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Electrical anisotropy in sea ice and a dual-polarization radar system to mitigate the effects of preferential attenuation in imaging sea ice

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ABSTRACT

Preferential alignment in the physical structure of the sea ice crystal matrix results in anisotropy in the electrical properties of the bulk sea ice. Previous field data and our data demonstrate that both sea ice conductivity and its electrical anisotropy can impede ice thickness profiling using ground penetrating radar (GPR). Preferential attenuation caused by conductive anisotropy can reduce or eliminate ice bottom reflections when the polarization is not optimally aligned. A dual-polarization GPR configuration reliably imaged the sea ice/water interface, even in the presence of well-developed conductivity anisotropy. Additionally, by combining data from both polarizations, the system provides information about the horizontal direction of the ice matrix alignment, which may indicate the direction of dominant current flow underlying sea water.

1. Introduction

In certain cases, sea ice is well-known to be anisotropic with respect to its mechanical, physical, and electrical properties (Campbell and Orange, 1974; Kovacs and Morey, 1979; Timco and Weeks, 2010). In particular, first-year sea ice is an "anisotropic, stratified, strongly absorbing, inhomogeneous dielectric" with electrical and physical properties dependent on temperature, salinity, age, and crystal structure (Kovacs and Morey, 1978). Both the dielectric permittivity and conductivity structures of sea ice may be anisotropic (Kovacs and Morey, 1986). In particular, the anisotropy in the conductivity structure of sea ice has ramifications for effective implementation of ground penetrating radar (GPR) to image the sea ice bottom.

The driving mechanism for sea ice conductivity is the salinity (Nakawo, 1981). As ice forms from sea water, growing ice crystals exclude salt. Some of this excluded salt remains within the ice and is concentrated in brine pockets and channels. In general, these brine pockets are probably ellipsoidal or cylindrical (Fig. 1) (Jones et al., 2010; Kovacs and Morey, 1986; Morey et al., 1984). Nevertheless, the volume fraction, size, shape, and connectivity of the brine inclusions vary over several orders of magnitude depending on environmental factors (Arcone et al., 1986a; Buchanan et al., 2011; Jones et al., 2010). The concentration of the brine within the inclusions depends largely on the rate of ice growth for early- or mid-season ice. Ice growth rates, in turn, depend on temperature and on the age and thickness of the ice (Arcone et al., 1986b; Jones et al., 2010).

The bulk effective conductivity of the ice sheet is a function of the brine concentration and of the orientation of the brine inclusions. This orientation depends on the microstructure of the ice, which is generally either granular or columnar (Timco and Weeks, 2010). Granular ice has no preferential orientation and is usually isotropic (Fig. 1a). Similarly, multi-year ice often has no preferential orientation and is also isotropic (Timco and Weeks, 2010). The conductivity of columnar ice, on the other hand, can be strongly anisotropic due to the preferential shape and orientation of the ice columns.

In the case of anisotropic columnar sea ice, elongated vertical columnar crystals extend throughout the ice sheet (Arcone et al., 1986b). The columns enclose brine pockets oriented perpendicularly to the c-axes of the crystals (Fig. 1a) (Kovacs et al., 1987; Timco and Weeks, 2010). This matrix of crystals and brine inclusions can align in the horizontal direction in response to dominant ocean currents (Fig. 1b) (Campbell and Orange, 1974; Golden and Ackley, 1981; Tucker et al., 1984; Weeks, 2010; Weeks and Gow, 1980; and others). The net result is that the conductivity (σ_{si}) and dielectric permittivity (ε_{si}) of the sea ice varies with azimuth. Effective conductivity is higher along dominant direction of brine inclusion alignment than perpendicular to it. Although the percentage of sea ice showing such preferential alignment is unknown (Tucker et al., 1987; Weeks, 2010), when it does occur, such alignment can affect radar measurements of sea ice (Kovacs et al., 1987).

In order to understand the implications of this anisotropy for imaging sea ice using radar in the GPR frequency range (10 MHz to 1 GHz), we begin by examining the relevant electrical properties of sea ice with respect to polarization. Then we discuss a data example

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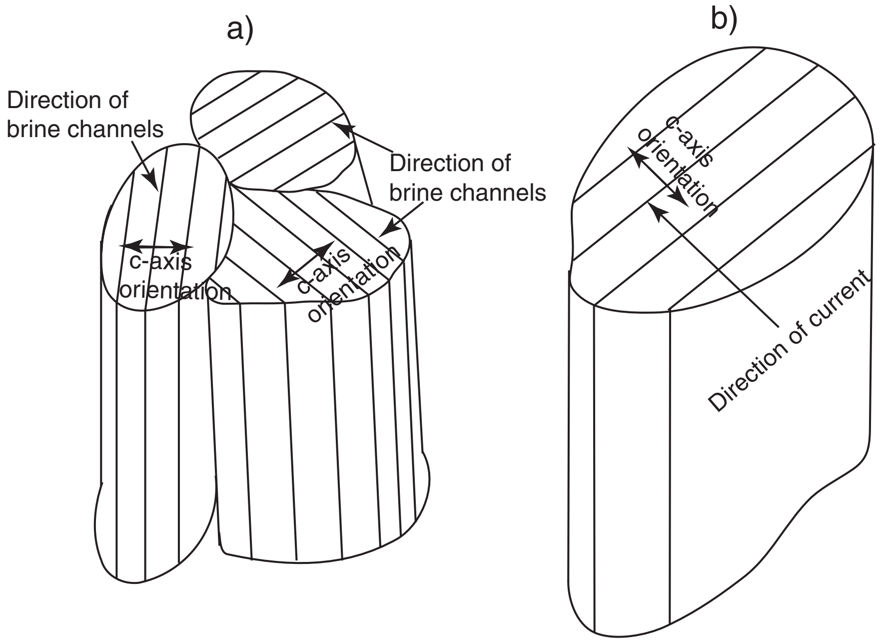

Fig. 1. Sea ice crystals in columnar ice having a) oriented brine pockets with varying shape and size within randomly-oriented columnar ice crystal matrix and b) possible orientation of the columnar ice matrix in response to dominant currents (following Kovacs et al., 1987). Direction of c-axes orientation corresponds to azimuth having lower effective conductivity, relative to the direction of ice structure.

that highlights the polarization-dependent response. Finally, we present a commercial radar system configuration that mitigates the effects of the sea ice anisotropy and allows us to reliably detect the ice bottom even when the ice is strongly anisotropic. Data collected at two field sites demonstrate the system's ability to reliably image the sea ice/water interface in the presence of well-developed anisotropy.

2. Sea ice electrical anisotropy

Radar wave propagation in sea ice depends on both ε_{si} and σ_{si}. Since sea ice may be strongly anisotropic, we begin by considering the problem as two separate cases corresponding to an electromagnetic (EM) plane wave, **E**, polarized in the parallel ($\mathbf{E}_{\parallel}$) or perpendicular ($\mathbf{E}_{\perp}$) direction with respect to the dominant orientation of brine inclusions. Many commercial radar antennas are approximately horizontal dipoles and emit a linearly polarized **E** field. By choosing the appropriate coordinate system, we can write the two cases with respect to that orientation as follows:

$$\nabla^2\mathbf{E}_{\parallel}-\mu_0\sigma_{si\parallel}\frac{\partial\mathbf{E}_{\parallel}}{\partial t}-\mu_0\varepsilon_{si\parallel}\frac{\partial^2\mathbf{E}_{\parallel}}{\partial t^2}=\mathbf{J}_{\parallel} \tag{1}$$

$$\nabla^2\mathbf{E}_{\perp}-\mu_0\sigma_{si\perp}\frac{\partial\mathbf{E}_{\perp}}{\partial t}-\mu_0\varepsilon_{si\perp}\frac{\partial^2\mathbf{E}_{\perp}}{\partial t^2}=\mathbf{J}_{\perp} \tag{2}$$

where $\mathbf{J}_{\perp}$ and $\mathbf{J}_{\parallel}$ are the sources of $\mathbf{E}_{\perp}$ and $\mathbf{E}_{\parallel}$, respectively, due to radar excitation; and ε_{si} and σ_{si} are azimuth-dependent and complex-valued. (Since sea ice is predominantly nonmagnetic, we assume the magnetic permeability μ to be equal to that of free space, μ_0.) Assuming that the radar waves are propagating approximately vertically and polarized horizontally, we neglect anisotropy in the vertical direction.

An anisotropic dielectric has a nine-element permittivity and conductivity tensor, but here we neglect any anisotropy in the vertical direction. The simplification necessary to derive Eqs. (1) and (2) also assumes that seven elements of the tensors are zero (Lin et al., 1988). With this assumption, any case of **E** polarized at an arbitrary orientation with respect to the dominant direction of the anisotropy may be decomposed into these two cases, e.g. the arbitrarily horizontally polarized field propagating vertically through the medium will split into two linearly polarized phases, having polarization aligned with the parallel and perpendicular directions of the ice crystal c-axes.

Taylor's (1965) mixing formulas provide the effective dielectric permittivity of the sea ice if the brine pockets are parallel to the introduced field ($\varepsilon^*_{si\parallel}$, where the superscript * indicates a complex-valued parameter) or if they are perpendicular ($\varepsilon_{si}\ {}^*_{\perp}$), given the complex permittivities of the brine and the pure ice crystals (ε^*_b and ε^*_i, respectively) and the volume fraction of the brine (υ_b). These formulas require that the long axes of the ellipsoidal pockets are small relative to the wavelength of the signal in the sea ice and that $\upsilon_b << 1$. These conditions are likely satisfied in cold sea ice (Arcone et al., 1986a, 1986b; Jones et al., 2010). With these assumptions we can calculate the complex-valued permittivities for the two-component system as follows (Morey et al., 1984):

$$\varepsilon^*_{si\parallel}=\varepsilon^*_i+\upsilon_b\left(\varepsilon^*_b-\varepsilon^*_i\right) \tag{3}$$

and

$$\varepsilon^*_{si\perp}=\frac{\varepsilon^*_i\varepsilon^*_b}{\varepsilon^*_b+\upsilon_b\left(\varepsilon^*_i-\varepsilon^*_b\right)}. \tag{4}$$

Inspection of these two equations reveals the need to calculate the complex-valued ε^*_b, ε^*_i, and ${}_b$.

The Debye (1929) formula provides the basis for computing complex-valued ε^*_b (Stogryn, 1971) and ε^*_i (Buchanan et al., 2011):

$$\varepsilon^*_i=\varepsilon_{i\infty}+\frac{\varepsilon_{i0}-\varepsilon_{i\infty}}{1+i\omega\tau_i} \tag{5}$$

and

$$\varepsilon^*_b=\varepsilon_{b\infty}+\frac{\varepsilon_{b0}-\varepsilon_{b\infty}}{1+i\omega\tau_b}+i\frac{\sigma_b}{\omega\varepsilon_c} \tag{6}$$

using the dominant relaxation time (τ) of the ice (τ_i) and brine (τ_b); the low frequency (ε_0) and high frequency (ε_∞) permittivity limits of