Optical Probing of Deep Glacial Ice using Short Laser Pulses

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Glacial ice has been called the most transparent naturally occurring solid on earth[1]. In the Greenland and Antarctic ice sheets, below where air bubbles convert to air hydrate clathrates, light at blue and violet wavelengths can propagate for tens of meters before being scattered and hundreds of meters before being absorbed. Currently, one can obtain simple in situ optical measurements of annual layers and dust using borehole logging[2,3], and ex situ measurements of fabric and chemical composition[4]. However, three dimensional maps of glacial properties and in situ fabric and chemical measurements are well-beyond the present state-of-the-art. The extreme propagation length of light in ice is comparable to that of early optical fibers, and this suggests that much of the technology developed for characterizing optical communication systems can be modified to characterize deep glacial ice. One of the most powerful optical fiber techniques is optical time-domain reflectometry (OTDR), where the time of flight of a light pulse is used to determine the position of features in the fiber. In this presentation, we propose that three dimensional maps of many properties of deep glacial ice may be obtained using fiber optic time-domain techniques. Perhaps the simplest OTDR measurement is that of ranging. Here a short laser pulse would be sent into a borehole wall, perhaps as part of a borehole logging system, where it would propagate for a certain distance, reflect or scatter off of an object, and return to the source. In glacial ice, this type of measurement might, for example, determine the distance to bedrock or the location of a meteorite. Ranging can also obtain data about dust content because the laser pulse continuously backscatters small amounts of light from dust in the ice. Therefore, regions of ice with different dust content will produce different scattering intensities, and a single borehole could provide a map of dust concentrations for hundreds of meters in all spatial directions, allowing researchers to evaluate whether layer-to-layer fluctuations in an ice core represent actual deposition conditions or just a local fluctuation. Such information may even allow one to avoid drilling multiple holes at the same site.

OTDR will also advance the state-of-the-art for determining ice fabric. Currently, the average orientation of crystals in large volumes of ice is determined using acoustic wave measurements, which have poor resolution. Since the speed of light changes with polarization, time-of-flight differences from laser pulses with different polarizations will be able to map the average fabric of ice with a resolution of millimeters in height and width and centimeters in depth. Such resolution brings up the interesting possibility that OTDR could identify the minimum stress planes for glacial ice even when they are oriented obliquely to a borehole wall, which would simplify flow modeling based on borehole data. Finally, since an OTDR system for ice would use wavelengths of light (e.g. ƒÜ=405nm) where ice is maximally transparent, Raman spectroscopy measurements could be taken using the same optics to obtain information on the chemical content of ice and the gas content of bubbles within it. These measurements could be performed in situ in a borehole without any concerns about contamination, outgassing, cracking, or other depressurization issues. Bubbles in the upper section of an ice sheet and bubble-free ice in the lower sections can be tested. Among the features of interest would be the concentration of N2/O2 and CO2 in bubbles, the concentration gradients of gases near bubbles, the relative concentrations of H2O, HDO, H218O in ice, and the composition of dust grains and salt inclusions. Early data on (laboratory based) fabric measurements in ice and Raman measurements in bubbles will be discussed.

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