PROCEEDINGS OF SCIENCE

EUSO-SPB2 Cosmic Ray Searches and Observations

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The Extreme Universe Space Observatory on a Super Pressure Balloon 2 (EUSO-SPB2) flew in May of 2023, marking an important step towards the observation of ultra-high-energy cosmic rays (UHECR) and neutrino-induced showers from space. The ultimate goal of this endeavor is to complement ground-based detectors and achieve unprecedented exposure and nearly uniform full-sky coverage at the highest energies, thereby enabling charged particle astronomy and enriching the multi-messenger approach to high-energy astrophysics and astroparticle physics. As a pathfinder to the POEMMA mission (Probe Of Extreme Multi-Messenger Astrophysics), EUSO-SPB2 flew two distinct cameras at the focus of two Schmidt telescopes, one made of multi-anode photomultiplier tubes (MAPMTs), looking towards the nadir for fluorescence light detection, the other made of Silicon photomultipliers (SiPMs), looking towards the limb of the Earth for direct Cherenkov light detection. The flight was terminated prematurely due to a failure in the balloon, and thus no showers were detected in the fluorescence mode. However, several lower-energy (PeV scale) cosmic-ray events were observed in the Cherenkov channel. The data collected by both telescopes also confirmed the pertinence and maturity of the technology. We will report on the mission's cosmic ray results, and lessons learned for future balloon and satellite missions, notably the POEMMA Balloon with Radio (PBR), currently under development.

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1. Introduction

Understanding the origin and nature of ultra-high-energy cosmic rays (UHECRs) and neutrinos remains one of the most compelling challenges in astroparticle physics. These particles, with energies exceeding 10^{18} eV, carry unique information about the most energetic processes in the universe, yet their extremely low flux requires novel observational strategies to achieve statistically significant measurements. Ground-based detectors such as the Pierre Auger Observatory [1] and the Telescope Array [2] have made considerable progress, but they are fundamentally limited in aperture and sky coverage. To overcome these limitations, space-based observatories have been proposed to complement terrestrial efforts by vastly increasing exposure and enabling full-sky coverage with a single instrument and nearly uniform exposure [3].

The Extreme Universe Space Observatory on a Super Pressure Balloon 2 (EUSO-SPB2) represents a critical step toward this vision. Flown in May 2023, EUSO-SPB2 served as a technology pathfinder and scientific demonstrator for future space missions, most notably the Probe Of Extreme Multi-Messenger Astrophysics (POEMMA) [4]. The mission deployed two complementary instruments aboard a high-altitude balloon: a fluorescence telescope employing multi-anode photomultiplier tubes (MAPMTs) to observe nitrogen fluorescence from EeV scale extensive air showers (EAS) [5], and a Cherenkov telescope using Silicon photomultipliers (SiPMs) to detect direct Cherenkov light from cosmic ray or ν_τ induced PeV scale air showers near the limb of the Earth [6].

The flight was completed after less than 37 hours afloat due to a technical failure of the balloon. Despite not reaching the expected minimum flight duration, data were recorded which validated the performance of the instruments in the near-Earth observing environment. These critical data[1] are invaluable for the development of future missions.

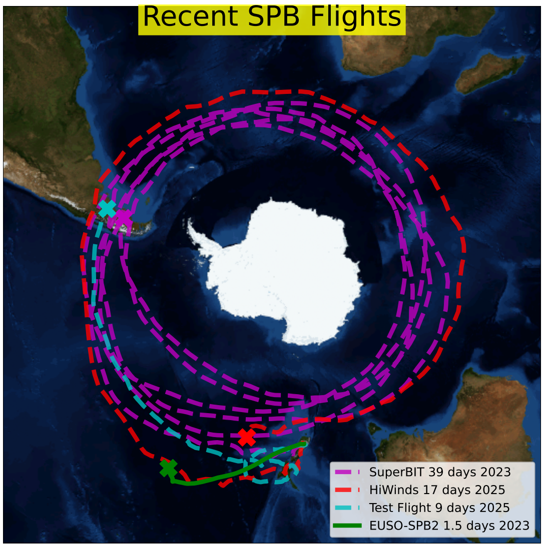

Figure 1: Recent NASA Super Pressure Balloon flights from Wānaka NZ. The 18.8 million ft^3 (532,000 m^3) balloon is designed to suspend a 5,500 lbs (2,500 kg) payload at 110,000 ft (33.5 km) altitude.

[1]downloaded via next generation telemetry at 100× the originally planned bandwidth

2. Fluorescence Measurements

The fluorescence telescope (FT) was built with the heritage of two previous balloon missions [7, 8]. The focal surface was made up of 108 MAPMTs, for a total of 6,912 channels. Each channel was capable of single photon counting, with a double pulse resolution of ~10 ns and an integration time of 1050 ns. The current from groups of 8 adjacent channels were integrated and digitized with the same cadence, providing sensitivity to very bright signals that could saturate the photon counting channel [9]. The MAPMTs are grouped in fours to form elementary cells (ECs). The MAPMTs along with accompanying ASICs and HVPS are potted in a gelatinous compound to prevent electrostatic discharge due to the high voltage (~1000V) operating in the near-vacuum of the stratosphere. Groups of nine ECs were connected to an FPGA board to form a photodetection module (PDM). A novel trigger was developed and worked on a per-PDM basis [10]. When one PDM triggered all three were read out. The three PDMs sat at the focus of a 1 m diameter entrance aperture Schmidt telescope with a $36^\circ \times 12^\circ$ field of view (FoV). The end-to-end efficiency of the detector was ~15%. The FT was fixed rigidly to the gondola and pointed nadir, which minimized the energy threshold for detecting UHECRs.

The pre-flight expectation was that roughly one UHECR event would be detected in the fluorescence channel for every 10 hours of moonless observation with a peak energy sensitivity around 3 EeV [11]. These expectations were validated by a field campaign at the Telescope Array Black Rock Mesa FD site during August of 2022 [12].

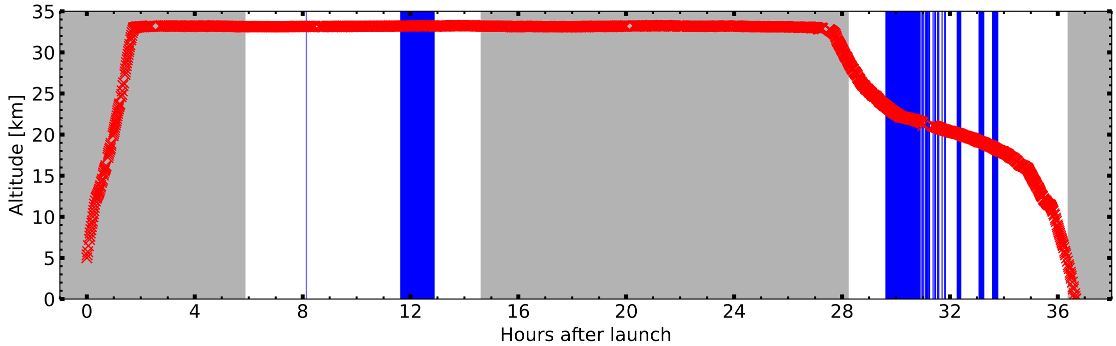

Figure 2: Flight profile with payload altitude shown in red. The gray regions represent periods where the background light was too high to safely observe due to either the sun or the moon, measured by an independent low-voltage photodiode. The blue regions represents periods where the DAQ system was operating normally and the data was downloaded to the ground.

In order to verify the data acquisition system (DAQ) in-situ, a set of two monitoring LEDs were flashed every 16 seconds. The LED system and the PDMs were completely independent, allowing the system to serve as a check of the trigger and to verify that the DAQ was not over-saturated. In order to quantify the "active" period of observation, the periods where consecutive LED flashes are recorded. In addition to verifying the DAQ system was operating normally, these periods represent data that was downlinked to ground. The times the system was "active" are shown in Figure 2. The total observing time was just under 3 hours. The majority of the observing time occured on the second night while the payload was descending. The first night was primarily dedicated to commissioning, with the active periods representing times when ~30-50% of the focal surface, and therefore FoV, were operating normally. On the second night, the full camera was operational. The periods without data are the result of data that was recorded, but not downloaded before the end of the flight.

Due to the nature of the observation, the aperture of the FT is not trivially defined. This is because there are many EAS geometries that cross the FoV without landing beneath the detector. One way the aperture can be estimated is by isotropically throwing a large number of simulated EAS with core locations covering a large area (R=100 km) below the detector. By comparing the number of EAS that trigger to the total number thrown, the aperture can be estimated. The response of the detector is highly energy dependent, due to higher energy EAS triggering in a larger number of geometries. The aperture also depends on the altitude of the payload. The higher the payload the larger the volume of atmosphere observed, and the higher the energy threshold for triggering due to being further away. In order to account for these effects, 24 million EAS were simulated using the EUSO-OffLine framework [13]. The achieved exposure of the instrument based on these simulations is shown in Figure 3.

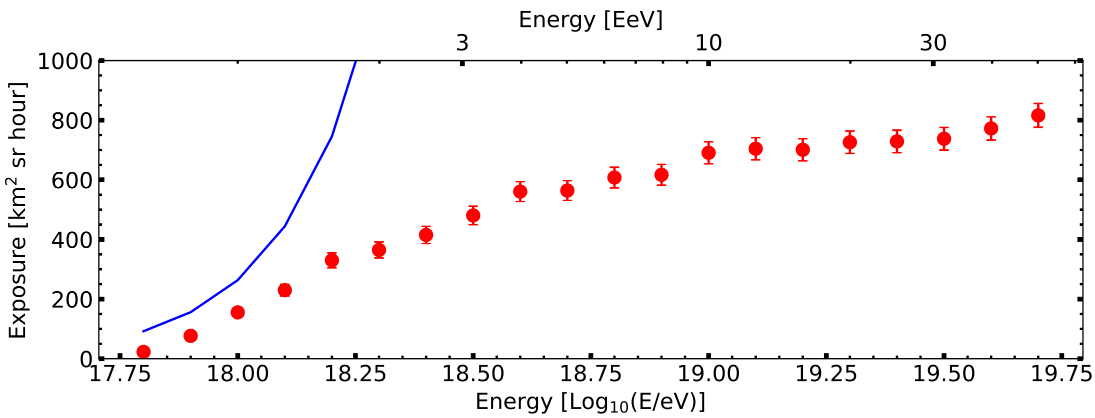

Figure 3: Exposure achieved by the FT over the course of the two night flight, based on extensive end-to-end simulations (red points) and the exposure required to "expect" greater than 1 event above a given energy based on the energy spectrum reported by Auger [14] (blue line). Methodology described in detail in [5].

Accounting for the altitude of observation, the expected number of events based on the energy spectrum reported by Auger [14] observed over the flight is 1.25. This estimate dos not account for clouds, due to the cloud monitoring infrared (IR) camera not operating normally during the decent. No EAS event was found in the $\sim 10^5$ downloaded events, consistent with this expectation.

While the downloaded data did not include any UHECR candidates, several important features were observed. These include the pressence of clouds alligning with the IR camera (on the first night of the flight) and a linear increase of the background with increasing lunar elevation. Further, the operation of the instrument in the near-space environment provided insights into the detector's stability. In particular the types of events that triggered the readout are different than those which do on the ground, possibly due to the radiation exposure at the altitude of the balloon.

3. Cherenkov Measurements

The Cherenkov Telescope (CT) was a first-of-its-kind instrument. The camera at the focus of this telescope was comprised of 32 SiPM matricies for a total of 512 channels. The analog signal was pre-amplified before being digitized by a modified AGET system, which digitized the signal in 10 ns time bins with 512 bins per readout. The electronics were actively cooled by a custom liquid cooling solution. Similar to the FT, the CT was a 1 m diameter Schmidt telescope with a smaller $12° \times 6°$ FoV. Two noticeable differences between the FT and CT were: 1.) the use of bifocal optics in the CT, with the incident light split into two adjacent spots on the focal surface in order to reject signals from charged particles interacting directly in the SiPMs and 2.) the capability of changing the elevation of the telescope from $+5°$ to $-15°$ relative to horizontal. The fully assembled CT was tested on the ground, in Utah in 2022 and in New Zealand in 2023 immediately prior to launch, where it observed bifocal signals consistent with the Cherenkov signal expected from EAS.

Similar to the FT, the first night of the flight was primarily dedicated to commissioning the CT. On the second night, the CT observed primarily below-the-limb searching for signals from ν_τ induced air showers. For ~45 minutes of the flight, the CT was pointed above-the-limb where it was sensitive to the Cherenkov light from cosmic ray induced EAS [15].

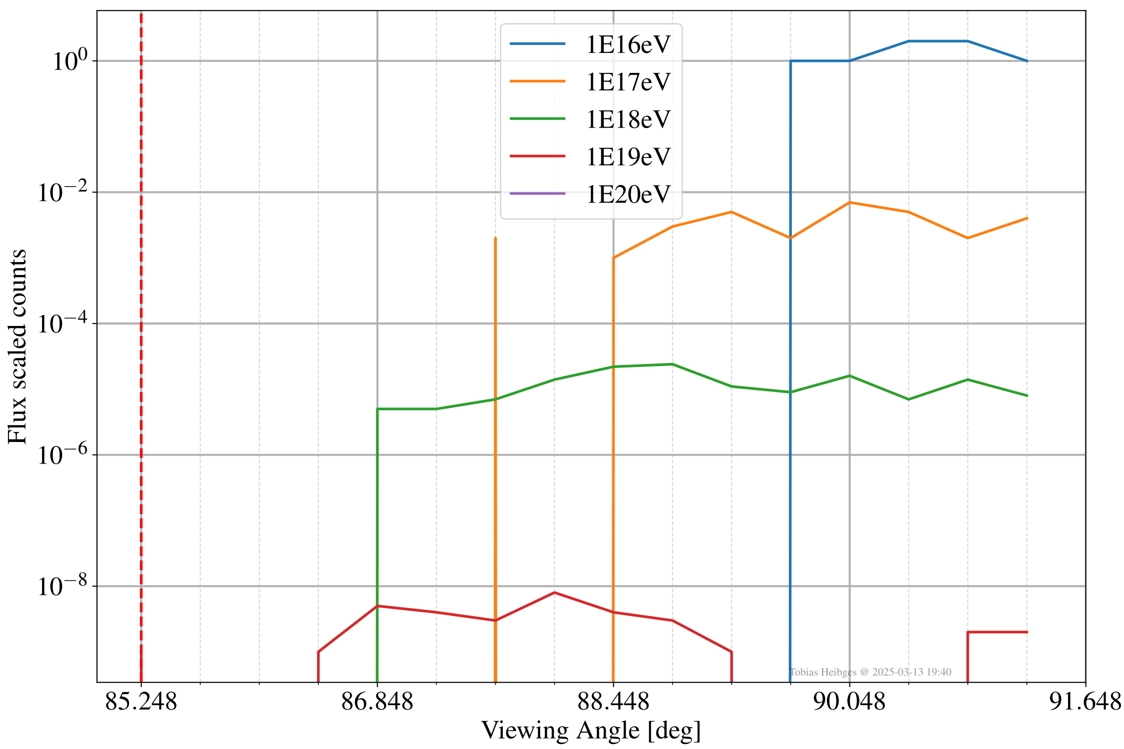

Figure 4: [16]

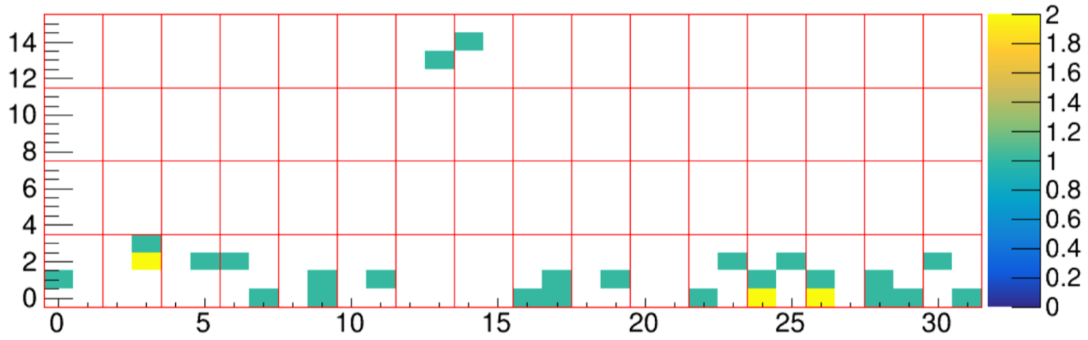

Figure 5: [17]

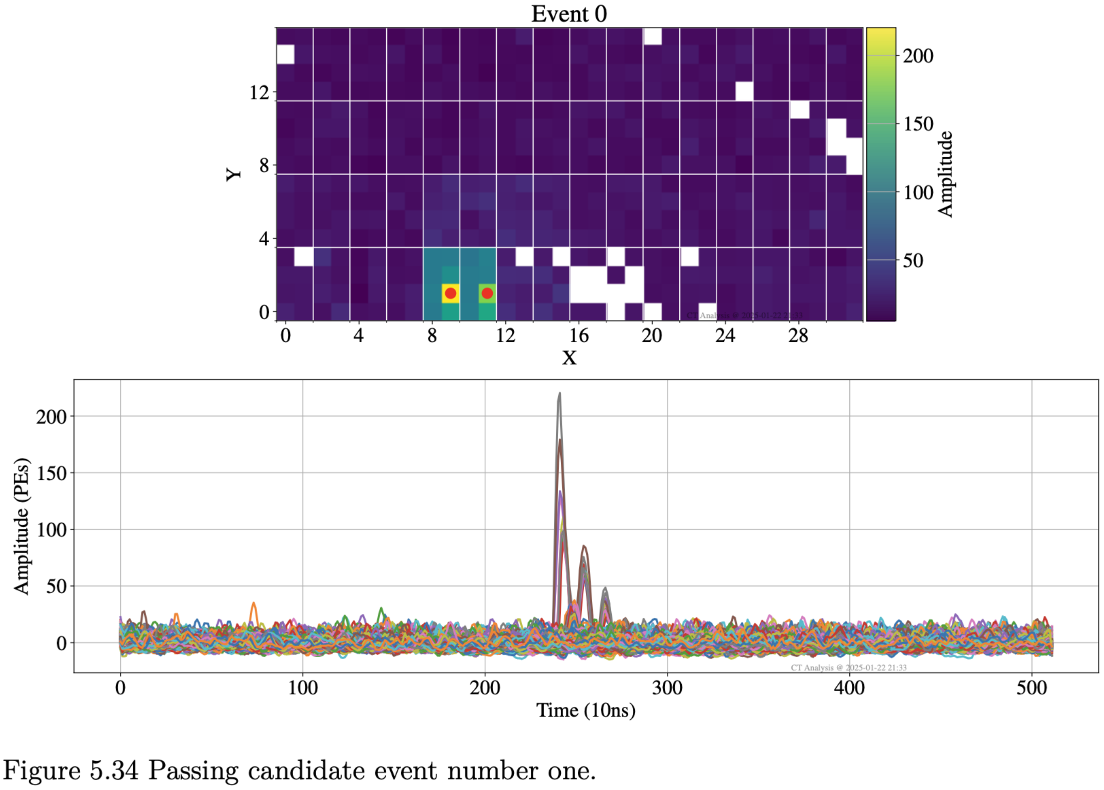

Figure 6: [16]

4. Outlook

References

[1] A. Aab et al.*N.I.M. A* **798** (2015) 172 [1502.01323].

[2] H. Kawai et al.*Nuclear Physics B - Proceedings Supplements* **175-176** (2008) 221.

[3] A. Coleman et al.*Astroparticle Physics* **149** (2023) 102819 [2205.05845].

[4] A.V. Olinto et al.*JCAP* **2021** (2021) 007 [2012.07945].

[5] J.H. Adams et al.*Astroparticle Physics* **165** (2025) 103046 [2406.13673].

[6] M. Bagheri et al.*N.I.M. A* **1070** (2025) 169999 [2406.08274].

[7] J.H. Adams et al.*Space Science Reviews* **218** (2022) 3.

[8] G. Abdellaoui et al.*Astroparticle Physics* **154** (2024) 102891 [2401.06525].

[9] H. Miyamoto et al.*PoS* **ICRC2023** (2023) 430 [2310.07388].

[10] G. Filippatos et al.*Advances in Space Research* **70** (2022) 2794 [2201.00794].

[11] G. Filippatos et al.*PoS* **ICRC2021** (2021) 405 [2112.07561].

[12] V. Kungel et al.*PoS* **ICRC2023** (2023) 468 [2310.06209].

[13] S. Abe et al.*Journal of Instrumentation* **19** (2024) P01007 [2309.02577].

[14] A. Aab et al.*Phys. Rev. D* **102** (2020) 062005 [2008.06486].

[15] A.L. Cummings et al.*Phys. Rev. D* **104** (2021) 063029 [2105.03255].

[16] T. Heibges, phd thesis, Colorado School of Mines, Golden, CO, 2025.

[17] E. Gazda, phd thesis, Georgia Institute of Technology, Atlanta, GA, 2024.