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CAREER: Translation, Acceleration, and Diversification of Science and Engineering with Open-Source Computational Electromagnetism and Additive Manufacturing

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 [1–4], 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. Two pathways for progress in phased array design and production that will enhance future scientific work are cost reduction and the introduction of open-source software. The electromagnetic properties of phased arrays are designed with expensive, proprietary software that does not interface with open-source machine learning tools [8]. Phased arrays are then 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 reducing financial barriers. Undergraduate STEM education will be enhanced with CEM, machine learning, and 3D printing, as research and educational opportunities can be integrated the STEM curriculum.

We propose to create the first open-source CEM and additive manufacturing ecosystem capable of 3D-printing phased arrays with conductive filament [8–10]. We have already shown that open-source CEM tools used in photonics can drive the RF phased-array design process [3, 11, 12]. This research will support diverse projects like IceCube Gen2 (radio), Center for Remote Sensing and Systems (CReSIS) 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]. The arrays are vertically polarized, due to mechanical constraints within the ice. By combining machine learning with CEM, we seek a *horizontally polarized* design that overcomes these mechanical constraints, boosting the chances of making the first UHE- ν observations in history [14]. This research will *accelerate* and *diversify* research in UHE- ν , climate science, and RF engineering by *translating* successes in CEM and materials research. This work will be integrated into our curriculum and research programming at Whittier College, a Title-V Hispanic Serving Institution (HSI).

This work will provide research and educational opportunities to diverse undergraduates at Whittier College. We have a proud tradition of providing access to higher education to Spanish-speaking and historically marginalized students, and we are the only HSI member of the IceCube Gen2 collaboration. People of color and first-generation students make up 63% and 29% of our student body, respectively. Internal assessment studies indicate that students of color receive lower grades than their peers in introductory STEM courses. We have learned from workshops hosted by the Cottrell Scholars Network that emphasizing the dignity and self-efficacy of diverse students can increase their performance [15, 16]. Emphasis in these areas makes students feel they *belong* in our courses, despite encountering adversity. In keeping with the theme of *translation*, and in order to emphasize the dignity of our students no matter their background, we seek to create a bilingual (Spanish and English) mobile application (app) that introduces STEM concepts within a welcoming digital environment.

There is precedent for learning apps enhanced by machine learning in the Duolingo method for language and mathematics [17]. We seek to provide data insights about student learning to instructors through the app, which will lead to more efficient and customized classroom instruction. A prototype application is being built by Whittier College undergraduates. The creation and implementation of this program represents an opportunity for Whittier College students to enhance the learning experience for their peers while gaining valuable coding and machine learning experience. 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 [18–21]. 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 lecture series and recruitment events designed to welcome the broader community into the Whittier College environment.

CAREER: Translation, Acceleration, and Diversification of Science and Engineering with Open-Source Computational Electromagnetism and Additive Manufacturing

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Project Description: Intellectual Merits

Radio-frequency (RF) phased arrays have applications in radar telemetry, telecommunications, ground-penetrating radar, scientific instrumentation, and remote sensing [1, 2, 5, 13, 22–24]. 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 background 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 (CReSIS) are flown in polar regions to perform radar sounding of ice sheets for the purposes of geophysics and climate science [5]. Reflected signals carry information about the ice depth, temperature, and internal structure of the ice. The radio echoes have small SNR values that require phased arrays.

Traditionally, RF phased arrays are designed with commercial computational electromagnetism (CEM) software. Radio antennas and phased arrays have *radiation patterns* that define directions of maximum transmission power and received sensitivity. Radiation patterns 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. Other parameters like S-parameters quantify the efficiency of the systems. CEM packages like XFDTD and HFSS are used to model these properties as a function of frequency [25, 26]. 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 (frequency) domain, the Finite Element Method (FEM). Depending on the software license and version, the current price of these products ranges between \$5,000 and \$40,000 USD. These costs are prohibitive for HSI undergraduate institutions like Whittier College. Removing this financial barrier to entry would enable diverse researchers to gain important skills in the field of RF design.

Another drawback of commercial CEM software is the lack of access to the source code, which impedes the incorporation of modern machine learning packages. Phased array properties are determined by the shape of the RF elements and the grid properties of the array. The parameter space is driven by the complex variety of RF element shapes. When combined with open-source CEM software, modern machine learning algorithms can locate optimal solutions within the parameter space. The authors of [8] review a number of open-source CEM packages, and conclude that there are viable open-source options for simple RF antenna shapes. For our proposed work, the open-source CEM software must be able to handle the growing complexity of RF antenna designs. One interesting choice is the MIT Electromagnetic Equation Propagation (MEEP) package [12]. Though MEEP was designed for μm wavelengths in photonics applications, we have shown that the scale-invariance of Maxwell's equations allows MEEP users to translate designs to wavelengths at the cm-scale. We have also shown that MEEP can drive the RF phased-array design loop, and that 3D printer schematics can be extracted from this process [3, 11, 12]. This research represents an opportunity for diverse undergraduates to gain experience applying machine learning tools to the design of practical systems.

Recent advances in materials research have led to the creation of 3D printer filament that has good conductivity in the RF bandwidth. Funded through an NSF Translational Impact (TI) award (1721644),

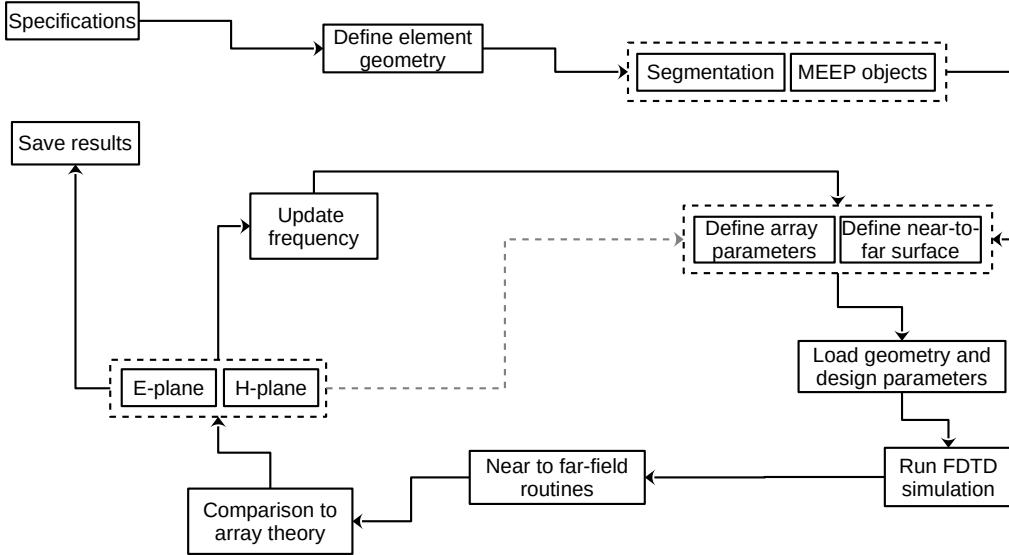


Figure 1.1: Our design process for RF phased arrays from [3], adapted from Fig. 1 of the review [8].

Multi3D LLC. has produced filament with a resistivity of just $10^{-2}\Omega\text{ cm}$: the Electrifi filament. Several antenna designs have already been produced [10,27]. 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 in particle astrophysics and geophysics. Further, whole new designs can be discovered that improve on designs like the horn and patch antennas by merging machine learning packages with MEEP. In Sec. 1.1, we review progress already made at Whittier College. In Sec. 1.2, we show how this work enhances the field of UHE- ν observations. In Sec. 1.3, we show how this work enhances the field of radio sounding of ice sheets and ice shelves. In Sec. 1.4, we articulate our vision for the integration of this research into our STEM curriculum at Whittier College. In Sec. 1.5, we provide a general project timeline, broken into manageable phases. In Sec. 1.5, we make the case that the general merits of our proposal are sound.

1.1 Computational Electromagnetism and Additive Manufacturing

In Summer 2020, we received a Faculty Fellowship from the Office of Naval Research (ONR) to study and design phased arrays in the [0.1 - 5] GHz bandwidth. This bandwidth is relevant for projects like IceCube Gen2 (radio), and Whittier College is a member institution of the IceCube Gen2 collaboration. With our background in NSF-funded projects like the Antarctic Ross Ice Shelf Antenna Neutrino Array (ARIANNA), the Askaryan Radio Array (ARA), and NASA-funded projects like the Antarctic Impulsive Transient Antenna (ANITA), we were qualified to teach our ONR colleagues about phased array applications. Our goal was to design a phased array system to be integrated as a transmitter in an anechoic chamber. The anechoic chamber will serve as a testing facility for active radar systems. We began by giving lectures on the electromagnetism of phased arrays and scientific and engineering applications. The audience included engineers and programmers that work in acquisition and development for the Naval Surface Warfare Center (NSWC), Corona Division (NSWC Corona). Our design flow is depicted in Fig. 1.1. To minimize costs and increase access to Whittier College students, we decided to investigate open-source CEM options for the design.

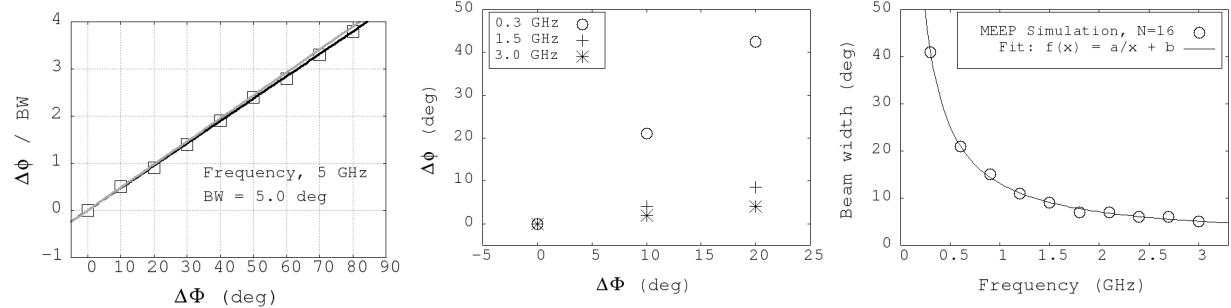


Figure 1.2: (Left) The beam angle $\Delta\phi$ divided by the beam width BW for the $N = 16$ one-dimensional Yagi array versus $\Delta\Phi$, the phase shift per element. The gray line represents theoretical expectation, and the black line is a linear fit to the data. (Middle) $\Delta\phi$ versus $\Delta\Phi$ 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. The black line is a functional fit to the data $f(x) = a/x+b$ with $a = 12.0 \pm 0.1$ degree GHz, and $b = 1.1 \pm 0.2$ degrees.

We encountered the aforementioned review article in the open-access journal *Electronics* that indicated there are open-source CEM tools that can be adapted to phased array analysis. Our design flow in Fig. 1.1 is adapted from Fig. 1 of the review to include specific tasks required for phased arrays, and algorithms for the computation of far-field radiation patterns. MEEP was noted by the authors in the review as the most advanced among open-source FDTD programs, but they did not benchmark it against HFSS or XFDTD due to the “steep” learning curve. As part of the ONR Summer Faculty Fellowship, we ascended the learning curve and adapted MEEP to 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 discretizing Maxwell’s equations for Python code.

Like other FDTD methods, MEEP uses a Yee lattice to discretize Maxwell’s equations [28]. 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. Assuming design components have sufficient conductivity at RF frequencies, we have re-purposed MEEP as an RF simulator.

By Fall 2020, we were producing CEM models using MEEP that matched expected phased array properties. For a one-dimensional array with N elements, there is a linear relationship between the radiated plane-wave direction $\Delta\phi$, and the phase shift per element $\Delta\Phi$. The $\Delta\phi$ is also called the *beam angle*. The coefficient of the linear relationship between $\Delta\phi$ and $\Delta\Phi$ is determined by the ratio of real wavelength to element spacing. Figure 1.2 contains results for our first phased array models in which the elements were Yagi-Uda antennas and horn antennas. The linear relationship between $\Delta\phi$ and $\Delta\Phi$ is evident in the data. The $\Delta\phi$ is divided by the beam width (BW) in Fig. 1.2 (left), and is left in degrees in Fig. 1.2 (middle). A beam width of a radiation pattern is the angular width of the main lobe, outside of which the radiated power has decreased by 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 designed for a single frequency. In Fig. 1.2 (middle), results are shown for an $N = 16$ array of horn antennas. The horns are broadband radiators, so the linear relationship is shown for 0.3, 1.5, and 3.0 GHz. The beam width is not constant, but inversely related to frequency. Thus, $\Delta\phi$ was left in degrees in Fig. 1.2 (middle). In Fig. 1.2 (right), the inverse relationship between beam width and frequency is shown.

We can also produce phased array radiation patterns with MEEP that match theoretical expectations. The radiation pattern of a one-dimensional array of N radiating point sources can be derived using first

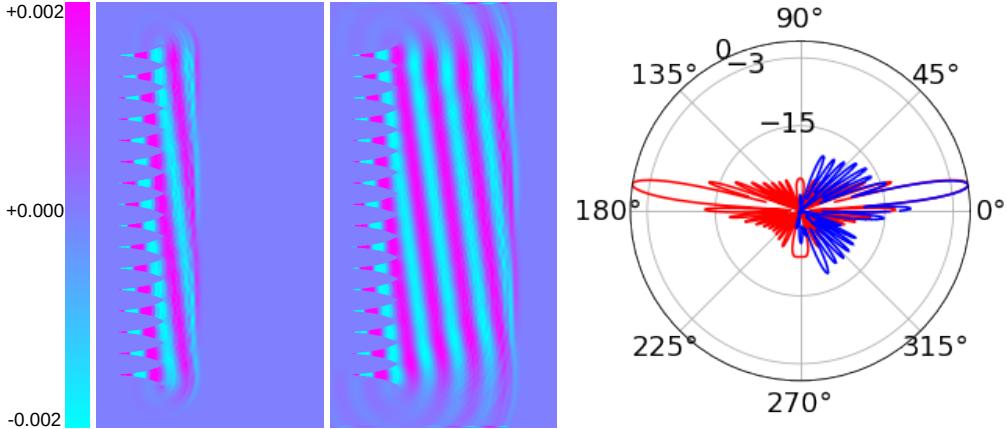


Figure 1.3: (Left) The $N = 16$ one-dimensional horn array, radiating a linearly polarized electric field $\vec{E}(x, y, t)$ (y-component shown, in arbitrary units) at $t = 1$ ns into the simulation run, and (middle) at $t = 2$ ns into the run. The 2D area is $80 \times 150 \text{ cm}^2$. The frequency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

principles [3]. The *pattern multiplication theorem* states that the radiation pattern of a one-dimensional phased array of N identical elements will be that of a row of N point sources, multiplied by the radiation pattern of the individual element. In Fig. 1.3 (left and middle), the radiated field of a $N = 16$ horn array is shown in the E-plane (x-y plane). The radiation pattern is shown in Fig. 1.3 (right). The beam angle of the main lobe is $\Delta\phi = 9$ degrees above the x-axis, matching the theoretical expectation. 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. The row of point sources is symmetric, creating a back lobe at $\Delta\phi = 171$ degrees. The horn array has no back lobe because the individual horns suppress backward radiation, as expected from the pattern multiplication theorem. 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 used to design phased arrays design earned the final article Top 10 honors for December 2020 to May 2021 from the editors of *Electronics*.

In Summer 2021, we again received a Faculty Fellowship from the ONR to continue this work. We focused on creating realistic 3D models of horn antennas that could be printed with 3D printers. Working with undergraduate researchers, we learned to create designs that can be expressed as Python3 functions and converted to a GDSII CAD file. GDSII files can be imported into MEEP, and converted to STL files for use with a 3D printer. Our CEM codes are therefore using the precise shape that we intend to print. We acquired NinjaTek proto-pasta 3D printer filament, advertised as conductive. We printed a horn with in-built SMA connector for RF cables (Fig. 1.4). The proto-pasta result had the right shape, but a measured resistance too large for an RF antenna. Multi3D LLC, the manufacturer of the Electrifi filament, has now provided resistivity results that compare proto-pasta with Electrifi (Fig. 1.5). The Electrifi filament will improve resistivity by two orders of magnitude. We seek to print Electrifi-based antennas, and to measure the radiation pattern and S-parameters.

In Summer 2022, we received a final ONR Faculty Fellowship that focused on GPS M-code and modernization. Alongside this work, we continued to refine the open-source RF horns. This included computing radiation patterns and S-parameters for the full 3D horns stored in CAD files. In Fig. 1.6 (a), the main lobes are designed to point to 0 degrees (x-direction) for the E-plane (x-y plane), and 90 degrees for the H-plane (x-z plane). The E-plane is the plane containing the linearly polarized radiation vector, and the H-plane is orthogonal to the E-plane. In Fig. 1.6 (b), the (voltage standing wave ratio) VSWR is shown. The VSWR is a common figure of merit for RF antennas, related to the S11 scattering parameter. The VSWR approaches 1 for an efficiently radiating antenna. The radiation patterns match expectations for

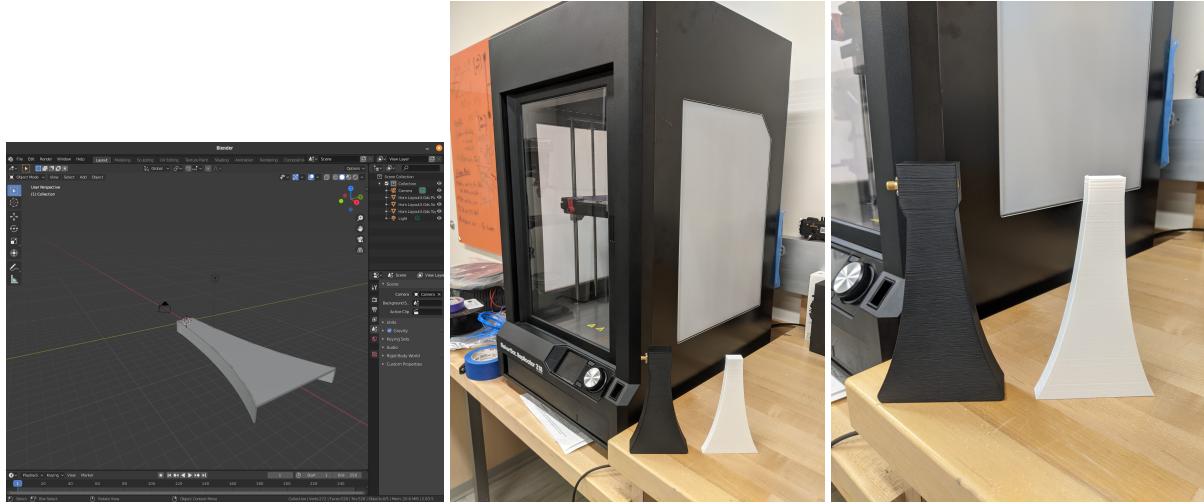


Figure 1.4: (Left) Blender/STL files extracted from MEEP code. (Middle) MakerBot 3D printer, with PLA horn model (white), and proto-pasta with SMA connector (black). (Right) Close-up of horns.

horn antennas (see Fig. 19 of [10]). The VSWR results demonstrate efficient radiation in the bandwidth [0.5 - 6] GHz. We presented our progress at the annual MeepCon 2022 at the Massachusetts Institute of Technology (MIT) [11]. We learned the extent to which MEEP can be integrated with Python3-based machine learning tools [29], and how eager MEEP developers are to collaborate in the RF regime. Extending MEEP to RF users widens the user base of MEEP, which has traditionally focused on photonics.

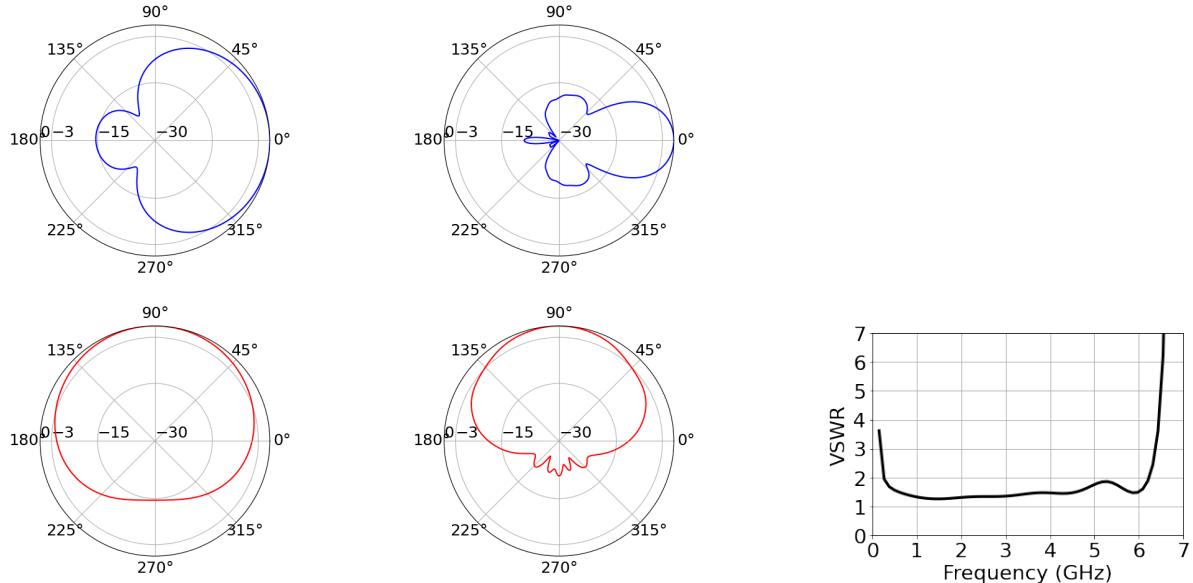
1.1.1 RF Laboratory Capability and Prior ONR Funding

As of May 2023, we have begun an Educational Partnership Agreement (EPA) between NSWC Corona and Whittier College. NSWC Corona now has the ability to transfer laboratory equipment to Whittier College. NSWC Corona has provided RF bench testing equipment that is perfectly suited to the proposed work (see Tab. 1.1). Our network analyzer and power sensors can perform S-parameter measurements over a bandwidth that encompasses the proposed bandwidth of [0.1 - 5 GHz] for our antennas under test (AUT). Our signal generator can create calibration signals for our calibration antennas and AUT in the proposed bandwidth. Our calibration antennas will serve as benchmark devices for comparison to our 3D printed AUT. Due to the precision and wide bandwidth of these devices, regular calibration is required. Our calibration kits serve this purpose. Our laboratory is therefore well-equipped to complete the proposed work, and this minimizes the budgetary impact of new equipment.

Horizontal Traces	Dimension ($X \times Y \times Z$ cm 3)	Resistance (Ω)	Resistivity (Ω cm)
Electrifi	0.2 \times 10 \times 0.2	3.0	0.012
Black Magic 3D	0.2 \times 10 \times 0.2	142.5	0.57
Proto-Pasta	0.2 \times 10 \times 0.2	1506	6.02

Vertical Towers	Dimension ($X \times Y \times Z$ cm 3)	Resistance (Ω)	Resistivity (Ω cm)
Electrifi	0.5 \times 0.5 \times 10	3.4	0.085
Black Magic 3D	0.5 \times 0.5 \times 10	103.6	2.59
Proto-Pasta	0.5 \times 0.5 \times 10	410	10.25

Figure 1.5: Resistivity results published by Multi3D LLC that compare the proto-pasta product with the new Electrifi conductive filament (<https://www.multi3dffc.com/faqs/>).



(a) Radiation pattern results using GDSII/CAD for (top left) E-plane at 0.5 GHz, (top right) E-plane at 5.0 GHz, (bottom left) H-plane at 0.5 GHz, (bottom right) H-plane at 5.0 GHz. See text for details.

(b) The VSWR figure of merit versus frequency in GHz for the RF horn.

Figure 1.6: Results for RF horn design, using the open-source design process open to 3D printing.

Equipment	Bandwidth	Cost
Rohde and Schwartz ZVL6 Network Analyzer	9 kHz to 6 GHz	\$20k
Rohde and Schwartz NRP-91 Power Sensors (2)	9 kHz to 6 GHz	\$8k
Aeroflex 3416 Digital RF Signal Generator	250kHz to 6 GHz	\$12k
Calibration antenna kits (2)	Varies by antenna	\$2k
Calibration test kits for Network Analyzer (2)	6 kHz to 9 GHz	\$6k

Table 1.1: A listing of the equipment provided to our labs by the Office of Naval Research.

According to ONR policy, Faculty Fellows who have received fellowships three years in a row must take a mandatory gap year. In Summer 2024, we will be eligible for Senior Faculty Fellowships because we received regular Faculty Fellowships in the Summers 2020-22. Our EPA contacts with NSWC Corona have indicated that our focus will broaden to include cybersecurity and reliability engineering projects. These projects will be in the form of student internships, curricular enhancements, and summer research projects. Given the connections to particle astrophysics and geophysics, it is wise to organize the proposed work under the NSF CAREER program, so that it will maintain this focus. We provide a summary of funding received related to this project in Tab. 1.2. Note the regular involvement of undergraduate researchers. These researchers have diverse majors and interests, including our 3-2 Engineering Program (Wildanger), Physics and Math double major (Hartig), and Math/Integrated Computer Science (Gómez-Reed) and Householder), and Physics and Astronomy (Goodman and Smith).

1.2 The Connection to Ultra-High Energy Neutrino Observations

The flux of neutrinos with energies between [0.01-1] PeV (10^{15} eV) has been detected by IceCube [30]. The UHE- ν flux could potentially explain the unknown origin of UHE cosmic rays (UHECR), and represents an opportunity to study electroweak interactions at record-breaking energies [31, 32]. Previous analyses have shown that the discovery of UHE- ν above 1 PeV will require an expansion in detector volume,

Student/Professor	Grant Opportunity	Amount	Dates
Jordan C. Hanson	ONR Summer Faculty Fellow	\$16.5k	Summer 2022
Dane Goodman	Summer researcher	Course credit	Summer 2022
Andrew Householder	Summer researcher	Course credit	Summer 2022
Raymond Hartig	Ondrasik-Groce Fellowship	\$5k	Summer 2022
Jordan C. Hanson	ONR Summer Faculty Fellow	\$16.5k	Summer 2021
Adam Wildanger	Fletcher Jones Fellowship	\$5k	Summer 2021
Jordan C. Hanson	ONR Summer Faculty Fellow	\$16.5k	Summer 2020
Raymond Hartig	Fletcher Jones Fellowship	\$5k	Summer 2020
John Paul Gómez-Reed	Ondrasik-Groce Fellowship	\$7.5k	Summer-Fall 2019
John Paul Gómez-Reed	Keck Fellowship	\$5k	Summer 2018
Cassady Smith	Keck Fellowship	\$5k	Summer 2018

Table 1.2: A listing of the grant opportunities awarded to our group for RF design, software development, and machine-learning. All students are at the undergraduate level.

because the UHE- ν flux is expected to decrease with energy [33–37]. Whereas the current version of IceCube detector observes neutrinos via optical signals that travel < 100 m, the Askaryan effect translates a UHE- ν interaction into an RF pulse that travels more than 1 km in dielectric media such as Antarctic and Greenlandic ice [38–40]. RF signals propagate such long distances in ice due to its crystal structure and low temperature, and this effect is characterized by long RF *attenuation lengths*. Utilizing the Askaryan effect therefore allows for detectors with vastly larger effective volumes than optical observations.

The Askaryan effect occurs when a neutrino with velocity larger than the speed of light in a dielectric medium initiates a high-energy cascade with negative total charge. The charge radiates energy in the RF bandwidth [41, 42]. The IceCube EHE analysis has constrained the UHE- ν flux to be $E_\nu^2 \phi_\nu \leq 2 \times 10^{-8}$ GeV cm $^{-2}$ s $^{-1}$ sr $^{-1}$ between $[5 \times 10^{15} - 2 \times 10^{19}]$ eV [35]. Arrays of $\mathcal{O}(100)$ *in situ* detectors encompassing effective areas of $\approx 10^4$ m 2 steradian per station, spaced by $\mathcal{O}(1)$ RF attenuation length could discover a UHE- ν flux beyond the limits of the EHE analysis. Polar ice formations in Antarctica and Greenland have the longest RF attenuation lengths. A group of prototype Askaryan-class detectors has been deployed in polar regions that seek to probe unexplored UHE- ν flux parameter-space [36, 37, 43, 44].

Askaryan radiation was first observed in laboratory settings [45–47]. The RF pulse shape is influenced by the shape of the cascade, and the observed pulse is strongest when viewed close to the Cherenkov angle. Working with an undergraduate researcher, we recently published a theoretical model of the electromagnetic field of Askaryan radiation [48]. Askaryan models are incorporated into simulations like AraSim in order to calculate expected signals and aid in detector design [49–51]. For example, software developed for IceCube Gen2 (radio) utilizes machine learning and the Askaryan pulse shape to provide a way to reconstruct UHE- ν properties in future data [14, 52, 53]. Askaryan electromagnetic fields are combined with RF channel responses to form “signal templates” used to search large data sets for signal candidates [36, 54]. Data sets are large for Askaryan-class detectors due to the inevitable RF thermal background data. For Askaryan signals, the SNRs at RF channels are expected to be small (SNR ≈ 3), because the amplitude of the Askaryan field decreases with the distance to the UHE- ν interaction, and the signal is attenuated by the ice [38, 55, 56]. Template-waveform matching between models and data is a powerful technique for isolating high-energy particles [36, 54, 57, 58].

Phased arrays have been incorporated into Askaryan-class prototype detectors, after it was noted that phased arrays would enhance the probability of observing UHE- ν [1, 2]. Phased arrays boost the SNR of observed signals by combining multiple observations of the same RF pulse coherently. Examples of this strategy are ARA5 [13], and the first deployments of Radio Neutrino Observatory, Greenland (RNO-G) [59]. The arrays in each are identical, vertically polarized dipole antennas. These decisions were made for mechanical reasons, because the array must fit in a 100 m deep, vertically-drilled borehole in the ice. The radiation pattern exhibits azimuthal symmetry, and there is no sensitivity to the horizontal Askaryan field component. Further, the designs assume a uniform index of refraction for the ice surrounding the array. As part of our proposed work, we seek to use machine learning to discover

horizontally polarized array designs that fit into the borehole and account for the index of refraction, n .

We included a short study of phased array behavior in the South Pole ice environment in our recent publications [3, 11, 12]. Most commercial CEM packages assume a uniform n in the surrounding medium. By contrast, MEEP gives the user 3D control of the index of refraction, $n(x, y, z)$. The RF index of refraction varies with the depth (z) near the snow surface. The $n(z)$ function is well-measured in a variety of locations in Antarctica [60], and Greenland [61]. ARA (South Pole) [13], RNO-G (Greenland) [59], and IceCube Gen2 (radio) (South Pole) [62] can all benefit from designs that account for $n(z)$ and have sensitivity to the horizontal component of the Askaryan field.

The common simulation package used for ARA, RNO-G, and IceCube Gen2 is NuRadioMC, built from prior experience with ARA and ARIANNA [37, 40, 51, 63, 64]. NuRadioMC addresses analytically the ray-tracing solution for UHE- ν signals as they propagate through polar ice. We derived the analytic ray-tracing solutions presented in [51] and [60], which were adopted into NuRadioMC. A goal of our proposed research will be to incorporate realistic, 3D field propagation into NuRadioMC using FDTD computations with MEEP, with our analytic Askaryan model as the MEEP source [48, 65]. This integration should boost the accuracy of the computations made with NuRadioMC, which will be matched with future ARA, RNO-G, and IceCube Gen2 data to isolate UHE- ν signals.

1.3 The Connection to Remote Sensing of Ice Sheets

A gap exists in Askaryan-based UHE- ν science that connects to the remote sensing of ice sheets. A knowledge of the RF attenuation length, λ , versus frequency, depth, and location is paramount to understanding UHE- ν detector sensitivity. Although we have made detailed measurements of λ versus frequency [38, 39, 66], we do not scan detector volumes to measure this parameter versus geographic location: $\lambda(x, y)$. Further, $\lambda(z)$ is merely inferred from the average attenuation and ice core temperature data (see Fig. 24 from [40]). IceCube Gen2 (radio) will require $\lambda(x, y, z)$ to be measured precisely. CReSIS radio sounding data, available on the Open Polar Server (OPS: <https://ops.cresis.ku.edu/>), have been used to constrain $\lambda(x, y)$ across Greenland [67]. Far less CReSIS data is available near the location of IceCube (South Pole), due to the complex logistics of organizing flights in that region. A new technological effort to incorporate radio sounding instrumentation into unmanned aerial systems (UAS) is underway, and it can benefit geophysics and particle astrophysics.

UAS systems offer a way to enrich radio sounding data for geophysics and particle astrophysics. OPS radio sounding data is generated from human-piloted fixed-wing aircraft with straight flight lines that carry on-board radar. Flight lines can be hundreds of kilometers long, scanning wide areas with synthetic aperture radar (SAR) techniques. There are, however, three key disadvantages. First, there may not be a flight near the desired location, which is the case for South Pole. Second, flights only give a snapshot of the ice at the time, and aircraft may not return to the same location for several years. Third, the bandwidth of the radar does not always overlap with the bandwidth desired for IceCube Gen2 (radio). Dedicated UAS could constrain $\lambda(x, y)$ in both the temporal and spatial regimes. UAS are able to hover and fly at lower altitudes, so they can collect a wider variety of data than traditional fixed-wing craft. For example, the CReSIS ultra-wide band (UWB) Snow Mini radar system was integrated onto the AeroVironment Vapor 55 UAS. The low altitude flight capability increases the SNR in difficult areas by pushing clutter angles outside the field of view. The SNR is also boosted by hovering due to increased integration time over a single site [5]. The average cost of the Vapor 55, however, is about \$90k USD.

In our RF design lab at Whittier College, our group has already constructed a 3D printed drone using PLA, carbon-fiber tubing, commercial motors, and commercial transmitters. The unit has ≈ 1 kg payload, a 20-min flight time, and is powered by LiPo batteries, for a total cost of ≈ 1 k USD (see Fig. 1.7). Before the onset of the COVID-19 pandemic paused in-person laboratory work, we had plans to equip it with solar charging and cold-temperature components. Thus, there is a potential for collaboration between CReSIS and IceCube Gen2 (radio) to solve a common problem: the solar rechargeable $\lambda(x, y)$ measurement system with vertical take-off and landing (VTOL). Our drone design with VTOL capability can be 3D printed and assembled from commercial parts for ≈ 1 k. We hope to collaborate with the CReSIS group on retro-fitting



Figure 1.7: Our 3D-printed quad-rotor drone, designed and assembled by Whittier College undergraduates using our RF design lab and machine shop. The unit is equipped with hand-held RC control, and GPS with programmable waypoints.

for cold temperatures and solar charging. When outfitted with a 3D-printed phased array radar, we will have a formidable system capable of filling gaps in our knowledge of polar ice sheets.

The incorporation of phased array radio sounding systems on UAS faces engineering limitations that must be overcome. The optimization of craft weight, thrust, payload, and flight time is the primary problem to be solved. To collect quality radio sounding data, the payload must be flown horizontally for $1 - 10$ km, implying ≈ 1 hr battery life at reasonable speeds. The requirement for longer flight times drives up battery size. Increased battery size increases weight, which tends to decrease flight time. Phased array payloads with a large number of elements could benefit data collection, but increased payload adds weight and decreases flight time. The optimization is made far easier if the radar transmitter and receiver system is integrated into the hull of the UAS. We propose to study how the RF phased array can be printed into the hull of the UAS, using machine learning to optimize beam-forming for radio sounding. The Electrifi filament has a similar density to aluminum, meaning it can serve as *both* a structural component and a phased array material. Manufacturing structural components as phased array elements reduces costs, weight, and payload. Through this research, we seek to advance the ongoing CReSIS effort to minimize radar units for UAS integration.

As part of this engineering effort, we also propose to simulate expected results using MEEP. Performing a CEM simulation that incorporates our current knowledge of ice properties with the UAS radar response would enrich the research in two ways. First, such simulations enhance the design process, revealing design requirements, shortcomings, and ways to overcome them. MEEP simulations require the user to specify the complex matrix for the dielectric constant of the medium, $\epsilon(x, y, z)$. The ϵ matrix determines how RF waves reflect, refract, and propagate back to the receiver. Optimizing UAS phased array design for maximal $\epsilon(x, y, z)$ precision will result in optimal precision for $\lambda(x, y, z)$. For dielectric materials, ϵ and λ are related analytically [38]. Second, building such MEEP simulations will provide a cross-check between the observed $\epsilon(x, y, z)$ from field data, and the simulated $\epsilon(x, y, z)$.

FDTD simulations are notorious for consuming computational resources like volatile memory, while providing the necessary resolution for $\epsilon(x, y, z)$, and electromagnetic fields versus time, frequency, and space. At Whittier College, we have acquired a System76 Helio desktop system with AMD Ryzen threadripper 3990x 64-core, 128 thread processor. The system has 0.5 GB of volatile memory per thread. We have already shown that running MEEP in parallel on our system reduces run times by an order of

magnitude [11]. The reduction is due primarily to increased set up speed for $\epsilon(x, y, z)$. Thus, we are already in a position to perform such CEM simulations quickly and efficiently. Learning how to introduce parallelism into CEM problems will also be of educational benefit to our STEM undergraduates at Whittier College.

1.4 Integration of Research and Education at Whittier College

The integration of CEM and additive manufacturing into our STEM curriculum will benefit our diverse undergraduates in two ways. The first benefit is learning gains and boosted engagement from integrating our research into existing courses. The second benefit will be the creation of undergraduate research opportunities. For course integrations, there are some that can be done within our Department of Physics and Astronomy, and others that can take place in the Department of Mathematics and Computer Science. We already have mathematics and computer science faculty at Whittier College who specialize in machine learning. For example, Prof. Fred Park specializes in the application of machine learning and parallel computing to computer vision and image analysis [68, 69]. We will work with those colleagues to integrate this research into courses like Computer Logic and Digital Circuit Design, Digital Signal Processing, Machine Learning, and Introduction to Data Science with Python. I personally teach two of these courses, and I note below when collaboration with another instructor is required. For undergraduate research opportunities, we already have a track record of success. Our undergraduate researchers have made wonderful achievements in CEM, firmware design, and theoretical physics with our local Ondrasik-Groce and Fletcher Jones Fellowships. Our goal is to expand this practice through NSF-sponsored research fellowships in additive manufacturing, CEM, and machine learning.

1.4.1 Course Integrations - Electromagnetism and Computational Physics

One straightforward set of course integrations that will take place within the Department of Physics and Astronomy are: Algebra-Based Physics II (Electricity, Magnetism, and Modern Physics)*, Calculus-based Physics II (Electromagnetism)*, Electromagnetic Theory, Optics, and Computational Physics¹. The first two courses contain the standard introductory level course content on electromagnetism. Simple web-based learning modules can be developed to illustrate the concepts of electromagnetic waves and optics via MEEP in Jupyter notebooks. Jupyter (<https://jupyter.org/>) is an open-source project that supports interactive data science and scientific computing across all programming languages. We have experience creating and sharing MEEP notebooks to accomplish research [3], and in teaching Computer Logic and Digital Circuit Design using the PYNQ-Z1 SoC (<http://www.pynq.io/>). Such notebooks and modules can be integrated into Moodle, our web-based content management system (CMS). The primary enhancement to student learning is to illustrate dynamic electromagnetic fields subject to interesting boundary conditions. These examples should be shown alongside similar textbook examples, so the students can compare them. The final projects are student-designed DIY physics experiments in DC circuits, optics, and magnetism. We look forward to introductory students who accept the challenge of matching simulation output to their real-world results.

As part of our tenure-track process, we at Whittier College are required to submit reflective analyses of our teaching, research, service, and advising every two years. The teaching reflections have revealed the learning value of the synergies between traditional lecture content, simulations, and lab experiments. Students are fully prepared to apply ideas of physics in their own projects when the ideas solidify in their minds. Solidification occurs when they demonstrate them as theoretical predictions, simulate them, and test them in the lab. After solidification, their confidence is such that they stop questioning their understanding of a concept and start to use it. A good example is DC circuit analysis. We first solve systems of equations that predict currents through multiple devices connected to a battery. In a popular PhET simulation, PhET DC Circuit Construction Kit, current and charge are animated, and students can

¹I personally teach Algebra-Based Physics II, Calculus-Based Physics II, and Electromagnetic Theory. Optics and Computational Physics are normally taught by my colleagues within Physics and Astronomy. Computational Physics will soon be handed to myself and others as the usual instructor retires.

make virtual (simulated) measurements. The students replicate the virtual circuit in the lab, and show that the volts and amps in real life match the simulation. Apprehension fades to confidence when they see that they got it all to match. There are relatively few HTML5 PhET simulations that illustrate dynamic electromagnetic fields, however. Jupyter modules utilizing MEEP routines can fill this gap for introductory students.

We have three opportunities to integrate this research within advanced physics courses: Optics, Electromagnetic Theory, and Computational Physics. Our Optics course introduces students to three areas. The first is ray optics, with discussions of lenses and optical instruments. The second is wave optics, with discussions of superposition, interference, and diffraction. The third is modern optics, with discussions of photons, spectra, lasers, interferometry, fiber optics, and nonlinear optics. One useful module in ray optics would be a lens example that demonstrates magnification of images and focal length. As the course progresses to wave optics, the lens example could be enhanced more complex, photonics examples [70]. The modern optics curricula presents rich opportunities to demonstrate course concepts, including flux and spectral monitoring for diffraction gratings [71], and waveguides for fiber optics [72]. These modules will prove useful to our students, because most Optics students have had at least one semester of Python (Computer Science 1) and one semester of Modern Physics. As I do not personally teach this course, the adoption of these modules can be at the discretion of the normal instructor. Our department is small (four faculty), and has a good track record of collaboration.

The course integration in Electromagnetic Theory carries great potential. This one-semester course usually covers chapters 1-7 of *Introduction to Electrodynamics* by D. Griffiths (Cambridge University Press, 2017), with some examples of electromagnetic waves. Though students are exposed to electromagnetic waves in an intermediate course (Modern Physics), the advanced course gives a minor elaboration on waves in vacuum. Using Jupyter modules with CEM, students can be exposed to the interaction of waves with non-uniform dielectric media. The difference between ray-tracing and true three-dimensional propagation in polar ice with $n(x, y, z)$ is an excellent example of how the UHE- ν research, CEM, and teaching all coalesce (see Sec. 1.2). Another possibility is to introduce waveguides and related devices. There are many examples in the MEEP documentation, including “the S-parameters of a directional coupler.” It was this example that provided the open-source code for computing the S-parameters of our RF antenna designs [11]. Finally, we can introduce a Jupyter module encompassing specular and diffuse reflection from rough surfaces. This module would connect the CReSIS radio sounding research, CEM, and teaching together (see Sec. 1.3). Once the 3D printed RF antennas are produced, they can be showcased as a practical application of electromagnetic theory and CEM.

1.4.2 Course Integrations - Computer Logic and Digital Circuit Design, and Digital Signal Processing

As part of my teaching practice at Whittier College, I regularly create and teach computer science courses. Among these are Computer Logic and Digital Circuit Design, and Digital Signal Processing. The former covers number systems, Boolean algebra and complex logic functions, adders, encoders, comparators, shift-registers and memory, counters, finite state machines, timing diagrams, firmware programming with Python, and lab techniques for digital circuits, and ADC/DAC. The laboratory component of this course is performed on the PYNQ-Z1 SoC (<http://www.pynq.io/>), allowing students to write firmware in Python. Examples of laboratory activities in this course include creating digital logic functions with LED outputs and ADC/DAC examples with Digilent PMODs. There are a plethora of examples with the PYNQ community that demonstrate neural networks and image/video processing that all involve some form of FPGA acceleration. These examples can serve as inspiration for algorithms that will aid in the CEM design phase for the phased array research. Many of the students who take this course will be actively seeking research opportunities, and we have recruited research students from this course in the past. Thus, boosting the machine learning and FPGA acceleration aspects of the course will serve educational and research purposes.

Digital Signal Processing (DSP) is another course I created and teach regularly within Computer Science. Among the topics covered are statistics and probability, complex numbers, noise in digital systems,

ADC/DAC, sampling and digitization, Fourier series, Fourier and discrete Fourier transforms (DFTs), Laplace and z-transforms, linear time-invariant (LTI) systems and filtering, audio and image processing, applications to digital circuits, and applications of neural networks. Though this course was originally created independently of Computer Logic and Digital Circuit Design, it has evolved to become a continuation of it. These two courses can take students all the way from basic binary to complex analysis of digitized signals. A potential course integration between DSP and our open-source CEM research is the application of DFTs to MEEP flux monitors and near-to-far-field monitors. These are CEM objects that compute the integrated flux of radiation passing through a surface as a function of frequency using a DFT. Students can see that the radiation is nothing more than a digitized sampled signal within a CEM context, and that the DFT is a tool for understanding the radiation spectrum. We can adapt Jupyter modules we have already written to this task.

1.4.3 Course Integrations - Introduction to Data Science with Python, and Machine Learning

Two additional courses within the Mathematics and Computer Science Department that represent integration opportunities are Introduction to Data Science with Python, and Machine Learning. The former is an introductory course that assumes the student has basic programming skills. The students learn import, explore, analyze, and visualize data using tools like Jupyter notebooks, NumPy, and Matplotlib. More advanced tools like Pandas, SciPy, and scikit-learn are introduced. The inclusion of Jupyter notebooks that generate data sets using CEM into the syllabus is straightforward. Quantities like radiation patterns and S-parameters versus frequency are fertile grounds for learning to visualize data with Matplotlib, as we have already done in publications [3]. Since scikit-learn is already included in the syllabus, performing RF antenna optimization with machine learning tools within scikit is also straightforward. Though I personally do not teach this course, it is taught by Prof. Glenn Piner, who is our colleague in the Department of Physics and Astronomy. By working together to incorporate these ideas as appropriate into this introductory course, our students will gain early preparation to perform the cutting edge research with MEEP and additive manufacturing. Ideally, once the RF antennas are manufactured, we can demonstrate their performance in class to provide the students with a real world application.

Our more advanced computer science course in this area is Machine Learning. Typically taught by Prof. Fred Park, this course assumes a more advanced knowledge of Python and Calculus II. Topics include unsupervised and supervised learning, data clustering, principle component analysis, logistic regression, support vector machines, neural networks, and deep learning. One topic that might prove a useful addition to the list of topics is genetic programming, because this technique has been used to optimize RF antennas [73, 74]. We will work together to incorporate genetic programming as appropriate into the syllabus. As with Data Science, demonstrations of the optimized RF antenna would be ideal. This integration should enhance the course, because students will see the practical application of technical ideas in the fields of physics and geophysics, and climate science. This course in particular will be in high demand, because students understand the large number of opportunities that await them in the defense and software development sectors in Southern California once they master machine learning. One such opportunity will be our newly created Educational Partnership Agreement (EPA) with NSWC Corona. Our students will be doubly prepared for internships through the EPA, through the engineering experience from the RF application, and the machine learning training.

1.5 Timeline and Project Planning, Intellectual Merits

Example

Project Description: Broader Impacts

Overaching 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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