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The AGILE silicon tracker: an innovative γ -ray instrument for space

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Abstract

AGILE (Light Imager for Gamma-ray Astrophysics) is the first small scientific mission of ASI, the Italian Space Agency. It is a light (100 kg for the scientific instrument) satellite for the detection of γ -ray sources in the energy range 30 MeV–50 GeV within a large field of view ($\frac{1}{4}$ of the sky). It is planned to be operational in the years 2003–2006, a period in which no other gamma-ray mission in the same energy range is foreseen.

AGILE is made of a silicon tungsten tracker, a CsI(Tl) minicalorimeter ($1.5X_0$), an anticoincidence system of segmented plastic scintillators and a X-ray imaging detector sensitive in the 10–40 keV range. The tracker consists of 14 planes, each of them made of two layers of 16 single-sided, AC coupled, 410 μm thick, $9.5 \times 9.5 \text{ cm}^2$ silicon detectors with a readout pitch of 242 μm and a floating strip. The readout ASIC is the TAA1, an analog-digital, low noise, self-triggering ASIC used in a very low power configuration ($<400 \mu\text{W}/\text{channel}$) with full analog readout. The trigger of the satellite is given by the tracker. The total number of readout channels is around 43 000.

We present a detailed description of the tracker, its trigger and readout logic, its assembly procedures and the prototype performance in several testbeam periods at the CERN PS.

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1. Introduction

In December 1998 AGILE (Astrorivelatore Gamma a Immagini LEggero—Light Imager for

Gamma-ray Astrophysics) was selected as the first small mission supported by ASI.

At present AGILE is entering the phase C/D, which is the construction and assembly phase of the satellite.

The AGILE mission will provide a powerful Observatory for γ -ray astrophysics in the energy range 30 MeV–50 GeV, during the years

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2003–2006. No other γ -ray mission in this energy range is planned in the same period.

The instrument is light (≈ 100 kg) and will be able to detect and monitor γ -ray sources within a large field of view ($\approx \frac{1}{4}$ of the whole sky). The instrument consists of (Fig. 1):

- a Silicon–tungsten Tracker that detects the electron–positron pair created in the photon conversion in order to provide the trigger to the whole instrument and to provide a complete representation of the event topology allowing the reconstruction of the incoming direction of the γ -ray,
- a $1.5X_0$ deep CsI(Tl) Minicalorimeter [1] that measures the energy released by the pair,
- an Anticoincidence system (AC) made of segmented plastic scintillators that is used to reject charged particle background,
- a silicon X-ray detector [2] in the range 10–40 keV with a coded mask system.

The overall instrument dimension is $63 \times 63 \times 58$ cm³. For a complete description of the payload, see [3].

In the following, we describe the AGILE Silicon Tracker and its assembly procedures (Section 2), its trigger logic (Section 3) and the prototype

performance as measured in several testbeam periods at CERN (Section 4).

2. The AGILE silicon tracker

The Silicon Tracker is the heart of the AGILE mission. It is a compact, low power 43 000 channel detector with self-triggering capability, fast timing possibility and full analog readout.

The AGILE Tracker is made of 14 planes of silicon strip detectors organized in 15 trays. Each tray is configured as follows:

- active part: two views of 16 silicon pads each (except trays 1 and 15 which have a single view) organized in 4 ladders of 4 detectors each; the strip orientation of the first view is perpendicular to the one of the second view resulting in a x – y detector.
- passive converter: one tungsten layer 245 μ m thick (corresponding to 0.07 radiation lengths) positioned above the silicon layer; the last 2 planes do not have this converter layer because of the trigger configuration

Each tray is made of a 12 mm core of aluminum honeycomb ($5056 \frac{3}{16}$, 0.0007) covered on both sides by a 0.5 mm thick carbon fibre layer (Amoco, K1100/cyanate ester) obtained from four 0.125 mm plies (0–90–90–0); the glue between the honeycomb and the fibre is REDUX 312L.

The tungsten layer is glued on the fibre with DC 3145 (Dow Corning).

The 4 ladder detectors are glued edge-on with a 50 μ m layer of H70E (Epotek) and the ladder itself is glued on a kapton foil 50 μ m thick with 5 dots of conductive H20E (Epotek) and 36 dots of DC 3145. The 4 detectors are bonded together and to the electronics with 25 μ m Al wires.

A sketch of the Silicon Tracker tray with all its components is shown in Fig. 2.

2.1. The silicon detector

The active element of the AGILE tracker is a single-sided, AC-coupled, 410 μ m thick, 9.5×9.5 cm² silicon strip detector with a readout pitch of 242 μ m and one floating strip with polysilicon

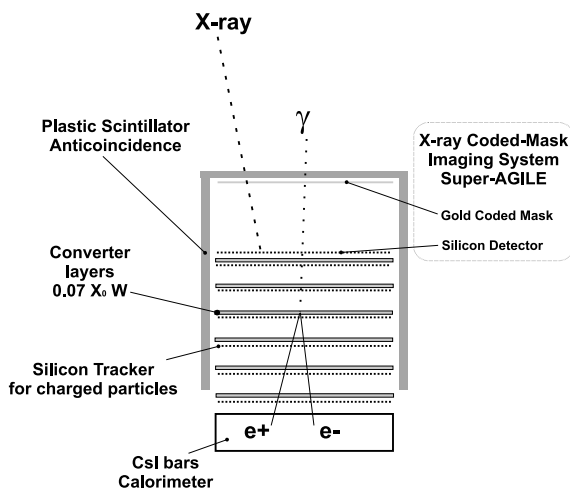


Fig. 1. Description and working principle of the AGILE instrument.

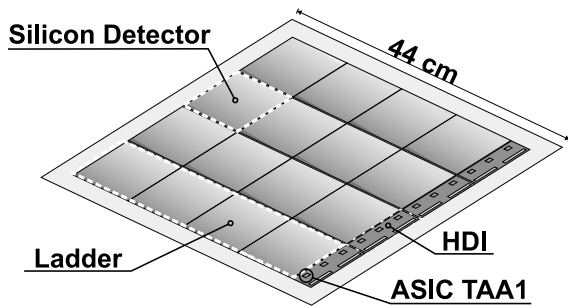


Fig. 2. Silicon tracker tray sketch.

resistors for the bias. It has been manufactured on high resistivity ($\geq 4 \text{ k}\Omega \text{ cm}$) 6" substrate by HAMAMATSU PK.

The main features of the detector are summarized in Table 1. The full supply of 550 detectors has been completed and 80.2% of the detectors have no defects. The other detectors are well within the user production tolerances (1% of bad strips at maximum, 0.5% in average), corresponding to an overall average value of 0.047% of faulty strips per detector.

2.2. The frontend ASIC

Each silicon ladder is read by three 128-channel, analog-digital, low noise, self-triggering ASICs used in a very low power configuration ($< 400 \mu\text{W}/\text{channel}$) with full analog readout. The ASIC is the TAA1 [6], designed by IDE AS¹ and produced by AMS² with 0.8 μm N-well BiCMOS, double poly, double metal on epitaxial layer technology.

Each channel is made of a folded cascode charge sensitive preamplifier, a CR-RC shaper, a sample and hold circuit, a level sensitive discriminator. The discriminator threshold is unique for the 128 channels with a 3-bit trimming DAC per channel to obtain a threshold uniformity better than 10%. The readout is a multiplexed analog readout with a maximum readout clock frequency of 10 MHz. We plan to use the ASIC with a 5 MHz clock.

¹ IDE AS, Oslo, Norway.

² Austria Mikro Systeme International AG, Austria.

Table 1

Main features of the AGILE silicon detector

Item	Value
Dimension (cm^2)	9.5×9.5
Thickness (μm)	410
Readout strips	384
Readout pitch (μm)	242
Physical pitch (μm)	121
Bias resistor ($\text{M}\Omega$)	40
AC coupling Al resistance (Ω/cm)	4.5
Coupling capacitance (pF)	527
Leakage current (nA/cm^2)	1.5

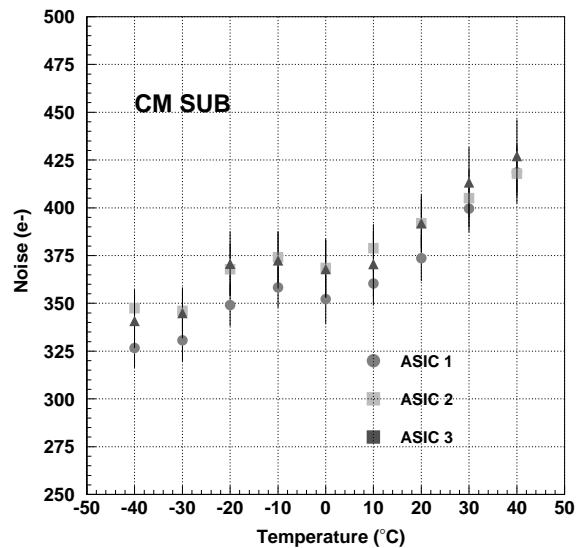


Fig. 3. Noise behavior of the three ASICs connected to an AGILE silicon detector as a function of the temperature in the temperature range foreseen for the satellite.

The behavior of the ensemble of the AGILE silicon detector and the ASIC has been tested between -40°C and $+40^\circ\text{C}$, which is the maximum temperature range foreseen for the worse working conditions of the satellite. The results are shown in Fig. 3 for the three ASICs connected to a single detector. The noise is the value obtained once the common mode component was subtracted.

3. The AGILE trigger

For the AGILE orbital environment, we expect a ratio of cosmic γ -rays to total background

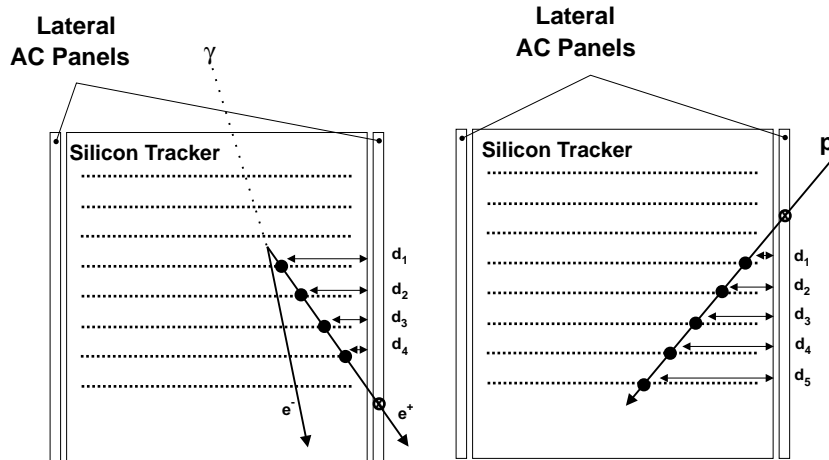


Fig. 4. DIS-algorithm processing in the Level 1.5 phase.

(charged particles and albedo photons) events near 10^{-4} for γ -ray energies larger than 100 MeV.

The AGILE trigger is divided into 3 levels, two hardware ones (Level 1 and 1.5) and a software one (Level 2) [4]. The main goal of the two hardware levels is to identify the γ -rays and avoid the readout procedure for background events, thus reducing these events of a factor near 100.

The Level 1 trigger is given by the coincidence of 3 out of 4 consecutive Silicon Tracker views. Veto signals from the top AC and a suitable combination of the lateral ACs are foreseen. For energetic photons ($E > 1$ GeV), an independent trigger can be generated by a high energy release in the minicalorimeter. The time available for the decision is $< 1\text{--}1.3$ μs .

The Level 1.5 trigger uses the information on the triggered ASICs to obtain a partial reconstruction of the track based on the ASIC position inside the tracker itself. We use two algorithms:

- R-trigger: the ratio of the number of triggered ASICs and the number of triggered views is computed; this ratio has a value of the order of 1 for a background event such as a single charged particle (1 ASIC per view) and greater for a cosmic γ -ray (if a photon has converted, two particles are produced which can trigger more than one ASIC per view).

- DIS-algorithm: the relative position of the triggered ASICs with respect to the lateral AC that was hit is compared as shown in Fig. 4. If only one of the lateral ACs gives a signal, the distance of the triggered ASICs from that AC is computed. This distance increases if the event is a charged particle which has entered the AC (right part of Fig. 4) and decreases if one particle of the pair created by the photon hits the AC (left part of Fig. 4).

The response time is around 10–20 μs and the event rate is reduced to 70 Hz.

A positive response from the Level 1.5 starts the readout phase which is still part of the synchronous part of the readout. The typical frontend freeing duration is 100 μs , three orders of magnitude better than the one of the previous γ -ray astrophysics experiment, EGRET. Only the triggered ASICs are going to be read (sparse readout). Pedestal subtraction, common mode subtraction and zero suppression are implemented in hardware and provide a data reduction greater than 90%.

The Level 2 trigger reconstructs the track in a 3D space using also the information from the minicalorimeter. The rate of the events transmitted to the ground segment is of the order of 30 Hz.

4. Testbeam prototype results

All the tracker components have been tested in several testbeam periods at the T11 beamline at the CERN PS (East Hall) [7]. Two different kinds of beams have been used:

- charged particles (pions and electrons) in the momentum range 0.3–3.6 GeV/ c to study the performance of the silicon detector and of the hardware trigger levels,
- photons produced by bremsstrahlung of electrons in the momentum range 0.3–1 GeV/ c to prepare the offline analysis (ground segment), improve the simulation and start the preparation of the satellite calibration facility.

Fig. 5 shows two of the ensembles we have tested: on the left, the AGILE silicon ladder (assembled by Mipot [5]) for the study of the detector performance and on the right, the four single layer structure made of four AGILE detectors at 1.8 cm one from the other for the trigger and photon beam studies. There is the possibility to position a converter behind each detector to simulate the AGILE tracker.

The AGILE silicon detector is characterized by one floating strip between each readout strip, which means that the total charge collected by the readout strips depends on the hit position of the particle. The choice of a floating strip configuration has been made in order to obtain a good position resolution together with power consumption saving.

The main features of the silicon detector such as implant width and interstrip capacitance have been chosen in order to have more than one strip per cluster while at the same time maintaining the signal high enough on the readout strips to generate a trigger even when the particle crosses the floating ones.

Fig. 6(a) shows the signal pulse height in ADC counts for the AGILE ladder and for a 2 GeV/ c beam as a function of the hit position in the strip itself as measured by a high resolution silicon telescope [8]: 0 μm is the center of one readout strip and 242 μm is the center of the nearby one; the position corresponding to 121 μm is the center of the floating strip. When the

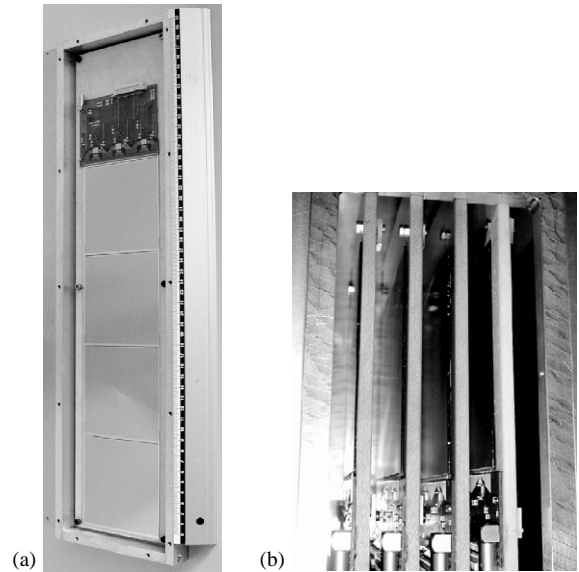


Fig. 5. Photo of one AGILE silicon ladder (a) and of the structure used to study the photon beam and the trigger (b).

particle crosses the center of the floating strip, the resulting collected charge (given by the sum of the charges collected by the readout strips on the side of the floating one) is 76% of the total charge.

Fig. 6(b) shows the analog signal of the readout strip obtained with a simulation of the AGILE silicon detector with SPICE [9] for the two cases of a particle crossing the readout strip and the floating strip. From the simulation, we were expecting a total collected charge in the worst case of 70% which is very similar to the experimental result.

The trigger efficiency of the silicon ladder as a function of the threshold is shown in Fig. 7 for two different incidence angles of the beam with respect to the strips (90° means orthogonal incidence). Even with a floating strip configuration, a threshold of $\frac{1}{4}$ of a MIP ensures 100% efficiency.

For a complete description of the AGILE ladder performance, see [10].

The four layer detector has given the possibility to implement the majority trigger and the first method of the Level 1.5 (the R-trigger). The boards have been designed with the same solutions

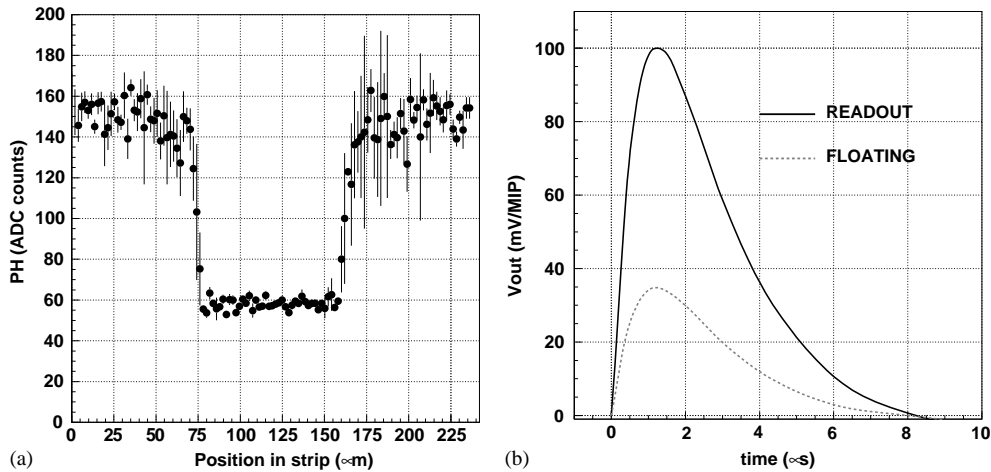


Fig. 6. (a) Signal pulse height in ADC counts for the AGILE ladder as a function of the hit position in the strip: 0 and 242 μm are the centers of two nearby readout strips. (b) Analog signal of the readout strip obtained with a SPICE simulation of the AGILE detector for a particle crossing the readout and the floating strip.

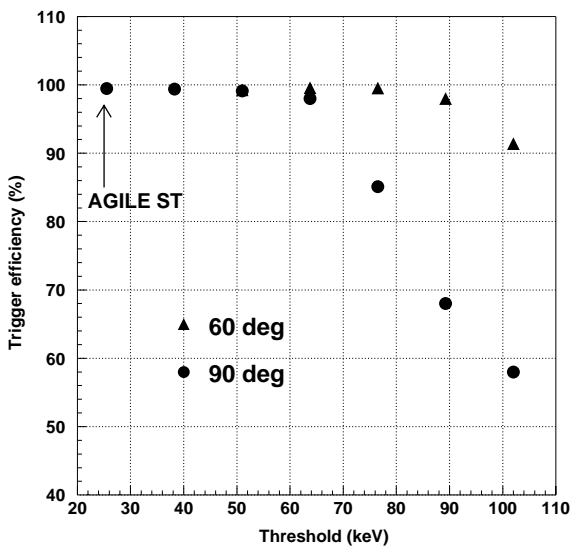


Fig. 7. Trigger efficiency of the AGILE ladder as a function of the threshold for two different incidence angles of the beam.

that will be used in the flight model. Fig. 8 shows two typical events:

- (a) a background event (one single charged particle): this event will be rejected on board (and thus the readout phase will be inhibited) because of a R-trigger value equal to 1,

- (b) a photon event, with the two tracks corresponding to the electron and the positron: this event is accepted.

For each of the plots, the x-axis is the strip number of one of the four modules and the y-axis the pulse height of the signal. Mod. 4 is the first module crossed by the beam.

The four layer structure has been used with a tagged photon beam in the energy range 10–450 MeV. Fig. 9 shows two photon events, respectively with energy 30 MeV (a) and 410 MeV (b) as measured by a silicon spectrometer, which has been converted in an electron–positron pair in the converter positioned before the first detector (mod. 4).

5. Conclusions

The AGILE silicon tracker will be launched in 2003 and with its 4 m² of silicon it will be the largest silicon detector used on a satellite up to now.

The prototype studies on both the detector and the electronics have demonstrated the validity of the analog readout and of the floating strip principle. The measured trigger efficiency is the

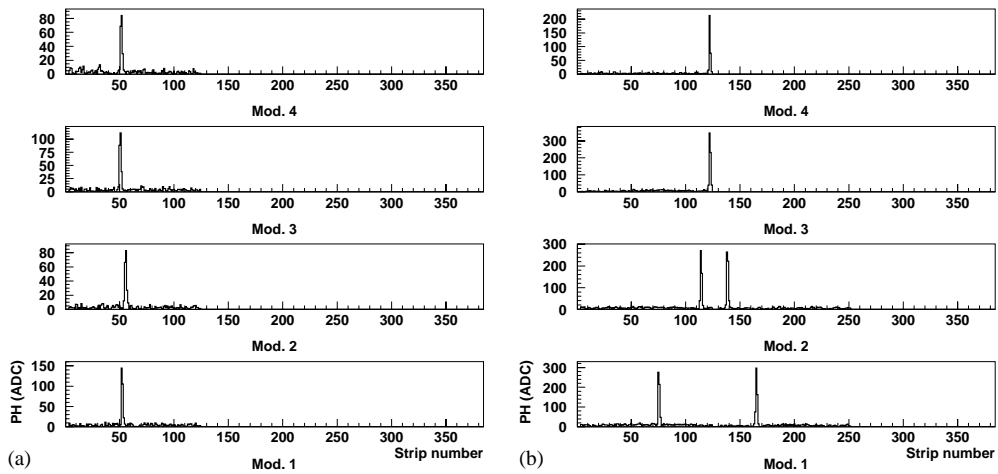


Fig. 8. (a) A background event that will be rejected on board due to an R-trigger value of 1 and will inhibit the readout phase and (b) a photon event.

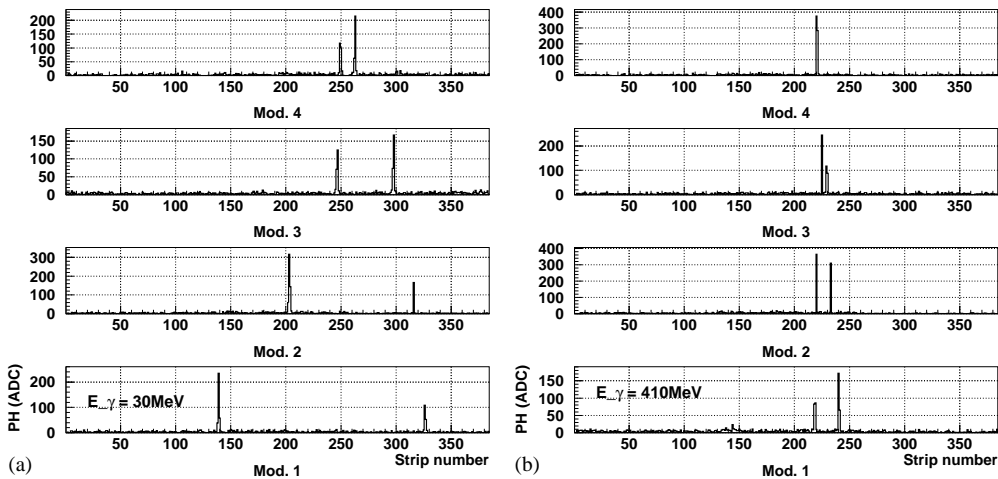


Fig. 9. Electron–positron pair as detected by the silicon 4 layer structure for a 30 MeV photon (a) and a 410 MeV one (b).

result of a low noise level even with a 38 cm long silicon ladder.

The implementation of hardware algorithms such as the R-trigger method will give AGILE the possibility of reducing the background rate while maintaining a good detection efficiency and a low dead time.

The development of the calibration facility has already been started and the statistics collected in terms of photon events in three different testbeams

is being used to develop the Level 2 algorithms and the offline analysis.

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