Understanding ANITA's Mystery Events with Time-Domain Electrodynamics Simulations

Daniel Smith on behalf of the Vieregg Lab / ANITA Collaboration
UChicago / KICP, danielsmith@uchicago.edu

Abstract

The Antarctic Impulse Transient Antenna (ANITA) experiment, an ultra high-energy neutrino experiment, has observed two events that appear to have originate from a particle coming up from the earth at an improbable angle [1]. To date, there is no confirmed explanation for these events. I use electrodynamics simulations to explore one potential benign explanation, that rough ice distort reflected signals from cosmic rays (CRs) to make them appear as if the signal came from a particle that passed through the earth.

Introduction: The Problem

ANITA is a balloon-borne radio detector used to search for the impulse signals produced by high energy particles that interact in and above the ice of Antarctica. In the energy scale of interest (EeV), interacting particles produce an extensive air shower (EAS) of secondary charged particles that emit an impulse radio signal [2]. The polarity of the signal is determined by the path taken by the radio to arrive at ANITA: signals that reflect off the ice before arriving to ANITA have a flipped phase. This allows for the separation of two types of signal: CRs that come down towards the ice and τ neutrinos that come up from the ice.

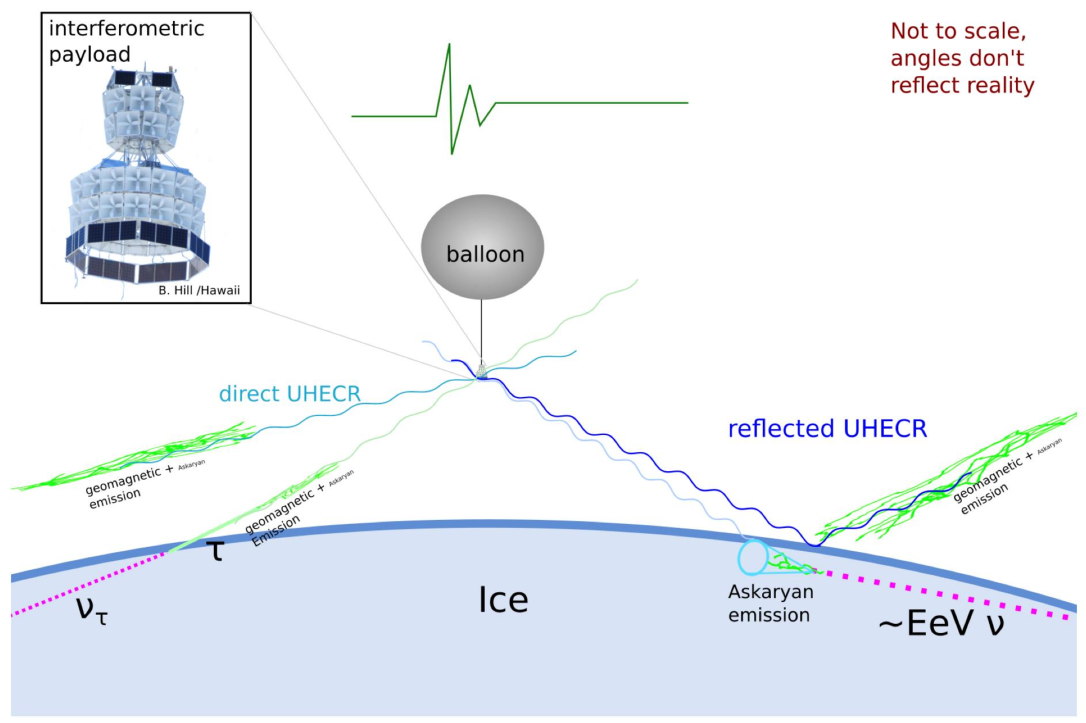

Fig 1. ANITA above the Antarctic Ice sheet with the various signal producing processes

ANITA has observed two events with signals that suggest that they were produced by an upward-going EAS at 35° and 27° below the horizon. A τ neutrino is unlikely to have produced these signals because the neutrino would have interacted in the earth before exiting. These "mystery events" have no confirmed explanation of their origin. One hypothesis is that the surface of the ice may have small-scale features that can distort the signal produced by a downward going CR to make the signal appear as if it has a direct polarity [3]. The goal of this work is to investigate this using time-domain electromagnetic simulation software.

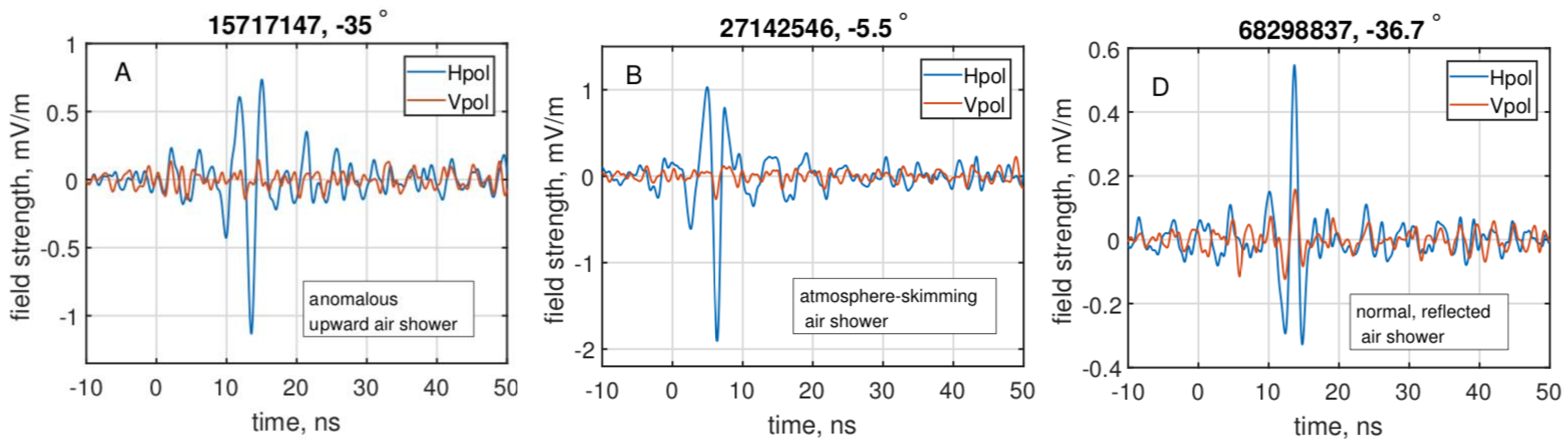

Fig 2. Three events from ANITA. Left: The mystery event, polarity consistent with direct event.
Middle: Direct CR event, polarity of direct event. Right: Reflected CR event, polarity of reflected event. [1].

Introduction: FDTD & MEEP

For this analysis, I use finite-difference time-domain (FDTD) electromagnetics simulation software. The software numerically solves Maxwell's equations,

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} - \sigma_B \vec{B} \qquad \epsilon \frac{\partial \vec{E}}{\partial t} = \frac{1}{\mu} \nabla \times \vec{B} - \vec{J} - \epsilon \sigma_E \vec{E}$$

The differential operators are solved using the numerical central-difference approximation on an even spatial and temporal grid, called the Yee lattice [4]. The even grid spacing is required to maintain the correct time dependency of the fields. The FDTD method is computationally expensive, scaling as $n^{(D+1)}$ for grid size of n. For this reason, simulation is nearly impossible in 3D and all the following work is using 2D spatial simulations. I use the open-source FDTD software package MEEP [4].

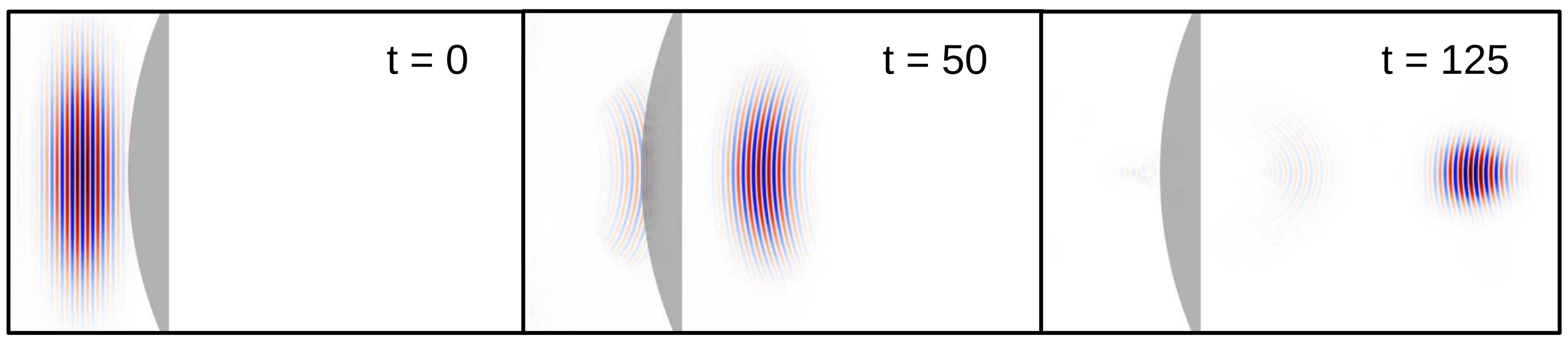

Fig 3. An example simulation in MEEP of a gaussian-enveloped plane wave passing through a plano-convex lens.
The different frames show the pulse traveling through space and becoming focused.

Simulation Setup

The relatively small wavelength and large distances means that the FDTD simulation can only be done in a localized area near to the reflection point with the remaining propagation done using the Green's function for EM propagation through a homogenous media [4]. ZHAireS was used to simulate the original pulse produced by the EAS [5]. The ice surface is made of dielectric triangles with random positions and heights to match surface altimeter data of a typical Antarctic surface [6]. The surface is tilted to minimize the total simulation size while maximizing the surface length. The final simulation size is 800x1000 at a resolution of 15 sim steps / ns, corresponding to a box size of ~240 x 300 m. A single simulation takes ~7 hrs on 28 MPI tasks.

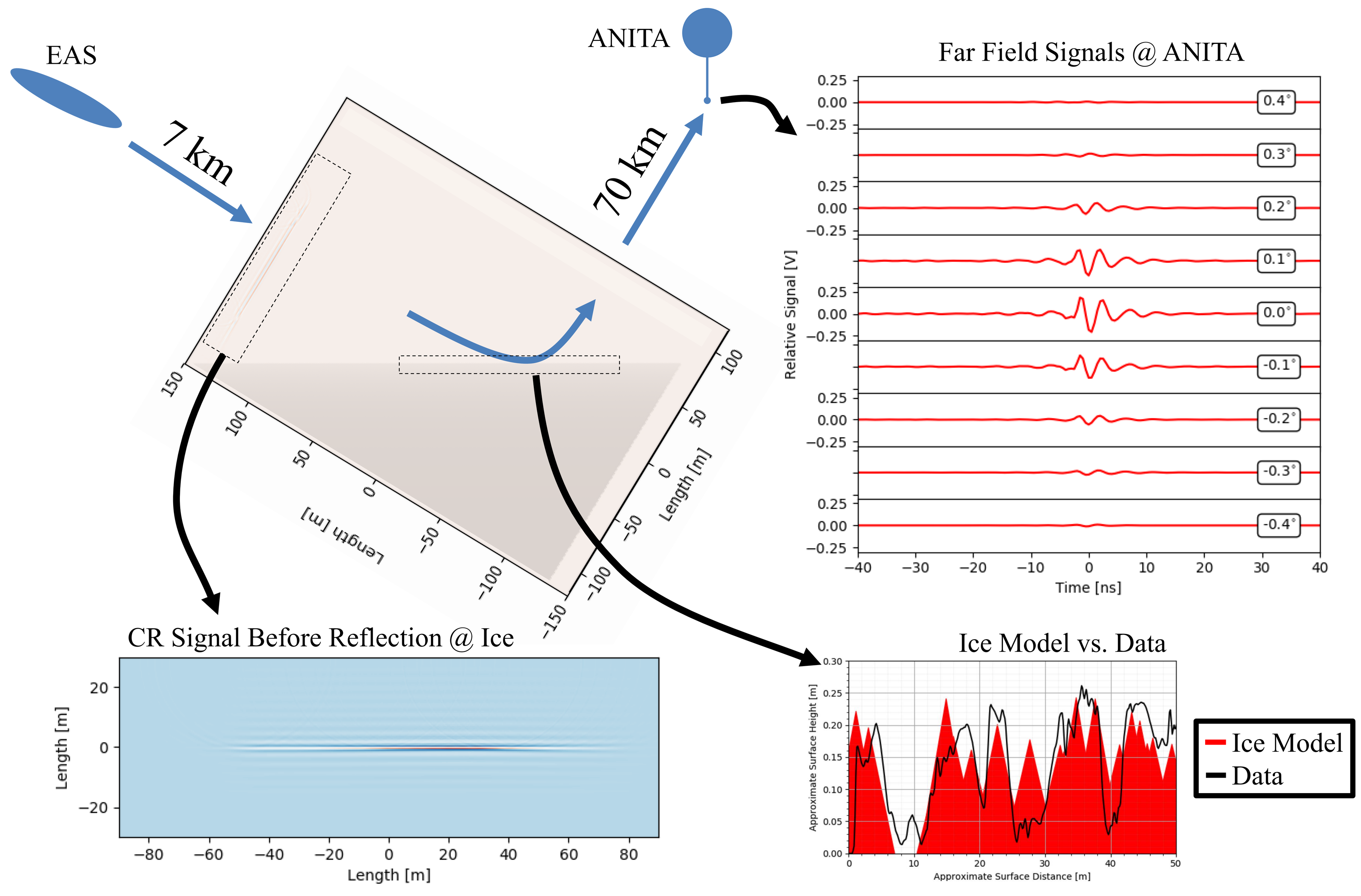

Fig 4. Diagram of the Simulation. Top Left, a cartoon with an image from MEEP of the simulation at t=0.
Top Right: Traces as they appear after being transformed into the far field.
Bottom left: E-Field of CR at the ice. Bottom Right: The Ice model compared against data.

A 3D reflection is emulated from 10 separate 2D simulations with a parameterized ice surface to allow for correlated ice structure. The resulting signals are summed after applying a phase shift from the extra propagation distance. One fully simulated event costs ~3500 SU.

Preliminary Results & Future Work

In ANITA, after quality cuts, events are primary determined as CR-like via a correlation against a template, labeling events with a maximum cross-correlation coefficient above 0.7 as signal-like and below 0.7 as sideband, or a region of phase space that should be empty after quality cuts. For the rough ice hypothesis to be realistic, it must change polarity of signals without creating significant contributions to the sideband. Signal polarity is determined by the "Peak-to-Sidelobe" metric, the ratio of the maximum and minimum correlation between the signal and a template.

Preliminary results, shown in Fig. 5, show that, at wider cone angles, the rough ice can flip signal polarity. The probability that the mystery events can be attributed to ice roughness is on-going work. To calculate the final probability, cone-angle distributions must be simulated and folded into the results shown.

Future work of this analysis include confirming the accuracy of the assumptions made in simulation that were made due to computational constraints. As well, with the FDTD framework, I plan to study other ice-related hypotheses, including ice caves, higher-density ice layers beneath the snow surface, and large-scale structures such as dunes.

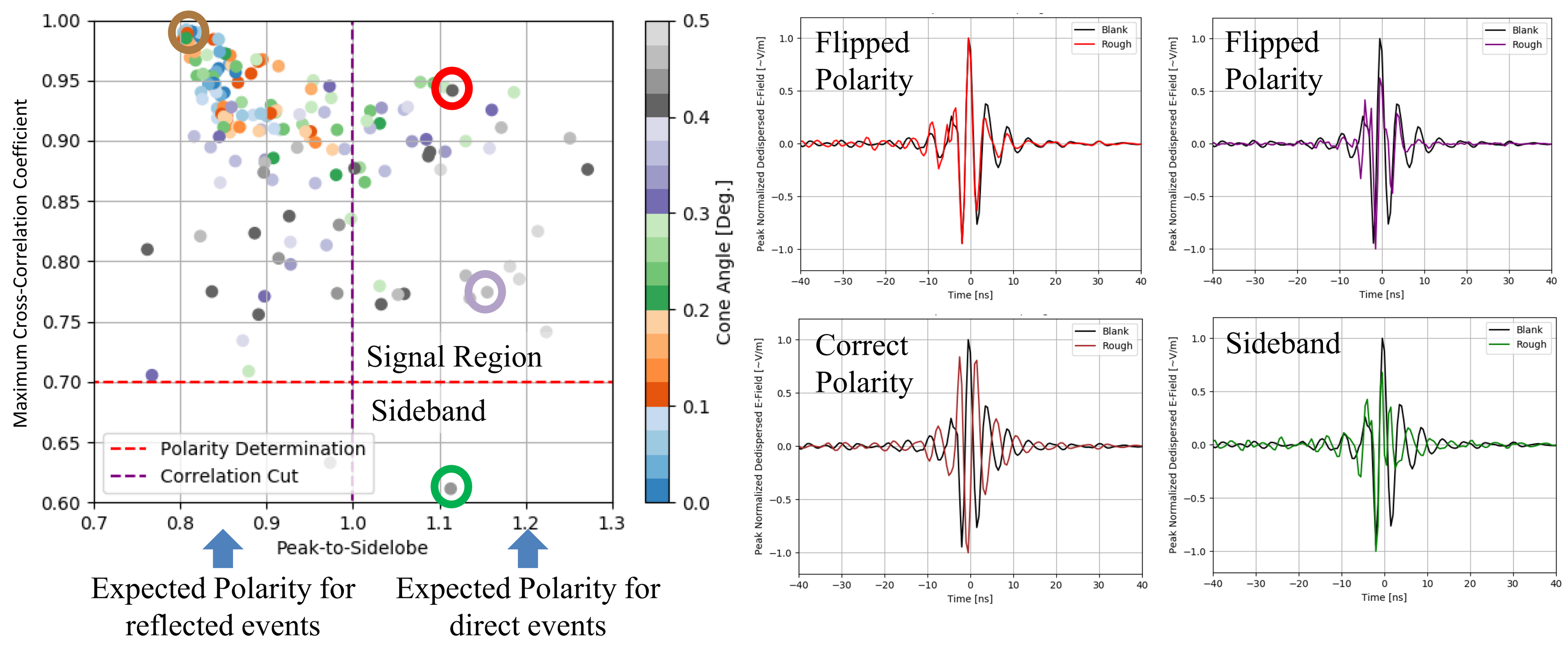

Fig 5. Left: Distribution of events as a function of maximum cross-correlation coefficient, peak-to-sidelobe and cone angle.
The various signal regions and sideband regions are labeled.
Right: Four sample traces corresponding in color to points circled on left plot, plotted with the template used.

References:
[1] P. Gorham, *et al.,* "Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANITA", Phys. Rev. Lett. 121, 161102 (2018).
[2] D. Saltzberg, P. Gorham, D. Walz, *et al.,* "Observation of the Askaryan Effect: Coherent Microwave Cherenkov Emission from Charge Asymmetry in High Energy Particle Cascades," Phys. Rev. Lett., 86, 2802 (2001).
[3] I. Shoemaker, *et al.,* "Reflections On the Anomalous ANITA Events: The Antarctic Subsurface as a Possible Explanation", arXiv:1905.02846 (2019).
[4] A. Oskooi, *et al.,* "MEEP: A flexible free-software package for electromagnetic simulations by the FDTD method", Computer Physics Communications, Vol. 181, pp. 687-702, (2010).
[5] J. Alvarez-Muñiz, *et al.,* "Monte Carlo simulations of radio pulses in atmospheric showers using ZHAireS", 10.1016/j.astropartphys.2011.10.005 (2012).
[6] Filhol, S., and M. Sturm, "Snow bedforms: A review, new data, and a formation model", J. Geophys. Res. Earth Surf., 120 (2015).

THE UNIVERSITY OF CHICAGO
Research Computing Center