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Optimization of the Array Configuration for HUNT

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The High-energy Underwater Neutrino Telescope (HUNT) is a proposed next-generation neutrino observatory with an instrumented volume of approximately 30 cubic kilometers. Its primary goal is to detect neutrino emissions from PeV cosmic-ray accelerators and identify dozens of high-energy neutrino sources within a ten-year observation period. We explore a multi-cluster design for HUNT, optimizing the array geometry by varying parameters such as cluster radius, height, and number of clusters to maximize the discovery potential for point-like neutrino sources at energies above tens of TeV.

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1. Introduction

The origin of cosmic rays has long been an important and unresolved question. Over the century, a number of significant observations have advanced our understanding of this fundamental question, from the ground-level enhancement events caused by solar cosmic rays ($\lesssim 10^{10}$ eV) to the anisotropy of ultra-high energy cosmic-rays ($\gtrsim 10^{18}$ eV) suggesting the presence of local source. In recent years, LHAASO (Large High Altitude Air Shower Observatory) has observed tens of ultra-high-energy γ-ray sources (> 100 TeV) [1]. These observations indicate that Galactic sources can accelerate cosmic rays up to PeV energies and even higher. High-energy neutrinos are expected to be observed from theses sources, particularly from those associated with gas clumps or dense radiation fields. IceCube has detected the diffuse Galactic neutrinos at 4.5σ post-trial significance, accounting for $\sim 10\%$ of the all-sky astrophysical neutrino flux [2]. The most significant neutrino source ever observed is the Seyfert Galaxy NGC 1068 at the post-trial significance of 4.2σ in the source list [3]. Regarding Galactic sources, the point-source scan in the Galactic plane ($|b| < 5°$) yields only 1.8σ post-trial significance [4].

The High-energy Underwater Neutrino Telescope (HUNT) is a proposed project designed to detect neutrino counterparts of Galactic sources that accelerate cosmic rays to PeV energies [5]. HUNT aims to fill the critical missing piece in resolving the long-standing mystery of Galactic cosmic ray origins by identifying Galactic neutrino sources. With the unprecedented sensitivity, HUNT has the ability to resolve the high-energy neutrino sky and explore the origin of extragalactic neutrinos as well. The full-scale array will comprise more than 50,000 optical modules (OMs) with the instrumented volume around 30 km^3. Each OM encapsulates a downward-facing 20-inch PMT. Two candidate sites are under consideration, Lake Baikal and South China Sea. The long-term operation prototype strings have been deployed at both locations in 2024 and 2025 to evaluate detector performance and site suitability.

Achieving HUNT's core science goals requires demonstrating sensitivity to point-like sources, particularly crucial given LHAASO-KM2A measurements of γ-ray sources showing a median angular size of 0.2°. This scale matches the angular resolution of track events ($E_\nu \gtrsim 10$ TeV) observed by in-water telescope like KM3NeT-ARCA [6]. This paper focuses on optimizing array geometries for optimal point-source discovery potential using only through-going track events.

2. Telescope geometry

In this analysis, the sunflower geometry is adopted. The detector strings are arranged within a circular area, and their positions, when viewed from above, are defined in a polar coordinate system [7]:

$$r_n = s\sqrt{n},\ \phi_n = \frac{2\pi}{g^2}n, \qquad (1)$$

where $g = \frac{1+\sqrt{5}}{2}$ and n is the label of string ($n = 1, 2, ..., N$). The full-array of HUNT is composed of one sunflower cluster or more. The two clusters are spaced sufficiently far apart (e.g., 10 km) to prevent the same muon from passing through both arrays, thereby increasing the effective volume of the full-array.

The configuration is denoted as ${}^{\rm H}H_c{}^{\rm R}R_c{}^{\rm C}N_c$, where H_c is the cluster height in meters, R_c is the cluster radius in meters, and N_c is the number of clusters. The vertical spacing is 40 m between OMs along strings. The surface density of strings in the cluster is $\rho = \frac{N}{\pi R_c^2} = \frac{1}{\pi s^2} = 63.7\,\mathrm{km}^{-2}$ with $s = 70.7$ m. For instance, in the configuration ${}^{\rm H}1880{}^{\rm R}800{}^{\rm C}9$, each cluster has $N = 128$ strings. The total number of OMs is 55,296 (9 clusters × 128 strings/cluster × 48 OMs/string).

Our analysis investigates the parameter space defined by cluster height and radius to optimize sensitivity to neutrino sources. Throughout this investigation, the following parameters remain fixed: the total number of OMs, the string surface density, and the OM vertical spacing.

3. Simulation and reconstruction

The charged current interactions between muon neutrinos and nuclei outside the array dominate the through-going track events. The package gSeaGen [8] is used to simulate the neutrino interactions, and the external package PROPOSAL [9] is applied to simulate the propagation of muons outside the array. The muons intersecting the cluster boundary are recorded. The neutrino sample is generated with the energy from 1 TeV to 630 TeV, following a power-law spectrum $\mathrm{d}N/\mathrm{d}E \sim E^{-1.4}$, while the spatial distribution is isotropic. The samples for atmospheric neutrinos, diffuse astrophysical neutrinos [10], and the neutrinos from an astrophysical source are produced via re-weighting. The package MCEq is used to calculate the atmospheric neutrino spectra in different directions [11].

The simulation inside the array comprises three principal components: (1) particle and photon propagation outside the OM, (2) photon propagation within the OM, and (3) the response of 20-inch PMT [12]. The first two steps are implemented using GEANT4 [13]. The simulation procedure has been applied to reproduce the cascade events observed by Baikal-GVD at the level of hits [14].

The direction of tracks are reconstructed through the maximum likelihood method using the residual time distribution between the photon hit times recorded at the OMs and the expected Cherenkov photon arrival times. The uncertainty of energy reconstruction is assumed to be $\Delta\log E_\mu = 0.3$. We have achieved such energy resolution for through-going muons with the incident energies around 100 TeV at the array boundary [15].

In this analysis, we adopt the optical absorption length for the South China Sea site [16] and a seabed depth around 3000 m. A hit is defined by integrating all photoelectrons (pe) occurring within a 500 ns time window starting at T_0, where T_0 is the time of the first pe in the hit. After each hit, a dead time of 500 ns is enforced. The number of hits $N_{\rm hit} \geq 7$ are required for event reconstruction. Events are selected if the total pe count at least twice the number of hits.

4. Telescope response

The through-going track events with zenith angle above $\theta_{\rm th} = 85°$ are used in the analysis to reject the background events induced by atmospheric muons. The event weights for up-going tracks are proportional to the projected area of cluster in the direction of neutrinos. Muon detection efficiency varies with the track direction, muon energy and the in-cluster track length. The point-spread function (PSF) depends not only on the muon properties, but also on the primary neutrino's direction and energy.

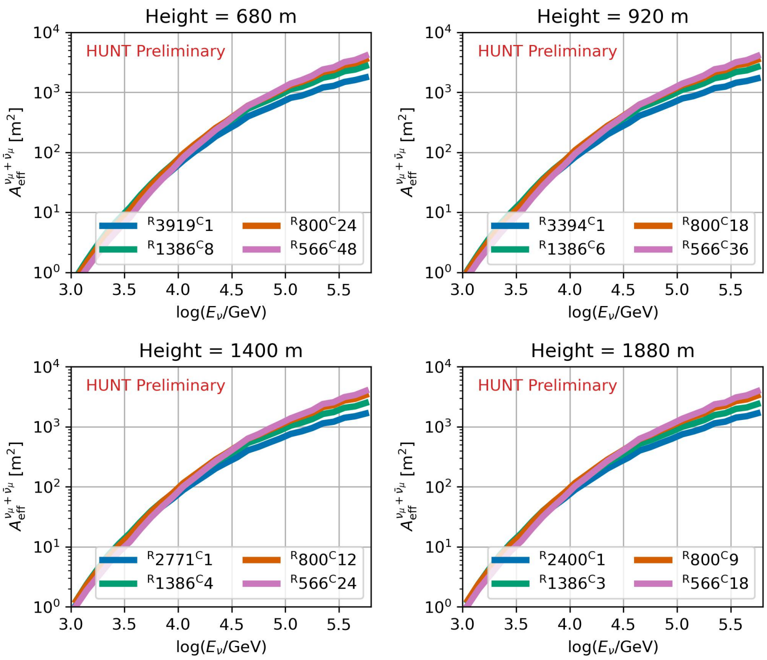

Figure 1: HUNT effective area for up-going tracks.

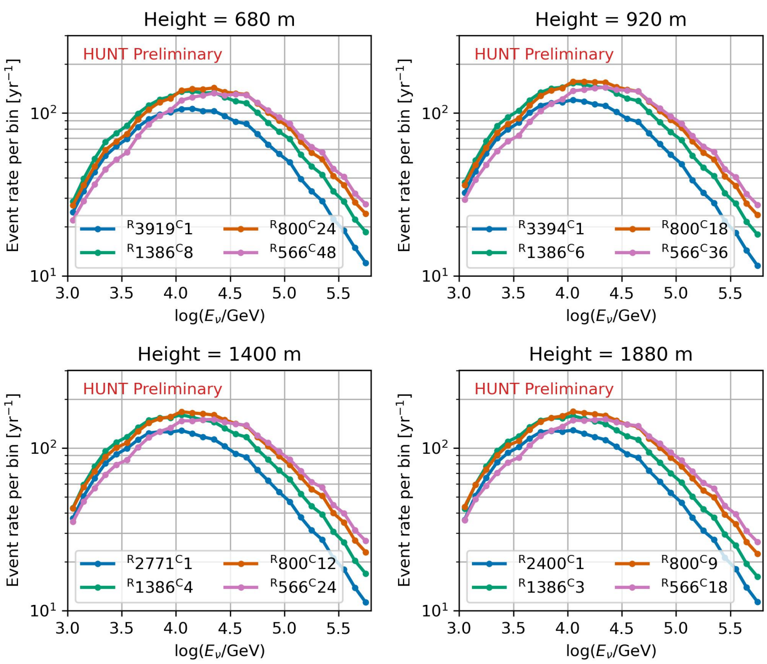

Figure 2: Event rate of up-going track events caused by diffuse astrophysical neutrinos [10].

The effective areas for up-going events is shown in Figure 1. The multi-cluster arrays have larger effective area than the one-cluster array, especially for neutrinos above 30 TeV. Figure 2 clearly shows how different designs affect astrophysical neutrino detection rates. The arrays with smaller-radius cluster ($R_c = 566\,\mathrm{m}$) detect more neutrinos above 100 TeV, larger-radius clusters ($R_c = 1386\,\mathrm{m}$) show better performance below 10 TeV. An optimal event rate of $2800\,\mathrm{yr}^{-1}$ is achieved for intermediate-scale cluster with $R_c = 800\,\mathrm{m}$ and vertical extension $H_c \geq 920\,\mathrm{m}$.

The angular resolution of up-going track events is shown in Figure 3. Larger clusters produce longer muon tracks, enhancing directional accuracy, especially for neutrinos with energies above 100 TeV. The angular resolution stays consistent at lower energies around TeV.

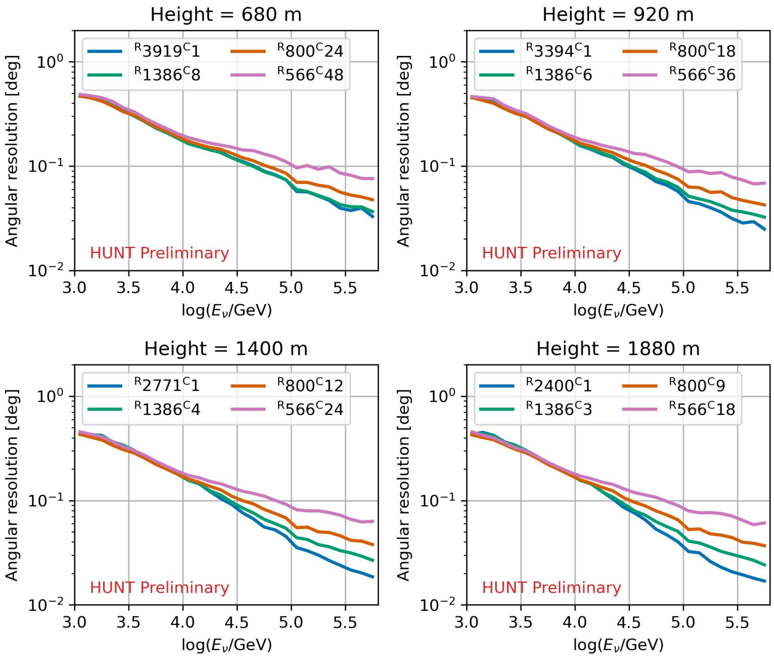

Figure 3: The median opening angle between the neutrino origin and the reconstructed muon direction for up-going tracks.

5. Discovery potential

We use the likelihood ratio to evaluate the HUNT's discovery potential to neutrino source with the given energy spectrum profile. The likelihood ratio is defined as

$$\frac{L_{s+b}(\mu_s)}{L_b} = \frac{\prod_{i,j} \mathrm{Poisson}\left(n_{i,j}^{\mathrm{obs}},\ \mu_s S_{ij} + \mu_b B_{ij}\right)}{\prod_{i,j} \mathrm{Poisson}\left(n_{i,j}^{\mathrm{obs}},\ \mu_b B_{ij}\right)}, \tag{2}$$

where μ_s and μ_b are the expected numbers of signal and background events, S_{ij} and B_{ij} are the probabilities of signal events and background events in the i-th spatial bin ($\Delta\Omega \sim 0.2^\circ \times 0.2^\circ$) and the j-th energy bin ($\Delta \log E_{\mathrm{rec}} = 0.4$, $E_{\mathrm{rec}} \geq 1\,\mathrm{TeV}$), and $n_{i,j}^{\mathrm{obs}}$ is the observed event number. We replace the $n_{i,j}^{\mathrm{obs}}$ with its expectation value to approximate the median significance [17]. The 5σ discovery potential corresponds to the minimum value of μ_s satisfying both $2\ln\left(L_{s+b}/L_b\right) \geq 25$ and $\mu_s \geq 3$. The flux normalization can be derived from μ_s.

HUNT is able to discover the neutrinos from NGC 1068 in 1-year observation, and even the neutrinos above 30 TeV in 10-year observation, as shown in Figure 4. Taking the configuration $^{H}1880^{R}800^{C}9$ as the reference, the HUNT discovery potential for different configurations are compared in Figure 5. A cluster radius of 800 meters performs well in the energy range from TeV to tens of TeV. For the same radius, a low-profile array is more sensitive to neutrinos above 100 TeV, while a high-profile array is more sensitive to the neutrino flux above TeV. The 5σ discoverable flux for the $^{H}1880^{R}800^{C}9$ configuration is approximately 30% lower than that for the $^{H}680^{R}3919^{C}1$ configuration at energies above TeV.

We also put the array ($H_c = 680$ m) at latitude of Lake Baikal, where the threshold angle $\theta_{\rm th}$ for distinguishing up-going events is set to 90° due to the water depth only 1360 meters. The array, with a cluster radius of 800 meters, shows performance comparable to the $^{H}1880^{R}800^{C}9$ array in the South China Sea for observing neutrinos above 10 TeV.

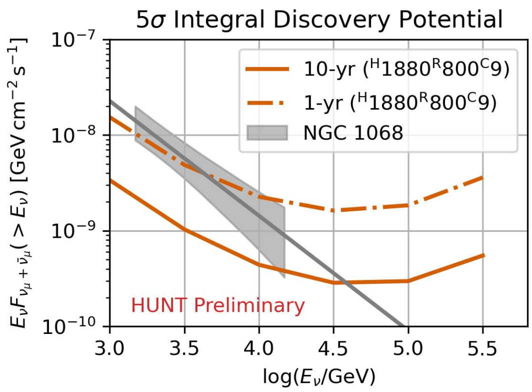

Figure 4: HUNT discovery potential for neutrinos from NGC 1068. The array configuration is $^{H}1880^{R}800^{C}9$. The solid and dot-dashed lines show 10-year and 1-year observations respectively. The gray shaded region represents NGC 1068 neutrino flux uncertainty [3].

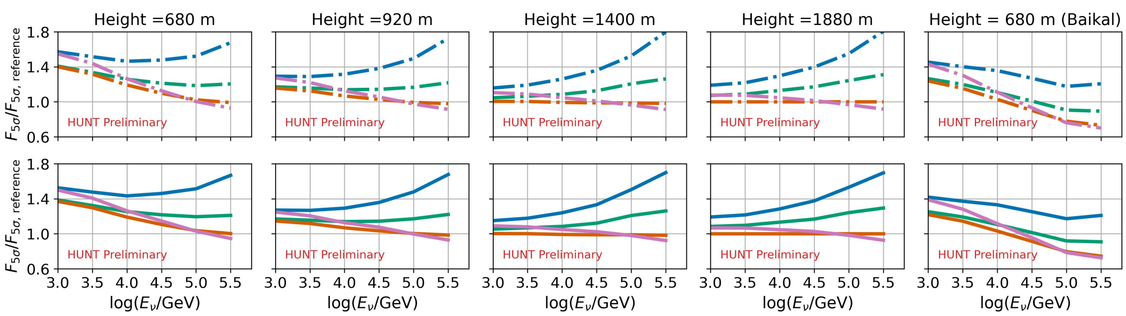

Figure 5: The 5σ discoverable flux ratio is calculated using the sensitivity curve in Figure 4 as the reference. The solid and dot-dashed lines represent 10-year and 1-year observations respectively. The colors of the lines correspond to different configurations, matching those in Figure 1. The last column is identical to the first column, except the telescope is moved from the South China Sea to Lake Baikal.

6. Summary

HUNT, the next-generation neutrino telescope, is designed to detect the neutrino counterparts of PeV cosmic-ray accelerators in our Galaxy and resolve the high-energy neutrino sky. By investigating the parameter space of cluster radius and height, we have assessed HUNT's 5σ discovery potential for point-like neutrino sources. The findings highlight HUNT's ability to observe neutrino sources at energies above tens of TeV, even for soft energy spectra with a spectral index of $\gamma \sim 3$. Among the configurations studied, arrays with clusters of 800-meter radii show comparable performance in observing neutrinos from NGC 1068 at energies above 30 TeV. Meanwhile, high-profile arrays ($H_c \gtrsim 1400$ m) demonstrate superior performance in TeV energies.

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