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The Sensitivity of Ice Keel Statistics to Upward Looking Sonar Ice Draft Processing Methods

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Abstract

Upward looking sonar (ULS) instruments have been used for several decades to provide continuous measurements of ice draft. The time resolution of the ice draft observations is typically 1-2 seconds. When fused with ice drift speed observations, a high horizontal spatial resolution can be realized. Such a high resolution allows for the identification of individual ice keel features and an analysis of their spatial characteristics. Many methods are available for transforming the ice draft series from an equispaced time domain to an equidistant spatial domain. This paper analyzed the sensitivity of ice keel statistics to three transformation methods applied to ULS sea ice measurements in the Beaufort Sea and North Chukchi Sea. Although differences were found between the methods, these were related to episodes when the sampling frequency is not high enough to profile an ice draft feature travelling with a high drift speed. Knowledge of maximum drift speeds in the region of a measurement location along with the enhanced power and storage capacities of modern ice profilers enable sampling configurations which avoid this scenario.

Introduction

Ice ridge keel geometry is important for the calculation of loads both on offshore structures and subsea installations in the Arctic. A means of obtaining information about the ice ridge keel population is the use of upward looking sonars (ULS). These could be anchored to the seafloor or mounted on submarines. In either case, the ice draft over the measurement location is determined on a regular time interval. If the ice drift speed or the submarine speed relative to the ice is also measured, the ice draft time-series profile can be transformed to an ice draft spatial-series, i.e. an ice draft time-series with a horizontal distance value assigned to each data points. Through such a transformation, the data are typically smoothed (Ekeberg et al. 2013) and/or transformed to equidistant data (Marcellus et al., 2011; Ross et al., 2012). The present study investigates how different transformation methods compare with respect to derived ice ridge geometry.

Data

The current analysis used ice draft and drift speed measurements acquired at two locations during the 2010/2011 ice season. The data was sampled in the Northern Chukchi Sea and the Beaufort Sea (Fig. 1) from October 2010 to October 2011 using an Ice Profiler Sonar (IPS) manufactured by ASL Environmental Sciences, Inc. and an Acoustic Doppler Current Profiler (ADCP) manufactured by Teledyne RDI, Inc.. The IPS measured the ice draft (along the y-axis, Fig. 2). The sampling rate varied from 1/3 to 1 Hz and the sonar beamwidth was 1.8°. The ADCP recorded ice drift speeds every 20 minutes in the Chukchi Sea and every 30 minutes in the Beaufort Sea.

Table 1: Location and operational frequency of the IPSs that were used.

Area	Location	Operating period (dd-mm-yyyy)		Frequency (Hz)
Northern Chukchi Sea	75°6'N, 168°0'W	09-10-2010	31-01-2011	1/2
		31-01-2011	02-10-2011	1/3
Beaufort Sea	70°19'N, 133°44'W	03-10-2010	01-11- 2010	1/3
		01-11-2010	01-06- 2011	1
		01-06-2011	28-09-2011	1/3

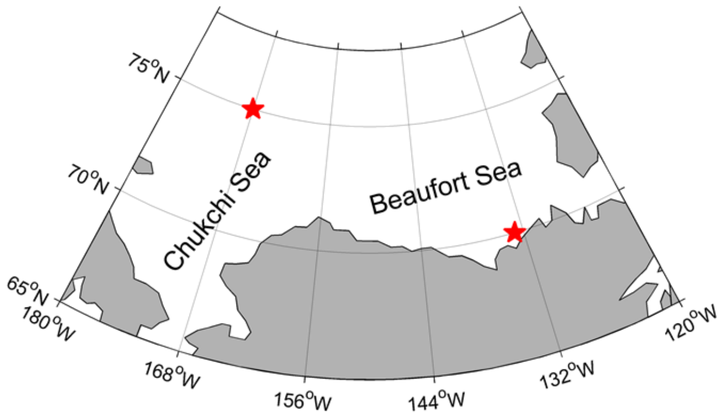

Figure 1: The stars mark the location of the two moorings.

Data Processing and Analysis Methods

The initial conversion from range data to temporal ice draft data follows that described in Melling et al. 1995. The IPS acquires observations of the range to the underside of the ice, the pressure at the instrument depth, and the tilt of the instrument. Combining these signals with a measure of the atmospheric pressure leads to the determination of the overhead ice draft time-series.

Conversion to spatial data

The ice draft time-series is mapped to a horizontal spatial extent. First, the ice drift measurements were linearly interpolated to correspond to the ice draft time-series (1/3 Hz to 1 Hz). The horizontal distance between the observed drafts y_i and y_{i+1} was dx_i (Equation (1)):

$$dx_i = x_{i+1} - x_i = (v_i + v_{i+1}) \cdot dt \quad (1)$$

where v_i and v_{i+1} refer to the point velocities in x_i and x_{i+1}, respectively.

Transformation to spatially equidistant data

Three different methods for transformation to spatially equidistant ice draft were tested: the running average (used by Ekeberg et al. 2013), the double-weighted double-quadratic transformation routine (used by Ross et al. 2012), and the cubic spline (used by NSIDC, 2006; Marcellus et al. 2011). The final product was an ice draft series mapped to an equidistant distance-series with a spacing of 1 m. This target distance-series is referred to below as the distance vector. All transformation methods were used to compute an equidistant ice draft series at 0.1 m spacing and then block averaged to produce a 1 m spaced series.

Running average

The running average transformation method computes an ice draft value, $\hat{y}_i$, mapped to the *i*th distance vector element as the mean value of all observations, $y(x_j)$, within a window of ±0.5 m:

$$\hat{y}_i = \frac{1}{j} \sum_{j=1} y(x_j) \quad (2)$$

for $x_j \in [x_i \pm 0.5m]$.

This transformation employs all ice draft observations and was applied if there were one or more observations available. If no ice draft observations occurred within a particular running average window, linear interpolation was used to fill this gap. This scenario occurs when the horizontal distance traversed by the ice during one ice draft sampling interval exceeds the window size, i.e. 1 m.

Double-weighted double-quadratic interpolation method

The double-weighted double-quadratic (DWDQ) interpolation method is described by Equation (3) where Y_1 and Y_2 are quadratic interpolants computed at the *i*th distance vector point, x_i, and u_i represents the index of *i*th ice draft observation. The quadratic interpolant Y_1, uses two ice draft observations - $y(u_{i-1})$ and $y(u_i)$ - to the left of x_i and one - $y(u_{i+1})$ - to the right of x_i while Y_2 uses two observations - $y(u_{i+1})$ and $y(u_{i+2})$ - to the right of x_i and one - $y(u_i)$ - to the left (ASL, 2011). The quadratically interpolated ice draft values are then weighted in correspondence to the proximity of their contributing observation values to the desired distance vector element:

$$\hat{y}(x_i) = \frac{Y_1 \cdot [|\, y(u_i) - y(u_{i-1})\,|] \cdot [|\, x_i - x(u_i)\,|] + Y_2 \cdot [|\, y(u_{i+2}) - y(u_{i+1})\,|] \cdot [|\, x_i - x(u_{i+1})\,|]}{[|\, y(u_i) - y(u_{i-1})\,|] \cdot [|\, x_i - x(u_i)\,|] + [|\, y(u_{i+2}) - y(u_{i+1})\,|] \cdot [|\, x_i - x(u_{i+1})\,|]} \quad (3)$$

Uniform cubic spline

The uniform cubic spline $\mathbf{S}_i(t)$ (Sederberg, 2009) approximates the interval between observations y_i, and y_{i+1} but does not use the observations as fixed points in the approximation. The observations on the interval could be found by solving Equation (4) where y_i are the control points which correspond to observed ice draft values. The cubic spline creates a continuous approximation which is differentiable.

$$\mathbf{S_i(t)} = \frac{1}{6} \cdot \begin{bmatrix} t^3 & t^2 & t & 1 \end{bmatrix} \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix} \begin{bmatrix} y_{\mathbf{i-1}} \\ y_{\mathbf{i}} \\ y_{\mathbf{i+1}} \\ y_{\mathbf{i+2}} \end{bmatrix} \quad (4)$$

for $t \in [0,1]$, $\Delta t = 0.2$.

Ridge identification and geometry

The ice ridges were identified from the equidistant ice draft series using the Rayleigh criterion with a threshold value of 2.5 m and a minimum draft of 5 m (Wadhams and Horne, 1980; Ekeberg et al., submitted). The ice ridge geometry is schematically shown in Figure 2 and follows the definitions in Ekeberg et al. (submitted). P_1 and P_2 are the start and end point of the ice ridge respectively and were either where the ice draft crossed the threshold value (h_{thres}) or the point shared by two neighboring ridges. Ridges that had an aspect ratio (keel width divided by the draft) less than one were disregarded because these ridges are unstable features that are likely to turn over due to buoyancy forces. Keel width is the observed keel width from the along-track ice draft measurements and should not be confused with the true keel width which is the cross section which could be different if the three dimensional ice drafts measurements were available in the vicinity of the keel feature.

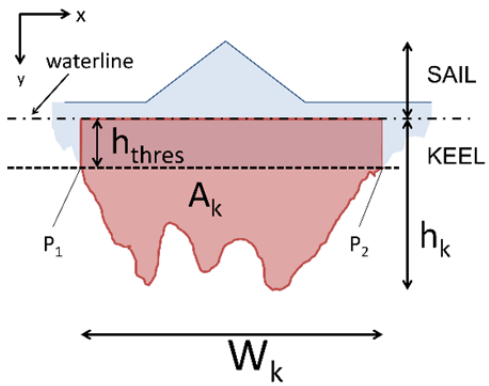

Figure 2: The schematics of the ridge keel geometry where h_k is the ridge keel draft, w_k the keel width and A_k the keel area (After Ekeberg et al., submitted).

Ice drift speed

The ice drift was on average higher in the Chukchi Sea than in the Beaufort Sea but the greatest drift speed was recorded in the Beaufort (Table 2).

Table 2: Key statistics for the drift speed.

Site	**Start** [yyyy-mm-dd]	**End** [yyyy-mm-dd]	**Ice drift** [m/s]			
			Mean	Standard deviation	Min	Max
Chukchi Sea	2010-10-25	2011-07-23	0.12	0.09	0	0.6
Beaufort Sea	2010-11-08	2011-05-18	0.08	0.12	0	0.8

Results

In rare cases in the Chukchi Sea data (0.4%), large drift speeds led to target distance vector elements further than 1 m from their closest observed ice draft neighbours. No such events occurred in the Beaufort Sea. The running average method used an average of 3.3 observations per meter in the Chukchi Sea. In the Beaufort Sea it used an average of 7 observations per meter. Extremely low drift speed events had more than 1000 points per meter; these were ignored as these ice drift speeds are well below the measurement accuracy and likely correspond to stationary ice conditions. The initial spacing from the cubic spline transformation was on average (standard deviation) 0.06 (0.05) m and 0.02 (0.02) m in the Chukchi Sea and the Beaufort Sea, respectively. The maximum spacing was 0.29 m and 0.17 m, respectively.

Dependence on the initial spatial resolution

The final spatially referenced ice draft series varied with transformation method, drift speed, and measurement frequency (Fig. 3 and 4). While the outcome from the DWDQ and the cubic spline methods was quite similar, the running average clearly stands out with deeper peaks. This is most notable at low initial spatial resolution (Fig. 4).

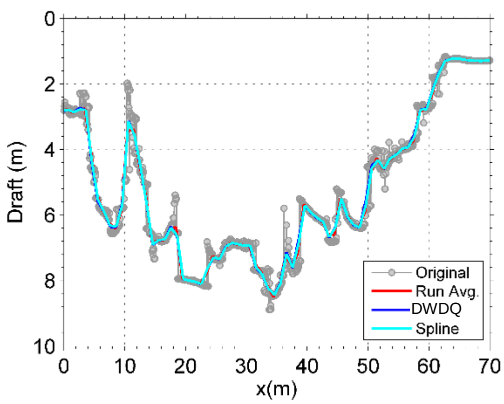

Figure 3: High resolution results, the drift speed was 0.02 m/s while the measurement frequency was 1/3 Hz.

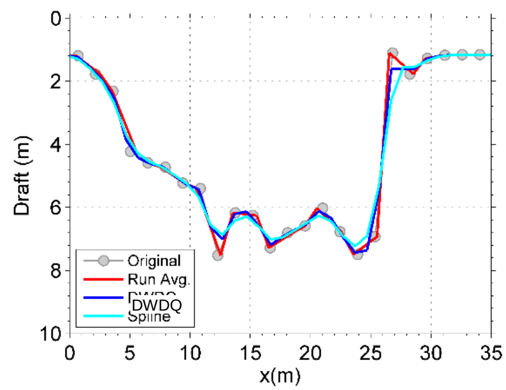

Figure 4: Low spatial resolution results, the drift speed was 0.41 m/s while the measurement frequency was 1/3 Hz.

By categorizing the Chukchi Sea data into low and high spatial resolution (correspondingly, high and low ice drift speeds relative to the sampling frequency) the variability on the impact on ridges statistics was studied (Table 3). The resolution was considered low when there were less than two observations per meter and high otherwise - a criterion which takes into account that the measurement frequency varied. Table 3 show that there was a greater difference within the ridge statistics derived from the low resolution episodes compared with the high resolution episodes. The effect from changing the transformation method from a running average to a cubic spline was an increase in the mean keel width of 9% and a 8% increase in the mean keel area. The pattern was similar at high resolution but with smaller changes (5% and 4%, respectively).

The number of ridges flanked by another ridge indicated the degree to which ridges which were divided by the ridge identification criterion and is referred to as neighboring ridges. A decrease in the number of ridges coincided with the number of neighboring ridges (Table 3). This suggested that increasing smoothing (leading to fewer ridges) result from "merging" of ridges which otherwise would be distinguished as individual ridges. Fewer neighboring ridges (comparing different methods) could suggest that the smoothing increased merging ridges which otherwise was considered as individual features. E.g. 4 ridges became 2 when it was assumed that none of the removed ridges were flanked by more than one ridge. By comparing the neighboring ridges in the different outcomes about 86% (low initial spatial resolution) and 95% (high initial spatial resolution) of the neighboring ridges in the DWDQ and the cubic spline results also existed in the running average results. This revealed that the ridges that are flanked, or identified as individual, do vary with method and that these are not simply a product of an initial set of "split ridges" which are more or less merged with transformation method.

Table 3: The ridge statistics for low drift and a high drift periods. Standard deviation values are provided in parentheses.

Method	High spatial resolution					Low spatial resolution				
	#	Neighboring ridges #	$\overline{h}_k$ (m)	$\overline{w}_k$ (m)	$\overline{A}_k$ (m^2)	#	Neighboring ridges #	$\overline{h}_k$ (m)	$\overline{w}_k$ (m)	$\overline{A}_k$ (m^2)
Run Avg.	4808	595	6.87 (1.86)	22 (14.4)	118 (107)	2363	1318	6.31 (1.38)	22 (13)	107 (80)
DWDQ	4715	576	6.88 (1.87)	23 (14.6)	121 (108)	2268	1258	6.33 (1.38)	23 (12.7)	111 (79)
Spline	4660	552	6.88 (1.87)	23 (14.7)	122 (109)	2176	1239	6.31 (1.38)	24 (13.2)	116 (82)

Keel width vs. draft

The running average method predicted slightly greater peaks compared with both the DWDQ and the cubic spline methods

(Fig. 3 and 4). This could lead to more ridges which are slightly greater than the minimum draft threshold that would only be included with the running average while the DWDQ and the cubic spline methods would have slightly too low draft to be included. An example of this is provided in Figure 5 and in Table 4. The lower mean keel width and area (Table 3) could thus be explained by the inclusion of an increasing number of small ridges.

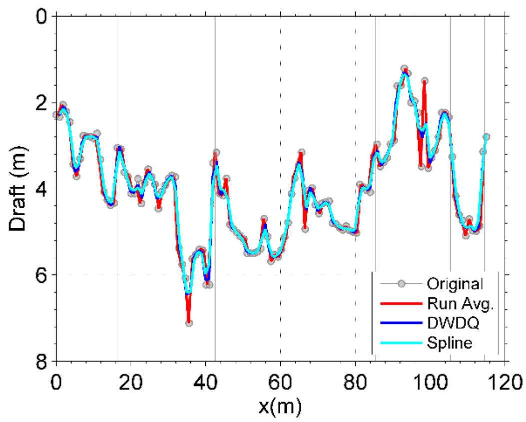

Figure 5: The 5 minute section measured 06:45 21st November 2010.The grey lines in the background indicate the start/end of an ice ridge analysing the data which were smoothed with the running average.

Table 4: Corresponding ridge properties to Fig. 5.

Location of peak (x in Fig.5)	Method	Ridges		
		h_k	w_k	A_k
35	Run avg.	7.11	26	118
	DWDQ	6.46	26	118
	Spline	6.40	26	118
56	Run avg.	5.68	23	111
	DWDQ	5.59	22	107
	Spline	5.58	22	107
79	Run avg.	5.02	20	88
	DWDQ	5.01	26	105
111	Run avg.	5.09	12	46

However, Figs. 6 and 7 demonstrate that there was a consistent difference in the obtained keel width and area between the transformation methods regardless of draft. In the figures the mean keel width vs. draft per method (DWDQ and cubic spline) are compared with the mean keel width based on the running average. The size of the anomaly did depend on the initial spatial resolution and by dividing into high and low initial resolution (Table 5) it was clear that the difference increased at low spatial resolution and was reduced at high resolution. Considering all the data regardless of the initial resolution the keel width and the keel area increased by about 3-6 % compared with the running average.

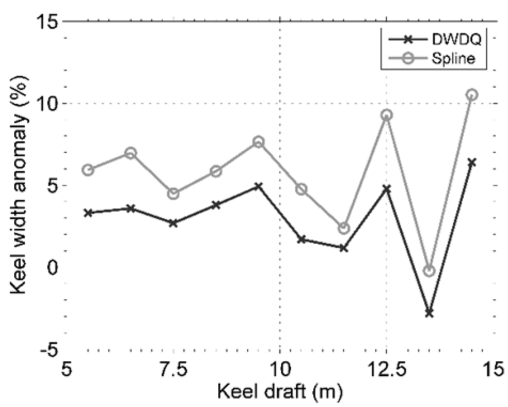

Figure 6: Anomalous keel width vs. draft compared with the running average method (minimum 5 ridges per bin, 1 m bin size).

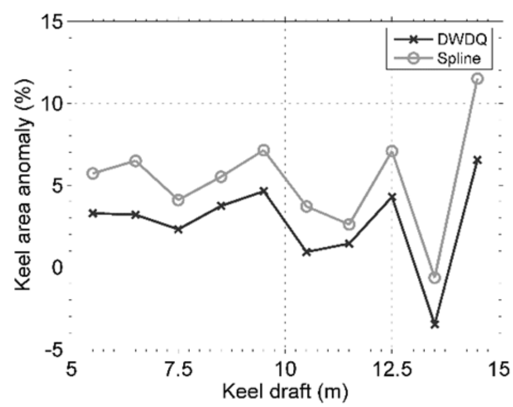

Figure 7: Anomalous keel area vs. draft compared with the running average (minimum 5 ridges per bin, 1 m bin size)

Table 5: The mean anomalous keel width and keel area for each method compared with the running average.

Method	Parameter	High spatial resolution	Low spatial resolution	All (Fig. 6-7)
DWDQ	w_k	1.7 %	6.6 %	3.0 %
Cubic spline	w_k	3.0 %	11.3 %	5.8 %
DWDQ	A_k	1.7 %	5.7 %	2.7 %
Cubic spline	A_k	2.7 %	10.0 %	5.3 %

Main results

Compared with ridges identified from the original untransformed data the ridge keel statistics are quite similar regardless of the transformation technique (Table 6). The difference in the final number of ridges varied by less than 60 in the Beaufort Sea and 335 in the Chukchi Sea. In both areas, but most notably in the Chukchi, a greater mean keel width and keel area coincided with fewer ridges. The greater difference in the Chukchi might originate from periods with low initial resolution which increased the difference between the methods.

Table 6: Mean ridge keel geometry from analysis of the different spatial series. The bar above the parameter refers to the parameter mean while σ refers to the standard deviation of the parameter.

Area	Method	#	$\bar{h}_k$ (σ)	$\bar{w}_k$ (σ)	$\bar{A}_k$ (σ)
Beaufort	Original	3299	7.24 (2.5)	20.4 (16)	128 (168)
	Running average	2753	7.33 (2.5)	29.2 (21)	172 (207)
	Cubic spline	2720	7.34 (2.6)	29.6 (21)	174 (209)
	DWDQ	2694	7.35 (2.6)	29.9 (21)	176 (211)
Chukchi	Original	9093	6.80 (1.8)	18.3 (12)	101 (94)
	Running average	7171	6.84 (1.8)	21.7 (14)	117 (107)
	Cubic spline	6983	6.85 (1.8)	22.4 (15)	120 (109)
	DWDQ	6836	6.84 (1.8)	23.0 (15)	123 (111)

Discussion

The analysis distinguished between high initial spatial resolution (<0.5 m) and low initial resolution (>0.5 m). There was a clear trend that the final ridge keel statistics varied more between the methods when the initial distance spacing increased due to higher ice speeds. It then follows that a way of reducing the differences due to different transformation techniques would be to make sure the measurement frequency is sufficiently high to provide an adequate number of distance samples of ice draft (at least one and preferably more) within the desired horizontal spatial resolution (1 m) in accordance with the maximum expected drift speed at the location. However choosing the measurement frequency involves considering the duration of the measurements, the storage capacity and the battery lifetime.

The three different transformation methods which were compared here have been used in three different contexts in earlier studies. While the DWDQ method is applied to data like those of the present study, the cubic spline and the running average have not. The cubic spline has been used to interpret submarine data. These data have an initial spacing which is primarily governed by the speed of the submarine because the measurement frequency is fixed (6 Hz, Rothrock and Wensnahan, 2007). Typical operating speeds then result in an initial spacing of about 1 m which corresponds to the low initial resolution (Rothrock and Wensnahan, 2007). The present study suggests that if the cubic spline would be replaced with the DWDQ method (or the running average) the observed keel width (w_k) and observed area (A_k) would be smaller but that there would be an increase in the number of ridges (as shown in Table 3).

Ekeberg et. al (2012, 2013, POAC/IAHR) interpreted draft data from the Fram Strait with respect to the number of ridges and the keel draft. The data were sampled at ½ Hz and a running average filter with a bandwidth of five points was used to smooth the data. The data was kept as equispaced temporal data due to the lack of ice speed data. An estimate from drift buoys gave a mean drift speed of 0.3 m/s (Ekeberg et al. CRST) which gives a mean initial spacing of 0.6 m. This suggests that more than half the observations in the Fram Strait fall into the low spatial resolution category which was used in the present study. Because the moving average was used with a five point bandwidth it avoided one of the deficiencies in the way it was applied in the present study which was that it did not smooth the data when only one observation or less was within the closest meter. Instead it potentially smoothed over greater spatial distances. In the Fram Strait it is expected that the drift speed exceeds 0.7 m/s (Yulmetov, 2013). The running average would then smooth over a spatial window corresponding to at least 7 m (1/2 Hz and 0.7 m/s). This does however resemble the present study where both the DWDQ and the cubic spline methods use four observations regardless of their initial spacing. Since the present maximum drift speed was 0.8 m/s (Beaufort Sea with 1 Hz) both methods used ice draft observations which were 3.2 m apart.

The resulting number ridges per method seem to vary primarily due to a reduction in the keel draft which becomes less than the minimum draft or because more or less ridges are split or merged. Because the ridge draft probability distribution is exponential (Ekeberg et al. submitted, Wadhams, 1992) the smallest ridges are the most frequent. A slight reduction in the draft could thus eliminate a significant portion of the ridges. The splitting/merging of ridges refers to the transformation method's capability to reduce the draft in depressions between peaks leading to less splitting by the ridge identification criterion. The difference in the number of neighboring ridges per method in Table 3 could be interpreted as an indicator of how much each method smoothed the representations of relative minima and maxima. At the low spatial regime the number of neighboring ridges was reduced by 79 ridges comparing the running average to the spline method. This could potentially cause a reduction in the total number of ridges of 40 (half). The total reduction in the number of ridges was 187. The "merging" therefore only constitutes 21 % of the reduction in the number of ridges could be explained by the splitting of ridges. This effect was apparently less for the data which had a high initial spacing which lead to a reduction of 15 %.

Both of these processes seem to govern the difference in the number of ridges since both contribute to changes in mean keel width and area. The inclusion of more ridges of about 5 m deep (here the minimum draft) would include more small ridges with a low draft and width and thus contribute to a reduction in the mean keel width and area. Splitting of ridges would naturally contribute to a reduction in the mean keel width and area while merging simply is the inverse situation.

The initial spacing had a great impact on the results and it was primarily in the data which had a low initial resolution that the methods differed. For comparative purposes the methods were not complemented with additional criterions which would reduce what could be considered as deficiencies in the methods. In the present analysis, the running average did not perform as desired when the spacing in the raw data was too wide. An alternative formulation in the present study could be to always apply the values within the closest meter or in the case there were say, less than four observations, the closest four observations should be used. The two other methods do not have the same incorporated flexibility but could instead be complemented with a running average when the initial spacing is considered too great.

Which technique is most suitable for ice studies is somewhat subjective but a final resolution of 1 m seems to be a reasonable choice as we do not expect that any significant features for ice load calculation to exist at distance scales of less than 1 m. Because the keel loads vary not only with the keel draft but also the keel area (Dalane et al. 2008) it is useful to be aware of the potential difference between transformation methods, as applied to ULS data, and their effect on ridge keel statistics.

Conclusion

When a ULS is used to sample data about the occurrence of ice features it is very important that the sampling rate is chosen to cover the range of drift speeds which are encountered in the area. If the sampling rate is chosen with care this could lead to an initial spatial resolution which is sufficiently high to reduce the impact of the smoothing methods considerably.

For moored ULS data obtained using an ASL Ice Profiler Model IPS5, as introduced in 2008, the ice range/draft sampling rate can be increased from the lower sampling rates considered in this study, in order to provide an adequate number of distance samples of ice draft (at least one and preferably more) within the desired horizontal spatial resolution (1 m). As an example, if the maximum expected ice speed is as high as 1.0 m/s (considerably larger than the maximum ice speeds in the moored ULS data sets considered in this study), a 1 Hz sampling rate will provide at least one measurement sample for each 1 m of distance travelled, and for the great majority of the data set several samples will be provided for each meter of ice distance. For a one year measurement period, the 1 Hz continuous sampling rate at an acoustic range of 50-60 m is easily realizable using the standard internal battery pack provided with the instrument. For a two year measurement period, and with the use of an optional extended internal battery pack, the sampling rate can be set, using the programmable measurement phases to 1 Hz for half of the measurement period and to ½ Hz for the other half of the measurement period. The slower sampling rate would be used when ice drafts and/or ice drift speeds are expected to be reduced. With optional lithium battery packs, continuous sampling at 1 Hz can be achieved for three years or more.

The results of this study shows that ULS data sampled with different instrument sampling rates, resulting in marked difference in the initial spacing of the acoustic ranges/drafts and then transformed with different temporal to quasi-spatial interpolation techniques, are not directly comparable in terms of the derived geometrical parameters for an ensemble of larger ice keels, especially keel width and keel area. As an extreme example, we expect that ridge keel width and keel area obtained from submarine data would be lower if the data had been smoothed with the DWDQ method rather than the cubic spline method.

The study did show that differences could be introduced by choosing different transformation techniques. These differences can be important if the initial spatial resolution was low (i.e. during times of large ice speeds when the acoustic range/ice draft sampling rates results in a small number of quasi-spatial samples per unit distance), then the mean observed keel width and keel area could increase as much as 9% and 8%, respectively, depending on the transformation method and there is a corresponding decrease in the number of keel features. For these situations of comparatively high ice speeds, it is important to understand that these differences in the derived parameters occur. The optimal transformation method will depend on the requirements of the analysis being undertaken. For the purposes of estimating loads on offshore structures and subsea installations, the use of the methods involving a greater amount of interpolation (DWDQ or cubic spline) is arguably more conservative and therefore preferable. On the other hand, if the application is focused on the number of ice keel features that encounter a platform, the running average method may be preferable.

This issue can largely be avoided by selecting a ULS sampling approach that recognizes the importance of adequately understanding the range of drift speeds which are encountered in the measurement area and setting the ULS instrument sampling rate accordingly. If the sampling rate is chosen with care this could lead to an initial spatial resolution which is sufficiently high in order to considerably reduce the impact of the smoothing methods as discussed above.

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References

ASL (2011), *IPS Processing Toolbox - User's Guide*, Report.

Dalane, O., V. Aksnes, S. Loset, and J. V. Aarsnes (2009), A Moored Arctic Floater in First-Year Sea Ice Ridges, ASME Conference Proceedings, 2009(43451), 159-167.

Ekeberg, O.-C., K. V. Høyland, and E. Hansen, *Ice ridge keel geometry and shape derived from one year of upward looking sonar data in the Fram Strait*, Cold Regions Science and Technology, Submitted

Ekeberg, O.-C., K. V. Høyland, and E. Hansen (2012), *Ice ridge identification methods and analysis of upward looking sonar data from Fram Strait 2006-2010*, paper presented at 21st IAHR International Symposium on Ice, Dalian University of technology press, Dalian, China.

Ekeberg, O.-C., K. V. Høyland, and E. Hansen (2013), *Extreme keel draft in the Fram Strait 2006-2010*, paper presented at Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, Espoo, Finland, June 9-13.

Marcellus, B., R. McKenna, D. McGonigal, and R. Pilkington (2011), *Old ice floe and ridge statistics from submarine upward looking sonar data for the Beaufort*, Chukchi and Arctic Seas, in POAC'11, Montréal, Canada.

Melling, H., P. H. Johnston, and D. A. Riedel (1995), *Measurements of the Underside Topography of Sea Ice by Moored Subsea Sonar*, Journal of Atmospheric and Oceanic Technology, **12**(3), 589-602.

NSIDC (2006), *Submarine Upward Looking Sonar Ice Draft Profile Data and Statistics*, National Snow and Ice Data Center, Boulder, Colorado USA.

Ross, E., D. B. Fissel, J. R. Marko, and A. Reitsma (2012), *An improved method for extremal value analysis of Arctic sea ice thickness derived from upward looking sonar ice data*, in Arctic Technology Conference, p. OTC 23811, OTC, Houston, Texas.

Rothrock, D. A., and M. Wensnahan (2007), *The Accuracy of Sea Ice Drafts Measured from U.S. Navy Submarines*, Journal of Atmospheric and Oceanic Technology, 24(11), 1936-1949, doi:10.1175/jtech2097.1.

Wadhams, P., and R. J. Horne (1980), *An analysis of ice profiles obtained by submarine sonar in the Beaufort Sea*, Journal of Glaciology, **25**(93), 401-423.

Wadhams, P. (1992), *Sea Ice Thickness Distribution in the Greenland Sea and Eurasian Basin, May 1987*, J. Geophys. Res., **97**(C4), 5331-5348.

Yulmetov, R., S. Løset and K.J. Eik (2013), *Analysis of drift of sea ice and icebergs in the Greenland sea*, paper presented at Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions, Espoo, Finland, June 9-13.