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Detection of terrestrial gamma-ray flashes with the AGILE satellite

A Ursi[1], M Marisaldi[2,3], M Tavani[1,4], P Sanò[5], D Casella[5] and S Dietrich[5]

[1] INAF-IAPS, National Institute for Astrophysics, Roma, Italy
[2] INAF-IASF, National Institute for Astrophysics, Bologna, Italy
[3] Birkeland Centre for Space Science, University of Bergen, Norway
[4] Department of Physics, University of Roma Tor Vergata, Roma, Italy
[5] ISAC-CNR, Institute for Atmospheric Science and Climate, Roma, Italy

E-mail: `alessandro.ursi@iaps.inaf.it`

Abstract.
Terrestrial gamma-ray flashes are brief submillisecond gamma-ray emissions, produced during thunderstorms and strictly correlated to lightning and atmospheric electric activity. Serendipitously discovered in 1994 by the Compton Gamma Ray Observatory, these elusive events have been further investigated by several missions and satellites devoted to high-energy astrophysics, such as RHESSI, AGILE and Fermi. Terrestrial gamma-ray flashes are thought to be bremsstrahlung gamma-rays, produced at the top of thunderclouds by avalanches of electrons accelerated within thunderstorm strong electric fields and abruptly braked in the atmosphere. Exhibiting energies ranging from few keV up to several tens of MeV, terrestrial gamma-ray flashes are the most energetic phenomenon naturally occurring on Earth and they can represent a severe risk for airplanes and aircraft transports, both for the crew and the on board electronics, that should be carefully investigated and understood.

The AGILE (Astrorivelatore Gamma ad Immagini LEggero) satellite is an entirely Italian mission, launched in 2007 and still operational, aimed at investigating gamma-ray emissions from cosmic sources. The wide energy range and the unique submillisecond trigger logic of its on-board instruments, together with the narrow quasi-equatorial orbit of the spacecraft, make AGILE a very suitable instrument to detect and investigate terrestrial gamma-ray flashes. Recent improvements rose up the terrestrial gamma-ray flashes detection rate and lead to the observation, for the first time, of multiple events occurring within single thunderstorm processes.

1. Introduction

Terrestrial Gamma-ray Flashes (TGFs) are brief and intense gamma-ray emissions coming from the lower part of terrestrial stratosphere ($\sim$ 15 km a.s.l.), strictly correlated with thunderstorms and atmospheric electric activity. All observed TGFs exhibit durations from tens of microseconds to few milliseconds and energies ranging from few MeV to several tens of MeV. TGFs take place at high altitudes, at thundercloud tops, making them very difficult to observe directly from the ground, due to the gamma-ray absorption in the high-density lower atmospheric layers: hence, despite being a completely terrestrial phenomenon, the only way to study these elusive objects is from space, by using high-energy detectors placed on-board satellites for astrophysics, on-board the International Space Station or on-board airplanes and stratospheric balloons. As space experiments specifically dedicated to TGFs are yet to come, most of the studies about this phenomenon have been carried out by using high-energy astrophysics satellites. TGFs are a sort of borderline phenomenon between atmospheric physics and astrophysics, representing a really attractive challenge for both the scientific fields.

TGFs were unexpectedly observed for the first time in the early 90s by the BATSE experiment [1], one of the four main instruments on-board the Compton Gamma-Ray Observatory, and subsequently more deeply investigated by the NASA Reuven Ramati High-Energy Solar Spectroscopic Imager (RHESSI). In the last seven years, wide contributions to their study have been brought by the AGILE and by the Fermi space telescope. Since the beginning, almost all of the observed events took place within the same geographic region (i.e., within the tropical region and over the continents) and the same time interval (i.e., mostly in the afternoon) of a thunderstorm, suggesting a correlation between the two phenomena, as shown in Fig. 1. Successive investigations pointed out that individual radio atmospheric Extremely Low Frequency and Very Low Frequency waves, briefly called sferics, which represent a sort of electromagnetic signature of lightning strokes, were associated with TGFs, highlighting a direct correlation between TGFs and the single lightning discharges of a thunderstorm.

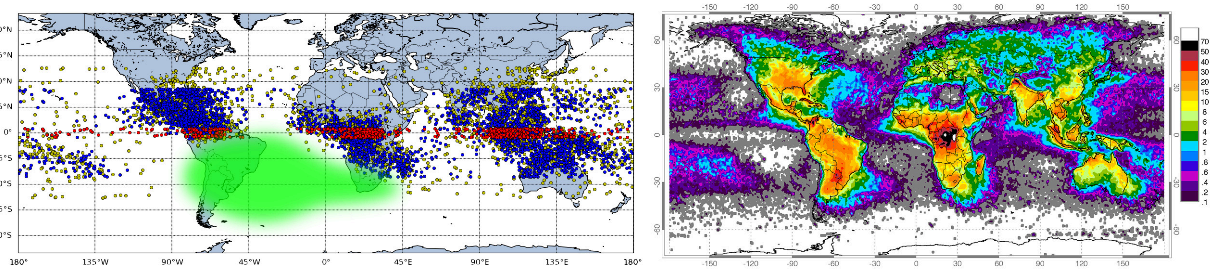

Figure 1. (a) Geographic distribution of all TGFs detected by BATSE (yellow), RHESSI (green), AGILE (red) and Fermi (blue). The green region corresponds to the South Atlantic Anomaly, where the enhanced charged particle background prevents any detection. (b) Lightning rate distribution acquired by the NASA Lightning Imaging Sensor.

The production mechanism of these events is still matter of debate. To date, the most accepted hypothesis suggests the upper part of Earth's troposphere behaves as a particle accelerator, under thunderstorm conditions: free electrons in air can be accelerated to relativistic energies by these intense electric fields and produce hard X- and gamma-rays via a bremsstrahlung process, against atoms and nuclei in the atmosphere. If the thundercloud electric field is strong enough, a huge number of electrons can reach ionization energies, producing secondary electrons, which may undergo the same acceleration process, giving rise to an avalanche process of so-called runaway electrons, named Relativistic Runaway Electron Avalanche [2]. Such a model needs an external seed, to initiate a process, such as a cosmic ray or some other energetic particle coming from outside the system. Nevertheless, two alternative mechanisms have been proposed, both providing avalanche processes without the necessity of external seeds: the Thermal Breakdown and the Relativistic Feedback [3,4]. These models require very strong electric fields and large avalanche distances, that make them impossible to be reproduced in laboratories, but not so hard to be achieved in typical thunderstorm conditions (especially near the lightning source region).

2. The AGILE satellite

AGILE is a mission of the Italian Space Agency, with coparticipation of the Istituto Nazionale di Astrofisica and the Istituto Nazionale di Fisica Nucleare, together with several Italian research Institutes, Universities and industrial partners [5]. A schematic view of AGILE is given in Fig. 2. The satellite was launched on 23 April 2007 from the Satish Dhawan Space Center (India) on a PSLV-C8 rocket and delivered into a low-inclination (2.5°) orbit, at 540 km altitude: the orbit was chosen near-equatorial in order to undergo a reduced background, being the lowest inclination orbit ever achieved by a high-energy astrophysics mission, to date. The nominal scientific observation started December 1st 2007. Aim of the AGILE program is to provide very effective detection and imaging capabilities, both in the hard X- and gamma-ray energy range [18 keV ÷ 50 GeV], providing coverage of the > 100 MeV window, left unobserved for 7 years after the end of the EGRET mission, in 2000. The AGILE energy range, together with an excellent timing resolution and large field of view, allows to investigate high-energy emissions from cosmic sources: main targets of the mission are compact objects, active galactic nuclei, galactic molecular clouds and gamma-ray bursts, soft gamma-ray repeaters, pulsars and pulsar wind nebulae, supernova remnants, the Galactic center and TeV sources, providing a diagnostic of particle acceleration and radiation processes in extreme conditions. The AGILE program and scientific objectives partially overlap and are complementary to those of other high-energy astrophysics missions (CHANDRA, INTEGRAL, RXTE, XMM-Newton, SWIFT, SUZAKU, RHESSI and the Fermi space telescope) and ground-based instrumentation (radio telescopes, optical observations and TeV observatories), providing fast response to new detected gamma-ray transients and alert for multiwavelength observations. Quicklook data analysis, rapid reaction and fast communication of new high-energy transients is a crucial part of the AGILE program and one of the key assets of the mission.

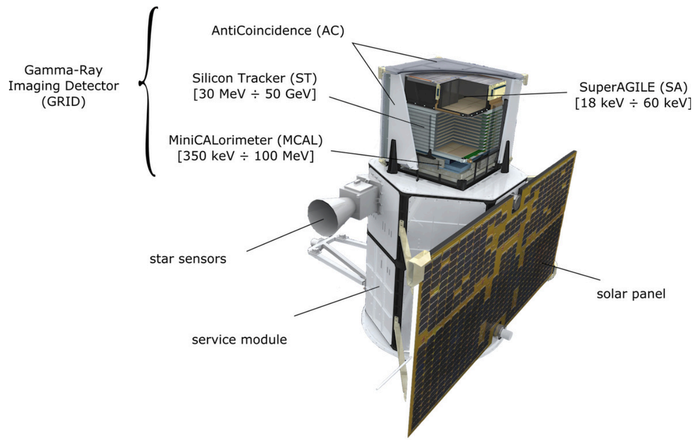

Figure 2. Schematic view of the AGILE satellite and its the scientific instruments and electronics: a silicon tracker, a minicalorimeter, a coded mask detector and an anticoincidence module, plus an on-board data handling unit.

3. The AGILE TGF detection algorithm

AGILE turned out to be a very suitable satellite for the detection of TGFs. Most of the events are detected by its MiniCALorimeter (MCAL) instrument, as its on-board trigger logic works on different trigger timescales, consisting in four dynamic software logics (8 s, 1 s, 256 ms, 64 ms) and three static hardware logics (16 ms, 1 ms, 293 μs): given the shortness of TGFs, most of the detected events are observed in the 293 μs and in the 1 ms time windows. The hardware logics do not depend upon the background variation and require a settable fixed threshold, kept as low as possible, to increase the detection efficiency. A large number of triggers in the submillisecond and in the 1 ms logics are produced by electronic noise in the instruments, affecting the detection: as a consequence, in order to be classified as genuine TGFs, the triggered events are carefully analyzed, by means of an off-line selection strategy. For each trigger acquisition, whose duration depends on the trigger logic and has been modified several times during the mission lifetime, due to telemetry requirements, all photon-by-photon data are scanned by means of a 1 ms dynamic time window: whenever a count is encountered, a secondary 300 μs wide time window is opened, starting from the count time. If at least 6 counts fall within this second time window, the count group is defined as a cluster, providing a preliminary estimate of the TGF duration. At this point, a selection algorithm is applied, that selects all clusters fulfilling the following requirements: on-board trigger fired is within 20 ms from the count cluster start time, a total number of counts $N \geq 9$, a hardness ratio HR ≥ 0.5 (with HR defined as the ratio between the number of counts with $E \geq 1.4$ MeV over the number of counts with $E < 1.4$ MeV), at least one count is released in each half MCAL detection plane and a maximum photon energy of 30 MeV.

This technique allows to reject spurious triggers, due to charged particles releasing counts in the MCAL planes or due to electronic noise, not requiring a successive visual inspection. This procedure allowed the publication of the first AGILE TGF catalog [6], consisting in 308 events, acquired in about 28 months of observation and available online at *http://www.asdc.asi.it/mcaltgfcat/*. The reliability of the obtained TGF sample is shown by the typical geographic pattern of the detected events, clustering over land regions, and by the local time distribution, that reflects the lightning activity: a relaxing in the algorithm selection criteria translates into a contamination of the selected sample, with both the TGF spatial and time distributions smoothed towards more uniform pattern, due to a probable contamination by erratic events, such as cosmic rays and electronic noise in the instruments.

4. Detection of high-energy TGFs

The cumulative energy spectrum of 130 TGF events, satisfying all the illustrated selection criteria, but no constraints on the photon energy, showed a high-energy spectral component, besides the well-known power law [7]: this component exhibits no exponential attenuation and extends up to 100 MeV, challenging the current accepted models for the TGF production mechanism.

5. Localization of TGFs

The AGILE satellite is the only mission that performed localization of TGFs, by means of an imaging instrument [8]: events have been searched with the Gamma-Ray Imaging Detector (GRID), sensitive between 30 MeV and 50 GeV, in correspondence (within 200 ms) to TGFs detected by the MCAL instrument. By considering a set of 119 TGFs, a total of 8 correspondences was obtained. The GRID photon directions are obtained by exploiting the standard analysis for gamma-ray photons in the AGILE field of view and are localized with an accuracy of $5° - 10°$, at 50 MeV. All events turned out to be completely compatible with a terrestrial incoming direction, from a production site close to the satellite footprint less than 400 km. The AGILE silicon tracker detected events provide both the first direct localization from space of TGFs and an evidence that these phenomena emit a significant fraction of their energy in the energy range well-above 20 MeV.

6. Enhanced detection of TGFs

A common issue affecting all TGF detectors is dead time, given the large fluence (~ 0.1 ph cm^{-2}), released in a very short timescale. During dead time, an instrument is busy in processing previous events and not sensitive to successive input pulses: such an effect increases with the event rate to which it is exposed. For what concerns AGILE, MCAL detections of TGFs were heavily affected by dead time, mostly induced by the AC (Anti-Coincidence) units, aimed at rejecting signals due to background charged particles, preventing as well the detection of events with duration shorter than $\sim 100\ \mu$s. The net result is, the time distribution of the AGILE TGFs is biased toward longer values, with respect to other satellites: the $\sim 100\ \mu$s average time duration observed by RHESSI and Fermi is shifted to about 300 μs for the AGILE sample, preventing the finding of correlated radio sferics [9,10]. A new enhanced configuration was set, by disabling the AC veto for the MCAL, maintaining the same selection criteria used in the previous catalog: the enhanced configuration increased the TGF detection rate of about one order of magnitude, allowing the observation of $60 \div 70$ TGFs per month and of events with shorter durations (down to few tens of μs) and the finding of 39 simultaneous sferics, detected by the World Wide Lightning Location Network, occurring within $\pm 200\ \mu$s from the associated event [11]. The absence of the AC veto also increased the number of spurious triggers, but the selection criteria adopted in the algorithm ensure the reliability of the new TGF sample, whose phenomenological features (geographic and local time distribution) are consistent with the TGF sample collected in the previous standard configuration. The high detection rate of events, concentrated within a narrow equatorial latitude belt, provides a large number of TGFs observed per unit area and per unit time: this constitutes a unique large TGF data set, unbiased by dead time effects, which can be exploited for understanding the relationship between TGFs and lightning activity and to test theoretical production models.

7. The AGILE TGF meteorological pipeline system

A fast-processing pipeline system was recently established for AGILE, aimed at retrieving meteorological data acquired by geostationary meteorological satellites and at reconstructing the meteorological scenario associated to the regions where the events occurred. All meteorological data are continuously downloaded from the EUMETSAT portal and stored into a 1 week buffer memory at the Istituto di Scienze dell'Atmosfera e del Clima in Rome: this allows the investigation of the initial stages of the evolution of the thunderstorm associated to the TGF, together with its on-set and successive development. The products processed by the pipeline are particularly aimed at highlighting the presence of convection in the atmosphere, by means of cloud top altitude estimates and of dedicated algorithms, such as the severe storm RGB composite or the Global Convective Diagnostics (GCD). Data from other non-geostationary satellites, microwave sensors and lightning detection networks can be implemented in the pipeline in a successive moment. By exploiting this pipeline and the associated meteorological archive, it is possible to perform both precise studies on individual events and associated storms, as well as statistical analyses on large scale samples. This data archive can be made available to the community in the near future and could help shedding light on the thunderstorm type, stage and degree of association correlated to the TGF production.

8. Detection of multiple TGFs from thunderstorms

A strong point of the AGILE satellite relies in its quasi-equatorial orbit, which represents a unique feature among the satellites currently detecting TGFs: such a low inclination allows AGILE to monitor the same geographic region at each orbital passage, without experiencing significant latitudinal shifts and making the satellite able to observe a large number of multiple TGFs from the same convective region, even at successive overpasses. The study of the waiting times distribution between successively detected events highlighted repeated enhancements, corresponding to the same passage and to each of the following orbital resonances. Such feature made the AGILE satellite observe 79 cases of convective systems producing multiple TGFs, in the period from March 2009 to November 2015: in particular, 28 of these systems produced more TGFs, detected by AGILE during the same passage, and 51 of these systems lasted several hours, producing events detected up to 4 overpasses after. Moreover, 3 mixed cases of repeated TGFs from the same thunderstorm system detected either during the same passage and at successive passages have been observed. Meteorological images acquired by geostationary satellites included in the AGILE meteo-retrieving pipeline show the presence of convective systems in the region of interest, frequently lasting several hours, in order to produce more TGFs detected at successive passages. The underlying thunderstorms exhibited very different extensions and structures, suggesting there are no privileged types of thunderstorm for TGF production, as already pointed out by previous studies [12-14]. A statistical study on the variation in time of the GCD algorithm in the region of interest was carried out: the cumulative distribution of the multiple TGFs occurrence times shows that these events tend to take place in the leading part of the thunderstorm development, when the system is increasing its height and size. This not only represents a further confirmation of the efficiency of the AGILE satellite as a TGF detector, but it is also the first reported evidence that single thunderstorm systems can produce multiple TGFs throughout their entire lifetime.

9. Conclusions and future perspectives

After almost 10 years since its launch, AGILE is still capable of producing high-quality scientific results, representing a successful and still promising mission both for high-energy astrophysics and geophysics. TGFs have driven an increasing attention from the scientific community, for their still poorly understood meteorological contest and their possible source of danger for planes flying nearby their production region; moreover, the small number of missions currently detecting these events make TGF science even more challenging. In this perspective, the AGILE satellite plays a major role: the recently increased TGF detection rate makes AGILE the mission with the highest TGF detection rate to date and the recently established meteorological pipeline allows for the development of a wide database of high-quality data, that can be exploited to perform improved analyses on the relationship between TGFs and other meteorological parameters, as well as to test the current theoretical production models. Finally, the narrow equatorial orbit of AGILE puts the satellite in a privileged condition, for what concerns the observation of repeated TGFs, produced by the same thunderstorm, further underlining the connection between these events and lightning discharges.

Acknowledgments

AGILE is a mission of the Italian Space Agency, with coparticipation of the Istituto Nazionale di Astrofisica), the Istituto Nazionale di Fisica Nucleare, and several Italian research Institutes, Universities and industrial partners.

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