Snowmass2021 - Letter of Interest

The Payload for Ultrahigh Energy Observations (PUEO)

Topical Groups:

■ (NF4) Neutrino Frontier: Neutrinos from natural sources
■ (CF7) Cosmic Frontier: Cosmic Probes of Fundamental Physics
■ (IF10) Instrumentation Frontier: Radio Detection

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Abstract:

The Payload for Ultrahigh Energy Observations (PUEO) is a proposed NASA Long Duration Balloon (LDB) payload that will launch from McMurdo Station, Antarctica in December 2023. PUEO detects radio emission from interactions of extremely high-energy cosmic particles, including neutrinos and cosmic rays. PUEO is especially well-suited for discovering the highest energy neutrinos and for multi-messenger point-source and transient searches. Because they view the largest target volumes for neutrino interactions, balloon-borne experiments such as PUEO access the rare fluxes expected at the highest neutrino energies. PUEO builds on the success of ANITA, employing the same detection principle, but with a new payload design that capitalizes on recent technological developments to lower the energy threshold and improve sensitivity to neutrinos and cosmic rays by an order of magnitude.

1 Science Case

High-energy neutrino astrophysics reveals a unique view of the most energetic particles from cosmic distances. Neutrinos travel virtually unimpeded through the universe, making them unique messenger particles for cosmic sources, and carrying information about very distant sources that would otherwise be unavailable. Neutrinos seen directly from sources are indicators of hadronic processes within the accelerators. PUEO will have the world's best sensitivity to neutrinos in a regime where sources might reach their ultimate acceleration energies. Unlike cosmic rays, neutrinos are not deflected by magnetic fields along the journey from their source, and so can be observed coincident in time and direction with photons or gravitational waves from the same source.

While the high-energy spectrum of astrophysical neutrinos has been observed by IceCube up to a few PeV[1–7], the spectral shape at higher energies is unknown, but is expected to include higher energy populations of neutrinos created by cosmic-ray-photon interactions. These interactions may occur from within the same sources generating the cosmic rays[8–11], or from cosmic-ray interactions with photons within about 50-200 Mpc of their source (the so-called Greisen-Zatsepin-Kuzmin (GZK) process[12;13]), generating cosmogenic neutrinos[14].

PUEO will lower the energy threshold of balloon-borne neutrino experiments to overlap with limits from ground-based observatories at $10^{18.5}$ eV. Above that energy, the $\sim 10^6$ km^3 instantaneous ice volume visible to balloon experiments combined with PUEO's improved sensitivity over ANITA will lead to either the best constraints or a first detection in this regime. Of particular interest to PUEO are models with a sizable proton component, very large maximum acceleration energies, and with sources more populous at large redshifts[15;16]. Conversely, UHE neutrino flux measurements uniquely probe cosmic ray acceleration and mass composition[17;18], and complement cosmic rays in source identification[14;15;19–33].

PUEO will additionally have the unique capability to search for transient sources of neutrinos with the largest instantaneous effective area of any instrument in its limited field of view. While the ~ 30 day exposures of PUEO and ANITA are small compared to the years of exposure from ground-based instruments like Auger[34] and IceCube[7], the large visible volume available to PUEO makes it uniquely suited to detecting transients from sources[35–65;65–84] with low flux in the few degrees near the horizon of the payload.

Tau neutrinos are observable by PUEO through a different channel wherein a tau neutrino interaction in the Earth results in a tau lepton exiting the ice and decaying in the air to produce observable radio emission[34;85–93]. For PUEO, this tau neutrino signature via air showers surpasses the Askaryan signature in importance below $10^{17.5}$ eV.

PUEO will also probe fundamental physics. The discovery of UHE neutrinos would allow a measurement of the neutrino-nucleon interaction cross section[94;95], which is sensitive to physics beyond the Standard Model[96;97] and the nucleus at small scales[98], in regions of parameters space that are inaccessible by the Large Hadron Collider. We expect that once events are observed, PUEO could loosely constrain cross sections at ~ 100 TeV center-of-mass energies based on the energy-dependent zenith angle distribution of the events[94;95;99–101].

2 Technical Approach

PUEO builds significantly on the heritage from the four successful flights of the ANtarctic Impulsive Transient Antenna (ANITA)[102–106] to scan the 1.5M km^3 of Antarctic ice within its horizon with unprecedented sensitivity. PUEO leverages recent technological developments to lower thresholds[107–110] with a novel trigger design and an expanded array to achieve an order-of-magnitude leap forward in sensitivity to rare fluxes below 10^{19} eV and a factor of several times improvement on the world's best sensitivity to fluxes at 10^{20} eV.

The overall concept of the PUEO payload is similar to that of ANITA. Much of the mechanical and RF design, the power systems, attitude and location systems, and data storage and transfer is inherited from ANITA. However, PUEO represents a significant improvement in sensitivity compared to the ANITA payload. This is achieved by: 1) an interferometric phased array trigger, which lowers the trigger threshold compared to the ANITA analog trigger, and increases the expected neutrino and cosmic-ray acceptance, 2) more than doubling the antenna collecting area above 300 MHz. This is enabled by increasing the low-frequency cutoff of the antennas from 180 MHz for ANITA-IV to 300 MHz for PUEO, which reduces the size of the antennas by a factor of two in area. We have also added a drop-down system of 24 antennas, to further increase the collecting area, especially for EAS events, 3) the addition of a low-frequency instrument designed to target detection of radio emission from air showers, 4) significantly improved ability to filter man-made noise in real time at the trigger level, and 5) significantly improved pointing resolution, especially in elevation, from a combination of better orientation measurements and a larger physical vertical antenna baseline. Improved elevation pointing resolution will allow us to improve analysis efficiency and reduce contamination from man-made backgrounds.

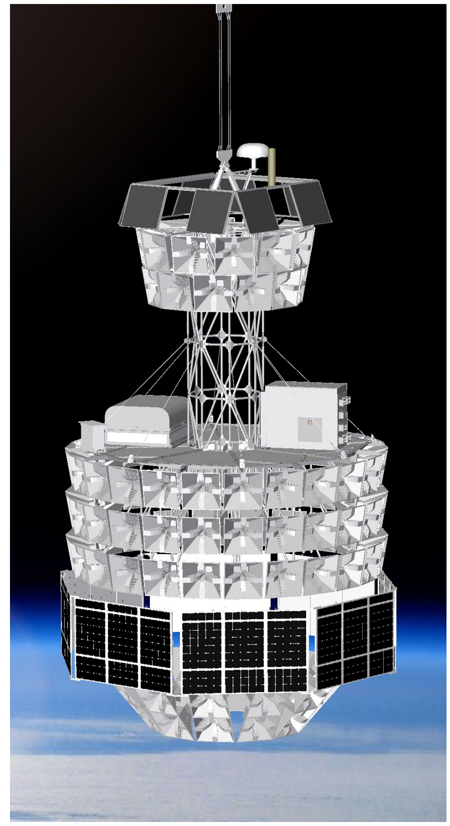

Figure 1: A rendering of the PUEO gondola.

PUEO receives radio signals from cosmic particles using 120 dual-polarized quad-ridged horn antennas, sensitive between 300 MHz and 1500 MHz. Radio signals observed by these antennas are amplified, digitized[111] above the Nyquist frequency, and a trigger decision is made using coherent combinations of the digitized channels in real time to determine which data are saved to disk. In addition, PUEO will host a separate low-frequency instrument that will target detection of radio emission from air showers produced by cosmic rays, tau leptons created in neutrino interactions, and possibly other more exotic particles. The low-frequency instrument will consist of an additional array of antennas that will drop down below the main gondola after launch.

3 Summary

PUEO is a discovery instrument that will significantly improve the reach of neutrino experiments at the highest energies, and is well-suited for multi-messenger point source and transient observations. PUEO takes advantage of technological developments coupled with a new design to produce a new payload that will improve sensitivity to the highest energy neutrinos by an order of magnitude.

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