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Design and construction of the Mini-Calorimeter of the AGILE satellite

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ABSTRACT

AGILE is a small space mission of the Italian Space Agency (ASI) devoted to gamma-ray and hard-X astrophysics, successfully launched on April 23, 2007. The AGILE Payload is composed of three instruments: a gamma-ray imager based on a tungsten-silicon tracker (ST), for observations in the gamma ray energy range 30 MeV–50 GeV, a Silicon based X-ray detector, SuperAGILE (SA), for imaging in the range 18–60 keV and a CsI(Tl) Mini-Calorimeter (MCAL) that detects gamma rays or charged particles energy loss in the range 300 keV–100 MeV. MCAL is composed of 30 CsI(Tl) scintillator bars with photodiode readout at both ends, arranged in two orthogonal layers. MCAL can work both as a slave of the ST and as an independent gamma-ray detector for transients and gamma-ray bursts detection. In this paper a detailed description of MCAL is presented together with its performance.

1. Introduction

AGILE[1] [1,2] is a small space mission of the Italian Space Agency (ASI) devoted to astrophysics in the gamma-ray energy range 30 MeV–50 GeV, with a monitor in the X-ray band 18–60 keV. The AGILE payload is composed of three instruments: a tungsten-silicon tracker (ST) [3,4], with a large field of view, good time resolution, sensitivity and angular resolution; a Silicon based X-ray detector, SuperAGILE (SA) [5], for imaging in the range 18–60 keV and a CsI(Tl) Mini-Calorimeter (MCAL) [6–8] for the detection of gamma-rays or charged particles in the range 300 keV–200 MeV. ST and MCAL form the so-called Gamma-Ray Imaging Detector (GRID) for observations in the energy range 30 MeV–50 GeV. The instrument is surrounded by an anticoincidence (AC) system [9], made with plastic scintillator layers, for the rejection of charged particles and is completed by the Payload Data Handling Unit (PDHU) [10]. AGILE was successfully launched on April 23, 2007 from Satish Dhawan Space Centre (India) on a PSLV rocket.

The AGILE GRID detection principle is based on the pair production process. The interaction of a high energy photon with a tungsten layer of the silicon tracker originates an electron positron pair whose direction of propagation is sampled by the ST detection panes. ST determines the direction of the incoming radiation, while MCAL, operating as a slave of ST, measures the energy deposited by particles reaching it. MCAL can also work as a stand-alone gamma-ray detector in the range 300 keV–100 MeV, with no imaging capabilities, for the detection of transient events and gamma-ray bursts (GRB) and for evaluation of gamma-ray background fluctuations. For GRBs in the SuperAGILE field of view, SA will be able to determine the position of the source and its hard X-ray spectrum, while MCAL will describe the spectrum above 300 keV and its time variation in correlation with SA. The two instruments are arranged to work together at PDHU level. Furthermore MCAL produces a broad-band spectrum of the gamma-ray sky (scientific ratemeters, SRM) with a refresh rate of 1 s, for the monitoring of gamma-ray background. The architecture of MCAL has been designed to accomplish its different tasks at the same time starting from a single detector system.

In this paper a detailed description of the MCAL instrument will be provided, from the design solutions adopted to the detector construction and tests. The pre-launch instrument performance will be discussed as well.

2. Scientific requirements and constraints

MCAL was conceived as a part of the GRID detector, to complement the ST in the detection of events, supplying the energy information of the tracked particles. For this detector its

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fate is also in its name: Mini-Calorimeter. AGILE is a small mission with severe constraints concerning payload dimension, weight and power consumption: the overall active payload weight is 120 kg, with a power consumption of about 120 W. The spacecraft total weight is 350 kg. Within this frame, just 30 kg and 6 W were allocated for the calorimeter so that the resulting detector could just be mini.

Apart from the weight and power constraints, few simple concepts had to be followed for the MCAL basic design: its geometrical area should match the ST cross-section and it should be capable of determining energy and position of triggered events. No constraints were put on the complexity of the electronic design of the system and on the number of its functions. Therefore, since it was not possible to add more scientific instruments to the mission due to payload weight constraints, it was decided to operate MCAL also to detect gamma-ray transients, the so-called BURST mode, and to monitor the overall low energy gamma-ray background during the orbit.

Concerning the MCAL contribution to GRID operations it was recognized since the early simulations of the AGILE payload that, due to the limited MCAL thickness (only 1.5 radiation lengths, about 3 cm), its efficacy as a calorimeter is restricted to the lower part of the whole GRID energy range. For photon energies where MCAL contribution is not conclusive, the energy of the detected photon is evaluated from the scattering angles of the particles moving through the ST detection planes. In this case MCAL can still contribute with a further positional information in the farthest location from the gamma-ray interaction. Moreover, the topological information provided by MCAL (i.e. number of hit detectors, position distribution of events) help the events filtering procedure for background discrimination.

The MCAL design arises from a trade-off between the instrument weight constraint and the efficiency requirements in the detection of high energy gamma-rays. Its thickness of about 3 cm gives an acceptable compromise, resulting in a good efficiency for gamma-rays of some MeV. MCAL energy threshold is about 300 keV, resulting as a trade-off itself between the minimum energy threshold requirement and the electronic noise performance as well as low power consumption constraints.

Operating as a GRB monitor, the main goal of MCAL is the detection of fast transients at MeV energies with microsecond time resolution. In detecting GRBs MCAL is complemented by the SA instrument, which operates at hard X-ray energy and has imaging capabilities in a $68^\circ \times 68^\circ$ field of view. MCAL can provide only limited information on burst direction, but it has a 4π sr field of view, thus behaving as a true all-sky monitor, even if, for GRBs out of the SA field of view, a localization from other satellites is required to proceed in spectral analysis (since the detector's response is direction dependent). For GRB detection a dedicated trigger logic must also be included in the system design, in order to trigger on fast rate increases above the background level.

GRBs at MeV energies have been detected by the BATSE and COMPTEL instruments on-board the Compton Gamma-Ray Observatory (CGRO) during the 1990s, and are currently observed by several instruments in space. GRBs at higher energy have been detected by the EGRET instrument on-board CGRO, and GeV emission has been predicted by some models [11] and reported for some bursts [12]. There are also many attempts to detect GRB at TeV energy [13,14], the most stringent upper limits being currently provided by the MAGIC telescope [15]. High energy GRB are rare events, which have not been studied in details up to now. For the first time we can study these events with an unprecedented time resolution, better than 2 μs, over an energy range spanning six orders of magnitude with all the three main AGILE detectors combined together. This search has recently led to the AGILE detection above 50 MeV of the first GRB after the EGRET era [16].

2.1. Monte Carlo simulations

Extensive simulations were done to verify the scientific performance of the instrument and to optimize its design [17,18]. A detailed representation of MCAL is included in the Monte Carlo code used for scientific simulations.

Fig. 1 shows the probability of interaction of photons in MCAL as a function of their energy, from Monte Carlo simulations. It is computed as the ratio between the number of hits observed in MCAL and the number of primary events whose trajectories intersect the MCAL active volume. Since the simulations are carried out considering plane beams hitting the whole AGILE satellite, for high off-axis angles and energies above few MeV the contribution from secondaries originated in the AGILE structure and hitting MCAL becomes important. This is the reason for the efficiency rapidly approaching unity for the 80° off-axis beam shown in Fig. 1. Below 1 MeV the efficiency trend is very sensitive to the energy threshold that, as it will be explained in Section 4, is variable on the detector surface. We have assumed here a reasonable but conservative value corresponding to 300 keV at the edge of MCAL bars, where the threshold is lower.

Fig. 2 shows the fraction of on-axis photons which reach MCAL prior to any interaction as a function of initial energy. Photons with energy above about 10 MeV mainly interact in the tracker or in the satellite's structural parts, and MCAL detects them trough secondary products, while photons with energy below 1 MeV can be easily stopped by ST itself.

Figs. 3 and 4 report the total and photopeak effective area, respectively, as a function of the incident photon energy. Despite the total effective area keeps rising for energies higher than 10 MeV, the photopeak effective area rapidly decreases above a few MeV because of the limited thickness of the detector.

The effective area plots reported in this section refer to MCAL operated as a self-triggering detector, i.e. in the so-called BURST mode, as described in Section 3.1. MCAL can also work as a slave to the AGILE silicon tracker (GRID mode), but in this case the effective area is determined by the silicon tracker efficiency and trigger criteria, discussed in Refs. [1,2].

Fig. 5 shows the total MCAL effective area as a function of the angle of incidence, for different energy values. The effective area remains almost constant for angles between 0° (on-axis beam) and 60° since the reduction in geometrical area is compensated by

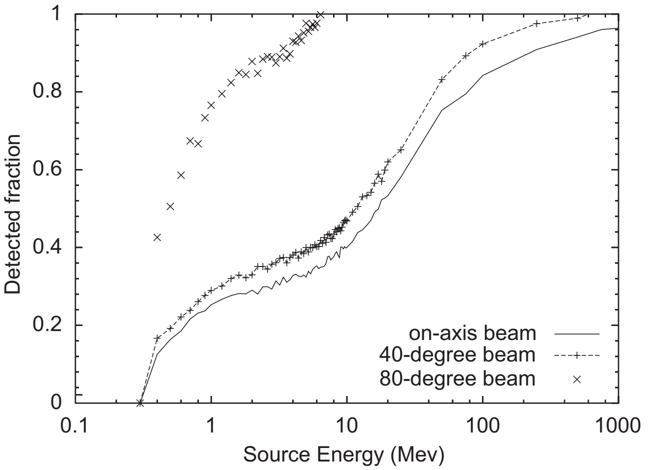

Fig. 1. Fraction of detected events as a function of energy, for different off-axis angles, from Monte Carlo simulations.