Modeling Frequency-Dependent GPR Wave Propagation through Sea Ice using the Reflectivity Method and Application to Oil-Spill Detection

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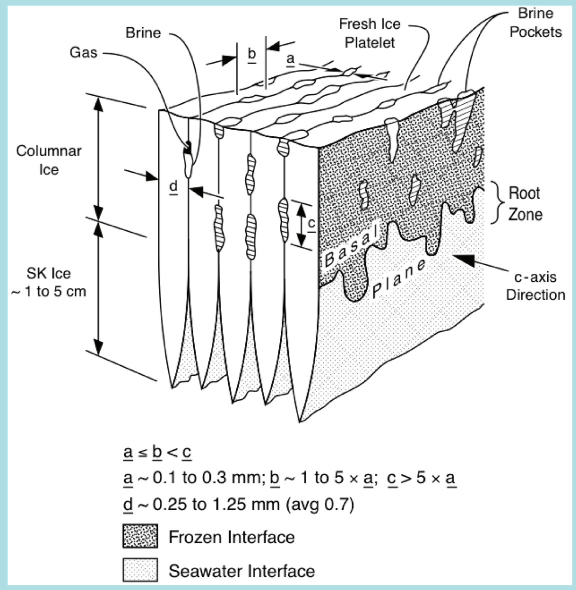
Introduction

To produce quantitatively useful GPR models it is necessary to first build realistic electric property models. Sea ice is a complex mixture of brine and ice crystals and the electrical properties depend on temperature, salinity, and ice crystal orientation. We developed a frequency dependent electric property algorithm based on existing empirical models. With only measured temperature and salinity, we compute brine volume, brine salinity, and brine conductivity. We then estimate complex dielectric permittivity of the brine and utilize Archie's law along with real effective conductivity of the brine to compute bulk ice conductivity. Simulation of the electric field polarized either parallel or perpendicular to the ice crystal alignment is accomplished through choice of the Archie's law exponent (1.5 for parallel or 1.75 for perpendicular polarization). Finally, we compute the bulk dielectric permittivity using either an isotropic or anisotropic multi-phase mixing formula. The result of this algorithm is a frequency dependent electric property model which we can then input to a variety of wave propagator algorithms to simulate the GPR response. In this study we utilize the reflectivity method which is an exact analytical solution for a plane wave incident on a horizontally layered medium. Layer thickness is arbitrary and property gradients can be simulated by a stack of very thin layers with gradually varying properties. The calculation is carried out in the frequency domain which facilitates inclusion of frequency dependent material properties. To test the ability of the modeling algorithm to accurately simulate radar response we compare the model results to field GPR measurements. The field data were acquired over an 85 cm thick laboratory grown saline ice sheet. The ice was grown for a controlled experiment designed to test the ability of GPR to identify anomalies associated with oils spills that occur beneath sea ice. The ice temperature and salinity measured in two ice cores were used as input for the model and the radar response with and without a 3 cm thick oil layer at the base of the ice was simulated.



Sea ice crystal structure. Source: Kovacs (1996)

References

Kovacs, A., 1996, Sea ice part 1. Bulk salinity vs. ice floe thickness: CRREL Report 96-7, Hanover, NH.

Morey, R.M., A. Kovacs, and G.F.N. Cox, 1984, Electromagnetic properties of sea ice: Cold Regions Science and Technology, v. 9, p. 53-75.

Mueller, G., 1985, The reflectivity method: a tutorial: Journal of Geophysics, v. 58, p. 153-174.

Conclusions

Despite some uncertainty in the orientation of the ice anisotropy, there is excellent agreement between modeled and field traces. The model correctly predicts relative changes in phase, frequency content, and amplitude that occur when an oil layer is present at the ice water interface. Further, the modeled electromagnetic properties are within measurement error of all field measurements. These results indicate that the model is capable of accurately predicting the field radar response to natural ice conditions given inputs of ice temperature, salinity, and oil permittivity.

The modeling tools developed as part of this project produce accurate simulations of field data. This is in part because actual measured values, specifically ice temperature and salinity, are used as primary inputs to the model. Based on the analytical tools we have developed, models can now be constructed and run in a matter of a few hours for any specific scenario. A recommended strategy for deployment of GPR in during an actual spill then becomes:

1) Collect a sample of the spilled oil if available, and measure its dielectric permittivity. This can be done rapidly using a time-domain reflectometry probe or the GPR system itself.
2) Acquire ice thickness, temperature and salinity profiles from the spill area.
3) Run numerical model with varying oil thickness to verify applicability of GPR to particular spill conditions and predict expected response.

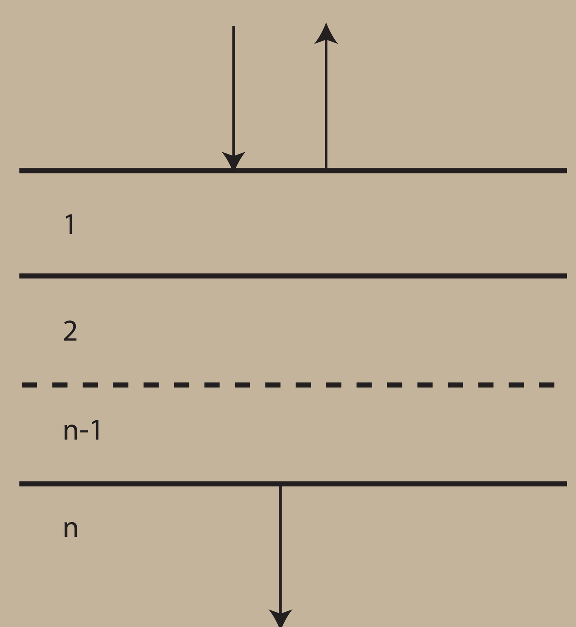
Following this protocol will enable responders to deploy the system appropriately and maximize the likelihood of successful oil detection.

Reflectivity Recursion Relation

$$R = MB_0$$

$$\mathrm{MB}_i = r_{i+1}^d + \frac{t_{i+1}^d t_{i+1}^u MT_{i+1}}{1 - r_{i+1}^u MT_{i+1}} \quad \text{i=1,2,3...n}$$

$$MT_i = MB_i e^{-2jl_i d_i}$$



R is the reflectivity from the top of the stack, r is the half space reflection coefficient, t is the half space transmission coefficient, l is the vertical component of the wavenumber, and d is the layer thickness. The superscripts d and u indicate a downgoing or upgoing incident wave respectively. The computation begins at the bottom of the stack and loops through each layer to the top of the stack. The computation is done in the frequency domain followed by multiplication with the source wavelet spectrum and an inverse FFT to compute the time domain response. Based Mueller (1985) for SH waves.

Petrophysical Relation

$$\varepsilon' - i\varepsilon'' = \varepsilon_\infty + \frac{\varepsilon_{dc} - \varepsilon_\infty}{1 + i\omega\tau} : \text{ Debye relaxation model for brine}$$

$$\sigma_{ef} = \sigma_{dc} + \omega\varepsilon'' : \text{ Real effective conductivity of brine}$$

$$\sigma_{si} = \sigma_{ef}\,\phi^m : \text{ Archie's Law - Conductivity of the sea ice}$$

The brine conductivity is given by an empirical relation as a function of temperature and salinity. The Archie's law exponent, m, is set to 1.5 for parallel polarization or 1.75 for perpendicular polarization relative to ice crystal alignment. The sea ice permittivity is determined using Taylor's anisotropic mixing formula with permittivity of pure ice as the host material and the Debye relaxation model for brine as the inclusion. From Morey et al. (1985).

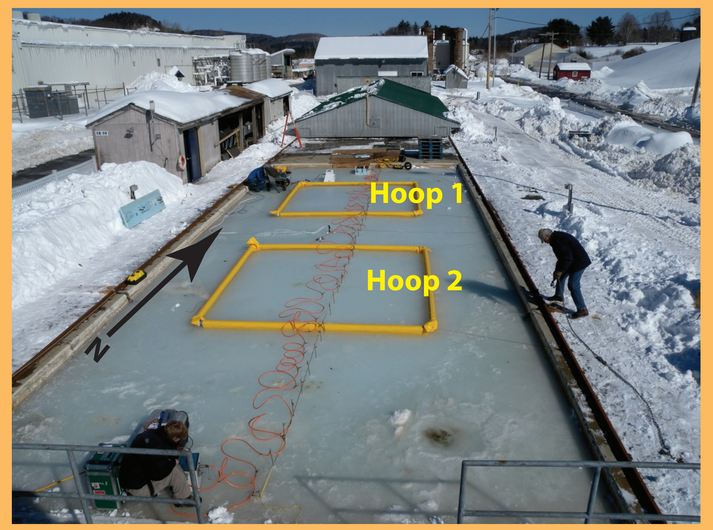
The Modeling Algorithm

Wave Propagator: The reflectivity method is an exact analytical solution to the electromagnetic wave equation for plane waves propagating through a 1D medium. The radar response is computed in a layered model using a recursion formula that correctly simulates primary and multiple reflections. The computation is carried out in the frequency domain and frequency dependent wave propagation is accurately simulated which is critical for this study where the conductivity values approach the propagation/dispersion limit in many cases. The properties of each layer are constant but smoothly varying vertical changes in material properties are incorporated into the model by dividing the model into many thin layers with small changes between each layer. The thin layers must be well below the scattering limit (~1/10 – 1/30 of a wavelength) for the radar wavelet being modeled. In all cases considered here, the ice was divided into 5 mm layers with electric properties interpolated from the measured vertical electric property distributions. The source wave for the code is a plane wave at normal incidence. The advantages of the reflectivity code are that it is computationally efficient and produces the exact radar response. The disadvantage of the method is that it is not capable of modeling the response to sharp lateral heterogeneity.

Electric property model: The radar response is controlled by the electrical properties of the medium through which the electromagnetic wave is propagating. These properties include the electric permittivity and electric conductivity of the medium. Sea ice is a complex mixture of brine and ice crystals as described under State of Knowledge (See Section 2.2). In natural sea ice the crystals are often aligned with the predominant current leading to azimuthal anisotropy in the electrical properties. Further, the electrical properties depend on temperature and salinity. Because of this complexity, it is necessary to use a set of empirical relationships to derive the electrical properties. For this study an electric property algorithm was employed based on the relationships given by Morey et al (1984). The algorithm proceeds as follows:

1) Input the measured temperature (T) and bulk salinity profile (S)
2) Compute brine volume (Vb) as a function of T and S
3) Compute the brine salinity (Sb) as a function of T
4) Compute the brine conductivity (σb) as a function of Sb and T
5) Compute the complex dielectric permittivity of the brine εb
6) Compute the bulk electric conductivity using Archies law as a function of Vb and σb and imaginary component of εb, then output to wave propagator. Simulation of the electric field polarized either parallel or perpendicular to the ice crystal alignment is accomplished through choice of the Archie's law exponent.
7) Using an anisotropic mixing formula, compute the bulk real effective permittivity as a function of Vb, the real component of εb and the permittivity of crystalline ice, output to wave propagator.

Modeling Field Data: Example from a Controlled Oil under Ice Spill at the U.S. Cold Regions Research and Engineering Lab (CRREL)



The project utilized the Geophysical Research Facility at CRREL to develop a test sea ice sheet. This facility consists of a concrete basin, 18.25 m long x 6.7 m wide x 2 m deep, with a removable roof that grows and maintains a growing ice cover in a refrigerated ambient environment and protects it from snow. The 80-90 cm thick ice sheet was grown between December and February 2011.

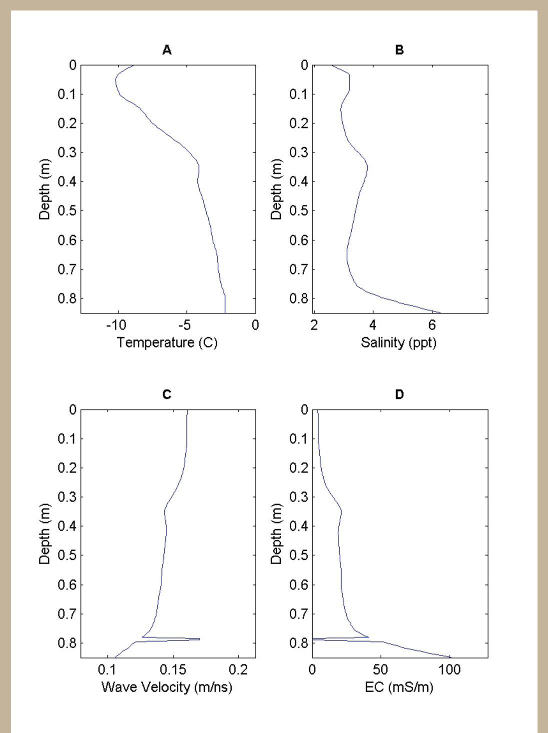
Experiment setup

As part of a series of experiments to test the ability of GPR to detect oil spills under sea ice we conducted a controlled spill experiment at CRREL's Ice Engineering lab in February-March 2011. Two spills were conducted, the first on February 18 prior to testing to allow the oil to become encapsulated by new ice growth, and the second on March 2 during the GPR surveys. In each case the discharge hose was positioned in the center of the skirted area via a water bottom trolley system.

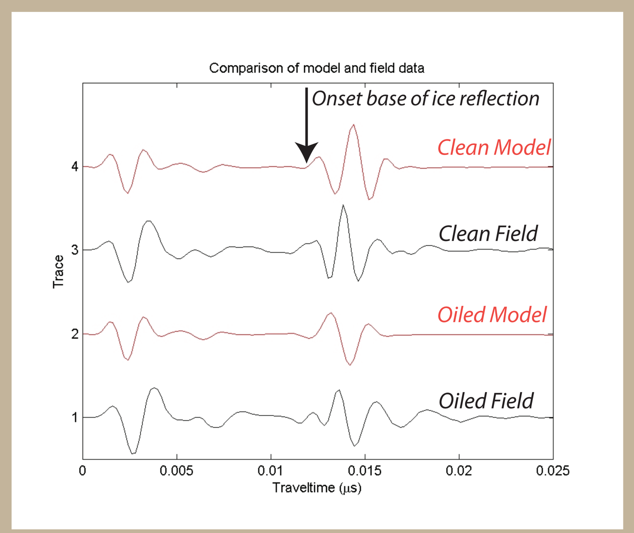
Approximately 150 gal ±5 (0.57 m3) was discharged into each test hoop. This translates to an average film thickness iof 3.6 cm, but the actual distribuion is non-uniform due to ice irregularity. On March 4, following completion of the radar surveys, CRREL personnel documented the ice properties (temperature and salinity), ice thickness, oil thickness (Hoop #1 only) and oil distribution through a series of cores and drillholes.

We tested both 1 GHz and 500 MHz pulsed antennas (Sensors & Software PE Pro) in ice coupled mode and suspended approximately 3 m above the ice from a gantry. Both antennas performed well and were able to image the base of ice in both airborne and ground-coupled modes. Efforts focused on acquiring data along a center line parallel to the long axis of the tank both before and after emplacement of the oil beneath Hoop 2. After the oil was emplaced, a 3D survey was completed in both ground coupled and airborne modes using the 500 MHz antennas. Finally, 4 sets of expanding spread gathers were acquired in each containment hoop, with 2 orthogonal polarizations parallel to both axes of the tank. These data enable electromagnetic velocity estimation and evaluation of offset dependent reflectivity anomalies.

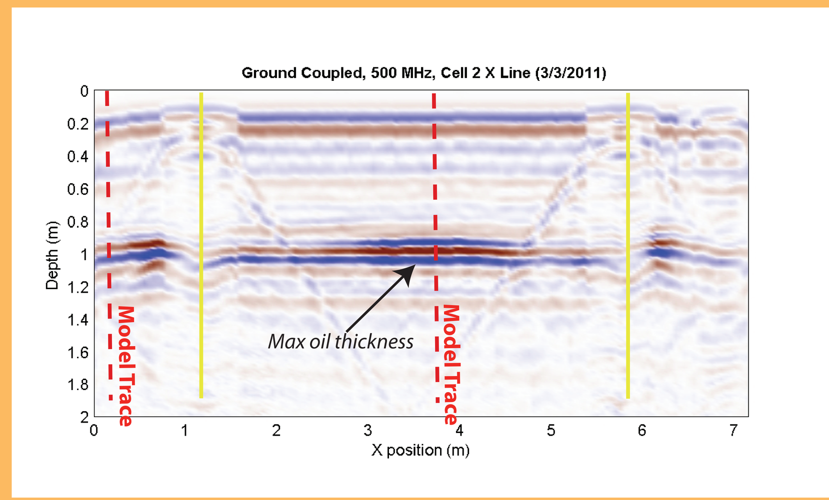
Model Results



A) Temperature and B) salinity measured from ice cores on March 4. C) Electromagnetic wave velocity, and D) effective electric conductivity computed from A and B. Note the spike at 0.78 m that corresponds to the depth of the thin entrapped oil sheen observed throughout the tank. Properties are at 500 MHz

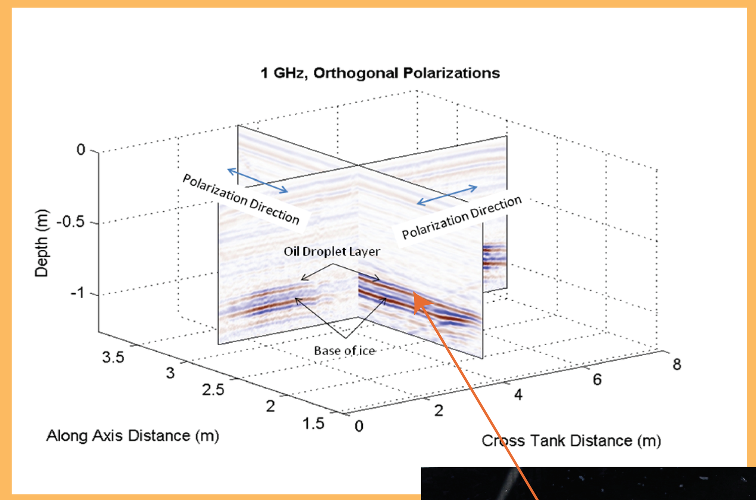


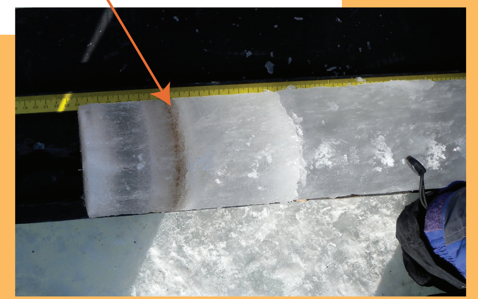
Model 500 MHz center frequency traces (red) and field data traces (blue) taken from the profile shown on the right. Traces 1 and 2 have no oil, and traces 3 and 4 have 3 cm of oil at the base of the ice. Note that 3.6 cm is the average expected oil thickness based on the known area and volume of oil. This parameter was not measured in the field.



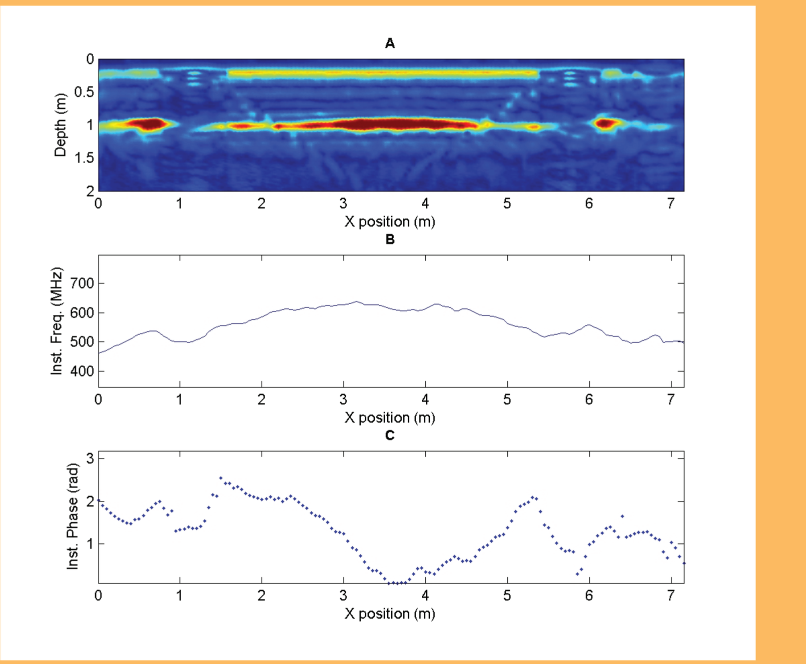
Cross tank profile with optimal antenna polarization. The base of ice is clearly evident over the entire profile with the reflection onset occuring at a depth of just over 90 cm. The hoop boundaries are shown in yellow with oil trapped under the ice reaching a maximum thickness between 3-5 m.

Ground coupled, 1GHz profiles with orthogonal polarizations acquired outside of the skirted areas and crossing south of Hoop 2. At this location, the polarization perpendicular to the tank axis is optimal along the center line. Along the cross tank line the crystal axis changes along profile; the antenna is optimally aligned near the edges but the signal is strongly attenuated near the center. Where the lines intersect, the base of ice reflection amplitude on the cross tank profile drops dramatically while reflection amplitude in the along axis profile remains high. The striking difference in amplitude at the intersection point indicates strong anisotropy.





Band of fine oil droplets (< 1mm) 9 cm from the bottom of the cores through clean ice. This indicates that a very small % of the oil pumped in the first discharge drifted laterally beyond the skirt boundaries and was incorporated in the growing ice interface throughout the tank.



Reflection attributes extracted from the cross tank profile over Hoop 2 clearly differentiate the oiled area with an increase in reflection amplitude, increase in instantaneous frequency, and decrease in instantaneous phase.

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