A foundation for orbital radar sounding of Europa from new measurements of the broadband dielectric properties of terrestrial polar ice cores

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Introduction

Why? Ice-penetrating radar will be a key instrument on any orbiter traveling to **Europa**. Previous studies established the **need for additional dielectric measurements of ice** to better constrain radar attenuation through Europa's ice shell, and to interpret subsurface radar reflections. Many other planetary ice masses are also of interest.

Our goals

1. To better **understand conduction mechanisms** in low-temperature ice, so that we may better predict the dielectric behavior of extraterrestrial ices that we can't sample directly. The dielectric properties of primary interest are the ice's **conductivity** at the high-frequency limit, its **temperature dependence** and soluble **impurity-concentration dependence**.

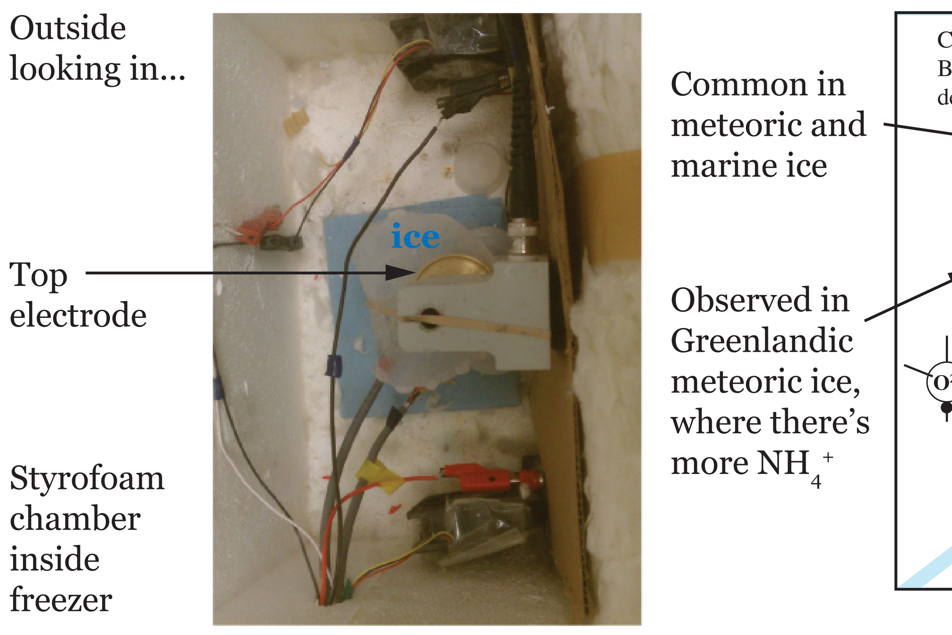
2. To **predict the dielectric properties of Europan ice** using the best available natural analogs and thermomechanical models.

How? We selected **46 ice-core samples from 7 different sites** in the National Ice Core Lab's inventory, covering a range of soluble and insoluble impurity concentrations (e.g., volcanic layers), in situ conditions, and geography (coastal and inland Antarctica, inland Greenland). We typically measured their broadband (**100 mHz–1 MHz**) dielectric properties between **188–238 K** using an impedance analyzer and parallel-plate electrodes.

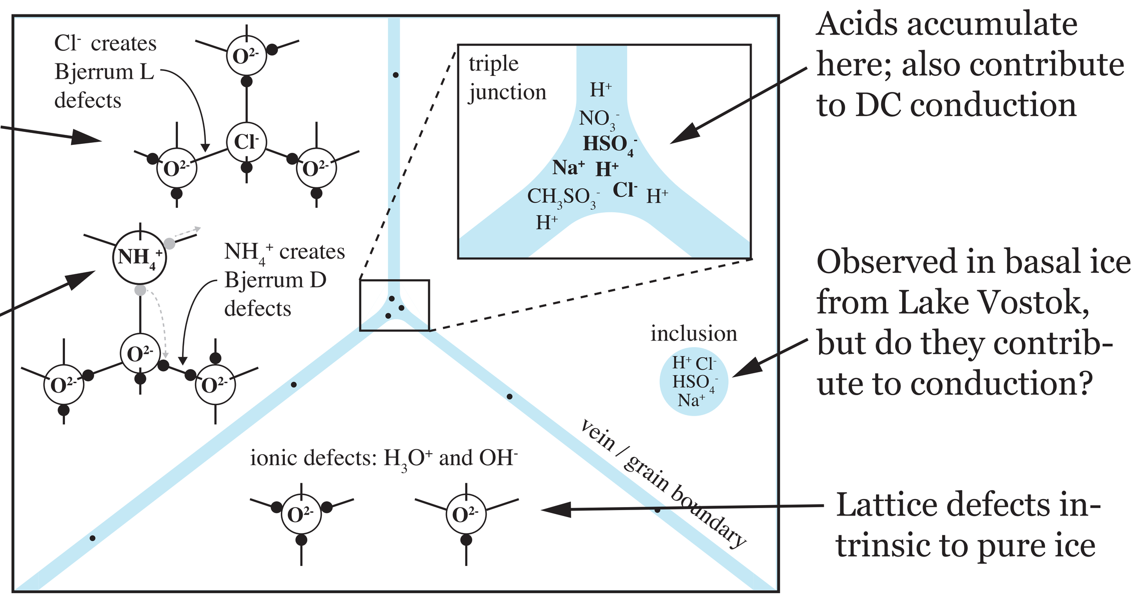
Initial results Our initial measurements emphasize the dielectric variability of natural ice. A sample accreted from Lake Vostok has the most Debye-like relaxation and lowest attenuation ever measured in natural ice, while a basal ice sample from the same core is saturated with lattice defects due to impurities and has the highest attenuation. A portion of a sample from South Pole is the purest natural ice ever measured. We also find unannealed meteoric ice (kept below −20°C) has both pure-ice and briny/dirty relaxations. Once annealed, they merge.

Dielectric variety is the spice of ice

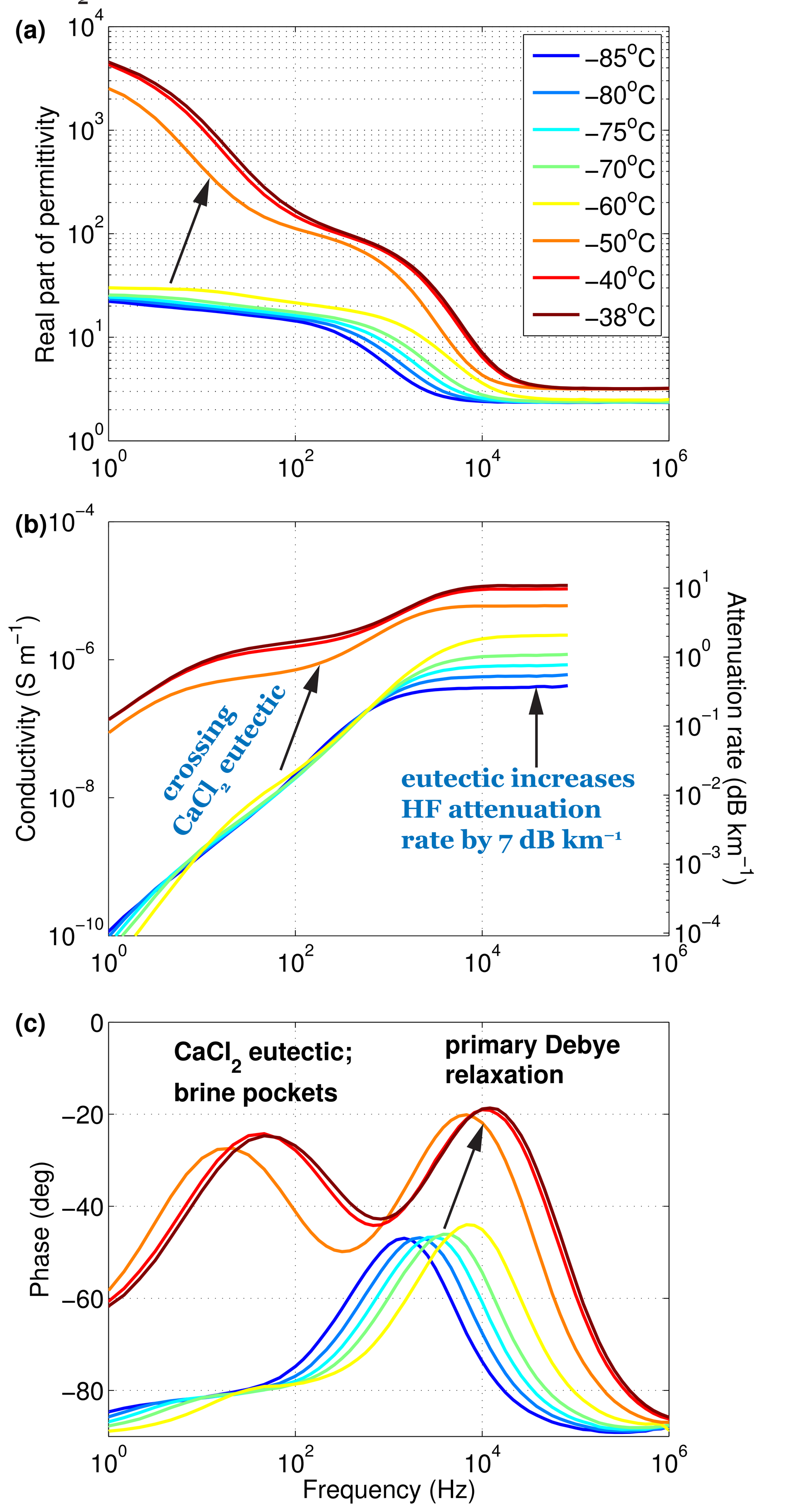
Measurement apparatus and ice-core sample



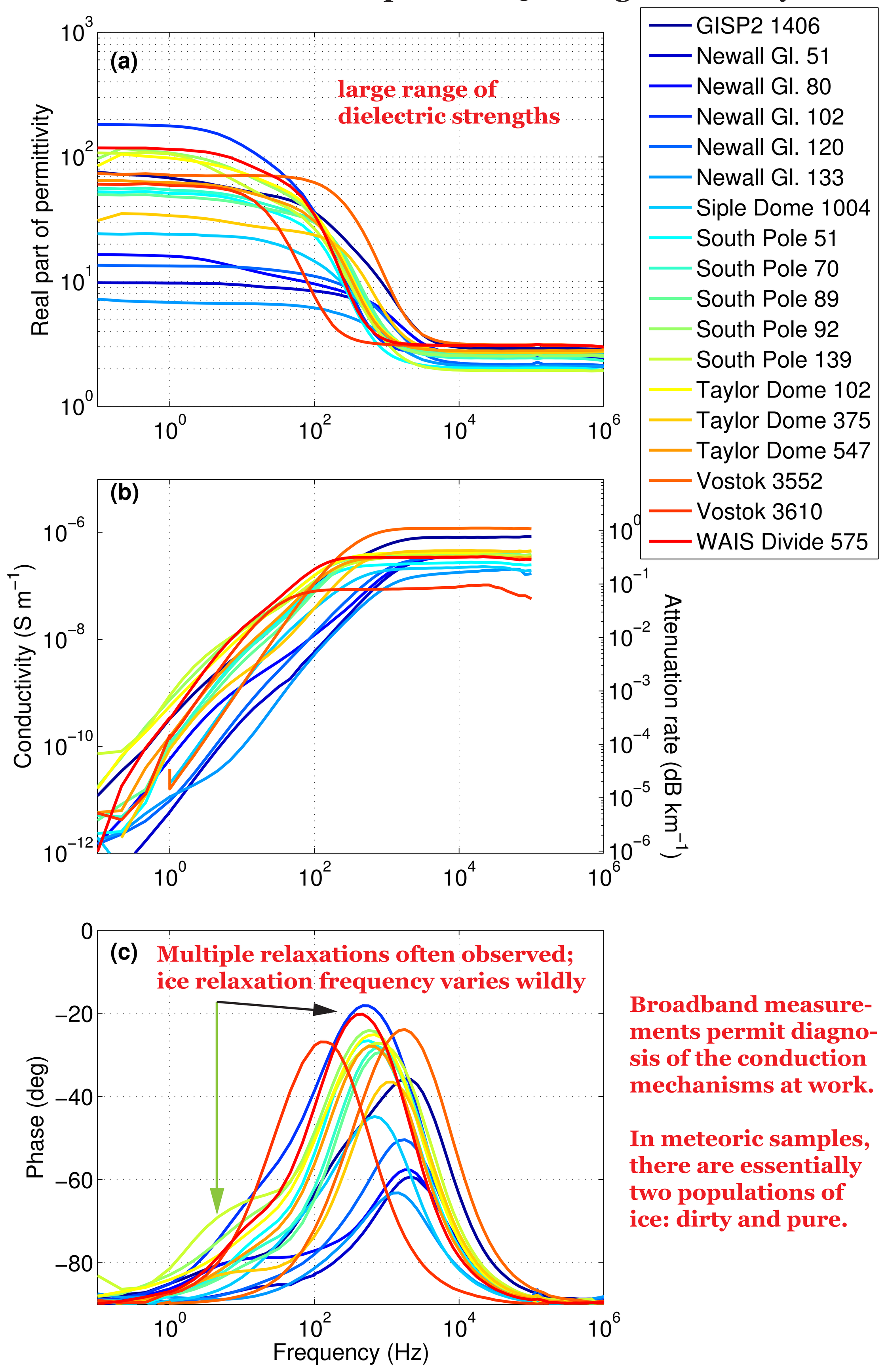
Conduction mechanisms in natural ice



CaCl$_2$ brine channels in East Antarctic meteoric ice



All measured samples at −85°C: huge variability



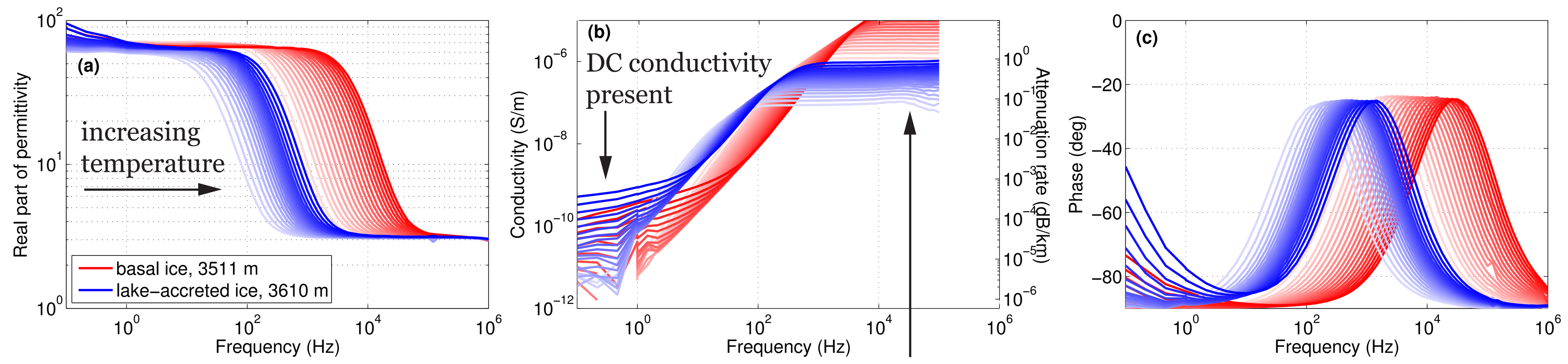
Broadband measurements permit diagnosis of the conduction mechanisms at work.

In meteoric samples, there are essentially two populations of ice: dirty and pure.

The crown jewels: Basal ice, and lake-accreted ice from Lake Vostok

It is challenging to make suitable lab-frozen ice. An alternative approach is to have nature make it for us.

Dielectric measurements of Vostok ice between −85 and −40°C



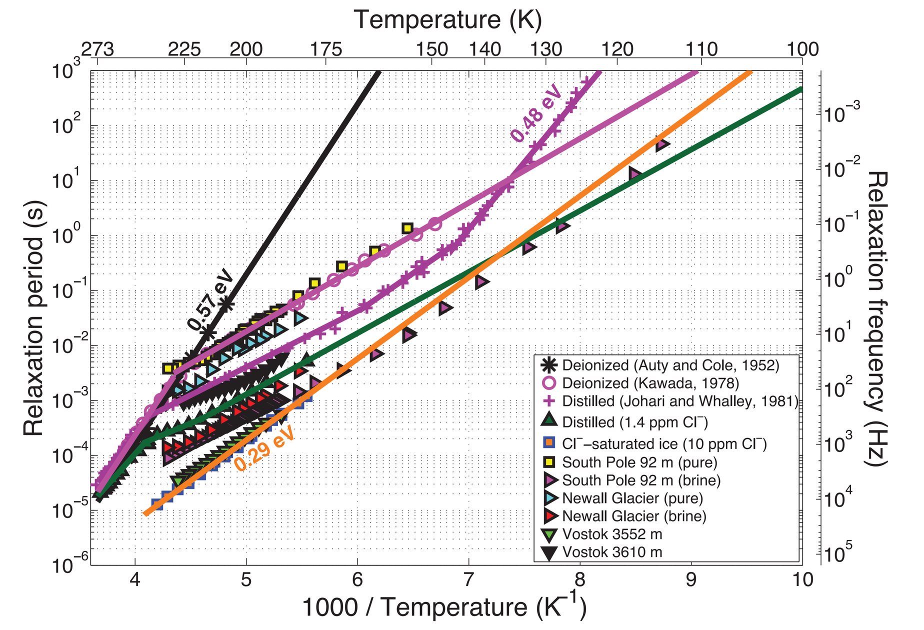
The basal ice has the highest relaxation frequency yet observed, consistent with earlier predictions

Basal ice is our most attenuating sample, lake-accreted ice the least

The lake-accreted ice has the most Debye-like relaxation yet observed in natural ice

Temperature dependence of observed relaxations

We fit our data using **Cole–Cole models**. Lattice defects intrinsic to pure ice dominate at higher temperatures than we initially measured here have a high activation energy (0.57 eV). Extrinsic defects due to impurities have a lower activation energy (0.20–0.24 eV), and their concentration is proportional to the relaxation frequency. The pure ice relaxation in a meteoric South Pole sample is just as pure as the deionized ice measured by *Kawada* [1978]. The basal ice from Vostok is saturated with lattice defects, as it compares well with lab-made saturated samples. No stable ice, natural or otherwise, has ever been found to have a relaxation frequency higher than this saturated curve.

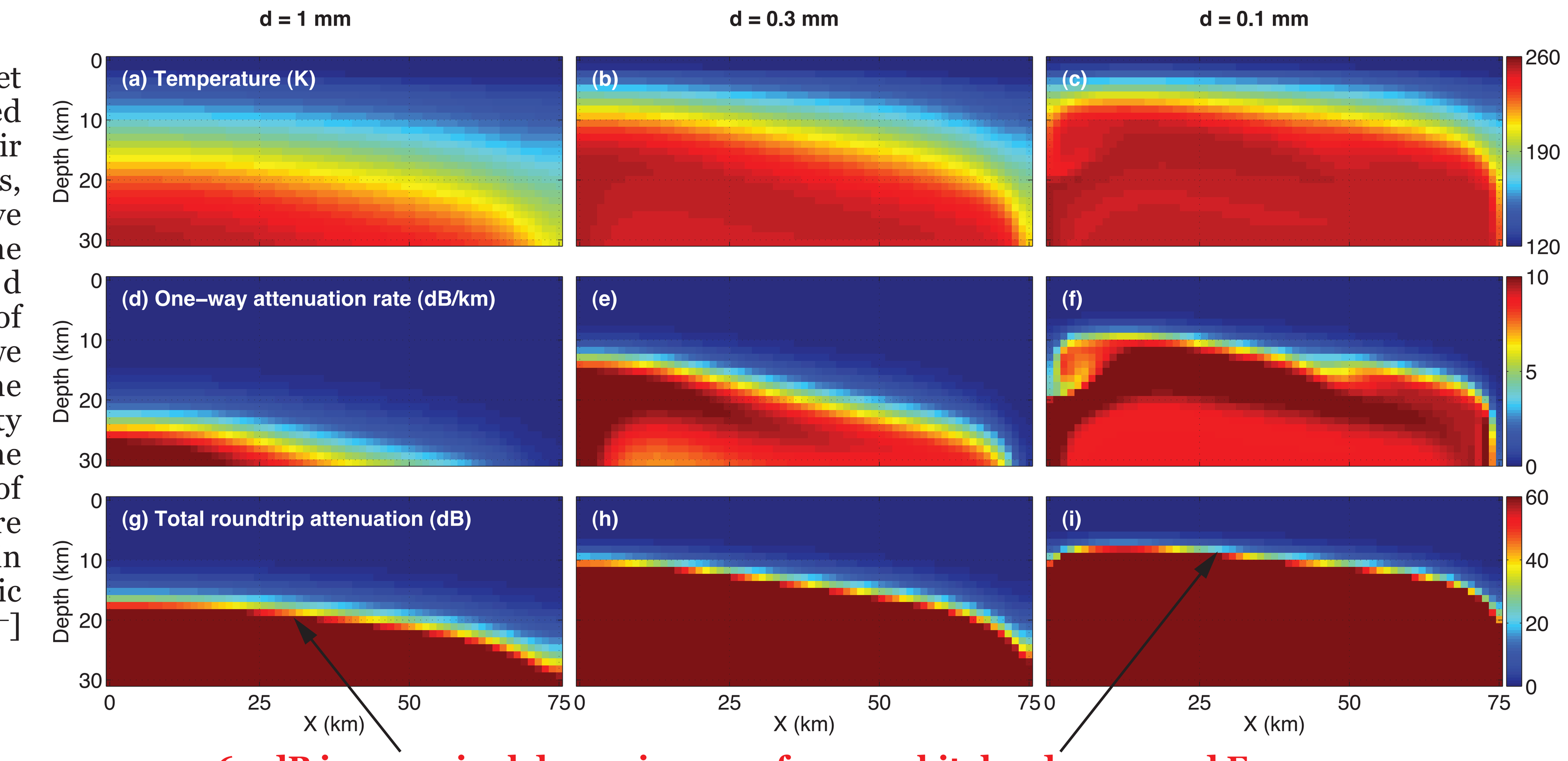


Initial radar-attenuation modeling

We modeled radar attenuation through the Europan ice shell using new thermomechanical models that simulate convection in the ice shell for **variable shell thicknesses and grain sizes**. **Radar penetration depths are ~10–20 km in these scenarios.**

Because we have not yet melted our measured samples to measure their impurity concentrations, we cannot yet improve constraints on the impurity-related dielectric properties of ice. For these models, we therefore assume uniform impurity concentrations in the shell that are ~50% of the values that are typically observed in meteoric East Antarctic ice ([H⁺] = 0.5 uM, [Cl⁻] = 1 uM).

Decreasing grain size (d), increasing convection →



60 dB is a nominal dynamic range for an orbital radar around Europa

What's next?

Measurements at lower and higher temperatures. Temperatures lower than −90°C are challenging to maintain stably with our measurement apparatus, because they require LN2 cooling. We have already performed **initial measurements at temperatures as low as 114 K (−159°C)**. More are forthcoming. We are also in negotiations to acquire and measure marine ice from East Antarctica.

Our intial measurements have also definitively shown that **measurements at temperatures greater than ~ −20°C are a one-way street**. Above −20°C, the ice begins to anneal away its lattice defects, permanently altering its dielectric character. After these higher temperature measurements, we will melt the ice and measure its soluble impurity concentrations.

We will **incorporate our improved estimates of the key parameters in the radio-frequency dielectric model of ice into our Europan radar-attenuation models**. Because of engineering requirements, the shell's dielectric character must be reasonably constrained prior to launch.

Acknowledgments

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