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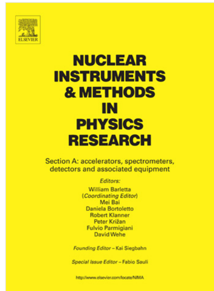

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HERMES: An ultra-wide band X and gamma-ray transient monitor on board a nano-satellite constellation

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Abstract

The High Energy Modular Ensemble of Satellites (HERMES) project is aimed to realize a modular X/gamma-ray monitor for transient events, to be placed on-board of a nano-satellite bus (e.g. CubeSat). This expandable platform will achieve a significant impact on Gamma Ray Burst (GRB) science and on the detection of Gravitational Wave (GW) electromagnetic counterparts: the recent LIGO/VIRGO discoveries demonstrated that the high-energy transient sky is still a field of extreme interest. The very complex temporal variability of GRBs (experimentally verified up to the millisecond scale) combined with the spatial and temporal coincidence between GWs and their electromagnetic counterparts suggest that upcoming instruments require sub-microsecond time resolution combined with a transient localization accuracy lower than a degree. The current phase of the ongoing HERMES project is focused on the realization of a technological pathfinder with a small network (3 units) of nano-satellites to be launched in mid 2020. We will show the potential and prospects for short and medium-term development of the project, demonstrating the disrupting possibilities for scientific investigations provided by the innovative concept of a new "modular astronomy" with nano-satellites (e.g. low developing costs, very short realization time). Finally, we will illustrate the characteristics of the HERMES Technological Pathfinder project, demonstrating how the scientific goals discussed are actually already reachable with the first nano-satellites of this constellation. The detector architecture will be described in detail, showing that the new generation of scintillators (e.g. GAGG:Ce) coupled with very performing Silicon Drift Detectors (SDD) and low noise Front-End-Electronics (FEE) are able to extend down to few keV the sensitivity band of the detector. The technical solutions for FEE, Back-End-Electronics (BEE) and Data

Handling will be also described.

Keywords: Nanosatellites, Gamma-ray Burst, Silicon Drift Detectors, Scintillator Detectors

PACS: 95.55.Ka, 29.40.Wk, 29.40.Mc,

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1. Introduction

Gamma-Ray Bursts (GRBs) are one of the most intriguing and challenging phenomena for modern science. Their study is of very high interest for several fields of astrophysics, such as the physics of matter in extreme conditions and black holes, cosmology, fundamental physics and the mechanisms of gravitational wave signal production, because of their huge luminosities, up to more than 10^{52} erg/s, their red-shift distribution extending from $z \sim 0.01$ up to $z > 9$ (i.e., much above that of supernovae of the Ia class and galaxy clusters), and their association with peculiar core-collapse supernovae and with neutron star/black hole mergers.

Since their discovery, GRBs were promptly identified as having a non-terrestrial origin [1]. First observations were done using radiation monitors onboard the VELA spacecraft constellation, that was a network of satellites designed to monitor atmospheric nuclear tests. Between 1963 and 1970 a total of 12 satellites were launched and the constellation was operating until 1985, with more sensitive detectors on later satellites. By analyzing the different arrival times of the γ-ray photon bursts as detected by different satellites, placed in different locations around the Earth, it was possible to roughly estimate the direction of the GRB, later improved using additional and better detectors, reaching a precision of ~10°. With a very similar approach, the Inter-Planetary Network (IPN[1], including all satellites with GRB-sensitive instruments on-board) was organised by GRB scientists in late '70s, aiming to localize GRBs for the observation of counterparts at other wavelengths. Basing on the availability of

[1] `https://heasarc.gsfc.nasa.gov/w3browse/all/ipngrb.html`

operating instruments, the IPN in its lifetime has involved up to more than 20 different spacecrafts. This experience demonstrates that the localization accuracy of GRBs is improved by increasing the spacing between different detectors, and also by a more accurate detector timing resolution. The IPN localizations are usually provided in few days, and although can reach angular resolutions of arcminutes and often arcseconds, the current typical accuracy, at high energies, is of the order of few degrees. This was demonstrated, e.g., in the case of the discovery of Gravitational Wave (GW) electromagnetic counterparts [2]. Such huge error box is too large to be efficiently surveyed at optical wavelenghts, where tens/hundreds of optical transient sources are usually found, increasing enormously the probability to find spurious correlations. The best strategy here is to perform a prompt search for transients at high energies, with a localization accuracy of arcminutes or arcseconds, reducing the probability of chance association.

2. HERMES Mission Concept

The *High Energy Modular Ensemble of Satellites* (HERMES) project aims to realize a new generation instrument for the observations of high-energy transients. The proposed approach here differs from the conventional idea to build increasingly larger and expensive instruments. The basic HERMES philosopy is to realize innovative, distributed and modular instruments composed by tens/hundreds of simple units, cheaper and with a limited development time. The present nanosatellite (e.g. CubeSats) technologies demonstrates that off-the-shelf components for space use can offer solid readiness at a limited cost. For scientific applications, the physical dimension of a single detector should to be compatible with the nanosatellite structure (e.g. 1U CubeSat of 10×10×10 cm^3). Therefore, the single HERMES detector is of course underperforming (i.e. it has a low effective area), when compared with conventional operative transient monitors, but the lower costs and the distributed concept of the instrument demonstrate that is feasible to build an innovative instrument with unprecedented sensitivity. The HERMES detector will have a sensitive area >50 cm^2, therefore with several tens/hundreds of such units a total sensitive area of the order of magnitude of $\sim$1 m^2 can be reached.

By measuring the time delay between different satellites the localisation capability of the whole constellation is directly proportional to the number of components and inversely proportional to the average baseline between them. As a rough example, with a reasonable average baseline of $\sim$7000 km (comparable to the Earth radius, and a reasonable number for low-Earth satellites in suitable orbits) and $\sim$100 nanosatellites simultaneously detecting a transient, a source localisation accuracy of the order of magnitude of $\sim$10 arcsec[2] can be reached, for transients with short time scale (ms) variability.

The current phase of the project, *HERMES Technological Pathfinder* (TP), focuses on the realization of three nanosatellites, ready for launch at mid-2020. The purpose here is to demonstrate the feasibility of the HERMES concept, operating some units in orbit and to detect a few GRBs. The next phase of the project, *HERMES Scientific Pathfinder* (SP), will demonstrate the feasibility of GRB localisation using up to 6–8 satellites in orbit. Although in both these preliminary phases reduced ground segment capabilities will be used, i.e. reduced data-downloading with a few ground contacts/day, the complete development of the HERMES detectors is expected. These activities will pave the way to the final HERMES constellation composed of hundreds of nanosatellites. Detailed mission studies, including orbital configuration, attitude control strategy, and sensitive area distribution will be performed, as well as a proper planning of the ground segment allowing to reach the ambitious scientific requirements, i.e prompt diffusion of the transient accurate localization. Thanks to the production approach, the context of a typical Small or Medium-class space mission seems to be compatible with HERMES final constellation, where most of the resources will be devoted to the multiple launches and to the realization of the

[2] $\sigma_{\rm pos} = \sigma_{\rm CCF}/Bc\sqrt{N(N-1-2)} \approx 10$ arcsec; where B is the baseline, N the number of satellites and $\sigma_{\rm CCF}$ is the error associated with the cross-correlation function.

ground segment.

3. Payload Description

A possible solution for the HERMES payload is allocated in 1U-Cubesat (10×10×10 cm^3), cf. Figure 1. A mechanical support is placed on the instrument topside. The support is composed by two parts to accomodate an optical/thermal filter in the middle. The electronic boards for the Back-End and the Data Handling unit are allocated on the bottom of the payload unit. The detector core is located in the middle: this is a scintillator-based detector in which Silicon Drift Detectors (SDD, [5]) are used to both detect soft X-rays (by direct absorption in silicon) and to simultaneously readout the scintillation light. The payload unit is expected to allocate a detector with >50 cm^2 sensitive area in the energy range from 3–5 keV up to 2 MeV, with a total power consumption <4 W and total weight of <1.5 kg.

3.1. Detector core architecture

Aiming at designing a compact instrument with a very wide sensitivity band, the detector is based on the so-called "siswich" concept [3, 4], exploiting the optical coupling of silicon detectors with inorganic scintillators. The detector is composed by an array of scintillator pixels, optically insulated, read out by Silicon Drift Detectors.

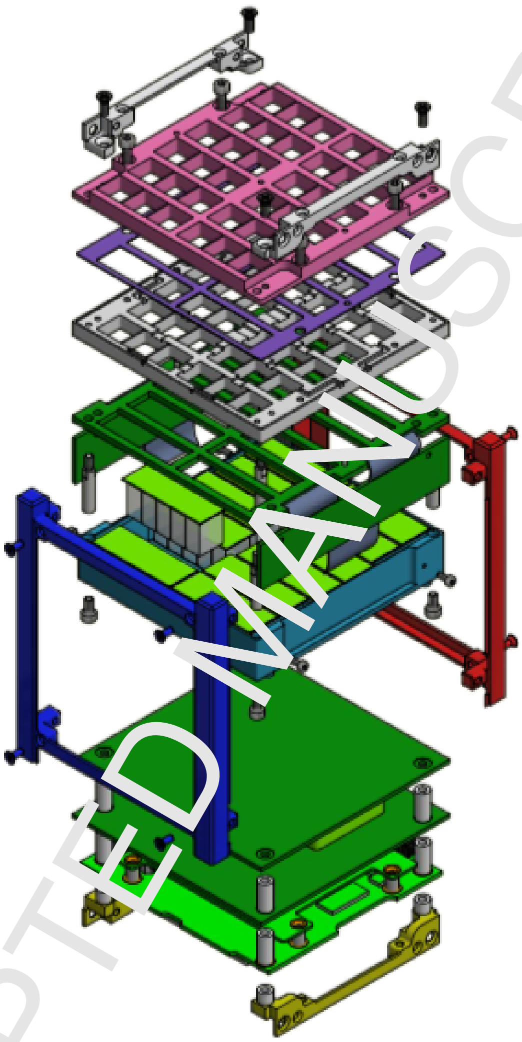

Figure 1: Exploded view of the payload unit (10×10×10 cm^3) on board the HERMES nanosatellite. From the top are shown the mechanical support composed by top (pink) and bottom (gray) parts, with optical filter (violet) in middle, the FEE board (dark green) allocating SDD matrices (light green), FE-LYRA chips on the top and BE-LYRA chips folded on the side (not shown for clarity), the GAGG crystal pixels (white trasparent) and their housing (greenish blue). Mechanical ribs on top (grey) and on bottom (yellow) are also visible, necessary to fix the payload components to the satellite structure (blue and red).

In this concept the SDDs play the double role of read-out device for the optical signal from the scintillator and of an independent X-ray solid state detector.

Low energy X-rays are directly absorbed by the SDD, while higher energy X-rays and γ-rays are absorbed in the crystal and the optical scintillation photons are collected by the same detector. Only very low noise read-out sensors and front-end electronics allow to reach a low energy scintillator threshold below 20–30 keV. Above these energies the increasing sensitivity of the scintillator is able to compensate the lack of efficiency of thin silicon sensors (450 μm), so a quite flat efficiency in a wide energy band for the whole integrated system is reached. The inorganic scintillators selected for this innovative detector is the recently developed [6] Cerium-doped Gadolinium-Aluminum-Gallium Garnet (Ce:GAGG), a very promising material with all the required characteristics, i.e. a high light output ($\sim$50,000 ph/MeV), no internal radioactive background, no hygroscopicity, a fast radiation decay time of $\sim$90 ns, a high density (6.63 g/cm^3), a peak light emission at 520 nm and an effective mean atomic number of 54.4. All these characteristics make this material very suitable for the HERMES application. Since GAGG is a relatively new material, it has not yet extensively investigated with respect to radiation resistance and performance after irradiation, although the published results are very encouraging [7–9]. These tests showed that GAGG has a very good performance, compared to other scintillator materials largely used in the recent years in space-borne experiments for γ-ray astronomy (e.g. BGO or CsI), i.e. a very low activation background (down to 2 orders of magnitude lower than BGO), and a minor light output degradation with accumulated dose.

The SDD development builds on the state-of-the-art results achieved within the framework of the Italian ReDSoX collaboration, with the combined design and manufacturing technology coming by a strong synergy between INFN-Trieste and Fondazione Bruno Kessler (FBK, Trento), in which both INFN and FBK co-fund the production of ReDSoX Silicon sensors. A custom geometry for a SDD matrix (Figure 2) was designed, in which a single crystal ($\sim 12.1 \times 6.94$ mm^2) is coupled with two SDD channels. Therefore, the scintillator light uniformly illuminates two cells, giving rise to a comparable signal output for both channels. This allows to discriminate scintillator events (higher energy γ-rays) by their multiplicity: lower energy X-rays, directly absorbed in the SDD, are read out by only one channel.

3.2. Readout ASIC: from VEGA to LYRA

The HERMES detector, constituted by 120 SDD cells distributed over a total area of $\sim$92 cm^2, requires a peculiar architecture for the readout electronics. A low-noise, low-power Application Specific Integrated Circuit (ASIC) named LYRA has been conceived and designed for this task. LYRA has an heritage in the VEGA ASIC [10, 11] that was developed by Politecnico of Milano and University of Pavia within the ReDSoX Collaboration during the LOFT Phase-A study (ESA M3 Cosmic Vision programme), although a specific and renewed design is necessary to comply with the different SDD specifications, the unique system architecture and the high signal dynamic range needed for HERMES. A single LYRA ASIC is conceived to operate as a constellation of 32+1 Integrated Circuit (IC) chips. The 32 Front-End ICs (FE-LYRA) include preamplifier, first shaping stage and signal line-transmitter, the single Back-End IC (BE-LYRA) is a 32-input ASIC including all the circuits to complete the signal processing chain: signal receiver, second shaping stage, discriminators, peak&hold, control logic, configuration registers and multiplexer. The FE-LYRA ICs are small (0.9×0.6 mm^2 die) allowing to be placed very close to the SDD anodes, in order to minimize the stray capacitances of the detector-preamplifier connection, maximizing the effective-to-geometric area ratio ($\sim$54 cm^2 vs. $\sim$92 cm^2). In this configuration (Figure 2), the BE-LYRA chips ($\sim6.5\times2.5$ mm^2 die) can be placed out of the detection plane, allocating SDD matrix and FE-LYRA ICs on a rigid part by means of embedded flex cables. The flat cables allow also avoiding the additional space required by connectors, offering the possibility to "fold" the boards allocating the BE-LYRA chips (on a rigid part) at right angle with respect to the detection plane, on the external side of the payload unit.

3.3. Back-End Electronics

The Back-End electronics (BEE) of HERMES includes the BE-LYRA chips, external commercial analog-to-digital (ADC) converters and a FPGA-based con-

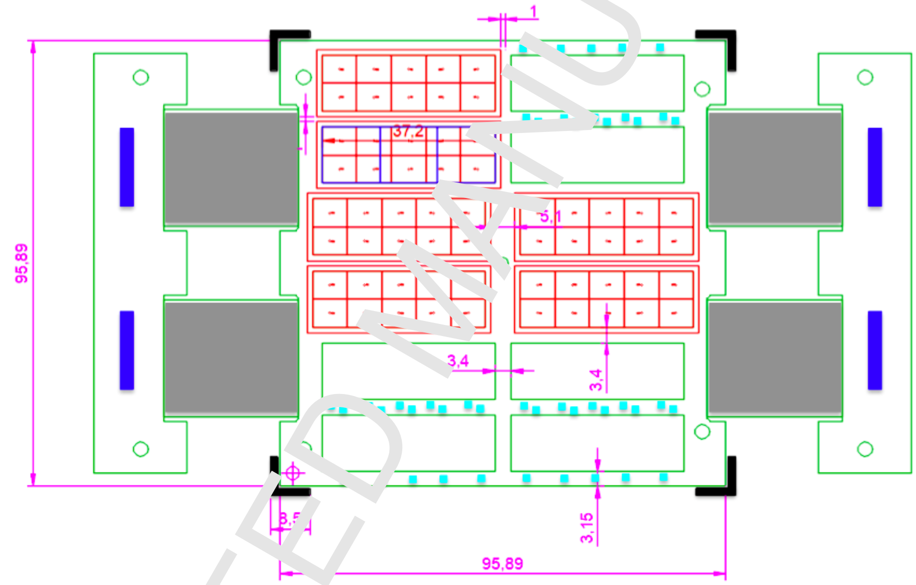

Figure 2: Sketch of the top view of FEE board for the HERMES nanosatellite. The black corner indicate the overall nanosatellite structure ($10{\times}10$ cm^2). The board will allocate SDD matrices (in red) and FE-LYRA chips (light blue) very close to each SDD anode. The BE-LYRA chips (blue) are allocated on the rigid part that will be folded on the side of the satellite, by means of flex cables (gray).

trol logic. The control logic takes care of the signal handshaking required to read out analogue signals from BE-LYRA chips, syncronizing the digital conversion operations, and time tagging the events based on conventional GPS sensor, combining an atomic clock signal (CSAC) to reduce as much as possible the natural shift/jitter of the GPS sensor ensuring a sub-microsecond timing resolution. Due to the peculiar architecture of the detector core, the BEE will also perform the Event Data Generator functionality, automatically discriminating the location of photon interaction (silicon or scintillator), on the basis of the multiplicity of the readout signals. This fundamental task has to be carried out in real-time to generate the photon lists that include channel address, time of arrival of photons and a raw energy estimation, which are mandatory for scientific data processing based on a suitable on-board logic.

3.4. Payload Data Handling Unit

The HERMES Payload Data Handling Unit (PDHU) will be implemented on iOBC, manufactured by ISIS, a commercial on-board computer. This model, with a weight of ∼100 g and an average power consumption of 400 mW, will implement all functionalities required for HERMES, such as telecommands (TCs), housekeeping (HKs), power system commanding (PSU), handling operative modes of the payload (by TCs or automatically), generating the telemetry packets (TMs) and managing the interface with the spacecraft. A custom algorithm making the satellites sensitive X-ray and γ-ray transients, continuously compare the current data rate of the instrument with the average background data rate taken previously. When a transient occurs, the events, recorded on a circular buffer, are then sent to the ground on telemetry packets. Due to the different families of GRB, ratemeters on different timescales, energy bands and different geometric regions of the detection plane will be implemented.

4. Conclusion

The HERMES project final aim is to realize a new generation instrument composed by hundreds of detectors onboard nanosatellites. This disruptive technology approach, although based on "underperforming" individual units, allows to reach overall sensitive areas of the order of $\sim$1 m^2, with unprecedented scientific performance for the study of high-energy transients such as GRBs and gravitational wave counterparts. The current ongoing phase of the HERMES project (Technological Pathfinder), focuses on the realization of the three nanosatellites to be launched in mid-2020, that will demonstrate the proposed approach to detector design (Silicon Drift Detectors coupled to GAGG:Ce scintillator crystals) and its performance. In this framework, relevant prototyping activities are currently under development, towards the implementation phase.

Acknowledgments

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