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

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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 $\nu_T$-induced Cherenkov airshower signal at above the OWL Cherenkov energy threshold of $10^{16.5}$ eV for limb-viewed events. Furthermore, the neutrino attenuation limits the effective terrestrial neutrino target area to $\sim 3 \times 10^5 \text{ km}^2$ 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 $\sim 1$/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 $10^{19}$ 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 $3 \times 10^{19}$ 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 $6 \times 10^5 \text{ km}^2$ for a 500 km satellite separation to nearly $2 \times 10^6 \text{ km}^2$ 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-
Each shower propagation distance step, relative to the view-determined the proper angle, shown as relation to an upward moving airshower induced by a tau Cherenkov airshower simulation accounts for this effect by direction. Figure 1 illustrates the geometry of this effect in gular sampling vector about the shower direction. The effects of the Earth’s curvature were modeled as these the electron angular sampling vector, and the other by an­
neutrino interaction in the Earth near the Earth’s limb. The
results which employ a full airshower Monte Carlo and 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 signal to a 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 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 curves show the Cherenkov light density (photons/m²) 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 \times 10^{-3} \text{ sr} for the nadir (\( \theta_V = 0^\circ \)) case and 1.9 \times 10^{-3} \text{ sr} for \( \theta_V = 55^\circ \), which corresponds to viewing close to the Earth’s limb (at an altitude of 1000 km, the Earth’s limb is given by \( \theta_V \approx 60^\circ \)). 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 \( \sim 10 \) decrease in the photon density for \( \theta_V = 55^\circ \), as compared to the nadir case, is mainly due to the effect of the Earth’s curvature. A factor of \( \sim 5 \) reduction is due to a \( 1/r^2 \) effect (for \( 0^\circ \) the distance from 1000 km altitude to shower max is 990 km while it is 2190 km for the \( 55^\circ \) case) and a factor of \( \sim 2 \) 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
Table 1: The terrestrial neutrino target depth for $\nu_\tau$ CC interactions, for water and rock targets, and the target mass for $10^6$ km$^2$ for rock as a function of energy.

<table>
<thead>
<tr>
<th>$E_{\nu}$ (eV)</th>
<th>Depth (km) $\rho = 1.2 g/cm^2$</th>
<th>Depth (km) $\rho = 2.3 g/cm^2$</th>
<th>Mass (mtons) for $10^6$ km$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{16}$</td>
<td>0.05</td>
<td>0.05</td>
<td>$1.3 \times 10^{14}$</td>
</tr>
<tr>
<td>$10^{17}$</td>
<td>0.5</td>
<td>0.5</td>
<td>$1.3 \times 10^{15}$</td>
</tr>
<tr>
<td>$10^{18}$</td>
<td>5</td>
<td>5</td>
<td>$1.3 \times 10^{16}$</td>
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<tr>
<td>$10^{19}$</td>
<td>29</td>
<td>16</td>
<td>$7.6 \times 10^{16}$</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>10</td>
<td>$4.8 \times 10^{16}$</td>
</tr>
</tbody>
</table>

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.

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 $\nu$ interaction length in Earth at $10^{17}$ eV.
4 Conclusions

moving airshowers indicate that an orbiting experiment of Scully & Stecker with a 3 m optical aperture and event/year using the Bartol model and assuming predicted observable tau neutrino event rate is reduced to from the analytic geometrical calculation. While the full area monitored by a tilted instrument is substantial, the effective area at within the numerical integration using the two cosmogenic flux models and assuming the neutrino attenuation length in 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 $2.6 \times 10^5$ 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 $3 \times 10^5$ 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 $\nu_e$ atmospheric channel, assuming a 10% duty cycle. There could also be a significant observable rate from $\nu_\tau$ interacting in the Earth observed via air fluorescence, if the energy threshold could be reduced.

References


Figure 4: A 2-dimensional schematic of the effective neutrino target area constrained by the $\nu$ 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.
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.

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

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

Track classification : HE 2.4 Theory and calculations

Contribution type : oral

Submitted by : Dr. KRIZMANIC, John

Submitted on Saturday 02 April 2011

Last modified on : Thursday 12 May 2011

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

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

Session HE2.4: August 15, 2011
Surface Area $\approx 10^6$ km$^2$
SatSep=500 km: $5.8 \times 10^5$ km$^2$
SatSep=2000 km: $1.6 \times 10^6$ km$^2$

Large Terrestrial Neutrino Target

OWL Parameters:
- UV ‘camera’ with 45° full FOV optics, 3 m optical aperture
- 5 x $10^5$ pixels with μs readout, 0.06° pixel angular size
- 1000 km orbits, stereo configuration
- Air Fluorescence Energy Threshold $\approx 10^{19}$ eV
- Duty cycle $\approx 10\%$
Upward Airshower Cherenkov Model

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 $E_{\text{CHER}}$ sample in decades for $E \geq E_{\text{CHER}}$
- 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 ($200 \text{ nm} \leq \lambda \leq 600 \text{ nm}$)

- 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 $\approx 25\%$ for 1.2 km scale height and $\lambda_A = 14 \text{ km}$)

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100 PeV Airshower Cherekov Results

Nadir Pointed Instrument
Vertical Airshower ($\theta_V=0^\circ$)
Signal: 400 photons/m$^2$
PE Signal: $\approx$ 400 PEs in OWL pixel
Lateral Size: $\approx$ 40 km at 1000 km
Solid Angle: $1.3 \times 10^{-3}$ steradians
Distance from $S_{Max}$: 990 km

Tilted Pointed Instrument
Slanted Airshower ($\theta_V=55^\circ$)
Signal: 35 photons/m$^2$
PE Signal: $\approx$ 35 PEs in OWL pixel
Lateral Size: $\approx$ 110 km at 1000 km
Solid Angle: $1.9 \times 10^{-3}$ steradians
Distance from $S_{Max}$: 2187 km
55° at $z=1000$ km -> 71 deg at $z=0$

Slanted signal reduction: $\frac{1}{4}$ factor due to larger distance ($1/r^2$)
and 60% additional reduction due to atmospheric scattering.

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Terrestrial Neutrino Target Depth

Consider $\nu_\tau$ Interactions: {Gandhi et al., PRD 58}

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

- $<E_\lambda> \approx 0.75 \times E_\nu$ 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:

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

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

<table>
<thead>
<tr>
<th>$E_\tau$ (eV)</th>
<th>Depth ($\rho_{\text{AVE}} = 1$ g/cm$^3$)</th>
<th>Depth ($\rho_{\text{AVE}} = 2.65$ g/cm$^3$)</th>
<th>Mass for $10^6$ km$^2$ (2.65 g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{15}$</td>
<td>0.05 km</td>
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<td>$1.3 \times 10^{14}$ mtons</td>
</tr>
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<td>0.5 km</td>
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</tr>
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<td>$10^{17}$</td>
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<td>5 km</td>
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<td>18 km</td>
<td>10 km</td>
<td>$4.8 \times 10^{16}$ mtons</td>
</tr>
</tbody>
</table>

Session HE2.4: August 15, 2011
Cosmogenic Neutrino Flux and $\nu$ Interaction Rates

$\Phi_{\nu_e} + \Phi_{\nu_\mu}$

Bartol: $\Lambda = 0.7$
Scully & Stecker

$\nu_\tau$ Event Rates' per year per decade in $E_\nu$

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

Session HE2.4: August 15, 2011
Geometry of the Calculation

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 $\nu$

- Effective area is defined by the chord determined by $\nu$ transparency: $\lambda_\nu = 1421 \text{ km at } 10^{17} \text{ eV (}\rho=2.65 \text{ g/cm}^3\text{)}$ and decreases as $E_\nu$ increases

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

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Full Ellipse Area (km$^2$)</th>
<th>Constrained Ellipse Area (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>$1.7 \times 10^6$</td>
<td>$1.6 \times 10^5$</td>
</tr>
<tr>
<td>1000</td>
<td>$3.8 \times 10^6$</td>
<td>$2.6 \times 10^5$</td>
</tr>
<tr>
<td>2000</td>
<td>$8.9 \times 10^6$</td>
<td>$3.9 \times 10^5$</td>
</tr>
</tbody>
</table>

Session HE2.4: August 15, 2011
Including the energy-dependent Neutrino attenuation by the Earth and the duty cycle leads to a more realistic $\nu_\tau$ Event Rate determination.

<table>
<thead>
<tr>
<th>$\nu_\tau$ Flux Prediction</th>
<th>Event Rate/Year ($10^6$ km$^2$ Area)</th>
<th>Event Rate/Year (Integrated via $A_{\text{EFF}}(E)$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bartol</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>Scully &amp; Stecker</td>
<td>13</td>
<td>1</td>
</tr>
</tbody>
</table>

**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, $E_{\text{THRES}} \approx 10\ PeV$, 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 $\approx 1$ event/year, assuming 10% duty cycle.
• However, these results re-inforce those obtained by studies of $\nu_e$ 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:

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