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AIRBORNE EM SEA-ICE THICHNESS PROFILING OVER BRACKISH BALTIC SEA WATER

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ABSTRACT

Helicopter-borne electromagnetic-inductive (EM) ice thickness measurements have been performed in February 2003 along the Finish Baltic Sea coast. Both, the Gulf of Finland and the Gulf of Bothnia were surveyed. Measurements have been performed with a small, two-frequency EM-Bird, a towed sensor suspended 20 m below the helicopter and operated 15 m above the ice surface. Results show that sufficiently accurate measurements were obtained even with minimum water salinities of 3 ppt in the Bay of Bothnia. Level ice thickness was in good agreement with information from ice charts. However, results also show the high degree of deformation of Baltic Sea ice, resulting in considerably higher mean ice thicknesses.

INTRODUCTION

In the EU-funded project IRIS (Ice Ridging Information for Decision Making in Shipping), led by the Ship Laboratory of Helsinki University of Technology, between 2003 and 2005 tools are developed for better detection and forecasting of sea ice pressure ridges, to support strategic ship navigation in ice infested waters. Detection and forecasting are mainly based on the use of satellite radar imagery and numerical model predictions. In order to validate remote-sensing ridge-detection algorithms and to support and validate model parameterizations of ridge formation and development, extensive ground-truth campaigns are performed to directly observe the frequency distribution of ridges and their temporal evolution. Because ridge distributions can only be described properly if large numbers of ridges are observed, airborne laser and electromagnetic-inductive (EM) thickness profiling are important components of the field programs. Although EM surveying does not yield the absolute thickness of pressure ridges (e.g., Kovacs and Holladay, 1990; Multala et al., 1996; Haas and Jochmann, 2003), their distribution and lateral extent, as well as their relative volume and temporal development can be well determined.

Here, we present results from the first airborne EM campaign performed in 2003. This campaign was performed as a pilot study for the main campaign planned for 2004. The main goals were the calibration of a new helicopter-borne EM sensor over brackish Bal-

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tic Sea water and a general assessment of the sea ice thickness distribution of the Gulf of Finland and Gulf of Bothnia.

MEASUREMENTS

After the pioneering work of Kovacs and Holladay (1990), airborne EM profiling has become an operational tool for sea ice thickness measurements, which is operationally used e.g. by the Canadian Ice Service (Prinsenberg and Holladay, 1993). With a fixed-wing aircraft EM system, Multala et al. (1996) have also performed thickness surveys over the Baltic Sea.

In short, an EM system consists of an assembly of coils for the transmission and reception of low-frequency EM fields and a laser altimeter. While the EM components are sensitive to the sensors height above the conductive sea water, the sensors altitude above the ice surface is determined with the laser altimeter. Over sea ice, the water surface coincides with the ice underside. Therefore, the difference of the height measurements of both components corresponds to the ice-plus-snow thickness. Because the low-frequency EM field is diffusive, its strength represents the some average thickness of an area of once or twice the instruments altitude above the ice surface. Due to this "footprint", maximum ridge thickness can be underestimated by as much as 50% in the worst cases, depending on the geometry and consolidation of the ridge keel (Kovacs et al., 1995; Haas et al., 1997; Haas and Jochmann, 2003).

Together with industrial partners, Alfred Wegener Institute (AWI) has developed a small, lightweight helicopter-borne EM Bird. This is a 3.5 m long, 100 kg towed sensor suspended 20 m below a helicopter and operated at heights of 10 to 20 m above the ice surface. Due to its small dimensions, the bird is essentially platform independent and can be operated by any helicopter. The AWI bird operates at frequencies of 3.6 and 112 kHz, sensitive to the conductivities of sea water and sea ice, respectively. Coil spacing is 2.77 and 2.05 m for both frequencies, respectively, which is very short compared with conventional systems used in geophysical exploration. However, signal generation, reception, and processing are performed with a computer inside the bird and are thus fully digital, maximising signal-to-noise ratio. Sampling frequency is 10 Hz (laser altimeter: 100 Hz), corresponding to a measurement point spacing of approximately 3 m (0.3 m).

Figure 1 shows the flight tracks over the Baltic Sea surveyed between February 17 and 23, 2003. Both, the Gulf of Finland and the Gulf of Bothnia have been profiled, with salinities between 6 and 3 ppt corresponding to sea water conductivities between 600 and 300 mS/m, respectively. In total, 12 flights have been performed, each longer than 100 km.

Here, only results of the in-phase component of the low frequency signal are presented which is the strongest and most sensitive signal. Figure 2 shows measured and computed EM responses over the Gulf of Finland and Gulf of Bothnia, with salinities of 6 and 3 ppt, respectively. While measurements over open water agree well with model curves, the presence of sea ice leads to a reduction of the measured EM signal at the same laser height measurements, and therefore to a scattered cloud of data points. From the model curves and corresponding data, it can be seen that salinity has a strong impact on the amplitude and dynamic range of the EM signal. However, signals are still sufficient to resolve thickness changes of 0.1 to 0.2 m with a noise level of 10 ppm peak-to-peak. The open-water measurements with zero ice thickness in Figure 2 are used to derive an equation to transform the EM signals into a distance above the water surface (Haas and Pfaffling, in prep.). From these, the laser height measurement is subtracted to compute ice thickness. Ice thickness can therefore directly be obtained from the horizontal distance between EM measurement and model curve in Figure 2.

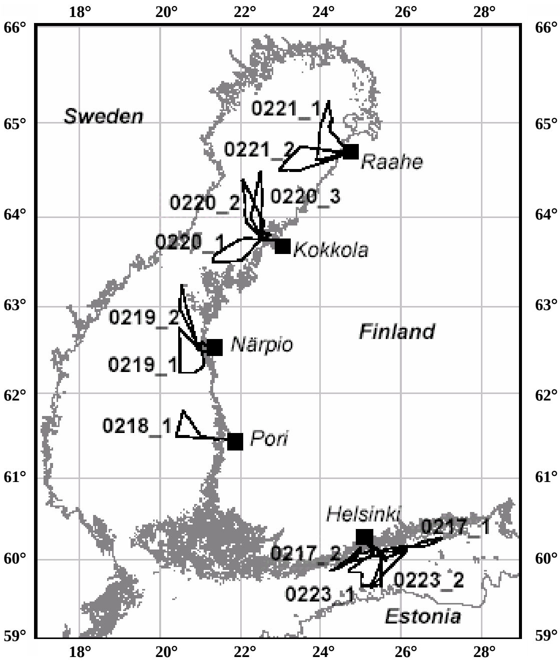

Fig. 1. Map of Northern Baltic Sea showing thickness flight tracks (see Table 1)

a)

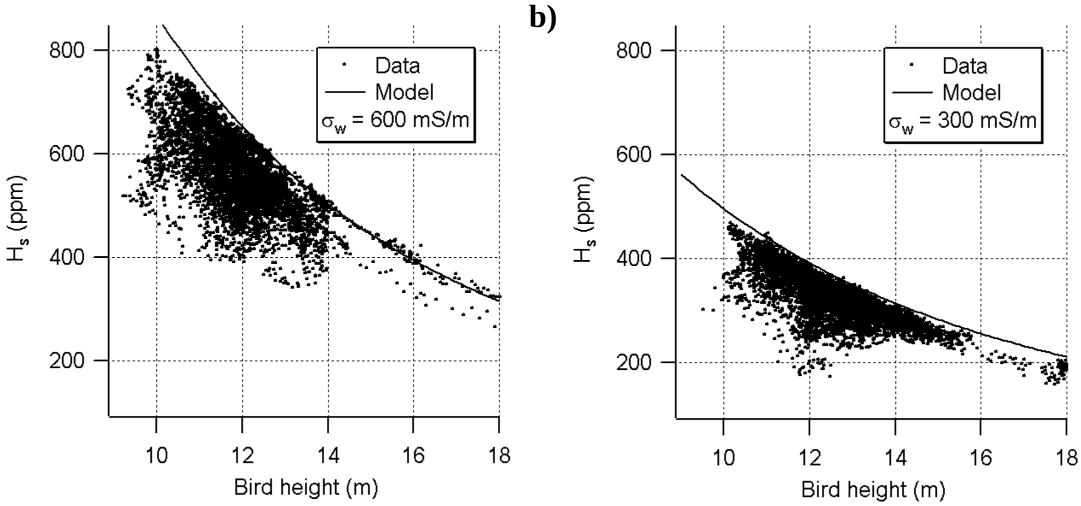

Fig. 2. Measured calibrated EM signal H_s (Inphase, 3.6 kHz) as a function of Bird height above the ice surface over the ice-covered (a) Gulf of Finland and (b) Bay of Bothnia

RESULTS

After early ice formation in 2002, the ice season 2002/2003 was more severe than average. In particular in the Gulf of Finland, ice navigation was severely hampered and became partially impossible. Table 1 summarizes the results of all thickness surveys. Flight labels mmdd_x correspond to the month mm (February), day dd, and flight number x (cf. Figure 1). Mean and typical thicknesses represent different ice regimes in the Gulf of Finland (Flights 0217_x & 0223_x), the Sea of Bothnia (0218_x, 0219_x), and the Bay of Bothnia (0220_x, 0221_x) very well. While the modes correspond well with typical ice thicknesses on Finish Ice Service ice charts, the table shows that the mean ice thicknesses can be much larger. This also explains the difficulties of navigation in the Gulf of Finland.

As an example, Figure 3 shows an ice thickness profile across the Gulf of Finland, from Estonia towards Finland, and a comparison with a Finish Ice Service ice chart. For flight-operation reasons, there was a gap between 38 and 46 km. A gradual thickness increase from the Estonian to the Finish coast can well be seen, corresponding to older ice towards the Finish coast due to prevailing south-westerly winds. The gradient is also suggested by the ice chart, showing only rafted ice on the Estonian side. However, our thickness data clearly show the presence of deformed ice with thicknesses in excess of 1 m in this rafted ice region. The typical level ice thickness of 0.6 m (Table 1, Fig.4), corresponds well to the upper thickness in the ice chart (Fig. 3). The obtained thickness distribution (Fig. 4) has another mode at 0 m, representing open water and very thin ice.

Table 1. Mean (± 1 standard deviation) and typical (mode) thickness for all 12 flights; cf. table 2 for more details

Flight	Mean, m	Mode, m
0217_1	1.65±1.51	0.5
0217_2	1.58±1.51	0.4
0218_1	0.35±0.47	0.3
0219_1	1.25±1.79	0.2
0219_2	1.81±1.88	0.6
0220_1	0.77±0.67	0.3
0220_2	0.95±1.24	0.6
0220_3	0.98±1.00	0.6
0221_1	1.84±1.52	1.1
0221_2	1.39±1.53	0.5
0223_1	0.92±0.88	0.6
0223_2	1.08±0.89	0.6

This was largely present in a flaw lead off the Finish coast, which was also accurately depicted by the Finish ice chart (Fig. 3). This polynya is also clearly visible in the thickness profile in Figure 3. That figure also shows that the fast ice adjacent to the northward edge of the polynya consists of very deformed, thick sea ice which has been attached to more level fast ice during a strong deformation event. This thick, deformed fast ice zone is clearly depicted on the ice chart as well, and seems to be typical for the majority of fast ice edges along the Baltic Sea coast.

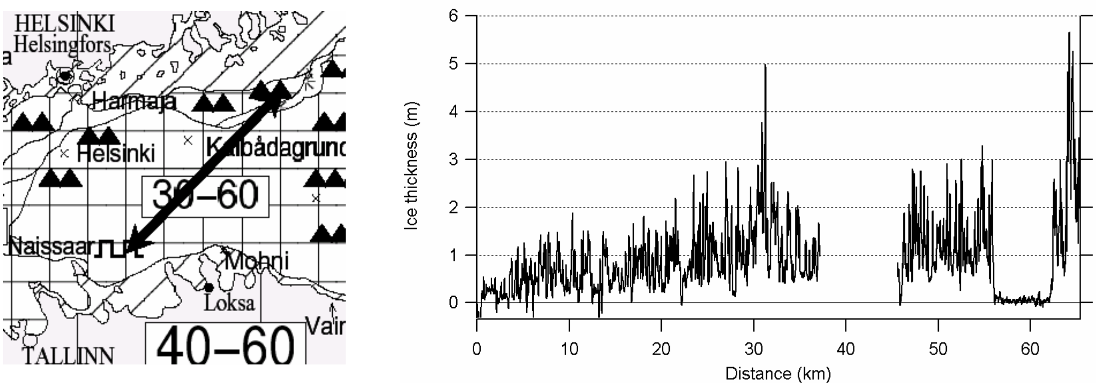

Fig. 3. Right: Ice thickness profile across the Gulf of Finland (from Estonia (left, southwest) to Finland (right, northeast)), obtained on February 23, 2003. Left: Ice chart of the same day, kindly provided by Finish Ice Service (Finish Institute of Marine Research, FIMR)

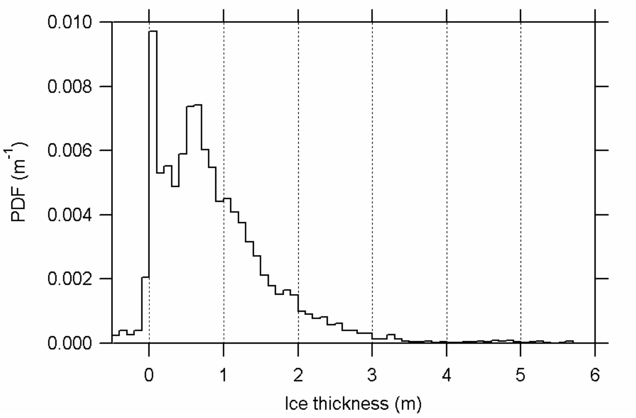

Fig. 4. Thickness distribution (probability density function pdf) of the thickness profile in Figure 3

DISCUSSION AND CONCLUSION

The results presented in this paper demonstrate the feasibility and gain of information obtained from airborne EM surveys in the Baltic Sea. Because details are hardly visible in plots of long profiles like those in Figure 3, Figure 4 shows an enlargement of a 10 km long section of the profile in Figure 3, revealing the degree of detail inherent in the data. Single keels and their lateral extent are clearly visible, although their maximum thickness is certainly underestimated. Comparison with ridge profiles obtained from the laser data will show the relation between these keels and the surface profiles. For example, the keels visible in Figure 4 suggest a mean keel density of 3-4 km^{-1}, which is relatively low compared with the visual impression of the ice surface. However, the lateral extent of the keels is quite large, as can be seen from the absence of larger level areas. This could explain the severe conditions for shipping.

Our measurements and visual observations during the flights confirm the high accuracy of Finish ice charts. However, our results also show that the mean ice thickness can be much larger than level ice thicknesses given in the charts. This demonstrates the importance of the IRIS projects, whose goal it is to quantify the ridging and deformed ice information in the ice charts.

In 2004, the IRIS project will perform an extended airborne and ground-truth campaign in the Bay of Bothnia, focussing on observations of the temporal evolution of the thickness distribution and the validation of satellite remote sensing ridge detection algorithms.

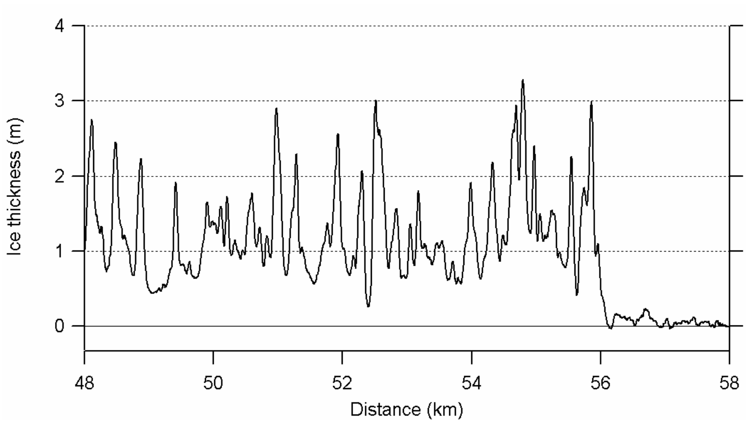

Fig. 4. Ten kilometre long section of the profile in Figure 3, adjacent to the prominent polynya at the right end of the profile

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