

Compact Photonics-Enabled Cosmic Muon Detector (COMET)

Cosmic-ray muons provide a naturally occurring, continuous flux of high-energy charged particles at sea level ($\sim 1 \text{ muon}/(\text{cm}^2 \cdot \text{min})$) [1]. Beyond fundamental particle physics, cosmic muon detection enables critical applied engineering systems: **Muon Tomography (Muography)** for non-destructive density inspection of civil structures (tunnels, dams, bridges) and geological formations [2]; internal void discovery in archaeological heritage sites [3]; **Space Weather Monitoring** to correlate secondary particle cascades with Single Event Upsets (SEUs) in digital avionics; and **Muon Positioning, Navigation, and Timing (Muon PNT)** for reliable tracking in Global Positioning System (GPS)-denied underground environments.

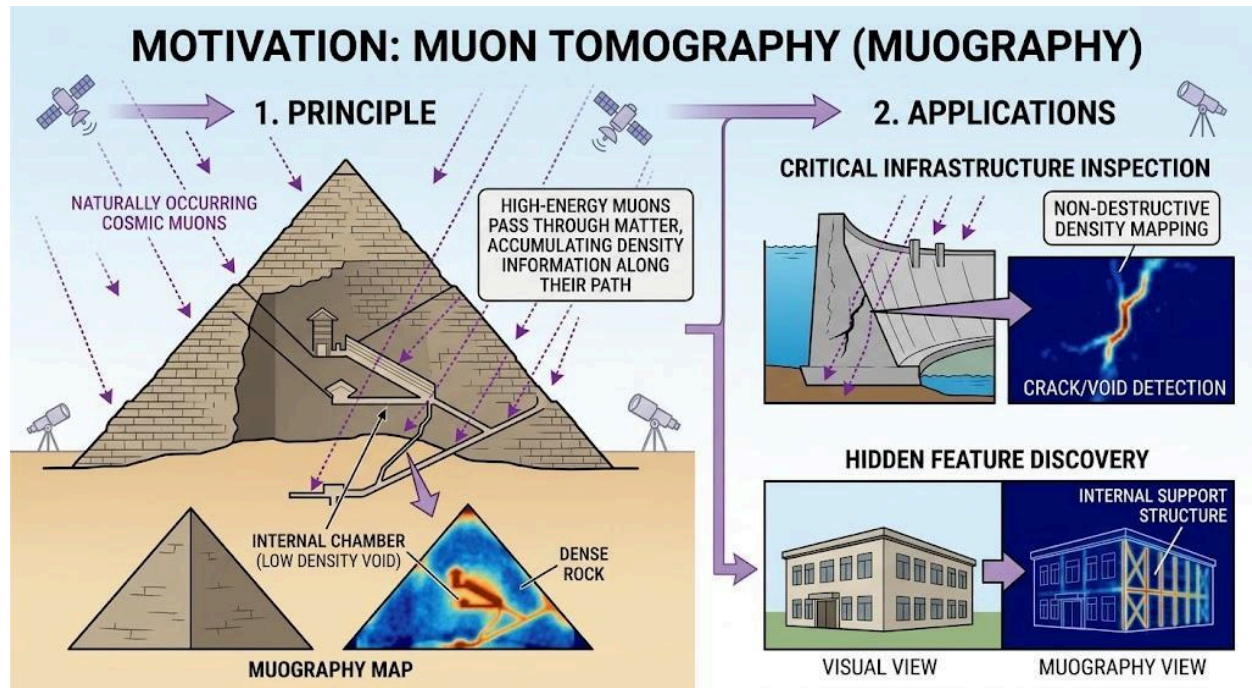


Figure 1. A representative sketch of muography principles and applications by GEMINI

The objective of this project is to design, implement, and experimentally characterize Compact Photonics-Enabled Cosmic Muon Detector (**COMET**), a **desktop-scale cosmic-ray muon detector consisting of two modular detection units**. This project requires designing custom analog pulse-conditioning electronics, an onboard low-noise bias supply, hardware-level nanosecond coincidence gating, and embedded event acquisition. The system will utilize solid-state Silicon Photomultipliers (SiPMs) optically coupled to plastic scintillators. The team will design the optomechanical housing, front-end electronic Printed Circuit Boards (PCBs), and coincidence logic, concluding with experimental validation of the atmospheric muon angular distribution [1].

Design Requirements & System Features

The designed system must incorporate the following features:

- Each detection module must securely house a plastic scintillator slab optically coupled to SiPMs. The module housing must be light-tight so that exposure to ambient indoor lighting does not saturate the detector or trigger false noise counts.
- The detector must operate from a standard 5 V USB rail or a single low-voltage DC source. An onboard DC-DC boost converter must generate the low-noise reverse-bias voltage (V_{bias}) required to operate the selected SiPM.
- A dedicated analog conditioning circuit (transimpedance amplifier, voltage amplifier, or active pulse shaper) must amplify fast SiPM current pulses into measurable voltage signals with an adequate signal-to-noise ratio (SNR) to distinguish muon events from baseline electronic noise.
- Each module must feature a comparator stage with an adjustable threshold voltage to filter out SiPM thermal dark counts and low-amplitude electronic noise.
- A dedicated hardware coincidence circuit (such as a fast logic gate or analog coincidence stage) must correlate signals between both modules. The coincidence time window must be ≤ 100 ns to reject uncorrelated background radiation and random noise hits.
- A microcontroller must record individual channel counts, coincidence events, and event timestamps. The system must deliver structured data to a computer interface for real-time monitoring and offline data logging.
- The two detector modules must be mounted on a mechanical assembly that allows variable vertical separation and adjustable tilt angles (0° to 90°).
- The team must experimentally measure and log the coincidence muon count rate across at least four different zenith angles (e.g., 0° , 30° , 45° , 60°) to validate the theoretical atmospheric distribution:

$$I(\theta) \approx I_0 \cos^2(\theta)$$

- **Material Attenuation Characterization:** Insert dense shielding materials (e.g., iron, lead, or concrete blocks) between the two modules to measure muon stopping power and absorption rates.
- **Power Supply Filtering Optimization:** Suppress DC-DC switching ripple < 5 mVp-p.
- **Active Temperature Compensation:** Implement closed-loop analog or digital feedback adjusting the SiPM bias voltage against temperature drift to stabilize overvoltage and gain.
- **GUI:** Develop a desktop dashboard displaying live event trajectories, count-rate time histories, and angular polar plots.

Performance Requirements & Constraints

The system must satisfy the following performance criteria:

- The accidental coincidence count rate in horizontal or non-aligned orientation must remain < 0.1 counts/min.
- The system must produce repeatable vertical axial coincidence rates consistent with the chosen scintillator geometry (typically 5–20 counts/min for desktop-scale detectors).
- Total dual-module electronics power consumption must not exceed 3.5 W (5 V USB operation).

Extra Features

- **Pulse-Height Spectroscopy:** Integrate an analog peak-hold or fast sampling circuit to measure pulse amplitudes and reconstruct the characteristic Landau energy-loss distribution.

Project Support & Sourcing

- Plastic scintillator materials can be supplied by **TENMAK**, if international procurement and customs clearance risks occur.

References:

1. Workman, R. L. et al. (Particle Data Group) (2022). Review of Particle Physics: Cosmic Rays. *Progress of Theoretical and Experimental Physics*, 2022(8), 083C01.
2. Tanaka, H. K. M. et al. (2007). High resolution cosmic-ray muon imaging of faults in the historical Mt. Asama volcano, Japan. *Earth and Planetary Science Letters*, 263(1-2), 104–113.
3. Morishima, K. et al. (2017). Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons. *Nature*, 552(7685), 386–390.