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Discovering the highest energy neutrinos with the Payload for Ultrahigh Energy Observations (PUEO)

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The Payload for Ultrahigh Energy Observations (PUEO) is a NASA Long-Duration Balloon Mission that has been selected for concept development. PUEO has unprecedented sensitivity to ultra-high energy neutrinos above 10^{18} eV. PUEO will be sensitive to both Askaryan emission from neutrino-induced cascades in Antarctic ice and geomagnetic emission from upward-going air showers that are a result of tau neutrino interactions. PUEO is also especially well-suited for point source and transient searches. Compared to its predecessor ANITA, PUEO achieves better than an order-of-magnitude improvement in sensitivity and lowers the energy threshold for detection, by implementing a coherent phased array trigger, adding more channels, optimizing the detection bandwidth, and implementing real-time filtering. Here we discuss the science reach and plans for PUEO, leading up to a 2024 launch.

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1. Introduction

The Payload for Ultrahigh Energy Observations (PUEO) is a NASA Long-Duration Balloon Mission that has been selected for concept development through NASA's Astrophysics Pioneers program, and will launch in December 2024 from McMurdo Station in Antarctica. PUEO will be sensitive to both Askaryan emission from neutrino-induced cascades in Antarctic ice and geomagnetic emission from upward-going air showers that are a result of tau neutrino interactions, and will have unprecedented sensitivity to ultra-high energy neutrinos above 10^{18} eV. For a more detailed discussion of the PUEO mission, please see Reference [1].

2. Science Case

PUEO will have an unparalleled view of the neutrino sky at extremely high energies, and is uniquely suited to observe neutrinos from sources that accelerate particles to the highest possible energies [13]. Neutrinos travel virtually unimpeded through the universe and carry otherwise-unavailable information about their origin, making them unique messenger particles for cosmic sources. 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. Observations from all of the messengers (neutrinos, gamma rays, cosmic rays, and gravitational waves) can be combined into a complete multi-messenger view of the high-energy universe as demonstrated by the groundbreaking observations of the first candidate extra-galactic neutrino source, TXS 0506+056 [14, 15] and the first gravitational wave source, the neutron star merger GW170817 [16, 17].

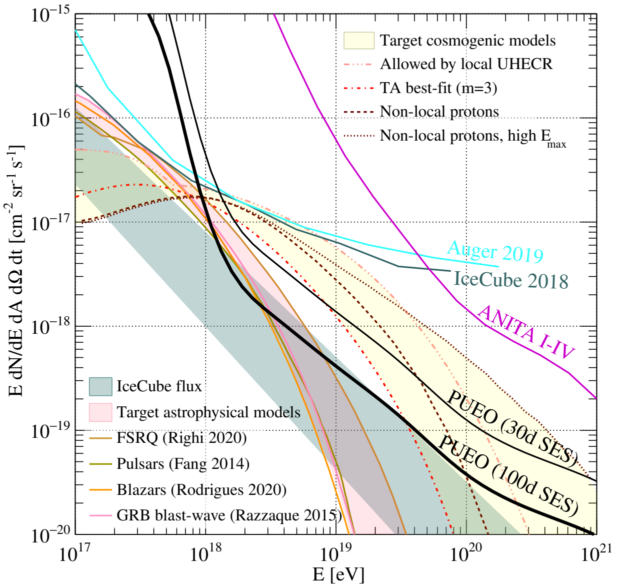

Figure 1: The PUEO single-event sensitivity (SES) to diffuse UHE fluxes, compared to existing limits [2–4] and some cosmogenic models [5–7] and astrophysical models [8–12]. The ANITA I-IV SES is shown for comparison. The non-local proton models were generated using CRPropa3 in a manner similar to [5] but with $z > 0.1$. For diffuse fluxes, the Askaryan sensitivity dominates, although the τ EAS channel also contributes significantly below a few EeV. From Reference [1].

In Figure 1, we compare the expected performance of PUEO with models for the flux of diffuse neutrinos, alongside current best constraints. Above about 10^{18} eV, the $O(1\,\mathrm{M})$ km^3 instantaneous ice volume visible to balloon experiments combined with PUEO's improved sensitivity over ANITA [2] will lead to either the best constraints or a first detection in this regime. IceCube and Auger [3, 4] have placed the most competitive constraints below $10^{19.5}$ eV so far. Compared to existing and

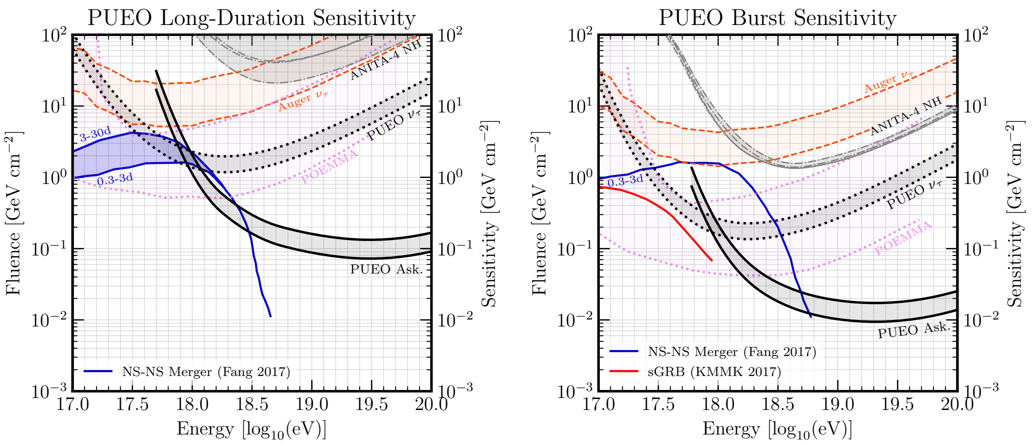

Figure 2: The peak single-event sensitivity of the PUEO air shower and Askaryan channels to long (left) and short (right) transients, such as NS-NS mergers ranging from 0.3 to 30 days in duration [18], high-luminosity FSRQs lasting the entire flight [19] and short GRBs [20]. The long-duration sensitivity considers the mean effective area of an optimal part of the sky over the entire flight while the burst sensitivity considers the mean effective area over a ~ 1000 s window. The shaded regions indicate possible sensitivities for different locations on the sky bounded by the mean sensitivity across PUEO's field of view and PUEO's peak sky sensitivity. Also shown are the fluence limits set by other experiments [21, 22]. From Reference [1].

proposed in-ice arrays, PUEO is unique in that it accesses the highest energies in the diffuse neutrino spectrum, has the largest instantaneous effective area across the energy band, and can uniquely measure the electron to tau ratio flavor ratio in the event of a detection.

Neutrino interactions in the ice are observable with PUEO through the Askaryan radiation signature. Tau neutrinos are observable by PUEO through an additional 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. While Figures 1 and 2 include the sensitivity of PUEO to both channels, we find that the tau neutrino signature via air showers dominates PUEO's effective area for energies below 10^{18} eV.

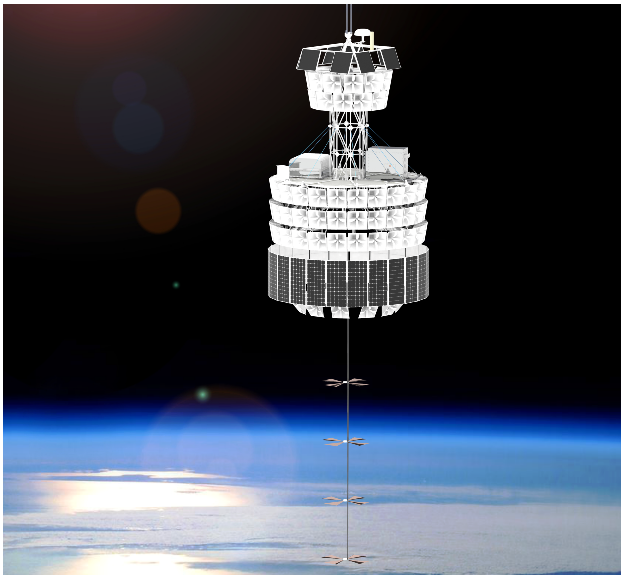

Figure 3: A rendering of the PUEO payload, including a design for the low-frequency (LF) drop-down instrument.

PUEO will have a unique capability to search for transient sources of neutrinos with the largest instantaneous effective area of any instrument. The large visible volume available to PUEO makes it uniquely suited to detecting transients from sources with low flux in the few degrees near the horizon of the payload. Figure 2 shows PUEO's sensitivity to transient bursts of neutrinos from NS-NS

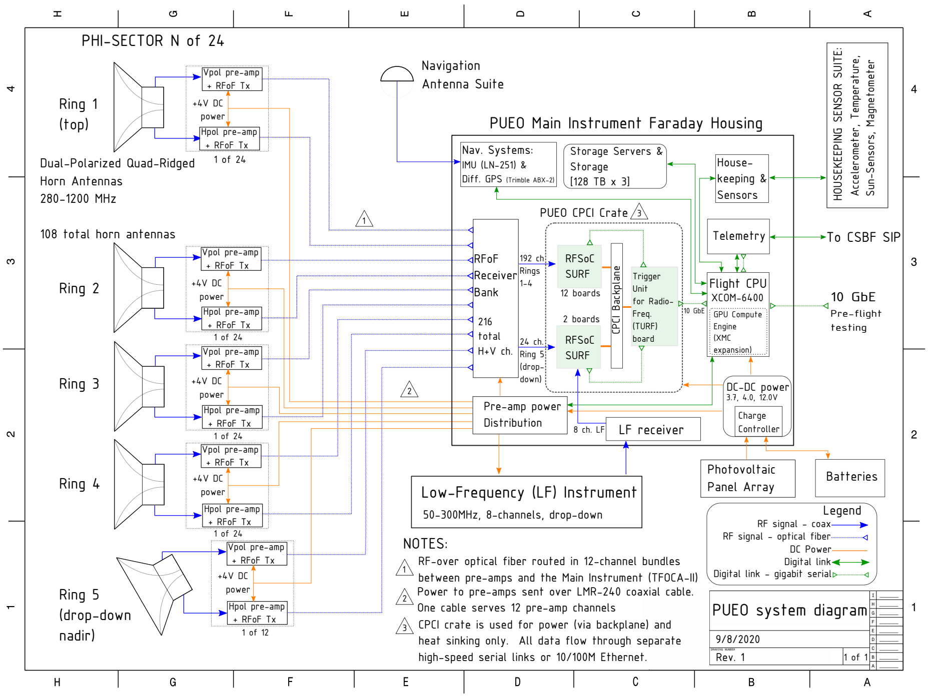

Figure 4: The PUEO System Diagram.

mergers [18], flares of FSRQs [19], or short GRBs [20].

3. The PUEO Instrument

The PUEO payload will consist of a 216-channel Main Instrument (300-1200 MHz) and an 8-channel Low Frequency (LF) instrument, which will cover 50-300 MHz. The overall concept of the PUEO payload is similar to that of ANITA. Much of the mechanical and Radio-Frequency (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, and increases the expected neutrino and cosmic-ray event rate. 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. 3) A drop-down dedicated LF instrument, as well as a downward-canted 12-antenna drop-down horn antenna array. These will improve PUEO's sensitivity to air showers created by high energy particles over a wide range of elevation angles. 4) Significantly improved ability to filter man-made noise in real-time at the trigger level. 5) Significantly improved pointing resolution from a combination of better orientation measurements and a larger physical vertical baseline. Improved elevation pointing resolution allows us to improve analysis efficiency and reduce contamination from man-made backgrounds.

Figure 3 shows a rendering of the PUEO payload, and Figure 4 shows the PUEO system diagram. PUEO receives radio signals from cosmic particles using its 108 dual-polarized quad-ridged horn antennas in the Main Instrument, and 8 antennas in the LF instrument. Radio signals observed by these antennas are amplified and filtered, and then sent via radio frequency over fiber optic (RFoF) to a central digitizing and triggering system crate, where they are digitized at baseband above the Nyquist frequency, and a trigger decision is made in real time to determine which data are saved to disk. All 224 RF channels in the combined Main Instrument and LF instrument are connected to the digitizing and triggering system crate, consisting of twenty-eight 8-channel Sampling Unit for RF (SURF) boards and a master trigger and data collection unit termed the Trigger Unit for RF (TURF).

We will use an interferometric phased array trigger for the main instrument of PUEO via delay-and-sum beamforming. This technology has been pioneered through the work of multiple groups in PUEO, and has successfully been demonstrated *in situ* at the South Pole on the Askaryan Radio Array (ARA) experiment [23], achieving the lowest demonstrated trigger threshold in any radio detector for cosmic neutrinos. The phased array trigger coherently sums the full radio waveforms with time delays corresponding to a range of angles of incident plane waves, averaging down the uncorrelated thermal noise from each antenna while maintaining the same signal strength for real plane-wave signals (such as neutrinos).

The interferometric trigger also provides improved rejection of man-made RF interference, which tends to come from localized directions. At any given time, we can mask from the trigger the beams that correspond to directions where there is man-made interference, which further improves detector performance.

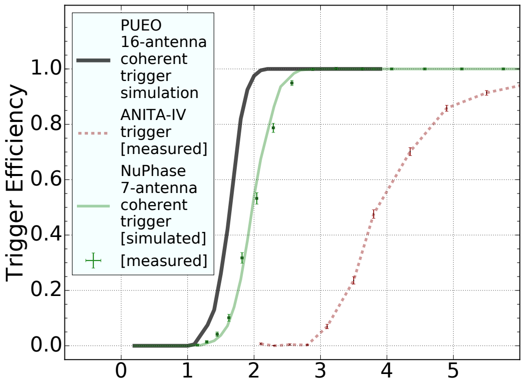

Figure 5: A simulation of the 16-antenna PUEO delay-and-sum trigger shows a 50% threshold at a voltage signal-to-noise ratio (SNR) of 0.8 as viewed in a single vertically-polarized antenna. Also shown are the performance of the ANITA-IV combinatoric trigger and ARA's coherent trigger system [23].

4. Calibration of PUEO

Ground calibration stations that will send ground-to-payload signals during flight will be established near the launch site at the Long Duration Balloon facility and in remote locations in Antarctica, as they were during previous ANITA flights.

We will also hand-launch a set of small secondary calibration payloads called HiCal-3, which is modeled after previous HiCal payloads [24] that were used with ANITA. HiCal-3 will comprise a set of three payloads, with extended capabilities for pulsing, capturing, and storing data relative to previous flights. HiCal-3 flies in tandem with PUEO, broadcasting calibration signals at regular intervals that are received directly and also reflected from the surface of the continent. The primary HiCal-3 payload will be solar-powered, have a low-throughput satellite link, local disk storage, and on-board signal generation and digitization capabilities. It will include a set of dual-polarized, wide-band antennas and a high-voltage commercial pulser, to produce sharp impulsive signals. Also on board will be an RFSoC ADC/DAC, to provide the capability to produce arbitrary waveform radio signals and to timestamp and digitize signals from a local receiving antenna.

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