

Radio Detection of Ultra-high Energy Cosmic Rays and Neutrinos

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At energies above 10 PeV or so, the scale for detectors of neutrinos must be much larger than the cubic kilometer scale that applies to the TeV-PeV range. If the goal for such detectors is the observation and characterization of the cosmogenic neutrino flux from the interaction of the highest energy cosmic rays throughout the universe, then the required target must approach or exceed 1000 km^3 of water equivalent mass. The only viable approach that has been proposed for such enormous target volumes is through radio Čerenkov detection. We review the basis for this, along with experimental results and plans. For high energy cosmic rays, radio detection may provide an alternative to direct particle detection which does not suffer from the low duty cycle of other complementary methods such as nitrogen fluorescence. The radio emission from high energy air showers may be detectable at the same duty cycle as the particle detector, and might also afford the possibility for ultra-large arrays at low cost.

1. INTRODUCTION

The presence of the radio-to-far-infrared diffuse photon gas that fills the universe has immediate consequences for the propagation of high energy particles to which they couple electromagnetically. For a given background photon energy and a given high energy particle, there are several interaction processes which lead to severe energy loss for the high energy particle. For high energy gamma-ray interactions, the important process is pair production: $\gamma\gamma \rightarrow e^+e^-$ which becomes important first on far infrared background photons at gamma-ray energies of $\sim 50 \text{ TeV}$, and then through interactions with the cosmic 2.7K microwave background radiation (CMBR), with a photon number density far more than any other, for gamma-ray energies of 0.1 PeV and up. For protons at the highest energies near 10^{20} eV , the same microwave background provides targets with center-of-momentum energies sufficient to exceed threshold for the $p\gamma \rightarrow \Delta^+$ resonance, an interaction that has come to be known known as the GZK process, after Greisen, Zatsepin, and Kuzmin [1], who first noted that it must necessarily terminate the ultra-high energy cosmic ray spectrum if the particles are extragalactic.

One important conclusion that can be drawn from all of this is that extragalactic astronomy as we have known it for nearly a century—relying on photons as the primary messenger—can no longer be used to directly probe sources of radiation above $\sim 100 \text{ TeV}$ beyond a few tens of Mpc, several “optical depths” of the $p\gamma$ interaction length. Since this limits us to a tiny fraction of the known universe, we must look for other messengers if we wish to study sources at even modest distances of 100 Mpc or more. High energy sources are certain to exist up to of order 1 ZeV (10^{21} eV), seven orders of magnitude in energy beyond where photons are cut off. This is equivalent in range to the entire near-infrared-to-MeV gamma-ray spectrum that now makes up a large fraction of current astronomical efforts. If we imagine where our understanding of extragalactic sources would be if we had to omit all data from any other seven-orders-of-magnitude portion of the electromagnetic spectrum, the importance of finding a channel over which we can probe this energy regime becomes acutely evident. The most obvious neutral, stable particle that can be used as a messenger in this energy regime is the neutrino.

Of course we are compelled to continue to seek the detection of the attenuated photons, protons, and nuclei as well, up to the highest energies we can do so, if only because they provide the best chance of determining the origins of such particles at least in the local universe. The problem of source identification and modeling is a difficult one; as R. Blandford has quipped during this summer institute, “These are desperate times” for both theory and experiment. The problem is not limited only to astrophysics; the existence of ZeV particles, with likely Lorentz factors of order 10^{12} , poses challenges that extend to high energy physics, cosmology, and other fronts as well.

On the experimental side of these challenges, the difficulties lie in the extremely small fluxes of the relevant particles, whether they are ZeV cosmic rays, which have been detected, or PeV-ZeV neutrinos, which have not yet been detected. The existence of neutrinos at fluxes closely tied to the flux of the UHE cosmic rays is widely held to be necessary for any standard model understanding of the UHECR sources and propagation [2]. For the UHECR, integral fluxes are at most 1 per km^2 per century

above 0.1 ZeV. For the associated neutrinos, integral fluxes from PeV to ZeV energies are currently bounded to be less than 1 per km² per day or so, but are almost certain to be less than 1/10th of that in practice. In addition neutrino interaction lengths at these energies range from of order thousands to hundreds of km in water, so “quantum efficiencies” or interaction probabilities, though far higher than for low energy ($\sim$ MeV) solar neutrinos, are still a fraction of a percent in any given cubic kilometer target mass.

The implication for experimental efforts at improving detection of these particles is that very large areas (for cosmic rays) or target masses (for neutrinos) are required. For cosmic rays, the interaction length of the particles is of order 50-100 gm cm⁻², and thus the atmosphere ($\sim$ 1000 gm cm⁻² vertically) is adequate both as a target mass and a fiducial volume, since instrumentation placed at the base of the atmosphere can observe events throughout its volume. Larger areas or numbers of detector elements observing larger volumes of atmosphere thus yield more events. Cost grows linearly with the ground area required. To detect 100 events per year above 0.1 ZeV (10^{20} eV) one requires $\sim 10^4$ km², of order that planned for the Auger Observatory. Assuming (very optimistically) an E^{-1} integral spectrum of UHECR, an area ten times larger would be required to probe the source spectrum at ZeV energies with similar statistics. For the more likely $E^{-1.5}$ spectrum, a factor of 30 larger detector is required, with implied costs of order \$1B or more. Since experimentalists must of necessity also be aware of what the market can bear, we are forced to look for techniques which are more cost-effective than the current approach if we are to extend UHECR measurements beyond the current end point. And for neutrinos in this energy regime, the situation is even more dire.

A possible solution is found in radio detection methods. In 1962 G. Askaryan [3] noted that electromagnetic cascades produced by the interactions of high energy particles must produce a coherent radio Cherenkov pulse, with a radio spectrum extending up to cm wavelengths in solids, limited only by the transverse size of the shower. This prediction initially generated interest for radio detection of high energy air showers, and soon after the prediction, John Jelley, who first measured optical Čerenkov radiation, had performed an experiment which detected the first radio pulses from air showers [4]. Over the next decade various measurements of radio pulses from air showers were made with mixed levels of success, and it was gradually realized that another other radiation mechanism, what has now become known as coherent geo-synchrotron radiation, is dominant in air showers, rather than the effect noted by Askaryan.

As a result of this, and of the difficulty of making air shower radio measurements in the presence of anthropogenic radio interference, the Askaryan effect was neglected for several decades. However, spurred on by renewed predictions of the importance of the Askaryan process for showers in the lunar regolith [5, 6] and in ice [7]. Saltzberg and Gorham [8] were able to confirm the Askaryan effect in an experiment at SLAC in 2000. Since that time, several experiments have now published limits on high energy neutrino fluxes based on the Askaryan effect, and these limits are now the best available constraints in the PeV-ZeV regime. This rapid progress has helped to also renew interest in the possibility of air shower radio detection, and several nascent efforts to build detector prototypes are underway.

In the following sections we will review the development of these techniques, leading up to the confirmation of the Askaryan process at SLAC. We then discuss several experimental results and current initiatives in both cosmic ray and neutrino detectors. We conclude with a discussion of future possibilities.

2. HISTORICAL BACKGROUND

2.1. Cosmic ray air shower radio detection

Askaryan’s major insight in applying the theory of Čerenkov radiation to electromagnetic showers was not simply his application of this radiation mechanism to radio wavelengths. By that time (1962) the frequency dependence of Čerenkov radiation was well understood, and the extremely low power implied at radio wavelengths by a single charged particle rendered the low frequencies uninteresting. Rather, Askaryan realized and showed by simple arguments that large multiplicative electromagnetic particle showers, since they develop in continuous matter (whether gas, liquid, or solid), must develop an excess of electrons over positrons, due to the combination of positron annihilation removing the positive charge, and Compton and delta-ray scattering adding new negative charge to the shower. This net charge asymmetry meant that, at wavelengths long enough that the individual particle Čerenkov radiation summed coherently in electric field strength, there would no longer be complete cancellation of the electron and positron emission, yielding a *quadratic* scaling of received power with the shower energy. This latter

property immediately suggests that radio emission might dominate the secondary radiation at the highest energies. Askaryan's estimate of a $\sim 10\%$ negative charge excess was in fact conservative; more recent simulations indicate twice or even three times this value in practice, giving up to an order of magnitude more radio power.

Askaryan applied this conclusion broadly to air showers, and showers in solids, concluding that the wavelengths of interest in the former case were in the range of hundreds of meters (several MHz), and in the latter case 1-100 cm. Interestingly, Askaryan also noted in his paper that V. I. Gol'danskii had suggested to him (Askaryan attributed it to a private communication) that geomagnetic polarization of air showers should also lead to significant coherent radiation—a prescient idea that has turned out to be in fact more important than Čerenkov radiation in the air shower case.

Spurred on by Askaryan's work, and his interest in Čerenkov radiation, John Jelley and his co-workers (including Trevor Weekes who has gone on to pioneer efforts in atmospheric Čerenkov gamma-ray detection at TeV energies) discovered the first evidence for radio emission from cosmic ray air showers in 1965 at a frequency of 44 MHz [4]. They used an array of dipole antennas in coincidence with Geiger counters. The results were soon verified and emission from 2 MHz up to 520 MHz was found in a flurry of activities in the late 1960's. Several experiments also established a strong geomagnetic dependence to the emission, which was by then recognized to be primarily due to what is effectively synchrotron emission from the partial-arc gyrations of the shower charged particles in the geomagnetic field. This process produces perhaps one order of magnitude stronger emission than the Askaryan effect, since it involves all of the charged particles, rather than just the excess charge.

These air-shower radio detection activities ceased almost completely in the subsequent years due to several reasons: difficulty with radio interference, uncertainty about the interpretation of experimental results, and the success of other techniques for air shower measurements. Only recently have these methods been revived, but with the current advantage of much more computational power for modeling, combined with the compelling problem of the highest energy cosmic rays, their appears to be every reason to believe that progress will be steady in bringing this approach to maturity.

2.1.1. Properties of the beamed radio emission

The radio properties of air showers are summarized in an excellent and extensive review by Allan (1971)[9]. The main result of this review can be summarized by an approximate formula relating the received voltage of air showers to various parameters, where we also include the presumed frequency scaling:

$$\epsilon_v = 20 \mu\text{V m}^{-1} \text{ MHz}^{-1} \left(\frac{E_p}{10^{17} \text{ eV}} \right) \sin \alpha \cos \theta \exp \left(\frac{-R}{R_0(v, \theta)} \right) \left(\frac{v}{55 \text{ MHz}} \right)^{-1}. \quad (1)$$

Here E_p is the primary particle energy, R is the offset from the shower center and R_0 is around 110 m at 55 MHz, θ is the zenith angle, α is the angle of the shower axis with respect to the geomagnetic field, and v is the observing frequency (see also Allan et al. 1970[11]; Hough & Prescott 1970[12]). The leading factor of 20 has been disputed over the years since it was first published, and could be an order of magnitude smaller. The controversy over this coefficient probably stems from the wide variation in measurement conditions and the uncertainties in the flux calibration of the radio antennas as well as in the energy calibration of the particles.

It is important to note that the coherent radio emission from air showers, because of the low density and refractive index of air, is a highly beamed process, and the emission pattern extends only to lateral distances comparable to the particle shower itself. It may also propagate much further than the soft portion of the particle shower, which is absorbed over distances of several tens of kilometers. The radio frequency spectrum is broad, extending out to of order a hundred MHz or so before falling off more steeply, and the pulse width is of order 10 ns within a few hundred meters of the shower axis.

2.1.2. The synchrotron model and recent work.

Experiments in the 1960's more or less clearly established that cosmic ray air showers produce coherent radio pulses. However, the dependence of the emission on the geomagnetic field detected in several later experiments indicated that interaction with the geomagnetic field played a significant role in the emission process, and this observation led to immediate doubt that the coherent Čerenkov mechanism was the primary source, since it had no dependence on magnetic fields. The basic view that then developed in the late 60's was that the continuously created electron-positron pairs were then separated by the Lorentz force in

the geomagnetic field which led to a transverse current in the shower. If one considers a frame moving along with the shower, one would observe electrons and positrons drifting in opposite directions impelled by the transverse electric field induced by the changing geomagnetic flux swept out by the shower front. (Only in the case of shower velocity aligned with the magnetic field lines will this induced electric field vanish). This transverse current then produces dipole (or Larmor) radiation in the frame of the shower. When such radiation is Lorentz-transformed to the lab frame, the boost then produces strongly forward-beamed radiation, compressed in time into an electro-magnetic pulse (EMP). This was calculated by Kahn & Lerche (1966)[13] and also Colgate (1967)[14].

Falcke & Gorham (2003)[15] suggested it might be better to think of the emission simply as being synchrotron-like in the earth's magnetic field, or "coherent geosynchrotron emission", as they called it. This process is probably equivalent to the previous suggestions since it is derived from the basic formula for dipole radiation and the Poynting vector but does not require a consideration of charge separation: the different sign of the charges is canceled by the opposite sign in the Lorentz force for electrons and pairs and hence both contribute in exactly the same way to the total flux (radio astronomers will surely remember that an electron/positron plasma produces almost the same amount of synchrotron emission as a pure electron plus proton plasma).

The basic and intuitive derivation of this effect can be found in Falcke & Gorham (2003)[15] using standard synchrotron radiation theory. One important effect which is explicitly neglected by this simple treatment is the Fresnel zone problem – vertical air showers at 10^{19} eV reach their particle maximum at ground level, and the radio emission arrive nearly simultaneously to the particle "pancake," indicating that the far-field conditions, where the radiation field has had time to become well-separated from its source, are not satisfied. Any estimate of the details of the received radio emission which is intended to help with detailed detector design must therefore treat the problem with much greater fidelity.

Such high-fidelity simulations of geosynchrotron emission are now beginning to appear in the literature, and as the interest in this approach grows, along with the compelling nature of the ultra-high energy cosmic ray problem, the simulations can be expected to improve as well. In the following section, we describe recent results in this direction.

2.1.3. Air shower electrodynamics: detailed modeling and Monte Carlo simulation.

The challenge of developing high-fidelity air shower radio simulations breaks into three distinct problems:

1. The adaptation of existing air shower simulation codes to provide the particle identification and sampling needed for electrodynamics modeling;
2. The implementation of actual electrodynamics computation within the modified air shower code, and the development of radiation propagation model; and
3. The modeling of the detector geometry and detection process.

To date, no group has implemented all three aspects of this program, but we describe here two efforts which have gone much further than others in addressing the difficult problem of the electrodynamics and detection modeling.

A. Simulations by the Chicago/Hawaii group.

One result with a first-order electrodynamics Monte Carlo simulation has been completed by Suprun et al. (2003)[16] in a joint effort of the Univ. of Chicago group headed by Jon Rosner, along with this author at the Univ. of Hawaii. This study investigated a 10^{19} eV vertical air shower, including explicit geomagnetic effects, with general interest in elucidating issues for detection by a possible radio augmentation to the Auger Observatory for ultra-high energy cosmic rays.

The Suprun et al. simulation did not make any simplifying assumptions regarding far-field conditions. Instead, the electrodynamics simulation began with the general formula for a radiating particle [7, 17] in arbitrary motion:

$$\mathbf{E}(\mathbf{x}, t_a) = \frac{e\mu}{4\pi\epsilon_0} \left[\frac{\mathbf{n} - n\boldsymbol{\beta}}{\gamma^2 |1 - n\boldsymbol{\beta} \cdot \mathbf{n}|^3 l^2} \right]_{\text{ret}} + \frac{e\mu}{4\pi\epsilon_0 c} \left[\frac{\mathbf{n} \times [(\mathbf{n} - n\boldsymbol{\beta}) \times \dot{\boldsymbol{\beta}}]}{|1 - n\boldsymbol{\beta} \cdot \mathbf{n}|^3 l} \right]_{\text{ret}} \quad (2)$$

which is correct regardless of the distance to the antenna. In this formula β is the velocity vector in units of c , $\dot{\beta} = d\beta/dt$ is the acceleration vector, divided by c , $\mathbf{n}$ is a unit vector from the radiating particle to the antenna, and l is the distance to the particle. $\mu \approx 1$ denotes the relative magnetic permeability of air, n the index of refraction. The square brackets with subscript “ret” indicate that the quantities in the brackets are evaluated at the retarded time, not at the time t_a when the signal arrives at the antenna.

The first term decreases with distance as $1/l^2$ and represents a boosted Coulomb field. It does not produce any radiation. The magnitudes of the two terms in Eq. (2) are related as $1/(\gamma^2 l)$ and $|\dot{\beta}|/c$. The characteristic acceleration of a 30 MeV electron ($\gamma \approx 60$) of an air shower in the Earth’s magnetic field ($B \approx 0.5$ Gauss) is $|\mathbf{a}| = ecB/(\gamma m) \approx 4.4 \cdot 10^{13} \text{ m/s}^2$. Even when an electron is as close to the antenna as 100 m, the first term is two orders of magnitude smaller than the second and can be neglected. The second term falls as $1/l$ and is associated with a radiation field. It describes the electric field of a single radiating particle for most geometries relevant to extensive air showers. It can be shown ([18]Wheeler & Feynman 1949) to be proportional to the apparent angular acceleration of the charge up to some non-radiative terms that are proportional to $1/l^2$. This relation is referred to in the literature as “Feynman’s formula.”

Suprun et al. did not, however, yet perform a full cascade calculation, but rather used a parametrization of the shower density to generate a shower profile, then used Monte Carlo techniques to sample the particle distribution obeying this parametrization. In one of the longest-standing empirical models for air shower development, called the Nishima, Kamata, Greisen (NKG) model, lateral particle density ρ_e is parametrized by the age parameter s of the shower ($s = 1$ for the shower maximum) and the Molière radius r_m [19–21]:

$$\rho_e = K_N \left(\frac{r}{s_m r_m} \right)^{s-2} \left(1 + \frac{r}{s_m r_m} \right)^{s-4.5}, \quad (3)$$

where

$$K_N = \frac{N}{2\pi s_m^2 r_m^2} \frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)}, \quad (4)$$

Γ is the gamma function, r the distance from the shower axis, N the total number of charged particles, and $s_m = 0.78 - 0.21s$. The Molière radius for air is approximately given by $r_m = 74(\rho_0/\rho) \text{ m}$, with ρ_0 and ρ being the air densities at sea level and the altitude under consideration, respectively.

As a shower travels toward the Earth and enters denser layers of the atmosphere, the age parameter increases while the Molière radius drops. Both processes affect the spread of the lateral distribution. The influence of the age parameter appears to be more significant. As it grows, the average distance of the shower particles from its axis increases. This effect overcomes the influence of a smaller Molière radius which tends to make the lateral distribution more concentrated toward the axis. For a fixed age parameter s , however, the Molière radius is the only quantity that determines the spread of the lateral distribution. At shower maximum ($s = 1$) the average distance from the axis can be calculated to be $(2/3)s_m r_m = 0.38 r_m$.

Fig. 1 shows the results of the Suprun et al. simulation for the shape of the intrinsic radio pulse, in terms of field strength vs. time at the receiving antenna location, though without any of the filtering effects of any antenna imposed on it yet. Fig. 1 (right) gives the Fourier transform E_v of this pulse. The nonzero thickness of the air-shower pancake translates into a loss of coherence at frequencies corresponding to wavelengths comparable to the shower thickness, thereby limiting the main part of the radiation spectrum to the frequencies below 100 MHz.

These simulations, though using a greatly thinned set of input particles (10^4 compared to 10^{10} in actuality) do show characteristics similar to what was observed historically. In addition, the simulations also begin to reveal some of the geomagnetic complexity of the emission pattern, suggesting reasons for some of the surprising variations observed in the measurements by antenna arrays.

Consider the frame centered at the antenna, with axis Ox going to the magnetic West, Oy to the South and Oz directly up. The initial velocity of all charged particles is assumed to be vertical: $\beta = (0, 0, -1)$, while the initial acceleration $\dot{\beta}$ is parallel to Ox , or, in other words, to the $(1, 0, 0)$ vector.

Electrons bend toward the magnetic West and positrons toward the East. The electric fields from both particles of an electron-positron pair are coherent; the opposite signs of their accelerations are canceled by the opposite signs of the electric charges.

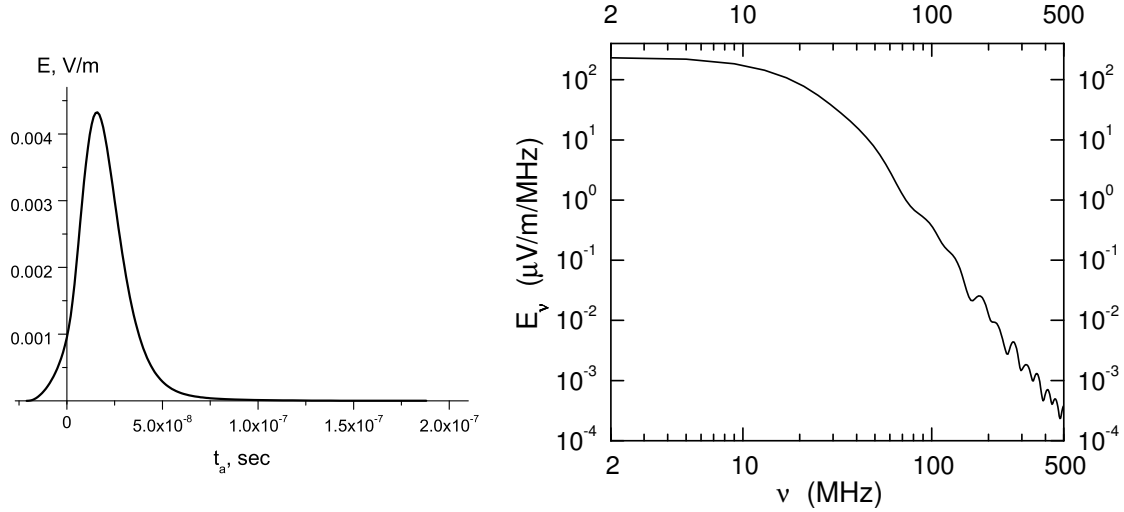


Figure 1: **Left:** The EW component E_{EW} of electromagnetic pulse of $0.33 \cdot 10^{10}$ radiating electron-positron pairs distributed over the thickness of the shower pancake at 1800 m above sea level. The axis of the pancake is located 200 m South of the antenna. The time axis was chosen in such a way that the pulse produced by a pair located in the axis at the bottom of the pancake starts at time 0. **Right:** The Fourier transform of the electromagnetic pulse shown in Fig. 1. The spectrum is very flat below 2 MHz. The limited statistics of the model results in some jitters at 200–500 MHz. The spectrum above 500 MHz is not shown because the statistics is not sufficient to make reliable predictions of the Fourier components at these high frequencies.

Let ψ be the angle between Ox and the direction to the shower core, R the distance to the core, and h the altitude of the radiating particle above the antenna. The denominator of the second term of Eq. (2) is independent of ψ . The numerator determines that, to leading (second) order in R/h , the initial electric field vector $\mathbf{E}$ received at the antenna lies in the horizontal plane and is parallel to $(\cos 2\psi, \sin 2\psi, 0)$ ([22]Green et al. 2003):

$$\mathbf{E} \parallel (\cos 2\psi, \sin 2\psi, 0). \quad (5)$$

The magnitude of the numerator is independent of the angle ψ up to terms of order R^4/h^4 . This result shows that although particles are accelerated by the Earth's magnetic field in the EW direction regardless of angle ψ , the radiation received at the antenna does not show preference for the EW polarization. Instead, it is directly related to the angle ψ . As the particle trajectory bends in the Earth's magnetic field and the velocity deflects from the vertical direction, the relation (5) between the direction of the electric field vector and angle ψ does not hold. Nonetheless, it will be useful for understanding the angular dependence of the electric field.

Suprun et al. computed electromagnetic pulses for the pancakes with axes located at the same distance $R = 200$ m from the antenna but at various angles ψ from the Ox direction. Fig. 2 shows the radio signal strengths that would be received by EW and NS-oriented antennas. Note that Eq. (5) predicts that components of the radiation coming from the start of the particle trajectory vanish at some angles ψ : $E_{EW} = 0$ at $\psi = \pm\pi/4, \pm3\pi/4$, while $E_{NS} = 0$ at $\psi = 0, \pm\pi/2, \pi$. This fact explains why E_{VEW} is relatively small at $\psi = \pm\pi/4, \pm3\pi/4$ and E_{VNS} is small at $\psi = 0, \pi$ (Fig. 2). Another mechanism is responsible for E_{VNS} being virtually 0 at $\psi = \pm\pi/2$. At these angles the trajectories of two charged particles of an electron-positron pair are symmetric with respect to the yOz plane. The NS component of radiation emitted by this pair vanishes not only at the start but throughout its flight.

B. Modeling by the LOPES collaboration.

Another simulation effort is under way in the Max-Planck-Institut für Radioastronomie at Bonn, led by H. Falcke. This group is part of a collaboration developing the LOFAR Prototype Experimental Station (LOPES), an engineering model of one station of the Low Frequency Array (LOFAR). LOPES is operating jointly with the KASCADE Grande air shower array in Karlsruhe (Schieler et al. 2003)[25]; LOFAR is a funded effort to develop a very large area ground array for radio astronomy in the HF

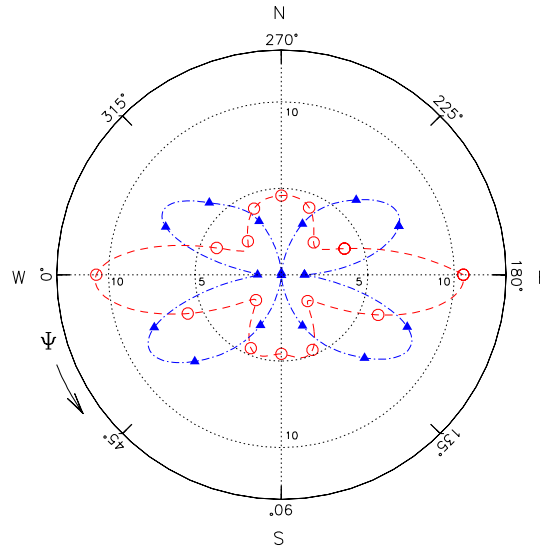


Figure 2: The East-West and North-South components of the field strength $|E_{VEW}|$ and $|E_{VNS}|$ (circles and triangles, respectively) at 55 MHz as functions of angle ψ between the magnetic West and direction to the shower core. The distance between the origin and a circle or a triangle represents the field strength in the units of $\mu\text{V}/\text{m}/\text{MHz}$. The angular spacing between circles or triangles is $\pi/8$. At $\psi = \pm\pi/2$ $|E_{VNS}|$ do not exceed $0.1 \mu\text{V}/\text{m}/\text{MHz}$ and two triangles overlap. All points were calculated for the vertical shower at a 200 m distance from the antenna.

to VHF regime. The LOPES group has recently published a detailed analysis of the geosynchrotron model for the case of a 10^{17} eV air shower [26][28] in preparation for a major effort at an electrodynamical air shower Monte Carlo code [29].

The LOPES group has taken special care of taking into account the longitudinal development of the air shower by performing an integration over the shower as a whole, and they have considered the variation of the field strength as a function of radial distance from the shower core as well. They use a shower parametrization based on the NKG model with a shower disk that flares out from the center, in a manner similar to the Chicago/Hawaii study, and thus, apart from the energy difference, the results do bear some comparison. The LOPES study also did an integral over a power-law distribution of electron energies, appropriate to an air shower. However, they did not do any near-field corrections to their results, but this is not a major drawback for a lower energy shower since these showers do reach their maxima at altitudes of typically several km away from an observer on the ground.

Fig. 3 shows the spectrum emitted by the air shower maximum for a shower disk profile with realistic flaring according to the parameterizations of Agnetta et al. (1997) [30] and Linsley (1986) [31]. As expected, the spectrum emitted by the Linsley flaring disk extends to higher frequencies than the one generated by the Agnetta flaring disk because of the lower thickness in the shower center where most of the particles reside.

The modeled radial dependence at different frequencies is also shown in Figure 3 (right). Here the three families of curves represent different frequencies, and the different slopes between the two curves at a given frequency are for the cases of an observer with a given distance from the shower center in the directions perpendicular and parallel to the geomagnetic field. This result thus indicates again the importance of the geomagnetic effects in the azimuthal distribution of radiation for a given magnetic field direction. Early results from the upcoming detailed Monte Carlo simulations of the LOPES collaboration, however, show that asymmetries in the emission pattern due to the geomagnetic field seem to be washed out to a high degree once realistic distributions of particle track lengths are taken into account [27].

Fig. 4 shows a reconstructed pulse generated by the flaring Agnetta disk as it would be measured by a receiver with a given bandwidth. The pulse amplitude drops noticeably when the observer moves from the center of the illuminated area on the ground to a distance of 100 m, and is already quite diminished at a distance of 250 m. The pulse length of ≈ 8 ns is a result of the filter bandwidth of 120 MHz, i.e. the pulse is bandwidth-limited.

The LOPES study addresses the important problem of integrating over the shower evolution as a whole in a simplified fashion by approximating the shower evolution with a number of discrete steps. The characteristic scale for these steps is given by the

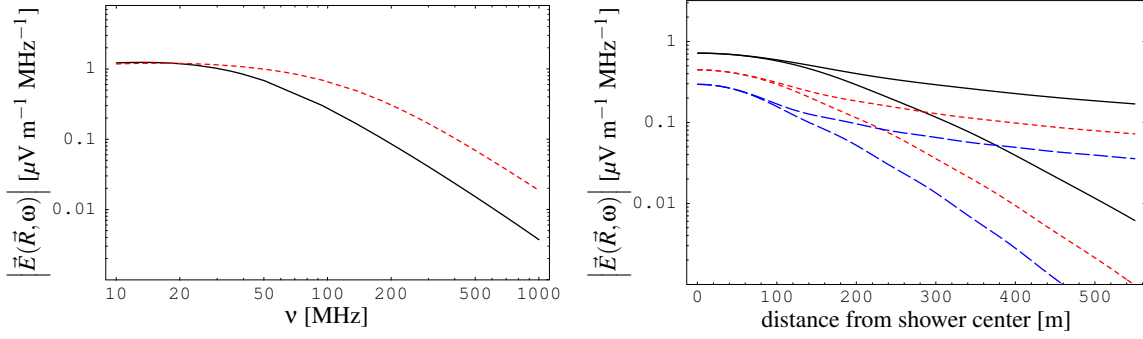


Figure 3: **Left:** $|\vec{E}(\vec{R}, 2\pi\nu)|$ -spectrum at the center of the area illuminated by the maximum of a 10^{17} eV air shower with flaring disk, $R_0 = 4$ km and a broken power-law energy distribution from $\gamma = 5$ –1000. Solid: flaring [30](Agnetta et al. 1997) lateral distribution, short-dashed: flaring [31](Linsley 1986) lateral distribution. **Right:** Radial dependence of $|\vec{E}(\vec{R}, 2\pi\nu)|$ for the maximum of a 10^{17} eV air shower with flaring (Agnetta et al. 1997) [30] disk, $R_0 = 4$ km and a broken power-law energy distribution from $\gamma = 5$ –1000. Solid: $\nu = 50$ Mhz, short-dashed: $\nu = 75$ Mhz, long-dashed: $\nu = 100$ Mhz, upper curves for distance from shower center to the east-west, lower curves for distance to north-south.

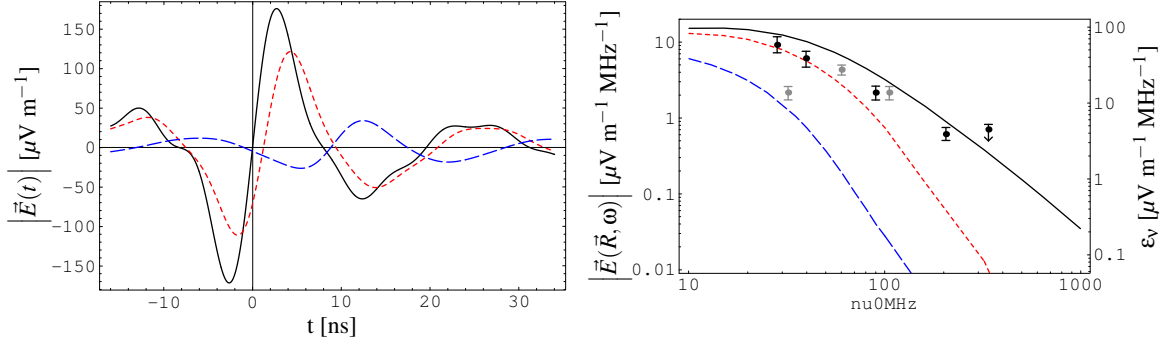


Figure 4: **Left:** Reconstructed pulses emitted by the maximum of a 10^{17} eV shower with flaring [30] (Agnetta et al. 1997) disk, broken power-law energy distribution from $\gamma = 5$ –1000 and $R_0 = 4$ km, using an idealized rectangle filter spanning 40–160 MHz. Solid: center of illuminated area, short-dashed: 100 m to north from center, dash-dotted: 250 m to north from center. **Right:** $|\vec{E}(\vec{R}, 2\pi\nu)|$ -spectrum of a full (longitudinally integrated) 10^{17} eV air shower with flaring [30] (Agnetta et al. 1997) disk, $R_0 = 4$ km and a broken power-law energy distribution from $\gamma = 5$ –1000. Solid: center of illuminated area, short-dashed: 100 m to north from center, long-dashed: 250 m to north from center, black points: *re-scaled* [33](Spencer 1969) data as presented by [9](Allan 1971), grey points: *re-scaled* [32](Prah 1971) data.

radiation length of the electromagnetic cascades in air, $X_0 = 36.7 \text{ g cm}^{-2}$, corresponding to ≈ 450 m at a height of 4 km. One can therefore discretise the shower evolution into “slices” of thickness X_0 , assuming these contain independent generations of particles and therefore radiate independently. Superposition of the individual slice emissions, correctly taking into account the phases arising from arrival time differences, then leads to the total emission of the shower.

For a vertical 10^{17} eV air shower at a height of $R_0 = 4$ km they add the emission from eight slices above and eight slices below the shower maximum to the emission from the maximum itself. The closest slice then lies at $R_0 = 950$ m from the observer, a distance they did not want to fall below because of approximations contained in their calculations that are only valid in the far-field.

Although this treatment is clearly oversimplified, the results depicted in Fig. 4 indicate that the integration over the shower as a whole significantly enhances the emission strength and thus cannot be neglected. In particular, this implies that the emission is actually not dominated by a narrow region around the shower maximum, but that the entire shower evolution contributes.

Data from the LOPES Experiment is now becoming available, and initial results indeed confirm the association of the air

shower with a sharp radio pulse, having the expected properties (e.g., Horneffer et al. 2004; see below)[34]. This puts the air-shower radio detection method on reasonably firm grounds.

It is interesting that in spite of the differences in the approach from the LOPES studies and those of the Chicago/Hawaii group, the results for the radio spectrum for a distance of 200/250 m from the shower core show a very similar frequency dependence, with the field strength falling about a factor of 300 as one goes from 10 to 100 MHz. The absolute value of the field strength is about a factor of 30 or so different, rather than the factor of 100 expected from a strict linear scaling of field strength with energy. This may be due to the fact that the Chicago/Hawaii group simulated a much higher energy shower (10^{19} eV) which produces more severe near-field conditions, and did so for an observation altitude of 1800 m above sea level, whereas the LOPES group simulated a 10^{17} eV shower observed from sea level. However, the agreement after scaling to within a factor of 2-3 is actually quite good considering the fact that these are completely independent efforts.

2.2. Possibilities for detection of incoherent radio emission from air showers.

During the development of a high energy cosmic ray air shower, the energy deposited by the relativistic and sub-relativistic shower electrons very quickly ends up as ionization of the air, leaving hot (~ 1 eV or more), high-mobility free electrons and low-mobility ions in the air shower wake. The electrons rapidly cool by collision with neutrals over a timescale of order 10 ns or less, and then just as rapidly attach to oxygen via two-body dissociative attachment and three-body processes mediated by nitrogen.

During this period, the electrons are repeatedly accelerated by the series of collisions with neutrals that lead to their cooling. This collisional cooling leads in turn to a type of emission known as molecular-field bremsstrahlung (MFB), an incoherent broad-spectrum process which yields continuum emission of photons with energy up to some fraction of the energy of the electrons, including radio, microwave, millimeter-wave and far- and near-infrared. Because of the flat spectrum of bremsstrahlung, emission in any of these bands should be directly proportional to the number of electron-ion pairs originally produced by the shower, which is in turn proportional to shower energy.

Generally, such emission is only of interest for detection if it can yield significant advantages over the nitrogen fluorescence (N2FL) technique, already a highly advanced approach to detection of another form of incoherent emission, the UV fluorescence from nitrogen de-excitation. N2FL has been an extremely effective approach to air shower detection, and is highly complementary to direct particle detection, but it suffers from a low duty cycle because of the need to operate on clear, moonless nights. Thus, any new technique which seeks to improve the high energy air shower detection situation must develop clear advantages. This will only be the case for MFB if atmosphere is transparent to the frequencies of interest, and the emission strong enough to yield efficient detection at high duty cycle, comparable to the particle detector arrays. For this reason, the Hawaii group has been evaluating the possibility that decimeter microwave emission, within bands used commonly by satellite television hardware, might be adequate to meet these requirements.

To calculate emission from a gas, we integrate the differential emission coefficient over the electron distribution function: The specific emission coefficient is the power emitted by a unit volume of gas per unit ω -frequency interval per steradian with particular polarization and can be expressed as

$$j_{\omega} = \int \eta_{\omega}(\mathbf{u}) f(\mathbf{u}) d^3\mathbf{u}$$

where $f(\mathbf{u})$ is the electron distribution function (typically Maxwellian), and $\eta_{\omega}(\mathbf{u})$ is the differential emission coefficient, which characterizes emission by an average single electron. It is

$$\eta_{\omega}(\mathbf{u}) = \frac{e^2 \omega^2}{16\pi^3 \epsilon_0 c^3} (u_x^2)_{\omega}$$

Here $(u_x^2)_{\omega}$ is the power spectrum of the individual electron velocity component u_x , assumed to be a stationary random process. The power spectrum of such a process is defined as

$$(A^2)_{\omega} \equiv \int_{-\infty}^{+\infty} \langle A(0)A(t) \rangle e^{i\omega t} dt$$

through the Wiener-Khinchin theorem and is normalized so that $\langle A^2 \rangle = \int (A^2)_{\omega} \frac{d\omega}{2\pi}$.

The correlation function for the velocities the electrons experiencing elastic collisions is

$$\langle u_x(0)u_x(t) \rangle = u_x^2 e^{-\nu|t|}$$

where ν is the momentum transfer rate. It is equal to collision frequency for collisions with isotropic cross-sections, such as electron-neutral collisions. Its Fourier transform is

$$(u_x^2)_{\omega} = \frac{2}{3} \frac{u^2 \nu}{\omega^2 + \nu^2}$$

averaged over the velocity direction.

The suppression factor $\omega^2/(\omega^2 + \nu^2)$, important for $\omega < \nu$, has analogies to Landau-Pomeranchuk-Migdal (LPM) effect in high-energy electromagnetic cross-section suppression. It is present because the highly collisional nature of the plasma produced in an air shower leads to disturbance of the radiating electrons within the radio emission formation zone. (It should be noted however, that this suppression has not been experimentally confirmed.)

To assess whether this emission process might yield an effective method for the detection of high energy air showers, consider an example of a 2.4 m diameter dish antenna (typical of satellite TV installations). The effective collection area of the antenna is of order $A_{eff} = 3.2 \text{ m}^2$, assuming an antenna efficiency (which accounts for scattering and feed mismatch losses) of 0.70. In a frequency interval $\Delta\nu$ at distance R from the emitting gas we get the detected electromagnetic intensity of

$$I = \frac{\partial W}{\partial \Omega \partial \nu} \frac{1}{R^2} \Delta\nu$$

We assume a central frequency $\nu = 4 \text{ GHz}$ in a $\Delta\nu = 0.8 \text{ GHz}$ bandwidth (commonly used parameters for C-band satellite TV receivers) and a distance $R = 10 \text{ km}$ from a $E = 10^{19} \text{ eV}$ shower. Integrating over the typical $\sim 2 \mu\text{s}^1$ that the shower is in the beam, we get an intensity of $I \sim 3.3 \times 10^{-16} \text{ W m}^{-2}$. Excluding the suppression term above the power flux is $I_0 \sim 2 \times 10^{-13} \text{ W m}^{-2}$.

This has to be compared to the minimum detectable flux limited by the thermal noise power

$$\Delta I = \frac{k_b T_{sys} \Delta\nu}{A_{eff} \sqrt{\Delta t \Delta\nu}}.$$

For antenna temperature $T_{sys} = 75 \text{ K}$, which is routinely achievable for good commercial quality receiver/antenna systems in this frequency range, $\Delta I \approx 3.9 \times 10^{15} \text{ W m}^{-2}$, indicating that the detection threshold at this distance is of order several times 10^{19} eV assuming full suppression, and much lower if the suppression is less. For example, the quadratic dependence of the suppression term on collision frequency favors detection of inclined showers whose maxima occur at higher altitudes than ground arrays normally detect them; in fact of order half of all ultra-high energy air showers occur as near horizontal showers with maxima above 15 km. At these altitudes, the suppression is an order of magnitude less at a given radio frequency due to the much lower density.

These estimates still contain much uncertainty, but given that even the estimates assuming full suppression of the radiation still give detectable energy thresholds at potentially interesting ranges, there is continued interest in this possibility, and it is being actively pursued.

2.3. Askaryan effect and its confirmation

As noted early in this discussion, the Askaryan effect was the original motivation for much of the effort to measure radio emission from air showers, but the coherent geo-synchrotron emission detailed above was found to be the dominant contribution

¹The duration of the emission is expected to be of order the electron thermalization and attachment time, which is of order $\tau_{th} \sim 10 \text{ ns}$ at sea level and can be an order of magnitude larger at altitudes of 10 km or so (relevant to horizontal or highly inclined air showers). Since this time is always much shorter than the typical shower crossing time for the degree-scale pixels possible at these frequencies and antenna sizes, the power can just be integrated for the typical crossing time as we have done above.

for air showers, and the coherent Cherenkov emission from the charge excess, while not discounted, was largely forgotten because of its small contribution. However, for showers in solid materials such as ice or the lunar regolith which are relatively radio-transparent, the shower lengths are short enough (~ 10 m) that the magnetic effects leading to synchrotron emission are negligible, whereas the far higher density and refractive index of the materials lead to much stronger coherent Cherenkov emission. Here the quadratic rise of radio power with frequency leads to the conclusion that, at energies above 10^{17} eV, the coherent Cherenkov emission will dominate all secondary radiation, including optical emission, by a wide margin.

Although it is not presently possible to produce EeV cascades in terrestrial accelerators, electromagnetic showers with composite total energies in this range can be easily synthesized by super-posing gamma-rays of energies above the pair-production threshold. If the gamma-ray bunch is small compared to the wavelength of the radio emission (true for most pulsed linacs), the resulting showers will differ from natural EeV showers only logarithmically, due to the details of the initial interaction. However, since the bulk of the radio emission arises from the region of maximum shower development, the differences in radio Cherenkov emission are modest and easily quantified.

After an initial experiment at the Argonne Wakefield Accelerator gave strong indications of the effect [35], Askaryan's hypothesis was in fact confirmed at the Stanford Linear Accelerator Center (SLAC) in mid-2000 in an experiment using a silica-sand target and pulsed gamma-ray bunches with composite energies in the EeV range (Saltzberg et al. 2001)[8]. In the 2002 follow-on experiment (Gorham et al. 2004)[36], the sand was replaced by synthetic rock salt, which has a higher dielectric constant and lower loss tangent than silica sand, and further studies were made of the polarization behavior of the emission.

Fig. 5A shows a typical pulse profile (inset) and a set of measured peak field strengths for pulses taken at different points along the shower in the 2000 experiment. The plotted curve shows the expected profile of the total number of particles in the shower, based on the Kamata-Nishimura-Greisen[8] approximation. Here the field strengths have been scaled in the plot to provide an approximate overlay to the relative shower profile. Clearly the pulse strengths are highly correlated to the particle number profile. Since the excess charge is also expected to closely follow the shower profile, this result confirms Askaryan's hypothesis.

Pulse polarization was measured with an S-band (2 GHz) horn directed at a shower position 0.5 m past the shower maximum. Fig. 5B shows the pulse profile for both the 0° and 90° (cross-polarized) orientations of the horn. The lower two panes of this portion show the derived degree of linear polarization and the angle of the plane of polarization, respectively. Because of the vector correlation of the pulse polarization with the shower velocity vector and the Poynting flux vector, it is possible to use the angle of the polarization to track the shower axis. An example of this is shown in Fig. 5C, where the angle of the plane of polarization is plotted at three locations with respect to the shower axis, showing the high correlation with the predicted angle.

Fig. 5D shows a typical sequence of pulse field strengths versus the total shower energy. The fitted linear rise of field strength with beam current is consistent with complete coherence of the radiation, implying the characteristic quadratic rise in the corresponding pulse power with shower energy. Fig. 5F shows a similar result for the 2002 experiment, but now covering a much wider range of energy, plotted as pulse power instead of field strength. The Askaryan process is found to be quadratic over four orders of magnitude in shower energy.

Fig. 5E shows the spectral dependence of the radiation, which is consistent with the linear rise with frequency that is also characteristic of Cherenkov radiation. Also shown is a curve based on a parametrization of Monte Carlo results (Zas et al. 1992)[7]. The uncertainties are estimates of the combined systematic and statistical uncertainties. Note that the figure compares absolute field strength measurements to the predictions and the agreement is very good.

In summary, there is clear experimental evidence that Askaryan's hypothesis is confirmed and that the predicted emission from high energy cascades is present in the expected amounts. This lends strong support to experiments designed to exploit this effect for high energy neutrino and cosmic ray detection.

3. COMPLETED, CURRENT & PLANNED EXPERIMENTS

3.1. Parkes "Lunatic" Experiment.

In the late 80's, Zheleznykh and later Dagkesamanskii & Zheleznykh [5, 6] proposed that large ground-based radio telescopes could detect neutrino-induced cascades via impulsive radio emission from the lunar regolith. The estimated threshold was high,

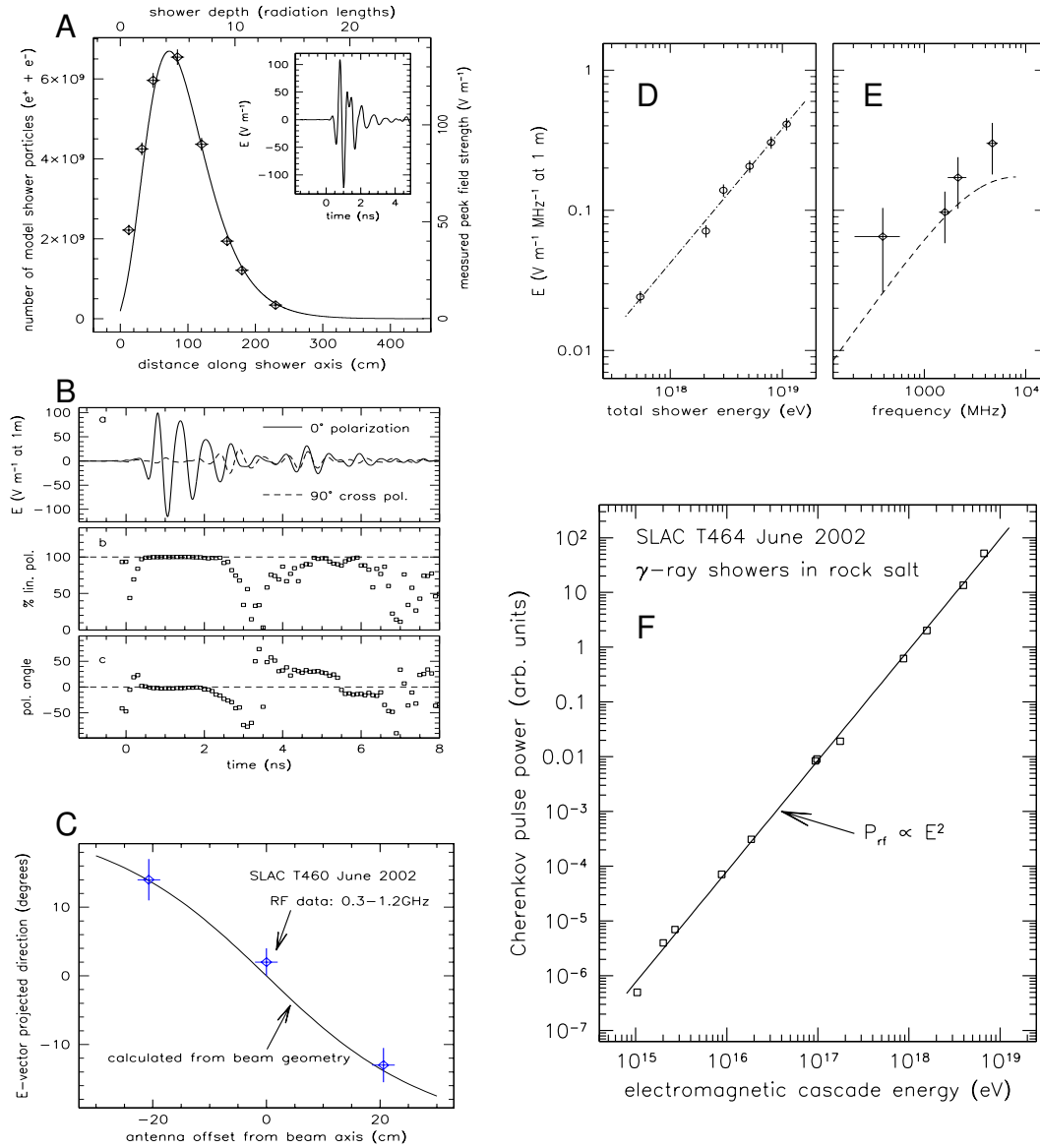


Figure 5: A: Shower RF field strength profile with typical pulse (inset). B: Polarization measurements of a typical RF Cherenkov pulse at 2 GHz. C: Correlation of plane of polarization with antenna offset from shower axis. D: Coherence of RF Cherenkov at 2 GHz, measured during 2000 SLAC experiment. E: absolute field strength and prediction from Cherenkov. F: Coherence of radiated power over the 0.2-1.2 GHz band.

in the neighborhood of 10^{20} eV, but given that there were no limits on neutrino fluxes in this energy regime, the idea was taken seriously by several radio astronomers and an experiment (denoted privately as the “Lunatic” experiment) was performed using the Parkes 64 m radio telescope in the early 1990’s [37]. A total of about 12 hours of pointed observations on the Moon were obtained using a system adapted for broadband pulsar measurements. No candidate events were found, and upper limits were not derived on the neutrino flux. This was however the first experiment to rely on the Askaryan effect for a neutrino search.

3.2. Radio Ice Čerenkov Experiment (RICE)

Somewhat later in the decade of the 1990’s, efforts by the University of Kansas group with the cooperation of the Antarctic Muon and Neutrino Detector Array (AMANDA) experiment resulted in the deployment of a modest-sized array of dipole anten-

Table I: Completed, active, or planned efforts exploiting the Askaryan effect for high energy neutrino detection.

Experiment/ acronym	Operation/ status	instrument & location	frequencies (GHz)	Energy range (eV)	exposure teraton sr yr
Parkes[37]	1994	64m antenna	1.2-1.7	10^{21-23}	0.01
RICE[38]	1997-now	Antarctic sub-ice	0.2-0.4	$10^{16.5-19}$	10^{-4}
GLUE[39]	1999-2003	70m+34m antennas	2.2-2.3	$10^{20.5-23}$	0.1
FORTE[40]	1997-2001	LEO satellite	0.03-0.05	10^{22-24}	~ 1
ANITA-lite[41]	2003-2004	Antarctic balloon	0.3-1.0	$10^{19.5-22}$	~ 0.01
ANITA[41]	2006-07	Antarctic balloon	0.2-1.2	$10^{18.5-22}$	0.05/flight
SalSA[36, 42]	2008-	salt-dome	0.1-0.5	10^{17-20}	0.3/yr

nas operating in the few-hundred MHz frequency regime at depths of up to several hundred m at the South Pole. The Radio Ice Cherenkov Experiment (RICE) [38] continues to function currently as a subelement of the larger AMANDA array. AMANDA is the first high energy neutrino telescope to operate effectively in the TeV to PeV energy range, and has demonstrated the effectiveness of precision embedded tracking Cherenkov arrays for these energies.

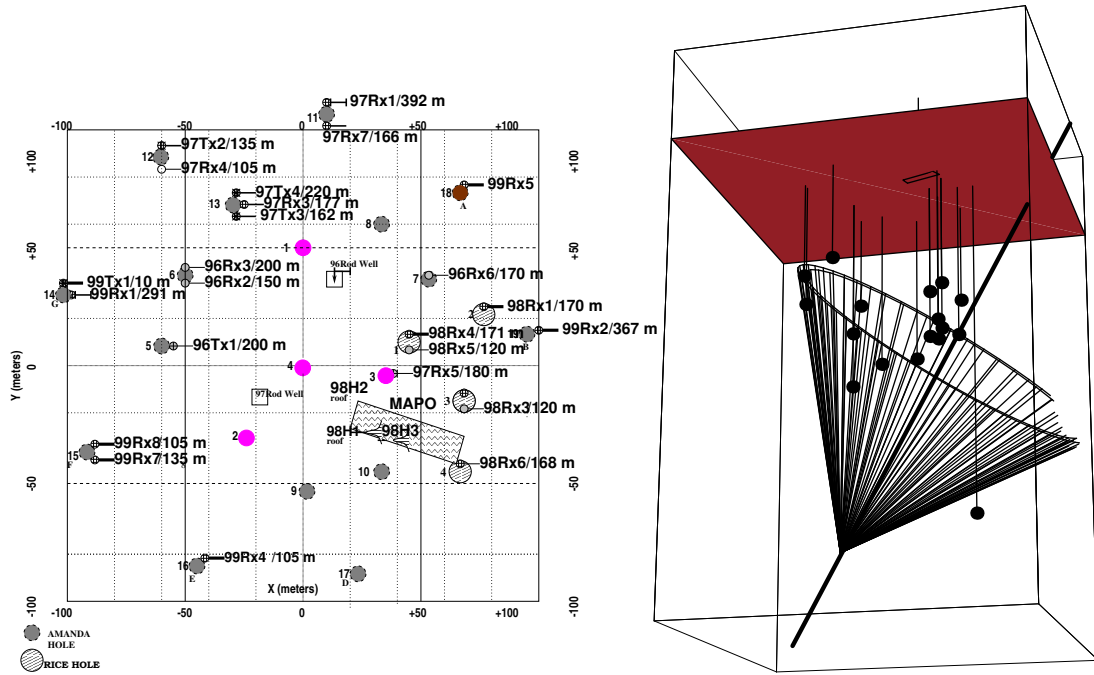


Figure 6: Left: RICE antenna locations along with AMANDA boreholes. Right: schematic event with Cherenkov cone coming up from below the RICE array.

RICE forms a subarray of antennas in a volume above the main optical array, about 100-400 m deep in the ice, primarily along the AMANDA supply cables. The layout of the array is shown in Fig. 6 (left), along with a schematic view of how an upcoming event would intersect the array elements (right). RICE is among the first experiments to attempt to exploit the Askaryan effect and has demonstrated that the noise levels in the upper layers of the ice are consistent with ambient thermal noise. RICE extends the reach of AMANDA up to EeV energies, although it is probably too small at present to achieve limits which can constrain GZK neutrinos in the near future. However, RICE has established the potential for Antarctic ice as an excellent medium for an embedded antenna array, and plans for large upgrades to the experiment are underway.

3.3. Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

The Goldstone Lunar Ultra-high energy Neutrino Experiment (GLUE), began in 1998 by investigators at the NASA Jet Propulsion Laboratory and later UCLA, was completed in 2004 with the final achievement of 120 hours of livetime, improving by an order of magnitude the exposure of the previous Parkes 64 m experiment. In addition, the use of a dual-antenna system was a major improvement over the Parkes approach, allowing conclusive rejection of electromagnetic interference.

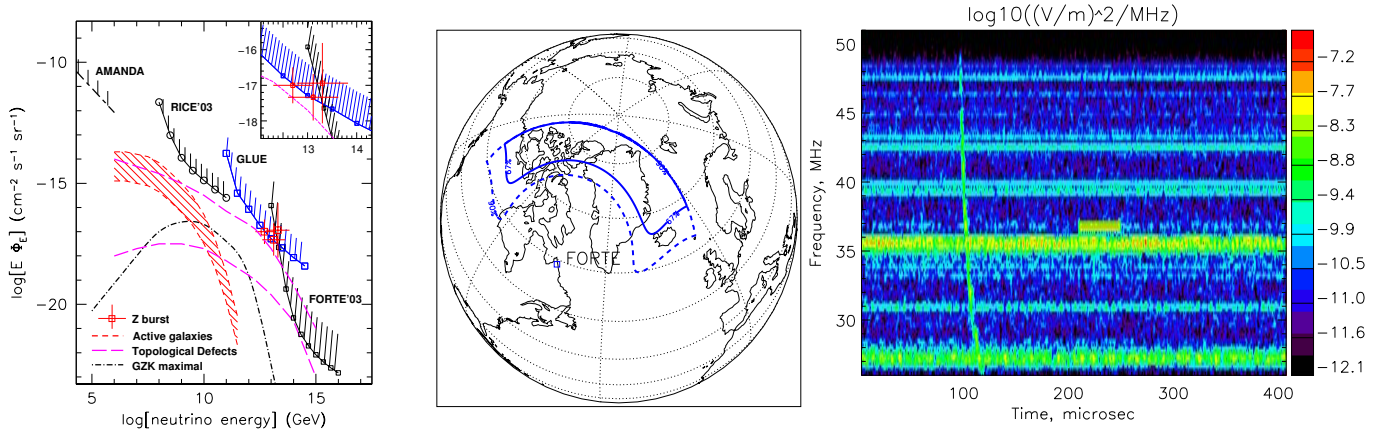


Figure 7: Left: Published limits from the GLUE experiment, 120 hours livetime, plotted along with various models and other limits. Right: An event from the FORTE database, along with a reconstructed position consistent with Greenland. This event was later determined to be due to lightning.

Fig. 7 plots the published limit for GLUE's differential sensitivity based on the 120 hours of livetime. GLUE's limits, combined with those of the FORTE satellite (discussed below) now provide significant constraints on the so-called Z-burst model for production of ultra-high energy cosmic rays through $\nu\bar{\nu}$ annihilation into Z-bosons in the galactic halo [43].

Although the GLUE experiment has now been completed with no detection reported, an approach along the same lines has been investigated conceptually for the planned Square Kilometer Array (SKA), which could in principle improve both the energy threshold and the sensitivity of the lunar Čerenkov approach. If realized, an SKA follow-on experiment might have significant capability for GZK neutrino detection at the high energy end of the spectrum [44].

3.4. Fast On-orbit Recorder of Transient Events (FORTE)

The Fast On-orbit Recording of Transient Events (FORTE) satellite [45], launched in August 1997, was designed and built through a collaborative effort of Los Alamos National Laboratory and Sandia Laboratory, with a primary goal of studying impulsive optical and radio transients that may be relevant to international nuclear treaty verification. The mission is non-classified and has a strong atmospheric physics program in studies of lightning and related upper atmosphere and ionospheric events. The satellite was launched into a nearly circular orbit at 800 km altitude and 70° inclination.

The system has recorded over 4×10^6 impulsive transient events, including new forms of lightning, and may in fact also be sensitive to radio emission from giant cosmic ray air showers. Fig. 7 shows an example of the types of events recorded, along with a reconstructed ground error box for the event location. The event is recorded as a function of time and frequency, yielding a radio spectrogram vs. time. The curvature in the near-vertical impulsive event trace is due to ionospheric dispersion, and the horizontal lines in the spectrum are anthropogenic noise due to narrow RF carrier bands. FORTE provides an excellent example of the ability of a synoptic antenna to operate effectively in the presence of noise over a wide radio bandwidth, and demonstrates that systems which seek to isolate specific impulsive events from a wide variety of anthropogenic noise can operate quite effectively.

FORTE can in principle trigger on neutrino-induced EMP events, but because of its high altitude and limited frequency range, FORTE's energy threshold is extremely high, of order 10^{22} eV. This ability has been recently exploited in analysis by N.

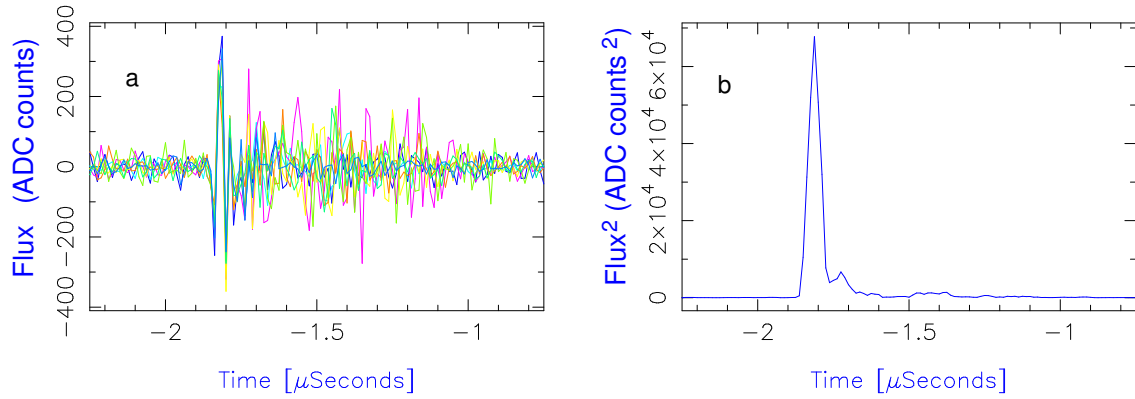


Figure 8: Candidate air shower radio event with energy of order $10^{17.5}$ eV. Left: Recoded raw waveforms from several radio antennas after the signals are phased up for the shower direction indicated by the KASCADE event reconstruction. The residual incoherent signals after the peak are due to interference from the readout of the KASCADE array. Right: the pulse power after in-phase summing of the individual antenna power, showing the incoherent cancellation of the interference signals and the improved SNR for the air shower radio impulse.

Lehtinen *et al.* [40] who analyzed 3.7 days of FORTE livetime over the Greenland ice sheet and was able to reject all but two one of the observed impulsive triggers, and thus set a strong upper limit on the flux of neutrinos in the 10^{22} eV range, which was able to significantly constrain the Z-burst model for high energy cosmic rays.

3.5. Low-frequency array Prototype Station (LOPES)

The detection of radio pulses emitted in the atmosphere during the air shower development of high-energy primary cosmic rays is the task of the LOPES project. To test this technology and to demonstrate its ability to measure air showers a "LOFAR Prototype Station" (LOPES) is set up to operate in conjunction with an existing air shower experiment (KASCADE-Grande). LOFAR (Low Frequency Array) is a new digital radio interferometer under development using high bandwidth ADCs and fast data processing to filter out most of the interference. By storing the whole waveform information in digital form transient events like air showers can be analyzed even after they have been recorded.

The LOPES antennas are operating in the frequency range of 40-80 MHz. For several air-shower events a coincident and coherent signal has been found and a preliminary analysis has already been performed. Fig. 8 shows an example of a candidate event where the particle detector array was able to provide a good direction and location for the shower axis. This allows phasing (or "beam steering") of the six LOPES antennas such that the radio signals can be combined coherently, yielding a large increase in the signal-to-noise ratio. This is particularly important in this case, because the particle detector array produces significant RF interference, which arrives at the LOPES antennas soon after the prompt radio impulse. In the absence of antenna beam steering the noise would tend to swamp the signal, but the phasing of the signals clearly eliminates the interference, and the Figure shows.

The main goal of further LOPES investigations is to calibrate the radio signal with help of the observables of the individual air-showers given by KASCADE-Grande [34]. The initial results of this array show great promise that this technique can become an important contributor to the next generation of large air-shower arrays.

3.6. Antarctic Impulsive Transient Antenna (ANITA)

The NASA-funded ANITA mission will fly a long-duration balloon payload, consisting of a 0.2-1.2 GHz horizon-to-horizon, nadir-pointing antenna array, first in the 2006-2007 Antarctic austral summer. ANITA seeks to exploit the very large volumes (of order 1.5M km^3) of ice observable from balloon float altitudes of 35-40 km to try to distinguish radio pulses due to EeV neutrino cascades. Since ice is known to be highly transparent to radio waves in this frequency regime, the cascades are

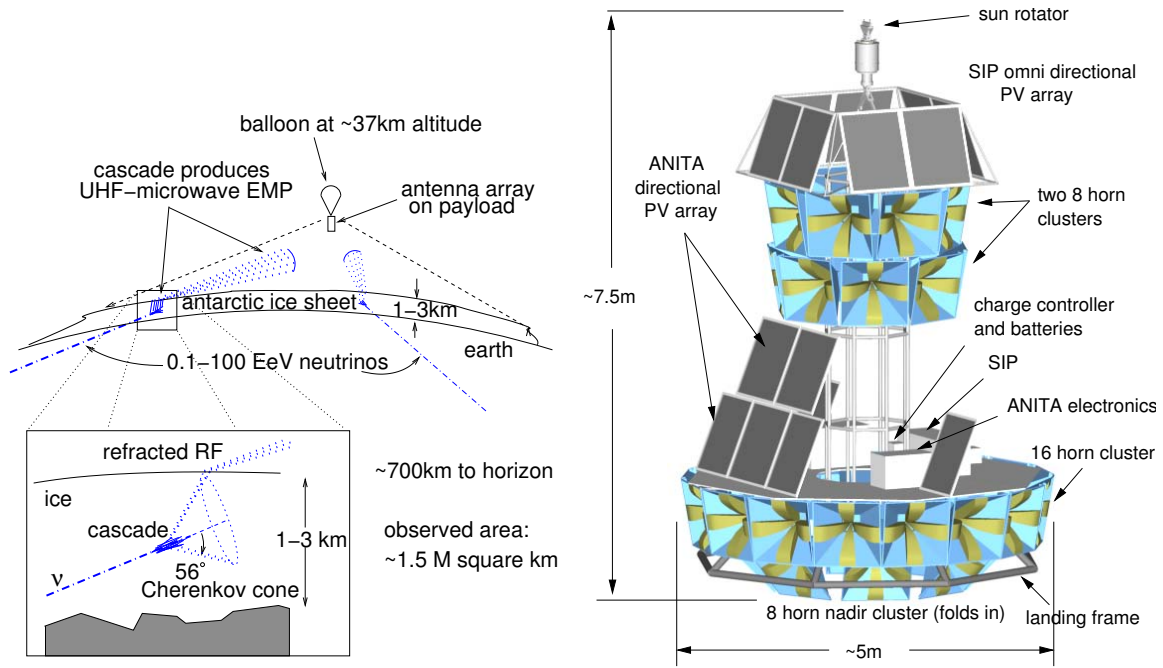


Figure 9: Left: Schematic of geometry for ANITA experiment. Right: layout of the payload.

observable as the emission emerges nearly unattenuated from several km deep in the ice. The basic approach and the current payload design concept is indicated in schematic form in Fig. 9.

ANITA has a great advantage over other detectors with regard to instantaneous sensitivity, but the average duty cycle for observations is low, since long-duration balloon flights average of order 15 days, with only about 2/3 of that time spent over deep ice. Payload typically require a 1 year refurbish before they can fly again. On several recent occasions, very long flights have been recorded: 33 days for the TIGER payload in 2001/2002, and 43 days for the CREAM payload in 2004/2005. This suggests that future flights may achieve higher average duration.

Another limitation of this approach which mitigates somewhat the enormous effective volume is the small acceptance solid angle, typically 0.02 steradian or less. However, even with this factor, ANITA can achieve effective apertures well in excess of a Teraton steradian, and if the exposure time can be increased, this approach shows the greatest promise in ultimate sensitivity to GZK neutrinos for the remainder of this decade and perhaps into the next.

ANITA has now completed one flight of a prototype instrument, called ANITA-lite, which carried two dual-polarization antennas operated in coincidence, to characterize impulsive and thermal noise backgrounds in Antarctica. The results from this flight have appeared to validate the technique, since anthropogenic backgrounds were found to be very low, and the primary noise levels were attributable to the thermal noise floor.

3.7. Saltdome Shower Array (SaISA)

If GZK neutrinos are discovered by ANITA or other first-generation experiments, the observation will likely be limited by event statistics. One may ask the question, what kind of detector is needed to increase the event collection by an order of magnitude?

The Saltdome Shower Array (SaISA) concept has been proposed [36] to address this question. If one accepts the need for exposure measured in [Teraton steradian years] to characterize GZK neutrino spectra, a very large volume embedded array, with calorimetric capability, is desired. Such a detector may be possible by antennas embedded in one or more salt domes. Rock salt is known to have excellent radio propagation qualities, and salt dome structures occur throughout the world, with many formations containing hundreds of cubic km of salt (density 2.2 times that of water) within their flanks. These structures are

also completely insulated against electromagnetic interference, and are straightforward to drill wells into, with 15 cm diameter boreholes a standard of the oil industry.

Figure 10 (Top, left) shows the basic concept for a SalSA, with borehole strings carrying a sparse antenna array into a several km diameter salt dome. In this case, Hainesville dome in East Texas is shown as a typical example. Such an array can be constructed using standard oil-well logging technology. To the right, we show the expected sensitivity for one realization of such an array [36], which instruments a 2.5 km^3 region of salt in a dome of similar scale to the Hainesville dome. The sensitivity is compared to estimated sensitivities for the IceCube neutrino array at the South Pole, and for the Auger Observatory, observing τ -neutrino events [46]. It is evident that a SalSA can in principle achieve a factor of 10 improvement over other techniques, and will clearly constrain even the most conservative GZK neutrino predictions.

At the bottom of Fig. 10, the triggered-antenna pattern for a 10^{18} eV shower in a SalSA is shown, where each antenna cluster required a 5σ signal level to trigger. In this simulation, a conservative attenuation length of 250 m, with 225 m spacing between antenna clusters is used. It is evident qualitatively that the 63° Čerenkov cone can be easily distinguished for this event. Given the high degree of development of ring-imaging Čerenkov detectors in other fields, there is every reason to believe that such events can be located and tracked to excellent precision in such an array.

4. OUTLOOK & CONCLUSIONS

More than four decades have passed since Askaryan first caught our imagination by noting that strong radio emission should be a distinguishing characteristic of high energy showers in dielectric materials. Since that time, interest has waxed and waned in the first application of this idea: radio detection of air showers. Now, with more compelling scientific needs for techniques to accommodate very large cosmic-ray apertures and high duty cycles, air shower radio detection is enjoying renewed interest, fueled by the enduring and increasingly acute mystery of the highest energy cosmic rays.

In contrast to radio air shower detection, radio detection of showers in solid media has seen a steady growth of interest since the first suggestions of applications about 20 years ago, and the first real experiments about a decade ago. The most important advance in this area has been the confirmation of the coherent Čerenkov emission at SLAC in 2000. Coupled with the growing recognition that measurement of the GZK neutrinos is crucial to the ultimate resolution of the ultra-high energy cosmic ray mystery, radio detection experiments using the Moon, Antarctic and Greenland ice, and rock salt, appear to be poised for discoveries within the very near future.

Acknowledgments

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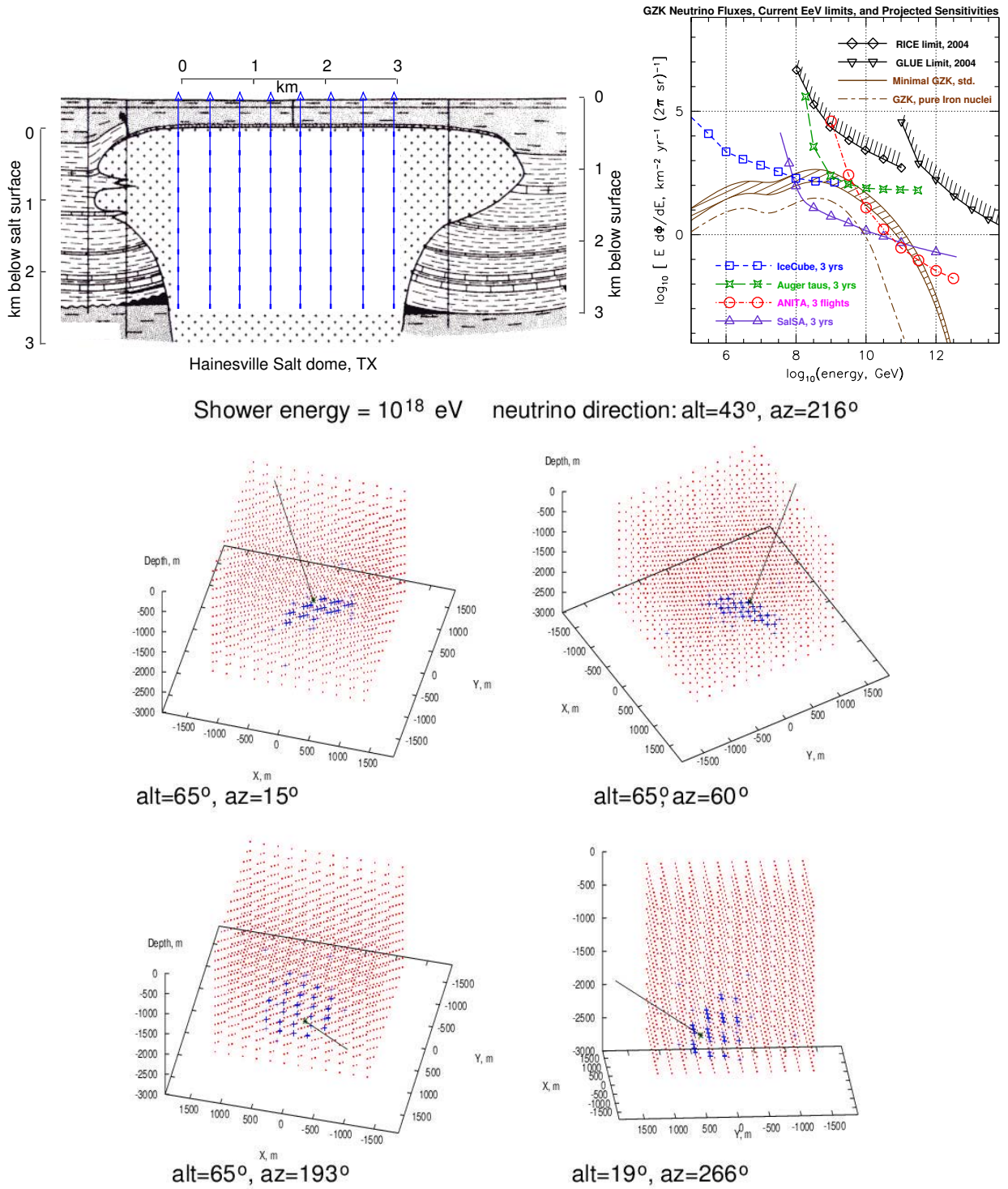


Figure 10: Top, left: The concept of the salt dome shower array (SalSA): and embedded grid of antennas inside a salt dome, in this case one of the larger domes in East Texas, the Hainesville dome. Top, right: Comparison of the estimated 3-year sensitivity of a SalSA to the sensitivity of several other experiments, along with predicted fluxes of GZK neutrinos for several representative models. Bottom: Four views of the same 10^{18} eV hadronic shower in a 2.5 km^3 antenna array, with directions in local altitude and azimuth (counter-clockwise from east) shown. The dots mark antenna nodes, and crosses mark triggered nodes, with the incoming neutrino track shown up to its termination at the shower vertex.

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