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# Ice ridge keel geometry and shape derived from one year of upward looking sonar data in the Fram Strait

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ABSTRACT

Ice ridge keel geometry was studied by analyzing one year of upward looking sonar data collected in the Transpolar drift stream at 79°N, 6.5°W in 2008/2009. Ridges were identified using the Rayleigh criterion with a threshold value of 2.5 m and a minimum draft of 5 m. The keel shape was studied after the identification of ridges from temporal data. On average ridge keels were symmetric both with respect to the centroid of the keel and the keel crest location. By quantifying the ratio between observed keel area and the keel area of an assumed triangular keel shape (often assumed for first year ridges) we observed that in 79% of the cases the ridge cross sectional area would be underestimated by a triangular keel shape. Because keel loads on ships and structures increase with keel draft and keel area it is important that an assumed keel shape maintains the observed keel area. Thus we suggest that a better generalization of the shape of first year ridges is a trapezoidal keel shape rather than triangular. Based on the observations the mean trapezoidal keel, representing both first year ridges and old ridges, has a keel bottom-width which on average is 17% of the keel width. For the deepest keels (>15 m) the mean keel bottom width was 12% of the keel width. The mean keel draft was 7.3 m and the deepest ridge was 25 m. The temporal data was converted to spatial data based on an ice drift speed estimate which assumed free drift. From the spatial data we found that the mean keel width was 28 m and the mean keel cross sectional area was 164 m$^2$.



## 1. Introduction

Ice ridges often give the governing design action for both pipelines and offshore structures in ice covered waters. Ice ridges are formed from ice floes as they break in compression and shear due to environmental forces. This breaking results in a pile of ice blocks which with time freeze together and form an ice ridge which has two distinct layers: a keel below the waterline and a sail above. At the waterline a completely frozen layer forms which is called the consolidated layer. The consolidation process progresses with time and when an ice ridge survives a summer's melt it is assumed to be close to fully consolidated. During its first winter an ice ridge is called a first-year (FY) ridge. Ridges which survive one or more summer are second-year- and multi-year-ridges respectively and have the collective term old ridges (ISO19906, 2010; World Meteorological Organization, 1989).

Ridge keel load models vary in which geometric parameters that represent the geometry of the ridge keel. The most common is the use of the keel draft as the only input, which is the case in the analytical models by Croasdale et al. (1994), Dolgopolov et al. (1975), Mellor (1980) and Prodanovic (1979), while the cross sectional area of the ridge keel is the only input to the analytical models by Croasdale (1980) and Prodanovic (1981). More advanced numerical models by Heinonen (2004) and Serré (2011) could employ any ridge shape. A less advanced numerical model was developed by Kärnä et al. (2001) who included both the failure modes suggested by Croasdale (1980) and Dolgopolov et al. (1975). This model assumes a trapezoidal ridge. Kärnä et al. (2001) suggest that if certain simplifications are included in the model it could be used in a probabilistic analysis.

The geometry of both the sail and the keel of an ice ridge can only be obtained by profiling an ice ridge by drilling. Discrete measurements of ridges, such as by drilling, only amount to about 300–400 ridges during the past 40 years (Strub-Klein and Sudom, 2012). Based on a collection of such ridges Timco and Burden (1997), and later Strub-Klein and Sudom (2012) suggest some parametric relationships between different geometric parameters for the sail and the keel. The findings of Timco and Burden (1997) also form the basis of the suggested relationships in ISO19906 (2010).

Discrete measurements of ridges assume a length and width of the ridge keel and the keel geometry is measured in the section which visually most clearly fits this assumption. While many assume that

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ridges are straight linear features Bowen and Topham (1996) did show that a portion of the ridge keels are not in the linear segments but in more complex corner structures.

An alternative way of sampling information about ice ridge geometry is the use of continuous scanning methods. These are limited to measurements of either the top surface or the bottom surface of the ice. The ice bottom surface has traditionally been measured using upward looking sonars but recently the bottom surface has also been mapped in three dimensions using a multi-beam sonar (Doble et al., 2009; Wadhams and Toberg, 2012). Upward looking sonars (ULS) have been in use since the beginning of the 1960s on submarines (Hibler et al., 1972) while bottom mounted sonars started to be developed in the late 1970s (Pilkington and Wright, 1991; Melling et al., 1995).

A ULS measures ice thickness by sending a sound pulse toward the ice surface and measuring the time it takes to return. Then, the distance to the ice surface is calculated by the speed of sound in the water above the ULS. Further, the distance to sea level is derived from pressure measurements at the ULS and the pressure at sea level. Ice draft is then the difference in distance between the water and the ice surface. The final product from a ULS is a time series of ice draft. A conversion to a spatial series is possible if the ice drift speed is recorded by an Acoustic Doppler Current Profiler (ADCP) (Melling et al., 1995) or as in the case of a submarine knowing the speed of the vessel. Melling et al. (1995) provide a comprehensive description of the most common moored ULS which is the Ice Profiler Sonar (IPS).

The main interest of those who have analyzed ULS data have been to monitor and estimate changes in the ice thickness probability density function and observe the ice export out of the Fram Strait (Rothrock et al., 1999; Melling et al., 2005; Vinje et al., 1998; Wadhams and Davis, 2000). Identification and analysis of ridges from ULS data have largely been reported in Davis and Wadhams (1995), Marcellus et al. (2011), Melling and Riedel (1995), Melling and Riedel (1996), Obert and Brown (2011), Wadhams (2000).

Since 1990, the Norwegian Polar Institute has measured ice drafts along 79° N in the Fram Strait using bottom mounted upward looking sonars (Hansen et al., 2013; Vinje et al., 1998). The Fram Strait is the output end of the Transpolar Drift, which continuously delivers Arctic sea ice through the strait. Hence the location naturally lends itself to monitoring Arctic sea ice thicknesses. In 2006, an IPS replaced the CMR ES-300 (described by Strass, 1998) which had been in use since 1990. The IPS measured the draft every 2 s in contrast to the CMR ES-300 which was typically sampled every 4 min.

## 2. Data collection and processing

From September 2008 to September 2009 an IPS, denoted F14, was recording the ice draft close to the edge of the Greenland continental shelf at 78°49′N, 6°26′W (Fig. 1). Water depth was 280 m and the instrument depth was on average 46 m. The mooring was deployed and retrieved during an annual scientific cruise to the Fram Strait in August/September by the Norwegian Polar Institute. This IPS measured the ice draft every 2 s and tilt and pressure every 120 s. It had a 1.8° beamwidth which gives a nominal footprint at the water surface of 1.5 m. The closest draft within the footprint was recorded as long its returning echo had sufficient strength and duration. Melling et al. (1995) and Rodrigues (2011) discuss effects that originate from this ‘footprint widening’. Conversion from raw data into a time series of drafts follows the methodology described in Melling et al. (1995). The accuracy of an individual draft observation was estimated to about ±5 cm by Melling and Riedel (1995). The 2008/2009 season ice was present year-round with most ridges from October to August.

### 2.1. Time series–spatial series

The geometry of an ice ridge keel could be studied both from temporal data and spatial data. Many parameters do not require a conversion to spatial data and are therefore derived directly from the time series. These were the *keel area coefficient*, the *location of the deepest point of the keel*, the *centroid of the keel* and the *keel draft*. Parameters that were derived from spatial data are the *keel width* and the *keel area*. The ridge keels were identified from the temporal data. Because no interpolation to evenly spaced values was used the ridges would have identical starting and ending points regardless if they were identified from temporal or spatial data.

### 2.2. Spatial parameters

#### 2.2.1. Ridge keel geometry

The geometry of a ridge is shown in Fig. 2. The start and end of the keel are labeled $P_1$ and $P_4$ and are either the point where the ice draft ($h_i$) crosses the threshold or the point shared by two keels which then

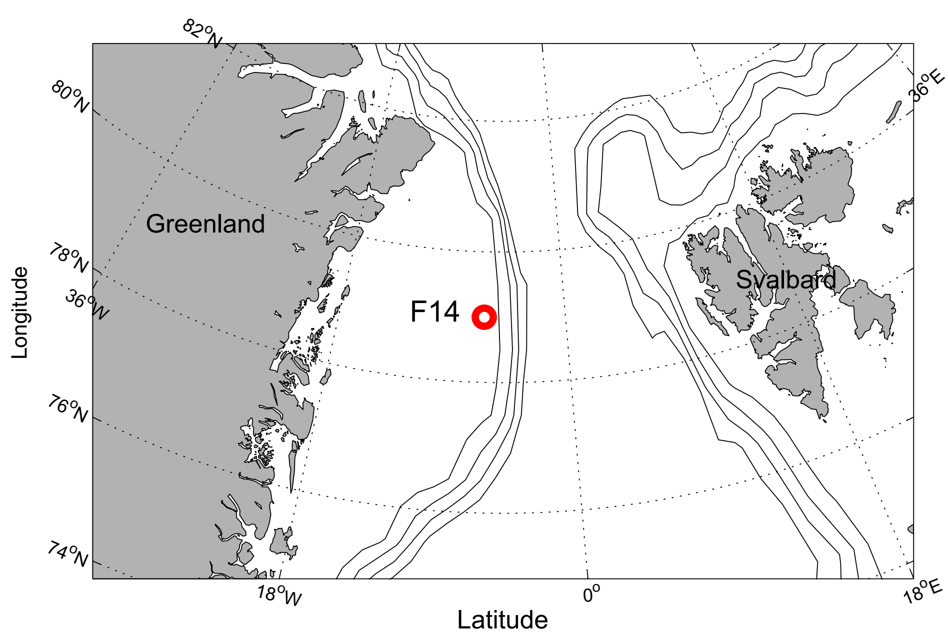


**Fig. 1.** Location of ice draft measurements, depth contours every 500 m.