PROCEEDINGS OF SCIENCE

Design of the PUEO Payload

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The primary science goals of the Payload for Ultrahigh Energy Observations (PUEO) are testing models of both candidate sources of ultrahigh-energy neutrinos (UHEN) and the propagation of ultrahigh-energy cosmic rays. PUEO is a balloon-borne observatory that scans the Antarctic ice for UHEN through their Askaryan emission (the successor to the ANtarctic Impulsive Transient Antenna (ANITA)). The payload design is optimized for the detection of the impulsive radio emissions with characteristics such as wide bandwidth and fast timing. The challenge in reaching high neutrino sensitivity includes outfitting many low-noise channels with linear polarization measurements and efficient filtering of backgrounds, with constraints on size, power, and weight to fit on a balloon-borne instrument. The Main Instrument of 96 dual-polarized antennas and a deployable Low Frequency (LF) instrument are custom-designed to detect the Askaryan emission. The antennas, filtering, and data acquisition system will be discussed in the context of meeting the science requirements of the PUEO mission.

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1. Introduction

PUEO is a balloon-borne UHE neutrino detector designed to measure the flux of neutrinos above 10^{18} eV. Measurements of the neutrino flux at this energy offer insights into the properties of the highest energy accelerators in the universe, such as the composition [1, 2] and the distribution of the sources of UHE cosmic rays (UHECR) [4]. For example, the UHECR spectrum measured by the Pierre Auger Observatory can constrain the distance to nearby sources [3]. The predicted neutrino flux for these cosmic ray local sources with heavy cosmic ray composition is shown in Figure 1 as the red band for the Auger best-fit. These model predictions are orders of magnitude away from the best limits at these neutrino energies. But, within the allowable parameter space of both the composition of these cosmic rays and the source distributions, also shown in Figure 1, the cosmogenic neutrino flux can increase to within an order of magnitude of experiment upper limits at some energies. Thus, more constrained upper limits, or even the first measurements of the neutrino flux at these ultrahigh energies, offer constraining potential on the source population of the UHECRs, see for example [4].

The PUEO project aims to make these first UHE neutrino flux measurements by leveraging their predicted Askaryan pulses in dense media [5]. Neutrino interactions in dense media such as ice are predicted to give rise to particle cascades that produce coherent radio radiation in the bandwidth of 2GHz [5]. Although there is yet to be an observation of a neutrino-Askaryan pulse, cosmic ray showers have been measured with PUEO's predecessor, ANITA [6]. The Askaryan emission has been characterized in the lab from beamline testing utilizing electron bunches and extensively modeled [7]. Its characteristics of polarity, polarization, bandwidth, and amplitude are the foundation for the design of the PUEO project, and this flow-down of the science requirements to the hardware specifications is highlighted throughout.

2. Instrument Overview

PUEO is a radio experiment consisting of two broad instruments: the Main Instrument (MI) and a Low Frequency (LF) deployable system. The Main Instrument is an array of antennas designed to measure the Askaryan pulse from UHE neutrinos. These antennas are custom-built by Toyon Research Corporation to meet specifications in return loss (≤ -10dB), boresight gain (10dB), and port isolation (≤ -30dB). The dual-polarized quad-ridged horn antennas allow for vertical and horizontal linearly polarized signal measurements. Each antenna has an opening-square mouth of 25 in and a depth of 27 in. The size of the antennas is constrained by the required bandwidth and the weight is constrained by specifications of the balloon vehicle. Even with these constraints, the design allowed for 96 antennas on the main instrument system. These antennas are two-thirds the size of the ANITA-IV antennas, allowing PUEO to fit two times the number of antennas, and increasing the collecting area by four-thirds.

The ice target for UHE neutrino interactions fills a significant fraction of the below-horizon sky. The MI antennas are distributed in 4 rings of radius ~ 75 in for full azimuthal coverage, with 24 antennas per ring. Antennas from each ring at the same location in azimuth make a phi sector. 3 of these rings are separated along the vertical by a distance of 28 in and pointed downward by 10 °, designed for triggering on upward going RF pulses, corresponding to a delay time of ~ 30 ns. The

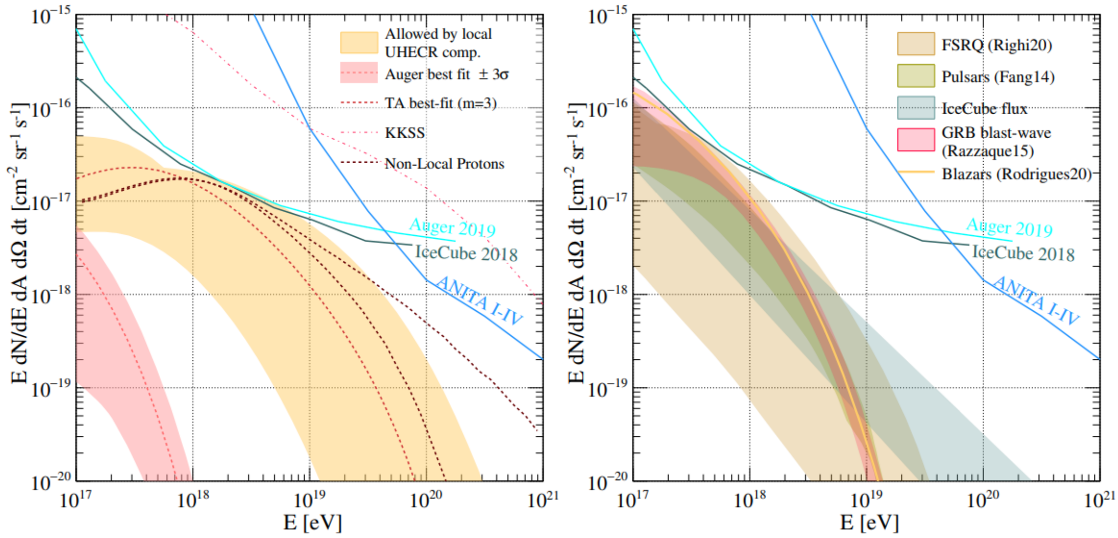

Figure 1: Left: Cosmogenic neutrino flux models are shown along with upper limits by Auger, IceCube, and the ANITA flights. The neutrino flux in these models are dependent on the distributions of sources, including non-local cosmic ray sources with a proton-only primary component (shown). Measurements of the neutrino flux at these highest energies (above 10^{18} eV) can constrain cosmic ray source distributions. **Right**: Astrophysical neutrino fluxes from some example high-energy particle source objects are shown, along with the same upper limits. Figures from [4]

last ring, the top, due to launch vehicle clearance requirements, has a smaller radius of 35 in, and so the antennas in this ring have a vertical stagger to fit all 24. The 4 rings of MI antennas along the vertical column are shown on the left of Figure 2, and one of the MI antennas being tested in an anechoic chamber is shown to the right. Hanging below the MI antennas is the deployable Low Frequency (LF) instrument. This system is described in more detail in another proceeding for this conference. The LF antennas extend the lower end of the bandwidth down to 150 MHz, where more power is CW noise. In this way, the system can separate the lower-frequency information for triggering purposes.

2.1 RF Chain

Each channel of the MI antennas is amplified and filtered for triggering in the bandwidth of 300 to 1200 MHz. These electronics are designed and tested to meet the specification of < 80 K of noise temperature while amplifying the antenna signals by 70 dB in the antenna band. One of the amplification and filtering systems (AMPA) is shown at the bottom left of Figure 4. These modules utilize a Low Noise Amplifier (LNA) and low pass filter. There are a total of 192 AMPAs, each within an EMI-rated enclosure mounted directly on each antenna polarization port. The signal from the output of an AMPA is passed to an Octal Receiver input. Each Octal Receiver board hosts 8 RF channels to amplify and filter the signal, as well as power the AMPAs. Receivers are housed in enclosures, 4 per enclosure, which are then secured inside the Main Instrument Enclosure (MIE). RF shields and front panel gaskets are instrumented on all receivers to meet the specifications on noise level inside the MIE. All of the receiver boards and their enclosures have been constructed

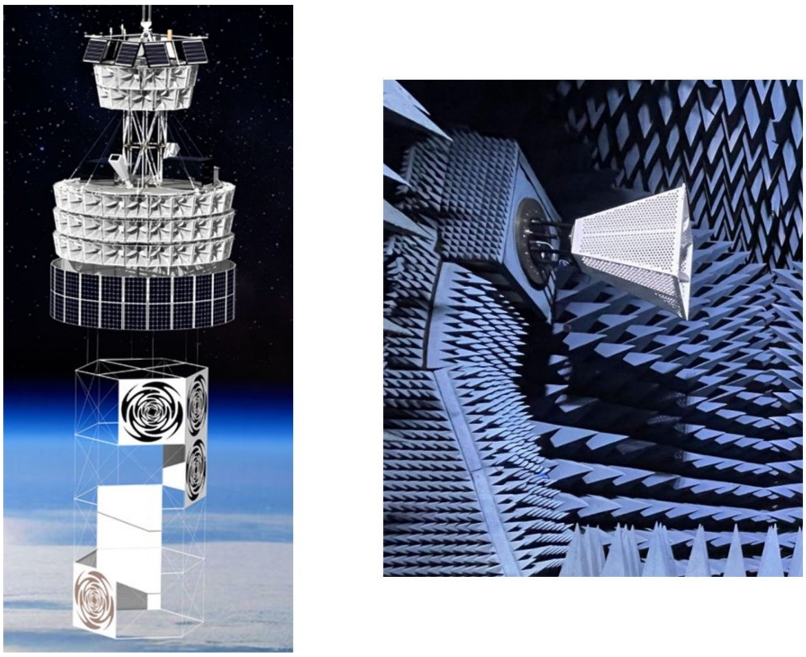

Figure 2: Left: A rendering of the PUEO design. The Main Instrument antennas are distributed in 3 lower rings and a staggered pair of top rings. The Low Frequnecy antennas are deployed below the Main Instrument antennas after launch. Just above the middle ring (the upper ring of the 3 lower rings) is the main deck of the payload housing the Main Instrument enclosure. The telemetry antennas are situated above the top ring of the Main Instrument. **Right**: A picture of a Main Instrument antenna undergoing testing in an anechoic chamber for beampattern and impulse response measurements.

and are currently undergoing qualification. Thermal vacuum testing of the systems is imminent.

2.2 Data Acquisition

RF signals are routed to the inputs of the Sampling Unit for Radio Frequencies (SURF) after the receiver boards as shown in the system diagram for PUEO in Figure 3. Each SURF has 8 channel inputs where the signal is digitized and sampled, and the beamforming power is calculated. The central component of a SURF is an RFSoC (Radio Frequencies System-on-Chip). The RFSoC includes both an FPGA (Field Programmable Gate Array) and an 8-channel ADC in the same fabric, allowing for lower power and lower noise than the trigger and digitizer system on the ANITA flights. Digital filtering is applied on each sampled ADC waveform at the SURF in firmware for computation of the first level of triggering (L1). This filtering process includes a dual biquad and Finite Impulse Response (FIR) and decimation to 5-bit waveforms that are then used for delay-and-sum beamforming for all antennas in two phi sectors. This beamforming algorithm is under investigation to optimize the number of beams for all 8 channels within the RFSoC, which are all the same polarization.

If a beam goes above the trigger threshold, the L1 trigger is asserted, which is set to a fixed rate of 100 Hz. An L2 trigger is determined from the neighboring SURFs (phi-sectors) asserting L1 triggers, with a repeated beamforming calculation performed. With these new beams including up to 4 phi-sectors, L2 triggers are estimated at a rate of 5 Hz. There are 24 SURFs on the PUEO

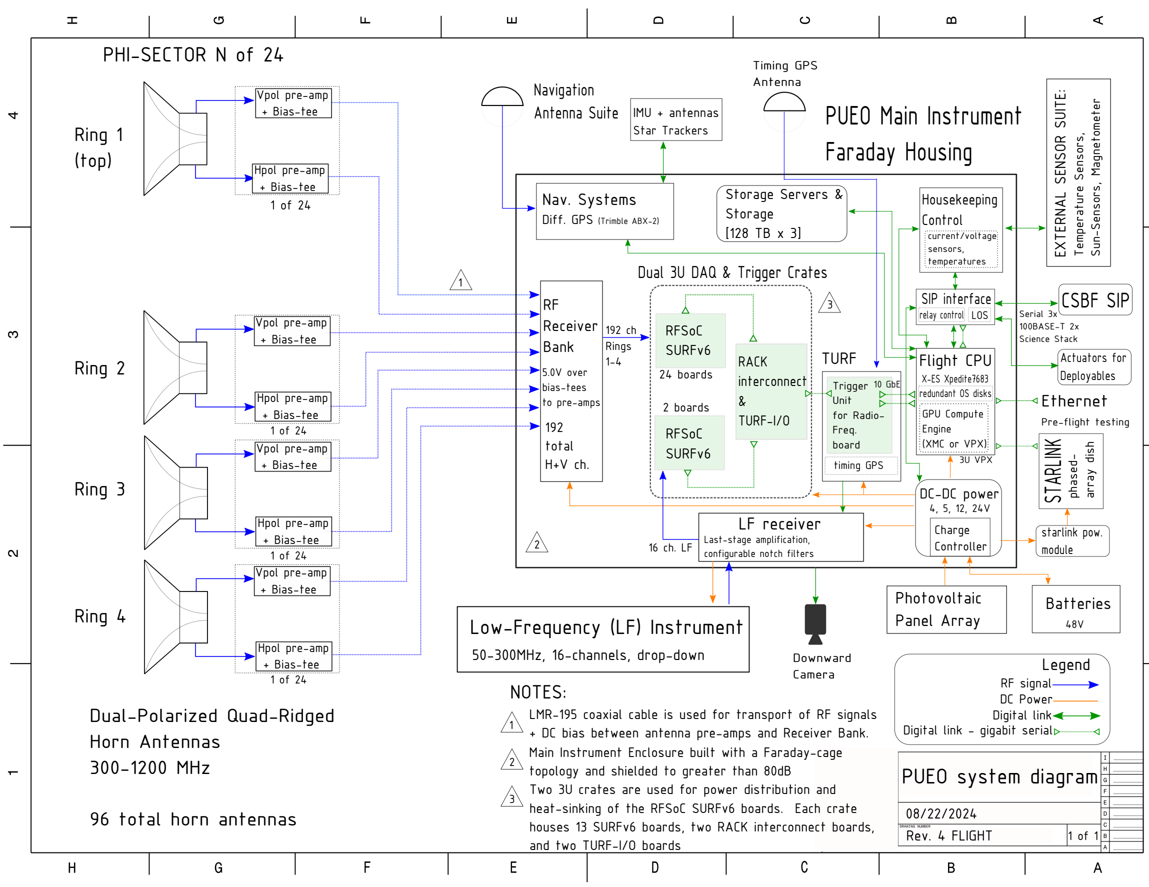

Figure 3: The system diagram for the PUEO payload. The central region depicts the MIE and its components, which are the majority of the electronics, mitigating the RF emission at the level of 70dB. The Main Instrument antenna and Low Frequency antenna RF chains are shown at the left and bottom. Following the RF chain are the receiver banks internal to the MIE, and readout at the SURFs on the RFSoCs. power, telemetry, navigation, and housekeeping systems are also shown, including which systems require external components to the MIE.

payload main instrument and 2 more for the Low Frequency Instrument, where the firmware is different and reported in a dedicated proceeding. All 26 SURFs are housed inside two large Data Acquisition custom-built electronics crates, with both EMI mitigation and thermal dissipation at the forefront of the design. These crates also house the 4 Triggering Unit for Radio Frequencies Input/Output (TURFIO) PCBs that interface the SURFs, forwarding L1 and L2 trigger information and raw waveforms downstream. Each TURFIO interfaces with the main TURF which ultimately provides a digital notch filter on the SURF L2 beams for the highest level of trigger, L3. This final filter in firmware significantly decreases the Continuous Wave (CW) noise impact on the DAQ system. It is implemented on the TURF central component, an iWave multiprocessor systems-on-chip (MPSoC). The event waveforms are forwarded upon L3 triggering to the Science Flight Computer (SFC) via a 10GBe connection.

PUEO's SFC is an X-ES Xpedite7683 that is housed in a custom-built conduction-cooled crate. Within the SFC system is a GPU unit for implementing a data prioritizer analysis, a USB hub for

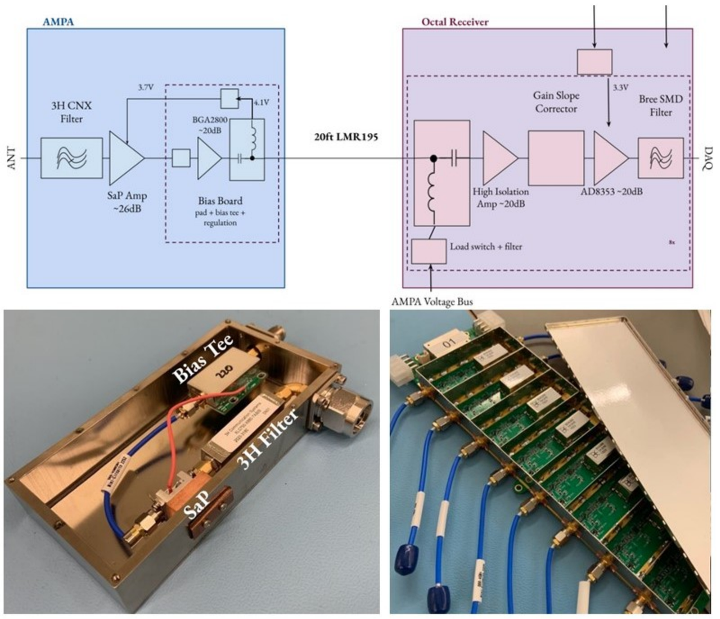

Figure 4: The Main Instrument RF chain. The left top and bottom show the diagram and a picture of an AMPA, with filter and amplifier shown. Each antenna channel output is sent to an Octal Receiver Board (right) post-AMPA, and the right shows the diagram and a picture of a receiver board.

interfacing with the housekeeping microcontroller, cameras, and navigation suite components, and a network switch for telemetry. The SFC records PUEO event data (estimated at 0.5 MB) at the L1 data rate of 100 Hz. The events are written to a triply redundant storage system of total capacity 128 TB, enough for a 30 day flight. The enclosure for the data disks is easily removable from the MIE upon recovery. The SFC is commanded via multiple telemetry paths including TDRSS, Iridium, and Starlink.

2.3 Navigation

The flow-down of PUEO science goals to attitude and position requirements constrains the systems chosen for navigation. To reach the accuracy on heading, pitch, and roll of 0.05 °, two Inertial Measurement Units (IMUs) will be flown that exceed these specifications: Novatel's CPT7 and Advanced Navigation's Boreas INS unit. Specifically, the Trimble ABX-Two Global Navigation Satellite System unit. A Magnetometer from Applied Physics Systems, model 539 is also in this suite. Finally, there are both star trackers and sun sensors to provide high-precision positioning to achieve better than the 50 m requirement.

2.4 Power and housekeeping

The power to payload components is derived from a pair of batteries with a nominal output bus voltage of 48 V. An omnidirectional solar array in an icositetragon (24) configuration underneath the bottom-most ring of antennas is constructed with SunCat Solar panels on Nomex honeycomb backings. The estimated power output of the array is nearly 1800 W, above the requirement of $\sim$ 1250 W. Solar power is controlled with a TriStar MPPT to charge the batteries in flight. The battery bus voltage is down-converted with isolated DC/DCs to 24, 12, 5, and 4V. The power system is monitored and controlled by the HouseKeeping and Slow Control system (HKSC) which is built around a TM4C123GXL launchpad. The HKSC interfaces with the SFC to forward information on the power system. In addition, the HKSC records temperature measurements with DS18B20 probes around the payload to create a profile of the antenna array and gondola temperature. Lastly, the HKSC commands the receivers board power lines for control over individual phi sectors and rings as a contingency for masking channels during flight.

2.5 Calibration

For proper calibration of the PUEO instrument, both ground station pulsers and secondary balloon-borne payloads are deployed. Pulses from the planned Hi-Cal 3 instruments are polarized linearly with a FID pulser through a splitter, allowing for commanding of both H and V pulses. The electronics and antenna for Hi-Cal 3 are housed in pressure vessels for FID operation at 5 kV at atmospheric pressure. Hi-Cal 3 builds on the heritage of Hi-Cal 2 flown with the ANITA-IV payload [8]. The Hi-Cal 3 systems are undergoing construction and testing at Kansas University.

3. Conclusions

Many of the PUEO MIE components are currently being validated and integrated, including the DAQ, SFC, RF receiver bank, and power system. Flight software, housekeeping control and monitoring, and data prioritizing are being developed. The MI and LF antennas are being characterized and the gondola fabricated. The payload design of PUEO inherits the flight heritage of some key systems from the 4 successful ANITA flights while also building on the lessons learned by deploying new hardware in the DAQ system and utilizing an interferometric trigger. The PUEO simulation suite implements these features to calculate the Single-Event Sensitivity (SES), which is shown as a projection for a 30 day flight in Figure 5, illustrating the improvements anticipated for the PUEO design over the ANITA project [9]. The first PUEO flight is planned for the Austral Summer of 2025 from McMurdo Station, Antarctica by long-duration balloon.

4. Acknowledgements

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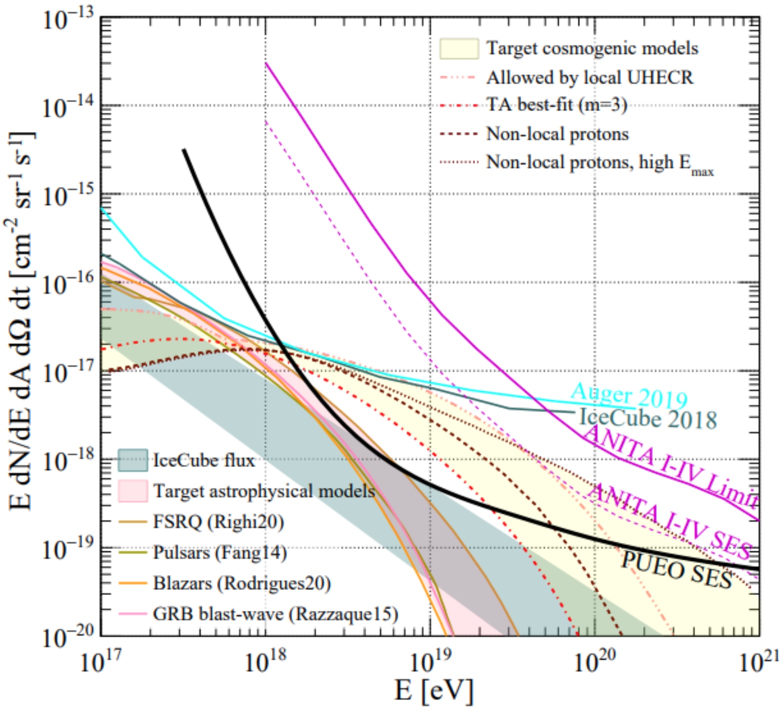

Figure 5: The neutrino flux predictions along with upper limits set by the ANITA flights, IceCube, and Auger. The PUEO Single Event Sensitivity (SES) for a 30 day flight is shown in black, calculated with the monte carlo simulations in [9].

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