The Potential of Spaced-based High-Energy Neutrino Measurements via the Airshower Cherenkov Signal

JOHN F. KRIZMANIC[1,2], JOHN W. MITCHELL[2]

[1]*CRESST/USRA*

[2]*NASA/Goddard Space Flight Center, Greenbelt, Maryland, 20771 USA*

John.F.Krizmanic@nasa.gov

Abstract: Future space-based experiments, such as OWL [1] and JEM-EUSO [2], view large atmospheric and terrestrial neutrino targets. With energy thresholds slightly above 10^{19} eV for observing airshowers via air fluorescence, the potential for observing the cosmogenic neutrino flux associated with the GZK effect is limited. However, the forward Cherenkov signal associated with the airshower can be observed at much lower energies. A simulation was developed to determine the Cherenkov signal strength and spatial extent at low-Earth orbit for upward-moving airshowers. A model of tau neutrino interactions in the Earth was employed to determine the event rate of interactions that yielded a tau lepton which would induce an upward-moving airshower observable by a space-based instrument. The effect of neutrino attenuation by the Earth forces the viewing of the Earth's limb to observe the ν_τ-induced Cherenkov airshower signal at above the OWL Cherenkov energy threshold of $\sim 10^{16.5}$ eV for limb-viewed events. Furthermore, the neutrino attenuation limits the effective terrestrial neutrino target area to $\sim 3 \times 10^5 km^2$ at 10^{17} eV, for an orbit of 1000 km and an instrumental full Field-of-View of $45°$. This translates into an observable cosmogenic neutrino event rate of ~ 1/year based upon two different models of the cosmogenic neutrino flux, assuming neutrino oscillations and a 10% duty cycle for observation.

Keywords: Neutrino, Space-based Measurements, UHECRs, Cherenkov, Simulations

1 Introduction

Future space-based air fluorescence experiments employ wide field-of-view optics from a orbiting platform(s) to monitor a vast amount of the atmosphere. For the OWL (Orbiting Wide-angle Light Collectors) mission, the mass of the viewed atmosphere corresponds to more than 10^{13} metric tons (mtons). The design choices for OWL were driven by the goal to measure the UHECR spectrum, via the air fluorescence technique, with high statistics above $\sim 10^{19}$ eV. Studies indicated that the ability to measure neutrino interactions in the atmosphere via the air fluorescence signature exists, but the predicted event rate based upon cosmogenic neutrino flux models [3] is < 1/year (assuming a duty cycle of 10%) due to the paucity of neutrino flux above 10^{19} eV. Furthermore, the neutrino event rate quickly diminishes as the energy threshold becomes further away from the $\sim 3 \times 10^{19}$ eV threshold for full neutrino aperture, which assumes both OWL satellites stereoscopically view each event.

Airshowers also produce an intense, beamed Cherenkov signal. OWL simulation studies indicated that the energy threshold for observing the optical Cherenkov signal form a nadir-viewed, upward-moving vertical airshower initiated by a particle at sea level would be $\sim 10^{15.5} eV$. OWL also views a large terrestrial area: assuming 1000 km orbits and the two OWL satellites are tilted to view a common area, the terrestrial area monitored ranges from 6×10^5 km^2 for a 500 km satellite separation to nearly 2×10^6 km^2 for a 2000 km satellite separation. These vast areas offer a large neutrino target, depending upon the depth that provides a measurable signal. Tau neutrino charged-current (CC) interactions offer a mechanism to exploit this large, terrestrial neutrino target: at high energies, the produced tau lepton has a sufficient Lorentz-boosted length to escape the Earth, decay in the atmosphere, and create an upward moving airshower that could be observed via the Cherenkov signal.

This paper details the calculations used to quantify the sensitivity of measuring the cosmogenic neutrino flux using space-based measurements, assuming the performance defined by the OWL experiment, of the Cherenkov signal created from upward-moving tau neutrino induced airshowers originating in a terrestrial neutrino target.

2 Optical Cherenkov Signal Simulation

In order to determine the optical Cherenkov signal strength and profile at a orbiting instrument, a computer-based simulation was constructed based upon parameterizations described by Hillas [4, 5]. The charged-particle density for an airshower is given by the Greisen parameterization as a function of shower age, with the airshower electron angu-
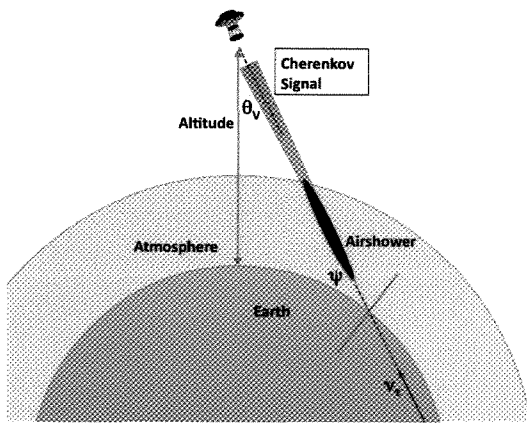
Figure 1: Schematic of the Cherenkov signal generated by an upward-moving airshower induced by a tau neutrino interacting in the Earth.
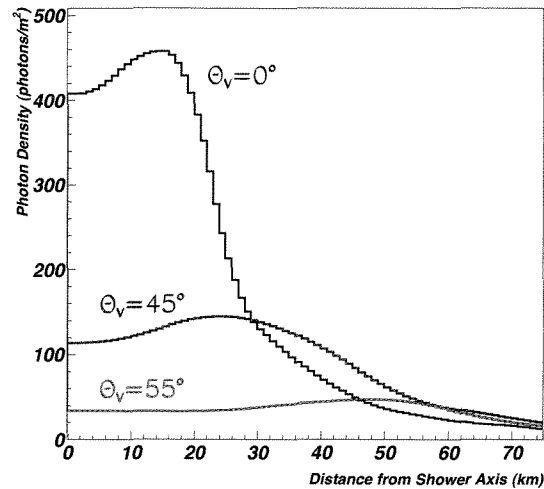

Figure 2: The radial profile of the simulated Cherenkov light density at an altitude of 1000 km for upward-moving 10^{17} eV airshowers viewed at angles of $0°, 45°$, and $55°$.

lar distribution and the energy-dependent, charged-particle track length fraction defined by well-behaved mathematical functions dependent upon shower age. The index of refraction of air is given as a function of atmospheric grammage, or altitude, which defines the Cherenkov angle and Cherenkov energy threshold. The latter, combined with the charged-particle track length fraction, determines the fraction of the particles in the airshower that contribute to the Cherenkov signal for a given altitude. The atmosphere is described by the Shibata parameterization [6], and the wavelength-dependent attenuation of UV light in the atmosphere is described by a parameterization [7] based upon more detailed models.

The parameterizations are then used to generate the Cherenkov signal at an arbitrary altitude for an upward-moving airshower. The lateral spread of the charged particles in the shower was not considered since this is a small effect for large viewing distances. A 100 m airshower step size was used starting at sea level, and the sampling of the electron angular distribution at each step was $\leq 10^{-3}$ radians. The charged particle track length fractions were sampled in decades of energy for each step, from the Cherenkov energy threshold to a factor of 10 below the total airshower energy. The Cherenkov light was generated at each step from 200 nm to 600 nm in increments of 25 nm, but the effects of ozone absorption, in the atmospheric attenuation model, significantly reduces the signal below ∼300 nm. Two numerical azimuthal integrations were performed: one defined by the Cherenkov angle about the electron angular sampling vector, and the other by angular sampling vector about the shower direction.

The effects of the Earth's curvature were modeled as these become important for viewing angles away from the nadir direction. Figure 1 illustrates the geometry of this effect in relation to an upward moving airshower induced by a tau neutrino interaction in the Earth near the Earth's limb. The Cherenkov airshower simulation accounts for this effect by determined the proper angle, shown as ψ in the figure, at each shower propagation distance step, relative to the view-

ing angle θ_V. Thus the atmospheric attenuation depth and the distance from the shower and the UV detector in orbit can be accurately determined.

The results of the Cherenkov airshower simulation are shown in Figure 2 for $\theta_V = 0°, 45°$, and $55°$ at an altitude of 1000 km. The curves show the Cherenkov light density (photons/m^2) as a function of radial distance from the projected location of the airshower core in the plane perpendicular to the airshower direction at 1000 km altitude. The form of the curves show that the Cherenkov light cone (illustrated in Figure 1), is approximately uniform in photon density up to a radius which closely corresponds to that defined by the Cherenkov angle at shower maximum and the distance from shower maximum to the measurement. This implies that a good energy resolution can be achieved by sampling the uniform part of the distribution, e.g. by one of the two OWL satellites. The lateral size of the Cherenkov light cone also defines the solid angle: 1.3×10^{-3} steradians for the nadir ($\theta_V = 0°$) case and 1.9×10^{-3} sr for $\theta_V = 55°$, which corresponds to viewing close to the Earth's limb (at an altitude of 1000 km, the Earth's limb is given by $\theta_V \approx 60°$). A comparison of the results presented in Figure 2, after scaling the energy and altitude, are in good agreement (30% difference) with results which employ a full airshower Monte Carlo and more detailed atmospheric attenuation modeling [8].

The factor of ∼10 decrease in the photon density for $\theta_V = 55°$, as compared to the nadir case, is mainly due to the effect of the Earth's curvature. A factor of ∼5 reduction is due to a $1/r^2$ effect (for $0°$ the distance from 1000 km altitude to shower max is 990 km while it is 2190 km for the 55° case) and a factor of ∼2 reduction is due to atmospheric attenuation of the Cherenkov signal.

The signal strength in an OWL 'eye' is defined by the 3 m optical aperture, the optical transmission, and the quantum efficiency of the focal plane detector. When these are combined, the photo-electron signal strength in an

E_τ (eV)	Depth (km) ($\rho = 1\frac{g}{cm^3}$)	Depth (km) ($\rho = 2.3\frac{g}{cm^3}$)	Mass (mtons) for 10^6 km^2
10^{15}	0.05	0.05	1.3×10^{14}
10^{16}	0.5	0.5	1.3×10^{15}
10^{17}	5	5	1.3×10^{16}
10^{18}	29	16	7.6×10^{16}
10^{19}	18	10	4.8×10^{16}

Table 1: The terrestrial neutrino target depth for ν_τ CC interactions, for water and rock targets, and the target mass for 10^6 km^2 for rock as a function of energy.

OWL pixel is approximately the photon density in units of photons/m^2, which unit of the ordinate axis in Figure 2. Thus a Cherenkov signal of 400 photons/m^2 corresponds to a signal in a OWL instrument of $\sim$400 photo-electrons.

3 Cosmogenic Neutrino Rate Determination

For charged-current tau neutrino interactions in the Earth, the target depth is estimated by the propagation distance of the tau lepton: $\gamma c \tau$. At energies above 10^{16} eV, neutrinos and antineutrinos have similar cross-sections for neutrino-quark scattering, and the produced lepton carries $\sim$75% of the incident neutrino energy at 10^{16} eV with the energy fraction increasing to $\sim$80% at 10^{20} eV [9]. $E_\tau = E_\nu$ is assumed for this ICRC paper. At higher energies, catastrophic energy losses (a convenient parameterization is used [10]) limit the effective depth of the neutrino target above $\sim$10^{18} eV. Table 1 details the terrestrial neutrino target depth for ν_τ interactions, as a function of E_ν, for both water and rock and calculates the mass for a target area of 10^6 km^2 assuming rock ($\rho = 2.3$ g/cm^3). Note that tau energy losses limit the target depth above $\sim$10^{18} eV while the maximum neutrino target mass also occurs at $\sim$10^{18} eV.

Assuming a terrestrial neutrino target area of 10^6 km^2, the rate of cosmogenic neutrino interactions that lead to an observable tau-induced, upward-moving airshower via the Cherenkov signal can be calculated by numerically integrating the neutrino flux, cross-section, target mass, ..., with respect to the neutrino energy, and accounting for the solid angle of the Cherenkov signal. Two cosmogenic flux models were used, the Bartol ($\Omega_\Lambda = 0.7$) model [3] and a more recent calculation by Scully&Stecker [11]. The models, both which assume proton dominated UHECRs, provide the electron and muon neutrino and antineutrino fluxes. These were summed for each model and divided by 3 to predict the ν_τ flux, eg assuming neutrino oscillation yields equal flavor fractions at Earth.

Figure 3 shows the results presented as observable events/year per energy decade for the two cosmogenic models, assuming a solid angle of 1.5×10^{-3} sr, a terrestrial neutrino target area of 10^6 km^2 and a 100% duty cycle for the experimental measurement of the Cherenkov signal. The rate prediction based upon the Bartol flux is given by the upper curve while that based upon the Scully&Stecker model is given by the lower curve. An interesting feature is
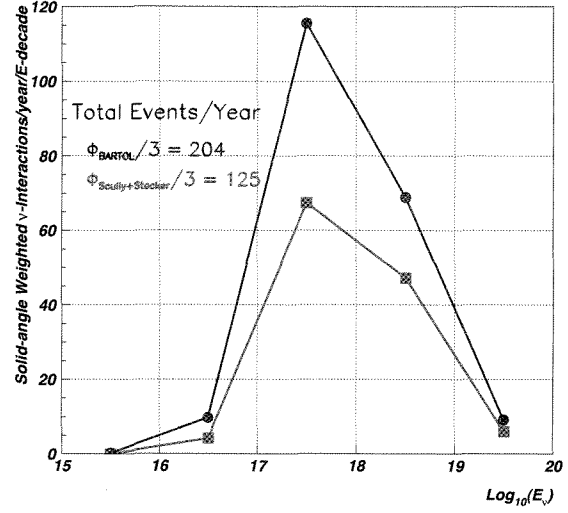

Figure 3: The rate of observable tau neutrino interactions via the airshower Cherenkov signal for two cosmogenic neutrino flux models. The rate is presented in number of events/year per energy decade.

that the event rate does not become appreciable until above 10^{16} eV, indicating that the neutrino target mass, and, to a lesser extent, the neutrino cross-sections, becomes sufficiently large at this energy to yield a significant rate.

While the neutrino rate prediction of > 100 events/year is encouraging, the calculation does not take into account the fact that the duty cycle for observation of the Cherenkov signal is closer to 10% and the Earth is relatively opaque to these energetic neutrinos. This latter point forces the orbiting instrument to view the limb of the Earth to observe airshowers induced by neutrinos with sufficiently short path lengths in the terrestrial target. Figure 4 details the geometry: the orbiting detector must be tilted to view the limb of the Earth, and the effective terrestrial neutrino target is constrained to be no larger than an appropriately short neutrino path length in the Earth.

The problem now effectively becomes one of analytic geometry. The tilt angle of the instrument is defined by its FOV and the angle to the Earth's limb, the calculation of the viewed elliptical area on the Earth's surface is determined by the intersection of the tilted cone defined by the FOV and a sphere of radius 6378 km. The 2-dimensional (eg flat) area of the ellipse can be determined using the conic section relationship between the angle of the plane,

Altitude (km)	Full Area (km^2)	Effective Area (km^2)
500	1.7×10^6	1.6×10^5
1000	3.8×10^6	2.6×10^5
2000	8.9×10^6	3.9×10^5

Table 2: The full and effective viewed surface areas for an 45° FOV instrument, tilted to view the Earth's limb, as a function of altitude. The effective area is constrained by chord equal to the ν interaction length in Earth at 10^{17} eV.
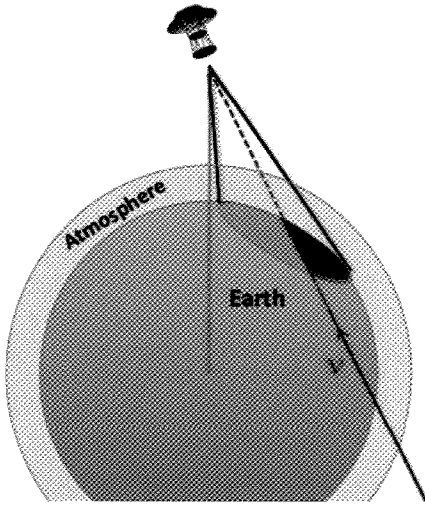
Figure 4: A 2-dimensional schematic of the effective neutrino target area constrained by the ν interaction length. Only those neutrinos with a chord length sufficiently small will be relatively unattenuated by the Earth. While a tilted wide FOV UV imager monitors a large, elliptical area of the Earth, only a small (darkest region) portion samples a significant neutrino flux.

which defines the ellipse in the cone, and the eccentricity of the ellipse [12]. The 2-dimensional area of the viewed ellipse was then increased by 5% to account for the effects of the sphere's (Earth's) curvature. The effective area (darkest area in Figure 4) is defined by the chord whose length is the neutrino attenuation length in Earth, for a particular energy. This describes a truncated ellipse which is inscribed in a rectangle of calculable dimensions. Assuming the truncated ellipse can be approximated by a parabola of similar width, one can use the fact that the area of the parabola is 2/3 that of the bounding rectangle [13] to approximate the area of the truncated ellipse, which is the effective area of the terrestrial neutrino target.

Table 2 presents the total, tilted viewed terrestrial area for an instrument with 45° FOV and the effective neutrino target area at 10^{17} eV, as a function of altitude, determined from the analytic geometrical calculation. While the full area monitored by a tilted instrument is substantial, the effective neutrino target area available near the Earth's limb is reduced by more than a factor of 10, to 2.6×10^5 km^2, assuming a 1000 km altitude.

Combining the energy-dependent effective area results within the numerical integration using the two cosmogenic flux models and assuming 10% duty cycle, the predicted observable tau neutrino event rate is reduced to ~ 2 event/year using the Bartol model and ~ 1 event/year using that of Scully&Stecker.

4 Conclusions

Simulation studies of the Cherenkov signal from upward-moving airshowers indicate that an orbiting experiment with a 3 m optical aperture and UV sensitivity of an OWL

instrument would have an energy threshold of slightly higher than 10^{16} eV for airshowers generated near the Earth's limb. This is well-matched for tau-induced airshowers generated by cosmogenic neutrino interactions in the Earth. However, the 10% duty cycle inherent for the Cherenkov observation and the Earth's attenuation of the neutrino flux limit the effective terrestrial area, which is estimated to be $\sim 3 \times 10^5$ km^2 for $E_\nu = 10^{17}$ eV, assuming an instrument with a 45° full FOV tilted to observe the Earth's limb. Using two different cosmogenic neutrino flux models, the predicted observable event rate is ~ 1 event/year. While factor of 2 improvements may be available using different orientations of the two OWL satellites or realizing a gain in the duty cycle, the net effect of these improvements may be balanced by potential decreases caused by more realistic modeling of the energy distribution of the create tau lepton, the airshower generated by the tau decay, and the inherent shower fluctuations.

While the tau-induced airshowers could be observed via the air fluorescence technique, which has a much larger observational solid angle than that inherent to the Cherenkov signal, the higher energy threshold of $\sim 10^{19}$ eV (and a factor of ~ 10 higher for viewing near the Earth's limb), severely limit the sensitivity to the cosmogenic neutrino flux. This reinforces a similar result from more detailed Monte Carlo studies of the ability of OWL to measure airshowers induced by cosmogenic electron neutrinos in the atmosphere, which predict < 1 event/year. However, if the energy threshold for air fluorescence could be reduced to 10^{18} eV for an OWL-type mission, studies have indicated that the measurable cosmogenic neutrino event rate would be ~ 50 events/year for the ν_e atmospheric channel, assuming a 10% duty cycle. There could also be a significant observable rate from ν_τ interacting in the Earth observed via air fluorescence, if the energy threshold could be reduced.

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Abstract ID : 1331

The Potential of Spaced-based High-Energy Neutrino Measurements via the Airshower Cherenkov Signal

Space-based air fluorescence experiments, such as OWL and JEM-EUSO, view a large atmospheric and terrestrial neutrino target. With energy thresholds for observing air showers via fluorescence ~10^19 eV or higher, the potential for observing the cosmogenic neutrino flux associated with the GZK effect is limited. However, the forward Cherenkov signal associated with the airshower can be observed at much lower energies, OWL studies showed this to be ~ PeV. The potential for using this signal to measure the cosmogenic neutrino flux in the energy range PeV to EeV will be presented.

Primary authors : Dr. KRIZMANIC, John (CRESST/USRA/NASA/GSFC)

Co-authors : Dr. MITCHELL, John (NASA/GSFC)

Presenter : Dr. KRIZMANIC, John (CRESST/USRA/NASA/GSFC)

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Comments :
        This talk could also fit in HE 2.3 if the organizers prefer.
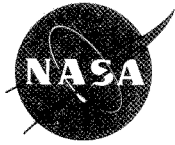
The Potential of Spaced-based High-Energy Neutrino Measurements via the Airshower Cherenkov Signal

John Krizmanic[1,2] and John Mitchell[1]

1 NASA/GSFC Code 661, Greenbelt, Maryland 20771 USA

2 CRESST/Universities Space Research Association

Outline:

1. Motivation
2. Simulation Model
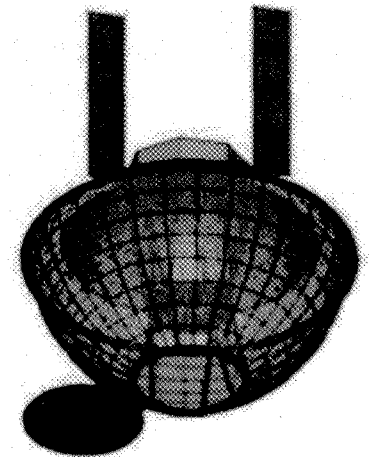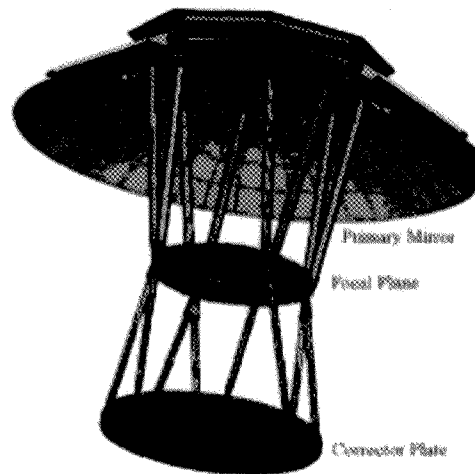3. Cosmogenic Neutrino Event Rate Estimate
4. Conclusions

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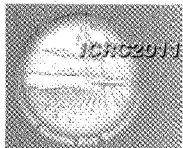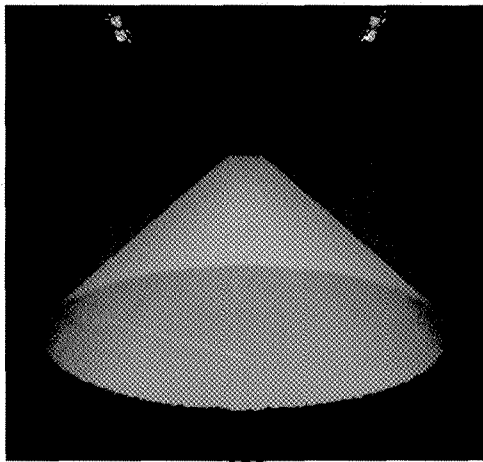
Surface Area ≈ 10^6 km^2

SatSep=500 km: 5.8×10^5 km^2

SatSep=2000 km: 1.6×10^6 km^2

Large Terrestrial Neutrino Target

OWL Parameters:
- UV 'camera' with 45° full FOV optics, 3 m optical aperture
- 5×10^5 pixels with μs readout, 0.06° pixel angular size
- 1000 km orbits, stereo configuration
- Air Fluorescence Energy Threshold ≈ 10^{19} eV
- Duty cycle ≈ 10%

Airshowers generate a strong Cherenkov signal

Model of Upward-going (relative to Earth) created based upon parameterizations given by Hillas (JPhysG 8)

- Index of refraction of Air vs altitude
- Track length fraction vs shower age and energy
  - Definition of E_{CHER}, sample in decades for $E \geq E_{CHER}$
- Angular distribution of particles vs angle, energy, and age

Use to build Cherenkov light generation model based upon Greissen shower parameterization in 100 m steps (200 nm $\leq \lambda \leq$ 600 nm)

- Model atmospheric attenuation
  - Shibata atmospheric model (see Gaisser's book)
  - Rayleigh scattering (see Sokolsky's book)
  - Ozone absorption (Krizmanic 28th ICRC, Salt Lake City)
  - Effects of Earth's curvature modeled
  - Aerosols not modeled (est of signal reduction at large angles ≈ 25% for 1.2 km scale height and λ_A=14 km)

θ_C

θ

100 bins for δφ

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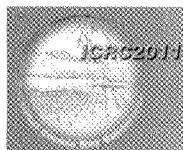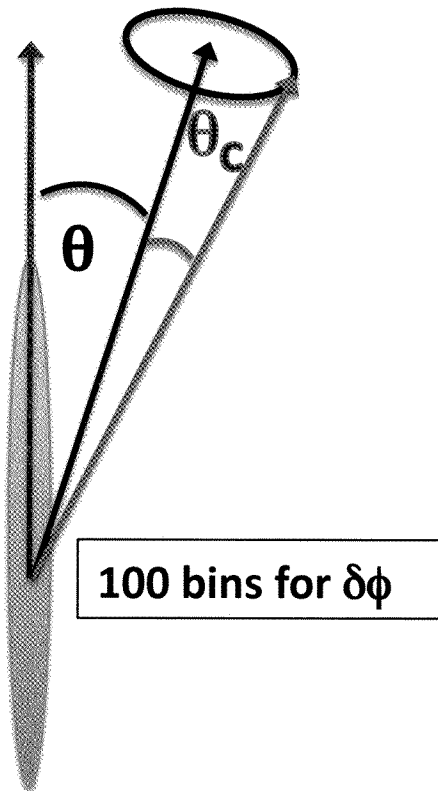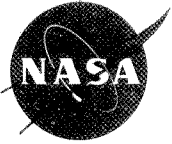
100 PeV Airshower Cherekov Results
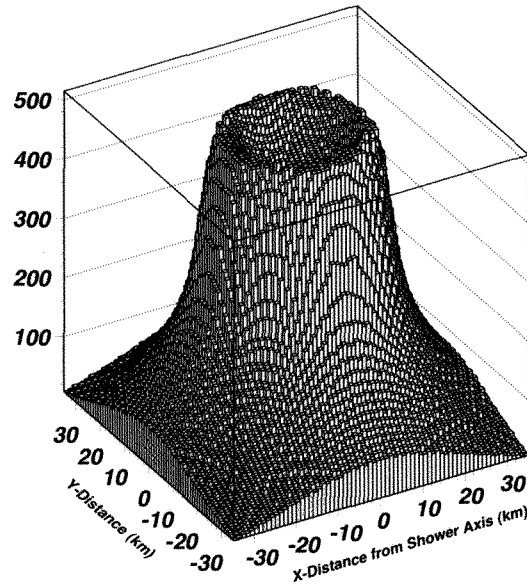
Nadir Pointed Instrument

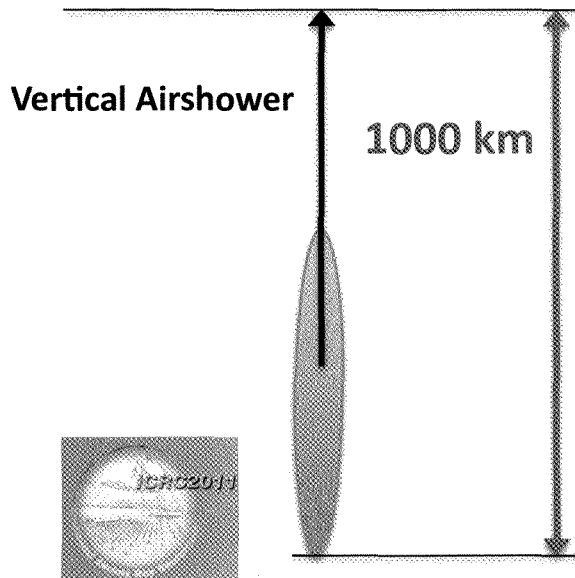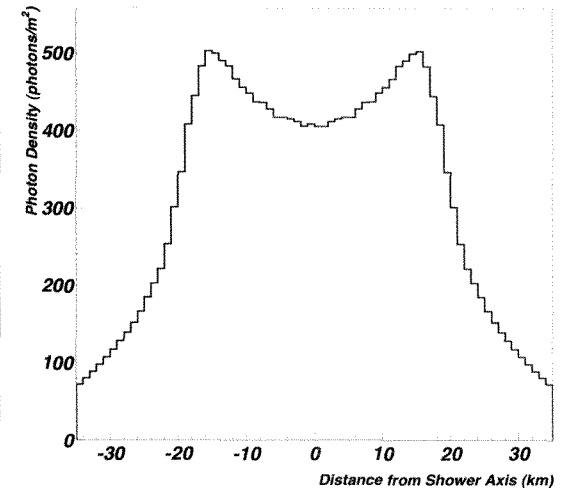Vertical Airshower ($\theta_V = 0°$)

  Signal: 400 photons/m^2

  PE Signal: ≈ 400 PEs in OWL pixel

  Lateral Size: ≈ 40 km at 1000 km

  Solid Angle: 1.3 × 10^{-3} steradians

  Distance from S_{Max}: 990 km

Tilted Pointed Instrument

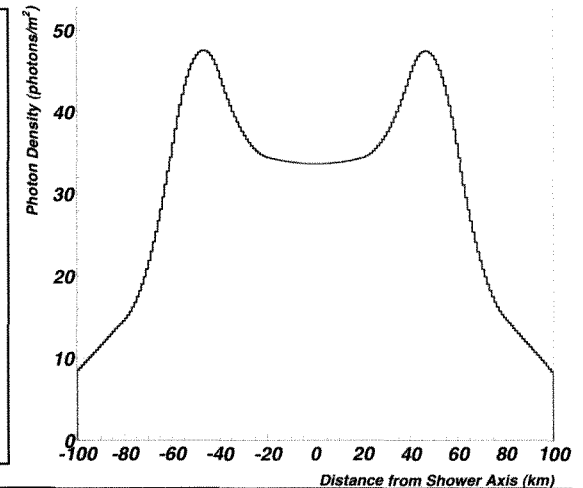Slanted Airshower ($\theta_V = 55°$)

  Signal: 35 photons/m^2

  PE Signal: ≈ 35 PEs in OWL pixel
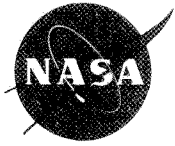
  Lateral Size: ≈ 110 km at 1000 km

  Solid Angle: 1.9 × 10^{-3} steradians

  Distance from S_{Max}: 2187 km

  55° at z=1000 km -> 71 deg at z=0

Vertical Airshower

1000 km

Slanted signal reduction: ¼ factor due to larger distance ($1/r^2$) and 60% additional reduction due to atmospheric scattering.

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Consider ν_τ Interactions: {Gandhi et al., PRD 58}

- $\sigma_{cc}(\nu N) = \sigma_{cc}(\bar{\nu} N) = 5.5 \times 10^{-36} (E_\nu / 1 \text{ GeV})^{0.363}$, $E_\nu > 10^{16}$ eV

- $\langle E_\lambda \rangle \approx 0.75 \times E_\nu$ at $E_\nu = 10^{15}$ eV, rising to $\approx 0.8 \times E_\nu$ at $E_\nu = 10^{20}$ eV

Depth of neutrino target given by the minimum of:

- $\gamma c \tau$ for the produced taon

- λ_{Loss} due to taon catastrophic energy losses at higher energies:
  $\lambda_{Loss} = (\beta \, \rho_{AVE})^{-1}$; where ρ_{AVE} is the average density and
  $\beta[E] = \beta_{19}[\rho_{AVE}](E_\tau/10^{19} \text{ eV})^{0.2}$ {Palomares-Ruiz et al., PRD73}

E_τ (eV)	Depth (ρ_{AVE} =1 g/cm³)	Depth (ρ_{AVE} =2.65 g/cm³)	Mass for 10^6 km² (2.65 g/cm³)
10^{15}	0.05 km	0.05 km	1.3×10^{14} mtons
10^{16}	0.5 km	0.5 km	1.3×10^{15} mtons
10^{17}	5 km	5 km	1.3×10^{16} mtons
10^{18}	29 km	16 km	7.6×10^{16} mtons
10^{19}	18 km	10 km	4.8×10^{16} mtons

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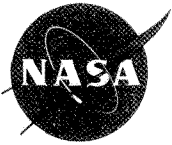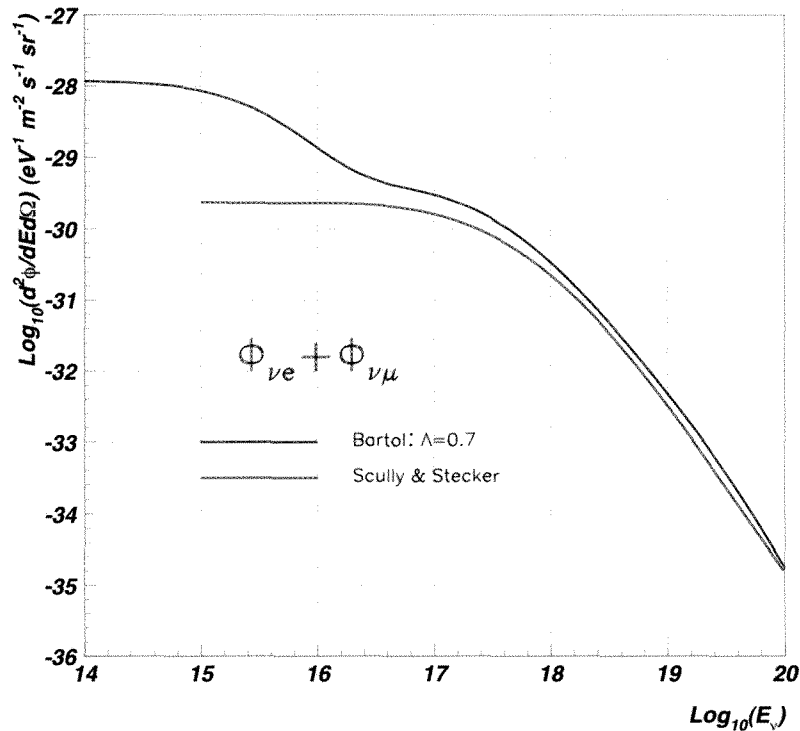
Bartol: Engel et al., PRD 64
Scully & Stecker: AstroPartPhys 34
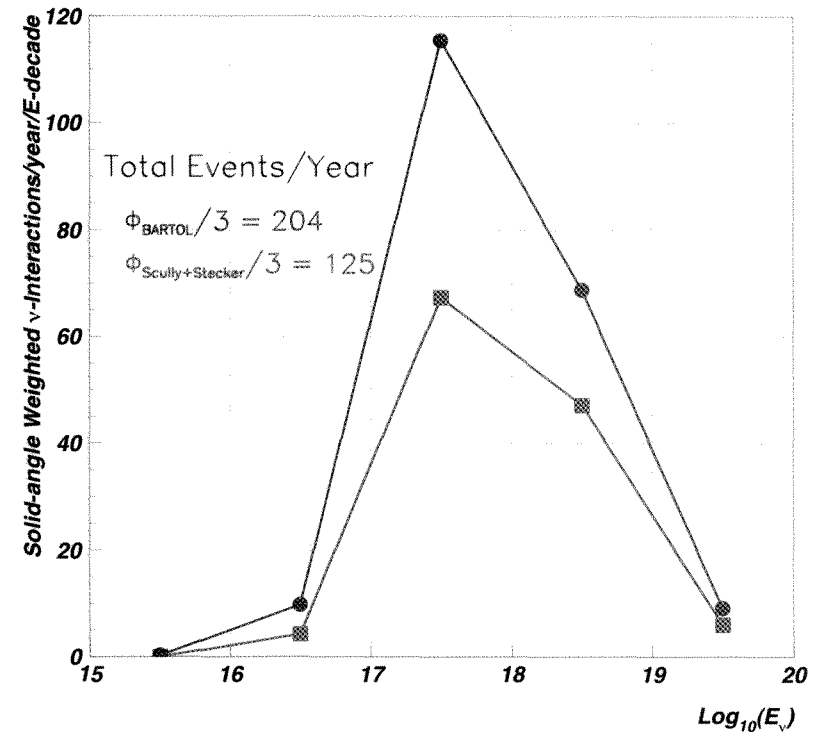
ν_τ 'Event Rates' per year per decade in E_ν

Assuming:

1. 10^6 km^2 area
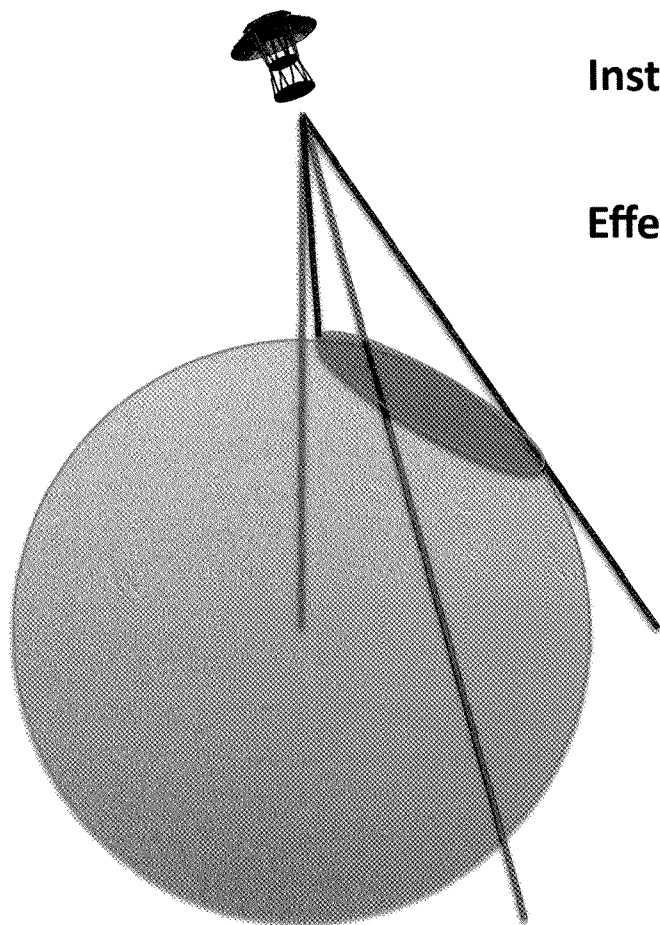2. ν_τ target depth prescription
3. $\Omega = 1.5 \times 10^{-3}$ steradians
4. Un-attenuated ν_τ flux
5. **100% duty cycle**

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Instrument is rotated to view limb of Earth at edge of FOV

- Viewed surface area is ellipse on a sphere

Effective area limited by transparency of the Earth to ν

- Effective area is defined by the chord determined by ν transparency: λ_ν = 1421 km at 10^{17} eV (ρ=2.65 g/cm^3) and decreases as E_ν increases

For an instrument with 45° full FOV at 10^{17} eV:

| Altitude (km)	Full Ellipse Area (km^2)	Constrained Ellipse Area (km^2)
500	1.7×10^6	1.6×10^5
1000	3.8×10^6	2.6×10^5
2000	8.9×10^6	3.9×10^5

Including the energy-dependent Neutrino attenuation by the Earth and the duty cycle leads to a more realistic ν_τ Event Rate determination.

ν_τ Flux Prediction	Event Rate/Year (10^6 km^2 Area)	Event Rate/Year (Integrated via $A_{EFF}(E)$)
Bartol	20	2
Scully & Stecker	13	1

Relevant Parameters:
- 10% Duty Cycle
- 1000 km altitude
- 45° full Field-of-View
- $\approx 10^{16}$ eV (or less) Airshower energy threshold
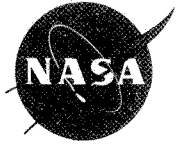
Conclusions

• **Upward-moving airshowers are in principle observable from space-based experiments, with an energy threshold dependent upon the size of the optics:**

    • **for OWL parameters, $E_{THRES} \approx 10$ PeV, depending on viewing angle.**

• While a large area of the Earth is viewed by OWL-type instruments, the effective area for 'Earth-skimming' neutrinos is limited by the attenuation of the neutrino signal by the Earth

• Geometric calculations demonstrate the observable rate for the cosmogenic neutrino flux via observation of the Cherenkov airshower signal is ≈ 1 event/year, assuming 10% duty cycle.

• **However, these results re-inforce those obtained by studies of ν_e interactions in the atmosphere observed via the air fluorescence signal: if the energy threshold for the air fluorescence measurements can be significantly reduced (eg to 10^{18} eV), the event rate predicted by cosmogenic flux models would be appreciable:**

    • **this would require at least a factor of 3 increase in the size of the optics:**