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Radiation issues in the Gamma-ray Large Area Space Telescope GLAST

Hartmut F.-W. Sadrozinski

SCIPP, University of California Santa Cruz, Santa Cruz, CA 95064, USA

Abstract

The GLAST large area telescope instrument has been designed for high sensitivity, high precision gamma-ray detection in space. It will contain more than 80 m^2 of single-sided AC-coupled silicon detectors. The use of silicon detectors in space will pose special challenges for the design, testing and operation, among them attention to radiation issues unique to the space environment. © 2002 Published by Elsevier Science B.V.

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1. GLAST overview

The Gamma-ray Large Area Telescope (GLAST) is a space mission to explore the gamma-ray universe. The principal instrument on the GLAST mission is the GLAST Large Area Telescope (LAT) [1,2]. GLAST LAT will be a follow-up to the highly successful EGRET experiment on the Compton Gamma-ray Observatory (CGRO) [3], which opened up the high-energy gamma-ray sky to detailed investigations. The method of detecting gamma-rays through conversion to electron–positron pairs and measurement of their direction in a tracker (TKR) and their energy in a calorimeter (CAL) is unchanged from EGRET. Technological improvements, i.e. the use of silicon microstrip detectors as the tracking device, a deeper hodoscopic CAL and a segmented charged particle veto shield together, increase the sensitivity of our instrument by a factor of 50 over EGRET. GLAST's principal science goals are discussed in Section 2.

As shown in Fig. 1, GLAST LAT is a highly modular instrument, with a 4×4 array of "towers" of TKR and CAL modules, surrounded by a hermetic anti-coincidence shield (ACS) and a thermal blanket. The design and the predicted performance will be discussed in Section 3.

The use of silicon detectors is crucial for the GLAST instrument: they are highly efficient for min. ion. particles over the whole active area of the detector, have fast response, can be operated with negligible dead time and allow very high tracking resolution. They are very reliable, need relative low operating voltage and have no consumables. There has been a steady increase in the use of silicon detectors in space science (NINA [4]. ACE/SIS [5], AMS [6]), but on a smaller scale. Note that the area covered by silicon detectors in GLAST will be of the order 80 m^2, on a par with the inner detectors in both ATLAS and CMS. The special challenges for the silicon TKR are discussed in Section 4. The radiation issues will be discussed in Section 5.

E-mail address: hartmut@scipp.uscc.edu (H.F.-W. Sadrozinski).

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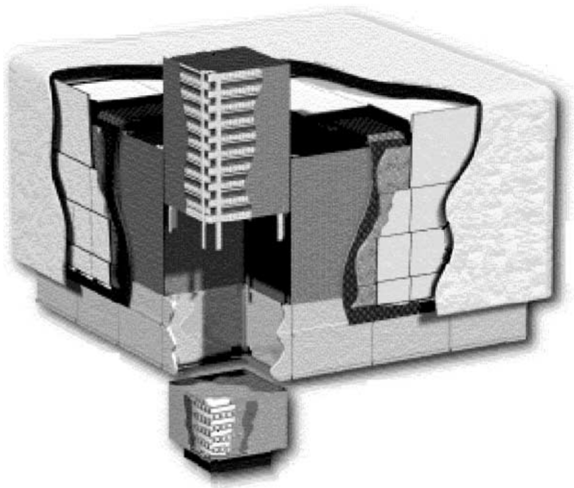

Fig. 1. Design of the GLAST LAT instrument. The tracker and calorimeter modules of one of the 16 towers are shown through the cut-away portion of the segmented anti-coincidence shield and the thermal blanket, both act as shielding for the silicon detectors.

2. GLAST science goals

Our understanding of the universe has experienced a revolution in the last few years. Gamma-rays provide a unique window into a variety of violent, transient processes, and they have a distinct advantage over other high-energy cosmic rays in that they point back to their source, thus allowing identification of counterparts in other wavebands, including radio, optical and X-ray regions.

The principal GLAST science objectives may be grouped into four themes:

- *Probe dark matter and the early Universe*. GLAST will have good sensitivity to observe mono-energetic gamma-ray "lines" above 30 GeV from the annihilation of super-symmetric particles χ, which are candidates of dark matter. Observations of gamma-ray Active Galactic Nuclei (AGN) serve to probe super massive black holes through jet formation and evolution studies, and provide constraints on the star-formation rate at early epochs through the absorption over extragalactic distances.
- *Determine the high-energy behavior of gamma-ray bursts (GRBs) and transients*. Variability has long been a powerful method to decipher the workings of objects in the Universe on all scales. Variability is a central feature of the gamma-ray sky. GLAST will detect about 200 GRBs per year, provide localization to better than $3'$ for 25% of the bursts, and will provide spectra up to 100 GeV, with less than 20 μs deadtime per event.
- *Understand the mechanisms of particle acceleration in AGN, pulsars and Super Nova Remnants (SNRs)*. GLAST will attempt to solve the mysteries of the formation of jets, the extraction of rotational energy from spinning neutron stars, and the dynamics of shocks in SNRs. GLAST will detect $\sim 10^4$ extragalactic sources and from hundreds to perhaps a thousand Galactic sources during the first 2 yr of operation. The large FOV, sensitivity and good energy measurement capability will allow detailed comparisons with models of AGN jets.
- *Resolve the gamma-ray sky: unidentified sources and diffuse emission*. Interstellar emission from the Milky Way and a large number of unidentified sources are prominent features of the gamma-ray sky. GLAST will help determine the identity of the latter by source localization to $\sim 1'$ and through searches for time variability or pulsations.

3. Design and predicted performance of GLAST

Detailed simulations, trade studies and technology development have resulted in the design of a modular instrument composed of three detector subsystems (Fig. 1):

- *Precision converter–tracker*. Incident photons convert in one of the 16 layers of lead converters, and resulting e^- and e^+ particles are tracked by single-sided silicon-strip detectors (SSDs) through successive planes. The pair conversion signature is also used to help reject the much larger background of charged cosmic rays.

- *Calorimeter*. CsI(Tl) bars, arranged in a segmented manner, give both longitudinal and transverse information about the energy deposition pattern. The depth of the CAL is 8.5 R.L., for a total instrument depth of 10.1 R.L. Gamma-rays incident under large angle encounter much more depth and will be measured with a spectral resolution needed for dark matter search.
- *Anti-coincidence detector*. The ACD array of plastic scintillator tiles provides most of the rejection of charged particle backgrounds. Its segmentation avoids the "backsplash" self-veto that affected EGRET above a few GeV.

The overall aspect ratio of the instrument (height/width) is 0.4, allowing a large angular acceptance FOV and ensuring that nearly all showers initiated in the TKR will pass into the CAL for energy measurement.

We have performed studies of the instrument characteristics to improve the design. For example, advances in the TKR ASIC design and prototyping [7] allowed us to make longer silicon ladders, which in turn permitted us to increase the footprint of the towers and reduce the number of towers from the original 49 (7×7) to 25 (5×5) and finally to 16 (4×4). The fraction of active material was increased by baselining silicon detectors from 6″ wafers instead of the older 4″ wafers [8]. At the same time, the number of sensors was cut in half from about 20,000 to 10,000, which results in savings of glue joints, wire bonds and testing. The TKR will be build in modular fashion in the form of double layers of silicon mounted on support structures ("trays"), with every other tray rotated by 90° to allow measurement of both x and y. Thus, only one type of basic building block has to be built, containing 2×32 silicon detectors, and replicated 16×18 times. Details can be found in Ref. [9].

Our baseline design combines 12 high-precision layers of thinner 2.5% converters ("front" section) with 4 layers of 25% converters ("back" section), thus ensuring efficient conversion of the incident flux. The dependence of the effective areas of the two groups on the photon energy is shown in Fig. 2b. Note that the effective area calculation includes the effect of all cuts, including those needed for cosmic ray background reduction. The photon angular resolution (68% containment angles) is shown in Fig. 2a as a function of photon energy. The resolution improves by about a factor of 10 with every energy decade and exhibits a degradation of about a factor of 2–3 in the last four (thicker) layers, both due to the effect of multiple scattering. The field of view is shown in Fig. 2c. The instrument design with thick bottom converters does lead to a worsening of the energy resolution (mainly at energies below 100 MeV). Our predicted energy resolution is shown in Fig. 2d, showing not much improvement with respect to EGRET at low energy.

Track reconstruction in the silicon TKR is at the heart of the GLAST analysis software. The gamma-ray is reconstructed from the direction and energies of the electron–positron pair, which in turn are reconstructed from silicon strip hits. This is optimally done with the Kalman filter method [10].

4. Technical challenges for GLAST

Any large-scale application of a detector technology, be it in HEP or in space, generates its specific challenges.

Challenge 1: *Launch*. The launch on a Delta II rocket with expected accelerations of 10 g requires mechanical design solutions not needed in accelerator based research. Vibration and acoustic shocks have to be included in the designs. Potential failure modes include breakage of detectors, wire bonds and destruction of the trays. We have performed several shake tests of our tray structures, both with mechanical samples and with live detectors, and have found that none of the ~5000 wire bonds were broken and that the leakage current characteristics were unchanged after vibrations with 14 g.

Challenge 2: *On board cosmic ray rejection*. The down-load bandwidth of the instrument will limit the average transmitted data rate to about 30 Hz, while the expected trigger rate from charged cosmic rays is about 5 kHz. The data reduction has to be done in successful triggers, where level 1

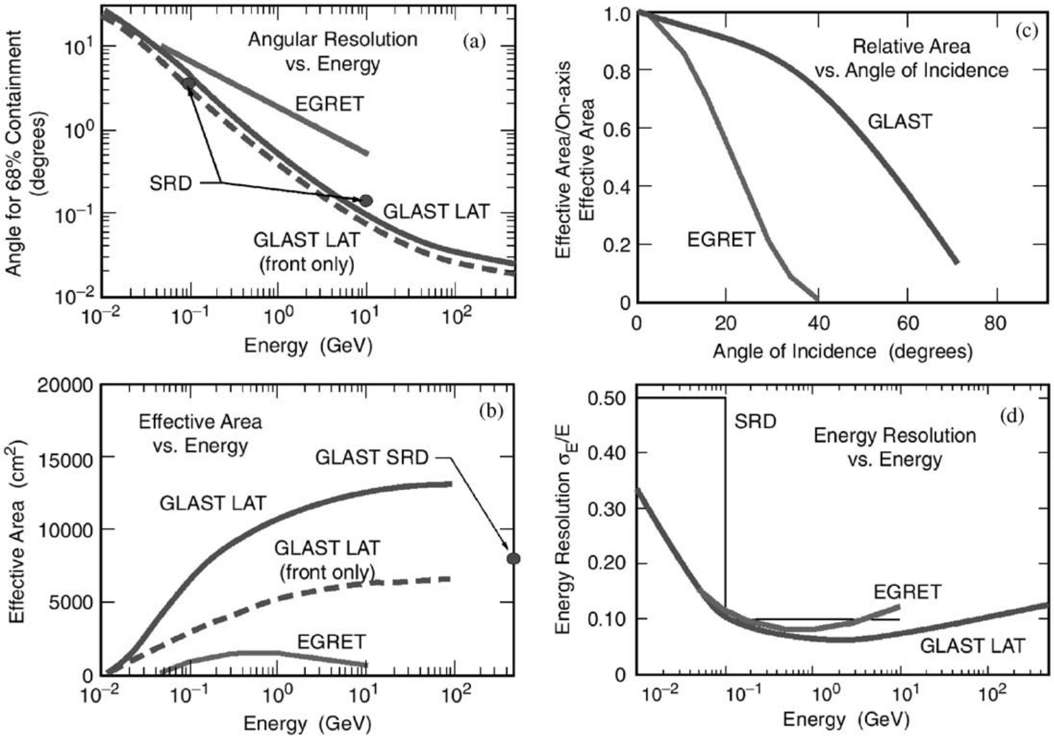

Fig. 2. Predicted performance of the GLAST LAT. The performance is compared to the GLAST Science Requirements Document (SRD) and EGRET. The front part of the tracker is shown separately, when appropriate [1].

is hardware (TKR or CAL) initiating a readout of the complete instrument, level 2 a tracking trigger to reject charged particles on the tower level and level 3 a full instrument trigger.

Challenge 3: *1* M *channels, 250* W *power*. The electrical power of a satellite mission is limited. The LAT instrument has a power budget of 650 W, of which less than half is available for the TKR, allowing less than 250 μW for each of the 1 million channels. This is about $\frac{1}{10}$th the power consumption of previous ASICs with comparable noise performance. The details for the front-end electronics prototypes satisfying the power and noise budget are given in Ref. [11].

Challenge 4: *TKR noise and efficiency*. The noise and efficiency requirements of the GLAST LAT TKR are more stringent than in particle physics application because the main instrument trigger is based on the silicon TKR alone. The signals from individual single silicon layers with about 1500 channels are OR'd and than put into a coincidence with additional five layers. This requires that the noise occupancy of a single channel is less than 10^{-4}. As shown in Ref. [11], this performance goal has been attained in the ASIC prototypes. In addition, the system allows masking of noisy channels. The single-track efficiency has to be of the order 99% to permit high trigger and reconstruction efficiency. Another important requirement is derived from the need to identify and measure the first hit after the conversion in order to minimize the tails in the photon resolution.

Challenge 5: *Space environment*. The remoteness and forbidding nature of space poses additional experimental complications. The radiation effects will be discussed in Section 5. A challenging problem arises from the mismatch of the coefficient of thermal expansions (CTE) in the TKR: silicon detectors, lead converter and the structural materials have different CTE, which leads to very large forces in large temperature excursions, which might be unavoidable during flight. The zero gravity environment requires low-outgassing of all materials, including glues.

5. Radiation effects

5.1. Radiation levels

The radiation levels in space are a strong function of the orbit. The low-earth orbit of GLAST (~ 550 km) is below the radiation belts, although the GLAST orbit of 28° inclination traverses the South Atlantic Anomaly (SAA), a region of trapped protons and electrons of fairly low momenta, during which the trigger rate is so high that the experiment is shut down. In addition, part of the primary charged cosmic ray flux of protons and heavy ions is present during the whole orbit, with cut-offs due to earth's magnetic field. The particle fluxes have been traced reliably, for example by EGRET and recently by AMS [12].

Both the thermal blanket and the ACD surrounding the GLAST silicon TKR provide considerable shielding against low-energy electrons and protons. This is shown in Fig. 3, where the total dose for a 5 yr GLAST mission is shown as a function of shielding: at the shielding mass value of about 2.5 g/cm^2 of Al for GLAST, all electrons are filtered out and the remaining protons amount to a total dose of 1 krad [13]. The NASA GLAST Interface Requirements Document (IRD) [14] allows for uncertainty in the dose determination by requiring a design margin of $5\times$ in the radiation levels.

5.2. Total dose and displacement effects

The radiation levels are extremely low by LHC standards. The flux of low-energy protons in the SAA causes limited surface and bulk damage, mainly in a modest increase in the leakage current. Yet due to the long shaping time (1.3 μs) and the considerable length (37 cm) and width (230 μm) of the strips, the expected leakage current increase is

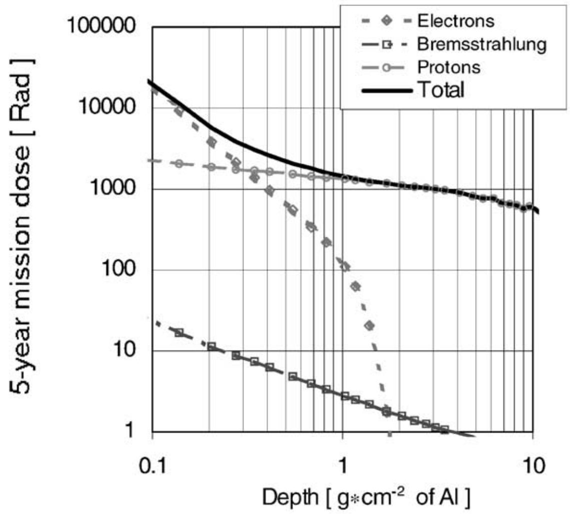

Fig. 3. Predicted total dose for a 5 yr GLAST mission, as a function of shielding. The GLAST silicon detectors are behind a shield of blanket, ACD scintillators and tracker walls of at least 2.5 g/cm^2 [13].

enough to limit the operating temperature of the silicon detectors to below +25°C, in order to keep the signal-to-noise ratio above 20.

5.3. Single event effects (SEE)

Part of the cosmic ray flux is in heavy ions, and their very high specific ionization ($\sim Z^2$) can induce SEE like latch-up (SEL) and single-event upsets (SEU) in the readout electronics and damage to silicon detectors [15]. SEE are characterized by the Linear Energy Transfer (LET), which is about 1.3×10^{-3} MeV/(mg/cm^2) for min. ion. particles, but about 1000 times larger for Fe ions (1–2 MeV/(mg/cm^2), as shown in Fig. 4) of the expected LET spectrum for GLAST. The GLAST IRD [14] requires SEE immunity below an LET of 10 MeV/(mg/cm^2).

Single event upset is caused by a large charge deposit in the transistors, which changes the transistor state and thus flips a bit. Both transistor and circuit design features can mitigate the problem.

Latch-up is due to very large ionization in the space between two transistors shorting out the

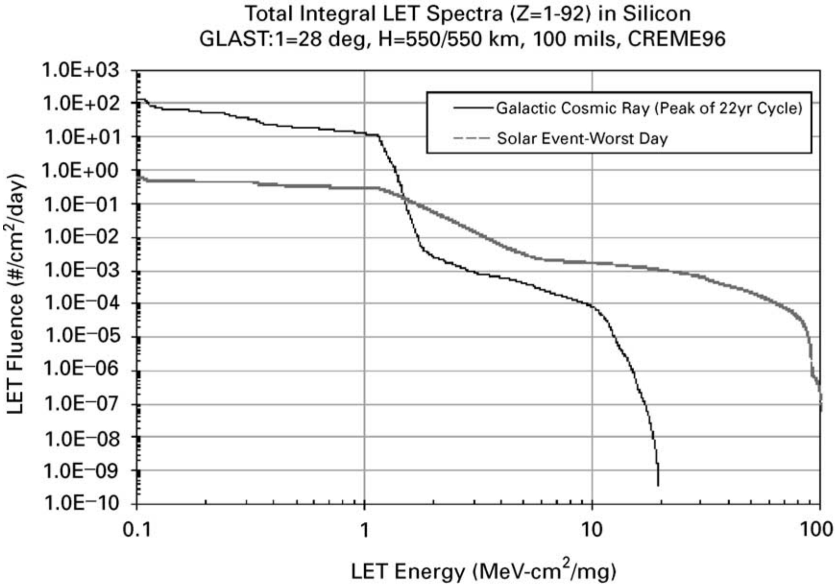

Fig. 4. Integrated daily LET spectrum for silicon. The shielding of the GLAST silicon detectors is taken into account [14].

implants through the substrate and generating parasitic bipolar transistors, which connect the power supply and ground and can lead to destruction of the ASIC. The I–V curve leading to SEL is shown in Fig. 5: SEL requires that the voltage exceeds the breakover voltage V_B, leading through a region of negative resistance to the latch-up region, which is maintained as long as the voltage exceeds the holding voltage V_H. Again, certain layout techniques can mitigate the vulnerability to SEL, like increasing the separation of the transistor. Very important is the choice of CMOS technology: in Ref. [16], the latch-up resistance of the HP 0.5 μm process to LET of 50 MeV/(mg/cm^2) is demonstrated. Another choice is an SoI process. We are testing latch-up and SEU both with lasers and heavy ion beams.

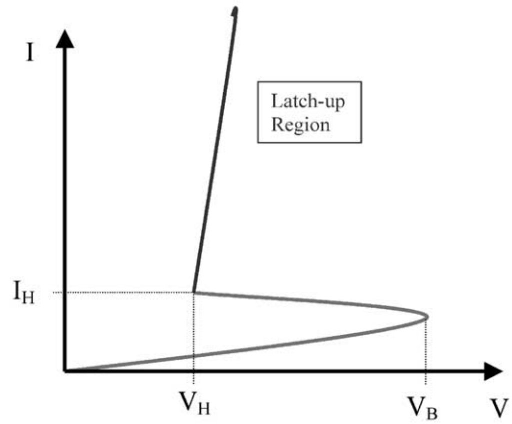

Fig. 5. I–V characteristic of the parasitic bipolar structures at latch-up. The holding voltage V_H is of the order of 1 V.

Heavy ions are also a threat to AC-coupled silicon detectors. As show in Ref. [17], the large ionization from heavy ions can short out the detector bulk for extended times and builds up large voltage differences across the coupling capacitors, which could lead to their breakdown. For detectors with floating readout electrodes, the potential in the detectors float to $\frac{1}{2}$ of the biasing potential. In detectors under operation, the potential on the implants will depend on the biasing and by-passing network of resistors and capacitors. Fig. 6 shows the peak voltage on the implants during laser irradiation, while the detectors are biased with 100 V from the backplane and the implants are biased to ground: unless the resistors on the backplane are large and the

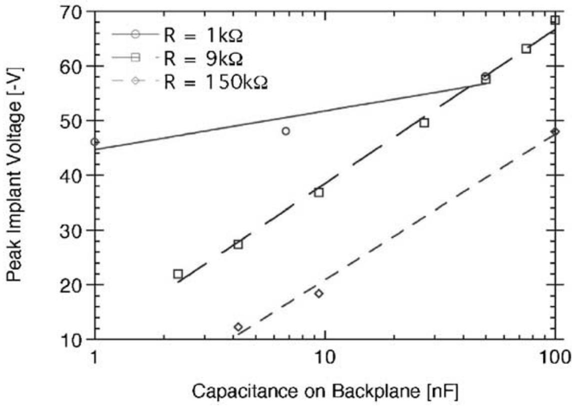

Fig. 6. Voltage on implants of AC-coupled silicon detectors during shortening-out of the bulk with a high intensity IR laser beam. The dependence on both capacitor and resistor values of the by-passing network on the backplane is shown [17].

by-pass capacitors are small, the potential on the implants can reach a large value. This requires testing of the coupling capacitors up to the biasing voltage.

6. Status and schedule

Using resources from NASA, US Departments of Energy and Defense and non-US collaborators, critical technologies and design aspects for the instrument have been demonstrated and validated. This includes thermal and vibration tests and beam tests at SLAC and CERN with simple versions of the TKR, CAL and ACD. Detailed comparisons of beam-test data with the simulations validated our Monte Carlo design tool. The results are described in a paper accepted for publication in NIM A [18]. We have since then designed and constructed a full-scale tower, the beam test engineering model (BTEM), which includes all three subsystems and was used in a beam test at SLAC in 1999/2000. This tower essentially constitutes $\frac{1}{16}$ of the final instrument, and will be used in the future for a balloon flight test. It also serves as an important software development platform and test bed of production and quality assurance methods [9].

In February 2000, the proposal of our collaboration to build and operate the GLAST LAT instrument was accepted, with the launch of the GLAST mission scheduled for the year 2005.

Acknowledgements

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