Funded by the Horizon 2020 Framework Program of the European Union Grant Agreement No. 871158

WP 11 Deliverable No. 11.1

Technical report describing the performance of the GRB detector

Project acronym:
AHEAD2020

Project Title:
Integrated Activities for the High Energy Astrophysics Domain

Grant Agreement No: **871158**
This deliverable is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme

Start date of the project:
2020-03-02

Due date of deliverable: 29/11
Submission date: 30/11/2021
File Name: WP11_D11.01_GAGGDet_v01
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Version	Revision Date	Prepared by	Review and approval
1.0	29/11/2021	P.Ubertini, L.Natalucci	L.Hanlon

Distribution List	Date	Version
Consortium Board	30/11/2021	1.0

Acronyms and abbreviations

Agenzia Spaziale Italiana (ASI),

Data Acquisition System (DAQ),

Gadolynum Aluminum Gallium Garnet (GAGG),

Gamma-Ray Astronomy Small Sensor (GRASS),

International Gamma-Ray Astrophysics Laboratory (INTEGRAL),

SiPM (Silicon Photomultiplier),

Swedish Space Corporation (SSC),

Technical Readiness Level (TRL),

Terrestrial Gamma-ray Flashes (TGF),

Zero-Pressure Balloon (ZPB).

1. Introduction

Gamma-ray astronomy has been always using scientific ballooning from the early times of the pioneering discoveries to the present days. High energy photons from cosmic sources are absorbed at their impact at the upper atmosphere, so telescopes can be operated only at altitudes >30km from sea level. Therefore, balloon flights offer a good opportunity to validate an experimental technique and/or test a gamma-ray detector under harsh conditions, similar to the ones found when operating on a satellite.

At INAF/IAPS we have developed a small detection module, called GRASS (Gamma-ray Astronomical Small Sensor), compact and light that was flown as piggy-back aboard a gondola of the Swedish Space Corporation (SSC) from Esrange, near the Arctic Circle. The access to this 2021 ZPB flight campaign, that carried onboard several payloads from different research groups in Europe, was provided in the framework of the HEMERA H2020 project [1,2].

The instrument is based on a low energy ($\sim 0.1 - 10$ MeV) gamma ray scintillation detector which has as its baseline the use of a GAGG:Ce scintillator[1] with 25cm^2 sensitive area and a readout system with latest generation solid state sensors (SiPM). This is based on an array consisting of 8x8 SiPM sensors developed by OnSemiconductor (former SensL). This concept allows a compact design while maintaining the high TRL typical of these instruments. The detector prototype is a very light object (~1kg excluding the external support structure).

GRASS had been scheduled onboard HEMERA zero-pressure balloon flights in 2021 and 2022. At ceiling altitude, typically above 30 km the instrument can be used to measure the energy of the gamma-rays that are either produced in the atmosphere or are incident from the outer sky. The latter component, called diffuse X-ray background is well known as measured by several instruments on orbiting satellites, see e.g. [4] and Fig. 1. It is of cosmic origin as is mainly due to the integrated emission of many active galaxies [3]. At stratospheric altitudes, high energy

[1] The GRB detector was initially proposed as based on a BGO scintillator. However, laboratory activities have been carried out on BGO using both PMT and SiPM readout and it was found that all measurements suffered from relatively poor light collection. The much higher photon yield of the GAGG:Ce scintillator allows to obtain higher quality spectra while retaining a gamma-ray stopping power similar to BGO and is similarly non-hygroscopic.

detectors also see additional radiation produced by the reflection of these primary photons by the atmosphere.

Instruments flying on stratospheric balloons or in space are also exposed to additional signals induced by hadronic particles in the cosmic-ray and solar radiation, as protons, ions and neutrons, with all components varying with altitude, cutoff rigidity, geomagnetic latitude and other parameters (see Fig. 2). Together with the gamma-ray background these constitute a source of noise that limit the sensitivity of the instruments for astronomical observations. In general, a correct exploitation of the data require subtraction of this component and cannot leave out a detailed characterisation, both in terms of spectral shape and variability.

Whereas there is available a wealth of data from space instruments such as X-ray and gamma-ray telescopes, and particle monitors, on balloon flights the typical integration times do not allow a detailed modelling of instrument response to background conditions. Therefore, the acquisition of data as a function of altitude, cutoff rigidity and other parameters could be a useful tool for stratospheric background modelling.

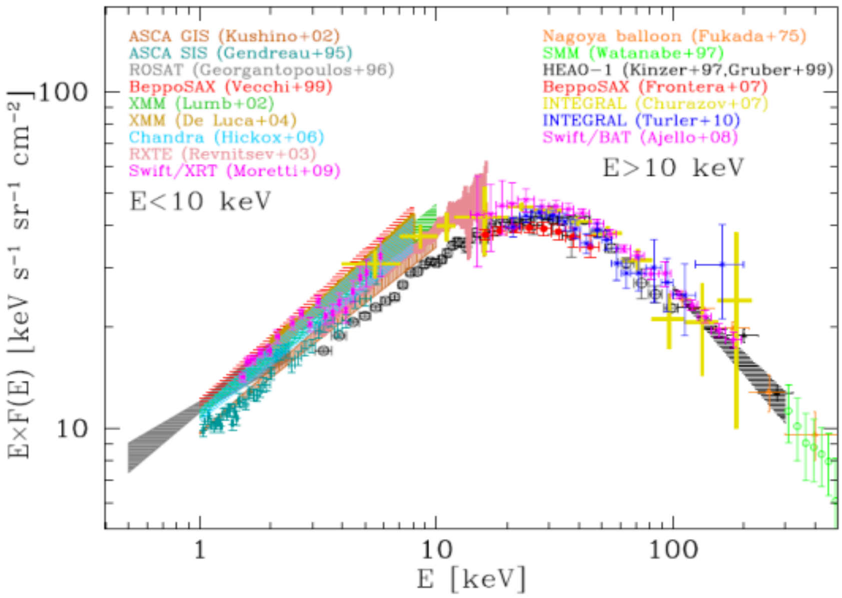
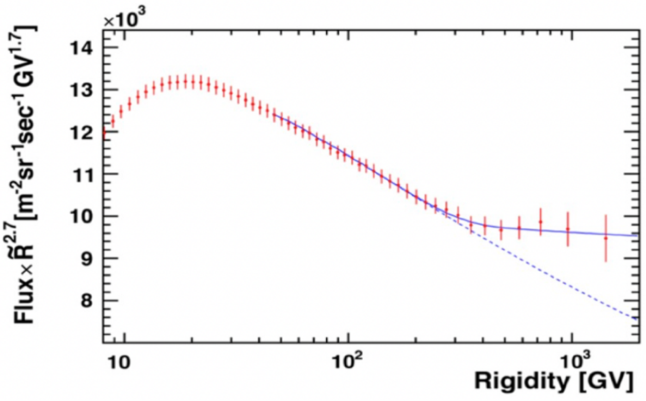
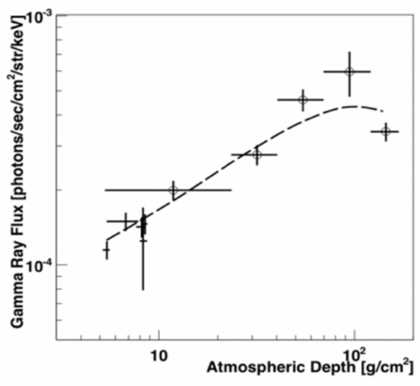


Fig. 1. The cosmic X-ray/gamma-ray background has been extensively measured up to the soft gamma-ray range (e.g. Revnitsev, 2014).





(a) (b)

Fig. 2. (a) The variation of proton flux on cutoff rigidity as observed by the AMS experiment on board the International Space Station [9] (the flux is multiplied by R2.7); (b) Variation of background gamma-ray flux with atmospheric depth measured by a stratospheric balloon experiment [10].

2. The GRASS experiment

GRASS has been designed as a High-TRL, consolidated technology instrument based on space qualified, rad-hard device. Our team has long-lasting experience on the development of scintillation based detectors, mostly inherited by the development of instrumentation for the ESA INTEGRAL satellite, launched in 2002 and still operational [11]. Today, modern technology allows to build scintillation detectors much lighter and more efficient than in the past. The choice of SiPM technology as readout also allows to avoid the use of high voltages, as required in PMT-based applications.

The core of the GRASS detector is a GAGG scintillator crystal coupled to a single, large sensitive area SiPM array (see Fig. 3a). The SiPM array is an ArrayJ-60035-64P-PCB developed by OnSemi. It is readout by a frontend electronics that multiplexes the signals from into 4 encoded position channels X-,X+,Y-,Y+. This readout scheme is very similar to the Anger camera method [12] that allows to simultaneously measure the two-dimensional position and amplitude of each event. For incident gamma-rays, the obtained position is then used as an estimator of the impact position of the photon onto the detector. A temperature sensor is integrated in the frontend board.

The data acquisition system (DAQ) receives the 4 pre-amplified signals from the external frontend, provides the bias and amplifier voltage and monitors the detector temperature. The DAQ triggers via a leading edge discriminator on the sum of all the 4 input channels. The trigger threshold is programmable. A time stamp for each event is provided with a resolution of 10ns.

An overall view of the experiment and its mechanical support structure is shown in Fig. 3b.

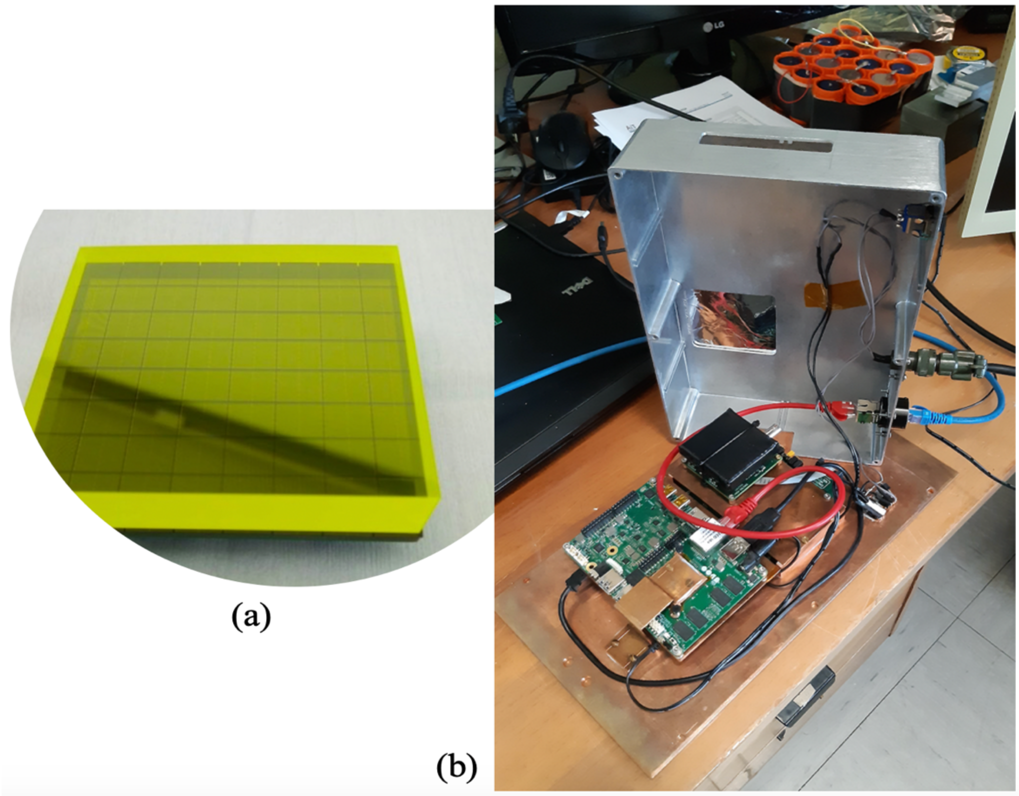


Fig. 3. Details of the GRASS instrument. (a) The 5x5 cm2 monolithic GAGG crystal is shown on top of the SiPM sensor array; (b) the GRASS instrument with the mechanical support structure surrounding the detector. The black-tapered crystal assembly and the copper plate for heat dissipation are clearly visible.

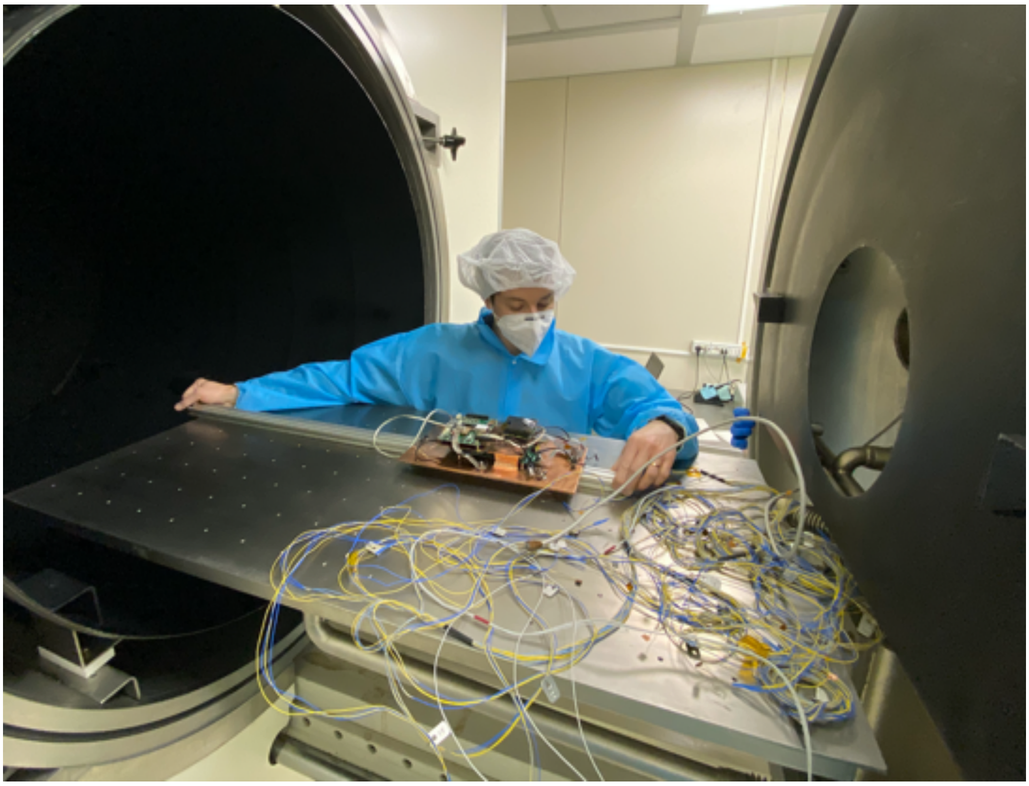


Fig. 4. The GRASS flight model during the thermal vacuum tests at the IAPS facility in Rome.

3. Laboratory tests and calibration

3.1 Thermal vacuum tests

An extensive thermal-vacuum test was performed on the flight unit of the GRASS experiment in the climatic chamber of the IAPS in Rome (see Fig. 4). During the test, the vacuum reached was 2x10-6 mbar and with typical max. temperatures below 40oC at the detector level. In the present configuration the heat is dissipated through a copper plate at the base of the support structure. The test has demonstrated that the thermal configuration of the experiment is able to maintain the various temperatures examined at an acceptable level for its operation. The instrument passed the tests without any failure, and the temperatures recorded during the various heat-vacuum cycles were within the expected values in flight.

3.2 Calibration

The calibration is based on the use of radioactive sources providing specific features that can be recognised in the energy spectra (see Table 1). The calibration procedure consists in illuminating the detector with each calibration source positioned at 2 cm from the crystal surface, reading each event data from the DAQ and histogramming the signal amplitudes to obtain the recorded spectra. The data acquisition is programmed to stop each 5 minutes. Interleaved with each source measurement, we acquire the background spectra that can be subtracted in the further analysis. A typical calibration spectrum obtained using the Ba133 and Cs137 sources together is shown in Fig. 5. A number of known features can be identified that are typical of these source spectra, and are due to either the full deposition peak or to the scattering of the incoming gamma-rays.

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The simultaneous measurement of these features allows to determine the linearity level of the response in the channel-energy space. Since this relationship depends on the temperature of the device, we have acquired this data at different ambient temperatures in the range 27-38°C.

Table 1. Radioactive sources used for the calibration of the GRASS experiment.

Isotope	Intensity (μCi)	Line Energy* (keV)
Am241	10.6	**60**
Co57	1.7	**122**,136
Ba133	1.3	**81**,276,302,**356**,384
Cs137	52.0	**662**
Co60	1.0	**1173,1332**

* Major line features are indicated in bold.

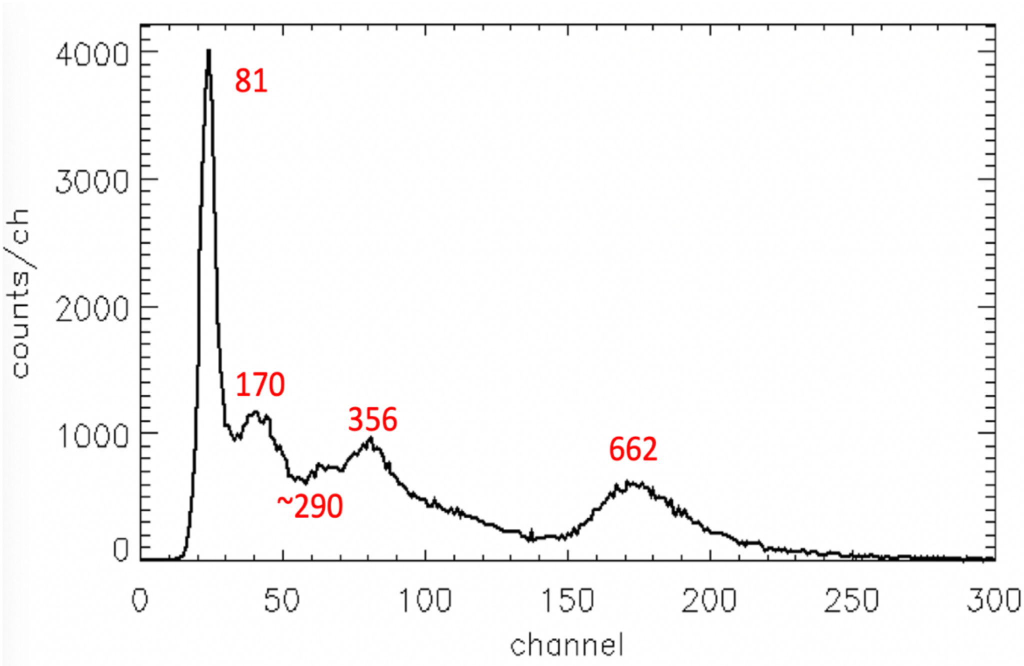

Fig. 5. Calibration spectra obtained in the laboratory. 5 minutes exposure to Cs137 and Ba133 sources simultaneously, at a temperature of 27°C. The energy in keV associated to the known spectral features is shown in red. The energy resolution is ~15% FWHM at the energy of the Cs137 line.

4. Modelling activities

Nowadays high-energy physics heavily relies on a computational Monte Carlo (MC) approach along the entire experimental processing pipeline. In high-altitude gamma-ray applications such as the HEMERA/GRASS experiment, inorganic scintillators are often employed as radiation-to-light converters coupled to compact, pixelated photon detectors like silicon photomultipliers (SiPMs): this requires detailed MC optical tracking in order to predict light distribution from scintillation materials.

The C++-based Geant4 package represents one of the major MC simulation frameworks, which can be flexibly interfaced to a number of high-level modular toolkits that exploit macrolanguages able to extend Geant4 command interpreter to specific domains. Among these, OpenGATE [13] has been selected to implement the MC simulation of the GRASS instrument, being this software tool well-tested and tailored to the needs of scintillation detection.

OpenGATE's optical capabilities derive from the G4OpticalPhysics list (P. Gumplinger, GEANT4 Collaboration) and are quite extensive. Scalar and vector material properties (which control optical photon generation and transport) and surface properties (which control physical processes at interfaces) must be provided through detailed input .xml files. The time-consuming part of the simulation - i.e., the control of radiant intensity at interfaces - is performed either by means of UNIFIED libraries [14], which apply a Gaussian modeling of the distribution of vectors normal to interface micro-facets (that also takes surface finish and reflectivity into account), or taking advantage of lookup tables typical of the DAVIS model [15], based on experimental AFM characterizations and much more accurate in describing non-polished surfaces (though less reliable in the presence of opaque wrappings). Once the storage of hits in the sensitive volumes is completed, a digitization chain can be simulated as from a front-end electronics, with cross-talk, pile-up and electronic-noise phenomena possibly embedded.

At a first benchmarking stage, GRASS performances on ground (in response to a set of point-like calibration radiosources) is going to be MC-tested benefiting from pseudo-parallelization on a dedicated cluster. Subsequent assessment of in-flight performances will require the profiling of the stratospheric gamma environment, including a primary diffuse cosmic component (minor contribution) and a secondary, zenith-angle dependent component primarily due to bremsstrahlung of secondary and albedo electrons at energies < 50 MeV (dominant contribution) [16].

5. Results of the ZPB campaign

The GRASS instrument has been launched very recently onboard an HEMERA ZPB flight on September 11th, 2021. The launch was performed successfully from the Esrange SSC balloon launch facility. The flight lasted ~9 hours and gondola carrying the GRASS instrument and other HEMERA payload instrumentation reached a stratospheric altitude of 33 km and maintained this level for ~3 hours. The count rate of the instrument at ceiling altitude was in the range ~150-200 counts/s (see Fig. 6, bottom panel).

The peak which is observed during the ascent phase at around 10:30AM UTC, is most probably associated to the Regener-Pfotzer maximum, an altitude at which the ionisation rate of cosmic ray interactions is expected to be the highest. The variation of the count rate is also correlated with the sensor temperature (Fig. 6, top panel). During the descent phase at an altitude of ~24km, before separation of the balloon from the gondola we performed a shutdown of the experiment, resulting in a total time of data acquisition of 6h20m.

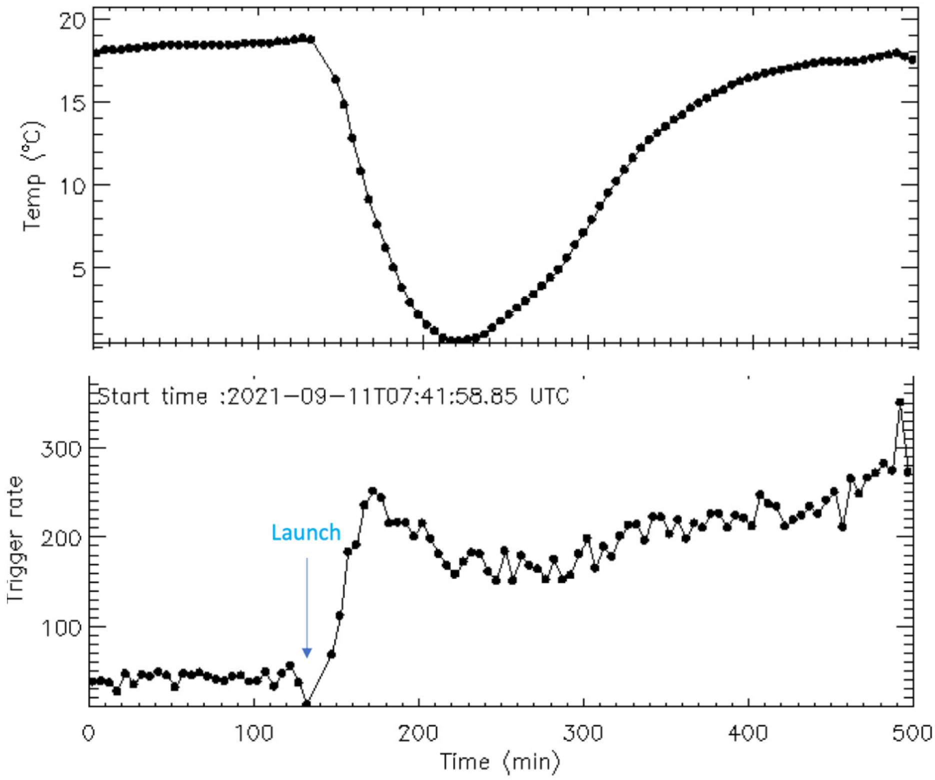

Fig. 6. Time profiles of GRASS parameters covering the ZPB flight. Temperature of the SiPM sensor array (top panel); count rate measured by the detector in units of counts/s (bottom panel).

After recovery, the instrument was found in perfect conditions and tested on site before being shipped to return to the laboratory. During the next few weeks we plan to perform new calibration measurements to reach a complete characterisation of the instrument against the range of temperatures met during the flight (0-18oC).

6. Conclusions

A small detector module has been built at INAF/IAPS to be tested as compact, high performance device to be used for space or stratospheric applications. These include cosmic and atmospheric background characterisation and other high energy phenomena involving cosmic-ray science, gamma-ray astronomy with special regard to time-domain and multi-messenger applications, as well as the detection of TGFs [17]. Our first balloon flight provided by the HEMERA infrastructure program was performed successfully with acquisition of ~6h of useful data.

Post flight activities, as additional calibrations and data analysis will be performed at the IAPS laboratory. Short term goals are to develop a more advanced detector design and to improve the readout technology to be ready for the next campaign, foreseen in 2022.

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