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The Payload for Ultrahigh Energy Observations (PUEO)

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PUEO is a long duration balloon experiment which will launch in 2024 from Antarctica that builds on the successes of the previous flights of the ANITA experiment in order to probe the cosmic neutrino flux above EeV energies. PUEO, like ANITA, seeks to measure coherent radio emission in the form of Askaryan emission from neutrino interactions inside the Antarctic ice sheet and both geomagnetic and Askaryan emission from i) decays of Earth-emergent τ-leptons in the atmosphere sourced from cosmic τ neutrinos ii) downward going cosmic rays reflected off the ice and iii) direct cosmic rays arriving above the Earth horizon.

Over the course of 4 flights, the ANITA experiment set the most stringent constrains on the diffuse flux of neutrinos with energies above 30EeV, in addition to measuring: 64 reflected cosmic ray candidates, 7 direct cosmic ray candidates, and an excess of candidates with non-inverted polarity from below the horizon that require further observation and analysis. PUEO improves upon the sensitivity of ANITA by over an order of magnitude below energies of 30EeV, thereby increasing the number of expected events from all event classes and allowing for stronger statistics, better constraints on physical models, and access to new energy regimes. These improvements are made primarily by i) more then doubling the number of antennas flown ii) including both dedicated low and high frequency drop-down instruments and iii) including an interferometric phased array trigger, thereby allowing for a decreased energy threshold via beamforming. PUEO also has significantly improved pointing resolution and ability to filter anthropogenic noise at the trigger level, allowing for better analysis efficiency and source classification. Using these improvements, over the course of a 30 day flight, PUEO will either make the first significant measurement of or set the strongest constraints to date on the diffuse flux of cosmic neutrinos above energies of 1EeV, in addition to following up the anomalous near-horizon events observed by ANITA and searching for transient sources.

9th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities (ARENA 2022)
7 - 10 June 2022
Santiago de Compostela, Galicia, Spain

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https://pos.sissa.it/

PoS(ARENA2022)004

1. Introduction

High energy neutrinos are ideal cosmic messengers to relay information from the most violent astrophysical events in the universe. Ultra-High Energy (UHE) neutrinos ($E_\nu > 1$ EeV) have long been predicted to exist from cosmogenic and astrophysical sources, but have yet to be detected by any experiment. One method of detecting these elusive particles involves using the entire Earth and its terrain as the instrumental volume for neutrino interactions and observing from high altitudes to cover a large swath of the ground. The Payload for Ultra-high Energy Observations (PUEO) experiment is a long-duration, high altitude balloon experiment that targets the UHE flux by measuring radio emission produced by neutrino-sourced secondaries in the air and Antarctic ice sheet [1].

Coherent radio emission is produced following neutrino interactions through two different channels: Askaryan emission and geomagnetic emission. Askaryan emission is produced through the negative charge asymmetry present in particle cascades developing in dense media, through interactions with atomic electrons, macroscopically manifesting as a single charge propagating at relativistic speeds. Geomagnetic emission is produced through the opposing deflections of electrons and positrons during cascade development inside Earth's geomagnetic field, macroscopically manifesting as a propagating dipole. PUEO measures these separate types of radio emission almost uniquely through two channels: i) the in-ice Askaryan channel and ii) the air shower channel. In-ice neutrino interactions (either via charged-current or neutral-current) produce Askaryan emission through quickly developing particle cascades, which propagates through the ice with km-scale attenuation lengths to reach the detector. This is the dominant channel for PUEO's neutrino sensitivity for $E_\nu > 1$ EeV. Extensive air showers (EAS) can be produced by ν_τ interactions near the Earth's surface, resulting in quickly decaying, Earth-emergent τ-leptons. The dominant form of emission from secondaries within an EAS is geomagnetic, with minimal contributions resulting from Askaryan emission. Geomagnetic emission is also readily produced in EAS sourced from cosmic rays, which can be observed directly (from above the horizon) and indirectly (reflected off the ice). A diagram of the different observation channels of PUEO is shown in the left panel of Figure 1.

PUEO is built on the heritage of the Antarctic Impulsive Transient Antenna (ANITA) experiment, which completed four successful flights between 2006 and 2016 and set stringent limits on the diffuse flux of UHE neutrinos [2]. Over the course of 4 long duration flights, ANITA observed 64 reflected cosmic rays candidates, 7 direct cosmic ray candidates, and several candidates with non-inverted polarity from below the horizon–consistent with the phenomenology of upward going extensive air showers. These candidate events can be broken into two categories: steeply upgoing and near-horizon. ANITA-I and ANITA-III each observed one steeply upgoing candidate event during flight with elevation angles $-27°$ and $-35°$, respectively, with reconstructed energies near 0.5 EeV [3, 4]. To be interpreted as τ-lepton candidates, these observations would be in strong tension with standard model predictions of τ-lepton emergence probabilities at high energies and steep emergence angles. New interpretations of these signals as transition radiation at the air-ice boundary have been proposed [5]. ANITA-IV observed 4 near-horizon upward going EAS candidates, which are more in line with standard model predictions of τ-lepton emergence probability, but have a non-negligible chance of being misidentified from a direct cosmic ray event [6]. Each of

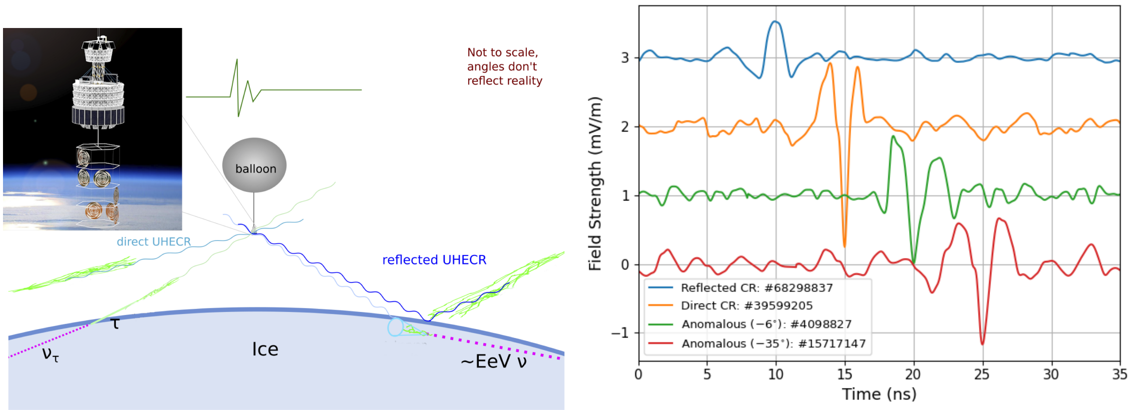

Figure 1: Left: modified diagram of PUEO's observation scheme of cosmic rays and neutrinos, taken from Cosmic Deaconu. Right: four example candidate classifications observed during the flights of ANITA, including i) reflected cosmic rays, ii) direct (above-the-horizon) cosmic rays iii) slightly below horizon upward going EAS iv) steeply upgoing EAS [3, 4, 6].

these candidate classes is shown in the right panel of Figure 1, with the observed electric fields in the horizontal polarization superimposed and offset by -1 mV/m.

PUEO will improve on the ANITA experiment in nearly every way, building on the existing framework and methodology to resolve neutrinos above EeV energies. Such observations will target the cosmogenic flux of neutrinos–the guaranteed flux of neutrinos sourced by Ultra-High Energy Cosmic Rays (UHECR)–as well as neutrinos from astrophysical sources and transient events. These measurements can help to confirm or exclude models regarding the evolution of UHECR sources and deliver information regarding the sources and environments of the most energetic processes in the universe. In addition, PUEO can probe unexplored parameter spaces regarding super-heavy dark matter and beyond-the-standard-model physics, helping to constrain many theoretical models at the highest energies.

2. Main Instrument

The main instrument of PUEO consists of 108 dual-polarization quad-ridge horn antennas that cover a frequency range of 300 MHz to 1200 MHz. Increasing the low frequency cutoff of the antennas from ANITA's 180 MHz to 300 MHz achieves two things: i) the overall area of an antenna decreases by roughly a factor of two, allowing for more than twice as many antennas as ANITA ii) the strong satellite continuous wave (CW) and other RFI signals that contaminated ANITA observations are avoided. The antennas are organized into 4 rings of 24 phi-sectors with a dropdown ring of 12 40° downward canted antennas below the main payload (see left panel of Figure 1). The main instrument dropdown ring functions to increase sensitivity to upward going EAS and will target the steeply upward going anomalous events observed by ANITA for further observation and analysis.

The most significant improvement of PUEO over ANITA comes from the inclusion of an interferometric phased array (or beamforming) trigger. The concept of beamforming involves coherently

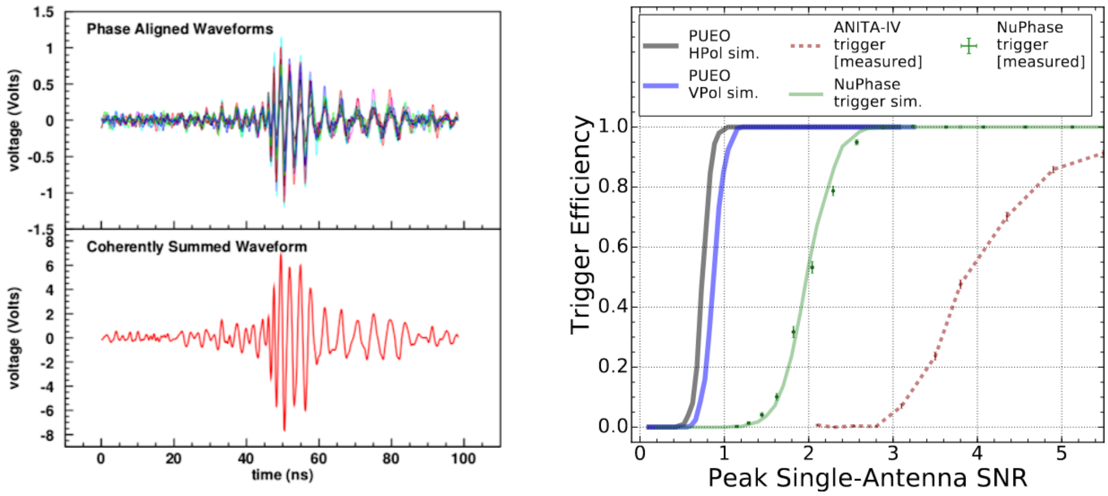

Figure 2: Left: simulated beamforming of a signal recorded by 16 PUEO antennas (4 phi-sectors), showing an increase in SNR of ~ 4. Right: single-antenna trigger efficiency curves of PUEO compared against the performance of the ANITA-IV combinatoric trigger and ARA's coherent trigger system [7].

adding the full radio waveforms recorded in multiple antennas with time delays corresponding to a range of angles of incident plane waves. When this summation is performed, the signal adds coherently, resulting in an amplitude increase of $N_{\rm ant}$, the number of beamformed antennas, while the noise adds incoherently, resulting in an RMS increase of only $\sqrt{N_{\rm ant}}$. The radio emission from cosmic rays and neutrino events is expected to be observed in 4 phi-sectors (or 16 antennas), resulting in a factor 4 increase in SNR. The beamforming of a simulated signal for PUEO is illustrated in the left panel of Figure 2. Thus, by beamforming, PUEO's SNR threshold for any given event is decreased, as shown in the right panel of Figure 2, allowing for observations of events with lower energies or further off axis, greatly increasing expected event rates and improving event quality.

PUEO will also include a Radio-Frequency System-on Chip (RFSoC) as a combined readout and interferometric trigger system. The RFSoC allows for dynamic digital notch filtering, supplanting the use of analog filters present during the flight of ANITA-IV. The use of an RFSoC significantly improves PUEO's ability to filter man made noise in realtime at the trigger level, thereby improving the SNR for any given event candidate, resulting in more recorded events and higher event quality.

3. Low Frequency Instrument

PUEO's dedicated LF instrument is a dropdown array of 8 dual-polarization sinuous antennas below the main instrument that operates in the frequency range 50 MHz to 300 MHz with full azimuthal coverage (see the left panel of Figure 1). Similar to the main instrument, the LF instrument will also beamform on a smaller number of antennas. Simulation studies estimate that beamforming will occur on ~ 5 antennas, resulting in an SNR increase of ~ 2.2. A diagram of one of the sinuous antennas of the LF instrument is shown in the left panel of Figure 3. The LF instrument

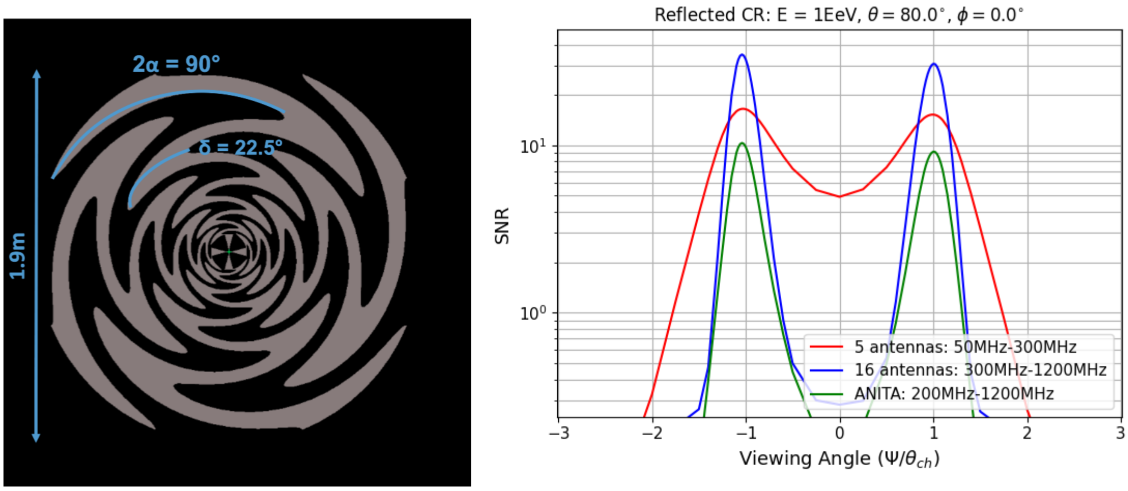

Figure 3: Left: diagram of a single antenna of PUEO's LF instrument. Right: the frequency integrated SNR of a reflected cosmic ray event as a function of viewing angle for the LF instrument compared against PUEO's main instrument and ANITA.

operates independently of the main instrument and provides complimentary measurements, helping to improve event quality through events with coincident triggers, and allowing for reduced energy thresholds via independent LF triggers.

Radio emission from air showers, sourced from either cosmic rays or τ-leptons, maintains coherence for broader viewing angles at low frequencies. Thus, by measuring radio emission from air showers in this range, events can be observed further from the coherent Cherenkov peak, increasing geometric acceptance. This concept is demonstrated in the right panel of Figure 3, which shows the frequency integrated, beamformed SNR of PUEO's main instrument and LF instrument to a reflected cosmic ray event as a function of viewing angle. Also shown is the SNR curve for an ANITA-IV antenna for comparison. While the peak SNR in the LF is lower due to increased noise temperatures at low frequencies and fewer beamformed antennas, emission can be observed more broadly inside and outside the Cherenkov peak. This behavior indicates amplified acceptances at the cost of increased energy threshold with respect to PUEO's main instrument.

4. Expected Performance

Simulation efforts have been made to use tools developed for ANITA to estimate PUEO's sensitivity to the diffuse flux of UHE neutrinos in both the Askaryan and ν_τ air shower channel, modifying the threshold scaling described above and adding the LF instrument properties. Figure 4 shows the expected PUEO single-event-sensitivity to the diffuse neutrino flux plotted against various source models and compared to different experimental sensitivities. The dominant channel for the observation of neutrinos comes from the Askaryan channel, with the τ-lepton air shower channel contributing below EeV energies. The LF instrument provides roughly an additional factor of 2 increase in sensitivity to the τ-lepton air shower channel.

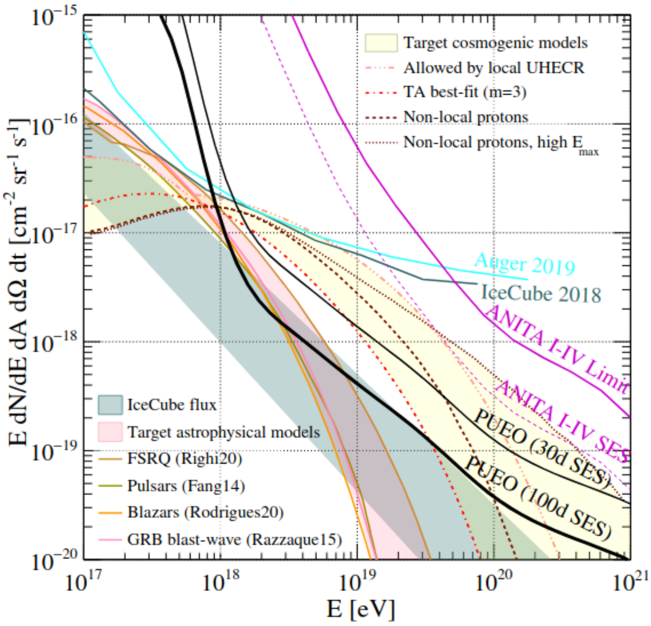

Figure 4: PUEO's single-event-sensitivity (SES) to the diffuse flux of UHE neutrinos, plotted against various cosmogenic [8, 9] and astrophysical [10–13] models of the diffuse flux and compared to limits set by the ANITA [2], IceCube [14] and Pierre-Auger [15] experiments.

Figure 4 demonstrates that PUEO achieves substantial improvements in sensitivity over the flights of ANITA, being nearly two orders of magnitude more sensitive at $E_\nu = 30$ EeV. Over the course of a single 30 day flight, PUEO will either measure the first neutrino above EeV energies or eliminate a number of cosmogenic models from non-local or subdominant proton sources. Over 100 days of flight, the best-fit TA composition of UHECR can either be confirmed or excluded and some neutrino sources (flat-spectrum radio quasars (FSRQs), pulsars and gamma ray bursts (GRBs)) may be observable. In addition, if the diffuse astrophysical flux measured by IceCube extends to EeV energies, a 100 day flight of PUEO may also observe this flux.

Beyond measurement of the diffuse flux of astrophysical neutrinos, PUEO also has the chance to record transient events. Figure 5 shows PUEO's single-event-sensitivity to transient events, both long-duration (left panel), occurring over the course of the entire flight, and short-burst (right panel), on the order of $\sim$ 1000 s. For the calculation of the long-duration sensitivity, the average effective area over a typical flight path was used, while for the short-burst sensitivity, the peak instantaneous sensitivity was used. Figure 5 shows that for certain models, PUEO is capable of masuring neutrinos from transient sources. Potentially measurable sources for PUEO include neutron star-neutron star mergers and short gamma ray bursts.

5. Conclusion

With the inclusion of significantly more antennas, a interferometric phased array trigger, a dedicated low frequency instrument, and better filtering of man-made noise at the trigger level,

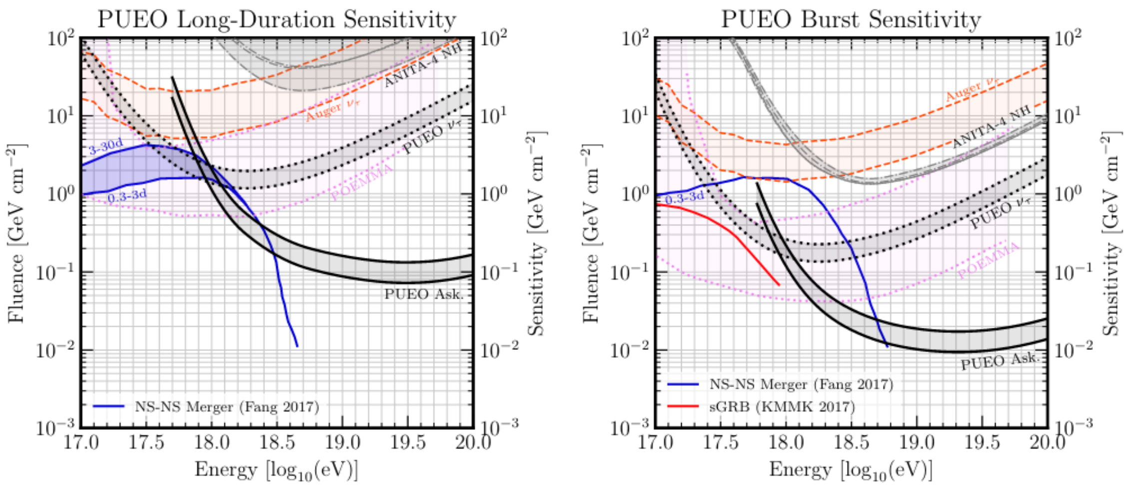

Figure 5: PUEO's peak single-event-sensitivity to long (left) and short (right) transient events. The sensitivity to long duration transients is calculated by considering the mean effective area of an optimal part of the sky over the course of the flight, while the sensitivity to short burst transients considers the peak effective area over a window of 1000 s. Also shown are the sensitivities of the ANITA [2], Pierre-Auger [15], and POEMMA [16] experiments to transients.

PUEO builds on the success of the ANITA experiment to achieve the best sensitivity to cosmic neutrinos with energies exceeding 1 EeV. In a single 30 day flight, PUEO will either measure the first cosmic neutrino with energy exceeding 1 EeV or set stringent limits that help to constrain source models of the cosmogenic neutrino flux. Over the course of a longer, 100 day campaign, PUEO will either confirm or reject the UHECR best-fit composition proposed by TA, and potentially measure astrophysical neutrinos from FSRQs, Pulsars and GRBs. Due to its large instantaneous aperture, PUEO shows a promising sensitivity to UHE neutrinos sourced from certain classes of transient events, such as neutron star-neutron star mergers and short gamma ray bursts, and may potentially make an observation during a given flight.

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