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Developments in frequency domain AEM: Tackling drift and noise with a ferrite-core, receiver triplet.

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SUMMARY

The polar oceans' sea ice cover is a challenging geophysical target to map. Current state of practice helicopter-electromagnetic (HEM) ice thickness mapping is limited to 1D interpretation due to common procedures and systems that are mainly sensitive to layered structures. We present a new generation Multi-sensor, Airborne Sea Ice Explorer (MAiSIE) to overcome these limitations. As the actual sea ice structure is 3D and in parts heterogeneous, errors up to 50% are observed due to the common 1D approximation. With MAiSIE we present a new EM concept based on one multi frequency transmitter loop and a three component receiver coil triplet without bucking The small weight frees additional payload to include a line scanner (lidar) and high accuracy INS/dGPS. The 3D surface topography from the scanner with the EM data at from 500 Hz to 8 kHz, in x, y, and z direction, will increase the accuracy of HEM derived pressure ridge geometry significantly. Experience from two field campaigns shows the proof-of-concept with acceptable sensor drift and receiver sensitivity. The preliminary 20 ppm noise level @ 4.1 kHz is sufficient to map level ice thickness with 10 cm precision for sensor altitudes below 13 m.

Key words: AEM, HEM, frequency domain, ice thickness, 3D.

INTRODUCTION

One of the key data sets for climate studies is sea ice volume and its interannual variation. Helicopter electromagnetic (HEM) surveys have been playing an increasing role in this field being the only geophysical method capable of directly measuring ice thickness rather than ice draft (sonar) or surface elevation (laser). With the work we present here, we strive to improve the versatility and accuracy of such systems.

Regional mapping of the sea ice thickness distribution using HEM began in the late eighties in North America with traditional exploration systems later leading to sea ice dedicated devices (Kovacs and Holladay 1990). Since the new millennium, purpose developed, digital sea ice HEM systems, have been used on an operational basis during ship and land based expeditions in the Arctic, Antarctic and Baltic seas (Haas et al. 2008).

Detailed studies on the accuracy of airborne EM (AEM) ice thickness data have revealed certain limitations, however. Several authors have addressed the effect of bird motion (attitude) both for AEM in general but also for sea ice AEM. Traditional systems don't measure pitch and roll, making it impossible to correct for attitude errors. Further, standard one-dimensional (1D) data processing tends to underestimate ice thickness for non-1D regions such as pressure ridges. 3D modelling shows that ridge thickness may be underestimated by up to 50%. 3D inversion of horizontal coplanar (HCP) data provided by traditional systems will only bring minor improvements, as the HCP configuration is mostly sensitive to horizontally layered structures; further EM orientations are needed as input data for 2D or 3D interpretation.

Based on the considerations above, we present a new generation system, the Multi-sensor Airborne Sea Ice Explorer (MAiSIE, Figure 1, Table 1). MAiSIE comprises a multi-frequency and multi-component EM induction system accompanied by high accuracy attitude sensors and three on board laser devices (altimeter, IR thermometer and 3D scanner). We believe that MAiSIE has the potential to initiate a second generation of sea ice systems and will improve the quality of AEM derived sea ice thickness estimates significantly.

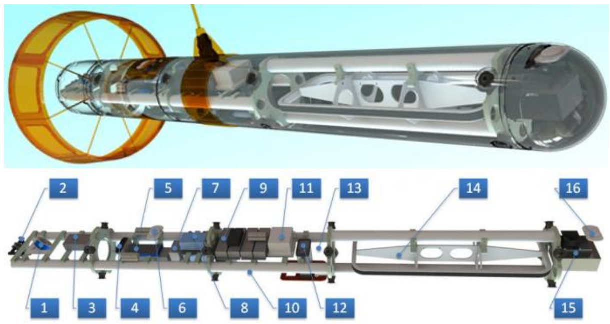

Figure 1: Design drawing showing main MAiSIE system components.(1) calibration coil, (2) EM receiver coils, (3) Rx amplifiers, (4) dual dGPS receiver, (5) digital data acquisition and EM controller, (6 & 16) GPS antenna, (7) SBC, (8) AC/DC converters, (9) EM transmitter power supply, (10) space for laser scanner, (11) INS, (12) laser altimeter, (13) space for IR thermometer, (14) EM transmitter loop, (15) EM transmitter amplifier.

EM ICE THICKNESS

The basic principle of HEM sea ice thickness profiling is to estimate the distance to the ice / water interface from the EM data (Figure 2), while a laser altimeter in the towed instrument (bird) determines the system height above the ice or snow surface. The difference of these two distances consequently corresponds to the ice (or ice + snow) thickness. Whenever sea ice thickness is mentioned in an EM context, it actually refers to the total thickness (ice thickness + snow thickness). We provided a detailed description and discussion of AEM ice thickness retrieval in Pfaffling et al. (2007).

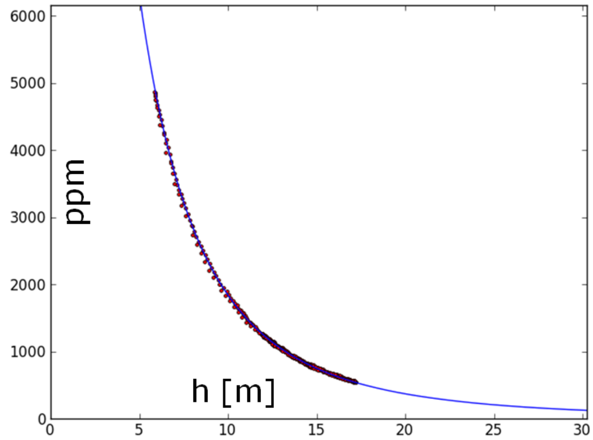

Figure 2: Measured (dots) and modelled (line) EM response (4.1kHz in-phase) over open water.

Figure 3: MAiSIE on arctic field campaign close to Barrow Alaska (Photo courtesy David Ball).

In contrast to fairly one-dimensional level ice, pressure ridges are porous, blocky structures formed in deformation events, when two convergent ice floes break due to lateral stress. These ridges, which may exceed thicknesses of 25 m, contribute to the thickest sea ice in ice-covered seas and present a hazard for commercial operations. They also govern the stability of the land-fast sea ice zone close to the coast when grounded ridges and their blocky structures result in a large ice-water interface, which might trigger ice melting in summer. The state of practice HEM sea ice data processing is strictly one-dimensional, leading to a general thickness underestimation of 2D or 3D structures such as pressure ridge by at least 50 % (Reid et al. 2003).

The limitation of traditional sea ice HEM instruments and processing techniques motivated model investigations to assess the retrieved ice thickness uncertainties for non-1D sea ice structures. Hendricks (2009) developed a 3D finite element forward modelling code within Comsol Multiphysics to simulate HEM data for 2D and 3D sea ice structures. The reliability of the 1D assumption for helicopter operations was tested on several 2D and 3D sea ice structures. The results showed that the underestimation of the thickness of so-called pressure ridges is significant and variable over a range of 20% to 50% (Hendricks 2009). Modelling results are consistent with findings in the field based on drilling profiles (Pfaffling et al. 2007) that traditional HEM systems are not capable of resolving the maximum thickness of pressure ridges and their porosity. Thus, an enhanced HEM ice thickness retrieval is needed to enable the investigation of the role of pressure ridges in the open sea and shallow coastal waters. We used the 3D forward model to set a baseline for frequencies and sensitivities for the retrieval of true ridge thickness and porosity and found that a frequency of 1 kHz is sensitive for the lower part of the pressure ridge, while a lowest frequency of 300 Hz is needed to resolve the depth of the water column. Ideally a sensitivity and accuracy below 10 ppm in amplitude and 0.5 degree in phase is desirable in order to resolve the grounding of ridges with 15m draft.

Physical data	Length 3.5 m, weight 100 kg (Figure 1&3)
EM system	Multi frequency system 500Hz – 8 kHz, freely programmable. One transmitter loop for all frequencies, current feedback transmitter amplifier, continuous monitoring of receiver sensitivity, on-board calibration. Coil geometries horizontal coplanar, fish tail and whale tail (vertical dipole transmitter, three-axis receiver). Coil separation: 2.65 m (Hz, Hx), 2.68 m (Hy). No primary field bucking.
Auxiliary sensors	Laser altimeter (Riegl LD 90), Inertial Navigation System (INS) combined with dual antenna differential GPS (Novatel SPAN CPT & FlexPac-G2), Prepared for laser scanner (Riegl VQ480) and IR ground surface thermometer (Heitronics KT19), On-board data acquisition (NI cRIO Real-Time controller and FPGA & single board computer).
Operational details	Towing cable length 20 or 30 m, Bird altitude 10-15 m above ice surface, speed 60-80 knots (30-40 m/s), System powered by helicopter power supply 400 W @ 28 VDC, system controlled by operator laptop via towing cable or WLAN

Table 1 detailed list of MAiSIE´s system components.

System concept

The EM system stands out with three main details: Firstly the transmitted signal follows a multi-frequency concept, similar to Geophex´s GEM-2A system. A time series composed of several frequencies is fed through the transmitter loop with a moment of 6 to 25 Am2 (NIA). The transmitter current is continuously monitored, and any potential transmitter drift (caused by changing TX amplifier gain) is corrected using a negative feedback control loop. Secondly, we apply a triplet of lightweight ferrite core coils to acquire the primary + secondary field in all room directions. Using receiver coils with a wide dynamic range (>120dB) eliminates the need for bucking, as the receivers are capable of measuring the response of the secondary field, while at the same time not being saturated by the primary field. Each of the three receiver coils are equipped with a second layer of windings that are used as local reference transmitters within the receivers.

Real time EM processing follows equation 1, providing calibrated and zeroed normalized secondary field Z

$$(1) \quad Z = \frac{H_s}{H_p} = cal \frac{R - cT}{cT}$$

with Hp being the primary (field in a non-conductive full-space) and Hs the secondary magnetic field strength (field above a conductive half-space arising from the eddy currents induced by the primary field). The sampled voltage on the receivers and transmitter current are expressed as R and T, respectively. The system's transfer function c is determined at high altitude as Hs must be then be zero and thus c=R/T. Finally, the calibration factor cal is applied to account for all remaining uncertainties (inaccuracies in loop size and shape, dimensions, gain settings and such). The correct value for cal is established during calibration flights over deep water with known conductivity. This fundamental system calibration is controlled during every flight by virtue of the on board calibration coil, providing a known secondary field at the receivers. All variables leading to the normalized secondary field, equation 1, are complex numbers required separately for each active signal frequency and for each of the three receiver components. A detailed list of MAiSIE´s system components is given in Table 1 and can be seen in Figure 1.

RESULTS

Data quality

The performance of the EM system has been evaluated during two field trials over arctic sea ice in 2012, one test flight over the North Sea in December 2011, as well as ground based reference measurements in October 2011 and February 2013. One of the primary focuses of these initial trials and tests has been to evaluate drift and noise in the EM system.

The chosen multi-frequency configuration included four frequencies (0.5, 1, 4 and 8 kHz), with 4 kHz as the main frequency of interest (Figure 2). The measured data agrees well with forward modelled responses assuming 4 S/m ocean water conductivity (typical for this area and season). High altitude noise tests revealed a standard deviation of 20 ppm for the 4.1 kHz in-phase channel, leading to a derived ice thickness uncertainty of 10 cm at a system altitude of 13 m. The lower frequencies, however, showed higher noise levels and noise reducing measures are subject of our ongoing research (Pfaffhuber et al. 2012). The actual signal to noise ratio (SNR) for the simultaneously transmitted frequencies is around 3-4 orders of magnitude with respect to background noise for airborne and groundborne data, respectively (Figure 4). The remaining RMS noise in the ppm data can easily be low pass filtered due to the high oversampling (3-4 m along the flight line).

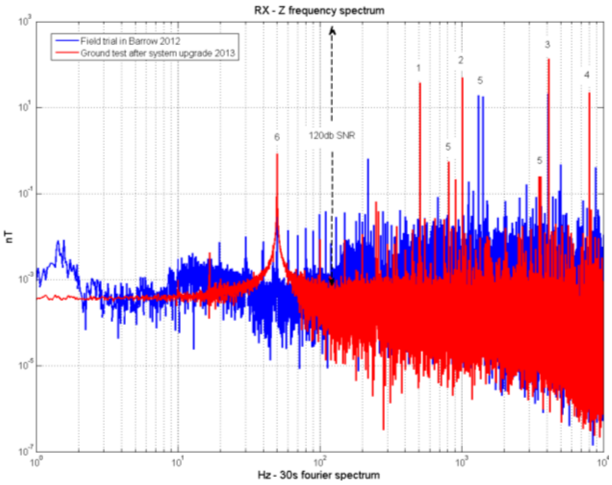

Figure 4: Fourier spectrum of received vertical magnetic field extracted from 30s groundborne (red) and airborne (blue) data. Intensity peaks indicate the transmitted frequencies (1) 510 Hz (2) 1010 Hz (3) 4110 Hz and (4) 7960 Hz, the reference frequencies (5) in the receivers and 50Hz noise (6). The stippled line indicates the 24bit AD conversion SNR.

Initial problems encountered with temperature dependent drift have been tackled by continuously monitoring the temperature and sensitivity of the receiver coils. Cause for the drift is the temperature dependent permeability of the receiver coil cores. Frequencies that are only transmitted on the local reference coils are not subject to any secondary field response, and the magnitude of these signals, when monitored on the receiver coils, are only dependent on this. Using those reference frequencies enables us to obtain virtually drift free data with a minor level of post processing (Figure 5).

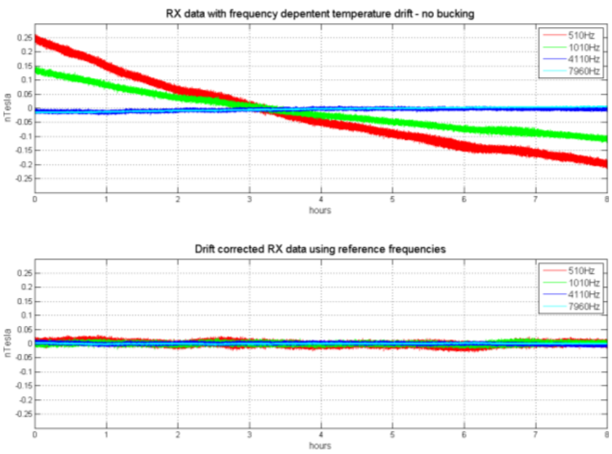

Figure 5: Drift in the EM system over a period of 8 hours caused by a temperature change of ~10ºC (top) significantly reduced using the reference frequencies (bottom).

Ice thickness

A 1D interpretation by direct inversion of the Inphase-component (Pfaffling et al., 2007 and Haas et al., 2009) for three frequencies was used to calculate ice thickness and to illustrate the accuracy of the system (Figure 7). The 500 Hz frequency was omitted due to the insufficient signal to noise level as the frequency is not suitable for ice thickness retrieval but rather bathymetry surveying. The 1 kHz EM data was low-pass filtered (Hamming filter) to suppress high frequency noise, while 4 and 8 kHz data are shown based on raw data quality. The comparably low sensitivity and higher noise level on the lower frequency is visible over open water, falsely indicating ice thicknesses up to 2 m. The two higher frequencies are mostly within the +/- 10 cm error level over open water (marked as horizontal lines). Over sea ice they also give very comparable thickness results. Small lateral differences are evident, which motivate more accurate ice thickness retrieval with a 2D or 3D interpretation. The apparent lateral shift between 1 kHz and 4&8 kHz is caused by the low-pass filter.

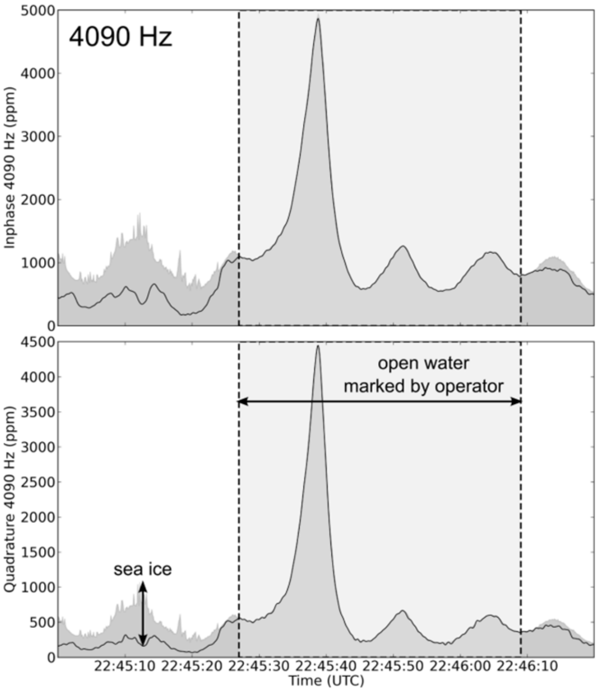

Figure 6: Measured (black line) and modelled (gray area) EM response over sea ice and open water (z-component only) given by In-phase (top) and Quadrature (bottom) channels at 4.1 kHz in multi-frequency mode.

CONCLUSION

Ground- and airborne tests as well as two field campaigns revealed the capabilities of a multi-frequency and multi-component EM configuration, but also showed room and need for further optimization. The comparably small coil spacing (2.65 m) is a major challenge compared to large exploration systems in terms of noise level. The small and light bird can, however, be flown two to three times lower than big and heavy systems and thus opens opportunities for higher lateral resolution due to the reduced footprint. The light and small receiver coils, originally developed space-borne magnetometers are capable to deliver low-noise HEM data without the need for active or passive bucking. To make full use of the multi-component EM data, we are now developing a 2D inversions scheme purpose designed for sea ice thickness studies.

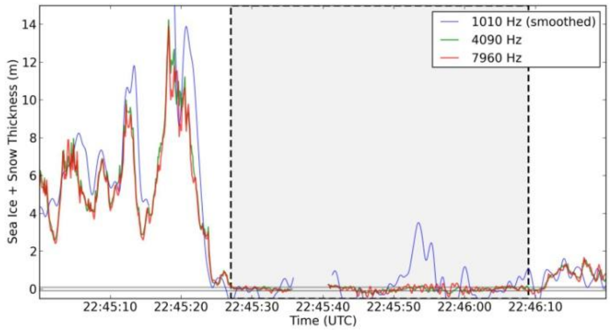

Figure 7 Ice thickness estimates derived from data segment shown in Figure 2 with a 1D interpretation of each frequency. The vertical lines indicate open water, the horizontal lines, the +/- 10 cm error level over open water.

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