Far Zone Gain of the ARA Bicone in an Ice Shell

Alan Salcedo Gomez

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1 Introduction

The Genetically Evolved NEutrino Telescopes for Improved Sensitivity (GENETIS) project aims to optimize detector design for science outcomes in physics. GENETIS uses a genetic algorithm to evolve the physical parameters (or genes) that define an antenna. Currently, GENETIS evolves bicone antennas to optimize ultra-high energy (UHE) neutrino detection for the Askaryan Radio Array (ARA) experiment at the South Pole. The genetic algorithm creates a generation of individuals whose performance is measured by a fitness score. The individuals are ranked according to that fitness score and selected for breading of the next generation. This process is iterated until the average fitness score of a generation plateaus.

2 Fitness Calculation

The description in this section comes from [Rolla et al., 2021].

The first step in evaluating the fitness of an individual is to model its geometry in XFdtd. XFdtd simulates the antenna response at 60 different frequencies (equal steps from approximately 100 MHz to 1000 MHz) at each azimuth-zenith coordinate (in steps of 5°). An antenna's gain is a measure of how efficiently it converts received radio waves into input power. XFdtd calculates the far-zone gain of an antenna at a specific (θ, ϕ) coordinate by Eq. 1:

$$G = \frac{2\pi r^2 |\tilde{E}(\theta, \phi)|^2}{\eta P_0} \tag{1}$$

G is the absolute far-zone gain of the antenna in a specific direction. $\widetilde{E}(\theta, \phi)$ gives the complex electric field incident on the antenna from the (θ, ϕ) direction, η is the wave impedance in the medium (377 Ω in free space), r is the distance between the power source and the sensors in the simulation (1 m), and P_0 is the power accepted by the antenna.

For the second step in calculating the fitness score, a neutrino detection simulation program called AraSim is used to measure the performance of the antenna. AraSim simulates high-energy neutrino interactions in the Antarctic ice that produce electromagnetic and hadronic showers resulting in the production of Askaryan radiation [Allison et al., 2015]. AraSim uniformly distributes these interactions within a cylindrical volume with a 3 km radius centered around the detector. The direction of the incoming neutrino is randomly distributed over a solid angle of 4π. The radio emission propagation is modeled using ray-tracing. The ray-tracing models the depth-dependent index of refraction of the ice, which is n=1.35 at the surface to n=1.78 at 200 m deep.

GENETIS determines an individual's fitness score with AraSim by setting the response of the bicone antennas to the individual's response generated by XFdtd for each of the 60 frequencies simulated. The sensitivity produced by AraSim, known as the effective volume, is used as the individual antenna's fitness score. The effective volume $[V\Omega]_{\text{eff}}$ is given by:

$$\text{Fitness Score} = [\text{V}\Omega]_{\text{eff}} \;=\; 4\pi\ \text{V}_{\text{ice}}\ \frac{\text{N}_{\text{detected}}}{\text{N}_{\text{simulated}}} \tag{2}$$

where V_{ice} is the total volume of ice simulated in AraSim, N_{detected} is the total number of neutrinos detected, and $N_{\text{simulated}}$ is the total number of neutrinos simulated.

3 ARA Bicone Geometry in XFdtd

In ARA bicone simulations, the antenna is submerged in a column of ice with dimensions $\Delta x =$ 4000 mm, $\Delta y = 1500$ mm, $\Delta z = 1500$ mm as shown in Fig. 1

The antenna is 600 mm long and has a diameter of 150 mm. The largest dimension of the ice is about 7 times larger than the antenna's length. Ideally, we want the ice to surround the antenna for distances of about 10 times of its largest dimension, in this case its length. In addition, the ARA bicone has a bandwidth of $150 - 850$ MHz. Using an index of refraction of $n = 1.5$ for ice.

The largest wavelength of interest is about 1.3 m. Thus, we want the antenna to be centered in an ice column with a radius of 13 m for $\lambda_{largest}/r \approx 1/10$, where r is the distance to the source. Finally, because the ARA bicone is located in a borehole with a diameter of 150 mm at the South Pole, we want to turn the ice column in XFdtd into a shell with a column of air at its center having

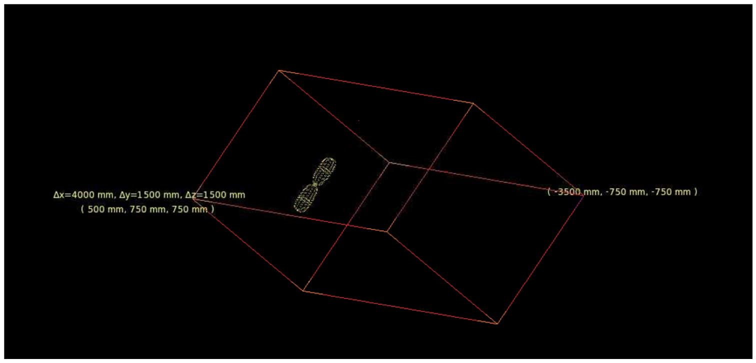

Figure 1: ARA bicone submerged in a column of ice.

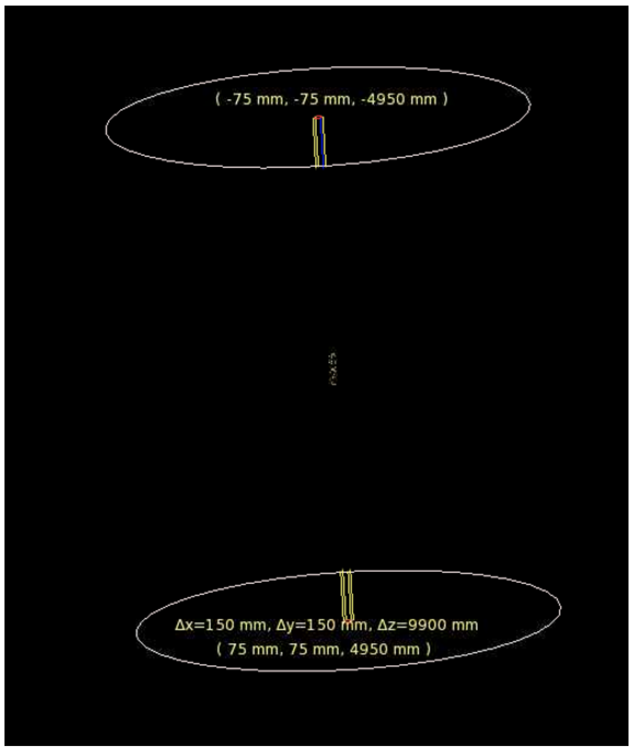

Figure 2: ARA bicone in a column of air surrounded by an ice shell.

the same the diameter as the borehole, as shown in Fig. 2

4 Gain Patterns in Ice Shells

4.1 Showing Azimuthal Symmetry

The gain of an antenna at a (θ, ϕ) coordinate is calculated using XFdtd. The geometry of the ARA bicone in an ice shell shows azimuthal symmetry. Due to this, we expect the gain patterns to also show this symmetry. We verify this by calculating the gain of the antenna with a frequency of

200 MHz in shells with radii of 5 m, 6 m, and 7 m at $\phi = 0°, 45°$. The results are shown in Fig. 3.

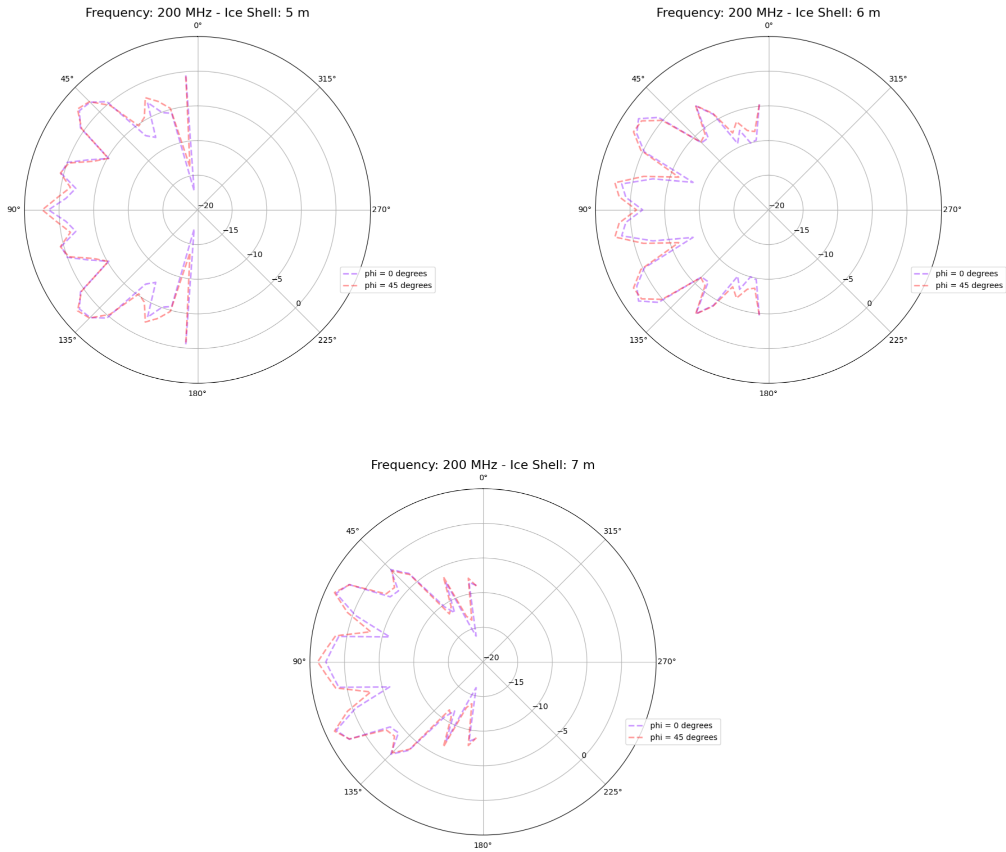

Figure 3: Gain comparison at azimuthal angles $\phi = 0°, 45°$.

The corresponding difference in gain for each figure at different angles (in steps of 5° starting from 0○) are shown in Fig. 4.

Differences in gain are up to 3.5 dBi in magnitude. These differences in gain could be explained by an asymmetric simulation grid around the antenna.

4.2 Radii dependence

The time of simulation in XFdtd to calculate the antenna's gain depends on the volume of the simulation and the grid size. The antenna is located at the center in an ice shell of 9.9 m high. Thus, its radius defines the simulation volume, assuming a constant grid size (1/10 of the shortest wavelengths of interest. For a frequency of 150 MHz and $n = 1.5$ the grid size is about 2.4 cm). For shells with radii from 1 m to 13 m in steps of 1 m, the simulation time is shown in Tab. 1.

Due to the increase of simulation time with radii, I want to find the minimum radius that makes

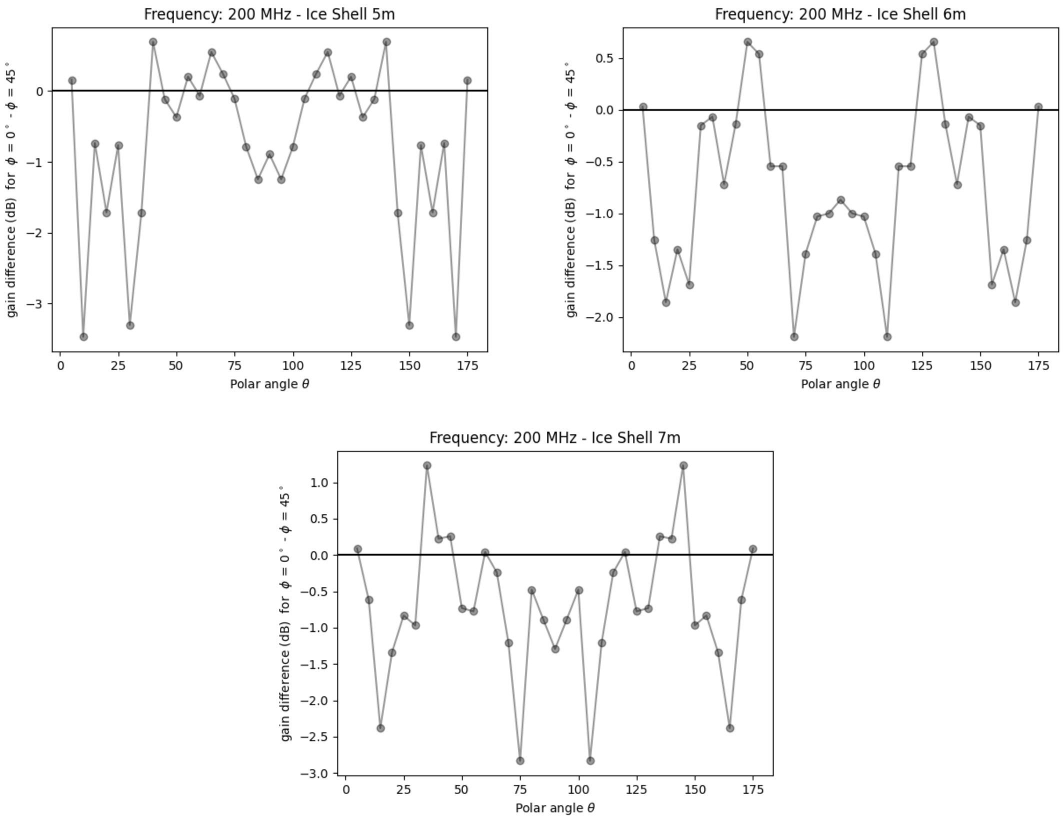

Figure 4: Gain difference at azimuthal angles $\phi = 0°, 45°$.

gain patterns converge to minimize computation time. In Fig. 5 and 6, I show the gain patterns for the bicone antenna in ice shells of radii ranging from 1 m to 13 m in steps of 1 m and under electromagnetic radiation of 200 MHz.

We expect the gain patterns to reach the convergence (20 dBi in this case) value at $\theta = 0°, 180°$. As seen from Fig. 6 this starts to happen at a radius of 10 m. For larger radii, subsequent gain patterns starts showing less differences.

4.3 Effects of the Ice Shell

In this section, I will compare gain patterns of three different configurations of the ARA bicone: in an ice column, in an ice shell, and in air. For a radius of 7 m and radiation of frequency 200 MHz, the gain patterns of the three cases are shown in Fig. 7.

Here, we see that having ice surrounding the antenna changes the gain pattern and, at least at 200 MHz, turning the ice column into a shell makes no difference. Nonetheless, at higher frequencies (shorter wavelengths) we expect differences. In Fig. 8 I show similar gain patterns for a frequency

Radius (m)	Time (hrs)
1	0.067
2	0.15
3	0.3
4	0.62
5	0.8
5	0.8
6	1.22
7	2
8	2.03
9	2.28
10	2.93
11	3.67
12	4.5
13	5.53

Table 1: XFdtd simulation time (in hrs) for the ARA bicone in ice shells of increasing radii.

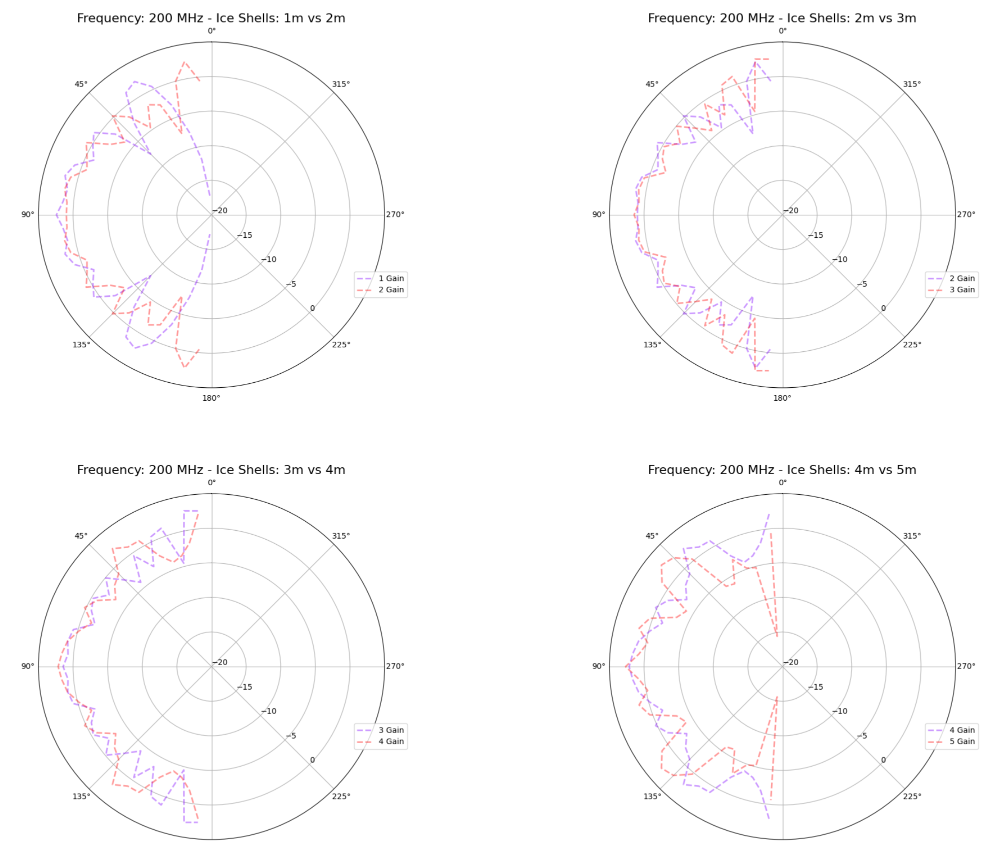

Figure 5: Comparison of gain patterns for the ARA bicone in ice shells of increasing radii.

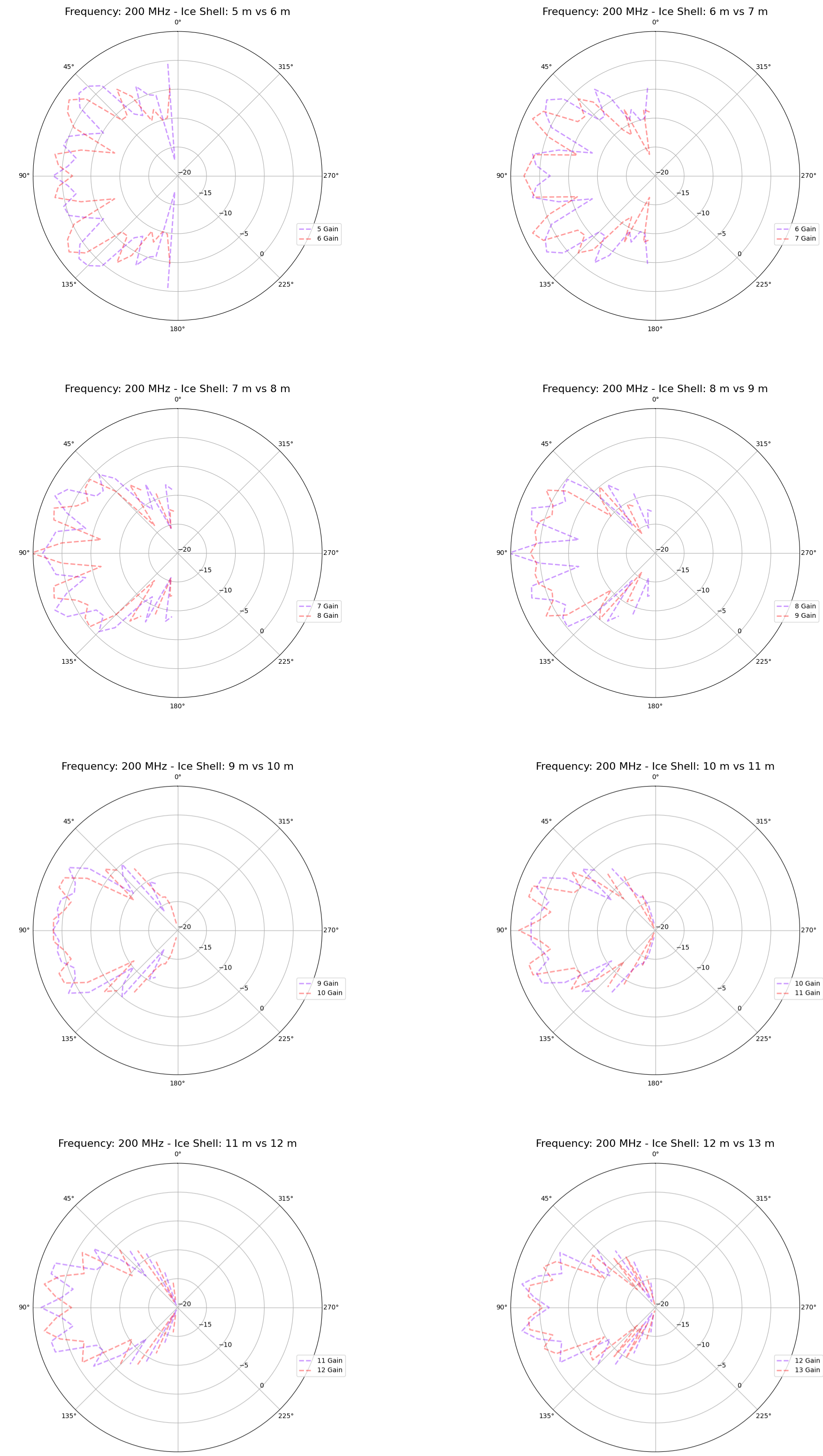

Figure 6: Comparison of gain patterns for the ARA bicone in ice shells of increasing radii.

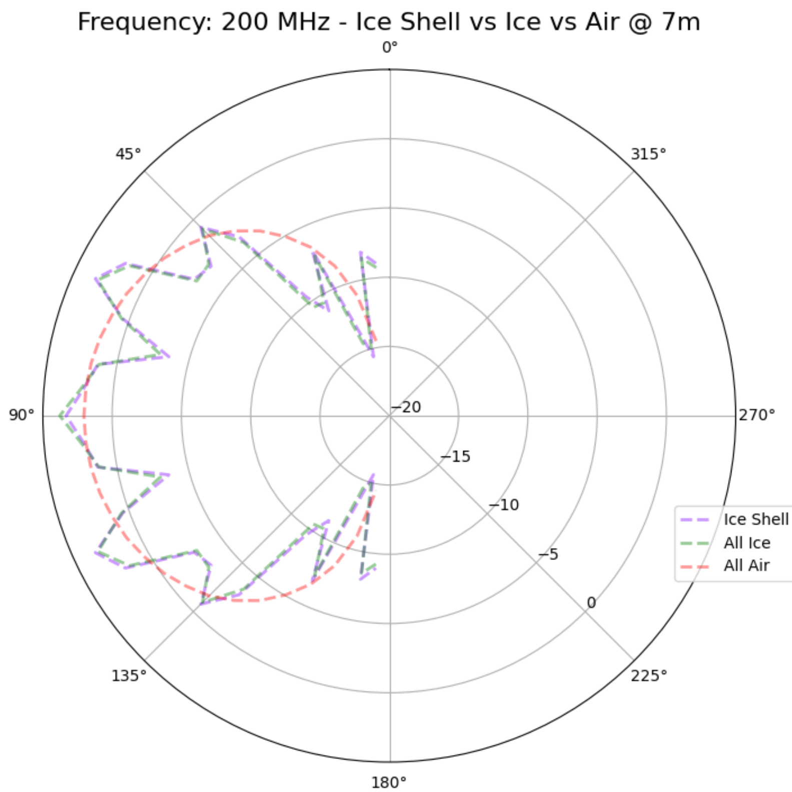

Figure 7: Comparison of gain patterns in an ice cylinder (radius of 7 m), an ice shell (radius of 7 m), and air with EM radiation of 200 MHz.

of 800 MHz where we see the difference on having an ice shell instead of an ice column.

Similar results are shown in Fig. 9, but only comparing gain patterns for the ARA bicone in air and an ice shell of 10 m.

4.4 Gain Patterns for Radii above 10 m

Here, I just show gain patterns for ice shells of radii above 10 m for frequencies of 800 MHz and 200 MHz.

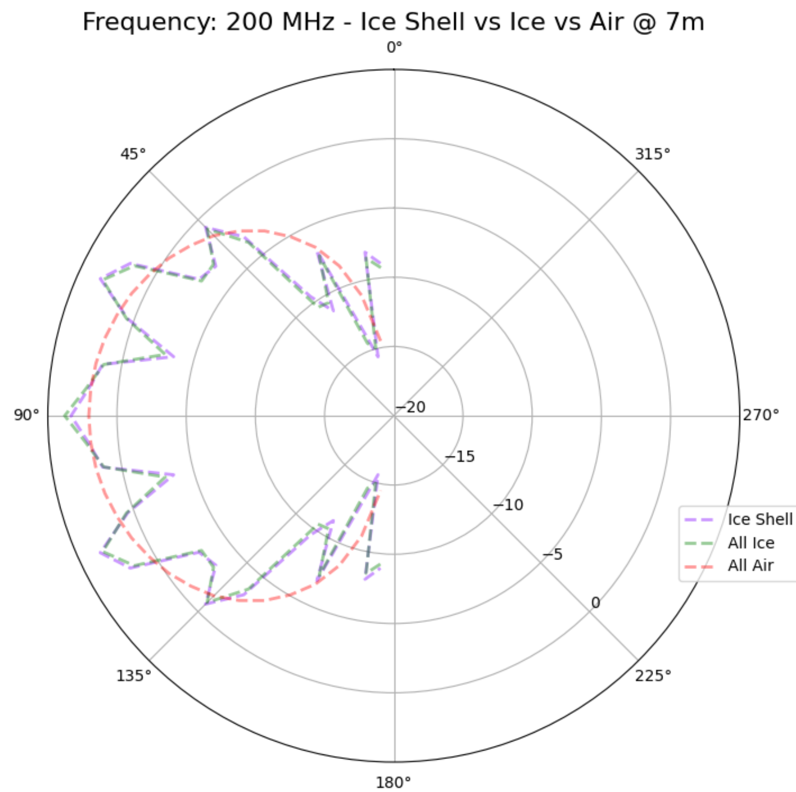

Figure 8: Comparison of gain patterns in an ice cylinder (radius of 7 m), an ice shell (radius of 7 m), and air with EM radiation of 800 MHz.

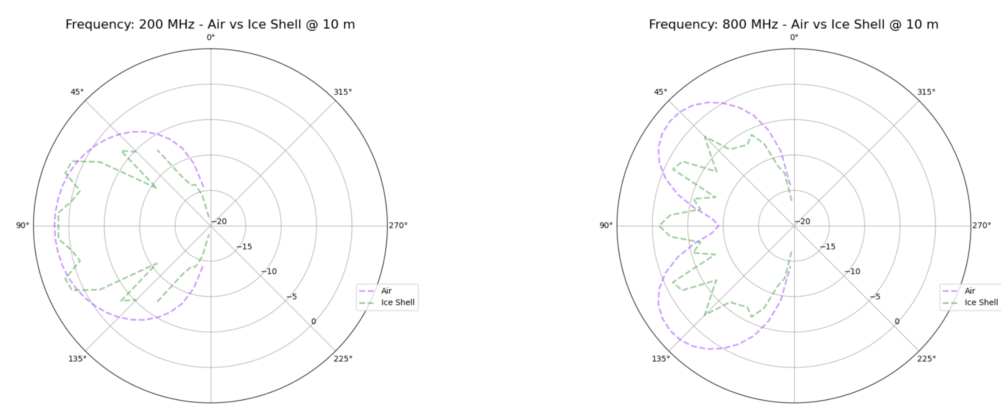

Figure 9: Comparison of gain patterns in an ice shell (radius of 10 m), and air with EM radiation of 200 MHz (Left) and 800 MHz (Right).

5 Work in Progress

5.1 ARA Bicone in Deep Ice

Up to now, all XFdtd simulations were done using an index of refraction of $n = 1.5$ for ice. However, it is known that for deep Antarctic ice, where the ARA bicone is located, the index of refraction

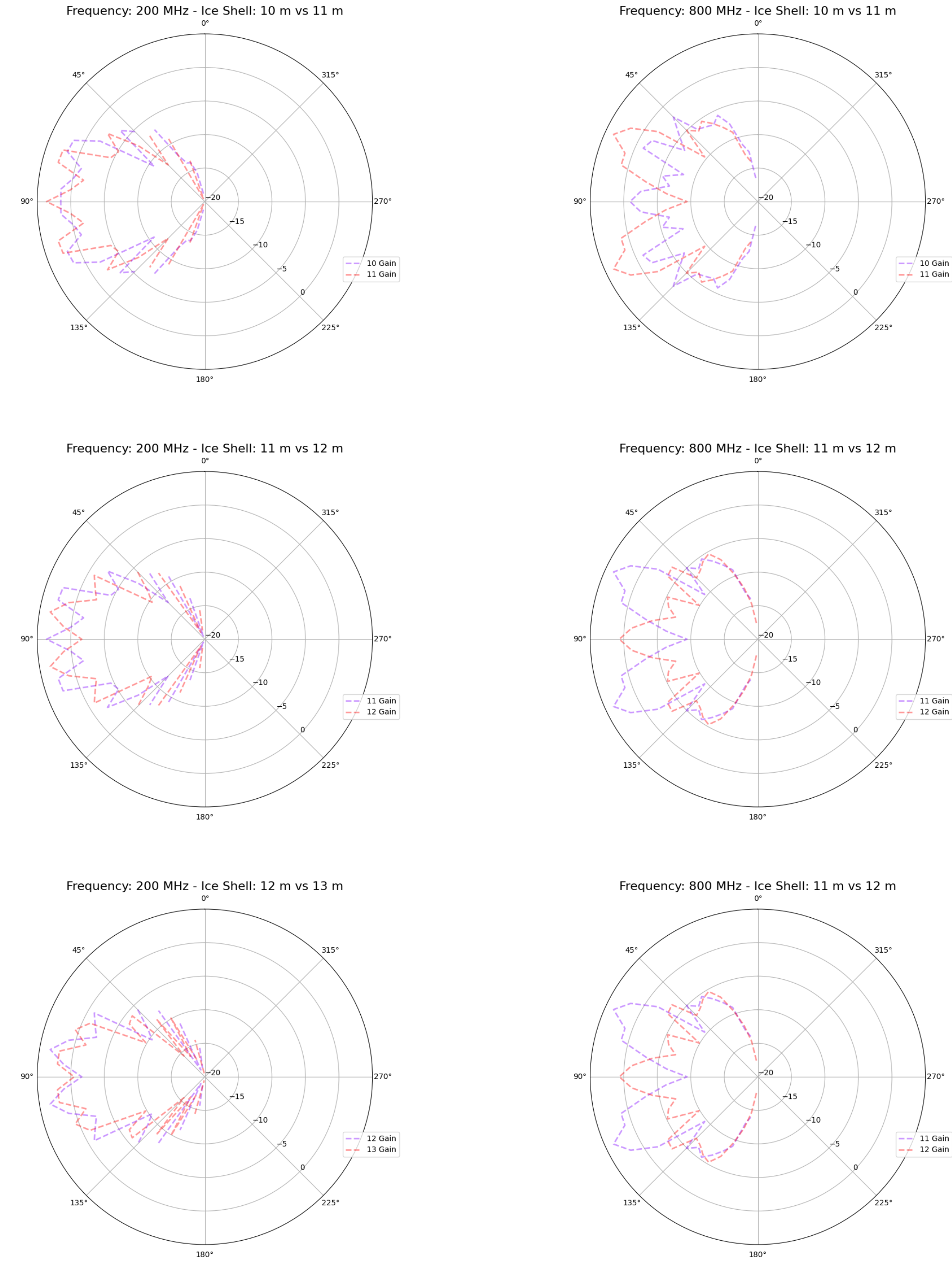

Figure 10: Gain patterns for the ARA bicone in ice shells of radii of $10 - 13\,\text{m}$ at frequencies of 200 MHz and 800 MHz.

approaches a value of $n = 1.78$. When changing the index of refraction, the grid size changes according to $\lambda_{shortest}/10 =$ cell size. This causes computation time to increase. For example, the gain patterns for a shell with radius of 5 m shown in Fig. 11 took 2 hours and 26 minutes to converge. This is about twice as much time as it would take with $n = 1.5$.

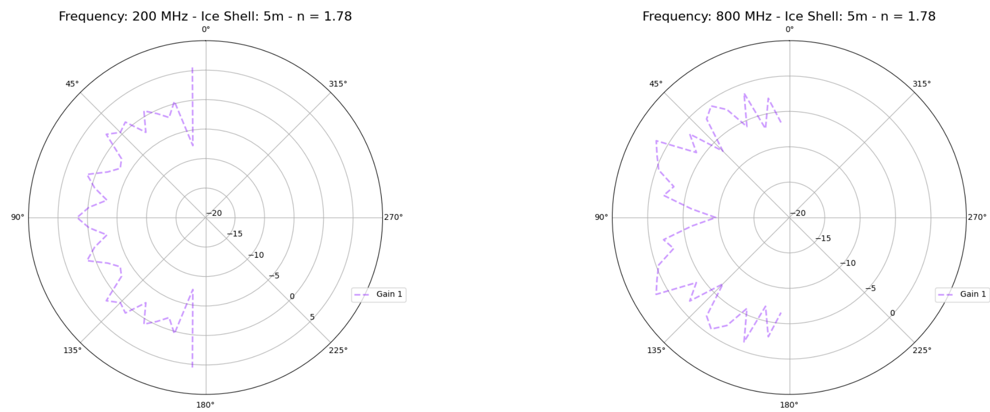

Figure 11: Comparison of gain patterns in an ice shell (radius of 5 m) with index of refraction $n = 1/78$ and EM radiation of 200 MHz (Left) and 800 MHz (Right).

5.2 Voltage Standing Wave Ratio

The Voltage Standing Wave Ratio (VSWR) is a measure that numerically describes how well the antenna is impedance matched to the radio or transmission line it is connected to. VSWR is a function of the reflection coefficient, which describes the power reflected from the antenna. If the reflection coefficient is given by Γ or reflection coefficient or return loss, then the VSWR is defined by the following formu la:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \tag{3}$$

The smaller the VSWR is, the better the antenna is matched to the transmission line and the more power is delivered to the antenna. The minimum VSWR is 1.0. In this case, no power is reflected from the antenna, which is ideal.

Calculations of VSWR for the ARA bicone in shells with a radius of 5 m and 7 m and $n = 1.5$ as a fuction of frequency are shown in Fig. 12.

I also compare the VSWR for $n = 1.5$ and $n = 1.78$ at a constant radius of 5 m, as shown in Fig. 13

We only see a noticeable difference in VSWR when varying the index of refraction.

5.3 E-Field in the Time Domain

I made some calculations of the electric field in the time domain which I show in Fig. 14. For the future, **I will want to locate the position of the sensor close to the antenna**. Since we use

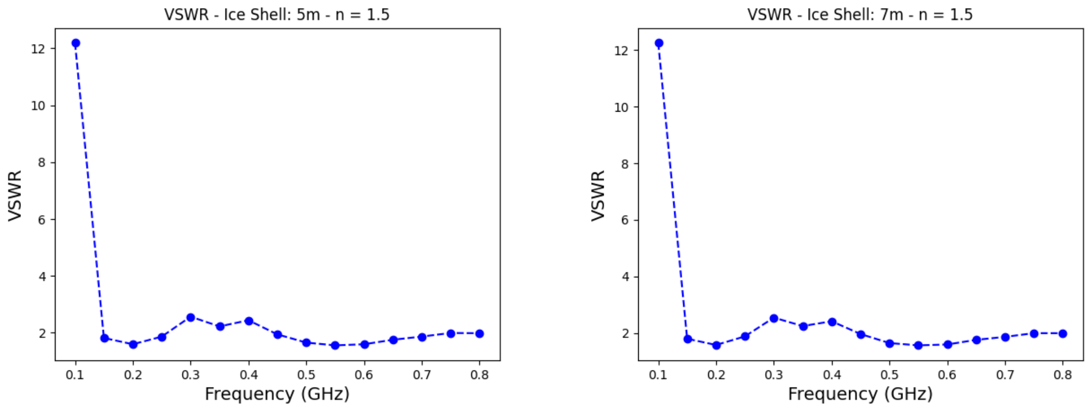

Figure 12: VSWR for the ARA bicone in ice shells with 5 m and 7 m and $n = 1.5$

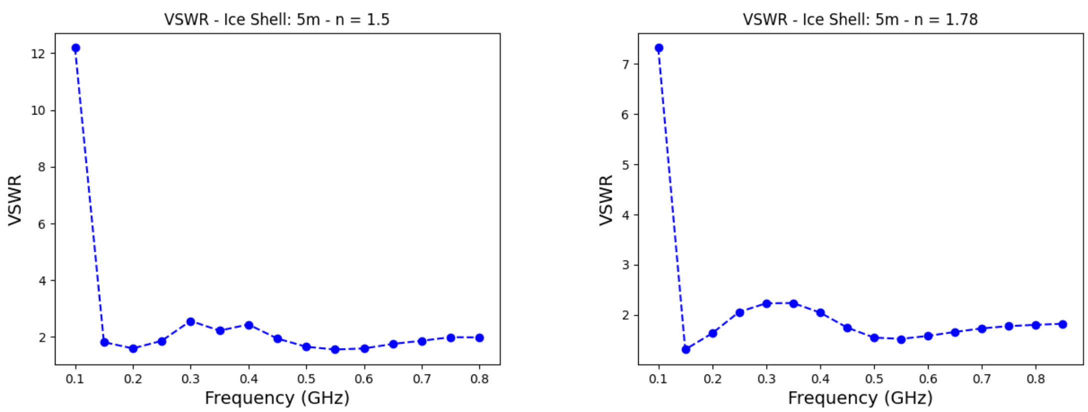

Figure 13: VSWR for the ARA bicone in ice shells with $n = 1.5$ and $n = 1.78$ with a radius of 5 m.

the antenna as a receiver, we would like to know what the antenna reads at the borehole. Right now, the sensor is at another location that I am not sure why it had been selected.

Figure 14: E-Field vs Time with 8m radius shell.

5.4 Implementation in the GENETIS Loop

I did this work through the XFdtd interface. As I intend to make XFdtd simulations of bicone antennas inside ice shells part of the GENETIS algorithm, I need to script on XF all the work that I did through the interface. Roughly, a list of the tasks to do goes as follows: (1) define Antarctic ice material, (2) create a shell with radius of 10 m, (3) run simulation, (4) get gain files. At this point, **I need to review my script and see where I left this.**

The code below is a copy of my additions to the *.xmacro* document that was being used to create the geometry of the bicone antennas in XF. It simply creates a shell of ice surrounding the bicone antenna and assigns a material to it. In this case, I had to define a new material called *Antarctic Ice* with its electric, magnetic, and physical properties.

As you can see, once the code is done, it may not be that hard to understand. Unfortunately, the documentation of XF is not that clear so you are mainly guided by script examples and intuition. You can access XF scripting documentation on the XF interface by going to **Help** > **Scripting API Documentation**. I have the full *.xmacro* file but it's currently being added to the GENETIS loop by Alex Machtay and I.

```
// Added by Alan //////////////////////////////////////////////////////////////

function CreateShell()
{
var shell_radius = 10;
var shell_height = 10;

    // First we create a circular base with radius of 7.5 cm
    var circle = new Sketch();
   var base1 = new Ellipse( new Cartesian3D(0,0,-1*shell_height/2 + " m"), new
       Cartesian3D(7.5 + " cm",0, -1*shell_height/2 + " m"), 1.0, 0.0, Math.PI*2 );
   circle.addEdge(base1);

    // Next we define an extrude to be applied to the circular base with the desired
        height of the shell. This creates a column with a circular base
    var extrude = new Extrude( circle, shell_height + " m" );
```

```
   // Then add a shell with a given radius to the column. The shell should go from the
       start to the end of the extrude
   var shell = new Shell(shell_radius + " m",
       ["face:Extrude(end)","face:Extrude(start)"])

    // And we create a recipe for building our shell
    var recipe = new Recipe();
    recipe.append( extrude );
   recipe.append( shell );
    var ice_shell = new Model();
    ice_shell.setRecipe(recipe);
    ice_shell.name = "Ice Shell";
    var ice_shell_InProject = App.getActiveProject().getGeometryAssembly().append(
        ice_shell );

    // Now we can assign a material to the shell:
    var ice_shell_Material = App.getActiveProject().getMaterialList().getMaterial(
        "Antarctic Ice" );
    if( null == ice_shell_Material )
    {
        Output.println( "\"Substrate\" material was not found, could not associate with
            the ice shell." );
    }
    else
    {
        App.getActiveProject().setMaterial( ice_shell_InProject, ice_shell_Material );
    }

}

function CreateIce() // Material for the surrounding shell
{
   var ice = new Material();
   ice.name = "Antarctic Ice";

    eiIndex = new ElectricIsotropic();                       //  Create new
```

```
    ElectricIsotropic for material's electric default property
 eIR = new ElectricIndexOfRefractionParameters();
eIR.setConductivity( 0 );
eIR.setIndexOfRefraction( 1.5 );
eiIndex.setParameters( eIR );

mFree = new MagneticFreespace();                       //  Create new MagneticIsotropic
   for material's magnetic default property

 physmat = new PhysicalMaterial();
 physmat.setElectricProperties( eiIndex );              //  Set default
    ElectricProperty
 physmat.setMagneticProperties( mFree );               //  Set default MagneticProperty
 ice.setDetails( physmat );



physparams = new PhysicalParameters();
 physparams.setDensity( "1000 kg/m^3" );
 physparams.setHeatCapacity( 0 );
 physparams.setThermalConductivity( 0 );
 physparams.setPerfusionByBlood( 0 );
 physparams.setMetabolicHeat( 0 );

 ice.setPhysicalDetails( physparams );

var iceBodyAppearance = ice.getAppearance();
 var iceFaceAppearance = iceBodyAppearance.getFaceAppearance(); // The "face"
    appearance is the color/style associated with the surface of geometry objects
    iceFaceAppearance.setColor( new Color( 20, 245, 245, 50 ) ); // Set the surface
        color to white. (255 is the maximum intensity, these are in order R,G,B,A).

 // Check for an existing material
 if( null != App.getActiveProject().getMaterialList().getMaterial( ice.name ) )
 {
        App.getActiveProject().getMaterialList().removeMaterial( ice.name );
```

```
    }
       App.getActiveProject().getMaterialList().addMaterial( ice );



}

////////////////////////////////////////////////////////////////////////////////
```

References

[Allison et al., 2015] Allison, P. et al. (2015). First Constraints on the Ultra-High Energy Neutrino Flux from a Prototype Station of the Askaryan Radio Array. *Astropart. Phys. J.* The AraSim repository can be found at https://github.com/ara-software/AraSim.

[Rolla et al., 2021] Rolla, J., Machtay, A., Patton, A., Banzhaf, W., Connolly, A., Debolt, R., Deer, L., Fahimi, E., Ferstle, E., Kuzma, P., Pfendner, C., Sipe, B., Staats, K., and Wissel, S. A. (2021). Using evolutionary algorithms to design antennas with greater sensitivity to ultra high energy neutrinos.