A FOUNDATION FOR ORBITAL RADAR SOUNDING OF EUROPA FROM NEW MEASUREMENTS OF THE BROADBAND DIELECTRIC PROPERTIES OF TERRESTRIAL POLAR ICE CORES. David E. Stillman[1], Joseph A. MacGregor[2], Amy C. Barr[1], Robert E. Grimm[1], Donald D. Blankenship[2], and Dale P. Winebrenner[3]. [1] Dept. of Space Studies, Southwest Research Institute, Boulder, Colorado (dstillman@boulder.swri.edu); [2] Institute for Geophysics, The University of Texas at Austin (joemac@ig.utexas.edu); [3] Polar Science Center, Applied Physics Lab, University of Washington, Seattle.

Summary. The thickness and internal structure of Europa's ice shell are unknown yet critical to understanding its formation history and interaction with a subsurface ocean. The planned Jupiter Europa Orbiter (JEO) will include HF/VHF radar sounders to probe the ice shell. Knowledge of the broadband dielectric properties of naturally forming ice across possible temperature and impurity-concentration ranges of the ice shell is critical for both predicting the success of these radar sounders and for interpreting any observed reflections. Here we present initial measurements of broadband (1 mHz – 1 MHz) dielectric properties of a suite of meteoric and accreted ice-core samples from Antarctica and Greenland, and across the Europan ice-temperature range. We find that the LF dielectric relaxation of naturally formed ice is generally weaker than that of lab-made ice, although natural ice's DC conductivity is consistently much higher. We observed a second lower-frequency relaxation in many samples, and a large increase in permittivity above the eutectic point of $CaCl_2$ in at least one sample. By combining this dataset with three-dimensional thermomechanical modeling of the Europan ice shell, we will improve constraints on the radar attenuation through the shell.

Motivation and background. Ice-penetrating radars will be key instruments on NASA's JEO for the study of Europa's ice shell. Previous studies (e.g., [1–4]) have established the need for additional dielectric measurements of ice to better constrain radar attenuation through Europa's ice shell, and to interpret potential subsurface reflections observed by JEO. Our goals are two-fold: 1. To predict the dielectric properties of Europan ice using the best available natural analogs and thermomechanical models; and 2. To better understand conduction mechanisms in low-temperature ice, so that we may better predict the dielectric behavior of extraterrestrial ices for which there are no natural terrestrial analogs. For this study, the dielectric properties of primary interest are the ice's conductivity at the high-frequency limit (e.g., Figure 1b), its temperature dependence (activation energy) and soluble impurity-concentration dependence (conductivity per unit molarity).

The primary LF dielectric relaxation of ice is the dominant loss mechanism at the HF and VHF frequencies relevant to JEO radars (e.g., Figure 1c). The bandwidth of our measurements was chosen to best resolve the center frequency, magnitude, temperature dependence, and character of this relaxation. Grain-boundary conduction of concentrated liquid impurities increases the DC conductivity. Higher concentrations of extrinsic Bjerrum–L defects, typically caused by Cl^- substitution for O^{2-} in the ice lattice, increase this primary relaxation's frequency and decrease its activation energy. Both of these shifts tend to increase attenuation at radar frequencies, particularly at low temperatures.

Ice-core samples. Terrestrial ice is an inherently imperfect analog for Europan ice, but it does contain many soluble impurities that are likely to be common in Europa's ice shell (e.g. Cl^-; [1, 5]). Ice can form on Earth in similar ways to mechanisms that are likely to be dominant on Europa, e.g., basal freeze-on underneath ice shelves or ice sheets, from oceans or subglacial lakes, respectively. Lab-made ice cannot easily reproduce these conditions, therefore existing broadband measurements of such ice may be of limited value for the prediction of the dielectric behavior of Europan ice.

We selected more than 30 ice-core samples from the U.S. National Ice Core Lab's inventory, covering a broad range of soluble and insoluble impurity concentrations (e.g., volcanic layers), *in situ* conditions, and geography (coastal and inland Antarctica, inland Greenland). Most of our samples are meteoric, but unique to this study of ice's broadband dielectric properties are samples from the bottom of Vostok 5G ice core, which penetrated into the ice that froze on onto the East Antarctic ice sheet from the base of Lake Vostok. A valuable characteristic of all of these samples is that they have not experienced significant annealing beyond that which may have occurred *in situ*, so their natural dielectric character should be preserved.

Initial measurements. Using an impedance analyzer and parallel-plate electrodes [6], we performed initial broadband (1 mHz – 1 MHz) dielectric spectroscopic measurements on all of our ice-core samples between 188–238 K. Other measurement techniques for low-loss materials above radar frequencies (e.g., cavity resonator; [7]) are unsuitable for ice cores. A key element of the accuracy of our measurements is temperature stability; during the > 1-hr period for a single frequency sweep, we maintain the sample temperature to within a standard deviation of < 0.04 K. Future measurements using LN2 cooling will allow us to measure dielectric properties down to the lowest

Europan ice temperatures (~ 100 K). We will then also measure the samples up to premelting temperatures (~ 263 K), and finally melt them for ion-chromatography measurements of their meltwater ion concentrations.

We find that the dielectric behavior of natural ice diverges significantly from that of lab-frozen samples. Their DC conductivity is often 1–2 orders of magnitude higher than lab-frozen ice, and is consistent with the range of values observed by existing ECM measurements of ice cores. Figure 1 shows an example of our broadband measurements for one ice-core sample. These data clearly show a second, lower-frequency relaxation that is only present above 223 K. This sample clearly crossed the eutectic point of $CaCl_2$, above which $CaCl_2$ frozen at grain boundaries became liquid and freely conducting [7, 8]. Although such eutectic behavior has been predicted for both the Antarctic ice sheet and the Europan ice shell [1, 3, 9], it has not been previously observed in natural ice. This eutectic transition could produce a detectable reflection if the *in situ* vertical temperature gradient is sufficiently large.

Most of our ice-core samples had a second lower-frequency relaxation, but not the eutectic behavior. Both dielectric relaxations are weaker than those of lab-frozen ice. However, once we raise the sample temperature above ~ 240 K, the lower frequency relaxatsion begins to anneal away, which may explain why it has not been previously reported. This second relaxation can raise radar attenuation at low temperatures significantly, and is a salient example of the poorly understood dielectric behavior at low temperatures that must be constrained for effective radar-attenuation modeling of Europa's ice shell.

Radar-attenuation modeling. Using our initial measurements, we will improve upon previous studies of the radar attenuation of the Europan ice shell [1–4] using data collected across a broad range of temperatures and soluble impurity concentrations. We will extend previous thermomechanical models of ice-shell convection [10, 11] into three dimensions, and convert modeled temperature fields into attenuation rates, assuming uniform chemistry.

Acknowledgements. This study was supported by NASA PG&G NNX10AJ65G. We thank NICL and NSF for providing the ice-core samples.

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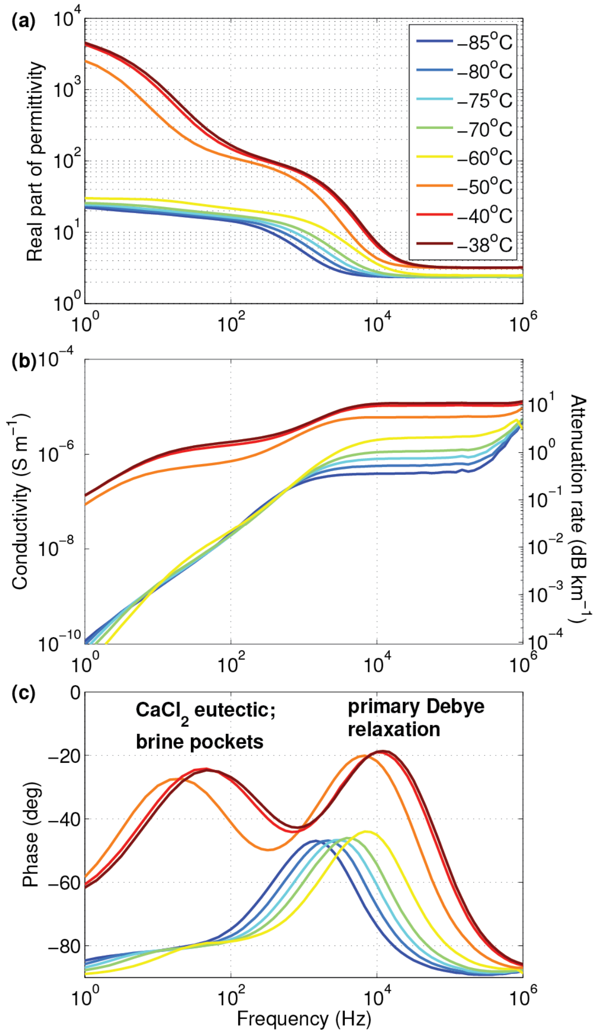

Figure 1. Dielectric spectroscopy of an ice-core sample from Newall Glacier, East Antarctica, at a depth of 80 m. Above 223 K (–50ºC), the permittivity increases dramatically across the entire frequency range, due to the crossing of the $CaCl_2$ eutectic point. The jump in the HF real part of permittivity indicates ~0.004% of the sample (by volume) became liquid above the eutectic. Although the center frequency of the resulting relaxation is more than 4 decades lower than that of the planned JEO radars, it still produces a ~ 7 dB km^{-1} increase in the attenuation rate near the HF range. The magnitude of this effect emphasizes the importance of broadband measurements for resolving the physical causes of significant changes in the HF/VHF dielectric properties of ice.