GammaSky: Edge AI Computing for X- and Gamma-Ray Phenomena in real-time

L. Castaldini[1], A. Bulgarelli[1], R. Falco[1], N. Parmiggiani[1], A. De Rosa[1], A. Aboudan[2], L. Amati[1], P. Calabretto[1], F. Calzolari[3], A. Di Piano[1], V. Fioretti[1], A. Marinoni[3], G. Mustafa[1,5], G. Panebianco[1], A. Rizzo[4], L. Spadoni[5], E. Virgilli[1]

[1]INAF/OAS Bologna, Via P. Gobetti 93/3, I-40129 Bologna, Italy.
[2]CISAS "G. Colombo" – Università di Padova, Via Venezia 1, I-35131 Padova, Italy.
[3]ISAC Bologna, Via P. Gobetti 101, I-40129 Bologna, Italy.
[4]INAF/OA Catania, Via Santa Sofia 78, I-95123 Catania, Italy.
[5]ALMA MATER STUDIORUM - Università di Bologna - Via Zamboni 33, I-40126 Bologna, Italy

ADASS XXXV

INAF ISTITUTO NAZIONALE DI ASTROFISICA

CNR ISAC

ABSTRACT

The GammaSky project investigates the use of artificial intelligence (AI) on edge computers for real-time detection and analysis of high-energy phenomena such as Gamma-Ray Bursts and Terrestrial Gamma-ray Flashes (TGFs) [1]. The experiment operates at the "O. Vittori" Observatory on Monte Cimone (Modena, Italy), observing TGFs in real conditions. The setup combines a fast NaI(Tl) scintillator detector coupled to a SiPM readout with a RedPitaya STEMlab 125-14 based acquisition board and an NVIDIA Jetson Orin Nano for low-power real-time processing. A dedicated C++ Real-Time Analysis pipeline manages waveform streaming, machine-learning event reconstruction and detection. GammaSky is a testbed for deploying AI in constrained edge environments representative of space applications, enabling efficient onboard data reduction and autonomous science alert generation for future gamma-ray.

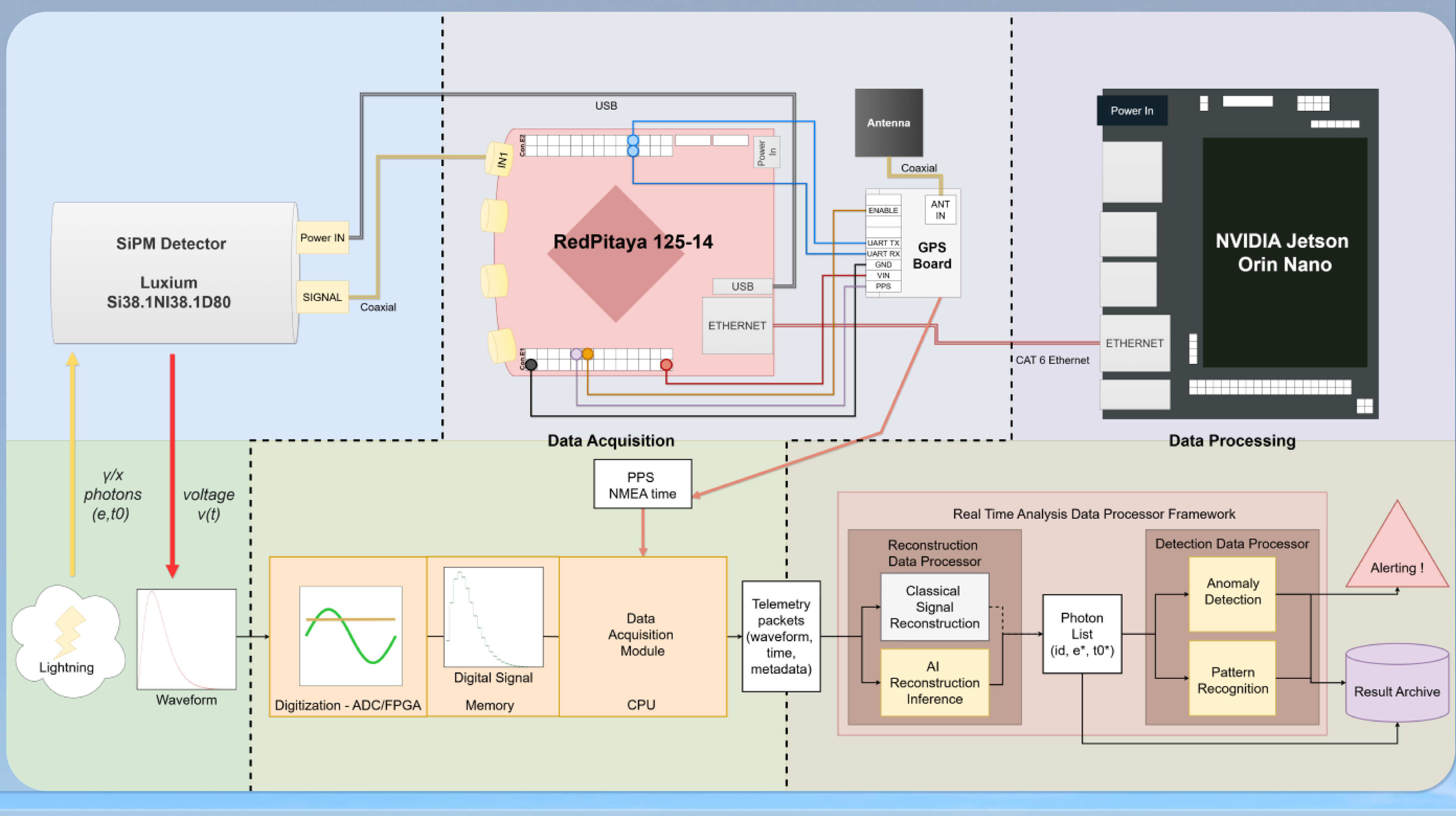
INTRODUCTION

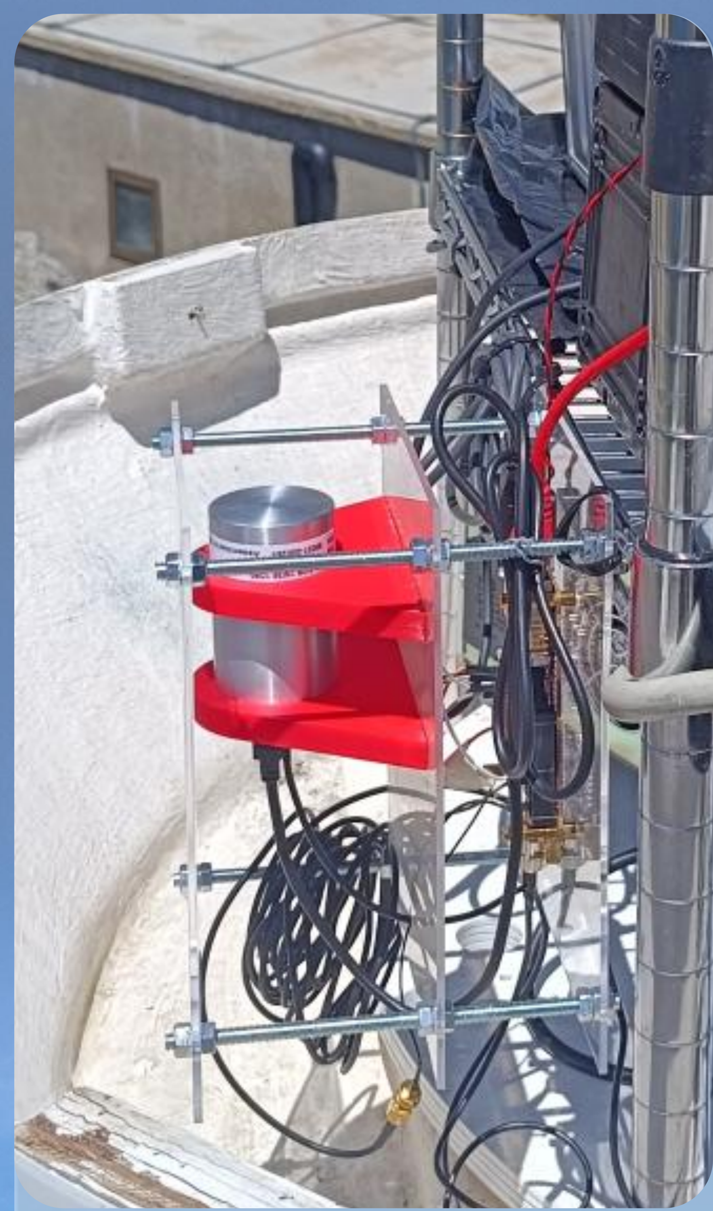
A growing trend in space applications is on-board AI, which considers the problem of moving inference of AI models on-board [2]. The **GammaSky** Project investigates real-time analysis of high-energy gamma-ray transients using AI on edge devices. Building on the heritage of the *AGILE* mission [3] and the *Gamma-Flash* project [4], it aims to develop **on-board AI** platforms for future space applications using atmospheric events— TGFs and Gamma-ray Glows—as a testbed for future space applications. Deployed at the "*O. Vittori*" Observatory (CNR-ISAC, Monte Cimone, 2165 m a.s.l.), GammaSky is designed to advance signal reconstruction, high-energy transient detection, and spectral characterization of real atmospheric gamma-ray events. This contribution presents the current experimental setup that brings real-time on-board AI data processing closer to operation.

Acquisition Board: To digitize the detector's signals, we use the *Red Pitaya STEMlab 125-14*, featuring a dual-core ARM CPU + FPGA, and a 14-bit 125 MSps ADC; an external GPS enables absolute timing, providing microseconds resolution, crucial for correlating TGFs with lightnings.

AI Processing Board: We adopted the *NVIDIA Jetson Orin Nano*, a COTS platform of growing interest for in-orbit AI; its Ampere GPU (1024 CUDA, 32 Tensor Cores) lets us run diverse ML/DL models and compare latency/throughput within a 15W power budget.

Detector:
The detector is a Luxium Solutions SiPM scintillation unit with a 1.5" × 1.5" NaI(Tl) crystal, offering a dynamic range from 9 keV to 6 MeV. It features low noise/voltage operation and insensitivity to magnetic fields; such properties enhance SNR and waveform stability. The fast front-end electronics produce pulses lasting a few hundred microseconds.





Installation

The detector and data acquisition board installed, together with other experiments, inside a dome of the "O. Vittori" Observatory.

Data Acquisition: On the Red Pitaya, the FPGA is configured as an oscilloscope, recording X- and gamma events in time windows of 16384 samples with 8ns resolution. A *Data Acquisition Module* (DAM) [5] configures the FPGA, reads raw buffers, and assigns absolute timestamps using GPS telemetry. The DAM streams the digitized waveforms as ZeroMQ (a lightweight messaging library) messages over the direct network connection to the Jetson.

Data Processing Pipeline: The C++ implementation of the *Real-Time Analysis Data Processor* (RTADP) framework [6] supports the integration of the processing pipeline. For on-board inference, we use the TensorFlow Lite (LiteRT) runtime together with XNNPACK (optimized CPU kernels), enabling efficient execution of both floating-point and quantized models on low-resource hardware. The analysis pipeline consists of a sequence of data processors operating in series. The first stage performs waveform-based reconstruction to estimate event energy and time, generating photon lists. The second stage conducts time-series analysis on the reconstructed counts to identify patterns indicative of increased activity. Custom workers allow each stage to execute user-defined algorithms or deep learning models. Final outputs include real-time scientific alerting for event detection and persistent storage of processed results.

Conclusions

GammaSky is an edge-computing platform for real-time gamma-ray analysis, integrating a SiPM-based detector, a Red Pitaya STEMlab 125-14, and an NVIDIA Jetson Orin Nano for AI processing. It enables energy reconstruction and low-latency detection of short transients. Field tests at 2165 m a.s.l. on Monte Cimone will validate the real-time detection of high-energy atmospheric events and support future CubeSat and small-mission implementations of onboard AI.

References
[1] Wada, Y. et al. : **Gamma-ray glow preceding downward terrestrial gamma-ray flash,** 10.1038/s42005-019-0168-y
[2] Izzo, D. et al. : **Selected Trends in Artificial Intelligence for Space Applications,** arXiv:2212.06662
[3] Tavani, M. et al. : **The AGILE space mission**, 10.1016/j.nima.2008.01.023
[4] Calabretto, P. et al. : **The Gamma-Flash Program: high-energy radiation and particles in thunderstorms, lightning, and terrestrial gamma-ray flashes,** 10.1088/1742-6596/2985/1/012015
[5] Bulgarelli, A. et al. : **The Gamma-Flash data acquisition system for observation of terrestrial gamma-ray flashes**, arXiv:2302.08321
[6] Bulgarelli, A., et al. : **The Real-Time Data Processor Framework for Data Handling and Analysis of High-Energy Instruments**. in Proceedings of the ADASS XXXIV, 2024

ACKNOWLEDGEMENTS

We gratefully acknowledge INAF to support the development of this project with a Mini Grant 2024. We acknowledge ISAC-CNR institute to host our experiment at the "O. Vittori" observatory.