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A DECADE OF AGILE

In-orbit operations of AGILE mission: 11 years successfully in space

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Abstract

Astrorivelatore Gamma ad Immagini LEggero (AGILE) is a high-energy scientific space program funded by the Agenzia Spaziale Italiana (ASI—Italian Space Agency); the mission was developed and is being operated in cooperation with INAF, INFN, CIFS and with the participation of several Italian companies. The satellite was launched from India on April 23rd, 2007 in an LEO equatorial orbit. The scientific payload includes: an imaging detector for hard X-rays (20–60 keV), an imaging gamma-ray detector (100 MeV–10 GeV), and a calorimeter (0.4–100 MeV). As of today, more than 57,700 orbits have been successfully completed with the satellite in operations more than 11 years (well beyond the 2-year nominal lifetime). This paper describes the operational activities performed at the ground segment level (satellite control and user segment) and discusses the high performance achieved during 11 years of successful in-flight operations. This result was obtained in the framework of a small mission and with a relatively small operation team. Important factors have been the implementation of an efficient automatic ground segment telemetry processing and a very fast scientific alert system. The service consists in the operational management of the satellite and of the ground segment in different phases of the mission both in nominal and contingency situations, carrying out the observations plan provided by ASI and the delivery of the scientific data to the ASI Space Science Data Center (SSDC, formerly ASDC). To achieve these objectives satisfying the mission safety requirements, specific operational procedures and strategies have been implemented together with ground segment automation and optimized use of onboard satellite capabilities. This work has been carried out under an ASI contract.

Keywords High-energy astrophysics · Gamma rays · Ground segment operations · Science operations · Terrestrial gamma-ray flashes · Gravitational waves

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1 The AGILE mission

1.1 An ASI scientific mission

Astrorivelatore Gamma ad Immagini LEggero (AGILE) is an Italian scientific space program for high energy astrophysics supported by the Italian Space Agency (ASI) and implementing detection of gamma rays by means of silicon technology. AGILE is a mission dedicated to observing the gamma-ray universe. The AGILE very innovative instrument for the first time combines a gamma-ray imager, a hard X-ray imager, a calorimeter and an anticoincidence system.

The AGILE satellite was successfully launched by a PSLV rocket on 2007 April 23rd from the Indian base of Sriharikota, and it was inserted in an equatorial low Earth orbit. Details on the AGILE scientific mission are reported in Tavani et al. (2009) see also Tavani et al. (2008a, b) (Fig. 1). Relevant information on the AGILE detectors are reported in Barbiellini et al. (1995), Prest et al. (2003), Labanti et al. (2006), Fuschino et al. (2008).

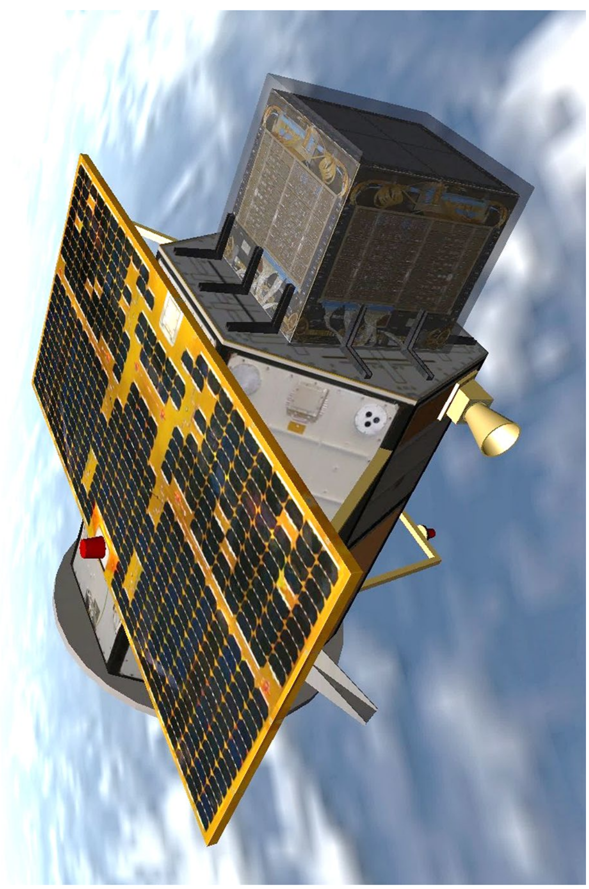

Fig. 1 The AGILE satellite (pictorial view)

1.2 The industrial team

The industrial organization in charge of the development and manufacturing phase (C/D phases) of the AGILE satellite, Ground Segment and operations is the following:

- Satellite system and AIV: Carlo Gavazzi Space (currently OHB Italia).
- Satellite platform: OHB Italia.
- Payload: INAF, INFN.
- Payload integration: LABEN (currently Thales Alenia Space Italia).
- Structure, thermal and solar panels: Oerlikon Contraves Italiana (currently OHB Italia).
- Ground Segment and operations: Telespazio.

1.3 The development phase

The development phase started in 2003 and it was completed in mid-2007. The main steps during this phase were the following:

- Contract signature with ASI for the C/D phase of the mission in the year 2003.
- Contribution of the Italian Scientific Institutes as part of the overall contract for the delivery of the instruments flight models.
- Contract based on the in-orbit delivery of the satellite.
- Satellite launched on 23/4/2007.
- Contractual lifetime: 2 years.

2 System characteristics and key performance

2.1 AGILE system characteristics

The main satellite technical data are the following:

- Orbit: LEO, equatorial, 550 km at BoL.
- Mass at launch: 350 kg.
- Satellite dimensions: $1.7 \times 2 \times 0.8$ m^3.
- Electrical power: 200 W (average).
- Sun pointing, fixed solar panel.
- Attitude knowledge: 1 arcmin.
- Onboard autonomy of 3 days without contacts.
- Gamma ray burst alert channel.
- Ground station in ASI Broglio Space Center (BSC) in Malindi (Kenya) with satellite visibility every orbit.
- Quick scientific processing time.

2.2 The AGILE mission status

Operations started upon the successful completion of the in-orbit tests and delivery, on June 2007. As of today, AGILE has accumulated more than 57,700 passes over the ASI BSC Malindi station in Kenya.

During the almost 11 years of operations AGILE has produced scientific data with more than 97% time efficiency. The natural orbit decay and the behavior of the satellite onboard systems show that the satellite could be operative at least until mid-2019 (worst case).

In October 2009, an onboard failure of the momentum wheel occurred. The satellite was then configured in a "spinning mode" rotating around its sun-pointing axis; it achieved a spin-stabilized attitude with a rotation of 0.8°/s. This configuration is the nominal observing mode of the satellite since 2009. All AGILE scientific operations were promptly reconfigured following the failure of the rotation wheel. The satellite is currently operating regularly in spinning mode surveying a large fraction (about 70%) of the sky each day.

3 The AGILE space segment: platform

The AGILE spacecraft is of the MITA class and was developed by OHB CGS (formerly Carlo Gavazzi Space) as prime contractor and by OHB CGS (formerly Rheinmetall Italia). The spacecraft has been customized for the AGILE mission and represents a very good compromise between the mission technical requirements and the stringent volume and weight constraints. The overall configuration has a hexagonal shape and is divided into two units: the "Payload Unit" hosting the instrument, its electronics; the navigation unit and electronics; a "service module" hosting all the other vital control units and the satellite OBDH systems (Fig. 2).

The space segment of the AGILE mission is composed by the following two elements:

- The AGILE platform;
- The AGILE payload.

The AGILE platform is in charge to provide the AGILE payload with the required services for its operations. It provides to the payload, for all the mission lifetime, power supply, communication with the ground, attitude control and thermal control capability. All these functionalities are managed by the onboard data handling (OBDH) subsystem that is also in charge of the onboard monitoring and control activities. The satellite electrical power is produced by fixed solar panels of about 2 m^2 area, equipped with triple junction GaAs cells.

To supply power during eclipse periods and during the attitude acquisition phase, the power S/S includes a

Fig. 2 The AGILE satellite at launch campaign (India, 2007)

re-chargeable lithium-ion battery with a capacity of 33 Ah. The battery charging activity and the power conversion and distribution to the satellite users are provided by a dedicated power box controlled by the OBDH through a dedicated software.

Communication with the ground station is ensured by an S-band transceiver that connects with the ASI ground station located in ASI Broglio Space Center in Malindi (Kenya) about 14 times a day, for a total visibility periods of about 160 min per day. During the visibility periods, the S-band transmitter downloads the payload data, previously stored in the OBDH mass memory, with a net data rate of 500 kbps. The S-band transceiver is also used to upload from ground the configuration telecommands necessary for satellite operations.

The attitude control subsystem (ACS) uses a set of sensors and actuators controlled by a dedicated SW running on the OBDH computer to guarantee the required pointing in all mission phases. After the launcher separation, the ACS was able to acquire, within a few orbits, a Sun pointing attitude to guarantee the necessary power generation from the solar array. Once acquired, the Sun pointing attitude has been maintained for the whole mission.

During the first part of the mission, a "fine" Sun pointing attitude ensured a pointing accuracy better than 1° and an attitude stability better than 0.1°/s. The fine Sun pointing provided the possibility to maneuver the payload instrument, while keeping the Sun pointing direction, to allow a global coverage of the sky and the possibility to perform fast re-pointing towards active sources. On October 2009, an irreversible failure of the momentum wheel forces the modification of the nominal satellite attitude. The ACS algorithm was modified to ensure the satellite stability through a slow rotation around the sun-pointing axis.

The satellite thermal control is passive. It is realized mainly by placing the most dissipating devices on radiating surfaces. A proper material selection allows obtaining the desired temperature variations with all device temperature limits within the required limits. A set of heaters, controlled by thermostats or by SW, is used on critical equipment (in particular, the li-ion battery and the payload) to guarantee the respect of the allowed temperature ranges (Fig. 3).

To guarantee the required reliability for the whole mission lifetime, most of all the main platform equipment has a full redundancy. The OBDH SW mainly performs the redundancy management autonomously to provide the required autonomy to recover possible failure that can be experienced during the mission.

4 The AGILE space segment: payload

The AGILE scientific payload is made of three detectors combined into one instrument with broadband detection and imaging capabilities. The payload is surrounded by an anticoincidence system to screen out the charged particle background. A sophisticated data handling system completes the instrument. We summarize here the main characteristics of the instrument.

The gamma-ray imaging detector (GRID) is sensitive in the energy range ~ 30 MeV–50 GeV, and consists of a silicon tungsten tracker, a cesium iodide calorimeter, and an anticoincidence system. The GRID trigger logic and data acquisition system (based on anticoincidence, tracker and mini-calorimeter information) allows for an efficient background

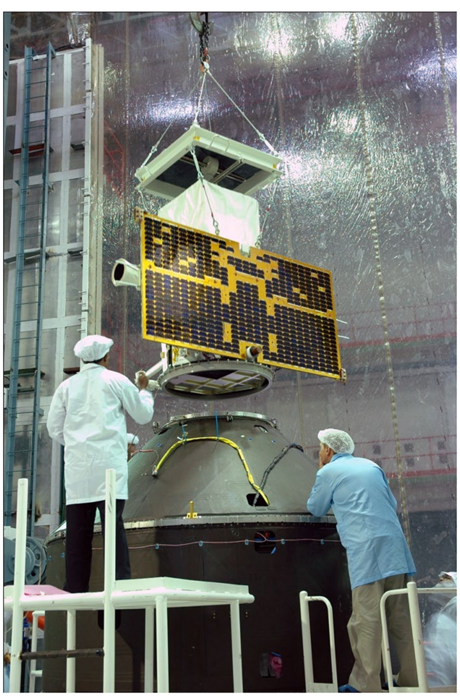

Fig. 3 The AGILE satellite during integration with the launch vehicle (Shriharikota, India, 2007)

discrimination and inclined photon acceptance (Tavani et al. 2008b; Argan et al. 2004, 2008; Bulgarelli et al. 2010). The GRID is designed to achieve an optimal angular resolution (source location accuracy ~ 6′–12′ for intense sources), a very large field-of-view (~ 2.5 sr), and a sensitivity comparable to that of EGRET for sources within 10–20° from the main axis direction (and substantially better for larger off-axis angles).

The hard X-ray imager (Super-AGILE) is a unique feature of the AGILE instrument (Feroci et al. 2007). The imager is placed on top of the gamma ray detector and is sensitive in the 18–60 keV band.

A mini-calorimeter operating in the "burst mode" is the third AGILE detector. It is part of the GRID, but also capable of independently detecting GRBs and other transients in the 350 keV–100 MeV energy range with excellent timing capabilities.

The anticoincidence (AC) system is aimed at a very efficient charged particle background rejection (Perotti et al. 2006). It also allows a preliminary direction reconstruction for triggered photon events through the DH logic. The AC system surrounds all AGILE detectors (Super-AGILE, Si-tracker and MCAL). Each lateral face is segmented into three plastic scintillator layers (0.6 cm thick) connected to photomultipliers placed at the bottom of the panels. A single plastic scintillator layer (0.5 cm thick) constitutes the top-AC whose signal is read by four light photomultipliers placed at the four corners of the structure frame. The segmentation of the AC system and the silicon tracker trigger logic contribute in an essential way to produce the very large field of view of the AGILE-GRID.

The data handling (DH) and power supply systems complete the instrument. The DH is optimized for fast onboard processing of the GRID, MCAL and Super-AGILE data (Labanti et al. 2009; Tavani et al. 2008b; Argan et al. 2008). Given the relatively large number of readable channels in the ST and Super-AGILE (~ 40,000), the instrument requires a very efficient onboard data processing system (Fig. 4).

5 The Ground Segment and operations

5.1 The Ground Segment architecture

The AGILE Ground Segment (GS) (D'Amico 2006a) constitutes the main system in charge of satellite monitoring and control and in charge of payload observations planning and execution upon scientific community requests. In supporting the AGILE mission, the GS main functions are the following:

– Satellite tracking and acquisition during the foreseen passes over the TT&C Malindi ground station.

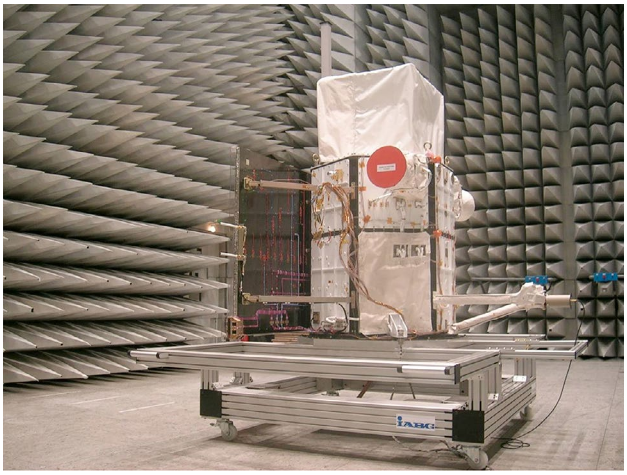

Fig. 4 The AGILE satellite during qualification tests (Munich, Germany, 2006)

- TC and TM handling (TM acquisition, processing, display, archiving; TC generation, verification and uplink).
- Satellite orbit determination and propagation, satellite attitude determination, support to satellite ACS onboard operations.
- Satellite sub-systems and payload monitoring and control, satellite modes of operations monitoring and control.
- Mission planning generation and execution.

The AGILE payload is monitored and controlled as the bus satellite sub-systems; payload handling is achieved in accordance with the mission planning and constraints. AGILE payload data are received, locally archived at the TT&C ground station and made available at the ASI Space Science Data Center (SSDC).

The AGILE Ground Segment is composed of the following main sub-systems:

- Satellite Control Center (SCC).
- Flight Dynamics Center (FDC).
- Mission Control Center (MCC).
- TT&C ground station.
- Communication network.
- ASI Space Science Data Center (SSDC).

The AGILE Satellite Control Center (SCC), (D'Amico 2006b) based at Telespazio Fucino Space Center, oversees all the satellite monitor and control functions, both in nominal and in contingency situations. The main SCC functions are the following:

- Satellite telemetry acquisition from TT&C ground station, TM processing, display and archiving.
- Handling of the satellite acquisition automatic procedures.
- Satellite database handling and maintenance.
- Satellite sub-systems and payload health monitoring and control through housekeeping telemetry processed data presented on alpha-numeric and mimic displays.
- Real time or time-tagged telecommand preparation, TC to be uplinked to the satellite.
- Co-ordination with the TT&C ground station for data and voice exchange and with reference to program track mode antenna operations and to satellite tracking data reception to be processed by FDC.
- Communication network management.

The AGILE Flight Dynamics Center (FDC), based at Telespazio Fucino Space Center, oversees the satellite orbit determination and prediction, of the satellite attitude dynamics determination and it supports the satellite ACS onboard operations. The ACS onboard operations support mainly consists of:

- ACS performance monitoring.
- Attitude maneuvers calculation for the pre-defined satellite pointing for scientific targets.
- Star trackers and navigation data handling.

AGILE FDC generates standard products, such as:

- Orbital files, necessary for the satellite in-orbit operations and for the mission planning activity.
- Attitude files, containing the reconstructed satellite attitude, necessary for the satellite in-orbit operations and for scientific activities support.
- Files containing the information necessary to prepare the payload configuration tables to be uploaded onboard (contact tables, SAA tables, occultation table, Earth vector table, star trackers table).
- Files containing the information on parameters necessary to support platform activity.
- Orbital file for scientific purposes.
- Sequence of the events.
- Standard trajectory data message (STDM).

The orbit determination is based on navigation telemetry data processing or it may be also based on TLE data or AMD (angular measurement data) stored at TT&C ground station when the antenna is in auto-track mode.

The AGILE Mission Control Center (MCC), (D'Amico 2006c) based at Telespazio Fucino Space Center, is mainly in charge of mission planning and of payload data handling. MCC is in charge of:

- Payload scientific raw data archiving (level 0 archiving) and delivery to SSDC.
- Mission planning generation and check, according to scientific observation requests.

The AGILE TT&C ground station, based at ASI Malindi (Kenya) Broglio Space Center, is in charge of.

S-band RF ground to space satellite communication during all the AGILE mission phases. The main TT&C ground station functions are the following:

- Ground to space RF S-band interface with the satellite, during all the mission phases.
- During satellite visibility over the station, the TM is received from the satellite and TCs are uplinked to the satellite; real-time TM is extracted and sent to SCC, while off-line TM is locally stored to be sent to SCC at the end of the satellite pass; TCs received from SCC are uplinked to the satellite for immediate or time-tagged onboard execution.
- During satellite visibility over the station, the satellite tracking is performed, in 'program track' or 'auto-track' modes of operations; auto-tracking data are useful to perform orbit reconstruction by FDC.
- Data and voice communication handling with SCC, through the usage of ASInet network.
- TM and TC protocol data handling is achieved through the usage of the base band equipment.
- Ground station equipment and configuration monitor and control.

The AGILE communication network, mainly based on the ASInet network provided by ASI, is in charge of data and voice communication between AGILE GS sub-systems during all the mission phases.

The AGILE Data Center, is part of the ASI Space Science Data Center (SSDC, previously ASDC), and it is the ASI official interface with the AGILE GS during the satellite operations; it interacts with GS entities in submitting scientific requests of observations and it receives from GS the AGILE payload raw data. In case of a gamma ray burst event it also receives notification.

Figure 5 describes the AGILE Ground Segment high-level functional scheme.

5.2 A fast and reliable Ground Segment

The equatorial orbit of the satellite allows the visibility of the satellite every 90 min, for a period of about 10 min, during which the satellite receives the telecommands from the ground station and downloads housekeeping and scientific telemetry.

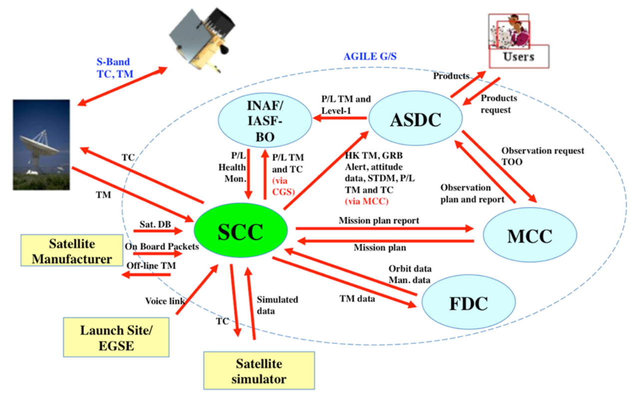

Fig. 5 A schematic view of the AGILE Ground Segment

The principal objective of the Ground Segment activities is to maintain the system and implement the necessary procedures to carrying out the operative service for the satellite in-orbit management and the delivery of scientific data to SSDC.

The service consists of satellite and Ground Segment management during all mission phases both in nominal and contingency situations. The service guarantees the implementation of the observations plan provided by ASI and ensures the delivery of all scientific data to SSDC according to agreed timeline and interfaces.

To guarantee the correct management of operations and respect the mission safety requirements, operational procedures and strategies have been foreseen to manage the satellite during nominal phases with enough temporal margins.

The nominal AGILE activity of command is exclusively executed during working hours (and, therefore, during working periods of on-shift personnel). Therefore, the tele-command sequence, prepared automatically from the Mission Control Center (MCC), is sent exclusively during such periods in "Time Tagged" format, exploiting the ability of storage of the satellite onboard buffer and distributed during the various passages to have enough time margin available before the beginning of the next attended shift.

In case of occurrence of an onboard anomaly during unattended periods, the satellite is able to self-configure in a "Safe" mode that guarantees its survival for at least 72 h. In this case, all commands contained in the onboard buffer and ready for the execution are automatically disabled and not executed.

The AGILE Ground Segment involved the following implementations finalized to the maximum automation of the operational activities both in Fucino SCC and at the Malindi T&C ground station:

- Development of the Satellite Control Center (SCC) based on SCOS 2000 evolutions that have involved the development of further additional modules to the SCOS kernel.
- Development and configuration of the monitor and control system and the station computer for the automatic management of the satellite passages.

5.3 An efficient operational approach

This approach led to design and develop a low-cost ground segment for the mission, and it also required to compress satellite operations during ‘working hours’ (see D’Amico et al. 2006d).

This operational approach has been selected in close agreement with the satellite manufacturer and ASI to reduce as much as possible operation costs but at the same time achieving safe satellite in-orbit operations.

Budget constraints also limited the architectural choices for the ground segment main system and sub-systems. The maximum re-use of existing facilities has been envisaged since the early phases of the program, and the development of new systems has been carried out using low cost and open source available software solutions.

Key re-usability features of the resulting product were:

- The satellite control center, based on SCOS 2000 open source code from ESA and working in an LINUX PC-based hardware environment.
- The flight dynamics center, developed in C++, partly derived from existing Telespazio Flight Dynamics systems.
- The mission control center, developed in Java, fully integrated with SCOS 2000 satellite control center environment and with flight dynamics center.
- The re-use of ASI BSC Malindi (Kenya) TT&C station and antennas, with specific AGILE mission customization of the existing equipment.
- The re-use of ASI-net communication network to link the ground segment facilities located in Italy, at the Fucino Space Center, with the Malindi TT&C station located in Kenya.
- The re-use of the ASI MITA satellite mission base band equipment.
- The re-use of the P/L Health Monitoring system, developed by the scientific team during the AIV activities of P/L and S/C and running at INAF/IASF Bologna (Bulgarelli 2009).

The important key issue for the AGILE mission is the optimization of in-orbit operations: the control centres and the ground station are nominally manned only during the ‘working hours’, thus allowing a significant personnel reduction in comparison with ‘24/7’ typical satellite operations.

5.4 Some figures in 11 years of successful operations

The AGILE Ground Segment architecture (Fig. 6) has been realized simply but very efficiently. It allows to promptly react and operate to deliver scientific data to scientific users. Up to February 2016, the time delay between satellite acquisition and data processing and availability was of only 2–2.5 h, already a record for a gamma-ray mission. Following the historical discovery in 2015 of the first detected gravitational waves (GW) by Ligo–Virgo collaboration (Abbott et al. 2016), AGILE joined the world hunt for electromagnetic counterparts of GW, and the scientific pipeline system has been recently further optimized, reaching a minimum latency of only about 25 min between data acquisition and scientific alerts.

A high degree of automation has been implemented in the ground segment to allow automatic data processing including weekend times.

Automatic setup for pre-pass activities:

- Set pass number.
- Connection with the ASI BSC Malindi station.
- Initialize the recording of VC0/VC1 file.
- Set of SCC variables to manage the creation of AUX files.

Pass activities:

- Processing of real-time TLM.
- Record the VC0 TLM.
- Display and alert for out of limit conditions.

Automatic post-pass activities:

- Receive the VC1 file from the station.
- Send VC0/VC1 to SSDC/OHB Italia.
- Copy TLM into the archive.
- Process in offline the VC1 TLM.

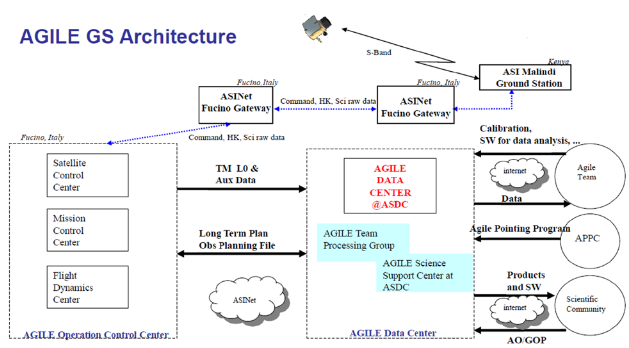

Fig. 6 The AGILE Ground Segment architecture

– Collect navigation and other TLM data in AUX files.
– Generate the attitude reconstruction.

Since the beginning of operations, several changes occurred, and the operations team has been solicited several times to promptly react to fulfill safe satellite operations:

– Momentum wheel failure → satellite available only in spinning mode.
– Payload configuration → Albedo, MCAL vs TGF, Chi2 threshold, observation in SAA.
– TT&C antenna not more available for all passages → modulate the planning of observation periods.

Therefore, a good trade-off between operations automation and highly skilled operations personnel led to achieve very successful 11 years in-orbit operations that could be highlighted as follows:

– More than 11 years in-orbit instead of the nominal lifetime of 2 years.
– As of today more than 57,700 orbits.
– More than 730 GB of downloaded telemetry data (TLM VC1 raw, value of compressed data) (Fig. 7).

6 The role of SSDC for the AGILE mission

The AGILE Data Center (ADC) is part of the ASI Space Science Data Center (SSDC), previously located in the ESA establishment of ESRIN in Frascati, and moved within the ASI Headquarters, Rome (Italy) in July 2013. ADC oversees all scientific-oriented activities related to the analysis, archiving and distribution of AGILE scientific data (Pittori et al. 2014).

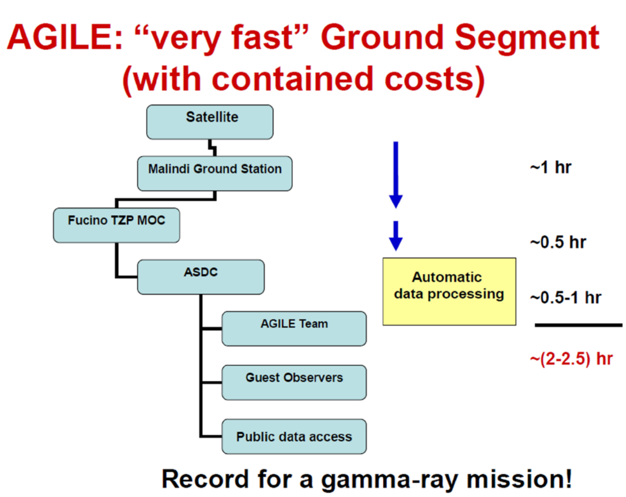

Fig. 7 The AGILE fast Ground Segment

AGILE scientific data (about 300 Mbit/orbit) are telemetered from the satellite to the ASI ground station in Malindi (Kenya) at each satellite passage (approximately every 95 min). A fast ASInet connection between Malindi and the Satellite Control Center at Fucino and then between Fucino and the SSDC ensures the data transmission every downlink.

Raw data are routinely archived at the ADC, and then converted to FITS format Level-1 (preprocessed data) through the AGILE preprocessing system (Trifoglio et al. 2008). GRID data are further processed for background rejection and photon-list determination (Level-2, or attitude corrected and calibrated event lists and Level-3, or sky maps, light curves and other high level scientific products) using software tasks developed by the AGILE instrument team and then integrated into the pipeline systems developed at ADC for quicklook monitoring and consolidated archive generation.

Super-AGILE data are deconvolved and processed to produce 2-D sky images through a correlation of current and archival data of hard X-ray sources. Super-AGILE dedicated software produces light curves, spectra, and positioning of sources detected in the hard X-ray (18–60 keV).

The AGILE main tasks carried out at the ASDC can be summarized as follows:

– Quicklook data reduction analysis.
– Standard data reduction analysis.
– New source validation.
– Complete data archiving.
– Data distribution to the scientific community.
– Management of the official web page of the AGILE mission.
– Publication of the official AGILE GRID and Super-AGILE source catalogs.
– Distribution of standard products (positions, fluxes, light curves) of AGILE sources.
– Management of the AGILE Guest Observer Program.

During the first 4 years of data taking (from Cycle-1 to Cycle-4) part of the AGILE Science Program has been open to guest observers on a competitive basis. The ADC has overseen managing the AGILE Guest Observer Program (GOP) open to the astronomical community.

A public AGILE software package aimed to allow the user to perform a complete science analysis of specific point like gamma-ray sources or candidates, as well as a timing analysis is also available for guest observers and general users.

6.1 AGILE science alert system

Automatic alerts to the AGILE team are generated within approximately $T_0 + 45$ min (Super-AGILE) and $T_0 + 100$ min

(GRID). Recent improvements and optimizations linked to the new "Gravitational Wave Astronomy" allowed to further reduce the data latency to about 25 min.

The AGILE GRID quicklook (QL) alert system is composed of two independent automated analysis parts: the QL Scientific pipeline running at ADC (Pittori et al. 2014) and the AGILE-GRID science alert system (SAS) pipeline running at the INAF–IASF Bologna (Bulgarelli et al. 2014). Data are automatically analyzed at every downlink and accumulated on different timescales. Light curves of potential gamma-ray sources are produced using blind search techniques and cross-correlation with a reference list of known gamma-ray emitters. As proper flux thresholds are exceeded, alerts for transient gamma-ray sources are automatically generated and notified through e-mails, SMS messages, and also through a dedicated application for smartphones and tablets (the AGILE Science App, used also by AGILE team for a fast check of the current gamma-ray sky, and to check the content of the alerts, the status of the P/L and the quality of the acquired data). These alerts are crosschecked, and a manual analysis is performed for the most interesting gamma-ray source candidates.

A backup link between Telespazio and INAF/IASF Bologna through OHB Italia enables the science alert system running at INAF–IASF Bologna to receive scientific data for the detection of flaring gamma-ray source even if the nominal link has problems.

In the public section of the AGILE Science App the AGILE gamma-ray sky map, updated every orbit, can be seen by the public for scientific and outreach purposes. This allows non-professional astronomer or interested people to follow the evolution of the gamma-ray sky "in real-time", providing a direct link between the AGILE G/S data flow and the mobile technology.

The daily monitoring activity of the AGILE QL alerts resulted in the publication of about 200 Astronomer's Telegrams and 50 GCN up to May 2018.

6.2 AGILE catalogs (GRID, MCAL, SA)

All published AGILE catalogs are also available from the SSDC webpages as interactive web tables also providing web tools which allow the user to browse both internal multi-mission archive catalogs (grouped by energy band) and external catalogs from other services (VIZIER, NED, SIMBAD, etc.), providing an easy way to explore and cross-correlate large data sets from radio to TeV.

The AGILE first catalog of high-confidence-ray sources detected by AGILE during its first year of operations (Pittori et al. 2009) is accessible online at the website: http://www.asdc.asi.it/agilebrightcat.

This first catalog has then been updated using data covering the whole period of pointed observations, of about 2.3 years (Verrecchia et al. 2013). In the online version, light curves from fluxes in each observation block are available from the AGILE-GRID data products tab within the ASDC data explorer at http://www.asdc.asi.it/agile1rcat.

The complete AGILE reference list of bright gamma-ray sources above 100 MeV over the first 2.3 years of observations includes now 62 sources, as compared to the 47 1AGL in the first catalog. Work is in progress to build new complete catalogs of AGILE-GRID sources over the whole observing period.

The Super-AGILE source catalog of X-ray sources detected up to December 2011, and including light curves is accessible online at http://agile.asdc.asi.it/sagilecat_sources.html.

The AGILE MCAL catalog comprising 85 hard gamma-ray bursts (GRB) observed by the mini-calorimeter since the launch until October 2009 is accessible online at the website http://www.asdc.asi.it/mcalgrbcat/.

The AGILE MCAL terrestrial gamma-ray flashes (TGFs, see following section) catalog below 30 MeV (Marisaldi et al. 2014) is accessible online at the website of the ASI Science Data Center http://www.asdc.asi.it/mcaltgfcat/.

6.3 AGILE terrestrial science: Terrestrial Gamma-Ray Flashes (TGFs)

AGILE is also providing significant contributions to Earth observation, especially in the field of high-energy radiation from thunderstorms and lightning, concerning the observation of terrestrial gamma-ray flashes (TGFs). TGFs are sub-millisecond bursts of gamma-rays emitted by active thunderstorms typically in association with lightning and currently observed from space by three satellites only, one of them being AGILE.

The AGILE payload is very well suited for TGF science especially thanks to the extended energy range of the mini-calorimeter and its trigger logic active on very short time scales (300 µs and 1 ms). The main AGILE achievements in TGF science mostly concern the TGF high energy spectrum, the localization of TGFs from space in gamma rays, and the asymmetry in the TGF/lightning flash ratio, and are summarized in Marisaldi et al. (2014), and references therein.

6.4 AGILE and gravitational wave astronomy

After the first direct observation of a gravitational wave (GW) signal in 2015 by the LIGO–Virgo collaboration (Abbott et al. 2016), several other GW events matching the predictions of general relativity for black hole-black hole merger, with no predicted nor observed associated electromagnetic (EM) signals, were announced. In 2017, the extraordinary discovery of the gravitational wave source GW 170817 associated for the first time with an X-ray short gamma-ray burst started the era of multi-messenger astronomy. Both the observed GW and EM signals for this event are in agreement with a neutron star-neutron star coalescence producing a prompt hard X-ray transient followed by time-delayed optical, radio and X-ray emission.

The AGILE instrument has unique characteristics for observations of the large GW localization regions: the very large GRID FoV exposes 80% of the whole sky every 7 min, with 100–150 useful passes every day for any region in the accessible sky, the sub-millisecond MCAL trigger for very fast events, and the hard X-ray triggers of GRB-like events in the SuperAGILE FoV (1 sr), with a localization accuracy of 2–3 arcmin in imaging mode.

Based on these characteristics and to the very fast AGILE Ground Segment alert system, the AGILE observations have provided the fastest response and the most significant upper limits above 100 MeV to the first detected gravitational wave event GW150914, and to all other GW events detected up to now with optimal gamma-ray sensitivity (Tavani et al. 2016; Verrecchia et al. 2017), including GW 170817. AGILE continues its exploration of the high-energy Universe, giving a crucial contribution in the search of electromagnetic counterparts of gravitational waves. We look forward for future follow-up gamma-ray observations of GW sources with AGILE.

7 Conclusions and lesson learnt

The AGILE mission has been designed to achieve a nominal lifetime of 2 years. The AGILE instrument is still working nominally since April 2007. The reaction wheel failure of 2009 did not influence the scientific return of the mission.

A highly skilled operations team has been able to successfully operate the satellite over more than 11 years, producing very good science, as in (Tavani et al. 2009) and as it has been demonstrated with the American Astronomical Society (AAS) "Bruno Rossi Prize" assigned in 2012 to Principal Investigator—Prof. Marco Tavani—and to the AGILE team.

AGILE has been a pioneer low-cost mission that could be considered as a benchmark for future small satellite missions. Its main achievements are

- The AGILE mission is considered a big success for ASI and for the scientific community.
- Very important results produced by a small satellite were obtained also for terrestrial science, i.e., TGF research.
- AGILE demonstrated the full feasibility of a scientific mission with a limited budget and a short development time.
- The key factor of the AGILE success was the strong and proactive cooperation among all the involved actors (ASI, industry, scientific and operations teams).
- The AGILE project has created many groups of young specialists in different disciplines that represent a key asset for future missions.

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