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 [?, ?, ?, ?, ?, ?, ?]. All AESAs have *radiation patterns* that define directions of maximum transmission power and received sensitivity, both due to constructive interferance of the transmitted or received RF plane wave. 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 one-dimensional phased arrays of dimension N is boosted by a factor of $\approx \sqrt{N}$, relative to a single RF antenna. The SNR boost increases sensitivity to signals that are otherwise unobservable with a single RF antenna. For example, systems created at the Center for Remote Sensing and Integrated Systems (CReSIS) are flown in polar regions to perform radio sounding of ice sheets in the context of geophysics and climate science [?]. 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. Some ice sheets can be several kilometers thick, so the radio echoes can have small SNR values that require phased array receivers.

Traditionally, phased array systems used in scientific projects are designed by hand, and commerical 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 [?, ?]. 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 [?] review a number of open-source CEM packages, and conclude that there are open-source options that match the performance of the commerical 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 [?]. We have shown that MEEP can drive the RF phased-array design process, and that 3D printer schematics can be extracted from this process [?, ?, ?].

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 Ω cm.

0.1 Computational Electromagnetism and Additive Manufacturing

Example

0.2 The Connection to Ultra-high Energy Neutrino Observations

Example

0.3 The Connection to Remote Sensing of Ice Sheets

Example

0.4 The Connection to Office of Naval Research Projects

Example