Broadband RF Phased Array Design for UHE neutrino detection

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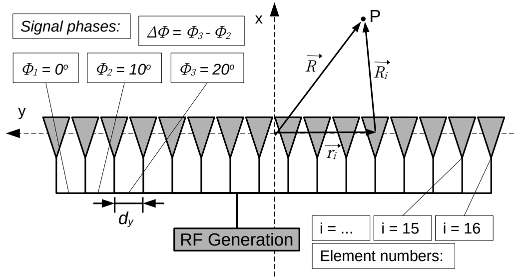
Abstract

Radio-frequency (RF) phased array systems have a wide variety of applications in engineering and physics research. Among these applications is ultra-high energy neutrino (UHE-v) detection above 100 PeV via the Askaryan effect. Phased array design usually requires numerical modeling with expensive commercial computational packages. Using the open-source MIT Electromagnetic Equation Propagation (MEEP) package, a set of phased array designs relevant for UHE-v detection is presented. Specifically, one-dimensional arrays of Yagi-Uda and horn antennas were modeled in the bandwidth of the Askaryan effect [0.1 - 5] GHz, and compared to theoretical expectations. Precise matches between MEEP simulation and radiation pattern predictions at different frequencies and beam angles are demonstrated. Finally, the effect of embedding a phased array within Antarctic ice is studied. Askaryan-class UHE-v detectors are being constructed in Antarctic ice because it is an ideal detection medium for UHE-v. Future work will develop the phased array concepts with parallel MEEP, in order to increase the detail, complexity, and speed of the computations.

Phased Array Theory



(1) $$\Delta\Phi \approx 2\pi(d_y/\lambda)\Delta\phi$$

(2) $$P(\phi) = \left(\frac{\sin(\pi N(d_y/\lambda)(\sin(\phi)-\sin(\phi_0)))}{N\sin(\pi(d_y/\lambda)(\sin(\phi)-\sin(\phi_0)))}\right)^2$$

Figure 1. The basic design of RF phased arrays is a line of RF antennas. When radiating or receiving plane waves, the relationship between incoming angle (Δφ) and phase shift between elements (ΔΦ) is linear (Eq. 1). The radiation pattern is derived from the far-field (Eq. 2).

RF Antenna Simulation in MEEP

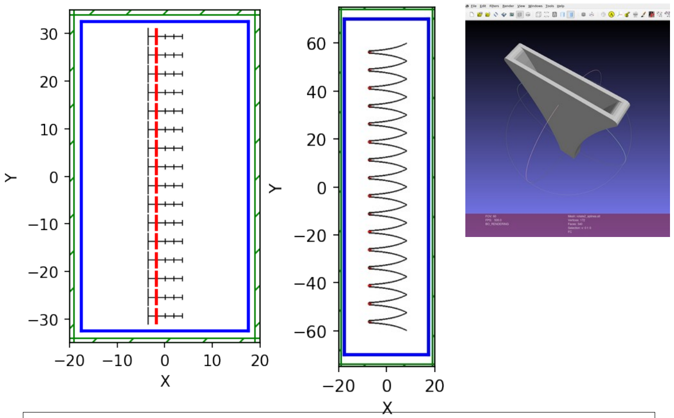
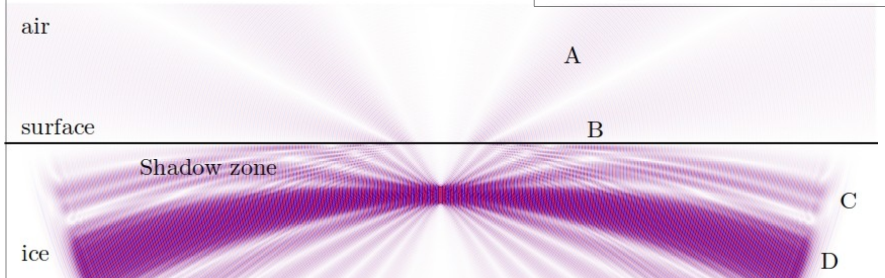


Figure 2. Examples of simulated phased array designs with MEEP. (Left) 16 Yagi-Uda elements. (Center) 16 horn antennas. (Right) Example CAD schematic file of horn. The electromagnetic radiation of these systems is computed in the far-field to obtain the radiation patterns.

Special Results: Non-Constant Index of Refraction, Antarctica and Greenland Cases for UHE-v detection. The radiated E-field was computed for a dipole array embedded in Antarctic ice with a realistic index of refraction profile. The index of refraction changes with depth, and therefore alters the radiation patterns.



The magnitude of the z-component of the E-field from the vertical dipoles. (A) Radiation refracting through the surface into the air. (B) Grating lobes reflect from the surface into the shadow zone. (C) Grating lobes propagating through the shadow zone. (D) The main beam bent downward due to the gradient in n(z).

Results: Constant Index of Refraction

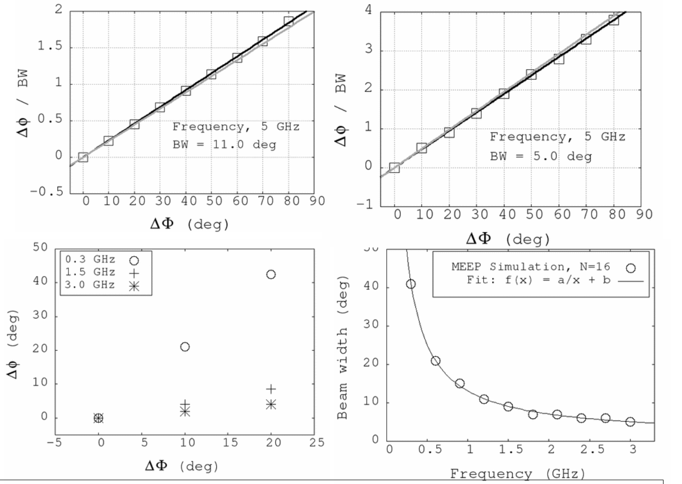


Figure 3. (Top left) Verification of Eq. 1, Yagi-Uda case, for 8 RF elements. (Top right) Verification of Eq. 1, Yagi-Uda case, for 16 RF elements. (Bottom left) Verification of Eq. 1 for 16 broad-band horns. (Bottom right) Horn beamwidth versus frequency. (Below) Examples of computed radiation patterns (blue) matching Eq. 2 (red), for 16 Yagi.