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Using Genetic Algorithms to Optimize Antenna Designs for Improved Sensitivity to Ultra-High Energy Neutrinos

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Genetic algorithms (GAs) are a type of computational optimization algorithms that emulate natural selection to “evolve" candidate solutions to a given problem. The GENETIS collaboration applies GAs to experimental design to efficiently optimize for improved performance. To this end, GENETIS has begun by designing GAs for the evolution of vertically polarized (VPol) antennas used in ultra-high energy (UHE) neutrino observatories. Due to the low flux of UHE neutrinos, as well as their small cross sections, it is essential to maximize the sensitivity of neutrino observatories at every step of the experiment. Neutrino observatories make use of radio signals produced by UHE neutrino interactions by observing large volumes of ice. The Askaryan Radio Array (ARA) achieves this by distributing stations of antennas across vast areas near the South Pole. Experiments like ARA measure their expected performance using simulation software that incorporates properties of the experiment and the physics of neutrino interactions in ice. The Physical Antenna Evolutionary Algorithm (PAEA) evolves the geometric properties of antennas within the physical constraints of specific UHE neutrino experiments and simulates their responses using EM simulation software XFdtd. To measure the performance of antenna designs, PAEA uses neutrino observatories' simulation software with the evolved antennas' responses included. This proceeding will discuss GENETIS' evolution of VPol antenna designs for ARA and upcoming work on evolving more antenna designs for ARA and the Payload for Ultrahigh Energy Observations (PUEO). New efforts to capitalize on the birefringent properties of Antarctic ice to evolve experimental design will also be discussed.

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1. Introduction

Neutrino astrophysics is a field of multi-messenger astronomy that uses neutrinos to observe astronomical phenomena. Because photons can be easily attenuated, multi-messenger astronomy has emerged as a field focused on filling in the observational gaps using neutrinos and gravitational waves. At the highest energy scales ($\sim 10^{18}$ eV), Ultra-High Energy (UHE) neutrinos can allow us to observe distant phenomena that would otherwise not be visible using photons [1]. However, due to the small neutrino-nucleon interaction cross-section [2] and the low flux [3–7] of neutrinos at the UHE scale, vast volumes of ice must to instrumented with maximum sensitivity to be able to detect incoming neutrinos. Radio neutrino observatories, such as ARA [8], achieve this by observing cubic kilometers of Antarctic ice to detect Askaryan radiation produced by particle cascades from neutrinos interacting with the ice.

The GENETIS (Genetically Evolving NEutrIno teleScopes) collaboration seeks to assist in the detection of UHE neutrinos by optimizing the sensitivity of neutrino observatories using GAs. To this end, GENETIS has begun by developing the Physical Antenna Evolutionary Algorithm (PAEA) [9, 10], a GA designed to evolve the physical parameters of antennas used in radio neutrino observatories. To begin, the parameters for a vertically polarized (VPol) antenna were evolved for the ARA experiment. The performance of the experiment using these antennas was simulated using ARA's simulation software AraSim. These proceedings will provide background on GAs and the GENETIS workflow, report on the performance of the VPol evolution, and discuss current and future work generalizing PAEA to more antenna shapes.

2. Physical Antenna Evolution Algorithm

GENETIS' PAEA is a GA that uses the physical parameters of antennas as their genes and the result of simulations of UHE neutrino experiments using these antennas as the fitness function. To start, the GA generates individuals in the initial generation by selecting the values of genes from uniform distributions within permitted ranges. Limits are put on the genes based on geometric and computational constraints. After the initial generation, each new population is generated using selection and generating operators [11–15]. Examples of selection operators are roulette, tournament, and rank selection [16, 17] while examples of generating operators are crossover, mutation, and immigration [18, 19, 19–22].

After individuals are generated by the GA, PAEA feeds the values of the genes into XFdtd, an antenna simulation program produced by Remcom. XFdtd models the geometry of an antenna using its genes and calculates the antenna's response to EM radiation in a specified bandwidth. These responses are then passed into simulation software used by UHE neutrino experiments to evaluate their performance. These programs are Monte Carlo simulations of UHE neutrinos interacting in ice and the experiments designed to detect those interactions. One output from these simulations is the effective volume, a measure of the experiment's sensitivity. The effective volume is proportional to the number of detected events and is used directly as the fitness score in PAEA.

VPol Bicone Evolution

To begin, GENETIS evolved VPol antennas for the ARA experiment. ARA's VPol antennas are biconical birdcage antennas. These antennas are placed into holes drilled into Antarctic ice and therefore are limited in size to have a radius less than that of the holes, 7.5 cm [8]. We evolved basic asymmetric biconical antennas, with each cone defined by an inner radius, length, and opening angle. The cones were separated by 3 cm. Fig. 1 shows a basic drawing of an asymmetric bicone.

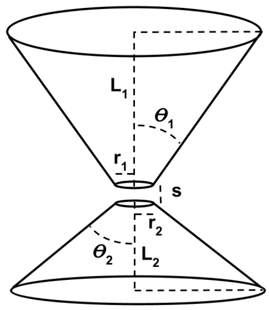

Figure 1: The geometry of an asymmetric bicone antenna. The lengths (L_1, L_2), inner radii (r_1, r_2), opening angles (θ_1, θ_2). The separation distance s was kept at 3 cm.

To match the physical restriction of the experiment, the evolved antennas were constrained so that the radius of each cone never exceeded 7.5 cm. This puts a direct constraint on the opening angle and the inner radius, while the length was restricted between 37.5 cm and 140 cm. We evolved 50 individuals per generation over 31 generations. The results of this evolution can be seen in Fig. 2 and are discussed in [23].

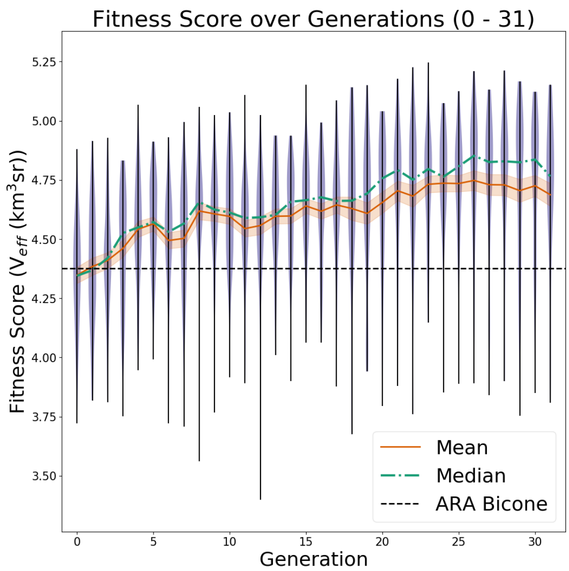

Figure 2: A plot showing the evolution of asymmetric antennas over 31 generations using PAEA. Each purple violin represents the full range of fitness scores in the generation, with the width representing the density of scores. The black dashed line represents the baseline score using the current ARA VPol antenna.

Since the asymmetric bicone evolution, PAEA has been expanded to be able to generate more designs. First, the bicone algorithm was modified to allow for curvature in the sides of the antennas. The opening angle gene was replaced by two coefficients for a quadratic (A) and linear term (B) in a polynomial. The sides of the cones, as measured from the central axis, are then given by $Ax^2 + Bx + r$, with x ranging from 0 to L, the antenna length. This allows for both convex and concave antennas to be generated. Fig. 3 shows an antenna generated in an evolution of curved bicones on the left.

HPol Evolution

In addition to the VPol antenna design for ARA, GENETIS has begun working on applying PAEA to ARA's HPol design. The HPol antenna in ARA is shorter than the VPol antennas due to the constraint from the width of the boreholes limiting their length rather than their width. Currently, the HPol designs use a ferrite-loaded, quad-slot design. GENETIS is modifying PAEA to be capable of generating antennas with this shape. Currently, the number of slots and their arclength are genes that will be used in the evolution.

GENETIS intends to conduct an evolution evolving both the VPol and HPol antennas simultaneously. This can be especially significant to improving the performance of ARA because both types of antennas can evolve together to best account for the effects of the biaxial birefringence of Antarctic ice. Crystals that have an anisotropic index of refraction are called birefringent. Antarctic ice is biaxially birefringent at radio frequencies [24], meaning that there are three independent principle axes for the index of refraction. While an isotropic medium will have two ray solutions to the wave equation, one direct and one refracted, Antarctic ice has two direct rays (and two refracted rays) that interfere with one another and change direction as they propagate [25]. This may mean that HPol antennas are more important to the performance of the experiment than previously thought

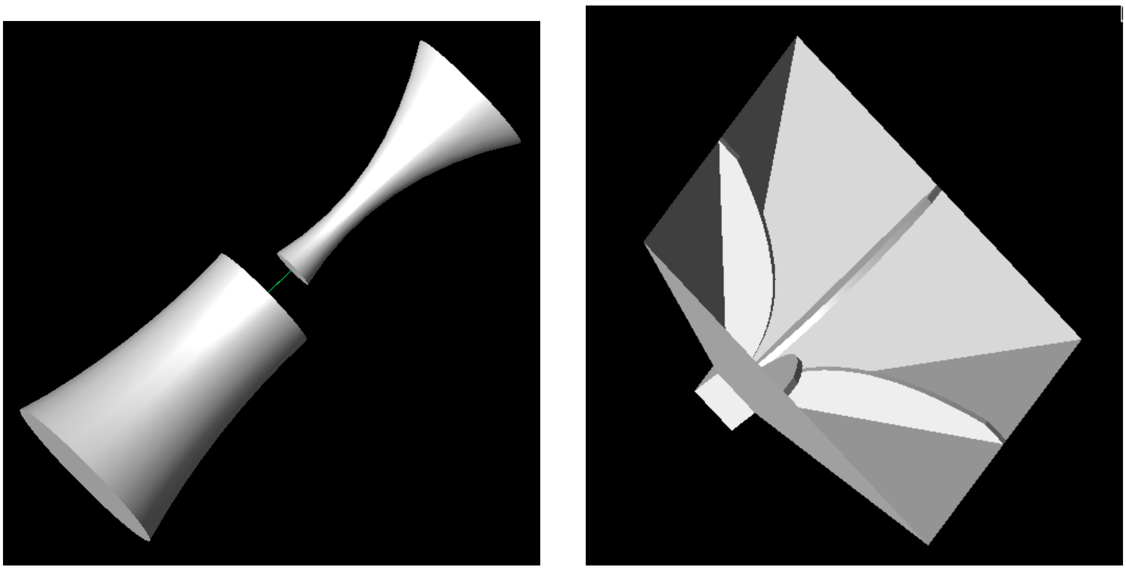

Figure 3: Example antennas generated by PAEA for the curved VPol (left) and quad-ridge horn (right) algorithms.

because Askaryan radiation will change polarization as it propagates through the ice, leading to more of the signal being horizontally polarized at the detector.

Horn Antenna Evolution

Beyond ARA, GENETIS has begun developing a GA for evolving horn antennas like those used in balloon experiments such as the Antarctic Impulsive Transient Antenna (ANITA) [26] and (PUEO) [27] experiments. UHE neutrino balloon experiments float above Antarctica to observe enormous volumes of ice in search of Askaryan radiation propagating upward. These experiments use horn antennas pointing down towards the ice. These antennas consist of four ridges divided into pairs for the VPol and HPol channels and are surrounded by outer walls for structural support and electrical connection of the two channels.

GENETIS has modified the GA to generate horn antennas for PUEO. The current framework for evolving these types of antennas with the GENETIS GA includes more genes and constraints than in our designs for ARA antennas. As in ANITA and PUEO, the four ridges are divided up into VPol and HPol channels. The GA also creates the outer walls, which are electrically connected to the ridges. Each individual is simulated in XFdtd to generate a response for the two channels, which is then fed into pueoSim, the simulation software for PUEO.

The GA uses the sidelength of the bottom of the horn and height of the antenna for the genes of the walls, with plans to generalize this to also allow for the opening angle of the walls to evolve as well. The ridges have seven genes, representing the position of the bottom of the ridges (x_0, y_0, and z_0), the position of the top of the ridges (x_f, y_f, and z_f), and the curvature of the ridges (β). The ridges are prevented from intersecting with their neighboring ridges by constraining their width and their distance from the center of the horn.

An example of a horn antenna created by GENETIS can be seen on the right in Fig. 3. While most of the geometry is straightforward, work is still being done on determining a functional form for the curvature of the ridges. Currently, the ridges are created using a parametric curve for the trajectory of the surface. This uses the curvature gene β in the z-component. This z-component is given by $z(t) = \beta * ln((e^{\frac{z_f}{\beta}} - 1.0) * t + 1.0)$, where t is the parametric time, ranging from 0 to 1.

3. Future Work

In addition to current work with PAEA, GENETIS has several more projects currently planned or underway to evolve more aspects of UHE neutrino observatories. The Antenna Response Evolutionary Algorithm (AREA) is a GA that evolves the beam patterns of antennas directly. This allows for a faster workflow by avoiding the need to simulate the response of physical designs. Doing this can put upper limits on the sensitivity improvement possible from evolving antennas by ignoring the geometric constraints placed on physical antennas. The beam pattern can also be used directly as a measure of fitness, which would substantially reduce the computation time spent on simulating the experiments. Current and future work on AREA is detailed in a dedicated poster and proceeding at this conference.

In the future, more aspects of radio neutrino experiments will be evolved using GENETIS GAs. For example, the orientation of stations for experiments like ARA can have significant effects on their sensitivity. Because of this, we plan to evolve station positions in simulations like AraSim [4]. As with antennas, this may be substantially affected by the biaxial birefringence of Antarctic ice.

4. Conclusion

These proceedings discuss past and ongoing work by the GENETIS collaboration to use GAs to improve the performance of UHE neutrino observatories. Optimizing the performance of these experiments is critical to achieving the detection of neutrinos at the highest energy scales. GENETIS has created a workflow for automatically evaluating the performance of these experiments with evolved antennas in simulations.

GENETIS has demonstrated the ability of GAs to improve on the sensitivity of these experiments [23]. Generalizing these GAs to new antenna types can compound these improvements by evolving multiple aspects of these experiments simultaneously. Further expanding the application of GAs to other aspects of these experiments can lead to even more improvements in their sensitivities.

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