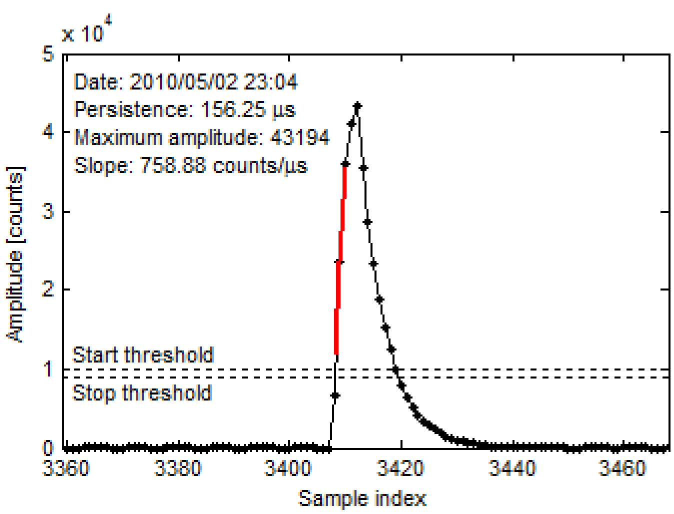

Figure 3. Example of the backscatter amplitude profile for an acoustic target.

Backscatter amplitude profiles exhibit a large amount of variation and target leading edges can be significantly complicated relative to the simple profile shown in Figure 3. The analysis software developed for this purpose handles these and other exceptional cases, e.g. when the inflection point occurs below the start threshold and above the system noise level.

Method 2 – Roughness Characterization of Sea-Ice Underside

In this method, the roughness scales of the underside of the sea-ice were examined to differentiate between the smoother underside expected to be associated with older ice in contrast to the greater variability in the form of short-scale roughness expected to occur with the more recently deformed first year ice. This involves analysis of ice drafts from several successive pings to determine a bottom roughness scale.

A 10 m running average was applied to the 1 m distance series for the undersides of larger ice keels available in the Beaufort Sea and Greenland ice draft distance data sets. The initial criteria for selecting the data segments is for relatively constant ice drafts (to avoid the edges of ice floes) with maximum ice drafts in each segment ranging from 3 to 10 m, which is expected to encompass most old ice features. Examples of two data segments showing the original ice draft data, the 10 m running average values and their differences is shown in Figure 4 for comparatively smooth underside of sea ice and in Figure 5 for a comparatively rough underside of sea ice.

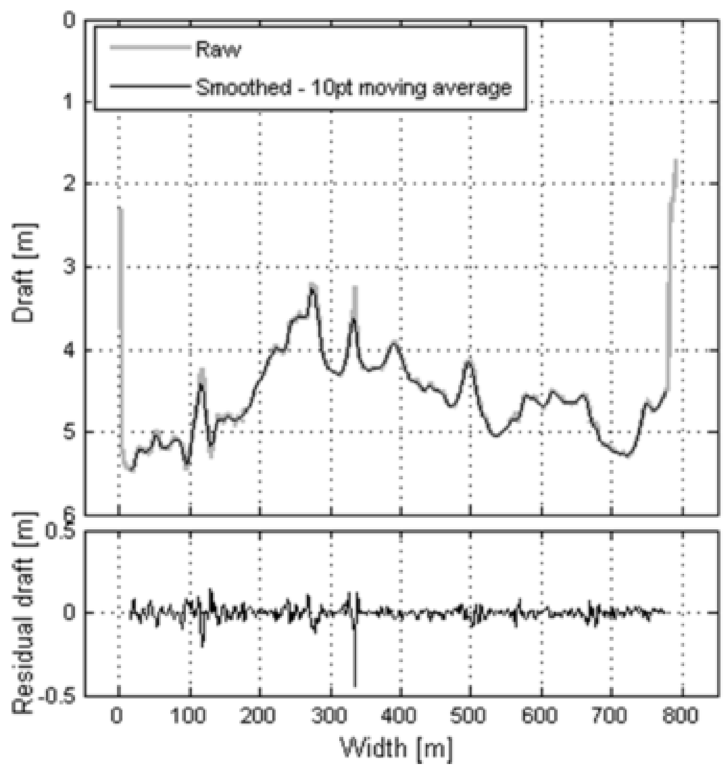

Figure 4. An example of a segment of comparatively smooth ice draft data showing the original raw data, the smoothed data computed using a 10 point running mean (upper panel) and the difference in ice draft between the raw and smoothed ice draft values (lower panel).

Two sets of statistics were calculated from the residual signal resulting subtracting the filtered spatial-series (using the running average) from the original spatial-series. The first statistic was the ‘mean’ of the absolute values of the residual signal computed over the entire sea ice feature and the second statistic was the standard deviation of the residual values over the entire sea ice feature. These statistics were computed on a weekly basis for all qualifying episodes that occurred in each week of ice draft data by each measurement site. Using the available sea ice charts, each individual week was categorized according to the percentage of first year ice (FYI) and old ice present.

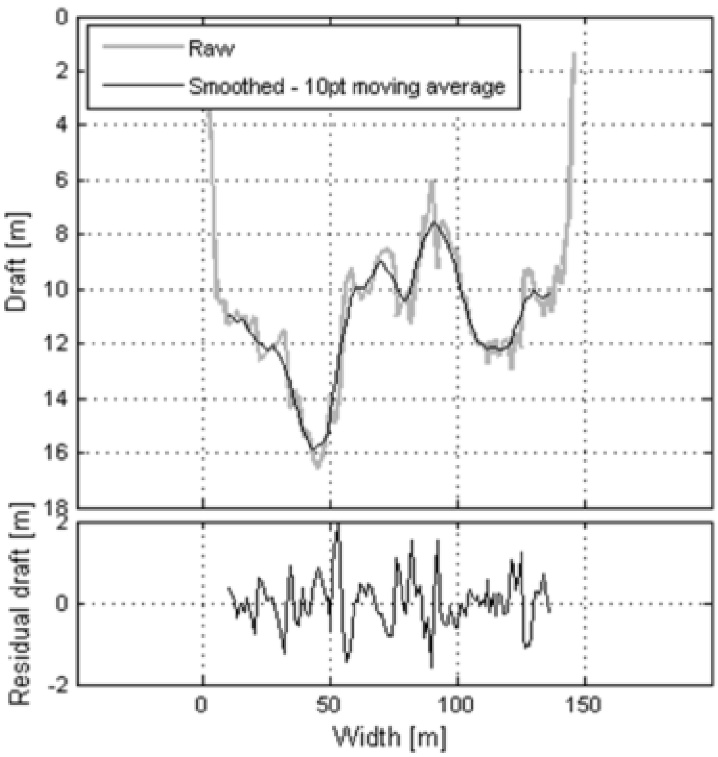

Figure 5. An example of a segment of comparatively rough ice draft data showing the original raw data, the smoothed data computed using a 10 point running mean (upper panel) and the difference in ice draft between the raw and smoothed ice draft values (lower panel).

RESULTS

Acoustic Pulse Leading Edge Method

The methods originally developed for the available ice profiler sonar (IPS) data sets on the Canadian Beaufort Sea shelf region were previously extended to the deeper slope waters of the Canadian Beaufort Sea (Figure 6) in Fissel et al. (2012). Multi-year ice occurs rarely in the shallower waters of the Beaufort Sea but is found more frequently, in the deeper waters closer to Arctic Ocean pack ice, although in the past several years, first year ice has been dominant in this region. The areas off Northeast Greenland have even more multi-year ice because of the Trans-Polar Drift Current of the Arctic Ocean which transports thick and older ice out of the Arctic Ocean into the North Atlantic Ocean through Fram Strait (Hansen et al., 2013).

Distinguishing between old and first year ice on the basis of the leading edge of the acoustic return for an individual acoustic ping is based on the concept that the harder and more compact old ice will have a steeper rate of increase in the leading edge of the acoustic returns on encountering the underside of the ice. An example of two different rise times for acoustic pings is given in Figure 7.

IPS profiles (acoustic backscatter returns vs. time from a single acoustic ping) from the 2009-2010 deployment at Sites F and G were selected based on a criteria designed to ensure representative responses from the instrument. In Fissel et al. (2012), parameters from selected profiles were examined for evidence of multi-year ice from weeks where Canadian Ice Service (CIS) weekly ice charts indicated its presence in the summer of 2009, and the results were compared to control data at the same measurement site from weeks where the ice charts indicated no presence of multi-year ice (spring of 2010).

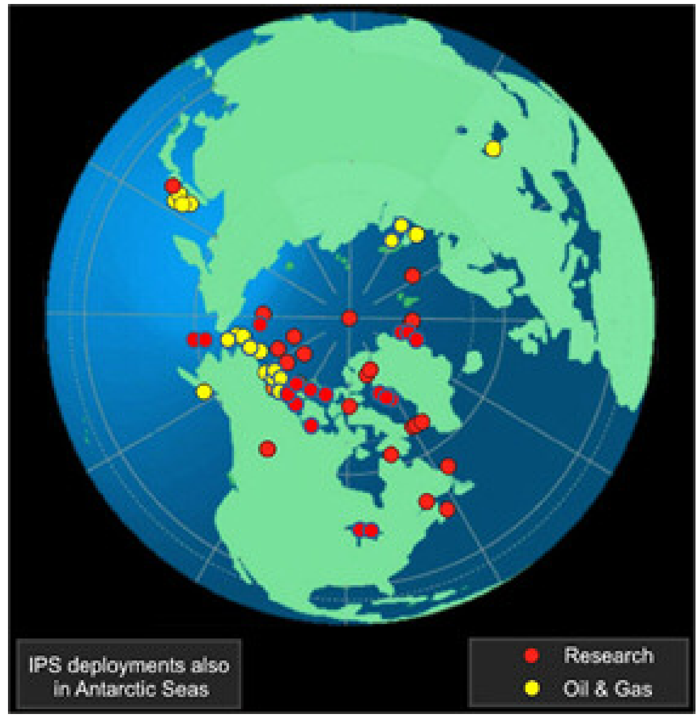

Figure 6. Locations of marine moored ice profiler deployments in the Northern Hemisphere from 1996 to the present. Ice profiler locations for scientific applications are shown by red symbols while oil and gas locations are shown by yellow symbols.

In this paper, we have refined the algorithm for computing the slope; in particular, we pre-screen the acoustic backscatter ping data to avoid slope regions and the computation of the slope itself has been changed to the algorithm described in the above Methods section.

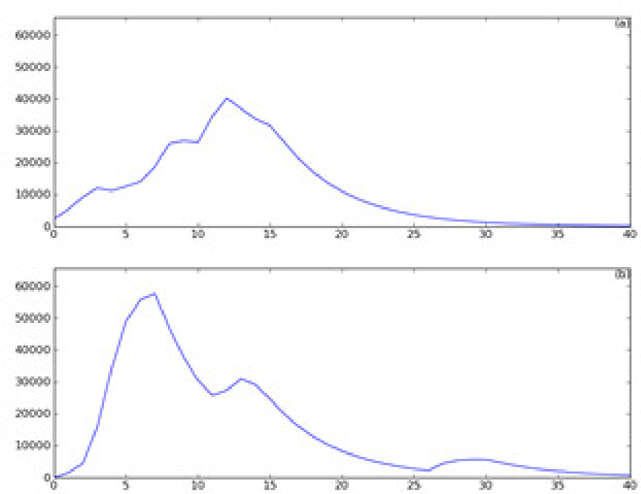

Figure 7. The acoustic backscatter return (as instrument analog to digital (A/D) counts) is shown for individual pings that may represent two different sea ice types: (a) from first year ice and (b) from old ice. The x-axis is in A/D samples count numbers, starting from the initial rise of the return for the ice target.

The analysis for the 2009-2010 Canadian Beaufort Sea data sets has been redone. The resulting revised method is also applied to detect potential occurrences of multi-year ice off Northeast Greenland. In this region, the fraction of old ice present during each week was obtained from ice charts prepared by the Norwegian Meteorological Agency.

The qualified profiles were combined by week, and the mean and standard error values of the persistence, maximum amplitude, and corrected slope were computed. The results of the re-analysis of the profile data sets for the deep moorings in the Canadian Beaufort Sea (Fissel et al., 2012) are presented in Table 1. It is seen that the slopes of the leading edge of the acoustic returns from the periods when old ice is present is approximately 37% larger at site F and 29% larger at site G than when no old ice is reported. When old ice was reported, the ice charts indicted that thick first year ice was also present at up to 50% of the total ice concentrations. Therefore, in the increase in the slope of the leading edge ice returns may actually be larger than indicated in the results of Table 1.

Table 1: A comparison of the acoustic returns of the leading edge of the ice returns from individual pings for site F and G in the Canadian Beaufort Sea in 2009-2010 for weekly periods when old ice was reported to present or not to be present from ice charts.

Date	Percent Old Ice Present	# of Qualified Profiles	Persistence (micro-sec)		Amplitude (A/D counts)		Corrected Slope (counts/micro-sec)	
Site F			Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.
2009/07/29	>50%	814	360	6	55367	671	1156	24
2009/08/01	>50%	314	335	9	53223	1130	1132	40
2009/08/08	>50%	128	388	15	57369	1413	1228	56
2009/08/15	>50%	108	353	17	54311	1952	1232	72
2009/08/22	>50%	98	369	15	56982	1732	1281	65
2009/08/30	>50%	58	382	21	57093	2364	1161	90
2009/09/05	>50%	54	398	18	60141	2003	1330	74
Totals with old ice	**Average**	**225**	**369**	**14**	**56355**	**1609**	**1217**	**60**
2010/05/03	none	197	163	10	22936	1045	322	22
2010/05/08	none	150	172	12	22948	1104	273	16
2010/05/15	none	253	170	9	24111	966	322	19
2010/05/22	none	246	189	11	24333	950	305	16
2010/05/29	none	73	155	13	24292	1929	371	43
Totals without old ice	**Average**	**184**	**170**	**11**	**23724**	**1199**	**319**	**23**
Site G								
2009/07/31	>50%	86	252	11	49249	2279	997	72
2009/08/08	>50%	39	301	13	58920	2374	1257	93
2009/08/14	>50%	117	281	9	51891	1760	1151	65
2009/08/21	>50%	17	287	20	53510	4163	1033	168
Totals with old ice	**Average**	**65**	**280**	**13**	**53392**	**2644**	**1109**	**100**
2010/05/03	none	161	123	6	21128	1076	302	21
2010/05/08	none	87	132	9	20026	1156	303	25
2010/05/14	none	138	126	7	22485	1249	353	28
2010/05/21	none	170	118	6	20553	975	329	24
2010/05/28	none	44	112	10	18317	1530	283	38
Totals without old ice	**Average**	**120**	**122**	**8**	**20502**	**1197**	**314**	**27**

Note that there is a large amount of variability in the corrected slope, and other values computed on individual pings. Therefore, the detection of old ice results from the realization of many profile pings, that are obtained over weekly intervals, rather than any single ping.

The analysis results derived for the acoustic pulse leading edge method for the northeast Greenland data sets differed from those of the Canadian Beaufort Sea in two key respects. In the Greenland data sets, it was difficult to find weekly periods with qualifying periods in which old ice was not present. In fact, there was only one week (in August) in which qualifying data was obtained from the full year of data collected. In addition, the computed slope values for the fall period were much smaller (typically around 450) even though old ice represented more than half of the ice present, according to the ice charts. These values are much less than for the Beaufort Sea data sets (Table 1). In summer, the slope values are higher (750 – 1120) but the qualifying data sets are very small in number.

Given the large discrepancies between the Beaufort Sea and Greenland results for the leading edge slope method, the analysis methodology which has been developed and appears to work reasonably well for the Beaufort Sea, clearly requires further review and refinements, for the Greenland region, where the results are somewhat counter-intuitive. Once additional analysis is completed to develop a more robust method, the results for the method of detecting old and multi-year ice using the slope of the leading edge will be updated in the future.

Roughness Scale of the Underside of Sea-Ice

Analysis of the second method, involving characterization of the vertical roughness scales of ice draft distance segments is presented for both the Canadian Beaufort Sea data sets and for the locations off north-east Greenland. As discussed in the Methods section, the two statistical parameters that are applied are (1) the 'mean' of the individual absolute difference values and (2) the standard deviation of the raw and smoothed ice drafts. Larger values of both of these statistics indicates a higher degree of roughness of the sea ice, that would be associated with highly deformed first year ice vs. the more smoothed underside of old ice, especially multi-year ice.

The compiled results of the 'mean' and standard deviation values is presented in Table 2 for the Canadian Beaufort Sea measurements and in Table 3 for the north-east Greenland measurements.

Table 2: The computed 'mean' and standard deviation values of the residual ice drafts after smoothing for qualified weekly data segments at two sites in the Canadian Beaufort Sea.

Date	Percent Old Ice Present	Anomaly from Smoothed Keel		
Site F		Mean	Std. Dev.	# Keels
2009/07/29	>50%	0.309	0.428	9
2009/08/01	>50%	0.305	0.395	4
2009/08/08	>50%	0.216	0.307	3
2009/08/22	>50%	0.281	0.348	3
2009/08/30	>50%	0.235	0.309	1
2009/09/05	>50%	0.243	0.308	1
Totals with old ice	**Average**	**0.284**	**0.382**	**21**
2010/05/03	none	-	-	0
2010/05/08	none	0.530	0.683	5
2010/05/15	none	0.443	0.565	5
2010/05/22	none	0.344	0.456	12
2010/05/29	none	0.457	0.594	5
Totals without old ice	**Average**	**0.408**	**0.532**	**22**
Site G				
2009/07/31	>50%	0.171	0.238	3
2009/08/08	>50%	0.284	0.447	1
2009/08/14	>50%	0.177	0.241	6
2009/08/21	>50%	0.247	0.295	2
Totals with old ice	**Average**	**0.196**	**0.267**	**12**
2010/05/03	none	0.549	0.737	4
2010/05/08	none	0.597	0.750	3
2010/05/14	none	0.519	0.663	19
2010/05/21	none	0.403	0.530	23
2010/05/28	none	0.457	0.560	3
Totals without old ice	**Average**	**0.472**	**0.612**	**49**

Table 3: The computed 'mean' and standard deviation values of the residual ice drafts after smoothing for qualified weekly data segments at three sites in the northeast Greenland area.

Date	Percent Old Ice Present	Anomaly from Smoothed Keel		
		Mean	Std. Dev.	Num Keels
Site 1				
2012/10/07	>50%	0.597	0.787	2
2012/10/09	>50%	0.362	0.518	4
2012/10/16	>50%	0.522	0.664	15
2012/10/23	>50%	0.430	0.560	35
2012/10/30	>50%	0.476	0.624	49
2012/11/06	>50%	0.474	0.629	21
2012/11/13	>50%	0.472	0.627	22
2012/11/20	>50%	0.551	0.722	11
2012/11/27	>50%	0.481	0.636	15
2012/12/04	>50%	0.448	0.591	20
2012/12/11	>50%	0.443	0.568	25
2012/12/18	>50%	0.451	0.588	1110
Totals with old ice	**Average/Sum**	0.476	0.626	1329
2013/07/07	>50%	0.195	0.267	1
2013/07/09	>50%	0.257	0.357	3
2013/07/16	>50%	0.306	0.408	1
2013/08/07	>50%	0.248	0.334	15
2013/08/13	>50%	0.317	0.423	22
Totals with old ice	**Average/Sum**	0.264	0.358	42
Total with ice-Both Seasons	**Average/Sum**	**0.469**	**0.618**	**1371**
2013/08/21	none	0.296	0.394	13
Totals without old ice	**Average/Sum**	**0.296**	**0.394**	**13**
Site 3				
2012/10/07	>50%	0.149	0.203	2
2012/10/14	>50%	0.426	0.551	6
2012/10/21	>50%	0.426	0.544	9
2012/10/28	>50%	0.447	0.585	31
2012/11/04	>50%	0.448	0.602	12
2012/11/11	>50%	0.544	0.703	47
2012/11/18	>50%	0.481	0.625	45
2012/11/25	>50%	0.479	0.642	13
2012/12/02	>50%	0.517	0.655	11
2012/12/09	>50%	0.493	0.644	25
2012/12/16	>50%	0.445	0.576	1184
Totals with old ice	**Average/Sum**	**0.441**	**0.576**	**1385**
Site 4				
2012/10/07	>50%	0.386	0.529	5
2012/10/11	>50%	0.207	0.292	6
2012/10/17	>50%	0.473	0.614	21
2012/10/24	>50%	0.444	0.574	25
2012/10/31	>50%	0.512	0.654	18
2012/11/15	>50%	0.475	0.618	17
2012/11/21	>50%	0.409	0.544	3
2012/12/05	>50%	0.478	0.641	12
2012/12/12	>50%	0.544	0.699	12
2012/12/19	>50%	0.438	0.565	551
Totals with old ice	**Average/Sum**	0.436	0.573	670
2013/07/07	>50%	0.324	0.426	1
2013/07/14	>50%	0.191	0.283	1
2013/07/25	>50%	0.365	0.507	6
2013/07/31	>50%	0.071	0.095	1
Totals with old ice	**Average/Sum**	0.238	0.327	9
Total with Both Seasons	**Average/Sum**	**0.434**	**0.570**	**679**
2013/08/21	none	1.088	1.349	1
Totals without old ice	**Average/Sum**	**1.088**	**1.349**	**1**

For the Beaufort Sea, the typical values of weeks with large quantities of old ice present are <0.3 m for the 'mean' statistic and < 0.4 m for the standard deviation statistic. By comparison, the respective values are larger when first year ice only is present, with values of the 'mean' being > 0.4 m and values of the standard deviation > 0.47 m. The 'mean' and standard deviation values are reduced by 30% for site F and over 50% for site G when large quantities of old ice are presented by comparison to first year ice. These results suggest that these roughness statistics may be useful indicators of the presence of old ice in place of first year ice for the Beaufort Sea data sets.

The comparison of roughness statistics for the Greenland data sets is somewhat less clear (Table 3). Nearly all of the ice drafts are associated with old ice according to the ice charts. The 'mean' and standard deviation statistical values tend to be larger than those in the Beaufort Sea data sets with old ice present, especially in the fall months, with typical values of 0.44 – 0.47 for the 'mean' and 0.57 – 0.63 for the standard deviation. These old ice values in fall are actually comparable to those of the rougher first year ice as measured in the Beaufort Sea. However in summer, when qualifying data sets are less frequently available, the 'mean' and standard deviation statistic values tend to be lower at 0.26 and 0.37 respectively which is closer to the Beaufort Sea values having large quantities of old ice. Unfortunately, the availability of first year ice roughness results are very limited to just one single value, albeit of much rougher statistical values (1.1 and 1.3 for the 'mean' and standard deviation. Assessing the capabilities of the roughness statistics for the northeast Greenland region will require additional data analysis in order to extract more results for first year ice, and to understand the reasons for the larger roughness values in the fall as compared to summer values.

CONCLUSIONS AND RECOMMENDATIONS

Two methods for identifying and quantifying the presence of old ice vs. deformed first year ice have been developed: the slope of the acoustic pulse return on the encounter of sea ice; and a computed roughness parameter derived over distance scales of 10 m. Both methods show promise for the capability of distinguishing old ice from first year ice, especially in the Beaufort Sea, using weekly ice charts as providing an independent source of information on old vs. first year ice. There appears to be a clear separation of results for old vs. deformed first year ice on a weekly basis in both the leading edge slope statistics and the roughness statistics in the Beaufort Sea data sets. However, there is overlap in both approaches when examining the event by event results.

The results for the northeast Greenland area do not show as clear a distinction of old ice vs. first year for either method, in part to paucity of qualified events of deformed first year ice. Moreover, there are large differences apparent within both methods between the fall period and the summer period for this regime of predominantly old ice.

Clearly more analysis effort is required for examining seasonal differences in the methods for northeast Greenland and it would be prudent to extend this examination to the Beaufort Sea data sets as well.

The difficulty in confirming the old and multi-year ice categorization through an independent method with a more appropriate temporal resolution than weekly ice charts is an important limitation in testing the results derived from both ULS data sets methods developed in this paper. Marine ice is typically composed of both old and deformed first year that can vary over time periods of a few to several hours rather than one week or more. Surface truth values of ice age are required on these hourly time scales to make more definitive comparisons with ULS based characterizations for differentiating old ice with deformed first year ice. Such temporal resolution could be achieved with surface-based measurement programs, supported by a ship, that are coincident with the ULS data sets obtained from moored instruments. It is suggested that research vessels that are involved in ice studies could provide such comparative data sets.

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