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Detection of Gamma-Ray Bursts with the AGILE MCAL

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Abstract The new onboard AGILE MiniCalorimeter (MCAL)-Gravitational Waves configuration increased the detector trigger capabilities for short duration high-energy transients, such as short duration Sub-Theshold Events (STEs), as well as short Gamma-Ray Bursts (GRBs). Aim of this change was the improvement of the satellite trigger logic, in order to make AGILE more competitive in the detection of possible electromagnetic counterparts to gravitational waves detected by the LIGO/Virgo experiments. At the moment, a new pipeline system has been established, running an automatic search algorithm, aimed at processing the MCAL data, searching for GRB and STE signatures, promptly distributing data to the AGILE Team, for more advanced off-line analysis. The new MCAL-GW configuration substantially improved the detection capabilities of MCAL, leading to the detection of 52 GRBs and more than $2 \cdot 10^4$ STEs.

Keywords gamma-ray burst · sub-threshold events · high-energy

1 Introduction

1.1 Gamma-Ray Bursts

Gamma-Ray Bursts (GRBs) are extra-galactic gamma-ray emissions, serendipitously discovered in 1967 by the Vela satellites [1], and later investigated by a number of high-energy astrophysics space missions. GRBs constitute the most energetic phenomenon observed in the universe, releasing isotropic energies up to $> 10^{51}$ erg, detected in a wide range of wavelengths. These bursts are classified on the basis of their T_{90} time duration (i.e., the time over which the

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central 90% of the total fluence is released), as long GRBs, with $T_{90} > 2$ s, and short GRBs, with $T_{90} < 2$ s. Moreover, long GRBs usually exhibit rather softer spectra with respect to short GRBs, due to the different nature of the related progenitors: long GRBs are produced by the collapse of Type Ic core-collapse supernovae [2], whereas short GRBs have been recently directly confirmed as the result of Binary Neutron Stars (BNS) [3–5], and are thought to be released by Neutron Star – Black Hole systems (NS–BH) as well [6–8]. On the other hand, Sub-Threshold Events (STEs) represent weak short duration transients, usually not triggering the on-board detection logic and identified by off-line algorithms: in the era of multimessenger astronomy, these sub-threshold triggers should be carefully evaluated, as they can represent the signatures of high-energy transients of astrophysical interests.

1.2 The AGILE MCAL and the MCAL-GW configuration

The AGILE MiniCALorimeter (MCAL) [9] is a all-sky non-imaging detector, sensitive in the 400 keV – 100 MeV energy range, composed of 30 CsI(Tl) scintillation bars organized into two orthogonal planes, providing a total on-axis geometrical area of 1400 cm^2. The calorimeter can act as a trigger for the AGILE Silicon Tracker (ST), or work independently, self-triggering transient events and acquiring high time resolution data as time-tagged events with a time resolution of 2 μs.

The on-board trigger logic includes 7 independent timescales, spanning five orders of magnitude, from 293 μs to 8.192 s. These timescales are managed by hardware and software trigger logics, depending on the count rate threshold required to start the data acquisition. The hardware logic is ruled by fixed count thresholds and is more sensitive to short duration transients, as it makes use of the [0.293 ms, 1 ms, 16 ms] timescales; on the contrary, the software logic sets the count thresholds by dynamically evaluating the background rate and is more sensitive to long-duration transients, as it makes use of the [64 ms, 256 ms, 1,024 ms, and 8,192 ms] timescales.

Data regarding a transient are then stored in a cyclic buffer, together with settable pre- and post-burst data acquisitions aimed at investigating the previous and successive time intervals, whose duration depends on the triggered timescale. The trigger logic is extremely flexible: all logic parameters (background estimation time, threshold, pre- and post-burst time acquisition) are fully configurable from ground by uploadable telecommands.

Starting August 2016, MCAL is running the so-called MCAL-GW configuration, constituted by: the inhibition of the Anti-Coincidence (AC) shield veto for the MCAL instrument, already implemented in March 2015 for increasing the detection of Terrestrial Gamma-ray Flashes [10], and a general lowering of the on-board trigger thresholds. In particular, hardware sub-ms, 1 ms, and 16 ms timescales thresholds are set to 7 counts, 8 counts, and 23 counts, respectively, whereas 64 ms, 128 ms, 1,204 ms, and 8,192 ms dynamic software logic timescales thresholds are set to 5σ, 4σ, 4σ, and 4σ, respectively, above

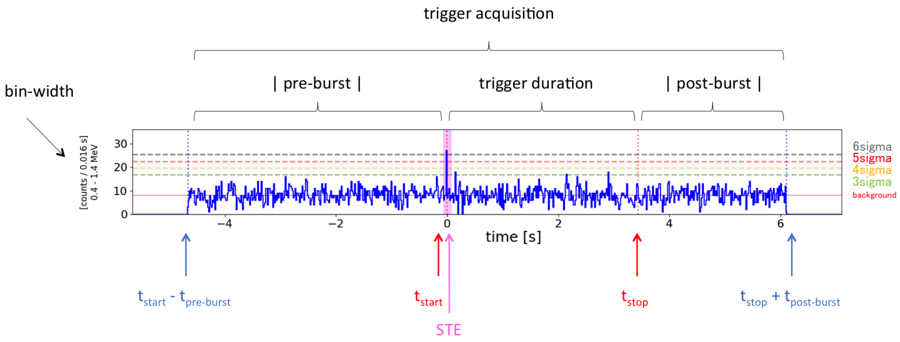

Fig. 1 Example of a MCAL trigger acquisition, for a 6.4σ STE (magenta vertical line), identified by the search algorithm in the 16 ms timescale. The trigger background is represented by the solid red line, together with the corresponding 3σ, 4σ, 5σ, and 6σ thresholds (horizontal dashed lines). Each trigger consists of a central data acquisition, included between a start and stop time (vertical red dashed lines), and an extra pre- and post-burst acquisition to investigate the previous and successive stages of the detected event (vertical blue dashed lines)..

the background rate. In comparison, the previous trigger configuration had logic thresholds of 7 counts, 8 counts, 23 counts, 5σ, 4σ, 4σ, and 4σ, for the sub-ms, 1 ms, 16 ms, 64 ms, 128 ms, 1,204 ms, and 8,192 ms timescales, respectively. Each data acquisition has a different duration that depends on the triggered logic, with hardware triggers lasting ~ 10 s on average and software triggers lasting up to 30–40 s.

In the MCAL-GW configuration, the number of on-board triggers rose from ~ 10 triggers/orbit to ~ 60 triggers/orbit, and about 90% of them is issued on the 16 ms hardware timescale, as it represents the easiest timescale to trigger for a fixed background rate: given a MCAL average background rate of 580 Hz, the 23 counts required to trigger the 16 ms timescale correspond to a 4.5σ signal, which is more easily achieved with respect to the 7 counts and 8 counts required to trigger the 0.293 ms and 1 ms timescales, respectively, corresponding to 16.5σ and 9.7σ signals above the background rate. As hardware trigger acquisitions last on average ~ 10 s and the satellite orbital period is ~ 96 min, MCAL has an average exposure time of > 540 s/orbit, corresponding to $> 10\%$ of the total orbit. On the other hand, the previous MCAL configuration provided a acquisition time ranging between 1% and 5% of the total orbit. As a consequence, this new configuration not only enhances the MCAL trigger capabilities to detect short duration transients, but also increases the instrument exposure time and thus the probability to detect weak events accidentally occurring within the trigger acquisitions. For the sake of completeness, the remaining 10% triggers acquired by the software timescales may last more or less than 10 s, depending on the triggered logic, and do not contribute significantly to the overall evaluation of the MCAL acquisition time.

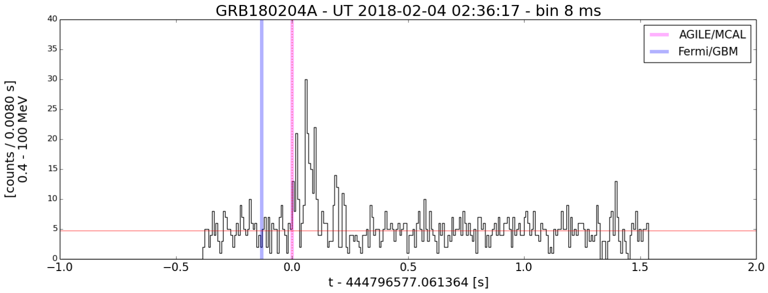

Fig. 2 Example of a short GRB (GRB180204A) detected by MCAL, and represented in a 8 ms timescale. The event, revealed by MCAL at UT 2018-02-04 02:26:17.06 (magenta line), was confirmed as a GRB by the simultaneous detection (i.e., offset of ~ 14 ms) of the Fermi/GBM, occurring at UT 2018-02-04 02:26:16.52 (green line).

In Fig.1, an example of a MCAL triggered data acquisition is shown, issued by a 6.4σ significance STE. The on-board trigger start at $t = 0$ (left red dashed vertical line) and the off-line search algorithm identifies an event (in this case, a STE) at the same time (magenta vertical line). The related background count rate and corresponding 3σ, 4σ, 5σ, and 6σ threshold levels are shown as well (horizontal lines). The total data packet consists of a central trigger acquisition, issued at $t = 0$ and stopped when the stop condition is encountered (right red dashed vertical line), plus two extra pre- and post-burst data acquisitions, aimed at investigating the previous and successive stages of the detected transient (blue dashed vertical lines). Pre- and post-burst durations, as well as the central trigger duration, depend on the logic timescale triggered on-board, as well as by the time profile of the detected event.

2 Detection of GRBs and STEs

MCAL high time resolution data are analyzed by an off-line search algorithm, aimed at identifying gamma-ray transients within each trigger acquisition window. The algorithm searches for short duration transients, by analyzing the trigger light curves in 32 ms and 64 ms timescales, looking for sharp variations in the count rate, or structured time profiles with respect to a stable background rate. At the same time, the algorithm searches STEs as well, looking for single bins in the light curve with high significance ($\geq 6\sigma$) with respect to the background rate, acting on four different timescales (16 ms, 32 ms, 64 ms, and 128 ms), for each of which four time shifts (+0/4, +1/4, +2/4, and +3/4 of bin) are considered. Fig.2 shows an example of a short burst detected by MCAL at UT 2018-02-04 02:26:17.06, and confirmed by the close time association (~ 14 ms) with the GRB180204A detected by the Fermi Gamma-ray Burst Monitor (GBM) at 2018-02-04 02:26:16.52.

Currently, the algorithm automatically runs whenever new MCAL data are delivered to ground. Whenever a GRB candidate or a STE are identified, data

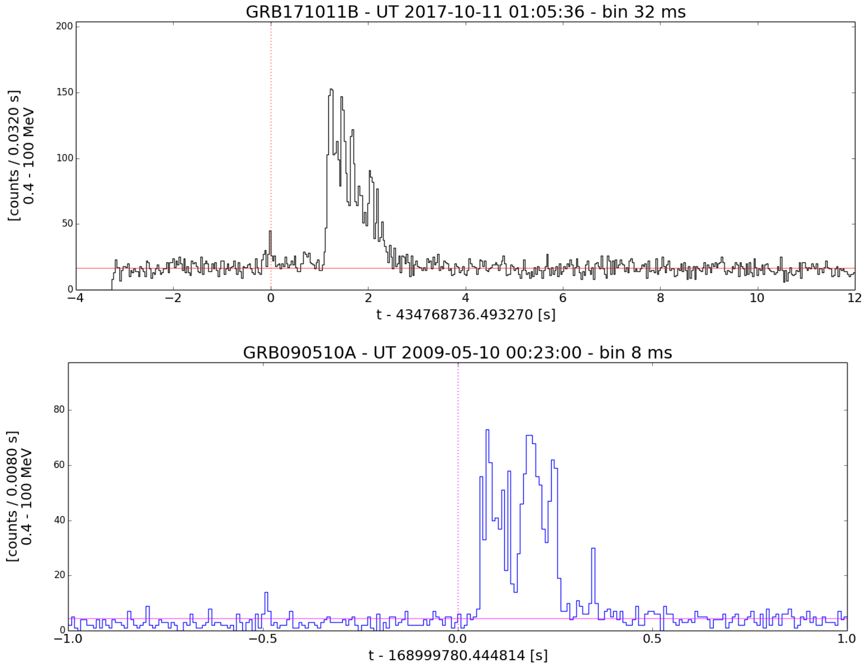

Fig. 3 (a) Short GRB171011B detected in the MCAL-GW configuration, triggered by MCAL on a weak anticipating peak, confirmed by public light curves of other space missions. (b) Short GRB090510A detected in the previous standard configuration, triggered by MCAL on the main prompt phase on-set, and not on the short precursor event, confirmed by other detections. This result highlights the renewed detection capabilities of MCAL for short transients.

are promptly distributed in real time to the members of the AGILE Team, to perform a successive manual analysis. When a GRB is identified by the off-line algorithm, an automatically generated Gamma-ray Coordinates Network / Transient Astronomy Network (GCN/TAN) notice is promptly delivered to the GCN Network community.

In the MCAL-GW configuration period, from 1 August 2016 to 1 June 2018, MCAL was triggered more than $3 \cdot 10^5$ times, collecting a total exposure time of > 1 day. The search algorithm ended up with a total of 52 GRB candidates and more than 26,000 high-significance STEs. The cross-check with the GRB database of the InterPlanetary Nework [14] (IPN web page: *http://www.ssl.berkeley.edu/ipn3/*) found 40 events occurring within ±10 s from our GRB candidates, confirming the astrophysical nature of these events. The remaining 12 unconfirmed bursts may be short GRBs as well, but cannot be solidly confirmed on the basis of MCAL data alone. On the other hand, the cross-check between IPN bursts and our STE sample ended up with no correlations, taking into consideration a coincidence window of ±2 s, in order to reduce the number of expected chance matches.

Among the 40 GRBs detected by MCAL in the 22 months of MCAL-GW configuration, a total number of 10 short GRBs have been detected: this number is compatible with the 9 short GRBs detected in the standard configuration in 2 years [11]. The real improvement of the MCAL-GW configuration is not represented by the number of detected bursts, but by the enhanced trigger capabilities to detect weak and short transients. Fig.3 shows two short GRBs, detected by MCAL: GRB171011B was detected in the MCAL-GW configuration, triggered on an anticipating weak peak episode of the burst (confirmed in public light curves of other missions), whereas GRB090510A, documented as a short GRB with an anticipating precursor [12,13,15], was detected by MCAL in the former less sensitive on-board configuration and was triggered not on the precursor, but on the successive main prompt phase. This represents a confirm of the renewed trigger capabilities of the instrument for the detection of short duration weak gamma-ray transients.

3 Conclusions

Since August 2016, the AGILE MCAL is running the new MCAL-GW on-board trigger configuration, more sensitive to short duration weak transients, aimed at making the satellite more competitive in the detection of electromagnetic counterparts to GW events detected by the LIGO/Virgo experiment. An algorithm has been implemented off-line, to promptly analyze MCAL data, searching for signatures of short gamma-ray events, such as short GRBs and other weaker short sub-threshold triggers. In the 22 months of MCAL-GW configuration, MCAL detected 52 candidate bursts, out of which 40 have been confirmed as real GRBs, by the cross-check with IPN bursts. The renewed detection capabilities of MCAL to short duration events is verified, by considering that a number of short GRBs, detected in the MCAL-GW configuration, were triggered on a weak anticipating peak episode, rather than on the main prompt phase; on the contrary, the previous less sensitive configuration, MCAL was not able to trigger on the anticipating weaker episodes, as in the case of the GRB090510A. Data acquired by MCAL are currently analyzed by an automatic pipeline, aimed at searching for GRBs and STEs in near real time, promptly distributing data to the members of the AGILE Team, and sending automatic GCN/TAN Notices.

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