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Project Summary: Translation of Machine Learning and Additive Manufacturing to Accelerate and Diversify Science and Engineering

Radio-frequency (RF) phased-array systems optimized with machine learning have become powerful tools in science and engineering. Recent progress in phased-array radar development has applications in particle astrophysics [1, 2, 3, 4], polar research [5, 6], and 5G mobile communications [7]. Phased-arrays are comprised of RF antennas working in tandem to boost received signal sensitivity, and to actively scan transmitted signals without moving parts. There are at least two barriers that impede phased-arrays from enhancing future science and engineering projects on a wide scale. First, the computational electromagnetism (CEM) properties of RF systems are designed with expensive, proprietary software that does not interface with open-source machine learning tools [8]. Second, RF systems are manufactured using costly and time-consuming traditional machining techniques. Ongoing scientific and engineering efforts can be enhanced by a solution that allows machine learning optimization to flourish, reduces design and manufacturing costs, and diversifies participation by removing technical and financial barriers.

We propose to create an open-source CEM and additive manufacturing ecosystem capable of 3D-printing phased arrays with conductive filament, following recent efforts for single RF antennas designed with proprietary software [8, 9, 10]. We have already demonstrated that open-source CEM tools used in photonics can drive the RF phased-array design process by relying on the scale invariance of Maxwell's equations [3, 11, 12]. This research will support diverse, ongoing efforts ranging from IceCube Gen2 (radio), Center for Remote Sensing and Systems (CRISIS) missions, and Office of Naval Research (ONR) radar projects. One application in particle astrophysics is the Askaryan Radio Array (ARA), in which phased arrays have increased sensitivity to ultra high-energy neutrino (UHE- ν) interactions in the ice sheet beneath the South Pole [13]. ARA phased arrays are vertically polarized, due to mechanical constraints within the ice. Our research could enhance ARA by discovering and adding a *horizontally polarized* design that overcomes the mechanical constraints through machine learning. This would enhance the precision of UHE- ν arrival direction and energy observations [14]. Discovery of a UHE- ν flux would be a major breakthrough in particle astrophysics, and measuring accurately the neutrino interaction properties will be key to that discovery. The societal impact of this research is to *accelerate* research in UHE- ν , climate science, and RF engineering by *translating* successes in CEM and materials research.

Whittier College is a Title-V Hispanic Serving Institution (HSI), with a proud tradition of providing access to higher education to Spanish-speaking and traditionally under-represented students in Southern California and beyond. People of color and first-generation students make up 70% and 40% of our student body, respectively. Studies conducted by our Bayard Rustin Fellows indicate that our diverse students experience a variety of difficulties in introductory STEM courses. Disparities in introductory STEM courses is a well-known and complex problem [15]. We have learned from workshops hosted by the Cottrell Scholars Network that emphasizing student dignity and self-efficacy can increase the performance of diverse undergraduates in our courses [16, 17]. Emphasis in these areas makes students feel they *belong* in our courses. In keeping with the theme of *translation*, and in order to emphasize the dignity of our students no matter their background, we propose a service project designed to boost performance and engagement in introductory STEM courses at Whittier College and in our broader community.

We seek to create a bilingual (Spanish and English) mobile application (app) that introduces STEM concepts within a welcoming digital environment. Our app will adapt to individuals using machine learning techniques. There is precedent for such an app in the DuoLingo method for language and mathematics [18]. We seek to provide data insights about student learning to instructors through the app, which should lead to more efficient and customized classroom instruction. A prototype application is being built by Whittier College undergraduates. In addition to algorithms presented within the DuoLingo method, the educational data mining (EDM) literature provides examples of apps that boost engagement and success in introductory STEM courses [19, 20, 21, 22]. Members of our community have shared that translating mathematics and physics exercises into Spanish aids in solving them. Our application will boost their skills and build confidence by offering them engaging, game-like physics training in the language of their choice. Finally, we propose to create a bilingual physics lecture series and recruitment events designed to welcome broader community members into the Whittier College research environment.

Translation of Machine Learning and Additive Manufacturing to Accelerate and Diversify Science and Engineering

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Project Description: Intellectual Merits

Radio-frequency (RF) phased array systems are examples of active electronically-scanned arrays (AESAs) that have applications in radar telemetry, telecommunications, ground-penetrating radar, scientific instrumentation, and remote sensing [1, 2, 5, 13, 23, 24, 25]. All AESAs have *radiation patterns* that define directions of maximum transmission power and received sensitivity, both due to constructive interference of the transmitted or received RF plane wave. Radiation patterns usually have a main lobe in which most of the radiation is concentrated, and the angular width of the main lobe is called the beam width. In the one-dimensional case, N three-dimensional RF antennas are arranged in a line with fixed spacing. In the two-dimensional case, $N \times M$ three-dimensional antenna elements are arranged in a two-dimensional grid with fixed spacing in both dimensions. The signal to noise ratio (SNR) of received signals in arrays of dimension N is boosted by a factor of $\approx \sqrt{N}$, because the N signals are combined coherently while thermal noise adds like \sqrt{N} . The SNR boost is critical for certain kinds of scientific observations. For example, systems created at the Center for Remote Sensing and Integrated Systems (CRISIS) are flown in polar regions to perform radar sounding of ice sheets for the purposes of geophysics and climate science [5]. Radio signals transmitted from aircraft propagate downward through the ice. Reflected signals carry information about the ice depth, temperature, and the presence of internal layers. The radio echoes have small SNR values that require phased array receivers.

Traditionally, phased array systems used in scientific projects are designed by hand, and commercial software is purchased to create the designs. Proprietary computational electromagnetism (CEM) packages like XFDTD and HFSS are used to model the response of elements within phased arrays and the behavior of arrays [26, 27]. The XFDTD package, for example, relies on the finite difference time domain (FDTD) method. The FDTD approach is a CEM technique in which spacetime and Maxwell's equations are broken into discrete form. HFSS uses a similar approach in the Fourier domain, called the Finite Element Method (FEM). Depending on the software license and version, the current price of these CEM products ranges between \$5,000 and \$40,000 USD. These costs are prohibitive for many academic institutions that primarily serve undergraduates, and Hispanic Serving Institutions like Whittier College. Reducing this financial barrier to entry would enable diverse researchers to participate in the design process.

Aside from the cost, a drawback of commercial modeling software is the lack of access to the source code. Having source code facilitates the incorporation of machine learning packages like NumPy and Scikit-Learn with the RF design process. Phased array system properties can be optimized to a given application using machine learning. These properties are determined by the 3D shape of the RF elements in the array, but the parameter space for RF element shapes is large. Machine learning tools can be used to locate optimal solutions within this space as long as they can interface with the CEM software. The authors of [8] review a number of open-source CEM packages, and conclude that there are open-source options that match the performance of the commercial choices for simple RF antenna shapes. Because Maxwell's equations are scale-invariant, open-source CEM packages designed for optical photonics can be used calculations at the cm-scale wavelengths relevant for particle astrophysics and geophysics. One such open-source package is the MIT Electromagnetic Equation Propagation (MEEP) package [12]. We have shown that MEEP can drive the RF phased-array design process, and that 3D printer schematics can be extracted from this process [3, 11, 12].

Recent advances in materials research have led to the creation of 3D printer filament that has conductivities relevant for RF antenna production. Resulting from an NSF Translational Impact (TI) award (1721644), Multi3D LLC. has produced filament with a resistivity of just $0.006 \, \Omega \, \text{cm}$: the Electrifi filament. Several antenna designs have already been produced [10, 28]. These examples include horn antennas with gain factors of 15 dB at 5.8 GHz, and microstrip patch antennas with gains of 1-2 dB at 2.5 GHz. The results match expectations from HFSS models, exhibiting no major differences with antennas made using perfect conductors. There are, however, virtually no examples of 3D printed RF phased arrays in the [0.1 - 1] GHz bandwidth. This bandwidth is the most relevant for the aforementioned applications. Further, the 3D printed results that take advantage of the Electrifi filament from Multi3D LLC appear to be well-known designs. These designs can be optimized, and whole new designs can be discovered, by fully incorporating machine learning tools into the CEM packages used to model the RF elements. In Sec. 1.1, we will review the progress already made at Whittier College along these lines. In Sec. 1.2, we will show how this work will enhance the field of UHE- ν observations. In Sec. 1.3, we will show how this work will enhance the field of radio echo sounding of ice sheets and ice shelves. In Sec. 1.4, we will show how this work can benefit active radar testing. In Sec. 1.5, we make the case that the overall intellectual merits of the proposed activities are sound.

1.1 Computational Electromagnetism and Additive Manufacturing

In Summer 2020, we received a Summer Faculty Research Fellowship from the Office of Naval Research (ONR) to teach US Navy RF engineers about phased arrays in the [0.5 - 5] GHz bandwidth. Whittier College is a member institution of the IceCube Gen2 collaboration, and we focus on the radio portion of the IceCube Gen2 design. With our background in NSF-funded projects like ARIANNA, ARA, and NASA-funded projects like ANITA, we were qualified to teach our colleagues in the ONR about the applications of phased arrays. Once the design process was understood, our goal was to design a phased array system that was to be integrated into an anechoic chamber. The purpose of the anechoic chamber was to become a testing facility for active radar systems used in a Naval context. We began by giving several one-hour lectures on the electromagnetism of phased arrays and applications within scientific research. The audience included engineers and programmers working to acquire and develop RF systems for the Naval Surface Warfare Center (NSWC), Corona Division (NSWC Corona). Our design flow is depicted in Fig. 1.1 below. As the COVID-19 pandemic took hold, in-person work was stopped and funding for engineering development began to wane. We made the decision to investigate open-source options for the CEM phase of the design.

We encountered a review article in the open-access journal *Electronics* that indicated there are several open-source CEM tools that can be adapted for RF phased array analysis [3]. Our design flow in Fig. 1.1 is adapted from Fig. 1 of the review to include specific tasks required for phased arrays, and near-to-far-field projections for the computation of radiation patterns. MEEP was noted by the authors in the review as the most advanced among open-source FDTD programs. The authors of the review did not benchmark it against HFSS or XFDTD due to the “steep” learning curve. As part of the ONR Summer Faculty Fellowship, we decided to figure out how MEEP can be used to model RF systems. The key insight was that MEEP takes advantage of the *scale invariance* of Maxwell’s Equations. The simplest way to understand this is to understand how MEEP uses relative units when breaking Maxwell’s equations into usable statements in algorithms and code.

Like other FDTD CEM methods, MEEP uses a Yee lattice to discretize Maxwell’s equations [29]. When the speed of light is set to unity ($c = 1$), distance and time units are set to be the same. Frequency and wavelength units are the inverse of each other. But distance and wavelength can take *any* unit of length in the Yee lattice. Most MEEP users interpret this unit of length to be $1 \, \mu\text{m}$ because the applications are for photonics. For example, a *relative* frequency (unit-less) of 0.5 corresponds to a *relative* wavelength of 2. When interpreted as $2 \, \mu\text{m}$, the frequency is 150 THz in real units that correspond to optical bandwidth. If we choose to interpret the *relative* wavelength as 2 cm, the real frequency is 15 GHz. A *relative* frequency of 0.05 corresponds to the RF frequency 1.5 GHz. Re-purposing MEEP from photonics simulator to RF simulator turned out to be simply a matter of interpretation.

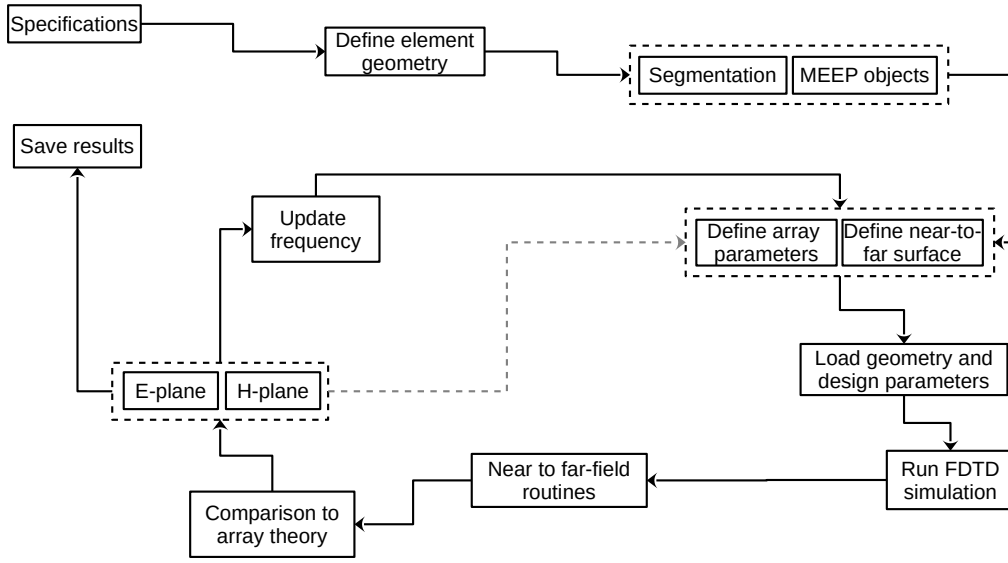


Figure 1.1: Our design process for RF phased arrays from [3], adapted from Fig. 1 of the review [8].

By Fall 2020, we were producing CEM models using MEEP that matched all expected properties of RF phased arrays. For a one-dimensional array with N RF elements, there is a linear relationship between the radiated plane-wave direction $\Delta\phi$, and the phase shift per RF element $\Delta\Phi$. The coefficient of the relationship is determined by the ratio of real wavelength to RF element spacing. Figure 1.2 contains results for our first phased array models in which the single RF elements were Yagi-Uda style antennas and horn antennas. The linear relationship is evident in the data. The radiated signal direction $\Delta\phi$ is divided by the beam width (BW) in Fig. 1.2 (left) and (middle) portions of the figure. A beam width of a radiation pattern is the angular width of the main lobe of radiation, outside of which the radiated power has decreased by at least 3 dB. In Fig. 1.2 (left), the $N = 16$ Yagi array can steer a 5 GHz plane wave up to four beam widths to the right or left of the forward direction. Yagi-Uda style antennas are simple dipole arrays designed for a single frequency. In Fig. 1.2 (middle), results are shown for an $N = 16$ array of horn antennas. Since horn antennas are broadband radiators, the linear relationship is shown for 0.3, 1.5, and 3.0 GHz. In Fig. 1.2 (right), the expected inverse relationship between beam width and frequency for broadband phased arrays is shown.

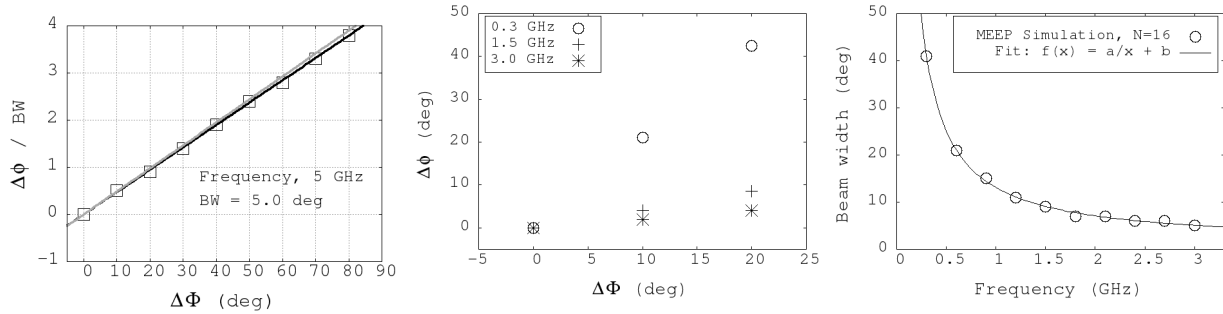


Figure 1.2: (Left) The beam angle $\Delta\phi$ divided by the beam width BW for the $N = 16$ one-dimensional Yagi array versus $\Delta\Phi$, the phase shift per element. (Middle) $\Delta\phi$ versus $\Delta\Phi$ for the $N = 16$ version of the one-dimensional horn array, for several frequencies. (Right) The dependence of the beam width on frequency for the one-dimensional $N = 16$ horn array.

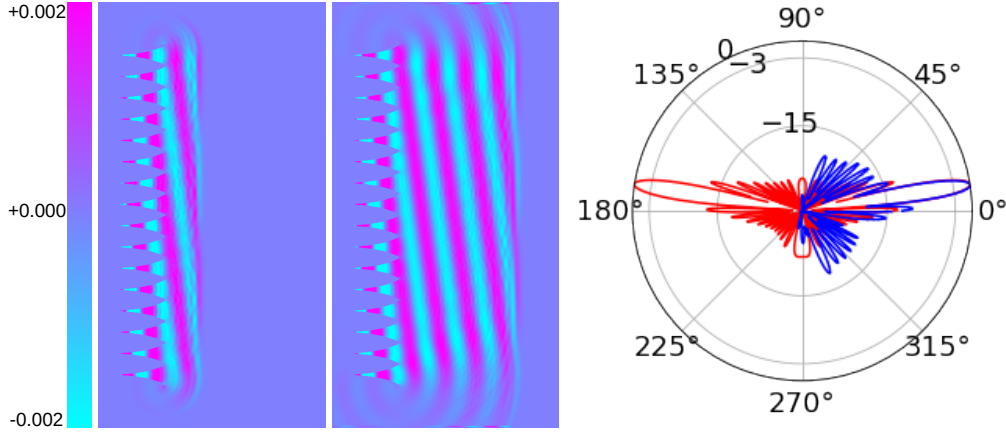


Figure 1.3: (Left) The $N = 16$ one-dimensional horn array, radiating a linearly polarized electric field $|\vec{E}(x, y, t)|$ at $t = 1$ ns into the simulation run, and (middle) at $t = 2.0$ ns into the run. The 2D area is 80×150 cm^2 . The frequency is 2.5 GHz, and the beam angle is $\Delta\phi = 9$ degrees from broadside (x-direction). (Right) The normalized radiated power versus $\Delta\phi$ known as the radiation pattern, in dB. The blue curve represents the results from MEEP, and the red curve is the theoretical expectation from N point sources.

We can also produce phased array radiation patterns with MEEP that match theoretical expectations. The radiation pattern of a one-dimensional array of N point sources of electromagnetic radiation can be derived using first principles [3]. The *pattern multiplication theorem* states that a one-dimensional phased array radiation pattern of N identical RF elements will be that of a row of N point sources, multiplied by the radiation pattern of the individual RF element. In Fig. 1.3 (left and middle), the $N = 16$ horn array is shown radiating in the E-plane (x-y plane) at an angle of 9 degrees with respect to the forward direction (x-axis). The radiation pattern is shown in 1.3 (right). The phase shift per horn and the ratio of wavelength to horn spacing combine to yield a beam direction of $\Delta\phi = 9$ degrees. If no phase shift per horn is introduced, then $\Delta\phi = 0$ degrees and the plane wave radiates in the x-direction. The blue curve in the polar plot represents the CEM radiation pattern from MEEP, while the red curve is the theoretical expectation from a row of N point sources. Though the row of point sources is symmetric, with a back lobe at $\Delta\phi = 180 - 9 = 171$ degrees, the pattern multiplication theorem dictates that the horn array should have no back lobe. The individual horns suppress backward radiation (in the negative x-direction). In the same publication, we also showed that two-dimensional arrays of Yagi-Uda and horn antennas matched theoretical expectations exactly.

Our revelation that the photonics code MEEP could be applied to one and two-dimensional RF phased array design in single-frequency and broadband applications led to the publication receiving Top 10 honors for December 2020 to May 2021 from the editors of *Electronics Journal*. In the same work, we showed that MEEP can be used to model the behavior of phased arrays in realistic polar ice environments. Unlike most CEM codes, which tend to assume a uniform ground plane and index of refraction in the medium surrounding the array, MEEP gives the user fine control of the index of refraction of each voxel, $n(x, y, z)$. The RF index of refraction in polar ice is $n = 1.78$ for solid ice, but varies with the depth near the snow surface. The transitional region between surface snow and solid ice in ice shelves and sheets in polar regions is known as the *firn*. The $n(z)$ function is well-measured in a variety of locations in Antarctica [30], and Greenland [31]. Though the ARA (South Pole) [13], Radio Neutrino Observatory, Greenland (RNO-G) [32], and the proposed IceCube Gen2 project (South Pole) [33] all use or plan to use RF phased arrays as the primary UHE- ν detector, the models blah blah ...

1.2 The Connection to Ultra-high Energy Neutrino Observations

Example

1.3 The Connection to Remote Sensing of Ice Sheets

Example

1.4 The Connection to Office of Naval Research Projects

Example

1.5 Conclusion, Intellectual Merits

Example

Project Description: Broader Impacts

Overarching Introduction

2.1 Translation of Scientific and Engineering Research

Do people really know how multi-lingual this area is, and why that is important? Cite the creation of *History of Science in Latin America*.

2.2 Mobile Application Development

Educational Application for Systematic Training and Learning of STEM (EASTLOS)

2.3 Bilingual Public Lectures and Recruitment Events

Example

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