Particle-level model for radar based detection of high-energy neutrino cascades

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Abstract

We present a particle level model for calculating the radio scatter of incident RF radiation from the plasma formed in the wake of a particle shower. We incorporate this model into a software module (“RadioScatter”) that can be used in conjunction with a Monte-Carlo program to model the expected reflected signal from a given particle shower. RadioScatter calculates the classical scattering amplitudes using the individual particle equations of motion, accounting for collisions, transmitter and receiver geometries, refraction at boundaries, and antenna gain patterns. We find appreciable collective scattering amplitudes with coherent phase for a range of geometries, with high geometric and volumetric acceptance. Details of the calculation are discussed, as well as the implementation of RadioScatter into GEANT4. A laboratory test of such reflections, currently scheduled at SLAC in the spring of 2018, is briefly described. Prospects for a future in-ice, high-energy neutrino detector, along with comparison to current detection strategies, are presented.

Keywords: neutrino, particle-shower, radio-frequency, GEANT4, radio
Part One: Particle-level model; RadioScatter; lab tests

1. Introduction

High-energy particles incident on dense media will produce a shower of secondary particles. As these shower particles traverse the interaction medium, they eject cold ionization electrons from atoms in the bulk, forming a tenuous particle-shower plasma (PSP), distinct from the energetic shower front particles responsible for ionization. For high incident particle energies ($E \geq 1$ PeV, consistent with, and beyond, the experimental reach of the IceCube[1] experiment), this plasma may become dense enough to reflect incident radio-frequency (RF) radiation[2]. It has been recently suggested[3][4][5] that this technique could be used to advantage in the field of high-energy neutrino physics, where low fluxes and small interaction cross-sections demand large detection volumes. In the radio scatter approach, a large volume of interaction medium, such as ice, is illuminated with RF, and any PSP of sufficient density within this volume will reflect the incident RF to a distant receiver. Several experimental tests have been made to detect this phenomenon[6][7], but none have approached the incident particle energies, and therefore densities, of a true high-energy neutrino/ice interaction. It is this scenario that we discuss here.

There are several advantages of the radio scatter method over the current RF-based detectors for high-energy neutrinos, including ARA[8], ARIANNA[9] and ANITA[10]. Those experiments seek to detect primary “Askaryan”[11] emissions from the showers themselves. “Askaryan radiation” denotes collective Cherenkov radiation, confined to a cone of angular thickness $\sim 1$ degree, beamed at the usual Cherenkov angle. Detection of such emission is therefore constrained to the limited solid angle of the cone, significantly limiting the geometric aperture. The radio scatter method does not suffer from this geometric limitation, and has acceptance over a much larger portion of the solid angle surrounding a high-energy neutrino shower axis. Additionally, whereas Askaryan
signals are directly proportional to the energy of the primary neutrino, the radio scatter signal scales with both the neutrino energy as well as the output power of the sounding transmitter, such that a strong transmitter can effectively lower the neutrino energy threshold. The impulsive signal shape of Askaryan emission is also easily mimicked by anthropogenic transients, particularly at the South Polar ARA site, making background rejection challenging; the return signal from the radio scatter method is a characteristic, coherent, 20–30 ns burst of RF with frequency content set by the transmitter-shower-receiver geometry, permitting a well-tailored firmware trigger.

The PSP itself is a unique physical system. The cold ionization electrons are quasi-stationary, with energies of $O(10 \text{ eV})$ and an electron number density $n_e$ decreasing by a factor of $1/e$ longitudinally (Figure 1), while the $\sim 3 \text{ m}$ long shower front which produces them advances at $\beta \sim 1$. The lifetime of the PSP electrons is medium-specific, with a typical value $\tau \sim 10 \text{ ns}$. Note that the plasma lifetime $\tau$ refers to the average time required for individual free PSP electrons to be captured by positive ions in the medium, in contrast to the much-longer lifetime of the shower itself. For our proposed in-ice experiment, the lifetime of the plasma electrons is not well-established; nevertheless, (as detailed below) our GEANT-4 simulations indicate detectable, coherent radar returns for PSP lifetimes as short as 0.1 ns.

Direct radio emitted from acceleration of the shower particles themselves is currently neglected in the module. This is due to the fact that it will be largely beamed in the forward direction, and therefore only interferes with a small percentage of the RadioScatter detectable solid angle. Reflections from the relativistically moving shower particles are included, but are predominantly manifest at frequencies beyond the range of our planned data acquisition system (DAQ).
Several macroscopic models for radio scattering, treating the PSP monolithically, have been presented[12, 13] elsewhere. Although computationally economical, such models require assumptions regarding the development and characteristics of the plasma. Here, we calculate the reflected radar signal from the PSP microscopically, by summing over the individual scatterers, as modeled by GEANT4, and accounting for collisions using the single-particle equation of motion (EOM). GEANT4 [14] is the premier suite of simulation tools for particle interactions with matter. Users can specify nearly any projectile incident on nearly any target material and geometry, with access to individual four-momenta at run-time.

In what follows, we detail our particle-level calculation of the expected RF reflection from GEANT4 simulated showers.

2. Particle-level PSP model

Our calculation starts from the classical equation of motion for an electron, under the influence of an incident plane wave, and subject to collisions with
frequency $\nu_c$.

$$m \left( \ddot{x} + \dot{x} \nu_c \right) = q E_0 e^{i(k \cdot x - \omega t)} \tag{1}$$

The collisional term $\nu_c$ is expressed as a sum over the species in the plasma, as in \[15\].

$$\nu_c = \sum_s n_s \bar{v}_e \sigma_s; \tag{2}$$

here, $n_s$ and $\sigma_s$ are the number density and collisional cross-section of species $s$, respectively, and $\bar{v}_e$ is the mean thermal velocity of the electrons. Solving for the acceleration of the charge in Eq. (1) gives

$$\ddot{x} = \frac{q \omega E_0 e^{i(k \cdot x - \omega t)}}{m(\omega + i \nu_c)} \hat{\epsilon}, \tag{3}$$

where $\hat{\epsilon}$ is the polarization vector of the incident wave. Inserting this into the Larmour equation for the electric field $E_a$ of a single charge due to acceleration, and solving for the real part yields

$$\text{Re} \left[ E_a \right] = \frac{q^2 \omega E_0}{c^2 m R} \left[ \frac{\omega \cos(kx - \omega t) + \nu_c \sin(kx - \omega t)}{(\omega^2 + \nu_c^2)} \right] \hat{\epsilon} \times \hat{n}, \tag{4}$$

with the unit vector $\hat{n}$ pointing from the vertex to the receiving antenna. Eq. (4) is the basis of our particle-level simulation, with each PSP electron producing a field $E_a$. The resultant signal is then the time sum of these individual fields, as explained below.

We note two approximations in the above derivation:

1. The Larmour approximation used above ignores fields that fall off faster than $R^{-1}$, and is therefore only valid in the far-field, that is $R >> c/\omega$. For frequencies of $\mathcal{O}(1 \text{ GHz})$, this corresponds roughly to $R > 5 \text{ m}$. Experimentally, where TX/RX baselines are in the 1-10 km range or greater, near field effects can be safely neglected.
2. A well-known effect is that of dispersion of incident RF fields in plasma\[16\]. The dispersion relation for incident RF on a plasma, neglecting collisions, is

\[ k = \frac{1}{c} \sqrt{\omega^2 - \omega_p^2}, \]  

(5)

Where \( \omega_p^2 = n_e q^2 / \epsilon_0 m \) is also called the “electron plasma frequency”. If the interrogating frequency \( \omega \) is less than the plasma frequency, the wavenumber becomes purely imaginary, and the interrogating wave cannot penetrate the plasma, in which case the incident wave will reflect from the surface of the plasma rather than probing the entire PSP. There is, of course, a density gradient over which the transition from real to imaginary wave number occurs. This skin penetration depth into the plasma for a low frequency field (\( \omega << \omega_p \)) is parametrized as an attenuation length

\[ L_{atten} \approx \frac{c}{2 \omega_p}. \]  

(6)

In hot tokamak plasmas, for example, \( n_e \) can range from \( 10^{18} m^{-3} \) on the sheath of the reactor plasma to \( 10^{20} m^{-3} \) at the core. Low-frequency incident RF in these cases probes the transition from low- to high-density in what is known as the ‘scrape-off layer’ and scatter from the imaginary wavenumber portion of the dense plasma. In practice, lasers are used to ensure the Thomson scattering regime (\( \omega > \omega_p \)), in which case the plasma number density can be characterized as a function of distance into the core. Elsewhere in the literature, such as in meteor scattering and macroscopic treatments of the particle cascade problem, the high-density regime is also referred to as ‘overdense’\[17\][18].

The plasma densities, for showers from even the highest energy neutrinos, are not as high as those described above. For an ultra high primary neutrino energy of \( 10^{20} eV \), e.g., the total number of scattering electrons is \( \mathcal{O}(10^{18}) \). The highest number density along the shower axis for such a neutrino is \( 10^{17} m^{-3} \), as illustrated in Figure 2 corresponding to \( \omega_p = \mathcal{O}(1 \text{ GHz}) \) and an attenuation length \( L_{atten} \approx 2 \text{ cm} \) for low-frequency interrogating frequencies. If collective, surface scattering effects are significant in this ultra-high energy case, the Ra-
dioScatter signal would underestimate or mis-characterize the scattering signal. For a primary energy of $10^{19}$ eV, the peak plasma frequency is in the VHF, individual particle scattering regime.

![Figure 2: Expected ionization electron number density $n_e$ m$^{-3}$ for a GEANT4 shower with a primary energy of $10^{20}$ eV. For computational speed, our simulation has been run with a single, lower-energy primary, with the signal strength scaled accordingly.](image)

3. **GEANT4 implementation**

Here we describe the actual implementation of RadioScatter within the GEANT4 simulation package. We describe how the PSP is generated, and the technique for calculating the scattered signal from the PSP.

3.1. **Generation of the PSP**

GEANT4 provides particle-level information to the user at each step of a shower’s evolution, including the length of each step in mm (medium-density specific, and
internally-defined in GEANT4) and the energy deposited in the medium over
that step. GEANT4 utilizes an extensive library of materials and their prop-
erties, including cross-sections and ionization energies. To find the number \( N \) of
ionization electrons produced in each step of each shower particle, we therefore
divide the amount of energy deposited in the step by the ionization energy of
the medium. It is these ionization electrons which comprise the PSP cloud and
from which we calculate the scattered signal.

3.2. Calculation of the signal

From the 4-vectors of ionization electrons provided by the GEANT4 simulation,
we calculate the scattered fields for a specified interrogation frequency using
Eq. \( [4] \). From the ionization 4-vector, we determine the retarded time at the
transmitter, and, from that, the phase of the incident wave at the point of
interaction. The resultant fields for all \( N \) PSP particles are propagated back
to the receiver and summed in time bins corresponding to the user-defined
sampling period. For example, the resultant real part of the total electric field
at the receiver for a single sampling period \( T \) is given by

\[
Re [E_{tot}] = \frac{1}{T} \sum_{n=1}^{N} \int_{t}^{t+T} Re [E_{n}(t)] \, dt,  \tag{7}
\]

where \( E_{n} \) is given in Eq. \( [4] \). The factor \( 1/T \) is present because, in practice, a
standard digitizer effectively averages the measured voltage over the sampling
period, so we similarly calculate the average value of each \( E_{n} \) over a single
sampling period, and sum these average values. We then take this electric field
\( E_{tot} \) and multiply by an antenna effective length to obtain the voltage read
on an oscilloscope, e.g. The imaginary portion, which defines attenuation, is
calculated, as well.

3.3. Example signal

The TX–RX–PSP geometry for a typical event is shown in Figure \( [3] \). In this example, the coordinate system is set so that the shower vertex occurs at \((0,0,0)\)
and the shower evolves in the $+\hat{z}$ direction. The polarization, angle, and geometry conventions are presented graphically in Figure 4.

Figure 3: The geometry of the radar set-up for Figure 5 The shower vertex is at (0,0,0) with the shower progressing in the $+z$ direction.

Figure 4: Geometry conventions used in RadioScatter.
Figure 5: Simulated radio reflection for a 5 GHz bandwidth receiver, from an electron-initiated plasma consisting of $10^9$ 13.6 GeV primaries, superimposed upon thermal noise, assuming a sounding frequency of 1.15 GHz CW and neglecting particle collisions. The observed red-shift results from the shower progressing away from, rather than towards, the TX-RX baseline.

Figure 5 is an example of a simulated reflection from RadioScatter, in units of voltage. In this simulation, a 13.6 GeV electron beam with a bunch count of $10^9$ electrons is incident on high-density polyethylene (HDPE, and corresponding to the target planned for our upcoming SLAC testbeam). The target is interrogated with 1.15 GHz continuous-wave (CW) radio signal, with horizontally polarized (i.e., antennas in the same plane as the shower axis) TX and RX. To obtain this result numerically, the user must specify an effective antenna height, in units of meters, to properly scale the electric field at the antenna. By default, RadioScatter sets the effective height at 1 m, so that the voltage recorded is simply the electric field at the antenna with units of voltage. To correctly calculate the arrival times of the re-radiated fields, it is necessary to calculate the time–of–flight for the rays. A full treatment of the ray-tracing, including refraction effects at a boundary and an analytic solution for Snell’s law in the plane, is included in RadioScatter and given in the Appendix.

The characteristic frequency shift shown in the right panel of Figure 5 is a generic feature of the return signal, and is observed in both horizontal and vertical polarizations. The phase relationships between reflections from different parts of the plasma as it progresses through 4-space result in a coherent
frequency shift of the received signal, even though none of the scatterers themselves have any appreciable 3-velocity, and the interrogating radio is monochromatic. Experimentally, such a unique signal can be used to advantage in a low signal-to-noise trigger, as in [19].

Since the number of shower particles is several orders of magnitude lower than the number of ionization electrons, scattering from the shower particles themselves is also neglected, as inverse Compton scattering of the relativistic shower particles shifts the interrogating frequency up and out of band.

3.4. Collisions

Collisional effects, which become evident at primary energies $> 10^{16}$ eV, and should roughly scale with density, are arguably the largest unknown in the model. The three dominant collision species are electron-electron (“e-e”), electron-ion, and electron-neutral. We employ Equation 1 using simple atomic cross-sections for the $\sigma_s$ terms. In general, within a plasma, e-e collisions have the highest collision frequencies, but because the transport and collision rates are not well-known for ice, we multiply the e-e rate by a factor of three to conservatively account for all species. Our testbeam experiment will measure the sum of these three effects.

As mentioned, GEANT4 returns the deposited energy at each step along a shower particle’s track. These energy deposits are divided by the ionization energy of the material (provided by GEANT4) to calculate the number of ionization electrons produced at each step, directly yielding the instantaneous electron number density. To minimize computational time, the signal from a high-energy ($E > 1$ EeV, e.g.) primary neutrino is approximated by scaling simulated showers of energy $E/N$ by the same factor $N$ (typically, $10^3$-$10^{12}$). The drawback of such a scaling, however, is that the effect of density fluctuations become non-statistical, and artificially magnified.

Figure 6 illustrates the effect that collisions can have on the coherence of a received signal for showers with very high densities in RadioScatter. If the number of ionization electrons in the shower is increased by a factor of $10^5$,
corresponding to a primary neutrino energy of $10^{23}$ eV, the received waveform is no longer fully coherent, with a peak amplitude well-below that expected for linear scaling with energy.

Figure 6: Simulated radio reflection from an electron initiated plasma with $10^{14}$ primaries with an energy of 13.6 GeV, including thermal noise for a 5 GHz bandwidth, and a 1.15 GHz interrogation frequency. The loss of coherence is due to the collisional term in Eq. (4).

Figure 7 shows the peak voltage of a received signal as a function of the primary neutrino energy, now accounting for collisions. The energy scaling is linear in log-log space until the primary neutrino energy reaches $10^{16}$ eV, at which point collisional effects dampen the growth in signal strength, underscoring the importance of direct measurement of such scaling in a controlled, test-beam environment.
3.5. Plasma lifetime

A further unknown in PSP physics is the true plasma lifetime for a given material, presumably dominated by ionic recombination or attachment to neutrals. In the classical picture, a free charge will oscillate in phase with an incident field. In the limit that the lifetime $\tau$ of this charge approaches zero, that is, $\tau << 1/f$, where $f$ is the interrogation frequency, the charge does not “live” long enough to make a full oscillation. Instead, the charge gets a ‘kick’ from the field, with a direction dictated by the polarization and phase of the incident RF at that point in 4-space. The different time-scales are compared graphically in Figure 8.
As \( \tau \to \infty \), once the charges \( q_1 \) and \( q_2 \) are freed from the medium, they begin to radiate in phase with the incident field. As \( \tau \to 0 \), the charges move only briefly (less than a single oscillation period), and their polarity is given by the instantaneous phase of the incident RF.

Figure 8: Graphical representation of the limiting cases for the free electron lifetime \( \tau \). As \( \tau \to \infty \), the charges \( q_1 \) and \( q_2 \) are freed from the medium, they begin to radiate in phase with the incident field. As \( \tau \to 0 \), the charges move only briefly (less than a single oscillation period), and their polarity is given by the instantaneous phase of the incident RF.

Figure 9: Simulated time traces and spectrograms for an array of scatterers with lifetimes of (top to bottom) 1 ns, 10 ns, and 100 ns. The frequency of the transmitter is set to 1 GHz, and the geometry is that of Figure 3. The duration of the return signal is observed to scale with lifetime.

Due to computational resources, there is currently no mechanism to set the lifetime of the plasma in RadioScatter when running within GEANT4 (this is planned for the next release). Nevertheless, we can, using a stand-alone simula-
tion, create an artificial, one-dimensional ‘shower’ with persistent electrons and estimate the signal dependence on lifetime. In Figure 9 we have simulated 1000 electrons with even spacing along the z axis. We interrogate these reflectors with 1 GHz CW, with TX power such that the signal is well above thermal noise, and using the same TX and RX geometry as in Figure 3. The resultant signals for lifetimes of 1 ns, 10 ns, and 100 ns are given in Figure 9. The duration of the return signal scales with lifetime, with no evident frequency dependence. Comparison of empirical results, derived from our testbeam experiment, to this short lifetime simulation should allow measurement of the plasma lifetime in the medium.

3.6. Antenna response

RadioScatter allows the user to input an antenna gain pattern as a text file with gain, specified separately for TX and RX, as a function of polar and azimuthal angles. Planned for future releases of RadioScatter is an antenna system response that can be convolved with the received signal. This response can be a complex effective height, or a group delay, or an impulse response—i.e., all the variables which characterize the dispersion and amplitude response of an antenna. We note that, unlike Askaryan detectors, which are sensitive to the peak Cherenkov voltage, summing over frequency, the RadioScatter approach is considerably less sensitive to antenna dispersive effects, e.g.

4. Upcoming experimental test

The end station test beam (ESTB) facility at the SLAC National Accelerator Laboratory is a user facility which allows researchers to install targets and detectors downstream of a \( \mathcal{O}(1 \text{ Hz}) \) switched electron beam (roughly \( 10^9 \) 10 GeV particles per bunch) from the main Linac Coherent Light Source (LCLS). We have proposed using the well-characterized T-510 Experiment target of high-density polyethylene (HDPE) to approximate an in-situ PSP mimicking that of a neutrino/ice interaction. We will then interrogate the PSP within the HDPE
target with pulsed CW radio, and measure the scattered RF signal. Figure 10 shows the experimental setup, which was originally designed and optimized for measuring the combined Askaryan and geomagnetic emissions from air showers.

Figure 10: GEANT4 representation of the SLAC beam line test, showing a particle shower inside of the HDPE target. The size and type of antennas are not to scale, although the relative distances are approximately accurate for an interrogation frequency of 2 GHz.

This experiment is tentatively scheduled for spring, 2018. The expected signal for the configuration shown in Figure 10 is that shown in Figure 5 with separation distances as given in Figure 3.

**Expected Science Reach**

We now consider the signals from high energy neutrinos in ice. In what follows, the transmitting frequency is 450 MHz unless otherwise stated, and, for distant neutrino interactions, the measured attenuation length of ice\cite{21} is used in all calculations. We note that the 10-kW, 10 MHz SuperDARN transmitter at South Pole would result in signals observable with the surface antennas deployed with ARA stations 1, 2, and 3.
5. Effective Detector Volume

Even for modest 100 W transmitter output power, our simulation indicates that the radio scatter method can achieve sensitivity to $O(10 \text{ PeV})$ neutrinos with greater sensitivity than the IceCube detector. Figure 12 shows the effective volume of a proposed radio scatter experiment in ice for various values of transmitter output power. The TX-RX configuration is shown in Figure 11, and consists of a single transmitter surrounded by 15 receiving antennas, 3 on each of 5 ‘strings’. To make this plot, $N=5000$ showers were produced at each decade of energy from $10^{13}$ eV to $10^{21}$ eV and distributed randomly within a $V=10 \times 10 \times 2.8$ km volume, to mimic the ice sheet at the South Pole. The effective volume $V_{\text{eff}}(\text{km}^3\text{sr})$ at each point in energy $E$ is given by $V_{\text{eff}} = n(E)2\pi V N^{-1}$, where $n(E)$ is the number of events detected.
at each energy. For simplicity we use a solid angle factor of $2\pi$ instead of $4\pi$ to restrict our study to down-going neutrinos (given Earth absorption), and assume a uniform distribution of interaction points within the target volume. We set an edge detection threshold of 150 $\mu$V at each receiver, corresponding to a signal-to-noise ratio for a 1.2 GHz bandwidth of roughly SNR$\sim$10, and, given the characteristic signature, we consider an event to be “detected” if any of the antennas trigger. For a 1 kW transmitter, a radio scatter experiment is projected to have greater sensitivity than IceCube above 1 PeV, and the newly-deployed ARA phased array\cite{ARA} up to $\sim$1 EeV. The radio scatter method is therefore a potential technique for bridging the gap between existing optical and RF detection schemes, essential to establishing the neutrino flux spectrum above 1 PeV.

Not included in the calculation (at the time of this writing) is a full treatment of the bending of rays in the slowly changing index of refraction over the upper $\sim$200 m of the Antarctic ice sheet. This is a geometric effect which will primarily result in re-distribution of signal flux and the presence of some shadow zones at horizontal viewing angles. We have therefore placed our receivers and transmitter in deep ice ($>200$ m deep), where the index of refraction is nearly constant, to mitigate the effect of such ray bending in the simulation.
Figure 12: Effective volume for a radio scatter experiment, for SNR=10, as a function of primary particle energy, for a 5 station, 3 antennas per station configuration. The geometry is shown in Figure 11. Curves correspond to fixed transmitter output power. For comparison, we also show the effective volume for RICE (reproduced from [23]), IceCube, and the projection for the ARA phased array with a ten station (16 phased antennas per station) configuration (reproduced from [22]).

6. Geometric acceptance

The geometric acceptance for the radio scatter technique is perhaps the most compelling rationale for further development of the technique, and is largely responsible for the apparent advantage over Askaryan detectors at < EeV energies. The Askaryan signal exploited by current experiments is forward-beamed, with measurable amplitudes constrained to the Cherenkov angle, corresponding to a restricted geometric aperture. By contrast, all of the individual ionization electrons within the PSP cloud are essentially separate dipole radiators polarized along the polarization axis of the TX antenna.
Figure 13: Trigger efficiency maps for a requirement of $\text{SNR} \geq 10$ as a function of angle for a $10^{18}$ eV primary $\nu$ at a radial distance of 1 km from the shower vertex. Left: vertically polarized TX and RX (perpendicular to, and out of the plane of, the shower axis). Right: horizontally polarized TX and RX (parallel to, and in the plane of, the shower axis). Angle and polarization conventions are shown graphically in Figure 4.

Figure 13 shows the trigger efficiency at $\text{SNR} \geq 10$ for a $10^{18}$ eV primary $\nu$ at a fixed radial distance of 1 km from the receiver as a function of spherical coordinates $\phi$ and $\theta$. To produce these maps, the receiver is moved around the solid angle of the shower at a fixed radial distance, and a trigger efficiency is calculated at each point. These threshold maps are very similar to dipole radiation patterns for vertical and horizontal antennas respectively. We observe that a high percentage of the solid angle map has high trigger efficiency.

7. Potential experimental setup

An in-ice radio scatter telescope could be installed with a minimum of apparatus. The geometry of Figure 11 would require drilling 5 holes to a depth of 1.5 km, with each of the 4 perimeter holes measured 1 km from the center hole. The transmitter would be lowered into the center hole, along with one detector string. Each detector string has 3 antennas separated vertically by 500 m. The antenna spacing has been chosen to maximize the distance between antennas while considering the attenuation length in ice.

For a 1 kW transmitter, an isolated location is most desirable, so as to not interfere with other RF experiments. A remote Antarctic location, such
as Dome C, or a location in Greenland may be considered for such a deployment. In this paper, the ice properties from South Pole were used, as they have been well-characterized, and South Pole currently sites several neutrino detection experiments. Were this detector to be located at the South Pole, a deep transmitter should not interfere with other experiments, with RF “leaking” out to the air only at angles approximately normal to the surface. Transmission from ice to air will be reduced at more glancing angles, owing to the Fresnel Coefficients.

The detector strings would be powered by solar during the austral summer, and possibly wind in the austral winter. Data may be relayed from the strings to a central hub via microwave ethernet link. The 1 kW transmitter can similarly be powered by a large solar bank during the austral summer, and wind in the winter.

As a pilot implementation, we mention that a preliminary test of the method could be performed by deploying a single transmitter and writing a firmware module trigger for the ARA experiment. The ARA array, though not ideally spaced for a radio scatter experiment, covers a sufficiently large area to be sensitive to the radio scatter method with high efficiency. A plot showing the effective volume for 3 ARA stations employing the vertically polarized antennas only, with a 1 kW transmitter placed centrally between the 3 ARA stations as shown in Figure 14. The sensitivity of such a setup is comparable to a 100 W, 5 station × 3 antenna, dedicated, setup as above.
8. Discussion and outlook

We have presented a particle-level model for radio/PSP interactions that can be simply incorporated into a GEANT4 simulation. We have shown that the sum of reflections from individual scatterers results in an appreciable scattered signal amplitude with coherent phase. We have included the effect of collisions, and observe appreciable signal amplitudes for plasma lifetimes as short as $O(100 \text{ ps})$.

An in-ice detector with a single 1 kW transmitter has been presented, which has higher calculated sensitivity to neutrinos between 1 PeV and 1 EeV than current optical and Askaryan detectors. This model will be tested in a test-
beam experiment at SLAC, planned for spring, 2018. Pending experimental verification, we hope that the radio scatter method may be the next step toward high energy neutrino detection.

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