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The array simulation of NEON

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The observation of high-energy neutrinos from extreme astrophysical sources would substantially broaden our understanding of high-energy phenomena in the universe, and reveal the origin of cosmic rays. A proposed cubic-kilometer scale high-energy neutrino detector located in the South China Sea, the Neutrino Observatory in the Nanhai (NEON), optimized for the detection of high-energy neutrinos in the PeV regime, is expected to explore more in the multi-messenger era. Here, as a first step to the optimization and construction of the experiment, the various detector layouts of the experiments are simulated, and the estimated angular resolution and effective area for muon are discussed.

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1. Introduction

The Neutrino Observatory in the Nanhai (NEON) is a proposed undersea cubic-kilometer high-energy neutrino detector deployed in the South China Sea. The main physics goal of NEON is to trace the high-energy neutrinos back to their origins in the Universe, where high-energy astrophysical phenomena occur. Located near the equator, the observation pointed toward the center of our Galaxy and the full coverage of the southern sky offer a comprehensive complementary to the under-ice telescope IceCube [1].

High-energy astrophysical neutrinos are detected indirectly by observing the Cherenkov light emitted by the secondary particles resulting from neutrino interactions. The faint Cherenkov photons are observed by a three-dimensional array of 17-inch optical modules (OMs), each containing 31 3-inch photo-multiplier tubes (PMTs). These OMs are arranged along the vertically aligned detector units (DUs), anchored on the seabed and pulled up by a buoy.

To guide the design and construction of the NEON experiment, simulations incorporating neutrino production and interaction processes are being conducted. The current pipeline of our simulation is divided into three parts. Firstly, we inject neutrinos into the vicinity of the detector array, simulating their interactions with water or earth, and obtain the secondary particles. This process is carried out using the `gSeaGen` tool [2]. Secondly, we simulate the detection of Cherenkov photons produced by the high-energy leptons propagating in water with `GEANT4`[3]. Finally, we reconstruct the neutrino events based on the detection of photons. For detailed information on this step, please refer to another contribution titled "The Reconstruction of NEON".

In this work, we perform the simulation aiming at the optimization of the detector design. The effects of two factors are studied, the density of OMs and the size of the whole array.

We outline the various layouts of the detector array in Section 2. The angular resolution of these layouts was comprehensively presented and discussed in Section 3. Lastly, the conclusion is drawn in Section 4.

2. Array layout

With the NEON project, we employ the Fibonacci layout (as illustrated in Fig. 1) to avoid the presence of "corridors". For an event whose secondary muon traverses the central region of the "corridors" (as shown in Fig. 2) within the detector array, the Cherenkov photons emitted will travel a considerable distance before reaching any detector, this would result in a weakened signal [4]. This effect could be avoided by applying an asymmetric layout. The Fibonacci layout [5] is one of the choices that satisfies both asymmetry and uniformity.

Propagating a large quantity of Cherenkov photons through a sizable water body is a significantly time-consuming task for the simulation. Therefore, when evaluating the performance of different layouts, it is more efficient to reuse the simulated data from one layout rather than performing the simulation repeatedly. To enable this reuse, we initially perform a simulation using a large and dense full array, as shown in Fig. 1. The full array utilized in the simulation comprises 400 DUs with a 50 m horizontal spacing, and each DU contains 100 OMs with a 10m vertical spacing. This configuration results in a geometric volume of approximately 0.8 km^3.

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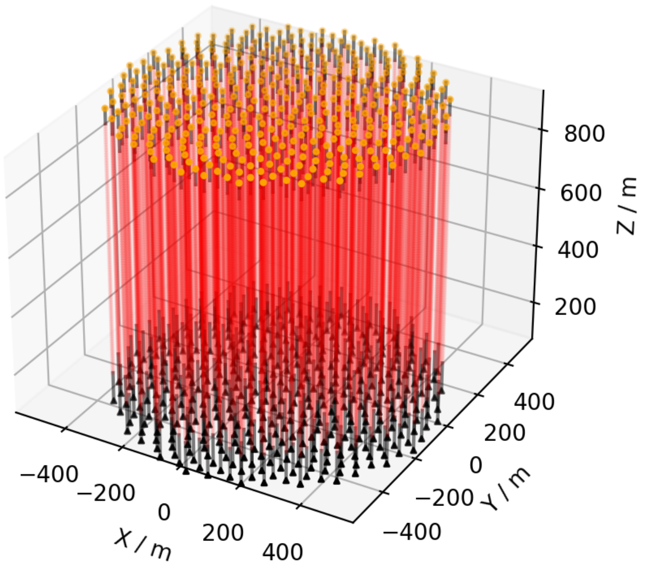

Figure 1: The 3-dimensional illustration of the array used in our simulation. The 400 vertical lines represent the DUs in NEON, each of which holds 100 OMs represented by the red part on the lines. The black triangles and orange circles on the bottom and top of vertical lines represent anchors and buoys, respectively.

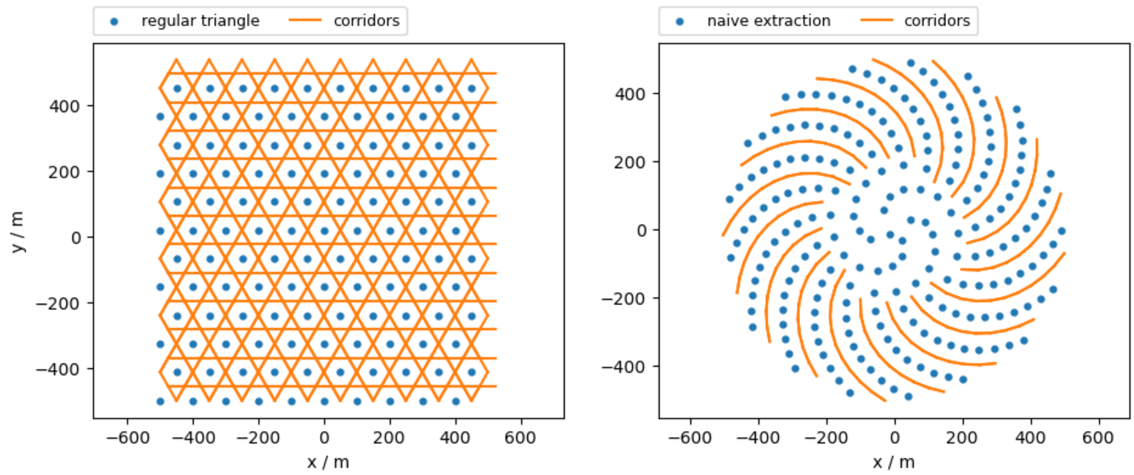

Figure 2: The two panels show the regular triangular layout and naively extracted subset of the Fibonacci layout respectively, and their corresponding corridors. The layout in the right panel is obtained by taking the first one in every two DUs in the order of distance from the center from the original Fibonacci layout.

With the simulation of a large and dense array, we could divide the array into subsets to obtain other layouts with smaller detector volumes or lower densities of OMs. In NEON's current design, the distribution of OMs on one DU is uniformly spaced. Therefore, in the vertical direction, we can get a sparser array configuration by selectively choosing every second or third OM on a DU. However, for the horizon distribution, it is non-trivial to uniformly extract a subset from the Fibonacci layout. As shown in the right panel of Fig. 2, simply taking one in every two DUs in the order of distance from the center results in the "corridors". We developed an algorithm for this DU extraction, following the steps:

1. Assign a status called "unscanned" to all the DUs except the most central one and assign the status called "selected" to this central DU.

2. Loop through the "unscanned" DUs, and change the status of the first one with at least one neighbor with a status other than "unscanned". If no neighbor has the status "selected", this DU changes to "selected", or changes to "dropped" otherwise.

3. Repeat the last step until no "unscanned" DU is left.

After the processes described above, the "selected" DUs form the extracted subset. Here the "neighbors" of each DU are defined as the ones connected after Delaunay triangulation [6], as shown in the left panel of Fig. 3. Besides, the volume of the array could be changed by removing the outmost DUs.

The right panel of Fig. 3 shows the basic Fibonacci layout and the subsets extracted with the method described above. It is evident that the subsets successfully preserve the uniformity of the Fibonacci layout, without any noticeable presence of the "corridors" pattern.

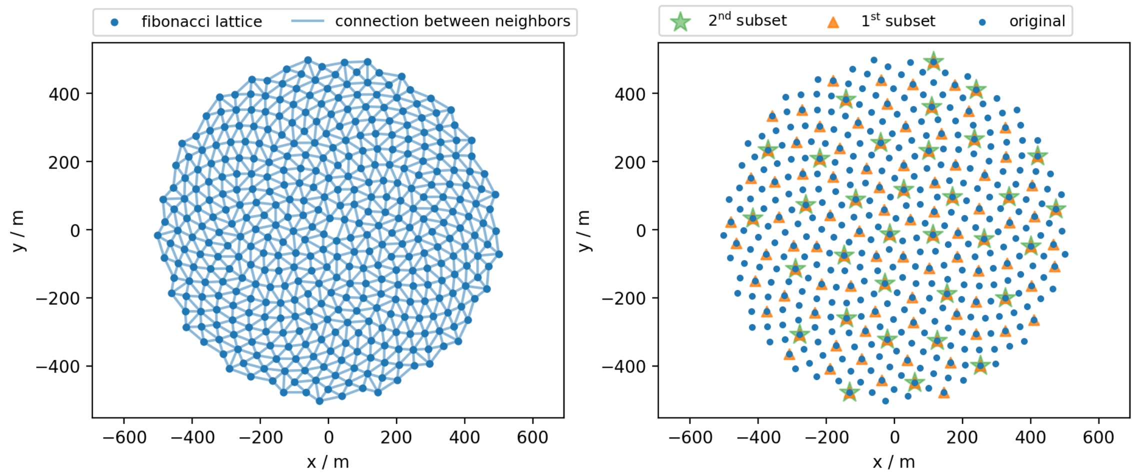

Figure 3: Here are the illustration of layouts used in our simulation. In the left panel, each blue dot represents a DU in the complete array, and the two dots with blue lines between them are neighbors of each other. In the right panel, the blue dots represent the complete array, the orange triangles are extracted from the complete array, and the green stars are extracted from the orange triangles.

3. Angular resolution and effective area

In this work, we generate a sample of muon neutrinos that follows a power-law spectrum with a spectral index of -2. The total number of the injected neutrino is $\sim 6\times10^{18}$, out of which around 10^6 neutrinos interacted with the medium and generated secondary muon. The distribution of injection direction follows the full-day track of the Crab Nebula.

With this sample, seven layouts are analyzed. As shown in Tab. 1, these layouts are various with the different values of the vertical spacing of OMs d_{vertical}, the horizontal spacing of OMs

$d_{\text{horizontal}}$, and the horizontal radius of the array R. The initial layout, referred to as the standard (STD), serves as the baseline, while the others vary in only one paramter of d_{vertical}, $d_{\text{horizontal}}$, and R.

type	d_{vertical}	$d_{\text{horizontal}}$	R	Ψ_{50}
STD	30 m	100 m	250 m	0.4
$\mathrm{L}^{\mathrm{den}}_{\mathrm{ver}}$	10 m	100 m	250 m	0.3
$\mathrm{L}^{\mathrm{spa}}_{\mathrm{ver}}$	50 m	100 m	250 m	0.4
$\mathrm{L}^{\mathrm{den}}_{\mathrm{hor}}$	30 m	50 m	250 m	0.2
$\mathrm{L}^{\mathrm{spa}}_{\mathrm{hor}}$	30 m	200 m	250 m	1.2
$\mathrm{L}^{\mathrm{large}}$	30 m	100 m	500 m	0.2
$\mathrm{L}^{\mathrm{small}}$	30 m	100 m	125 m	0.8

Table 1: Parameters of the 7 layouts and the corresponding median angular resolution. where d_{vertical} is the vertical spacing of OMs, $d_{\text{horizontal}}$ is the horizontal spacing of OMs, R is the horizontal radius of the array, and Ψ_{50} is median angular resolution in degree.

The median angular resolution Ψ_{50} of the 7 arrays is shown in Tab. 1, and the effective area $A_{\text{effective}}$ is shown in Fig. 4. The difference in angular resolution and the effective area between the layouts reveals that increasing the horizontal radius of the array and decreasing the horizontal spacing of OMs can significantly improve angular resolution and effective area while decreasing the vertical spacing of OMs has comparatively less impact.

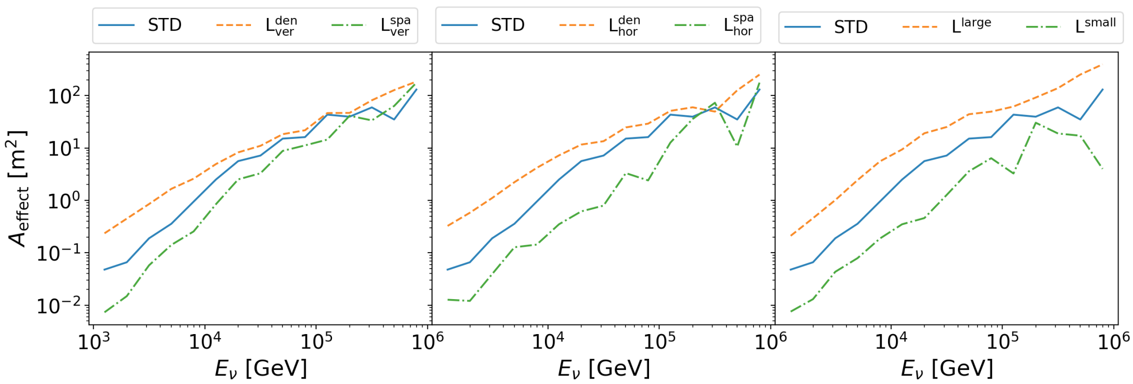

Figure 4: Effective area of the 7 layouts shown in Tab.1. The blue solid lines in all panels serve as the baseline, while the orange dashed line and green dash-dot line represent the improvement and degradation respectively.

Considering the first 5 layouts in Tab. 1 and the corresponding result, the improvement in angular resolution and effective area achieved by decreasing the spacing of OMs diminishes when the spacing reaches $\sim O(50\,\text{m})$. The comparison between the last 2 layouts indicates that the direction reconstruction quality of TeV muons, which traverse several kilometers in water, is related to the length of their trajectory inside the array.

4. Conclusion

In this study, we present the design and optimization of NEON. The Fibonacci layout has been chosen for its ability to minimize the presence of "corridors" and maintain uniformity. Then, the simulation data obtained from a large and dense array has allowed us to approach different layouts by selectively extracted subsets.

Furthermore, we have evaluated the angular resolution of different NEON layouts. Our results show that the improvement in angular resolution and effective area obtained by decreasing the spacing of OMs diminishes when the spacing reaches $\sim O(50\,m)$, and increasing the volume of the array could significantly improve the quality of direction reconstruction when the diameter of the array is less than several kilometers. Further investigation on the optimization would also consider the cost of building such an array.

In summary, the process of optimizing the NEON detector design and analyzing various layouts yields valuable insights aimed at improving the experiment's overall performance, and contributes to the ongoing efforts in the construction of NEON.

5. Acknowledgements

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