The Mini-Calorimeter on-board AGILE: the first year in space

M Marisaldi\textsuperscript{1}, C Labanti\textsuperscript{1}, F Fuschino\textsuperscript{1}, M Galli\textsuperscript{2}, A Argan\textsuperscript{3}, A Bulgarelli\textsuperscript{1}, G Di Cocco\textsuperscript{1}, F Gianotti\textsuperscript{1}, M Tavani\textsuperscript{3}, M Trifoglio\textsuperscript{1} and A Trois\textsuperscript{3}

\textsuperscript{1}INAF-IASF Bologna, Via Gobetti 101, I-40129 Bologna, Italy
\textsuperscript{2}ENEA Bologna, Via Martiri di Monte Sole 4, I-40129 Bologna, Italy
\textsuperscript{3}INAF-IASF Roma, Via del Fosso del Cavaliere 100, I-00133 Roma, Italy

E-mail: marisaldi@iasfbo.inaf.it

Abstract. AGILE, the Italian space mission dedicated to gamma-ray and hard-X astrophysics, was successfully launched on 23\textsuperscript{rd} April 2007 and is currently fully operative. The Mini-Calorimeter (MCAL) on-board the AGILE satellite is a scintillation detector made of 20 kg of segmented CsI(Tl) scintillator with photodiode readout with a total geometrical area of 1400 cm\textsuperscript{2}. MCAL can work both as a slave of the AGILE Silicon tracker and as an independent detector for gamma-ray bursts (GRB) detection in the 300 keV - 100 MeV energy range. Despite its limited thickness, due to weight constraints, MCAL has proven to successfully self-trigger GRBs at MeV energies providing photon-by-photon data with less than 2 µs time resolution and almost all-sky detection capabilities. The instrument design and characteristics, as well as the in-flight performance after one year of operation in space and the scientific results obtained so far are reviewed and discussed.

1. Introduction

AGILE\textsuperscript{[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 keV - 60 keV. The AGILE Payload is composed of:

- a Tungsten-Silicon Tracker (ST) \textsuperscript{[3, 4]}, with a large field of view, good time resolution, sensitivity and angular resolution;
- a Silicon based X-ray detector, SuperAGILE (SA) \textsuperscript{[5]}, for imaging in the range 18 keV - 60 keV;
- a CsI(Tl) Mini-Calorimeter (MCAL) \textsuperscript{[6, 7]} that detects gamma-rays or particle energy deposits between 300 keV and 100 MeV. ST and MCAL form the so called Gamma-Ray Imaging Detector (GRID) for observations in the energy range 30 MeV - 50 GeV;
- an anti-coincidence (AC) system \textsuperscript{[8]}, made with plastic scintillator layers, for the rejection of charged particles background;
- the Payload Data Handling Unit (PDHU) \textsuperscript{[9]}.

AGILE was successfully launched on April 23 2007 from Satish Dhawan Space Centre (India) on a PSLV-C8 rocket. The AGILE orbit is quasi-equatorial, with a 2.5 degrees inclination and an average altitude of 535 km.
2. The Mini-Calorimeter instrument

2.1. Design
MCAL has been designed with stringent constraints, mainly concerning detector geometry, mass and power budget. The detector is designed to provide also information on particles produced in the tracker after gamma-ray interactions, so it must be located below the ST and have the same footprint. The weight constraints put limits on the detector thickness, and the power budget allocated constrained the overall architecture and front-end electronics.

MCAL is composed of 30 CsI(Tl) scintillator bars each one 15x23x375 mm$^3$ in size, arranged in two orthogonal layers, for a total thickness of 1.5 radiation lengths. In a bar the readout of the scintillation light is accomplished by two custom PIN Photodiodes (PD) coupled one at each small side of the bar. A permanent optical coupling between PDs and CsI is made by means of a clear siliconic resin; that medium has been chosen to realize an elastic bond between two components that exhibit a quite different thermal expansion coefficient. To maximize the light output and to keep the light attenuation inside the bar within an optimal range of values, the bars surfaces have been polished and the bars have been first wrapped with a reflective coating [10] and then by a thin adhesive layer. Each bar is then arranged inside a carbon fiber structure, about 1 mm thick, that provides rigidity and modularity to the detectors. For each bar the PDs signals are collected by means of low noise charge preamplifiers, and then conditioned in the Front End Electronics, (FEE). For each bar, the energy and the position of interaction of either a gamma-ray or ionizing particle can be evaluated combining the signals of the two PDs. The detection plane is hosted in the upper part of MCAL main frame; the preamplifiers are arranged in four boxes on each side of the detection plane and at its same level. Below the detection plane is placed the FEE board that has the same area of the whole detection plane. The overall mechanical envelope of MCAL constitutes the lower part of the whole AGILE payload. Figure 1 shows the integrated MCAL during test benches, prior to integration in the AGILE payload. The upper layer of the detection plane and two preamplifiers boards are clearly visible. Table 1 reports the main MCAL engineering characteristics and scientific performance.

2.2. Operative modes
MCAL works in two operative modes:
- in GRID mode a trigger issued by the ST starts the collection of all the detector signals
Table 1. MCAL engineering characteristics and performance

| Detector property                  | Measured value |
|-----------------------------------|----------------|
| Active detector weight            | 20 kg          |
| On-axis geometrical area          | 1400 cm²       |
| Number of independent detectors   | 30             |
| Single detector dimensions        | $15 \times 23 \times 375$ mm³ |
| Detector light output             | $21 \pm 1$ e⁻/keV |
| Detector attenuation coefficient  | $0.028 \pm 0.002$ cm⁻¹ |
| Total power consumption           | < 6 W          |
| Electronic noise / channel        | < 1000 e⁻ RMS  |
| Energy resolution                 | 14% FWHM at 1.275 MeV |
| Position resolution               | 18 mm at 1.275 MeV |
|                                  | 7 mm at 11 MeV  |
| Timing accuracy                   | 2 µs           |
| BURST mode energy range           | 0.33 - 110 MeV (near PDs) for each bar |
| GRID mode energy range            | 1 - 100 MeV (near PDs) for each bar |
| Effective area                    | ∼200 cm² at 0.4 MeV on axis |
|                                  | ∼300 cm² at 1 MeV on axis |
| Field of view                     | ∼ 4π sr, non imaging |

...in order to determine the energy and position of particles converted in the tracker and interacting in MCAL;

- in BURST mode each bar behaves as an independent self triggering detector and generates a continuous stream of information of gamma events in the energy range 300 keV - 100 MeV. In the data handling system these data are used to detect impulsive variations in count rate. If a valid burst trigger is issued by the trigger logic, described in subsection 2.3, data are collected and stored in telemetry on a photon-by-photon basis. This means that for every photon the pulse height of both photodiodes of every triggered bar and an absolute time tag with 2 µs accuracy are available for analysis, so that energy and time binning are limited by counting statistics only.

Both operative modes can be active at the same time. Due to telemetry limitations BURST data are not sent on ground on a photon-by-photon basis unless a trigger for a transient is issued by a dedicated trigger logic. However BURST data are used to build a broad band energy spectrum (Scientific RateMeter, SRM) recorded and stored in telemetry every second. Scientific ratemeters provide information on the high energy gamma-ray background in space and its modulation through orbital phases. SRMs are organized in 11 bands for each of the two MCAL detection layers. An event’s assignment to one of the energy bands is based on the most significant bit of the energy binary word. This assignment policy is straightforward from the computational point of view and also defines the energy bands. The first useful band includes events between 0.18 and 0.35 MeV, the second band between 0.35 and 0.7 MeV, the third is between 0.7 and 1.4 MeV and so on until the last band which includes events with energy higher than 180 MeV.

2.3. Trigger logic

In the PDHU a dedicated trigger logic[11] is implemented to detect gamma-ray bursts (GRBs) and other impulsive events. The trigger algorithm is based on the assumption that bursts are phenomena producing count rates above a threshold determined by the current background value. Since the burst signal is strongly energy and timescale dependant, the crucial first
The task of the Burst Search (BS) software algorithm is the formation of several background ratemeters (RMs). These are evaluated integrating events on different time windows called Search Integration Times (SITs). SITs can be handled by Hardware (Sub-millisecond, 1 and 16 ms SITs) or by Software (64, 256, 1024 and 8192 ms SITs). The RMs are generated depending on the detector, the events energy and position of interaction. For each of the 7 SITs, 9 RM are evaluated covering three ranges of energy: from 0.3 to 0.7 MeV (Low Energy, LE), from 0.7 to 1.4 MeV (Medium Energy, ME), and above 1.4 MeV (HE). The limits of the ranges are fully configurable. Events in the first two energy ranges contribute to generate different RMs depending on the place of interaction on MCAL; in this case MCAL is divided into four zones (two zones for each detection layer). The HE events contribute to a single RM, regardless the position of interaction. A partial trigger can be generated independently for every RM and for every SIT. After one or more partial triggers are issued, a validation step takes place by means of a programmable Look-Up Table (LUT) aimed at spurious trigger rejection. With current configuration a valid trigger is issued when at least two coincident partial triggers on different ratemeters are issued.

Figure 2 shows the partial and rejected counters for a real GRB triggered on 3 March 2008. The trigger has been issued after the generation of two coincident partial triggers on the 8.192 s SIT, on the low-energy ratemeters of the bottom detection layer spatial zones.
3. In-flight performance

The scientific payload was switched on at the beginning of May 2007 and the commissioning phase lasted up to the end of June. During this phase the MCAL front-end configuration was tuned, the main task regarding the threshold setting. The average energy threshold was brought successfully from 650 keV, the on-board preset value for safety reasons, to about 330 keV, the expected final value. The threshold for each bar has been set independently in order to minimize the overall energy threshold but avoid triggers on electronic noise. A front-end configuration equivalent to the best one employed on ground was found to be stable and reliable. From early July to October 2007 the Science Verification Phase (SVP) took place, with activities mainly dedicated to in-flight calibration of the GRID and SuperAGILE instruments. During this period, for programmatic reasons, the MCAL on-board trigger logic was not activated. The trigger logic activation and tuning was carried out in November 2007, for time windows greater or equal than 64 ms, and finally switched on with the nominal configuration since the beginning of February 2008. During June 2008 another session dedicated to the MCAL trigger logic tuning has been successfully carried out, aimed at the configuration of the burst search algorithm on the 16 ms, 1 ms and sub-millisecond time windows.

The payload functional monitoring is carried out by means of housekeeping (HK) data. Several hundreds HK are collected and stored in a dedicated telemetry packet every 16 seconds. HK data include power supply voltages, input currents, reference voltages, basic ratemeters, configuration digital registers, detector and electronics temperature, and allow a complete monitoring of the health status of the payload and spacecraft’s systems. The average detector temperature ranges between 4 and 8°C, with a typical variation of about 0.3 °C on the time scale of one orbit.

The in-flight background is monitored by means of the scientific ratemeters data, SRM, described in section 2.2. The background level above 330 keV has an average value of about 200 counts/s for each of the two detection layers, with a variation of about 20% along the orbit excluding the SAA passage. During the SAA passage SRM are acquired as well, but the effective background level is masked by the high increase in dead time due to the high count rate in the anti-coincidence panels that causes a significant depletion of SRM counts for the deepest passages.

4. Gamma-ray bursts detection with MCAL

4.1. Detection capabilities

AGILE has the study of GRBs among its main scientific targets. SuperAGILE, as well as MCAL, is equipped with an on-board trigger logic. Moreover, a localization algorithm provides GRB positions with few arcmin accuracy for events in the SuperAGILE field of view, allowing rapid dissemination of the coordinates ([12]). The GRID has a wide field of view that makes it a valuable instrument for GRB detection in the poorly explored 30 MeV-50 GeV energy band. A simultaneous GRB detection with GRID, MCAL and SuperAGILE would allow a spectral coverage over six orders of magnitude.

With respect to GRB detection, MCAL strength points are mainly the good effective area in the MeV range, the microsecond timing accuracy for triggered events and the flexible trigger logic. The weak point is the quite high energy threshold (330 keV). MCAL is so tailored to the detection of medium-bright GRBs with peak energy above few hundreds keV.

Several GRB detectors are currently active in space, each with its own specific characteristics. Apart from Swift-BAT ([13]), INTEGRAL-IBIS ([14]), SuperAGILE ([5]) and GLAST-GBM ([15]), all the other detectors have no or very limited imaging capabilities and rely on triangulation between different spacecrafts for GRB localization, by means of the 3rd Inter-
Planetary Network (IPN). Among the current IPN instruments, only three have spectroscopic capabilities at MeV energies, in an energy range partially overlapping with that of MCAL: Konus-Wind ([16]), Suzaku-WAM ([17]) and RHESSI ([18]). Among these, only the RHESSI spectrometer is capable of photon-by-photon data download. Also GLAST-GBM, supposed to join the IPN too, have both spectral capabilities in the MeV range and photon-by-photon data download for triggered events.

Despite MCAL has no (or very limited) directional capabilities it can act as a sentinel for GRB search in the GRID energy range, since a GRB detectable above 50 MeV is expected to be bright in the MCAL range. So, the fluence observed in the MCAL range provides a preliminary ranking of the GRB and a hint of the likelihood for a GRB to be detected in the GRID. On 14th May 2008 MCAL and SuperAGILE triggered GRB 080514B [19], which was also detected by the GRID above 50 MeV [20]. This event is the first GRB detected above 50 MeV after the five events detected during the nineties by the EGRET instrument on-board the Compton Gamma-Ray Observatory (CGRO), and is the subject of a dedicated paper in preparation.

4.2. GRB detections

Between 22nd June 2007 and 30th June 2008 MCAL detected 51 GRBs, with an average detection rate of about 1 GRB/week. Most of these detections have been independently confirmed by other instruments. Only 16 events have been localized, either by Swift, SuperAGILE or the IPN. Since most of the MCAL events have been also detected by other IPN instruments ([21]) the number of IPN localizations is expected to grow when the IPN catalogues will be available. The detection rate is in good agreement with the sensitivity estimations reported in [22].

Several GRBs have been detected at off-axis angles greater than 90°, with the record being the bright GRB071020, localized by Swift ([23]), detected at 166° off-axis, i.e. coming almost from a direction opposite to the AGILE pointing. Despite for > 90° events it is difficult to provide reliable spectral information, due to the still incomplete modeling of the spacecraft shell with Monte Carlo simulations ([24, 25]), it demonstrates the MCAL all-sky detection capabilities.

Figure 3 shows the light curves for a GRB triggered on 3rd March 2008 at 21:34:37 UT. Both the light curve from SRM data for one of the detection layers, and the light curves in different energy bands obtained from photon-by-photon data are shown. The plot clearly points out the difference in the performance that can be achieved with SRM and photon-by-photon data, mainly concerning energy and time resolution. Before the permanent activation of the trigger logic in February 2008, 28 GRBs have been detected by scanning on-ground SRM data by means of a dedicated software task, but the scientific exploitation of these events is limited by the coarse time and energy binning. A detailed description of the first year of GRB detections with MCAL is reported in [26].

5. Conclusions

The MCAL design was limited by stringent constraints concerning geometry, weight and power consumption, but a clever architecture and a flexible trigger logic for transient events were implemented in order to exploit the instrument possibilities at best. MCAL main characteristics are its spectral capabilities in the MeV range and the photon-by-photon data download with microsecond timing accuracy for triggered events; very few instruments currently operating in space have these characteristics. The instrument in-flight performance are stable and nominal.

Between 22nd June 2007 and 30th June 2008 MCAL detected 51 GRBs, with an average detection rate of about 1 GRB/week. Moreover MCAL can work as a sentinel for the GRID, as actually happened for the detection of GRB 080514B. Since the end of June 2008 the trigger logic on the sub-millisecond, 1 ms and 16 ms time windows has been switched on and configured. The

---

1 IPN web page: http://www.ssl.berkeley.edu/ipn3/
Figure 3. Light curves for the GRB triggered on 3rd March 2008 at 21:34:37 UT. Top panel: scientific ratemeters for the upper detection layer (plane X) with 1.024 s time bin. Other panels: light curves in three energy bands from photon-by-photon data with 64 ms time bin.
analysis of triggers on such short time-scales is in progress. Cross-calibration activity with the Konus-WIND instrument, which is mandatory to fully exploit the MCAL spectral capabilities, is in progress as well.

Acknowledgments
AGILE is a mission of the Italian Space Agency, with co-participation of INAF (Istituto Nazionale di Astrofisica) and INFN (Istituto Nazionale di Fisica Nucleare). The authors wish to thank all the AGILE team for their help and fruitful discussions. The authors wish to thank also the industrial partners, namely the AGILE people at Thales-Alenia Space Italia, Carlo Gavazzi Space and Telespazio, for their fundamental contribution to the construction, integration, testing and in-flight operation of MCAL. Kevin Hurley, Valentin Pal'shin and Kazutaka Yamaoka are greatly acknowledged for fruitful discussions and IPN support.

References
[1] Tavani M et al. 2008 Nucl. Instr. and Meth. A 588 52–62
[2] Tavani M, Barbieriini G, Argan A et al. 2008 submitted to Astronomy and Astrophysics
[3] Barbieriini G et al. 2001 GAMMA 2001: Gamma-Ray Astrophysics 2001, AIP Conference Proceedings Volume 587 pp 754–758
[4] Prest M et al. 2003 Nucl. Instr. and Meth. A 501 280–287
[5] Feroci M, Costa E, Soffitta P et al. 2007 Nucl. Instr. and Meth. A 581 728–754
[6] Labanti C et al. 2006 proceedings of SPIE 6266 62663Q
[7] Labanti C, Marisaldi M, Fuschino F et al. 2008 submitted to Nucl. Instr. and Meth. A
[8] Perotti F et al. 2006 Nucl. Inst. and Meth. A 556 228–236
[9] Argan A et al. 2004 Conference Record of the IEEE Nuclear Science Symposium, October 16-22, 2004, Rome, Italy pp 371–375
[10] Weber M, Stover C, Gilbert L, Nevitt T and Ouderkirk A 2000 Science 287 2451–2456
[11] Fuschino F, Labanti C, Galli M, Marisaldi M, Bulgarelli A, Gianotti F, Trifoglio M, Argan A, Del Monte E, Donnarumma I, Feroci M, Lazzarotto F, Pacciani L, Tavani M and Trois A 2008 Nucl. Instr. and Meth. A 588 17–21
[12] Del Monte E, Costa E, Di Persio G et al. 2007 proc. of SciNeGHE 2007, Frascati Physics Series 45 201–208 arXiv: 0712.1548
[13] Barthelmy S D et al. 2000 Proc. SPIE 4140 50
[14] Ubertini P, Lebrun F, Di Cocco G, Bazzano A et al. 2003 Astronomy & Astrophysics 411 L131–L139
[15] Meegan C, Bhat N, Connaughton V et al. 2007 AIP Conf. Proc. 921 13
[16] Aptekar R L, Frederiks D D, Golenetskii et al. 1995 Space Science Reviews 71 265–272
[17] Yamaoka K, Sugita S, Ohno M et al. 2006 Proc. SPIE 6266 153
[18] Wigger C, Hajdas W, Smith D M et al. 2004 Nucl. Phys. B Proc. Suppl. 132 331–334
[19] Rapisarda M et al. 2008 GRB Coordinates Network 7715
[20] Giuliani A et al. 2008 GRB Coordinates Network 7716
[21] Hurley K 2008 private communication
[22] Ghirlanda G, Galli M, Longo F et al. 2004 AIP Conf. Proc. 727 704–707
[23] Holland S T, Barthelmy S D, Baumgartner W H et al. 2007 GRB Coordinates Network 6949
[24] Longo F, Cocco V and Tavani M 2002 Nucl. Instr. and Meth. A 486 610
[25] Cocco V, Longo F and Tavani M 2002 Nucl. Instr. and Meth. A 486 623
[26] Marisaldi M et al. 2008 submitted to Astronomy and Astrophysics