A New Concept for High-Elevation Radio Detection of Tau Neutrinos

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➤ **High Exposure**: High Elevation Mountain (>2 km) + Year-Round Duty Cycle

➤ **Scalable**: Low number of stations (~10), multiple sites

➤ Similar approach as TAROGE, and GRAND, but optimizing for small-number of stations, high-elevation, & multiple sites
**OVERVIEW**

Scalable High-Elevation RF Detector for Earth-skimming $\nu_\tau$?

**Acceptance Calculation**
- Monte Carlo including $\nu_\tau$ propagation, $\tau$ decay, radio emission from air showers, detector model

**Trade Study**
- Frequency band
- Elevation & Location
- Receiver gain ala Beamforming

**Goal**: Target $10^{17}$-$10^{19}$ eV to target both cosmogenic & astrophysical fluxes
Acceptance Monte Carlo

Exit Probability

- **NuTauSim**: Publicly available package that includes the effects of tau propagation through the Earth
  - [https://github.com/harmscho/NuTauSim](https://github.com/harmscho/NuTauSim)
  - Alvarez-Muñiz, et al. PRD 2018

Decay Probability

- Exponentially sampled tau decay length
  \[ L_{\text{decay}} \sim \left( \frac{E_\tau}{EeV} \right) \times 49\text{km} \]

Detection Probability

- Radio emission simulations using ZHAireS
- Peak E-field stored in interpolated look-up tables, binned in frequency, emergence angle
- Phased arrays of receivers convert E→V
- Trigger threshold based on SNR of the receiver band
Mountaintop elevations are in the regime where the signal grows with decay altitude.

$E_{\text{shower}} = 10^{17}$ eV, Detector altitude = 37 km, 300-900 MHz
**CHOICE OF FREQUENCY BANDS**

<table>
<thead>
<tr>
<th>30-80 MHz VHF Design</th>
<th>200-1200 MHz UHF Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>➤ Commonly available active electrically short antennas</td>
<td>➤ Readily available, high-gain antennas</td>
</tr>
<tr>
<td>➤ e.g. 1.8 dBi LWA Antennas</td>
<td>➤ e.g. ~10 dBi quad-ridged horns, LPDAS</td>
</tr>
</tbody>
</table>

**Advantage**

Broader beam at low frequencies → wider solid angle in acceptance

**Noise**

Dominated by sky noise, $V_{\text{rms}} \sim 10 \, \mu\text{V}$

**Advantage**

Easier to find higher gain antennas at UHF frequencies, smaller resonant antennas

**Noise**

Dominated by thermal noise

$V_{\text{rms}} \sim 14 \, \mu\text{V}$

**Combination of VHF & UHF:**

One or the other may be better for trigger; Both advantageous for event reconstruction

Photo Credit: OVRO-LWA
VHF vs. UHF Designs

3-km Altitude, $10^{17}$ eV $\tau$ Shower

- **VHF**: Broader range of triggerable view angles
- **UHF**: Stronger Cherenkov peak $\rightarrow$ lower energies and/or further distances
PHASED ARRAY TO INCREASE SNR

3-km Altitude, $10^{17}$ eV $\tau$ Shower

- 200-1200 MHz, 1 Antenna
- 30-80 MHz, 1 Antenna
- 200-1200 MHz, 10 Antennas
- 30-80 MHz, 10 Antennas

See E. Oberla’s talk next.
Vieregg et al JCAP 2015
Avva et al NIM 2017
**LOWER VS. HIGHER FREQUENCY BANDS**

➤ Broader beam width at low frequencies increases acceptance for **high energies** > $10^{17}$ eV

➤ Higher signal-to-noise ratio at higher frequencies increases acceptance for **low energies** < $10^{17}$ eV

![Graph showing acceptance vs. energy for different frequency bands](image)
LOWER VS. HIGHER FREQUENCY BANDS

➤ Broader beam width at low frequencies increases acceptance for high energies \( > 10^{17} \text{ eV} \)

➤ Higher signal-to-noise ratio at higher frequencies increases acceptance for low energies \( < 10^{17} \text{ eV} \)
Test Designs Against Flux Models

\[ \log_{10}(E_{\nu}/\text{eV}) \]

- Kotera mixed 2010
- IceCube Astro. Extrap. 2015/16
- Romero-Wolf Ave 2018

\[ EF(\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}) \]
Higher visible area at higher elevation, but further from Xmax

Factor of ~3 improvement in acceptance going from 1-3 km

Models that extend to higher energy prefer the VHF design at higher elevation

Mostly insensitive to elevation & frequency band

Bands are ranges of the assumed flux

10 phased antennas, 120° FOV, over rock
Design Considerations: # Antennas

Is it better to build a bigger array or more independent stations?

10 Antennas per station yields 5-6x events, but 100 antennas yields only 10x events.

Bands are ranges of the assumed flux.

3 km elevation, 120° FOV, over rock
**Design Considerations: Water?**

Should the array be on a land-locked mountain or an island?

- Largely insensitive to Water Depth, because integrating over full acceptance curves
- If anything, land-locked mountains perform better than mountains surrounded by ocean
- Ocean may be desired due to RFI considerations

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**3 km, 10 phased antennas 120° FOV**

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**Bands are ranges of the assumed flux**

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**Kotera Mix. 2010**

**Ice Cube 2015/2016**

**Romero-Wolf Ave 2018**
Plan to:
1. Measure trigger rates, spectra, time-domain noise traces over week long period at several sites
2. Test out various RFI-rejection schemes at the firmware level with a deployed phased array using 4 dual-pol LWA antennas over one year

Site Study

Site study this summer at White Mountain Research Station near Bishop, CA at ≥ 3.8 km, valley ~1.2 km

Challenge of RFI

Collaborating with:
- Vieregg group (Chicago) on phased array deployment in strong RFI environment
- Hallinan group (Cal Tech) at OVRO-LWA on RFI-rejection strategies & RF-only air shower detection
- JPL, UCLA
CONCLUSIONS

Trade Studies: High Elevation (>2km), 10-phased VHF Antennas

➤ 10 stations yields ~2-6 Kotera mix neutrinos in three years

➤ Optimistic models prefer VHF, but the more pessimistic ones are insensitive to frequency band.

➤ Better to build more stations than phase more antennas at each station, but phasing ~10 channels is cost-effective and useful for direction reconstruction

➤ Mountaintop stations can be placed in view of water or land

RFI Environment Critical

➤ UHF may be quieter than VHF and because improvement at VHF is marginal (factors of 2-3), measure radio backgrounds at each site and use that to inform instrument design
BACKUP
Acceptance Monte Carlo

Acceptance of Radio Detector to $\nu_\tau$'s

Points on the Earth's Surface

$A_{\nu_\tau}(E_{\nu_\tau}) = R_E^2 \int \int d\Omega_E \int \int d\Omega_{\nu_\tau} \hat{r}_{\nu_\tau} \cdot \hat{n}_E$

$\nu$ incident directions

All Possible exiting $\tau$ outcomes

All Possible $\tau$ decays in the atmosphere

$\int dE \cdot p_{exit}(E_\tau | E_{\nu_\tau}, \theta_{exit})$

$\int dt p_{\text{decay}}(t | E_\tau) p_{\text{det}}(E_\tau, \hat{r}_{\text{decay}}(t))$

Depends on Exit Probability, Decay Probability, Detection Probability
**Monte Carlo Parameters**

**Exit Probability**
- **NuTauSim:** Publicly available package that includes the effects of tau propagation through the Earth
  - [https://github.com/harmscho/NuTauSim](https://github.com/harmscho/NuTauSim)
  - Tau neutrino regeneration
  - Layered Earth model and ocean layers of varying thickness
- SM neutrino-nucleon interaction cross-section and tau lepton energy loss due to photonuclear interactions.

**Decay Probability**
- Exponentially sampled tau decay length
  \[ L_{\text{decay}} \sim \left( \frac{E_{\tau}}{E_{\text{eV}}} \right) \times 49 \text{ km} \]

**Detection Probability**
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TAU PROPAGATION

➤ Skimming tau neutrinos:

1. **Interact** with nucleons in the Earth via CC or NC interactions

2. **Regenerate** through tau lepton decay, and

3. Propagate through and may produce an exiting tau lepton

➤ Probabilities of tau lepton exit include:

➤ Differentiated layers of rock

➤ Ice or ocean layers of varying thickness

➤ Tunable neutrino-nucleon interaction cross-section and tau energy loss due to photo nuclear interactions

TAU EXIT PROBABILITY

Emergence angle acts as (energy) “spectrometer” for $\nu_\tau$

Pileup of $\tau$ exit energy at critical energy $\sim$ few $\times 10^{17}$ eV

Alvarez-Muñiz, et al. PRD 2018
**TAU EXIT PROBABILITY**

\[ P_{\text{exit}} \text{ higher in rock at low energies} \]

\[ P_{\text{exit}} \text{ higher in water at high energies} \]

Alvarez-Muñiz, et al. PRD 2018
Narrowly peaked (~1°) Cherenkov cone at high frequencies. Broader (~2.5°) degrees at lower frequencies.
Radio-Frequency Noise Model

- Combination of galactic synchrotron noise (Dulk A&A 2001), thermal noise, and system noise: 
  \[ T = G \left( \frac{1}{2} T_{gal} + \frac{1}{2} T_{thermal} + T_{sys} \right) N_{ant} \]
10^{17} \text{ tau energy, } 37 \text{ km detector altitude, decay at ground level, } 10 \text{ dBi gain}

\begin{align*}
V &= E \lambda \frac{R_l G}{Z_0} \\
E &= \text{ZHAireS electric field} \\
V &= \text{ZHAireS voltage at the receiver load} \\
R_l &= \text{Antenna impedance (Fixed at 50 } \Omega) \\
Z_0 &= \text{Free space impedance (377 } \Omega) \\
G &= \text{Gain (linear)} \\
\lambda &= \text{Wavelength} \\
f(\lambda, G) &= \text{conversion factor}
\end{align*}