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GLAST, a Gamma-Ray Large Area Space Telescope

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Abstract

The GLAST LAT instrument has been designed for high precision gamma-ray detection in space. It will contain more than 80 m^2 of single-sided AC-coupled silicon detectors. The design of the instrument will be described, and the predicted performance will be traced back to the scientific goals of the GLAST mission. The application in space will require stringent requirements for the silicon detectors, and the R&D work needed to put the instrument into space by 2005 will be described. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Silicon microstrip detectors; Space; Gamma-ray

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 and their energy in a calorimeter is unchanged from EGRET. Technological improvements, i.e. the use of silicon microstrip detectors as the tracking device, a deeper hodoscopic calorimeter and a segmented charged particle veto shield together, increase the sensitivity of our instrument by a factor 50 over EGRET. The large photon conversion probability expressed in the effective area A_{eff}, the improved angular resolution (point spread function PSF), the improved energy resolution at high energy and the elimination of the self-veto in the veto shield will extend the science capabilities of GLAST LAT into the TeV range and allow overlap with ground-based telescopes. 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 tracker (TKR) and calorimeter (CAL) modules, surrounded by a hermetic anti-coincidence shield (ACD) 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],

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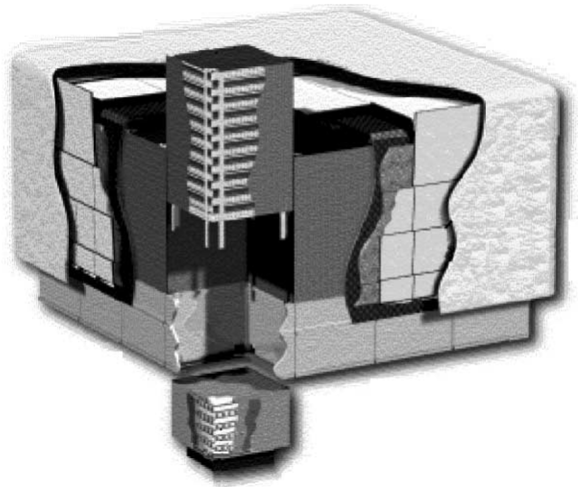

Fig. 1. Design of the GLAST LAT instrument. The tracker and calorimeter modules of one of the 16 towers is shown through the cut-away portion of the segmented anti-coincidence shield and the thermal blanket.

AMS [6]), but on a much smaller scale. Note that the area covered by silicon detectors in GLAST is of order $80\,m^2$, on par with the inner detectors in both ATLAS and CMS. The special challenges for the silicon tracker are discussed in Section 4. The schedule will be mentioned in Section 5.

2. GLAST science goals

Our understanding of the universe has experienced a revolution in the last few years. A major contributor has been the observations by EGRET of high-energy gamma rays from blazers, pulsars, and unidentified sources, of delayed emission from gamma ray bursts and solar flares, and of the diffuse radiation, which have done much to alter our picture of the universe. 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 of pointing back to their source, thus allowing identification of counterparts in other wavebands, including radio, optical and X-ray regions. EGRET's discoveries have posed many new questions, which GLAST will try to answer. GLAST is projected to discover about 10,000 new sources compared to EGRET's 270, with much better localization than possible with EGRET, allowing new systematic and statistically powerful approaches to all of these questions.

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 for dark matter

$$\chi\chi \to \gamma\gamma,\ \gamma Z.$$

The original indication for the existence of dark matter came from the rotation curves of galaxies. Hence, we would expect enhanced dark matter signals coming from the center of our own galaxy. GLAST will be able to explore a part of the parameter space for Higgsino's and Gaugino's up to masses of 130 GeV, both in the $\gamma\gamma$ and the γZ channels, as shown in detail in our proposal to DoE [2]. The two narrow photon lines from these two channels can be separated as long as the energy resolution is of order 4%.

In addition, we would be able to detect decays of relics from the very early Universe, such as cosmic strings or evaporating primordial black holes. A relatively new idea is to use photons from gamma-ray bursts to detect quantum gravity effects, which would show up as a spectral dispersion in the arrival time of gamma rays.

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 absorption over extra-galactic 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. In scanning mode, GLAST will detect the weakest EGRET sources, in a single day, with 5σ significance; bright AGN flares will be detected within minutes. On shorter timescales, GLAST will detect about 200 gamma-ray bursts 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 (compared with 100 ms for EGRET, see Fig. 2). The wide field of view (FOV) will also allow the study of delayed high-energy emission and how it relates to the afterglow at lower energies.

Understand the mechanisms of particle acceleration in Active Galactic Nuclei (AGN), pulsars, and Super Nova Remnants (SNRs): This understanding is a key to solving 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 hundreds to perhaps a thousand Galactic sources during the first two years of operation. The large FOV, sensitivity and good energy measurement capability will allow detailed comparisons with models of AGN jets over a range of flare intensities two orders of magnitude larger than EGRET could detect, and will allow the detailed study of a wide variety of pulsars (> 50) during scanning observations. Good calorimetry for measuring spectral roll-offs above 1 GeV, and phase-resolved spectra, uniquely probe cascade models. The expected shock acceleration of cosmic ray nuclei in SNRs will be observed for the first time by resolving the acceleration site both spatially and spectrally in > 10 nearby SNRs.

Resolve the gamma-ray sky: unidentified sources and diffuse emission: Interstellar emission from the Milky Way and a large number of unidentified

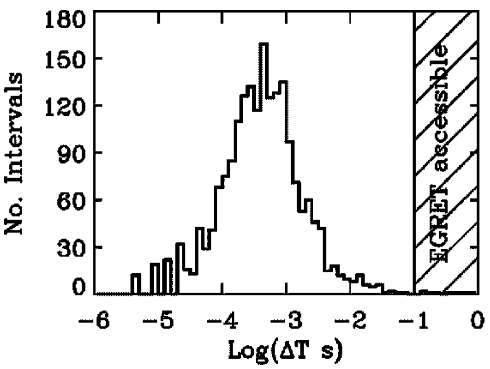

Fig. 2. Simulated time interval between gamma rays about 200 GRB expected for GLAST, enabling observation of substructure on the 10 μs scale.

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, including high-sensitivity blind searches for periodicity typical of pulsars and binary systems. With its improved angular resolution, GLAST will also address cosmic-ray propagation in the interstellar matter and magnetic field of the Milky Way on kpc and sub-kpc scales. On larger scales, GLAST will open up studies of cosmic-ray production and propagation in nearby galaxies and clusters of galaxies.

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 (TKR): 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. The high intrinsic efficiency and reliability of this technology enables straightforward event reconstruction and an excellent angular resolution (“point-spread function” (PSF)) with small tails.

Calorimeter (CAL): CsI(Tl) bars, arranged in a segmented manner, give both longitudinal and transverse information about the energy deposition pattern. The depth of the calorimeter is 8.5 RL, for a total instrument depth of 10.1 RL Gamma-rays incident under large angle encounter much more depth and will be measured with a spectral resolution needed for dark matter search. The depth and segmentation enable the high-energy reach of GLAST and contribute significantly to the background rejection.

Anticoincidence Detector (ACD): 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.

Incident particles successively encounter the ACD, the TKR and the CAL. 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. The instrument design is modular, with the TKR, CAL and associated DAQ modules forming an array of 16 identical towers supported by a low-mass grid structure. Modularity provides ample redundancy and offers many benefits, including:

- Simplified event reconstruction.
- Ease of fabrication, construction, and integration.
- Significant risk reduction through early testing at flight scale.
- Reduced schedule risk because comprehensive pre-flight calibration studies can be done in parallel with the production of the remaining towers.

We have performed studies of the instrument characteristics that have led to design improvements. These studies have addressed our desire to improve the performance and to simplify the instrument, and the need to bring the power, mass and linear dimensions into compliance with the limited resources of the space craft. For example, advances in the tracker 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 to half from about 20,000 to 10,000, which results in savings of glue joints, wire bonds and testing. The tracker 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 these proceedings [9].

The performance of the instrument was optimized in a study of the distribution of the converter mass. The amount and distribution of the converter mass in the tracker is an important parameter of the instrument. The number of photons converted in the tracker depends on the total amount of converter mass. Thus the effective area A_{eff} is increased by increasing the converter mass. Photons not converted in the tracker are converted in the calorimeter, with larger backgrounds and much less precise determination of the direction. On the other hand, the photon angular resolution, i.e. the 68% containment angle PSF(68) is degraded by material in the tracker due to multiple scattering of the electron–positron pair. The multiple scattering angle is proportional to the inverse of the energy and the square root of the traversed material (in radiation lengths). Thus it is desirable to minimize the amount of material in between measurements. To quantify the performance in terms of science impact, it is useful to combine parameters to form various figures of merit (FOM). For example, the significance of the measurement of a background-limited single source is approximately given by

$$\mathrm{FOM} = [A_{\mathrm{eff}}]^{0.5}/\mathrm{PSF}(68).$$

One approach to maximizing this FOM is to increase the number of measurement layers, with correspondingly reduced converter thickness. This would, in addition, increase the measurement lever arm, with a corresponding improvement of the angular resolution at high energy. However, it also increases cost and leads to an unfavorable aspect ratio, cutting down the field of view. Furthermore, the increase in lever arm would be useful only up to the point when the electrons start a broad shower, which happens after about 0.5 radiation lengths.

A tracker layout with converters of two distinctly different thicknesses combines the advantages of a precision tracker with that of a pre-shower detector having dramatically improved angular resolution compared with the calorimeter alone. In addition, because of the square-root dependence of the angular resolution on the amount of material, increasing the converter thickness by a factor of 10 degrades the photon angular resolution by only a factor of 3, while increasing the number of photon conversions by a factor of 10. This can, for example, give significantly greater sensitivity in low-background regions (but does not improve the figure-of-merit described above for background-limited regions).

Our baseline design combines 12 high-precision layers of thinner 2.5% converters ("front" section) with four layers of 25% converters ("back" section), thus ensuring efficient conversion of the incident flux. The effective area contributed by each layer is shown in Fig. 3 and compared with a layout with uniform 3.5% converters. The large increase in the effective area in the new converter design is evident. There are two distinct groups of photons, identified by their layer of conversion, each with roughly the same statistics. The dependence of the effective areas of the two groups on the photon energy is shown in Fig. 4b. 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) for the graded converter design is shown in Fig. 4a as a function of photon energy. The resolution improves by a factor of about 10 with every energy decade and exhibits a degradation by a factor of about 2–3 in the last four (thicker) layers, as expected from the effect of the increased multiple scattering. If there is no background, then the two photon populations mentioned above both contribute to science with the same weight. In the presence of the background, where the photon angular resolution is important, the two populations of photons have to be combined in quadrature, weighted by the respective effective area. The latter number is shown in Fig. 4a. The field of view is shown in Fig. 4c.

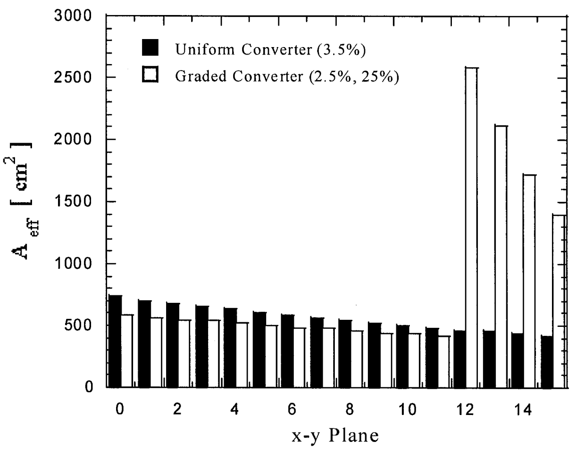

Fig. 3. Effective area per layer of a tracker with uniform converter thickness (3.5%) and of the graded converter design with 12 front layers (2.5%) and 4 back layers (25%). The attenuation of the gammas in the tracker is clearly visible.

It is worth emphasizing that the strategy of using thick radiators in the rear section of the tracker works only because of the precision and high efficiency of silicon strip detectors, which ensures a good angular measurement in the first two x, y planes following a conversion. 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. 4d, showing not much improvement with respect to EGRET at low energy, but benefiting from the calorimeter longitudinal segmentation at high energy, which permits much better resolution with the help of shower leakage corrections.

Track reconstruction in the silicon tracker 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. Crucial performance parameters depend on the efficiency, accuracy, and background-discrimination power of the tracking algorithm. Given that the charged-particle tracking resolution is dominated by multiple scattering up to very high energies, a tracking code is needed that properly treats multiple scattering at every measuring plane. This is optimally done with the Kalman filter method, and we have developed such a program, which has yielded a marked increase in efficiency and robustness when compared with the least squares method, both in track reconstruction and fitting [10]. The Kalman filter was developed in stages: first it was applied to single tracks in each projection separately, then to the two-dimensional fitting of track pairs coming from a common vertex. Finally, the pairs were fitted in three dimensions to correlate the x- and y-projections.

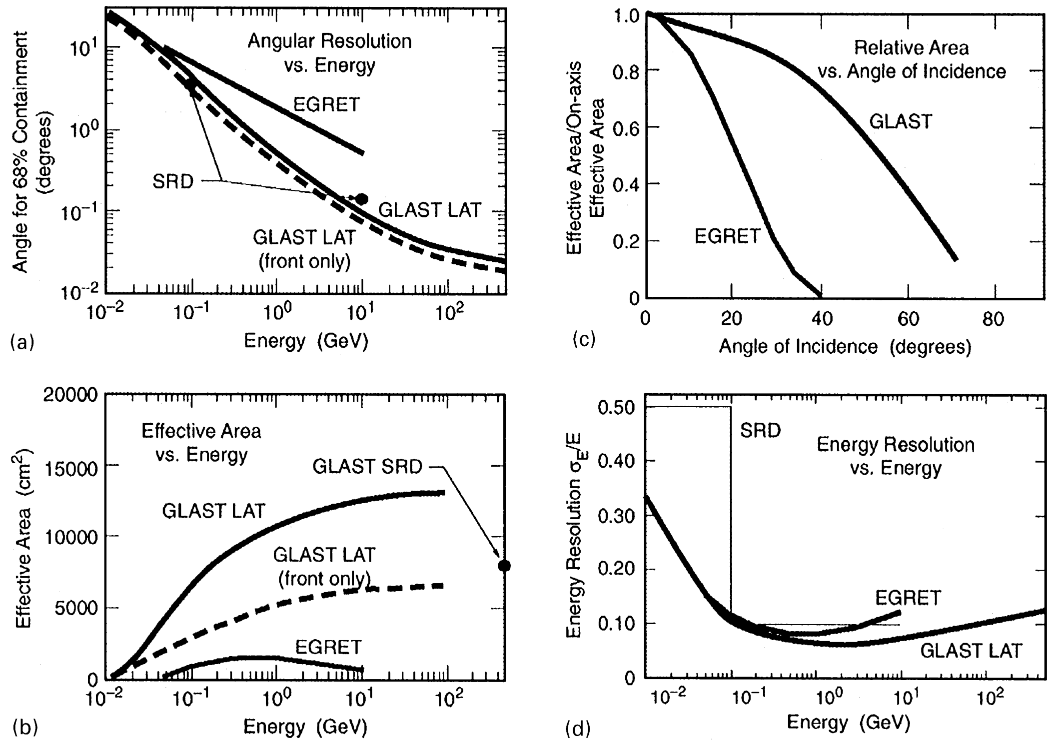

Fig. 4. Predicted performance of the GLAST LAT. The performance is compared to the GLAST Science Requirements Document (SRD) and EGRET. The front part of the tracker is shown separately, when appropriate.

4. Technical challenges for GLAST

Large-scale applications of detector technologies in HEP and in Space generate their specific challenges.

Challenge No. 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. Here, the low leakage current level provides extreme sensitivity to mechanical failures of the detectors during vibrations. 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 $\sim$5000 wire bonds were broken and that the leakage current characteristics were unchanged after vibrations with 14 g.

Challenge No. 2: On board cosmic ray rejection. The down-load bandwidth of the instrument will limit the 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 successive triggers, where level 1 is hardware (tracker or calorimeter) 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 No. 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 tracker, allowing less than 250 μW for each of the one million channels. This is about 1/10th the power consumption of ASICs with comparable noise budget. Our chip prototypes reach the goal. The details for the front-end electronics are given in Ref. [11].

Challenge No. 4: Tracker noise and efficiency. The noise and efficiency requirements of the GLAST LAT tracker are more stringent than in particle physics application because the main instrument trigger is based on the silicon tracker alone. The signals from individual single silicon layers with about 1500 channels are OR'd and then put into a coincidence with additional five layers. This requires that the noise occupancy of a single channel to be less than 10^{-4}. As shown in Ref. [11], this is easily 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 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 No. 5: Space Environment. The remoteness and forbidding nature of space poses additional experimental complications. The radiation levels are extremely low by LHC standards, with about 1 krad total dose expected in a five year mission, mainly in trapped particles. But a large fraction of flux contains low-energy protons, and with the 37 cm long strips we expect enough leakage current to increase so much so that we want to limit the operating temperature of the silicon detectors to below $+25^{\circ}$C. Part of the cosmic ray flux is in heavy ions, and they can induce single event effects (SEE) like latch-up and single-event upsets (SEU) in the readout electronics. We are addressing the SEE vulnerability by design features in the front-end ASICs, and we will have a first heavy ion test this summer. Heavy ions are also a threat to the detectors. As shown in Ref. [12], the large ionization from heavy ions can shorter out the bulk of the silicon detectors and build up large voltage differences across the coupling capacitors, which could lead to shortened ones.

An interesting problem arises from the mismatch of the coefficient of thermal expansions (CTE) in the tracker: silicon detectors, lead converter and the structural materials all 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. 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 tracker, calorimeter and anti-coincidence detector. 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 [13]. 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 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.

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