PROCEEDINGS OF SCIENCE

The NUSES Space Mission: Advancing Observations and Technology

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The NUSES (Neutrino and Seismic Electromagnetic Signals) mission is a pioneering space mission focused on exploring innovative technologies and observational strategies. NUSES aims to investigate cosmic radiation, GRBs, astrophysical neutrinos, the Sun-Earth environment, space weather, and Magnetosphere-Ionosphere-Lithosphere Coupling (MILC). This satellite hosts two advanced payloads: Terzina and Zirè. Terzina utilizes a compact optical instrument with a Cherenkov telescope, employing Silicon Photomultipliers (SiPMs) for the detection of very high energy EAS from the Earth limb. Zirè provides high-precision measurements of cosmic electrons and nuclei, and gamma-rays, contributing insights into cosmic rays, GRBs and potential MILC events. This paper provides an overview of the NUSES satellite's instruments and discusses the scientific and technological objectives of this mission.

PoS(EPS-HEP2023)063

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1. Introduction

The NUSES (Neutrinos and Seismic Electromagnetic Signals) satellite mission [1], led by the Gran Sasso Science Institute (GSSI), is a collaborative endeavor aimed at exploring new scientific and technological avenues for astroparticle physics detectors in space. Thales Alenia Space Italy (TAS-I) supports the mission by providing the 2MF/NIMBUS (New Italian Micro BUS) satellite platform, designed with a modular and flexible structure using additive manufacturing techniques. The NUSES project, scheduled for launch in 2026 under ASI's management, is a ballistic mission operating in Low Earth Orbit (LEO) with an altitude at the Beginning of Life (BoL) of 535 km and a high inclination of 97.8° (LTAN = 18:00), following a Sun-synchronous orbit along the day-night boundary. The nominal mission duration is three years (End of Life, EoL).

The NUSES satellite accommodates two innovative scientific payloads: Zirè and Terzina. Zirè aims to measure the energy spectra of low-energy Cosmic Rays (CRs) [2, 3] and gamma-rays. Additionally, Zirè explores possible signals related to Magnetosphere-Ionosphere-Lithosphere Coupling (MILC) phenomena [4, 5]. On the other hand, Terzina is a Cherenkov telescope designed to detect Extensive Air Showers (EAS) induced by high-energy CRs and neutrinos in the Earth's atmosphere [6, 7]. This paper offers an overview of the NUSES satellite's instruments and discusses the scientific and technological goals of this pioneering mission.

2. The Zirè Payload

Zirè is dedicated to precise measurements of the energy spectra of low-energy Cosmic Rays (CRs) within the range of a few MeV to hundreds of MeVs. This research complements findings from ground-based experiments and LEO satellites, which have identified anomalies in counting rates of low-energy electrons and protons from the inner Van Allen Belts. Zirè also aims to detect gamma-rays in the 0.1 MeV - 10 MeV range, contributing to the study of transient astrophysical phenomena.

To enhance its investigative capabilities for possible MILC signatures, Zirè includes a Low Energy Module (LEM) in its design phase [8], a particle spectrometer devoted to the observation of fluxes of relatively low-energy electrons in the 0.1–7-MeV range and protons in the 3–50 MeV range [9, 10] along the orbit of the mission.

Studying low-energy cosmic rays is driven by an additional motivation related to their energy spectrum, which is significantly influenced by solar activity. Consequently, measuring this spectrum plays a crucial role in monitoring high-intensity Solar Energy Particles (SEPs). These particles are responsible for space weather phenomena, posing a threat to both crewed and uncrewed orbiting objects, as well as impacting aviation mission plans.

An innovation in the NUSES mission is the use of Silicon Photomultipliers (SiPMs) for light detection in Zirè, setting a new standard for space-borne particle detectors.

Zirè, reported in figure 1, consists of five main sub-detectors:

- **Fiber Tracker (FTK)**: Using scintillating fibers, FTK precisely reconstructs the track of charged particles in X-Y coordinates.

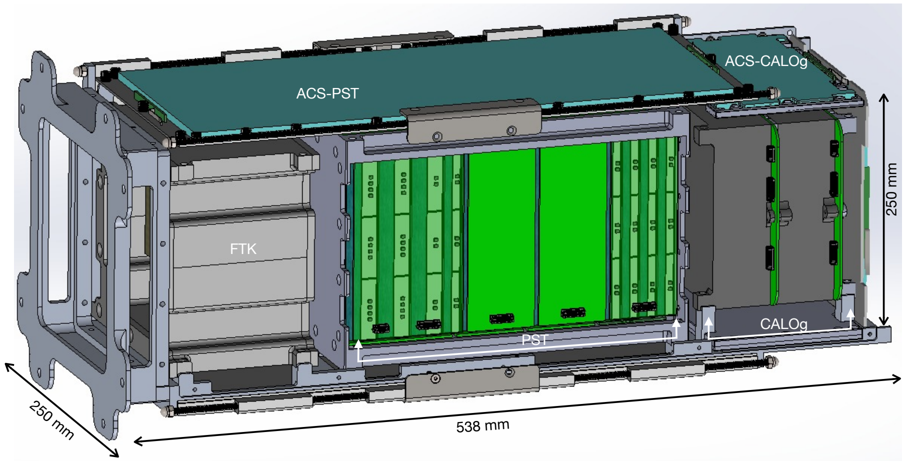

Figure 1: Mechanical layout and dimensions of the Zirè payload, featuring different subsystems. The experiment targets charged particles entering from the unobstructed view of the FTK on the left side and gamma-rays entering the CALOg on the right side.

- **Plastic Scintillator Tower (PST)**: PST, with layers of plastic scintillator bars, aids in particle identification in the Z (Atomic Number) and in providing its coarse direction.
- **Calorimeter (CALOg)**: CALOg employs optically independent LYSO scintillating crystals to measure energy released in the interactions and detect gamma-rays.
- **AntiCoincidence System (ACS)**: ACS, consisting of plastic scintillator tiles, suppresses charged particle-induced background and removes partially contained events.
- **Low Energy Module (LEM)**: LEM utilizes PIPS detectors to track and detect low-energy electrons, enhancing the capability to discover MILC signatures. The LEM spectrometer features an active collimation consisting of shaped plastic scintillators read out by SiPMs.

The mechanical configuration of Zirè is designed to meet the mission's physics requirements, with GEANT4 simulations used for preliminary studies to optimize the payload's geometrical acceptance and performance.

3. The Terzina Payload

Terzina consists of a Schmidt telescope (see figure 2) that focuses on Cherenkov emission in Extensive Air Showers (EAS) induced by high-energy Cosmic Rays (CRs) and neutrinos in the Earth's atmosphere [12, 13]. The primary source of Cherenkov emission in an EAS is high-energy electron-positron pairs, and Terzina's design allows it to detect Cherenkov emission from EAS with energies surpassing 100 PeV.

Terzina is expected to observe CRs with trajectories above the Earth's limb, providing a reference point for assessing the components of the Cherenkov telescope during the actual mission. This approach supports the validation of the detection technique through in-orbit testing therefore making the NUSES mission the ideal pathfinder for future missions[11].

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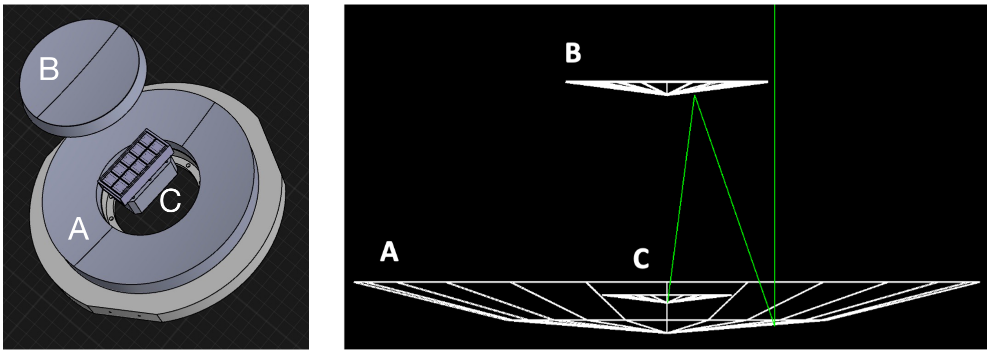

Figure 2: Schematic view of the preliminary design for the Terzina optics (left). The optical detection concept of the Terzina instrument (right).

The Terzina payload is under development to explore new observational methods for Ultra High Energy Cosmic Rays (UHECRs) with energies greater than 100 PeV, associated with cosmogenic tau neutrinos. The innovative use of Cherenkov observational techniques in space is pioneered by Terzina, aiming to achieve the first space-based detection of showers generated by UHECRs.

Terzina's optical axis points towards Earth's limb, where UHECRs can generate Extensive Air Showers (EAS) in the atmosphere, allowing the study of tau neutrinos that produce Upgoing Air Showers (UAS) with Cherenkov light emission.

4. Conclusions and Outlook

The NUSES project introduces two advanced payloads, Zirè and Terzina, each contributing unique capabilities. Zirè plays a crucial role by providing high-precision measurements of electrons, protons, gamma rays and light cosmic ray nuclei across a broad kinetic energy range. Terzina represents a groundbreaking development as the first space-borne Cherenkov telescope. Its primary focus is on characterizing the background affecting the observation of astrophysical neutrinos, particularly at energies exceeding 100 PeV. By pointing its optical axis towards Earth's limb, Terzina can study Extensive Air Showers (EAS) created by Ultra High Energy Cosmic Rays (UHECRs), leading to the detection of τ neutrinos that generate Upgoing Air Showers (UAS) with Cherenkov light emission. A significant innovation within the NUSES mission is the use of SiPMs as light detectors. SiPMs offer enhanced sensitivity and efficiency for capturing photons, crucial for accurately detecting Cherenkov radiation and other light emissions in the challenging space environment. The integration of SiPMs into both Terzina and Zirè sets new benchmarks for space-borne particle detectors, making NUSES a pioneering mission at the forefront of detector technology.

5. Acknowledgments

The NUSES project is a collaborative effort funded by the Italian Government through the Restart program, with strong support from the Gran Sasso Science Institute (GSSI), Thales Alenia Space Italy (TAS-I), and the Italian National Institute for Nuclear Physics (INFN).

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