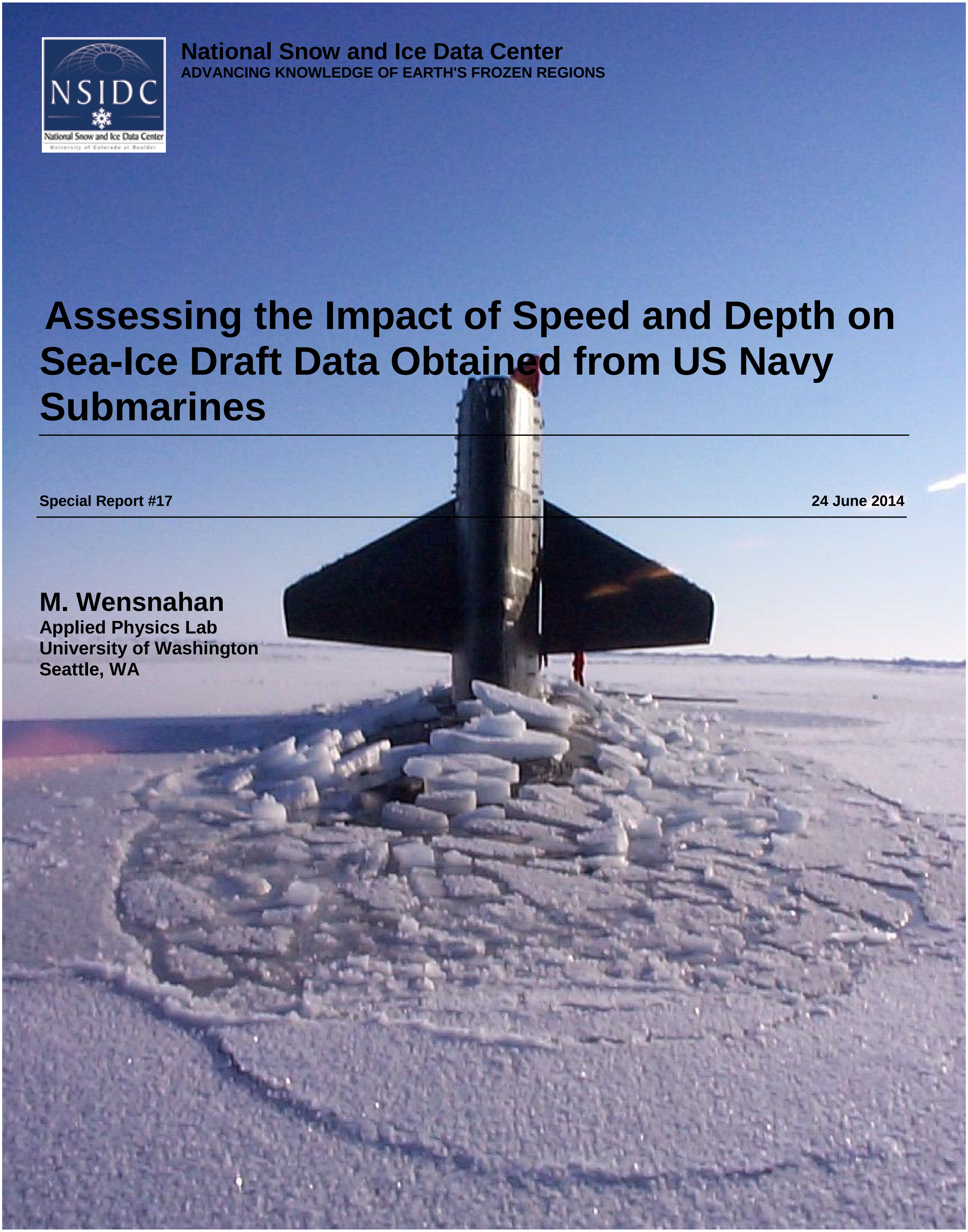
**National Snow and Ice Data Center**
ADVANCING KNOWLEDGE OF EARTH'S FROZEN REGIONS



# Assessing the Impact of Speed and Depth on Sea-Ice Draft Data Obtained from US Navy Submarines

**Special Report #17** **24 June 2014**

## M. Wensnahan
**Applied Physics Lab**
**University of Washington**
**Seattle, WA**

# Contents



## Citation

Wensnahan, M. 2014. Assessing the Impact of Speed and Depth on Sea-Ice Draft Data Obtained from US Navy Submarines. NSIDC Special Report 17. Boulder CO, USA: National Snow and Ice Data Center. http://nsidc.org/pubs/special/nsidc-special-report-17.pdf.

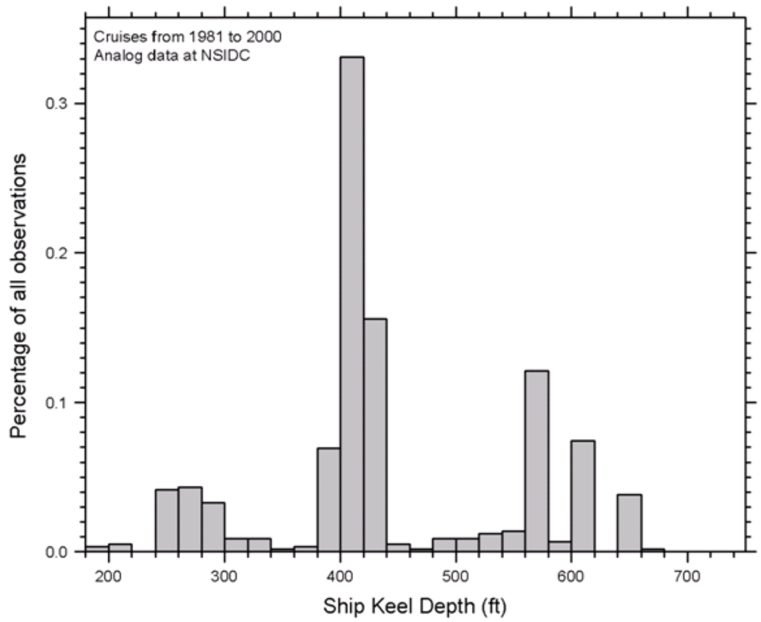
## List of Tables



## List of Figures

## Introduction

One of the greatest strengths of the submarine draft data is the length and consistency of the record. However, changes in how submarines operate within the Arctic have the potential to impact that continuity. Over the last several years submarines have started to use the Arctic Ocean as a transit region for traveling from the Pacific to Atlantic Oceans or vice versa. As such, the boats tend to travel fast and deep. This is in contrast to much of the last five decades when submarines used a mix of speeds and depths as they conducted various kinds of operations. The impact of the change to primarily higher speeds and greater depths is unclear but the potential exists that recent and future data will be of lower quality and will contain significant biases compared to the historical data.



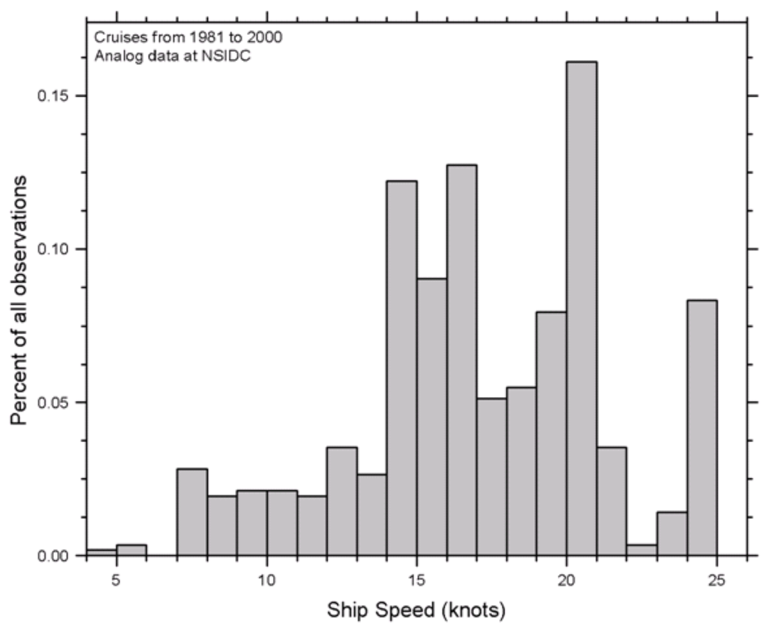




**Figure 1. Histograms of speed and depth of analog draft measurements archived at NSIDC for the years 1981 to 2000 inclusive.**

Figure 1 shows the submarine depths and speeds for data from 1981 to 2000 that are archived at NSIDC. In general, submarines have operated at three depth/speed combinations: slow and shallow – e.g. 3 knots/180 feet (55 m), moderate speed and depth – e.g. 14-20 knots/420 feet (128 m), or fast and deep – e.g. 24 knots/over 660 feet (200 m). The majority of the historical data are from a depth of around 400 feet (122 m) over a range of speeds.

Over the last several years, submarines have tended to operate primarily at the upper end of the depth and speed range. This practice will continue for the foreseeable future and much of the future draft data will be taken at speeds close to 25 knots and depths in excess of 700 feet.

## Impact of Increased Speed and Depth

The impact of increased speed and depth can be seen in the three analog traces of ice draft in Figure 2. The trace records the full sonar return six times per second resulting in what appears to be a continuous trace. The ice draft is highly variable over relatively short distances as the submarine moves under areas of thick level ice, open water, and very deep and localized features of highly deformed ice known as ice keels. At slow speeds and shallow depths these features are well resolved and quite distinct. As the ship speeds up and goes deeper the features become compressed and less distinct. The progressive signal degradation is due to two effects primarily related to ship depth: strength of return and increased footprint size.

First, the strength of the return signal received by the transducer decreases as the ship goes deeper due to attenuation within the water column and horizontal spreading of the sound pulse wavefront. This is most apparent for ice keels whose geometry tends to limit the return signal strength compared to flat sections of ice. Consequently, the return signal of keels gets fainter with increasing depth. The ice draft is determined by applying a threshold to the data and taking the first return from the ice (Wensnahan and Rothrock, 2005). As a result, keels are less likely to meet the signal strength threshold criteria of the recording system as the ship goes deeper; so they are less likely to be recorded. With a fixed threshold, the result is that the ice draft will be skewed toward thinner ice. This effect can be compensated for by varying the threshold or by increasing the power and gain of the sonar system. Adjusting power and gain, however, is somewhat limited by the noise constraints of the instrument.

The second impact of increased depth is due to the finite beamwidth of the transducer of around $2^{o}$ which means the area sampled by the sonar, the footprint, increases in size with increasing ship depth. The sonar records only the thickest ice in the instruments footprint with the result that, assuming no compensating factors, the draft measurements will become increasingly biased toward thicker ice as the ship descends. Using the methods of Rothrock and Wensnahan (2007), the estimated bias in mean draft could increase by over 40 cm as the ships go from operating at 400 feet to 700 feet (122 m to 213 m).

It is unclear whether the mean draft of future data will be biased toward thick ice or thin ice or whether the two effects discussed above will somehow compensate for one another.

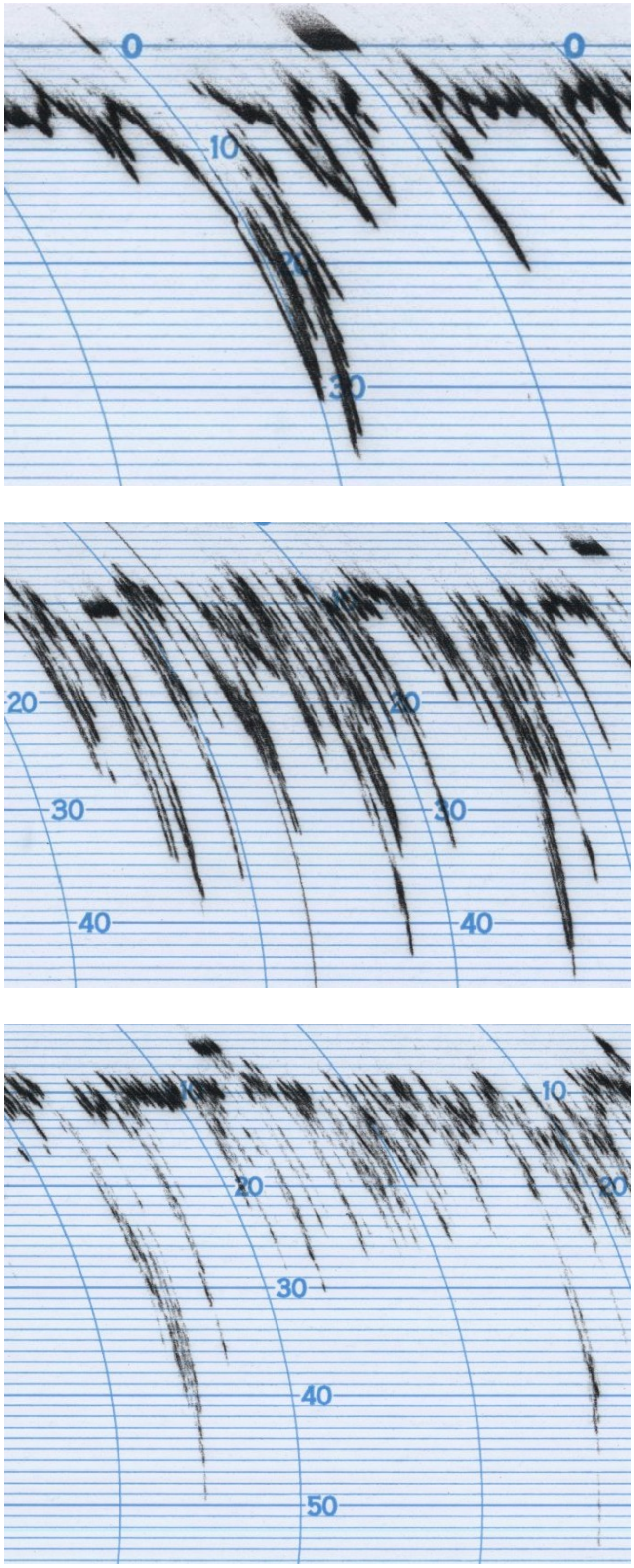



**Figure 2. Paper chart traces of the ice draft data from a recent submarine cruise taken at 3 depths and speeds. Depth-speed combinations from top to bottom are 5 knots and 180 feet, 14 knots and 400 feet, and 24 knots and 700 feet. The bottom panel represents decent quality data for this depth and speed.**

## Existing Archived Data

The mean draft varies with season, year of acquisition, and time of year. Rothrock et al. (2008) used multiple regression analysis to separate the mean draft (D) of 50 km segments of draft data into a regression (R) of the mean draft as a function of season, year, and location plus a residual (e). The equation is the following:

$$D = R(\text{season, year, location}) + e$$

The regression was able to explain approximately 80% of the variance in the mean draft leaving a residual with a standard deviation of 0.46 m. The residual is a combination of dependence of the draft on things other than season, year, and location plus instrument and sampling error.

For this report, regression statistics have been calculated including the original independent variables of Rothrock et al. (2008) plus ship speed and depth, both separately and together. In the latter case this was deemed appropriate since the covariance between depth and speed is not strong. The data used were mean drafts from 25 to 75 km long segments of cruise track. Only analog data were used as the digitally-recorded data do not contain metadata on the submarine depth and speed of individual segments. A total of 733 samples means were used for the regression.

The regression indicates a moderately strong covariance of speed with sample mean but little covariance of depth and mean. The coefficients of the regression and their uncertainty are given in Table 1 where X and Y are as defined in Rothrock et al (2008). The amount of variance explained by the regression is a modest improvement of 1% over one without speed and depth.

**Table 1. Regression coefficients and their uncertainties for mean draft of 25-75 km segments of analog data at NSIDC. Both X and Y are defined in Rothrock et al. (2008).**

| Parameter | Coefficient | Uncertainty |
|---|---|---|
| Constant | 3.130 | 0.128 |
| Year | 0.163 | 0.027 |
| Year^2 | -0.017 | 0.003 |
| Year^3 | 3.906E-4 | 6.566E-5 |
| Cos(day of year) | -0.328 | 0.043 |
| Sin(day of year) | 0.470 | 0.033 |
| X | -0.001 | 8.51E-5 |
| X^2 | -2.024E-6 | 1.435E-7 |
| X^3 | -6.155E-10 | 6.33E-11 |
| Y | -0.001 | 1.088E-4 |
| Y^2 | 7.299E-7 | 3.82E-7 |
| Y^3 | -3.611E-10 | 3.321E-10 |
| Speed | 0.029 | 0.005 |
| Depth | -7.245E-4 | 7.567E-4 |

The residual excluding the speed dependence gives a sense of the modest correlation with draft increasing as a function of speed (Figure 3). While the correlation may appear modest, the ratio of the coefficient to its uncertainty is statistically significant at nearly 6:1 (0.029:0.005). The effect of speed on the draft is likewise not negligible. Over a typical speed range from 14 to 25 knots this would result in a change in mean draft of 32 cm.

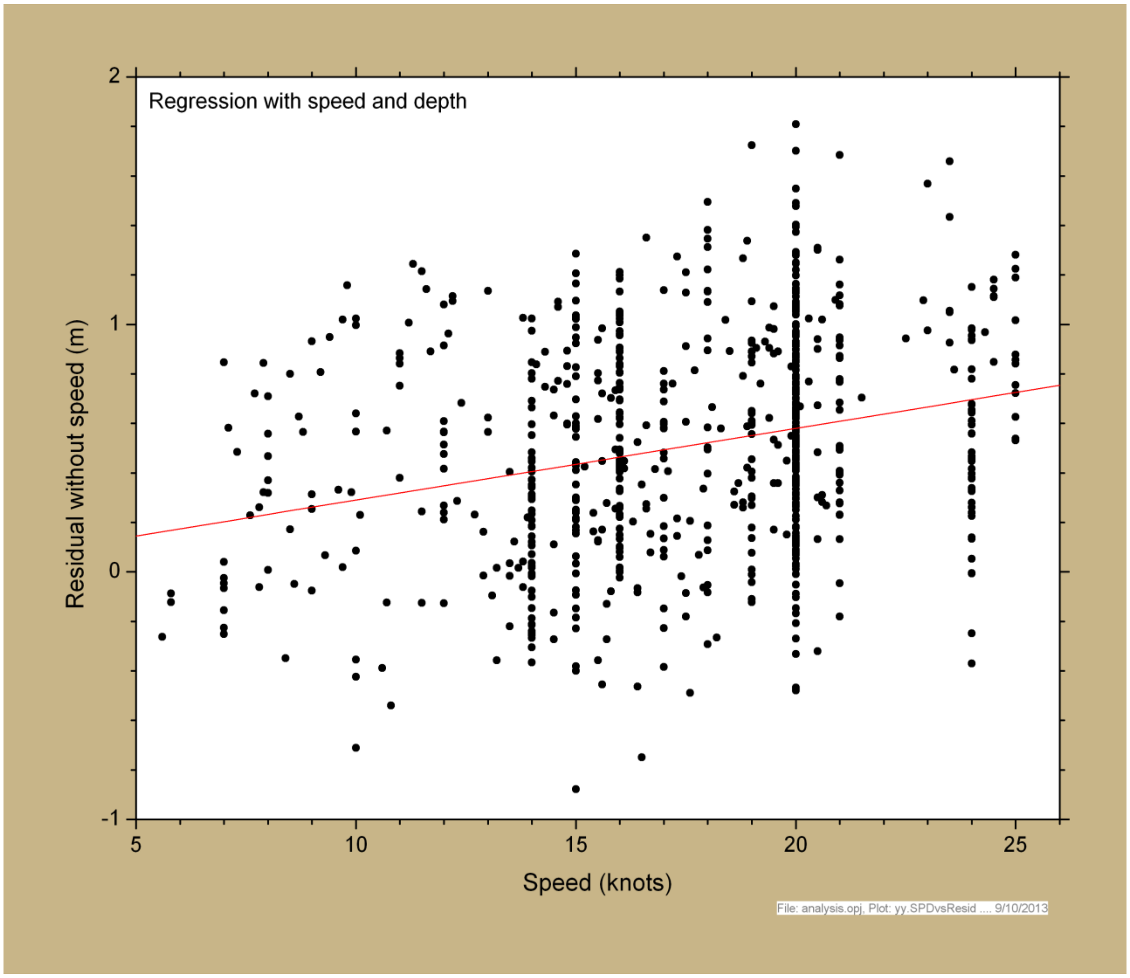



**Figure 3. Residuals of the regression vs mean draft excluding that portion of the residual due to speed plotted as a function of speed.**

A similar plot using depth makes it apparent that the correlation coefficient is essentially zero for this variable (Figure 4). A similar regression with the standard deviation of the sample mean as the dependent variable gives very similar results since the mean is highly correlated with the standard deviation of the mean. Again a moderate positive correlation was found between standard deviation and speed but none between standard deviation and depth.

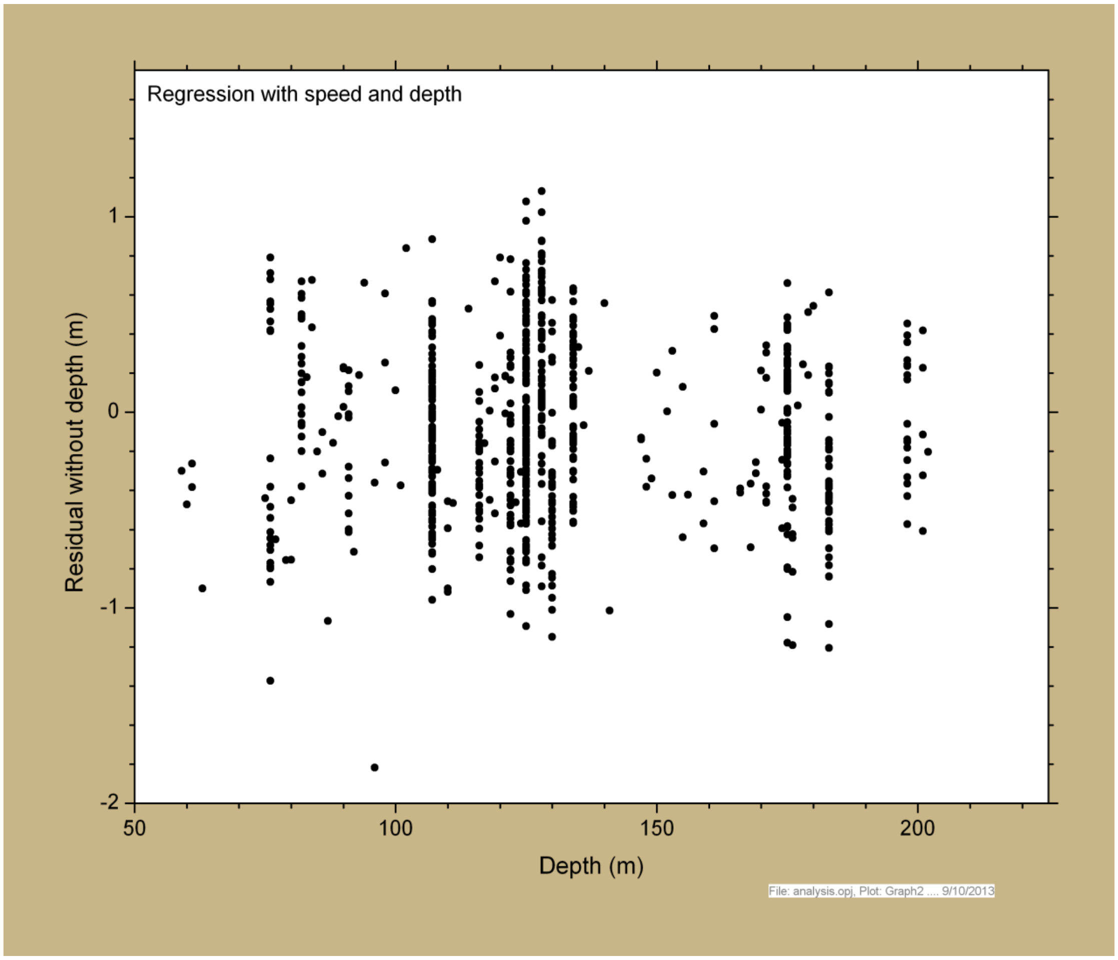



**Figure 4. Residuals of the regression vs mean draft excluding that portion of the residual due and depth plotted as a function of depth.**

A regression with the mode of the thickness distribution of the samples (using 10 cm bins) yields no dependence of the mode on depth and only a small positive dependence with speed. Hence, the mode is a somewhat more stable estimator of the character of the ice draft than the mean.

## Conclusions

It was expected that there would be some sort of correlation between depth and various parameters related to ice draft. This was not found to be the case. Instead, the correlation is with speed which was not expected.

The unusual nature of these findings appears to be a result of the unique properties of the analog charts. The charts record the full sonar return with return power indicated by the darkness of the analog trace. The threshold that defines the data is adjusted during processing to account for changes in return signal strength. That adjusted threshold appears to be just enough to offset the increased footprint size. This adjustment of threshold is unique to the analog chart data.

The dependence on speed appears to be related to overwriting of the analog chart. The sonar records data approximately 6 times per second. The paper chart advances slowly enough that the finite stylus width overwrites multiple sonar pings. When the boat is moving slowly the ice also changes slowly as a function of time and the overwriting has little effect. When the boat moves rapidly the ice overhead changes rapidly and it is more likely that thick ice will overwrite thin ice on the analog chart. The result is that there is a bias toward thicker ice as speed increases. The mode shows less covariation with ship speed. This is likely due to longer stretches of ice at or near the mode which would mitigate at least some of the over writing in the analog record.

The impact of speed and depth on the digital data is another matter. The effect of speed should disappear as there is no overwriting with digital data. However, the threshold is fixed for the digital signal and so the dependence of draft remains unclear.

With regard to the current archive at NSIDC, the impact is likely negligible. Speed varies randomly with location, year, and time of year for the existing data and so the dependence of the analog data on speed is an essentially random source of uncertainty on the order of +/- 15-20 cm. It would be helpful to have metadata on the speed and depths of the digital data in the archive. It would then be possible to rerun this analysis with all of the data.

Future data will be systematically taken at greater average speeds and depths than in the past, hence any errors due speed or depth become systematic as well. Future data can mitigate the impact of both speed and depth if the data are taken with a digital recorder, but one that records the full return signal and thus allows for adjustment of threshold as part of processing. In this way, the recorder would combine the strengths of the digital and analog recording systems while eliminating the most problematic aspects of each.

## References

Rothrock, D. A., D. B. Percival, and M. Wensnahan. 2008. The Decline in Arctic Sea-Ice Thickness: Separating the Spatial, Annual, and Interannual Variability in a Quarter Century of Submarine Data. J. Geophys. Res. 113(C05003). doi: 10.1029/2007JC004252.

Wensnahan, M., and D. A. Rothrock. 2005. Sea-Ice Draft from Submarine-Based Sonar: Establishing a Consistent Record from Analog and Digitally Recorded Data. Geophys. Res. Lett. 32(L11502). doi: 10.1029/2005GL022507.