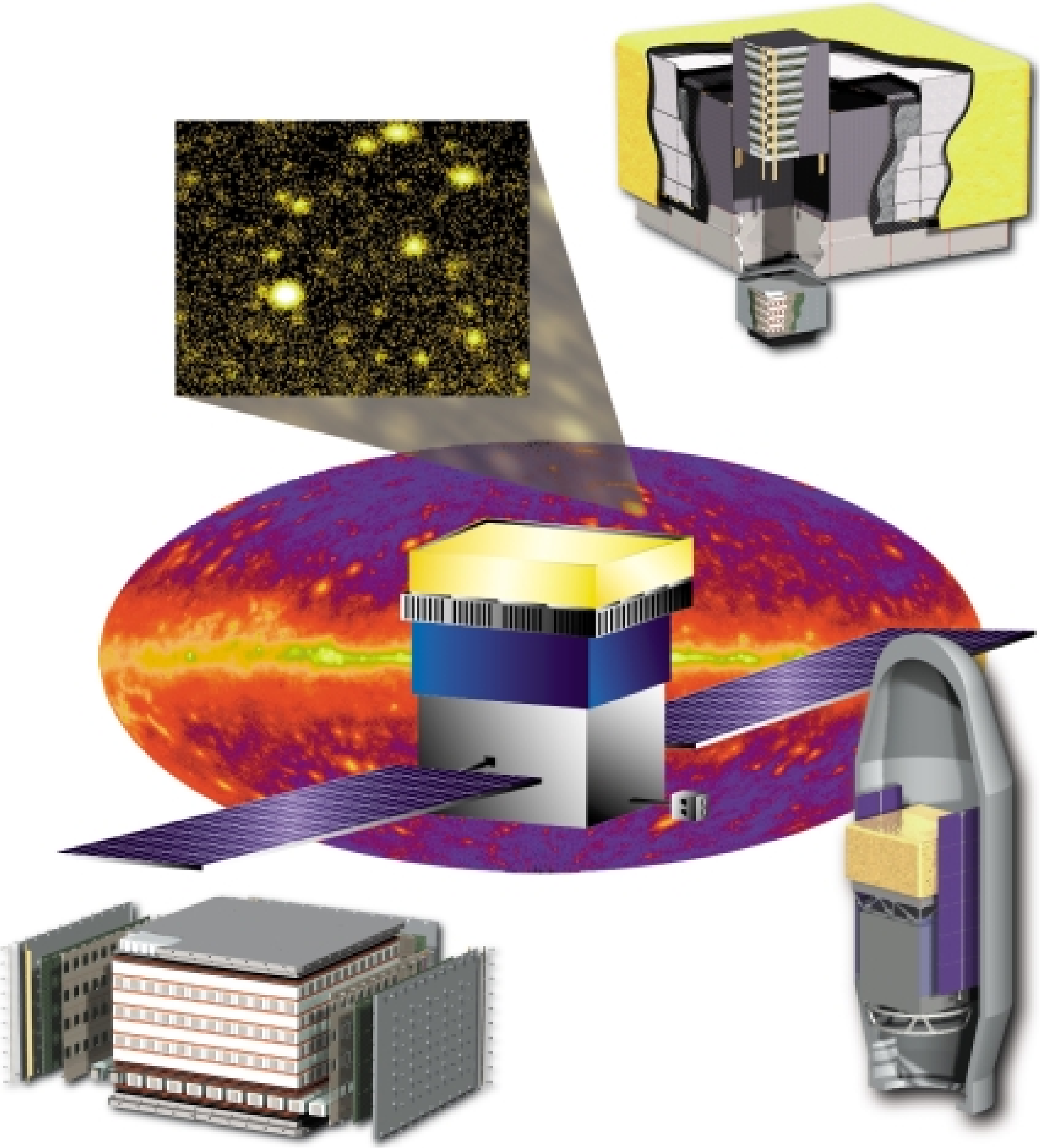
Response to AO 99-OSS-03

GLAST LARGE AREA TELESCOPE

Flight Investigation:

An Astro-Particle Physics Partnership Exploring the High-Energy Universe

Volume 1: Scientific and Technical Plan



November 1999
Stanford University

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AO-99-OSS-008

Proposal Cover Page

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AO 99-OSS-03 – Gamma Ray Large Area Space Telescope (GLAST) Flight Investigations

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Full Title

GLAST Large Area Telescope Flight Investigation: A Particle-Astrophysics Partnership To Explore the High-Energy Universe

Short Title: GLAST LAT Flight Investigation

Funding Data

Cost to NASA: $65,900,000

Total Cost: $181,900,000

Education/Outreach Budget: $1,288,000

NASA Grant or Contract Number of any current NASA award that the PI holds that is a logical predecessor of the newly proposed work
NAS5-98039

Type of Proposing Institution: Educational institution

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Theme 1: SEU
Theme 2: ASO
Theme 3: SEC
Theme 4:

Proposal Type: IPI

Type of Instrument(s):
Large Area Telescope

New Technologies Employed:
NONE

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E/PO Objectives:

Gamma-ray astronomy is an exciting field for the public as well as the researcher. Both young and old can be engaged by the exotic concepts of black holes and violent explosions seen across the Universe. Thus, we believe that the GLAST E/PO program is well suited to promote inquiry into the origin and structure of the Universe and the relationship between energy and matter, concepts included in the Physical Science Content Standards A,B, & D for grades 9-12. Therefore in the GLAST LAT E/PO program we will focus on the specific educational goal of utilizing the observations and scientific discoveries of the GLAST mission to improve understanding and utilization of physical science and mathematics concepts for grades 9-12. Results obtained from the program will be evaluated against well-defined metrics.

Proposal Summary/Abstract

Our understanding of the Universe has experienced a revolution in the last several years with breakthrough observations of many new phenomena that have changed our view of the high-energy Universe and raised many new questions. The GLAST mission stands poised to open enormous opportunities for answering these questions and advancing knowledge in astrophysics and particle physics. A Large Area high-energy gamma-ray Telescope (LAT), based on pair conversion, is proposed, by an international team, that will meet all of the GLAST mission requirements with large performance margins for critical telescope characteristics. The telescope consists of (i) a precision tracker, based on proven Silicon-strip detector technology, (ii) a finely segmented CsI calorimeter for energy measurement, and (iii) a segmented anticoincidence shield that covers the tracker. The instrument will support a broad scientific investigation. In particular, the LAT will (i) provide rapid notification of high-energy transients, (ii) provide an extensive catalog of several thousand high-energy sources obtained from an all-sky survey, (iii) measure spectra from 20 MeV to more than 50 GeV for several hundred sources, (iv) localize point sources to 0.3 – 2 arcmin, (v) map and obtain spectra of extended sources such as SNRs, molecular clouds, and nearby galaxies, and (vi) measure the diffuse isotropic gamma-ray background up to TeV energies.

Certification of Compliance with Applicable Executive Orders and U.S. Code

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2. **agrees t oaccept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal;**
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ACKNOWLEDGEMENTS

Since the beginning of the effort to develop the instrument and science program described in this proposal, Dr. William Atwood has made essential contributions to every major aspect of the project. The technical content of this proposal builds upon the foundation of his original ideas, brilliant insight, and years of dedicated work.

NOTICE

This proposal was submitted in its original form to the National Aeronautics and Space Administration on November 4, 1999. Except for correction of typographical errors, this reprint (1/18/2000) is identical to the original proposal.

Volume 1 - Scientific and Technical Plan

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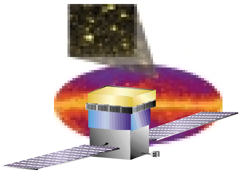
GLAST LAT
Factsheet

http://www.glast.stanford.edu



GLAST Large Area Telescope

Relation to GLAST Mission Science

Key Scientific Questions Addressed:

- What are the mechanisms of particle acceleration in the universe?
- What are the origins and mechanisms of Gamma-Ray Bursts and other transients?
- What are the unidentified EGRET gamma-ray sources?
- What are the distributions of mass and cosmic rays in the galaxy and in nearby galaxies?
- How can high-energy gamma-rays be used to probe the early universe?
- What is the nature of dark matter?

GLAST LAT Provides:

- Rapid notification of high-energy transients
- Detection of several thousand sources, with spectra from 20 MeV to more than 50 GeV for several hundred sources
- Point source localization to 0.3 – 2 arcmin
- Mapping and spectra of extended sources such as SNRs, molecular clouds, interstellar emission, and nearby galaxies
- Measurement of the diffuse gamma-ray background to TeV energies

Large Area Telescope

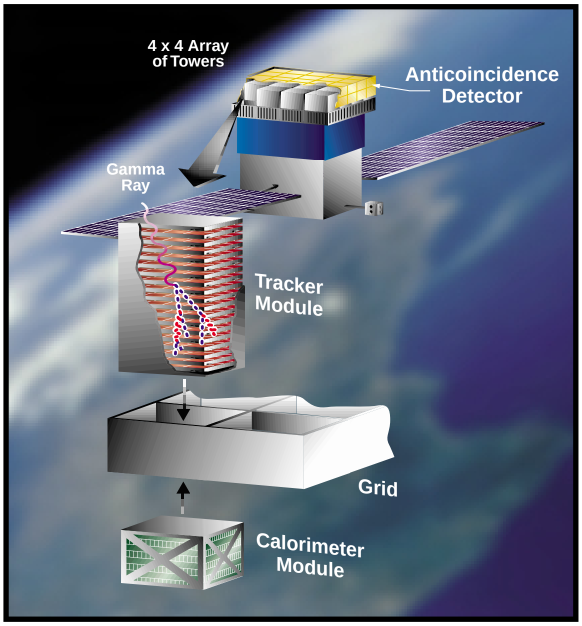
Mature design based on proven technologies and more than 7 years of focused design, development and demonstration efforts by the proposing team

Pair-ConversionTelescope Design:

- **Precision Tracker (TKR):** single-sided silicon-strip particle detectors and converters arranged in 18 x,y tracking planes, providing precision determination of photon direction;
- **Calorimeter (CAL):** finely segmented array of CsI(Tl) crystals, read out by PIN diodes for energy measurement and precise shower localization;
- **Anticoincidence Detector (ACD):** array of plastic scintillator tiles covering TKR, read out by waveshifting fibers and PMTs;
- **Modular Design:** TKR and CAL composed of 16 identical tower modules, providing redundancy. Each tower includes an independent data acquisition board (DAQ) to implement level-1 and level-2 triggering and data capture.

Relation to NASA Space Science and SEU

- Determine the mechanisms of particle acceleration in AGN, pulsars and supernova remnants
- Use high-energy gamma rays as probes of the universe
- Understand the origin of gamma-ray bursts
- Probe the nature of dark matter
- Perform sensitive high-energy gamma-ray survey, the first all-sky survey above 10 GeV

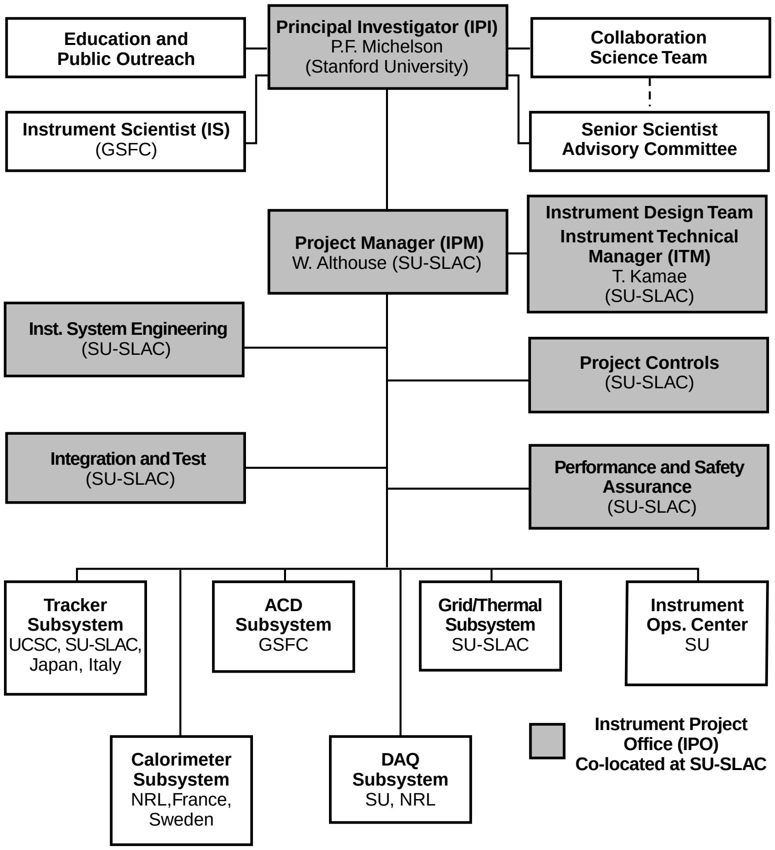


Key Telescope Characteristics

Meets all GLAST mission requirements with large performance margins for critical characteristics

- Two-year point source sensitivity: 1.6×10^{-9} cm^{-2} s^{-1}
- Background rejection: $2.5 \times 10^{5} : 1$
- Effective area: 12,900 cm^{2} @ 10 GeV
- Field of view: 2.4 sr
- Angular resolution: 0.39^{o} @ 1 GeV
- Energy resolution: $\Delta E/E \leq$ 10%, 100 MeV -100 GeV
- On-board transient analysis for rapid alert
- Mass: 2,557 kg
- Power: 518 W

The GLAST LAT Collaboration brings to the GLAST mission more than 7 years of focused LAT technology development. The team is a partnership of individuals and organizations with broad experience in experimental high-energy particle physics and space science instrumentation. This partnership is reflected in the support for the GLAST LAT team from the U.S. Department of Energy and foreign funding agencies.



Principal Investigator (IPI)
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(Stanford University)

Education and Public Outreach

Instrument Scientist (IS)
(GSFC)

Collaboration Science Team

Senior Scientist Advisory Committee

Project Manager (IPM)
W. Althouse (SU-SLAC)

Instrument Design Team
Instrument Technical Manager (ITM)
T. Kamae
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Inst. System Engineering
(SU-SLAC)

Project Controls
(SU-SLAC)

Integration and Test
(SU-SLAC)

Performance and Safety Assurance
(SU-SLAC)

Tracker Subsystem
UCSC, SU-SLAC, Japan, Italy

ACD Subsystem
GSFC

Grid/Thermal Subsystem
SU-SLAC

Instrument Ops. Center
SU

Calorimeter Subsystem
NRL, France, Sweden

DAQ Subsystem
SU, NRL

Instrument Project Office (IPO) Co-located at SU-SLAC

Instrument Team Projects

- Conduct All-Sky Survey
- Provide Transient LAT Catalog and Alerts
- Perform in-depth analysis of selected sources

Organizations with Hardware Involvement

Stanford University: SLAC & HEPL

Goddard Space Flight Center

Naval Research Laboratory

University of California, Santa Cruz

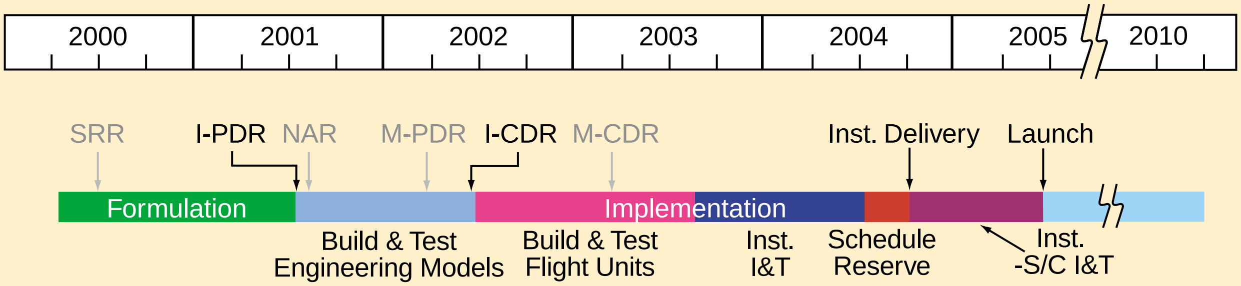
Hiroshima University, University of Tokyo, ISAS, & ICRR, Japan

INFN & ASI, Italy

Laboratorie du Commissariat a l'Energie Atomique & IN2P3, France

Royal Institute of Technology, Stockholm, Sweden

SCHEDULE (calendar year)



Science Investigation Cost:

	Cost to NASA	Total Cost
Formulation:	$7.0M	$33.6M
Implementation:	$51.9M	$107.0M
Operation:	$7.0M	$41.3M
TOTAL:	**$65.9M**	**$181.9M**

*All costs in FY99$, including reserves

1.0 EXECUTIVE SUMMARY

Our understanding of the Universe has experienced a revolution in the last several years. In particular, breakthrough observations by EGRET of high-energy gamma-ray blazars, pulsars, unidentified sources, delayed emission from gamma-ray bursts and solar flares, and diffuse radiation from our Galaxy and beyond, have all changed our view of the high-energy Universe and raised many new questions. The GLAST mission stands poised to offer enormous opportunities for unraveling these mysteries and advancing knowledge in astronomy, astrophysics, and particle physics. Members of these communities have come together in partnership, culminating in this proposal to design, build, and operate the GLAST Large Area Telescope (LAT). The proposed LAT instrument will provide data of high quality to the scientific community.

This proposal offers proven, low-risk technology (TRL 6-7), foreign collaboration with 9 institutions worldwide supplying funding and hardware, DOE facilities and funding participation, and an international team of scientists committed to operating LAT as part of a facility-class observatory for the scientific community.

Critical analysis by the team and reviews by the collaborating agencies have resulted in a well-understood budget with adequate margins and contingencies.

The proposing team brings experience in gamma-ray astrophysics, space instrumentation, and accelerator-based high-energy physics experiments. Team members include veterans from SAS-2, COS-B, and EGRET. Members also carried out the Mission Concept Study that originally defined the GLAST mission and were part of the GLAST Facility Science Team.

The performance of LAT exceeds the requirements developed in the Science Requirements Document (SRD). The performance parameters are calculated using realistic, detailed simulations of the instrument, and robust event reconstruction and background rejection algorithms. The design also meets all the technical interface requirements specified in the Interface Requirements Document (IRD).

Summary of Science Objectives

The science objectives are largely motivated by the discoveries of the EGRET experiment and of ground-based atmospheric Cerenkov telescopes (ACT) above 300 GeV. Because of the combined advances in point spread function (PSF), effective area, energy range, and field of view (FOV), LAT will have a point-source sensitivity of $1.6 \times 10^{-9} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ (E>100 MeV) after a 2 year all-sky exposure -- an effective improvement over EGRET by more than a factor of 50. LAT will explore with ~10% spectral resolution the energy band beyond EGRET’s reach and will overlap with ACTs up to 1 TeV, providing them with absolute calibration. Sources below the EGRET threshold (~ $6\times10^{-8} \mathrm{cm}^{-2} \mathrm{s}^{-1}$) will be localized with subarcminute precision. These capabilities, the result of a carefully optimized instrument design, enable a wealth of science investigations that can be summarized as:

- ***Understand the mechanisms of particle acceleration in AGNs, pulsars, and 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. LAT will detect ~10^4 extragalactic sources and hundreds to perhaps 10^3 Galactic sources during the first two years of operation. The large FOV 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. The large FOV and sensitivity of LAT 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 sources are prominent features of the gamma-ray sky. LAT

will help determine the identity of the latter by source localization to ~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, LAT 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, LAT will open up studies of cosmic-ray production and propagation in nearby galaxies and clusters of galaxies.

- ***Determine the high-energy behavior of gamma-ray bursts 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, LAT will detect the weakest EGRET sources, ($>6\times10^{-8}$cm^{-2}s^{-1}) in a single day, with $>5\sigma$ significance; bright AGN flares will be detected within minutes. On shorter timescales, LAT 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). The wide FOV will also allow study of delayed high-energy emission and how it relates to the afterglow at lower energies.
- ***Probe dark matter and the early Universe.*** Observations of gamma-ray AGN serve to probe supermassive black holes through jet formation and evolution studies, and provide constraints on the star-formation rate at early epochs through $\gamma\gamma$ absorption over extragalactic distances. There are also the possibilities of observing monoenergetic gamma-ray “lines” above 30 GeV from supersymmetric dark matter interactions; detecting decays of relics from the very early Universe, such as cosmic strings or evaporating primordial black holes; or even using gamma-ray bursts to detect quantum gravity effects.

Instrument Team Projects

Our team has all the capabilities and experience necessary to carry out the following scientific projects in a timely way. The proposed projects are:

- ***Conduct all-sky survey.*** This task includes producing all-sky intensity maps, diffuse emission models, source catalogs, and residual maps and analyses. The catalog and maps will be produced and published after 1, 2, and 5 years.
- ***Provide transient alerts and catalogs.*** Transient alerts will be provided by the instrument to the community on timescales of seconds for GRBs (via GCN) to days for AGN flares and other such phenomena via WWW and IAU circulars. The histories of these transients will be cataloged by our team and distributed monthly via WWW and periodically via refereed publications.
- ***Perform in-depth analysis of selected sources.*** LAT is expected to detect ~10^4 sources during the first two years of operation. As part of our science program we propose in-depth analysis of a selected set of sources. These have been carefully chosen to initiate our scientific program, best evaluate the LAT performance, and to drive refinement of specific analysis tools such as pulsar timing analysis.

Operations and Interface to SOC

The GLAST era will be marked by an extensive catalog of high-energy sources and a high-quality sky survey. We anticipate this will stimulate broad interest in gamma-ray observations. Instrument operations, including calibration, monitoring state of health, generating instrument command loads, and level-1 data reduction on the ground will be the responsibility of the LAT team at Stanford University. Calibrated data, along with analysis tools developed and maintained by the team, will be made available to the science community in a timely and user-friendly manner through a well-defined interface with the SOC.

Instrumentation – LAT

LAT is a high-energy pair conversion telescope. The design is based on our team’s direct experience with EGRET, and on proven technologies with either flight heritage or comprehensive experience derived from widespread and documented performance in high-energy accelerator-based experiments. Detailed simulations, trade studies and technology development by our team have resulted in a modern, versatile, robust, and well-understood instrument design that uses no consumables. The major subsystems are:

- ***Precision converter-tracker (TKR).*** Incident photons convert in one of the layers of lead converter, and the 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 PSF with small tails. These ease-of-use properties will maximize the mission science return for guest observers.
- ***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 r.l., for a total instrument depth of 10.1 r.l. The depth and segmentation enable the high-energy reach of LAT 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.
- ***Data Acquisition System (DAQ).*** This system collects the data from the subsystems, implements the multi-level event trigger, and provides an on-board science analysis platform to search for transients.

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 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. Starting at the earliest stages of production for flight, towers will be tested and calibrated together to avoid last-minute problems.
- Comprehensive pre-flight calibration studies can be done in detail over many months using a subset of towers during production without impact on the overall production schedule.

Results of Instrument Development

Enabled by 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. These results include:

- Design, development, and production of custom electronics for the TKR that meet all requirements for power, noise occupancy, self-triggering, and efficiency.
- Design, development and production of a prototype analog ASIC for beam tests of the CAL, demonstrating that noise, power and dynamic range requirements can be met.
- Fabrication and successful shake testing of early versions of TKR mechanical components, including tests with mounted and wire-bonded silicon detectors. Similar tests were performed for a prototype CAL. Preliminary thermal modeling of the full instrument has been done.
- Beam test programs at SLAC and CERN with simple versions of the TKR, ACD and CAL. They produced many conclusive results on TKR performance (using the custom electronics), event reconstruction and PSF, CAL response and energy resolution, and ACD performance. 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 (Atwood et al. 1999).
- Design and construction of a full-scale tower. This demonstration tower includes all

four subsystems and will be completed in late November, 1999 for use in a beam test at SLAC and for a suborbital flight test. It also serves as an important software development platform and testbed.

Cost and Schedule

The NASA funding profile and schedule as given in the AO together represent considerable risk. However, because of the advanced state of the instrument design, international teaming and inter-agency support, we are confident the project can be accomplished on schedule and within the NASA cost cap and funding profile. In particular:

- The instrument design is well advanced as a result of our 7-year development program, that has included key trade studies, detailed simulations, independent reviews of all the subsystems, and early development and demonstration of the critical components.
- SU-SLAC, with DOE funding, will provide instrument project management, overall instrument system engineering and integration, software management, and computing resources for level-1 data, reduction and simulations, and will take overall responsibility for delivering the TKR.
- More than half of the TKR silicon detectors will be provided by our Japanese collaborators. These scientists are among the world's top experts in this technology.
- Nearly half of the TKR modules will be assembled by our Italian collaborators at INFN. These scientists have recent and extensive experience with silicon-strip detectors in space instrumentation. Italy (ASI) will also provide use of their Malindi ground station for data recovery.
- France will provide the CAL diode readout, front-end analog ASIC, the mechanical design, fabrication and assembly, and CAL simulations. Our French collaborators at CEA and IN2P3 have considerable expertise in high-energy space-borne telescopes and in calorimetry for accelerator experiments.
- Swedish collaborators at KTH and Stockholm University will provide and acceptance test the CAL CsI bars.

The foreign contributions have been reviewed by the relevant funding agencies in France, Italy, Sweden and Japan. Written endorsements have been obtained from all foreign partners. The DOE commitment is based on a detailed proposal submitted in 1998 that was approved after being extensively peer-reviewed.

Management

The LAT team has experience in all aspects of both the science and the instrumentation necessary for success. We have the capabilities to build the proposed instrument on time, within budget, and to produce the full science return proposed.

The management approach adopts the best practices of the collaborating institutions and incorporates management practices successfully implemented by SU-SLAC to manage large, international, multi-institutional projects of a scale similar to GLAST and consistent with NPG 7120.5A.

Peter Michelson is the Instrument Principal Investigator (IPI) and has responsibility for implementation. William Althouse is the Instrument Project Manager and is responsible to the IPI for overall management, particularly for delivery of the instrument within cost and schedule constraints. He has successfully managed several gamma-ray and cosmic-ray flight detectors under NASA sponsorship. Tuneyoshi Kamae is the Instrument Technical Manager and chairs the Instrument Design Team. Each of these individuals has a decade or more of relevant experience and successful records of project leadership. The instrument project leadership will be co-located at SU-SLAC in the Instrument Project Office.

The LAT management team will work to support NASA's goal of placing 8% of contract dollars with small, disadvantaged, and women-owned small business concerns.

The LAT team will institute a vigorous E/PO program, under Lynn Cominsky's leadership, within the established OSS Education ecosystem. Our proposed E/PO program satisfies all the criteria given in NASA's E/PO guide.

2.0 SCIENCE INVESTIGATION AND TECHNICAL DESCRIPTION

2.1 SCIENCE GOALS AND OBJECTIVES

The GLAST mission offers tremendous opportunity for discovery in high-energy astrophysics. The science investigation we describe here takes advantage of the LAT's capabilities (Table 2.2.1) to exploit this opportunity fully. The LAT's performance exceeds many of the requirements listed in the GLAST Science Requirements Document (SRD). As an observatory for the community, the LAT will enable study of scientific objectives significantly beyond those described in the SRD.

Table 2.1.1: Correlation of Key Science Themes and LAT Capabilities with Relevant NASA OSS Goals

GLAST LAT Strengths					Science Themes	NASA OSS Goals			
Large FOV (2.4 sr) with calorimetry & low bkgrnd.	Energy range to > 300 GeV with < 10% spectral res.	Fine Angular resolution (0.39° @ 1 GeV)	Low instrument dead time (20 µs)	Bckgrnd. rejection 2.5x10^5:1 with high γ efficiency		Formation of structure in the early universe	Extreme environments	Nature of dark matter	Exchange of energy & matter between stars & ISM
√	√	√		√	Particle acceleration in AGNs, Pulsars & SNRs		√		√
√		√		√	Resolve the γ-ray sky		√		√
	√		√		High-energy behavior of GRBs and transients	√	√		
√	√	√	√	√	Galactic dark matter and the early universe	√		√	

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2.1.1 Overview of High-Energy Gamma-Ray Astronomy

A revolution is underway in our understanding of the high-energy sky. The early SAS-2 (Fichtel 1975) and COS-B (Bignami 1975) missions led to the CGRO-EGRET instrument (Thompson 1993) which performed the first all-sky survey above 50 MeV. The 3rd EGRET catalog (Hartman 1999) contains 271 point sources, an order of magnitude more than previously known. New source classes of gamma-ray blazars and radio-quiet gamma-ray pulsars have been discovered with hints of others (ms pulsars, radio galaxies, supernova remnants, X-ray binaries).

EGRET has raised new mysteries. There are hints of new classes of sources among the 170 sources that remain unidentified. Blazars are detected almost exclusively in flaring states, but what is their quiescent emission? Delayed emission has been found in both gamma-ray bursts and solar flares, lasting many times longer than anyone expected. The delayed emission from GRB940217 hints at a powerful accelerator at work long after the initial explosion, but how common is this situation?

To make significant progress in understanding the high-energy sky, a highly capable instrument is required with

- good angular resolution for source localization and multiwavelength studies,
- high sensitivity over a broad field-of-view to monitor variability and detect transients,
- good calorimetry over an extended energy band to study spectral breaks and cut-offs,
- good calibration and stability of the instrument for absolute, long term flux measurement.

Our instrument, designed specifically with these requirements in mind, will deliver high-quality data to explore new energy domains and to answer many questions from the EGRET era.

2.1.2 Relevance to NASA Program

The Office of Space Science (OSS) Strategic Plan outlines eleven Science Goals, which range from understanding the formation of structure in the early Universe to how life might originate and persist beyond Earth. Technically and scientifically, GLAST belongs at the center of the program. The LAT will make key contributions to four of the OSS Science Goals as shown in Table 2.1.1.

2.1.3 Mission Overview

The LAT consists of a 4×4 array of towers, each composed of a silicon-strip detector tracker, a hodoscopic CsI calorimeter, and data acquisition module. A segmented, plastic scintillator anticoincidence detector covers the tracker array. The instrument design is based on detailed computer simulations that have been verified by beam tests of prototypes at SLAC and CERN. Details of LAT performance are given in Table 2.2.1 and in Foldout B (5a–5d).

The performance highlights are:

- peak effective area of 12,900 cm^2, exceeding the SRD goal,
- angular resolution of <0.10° at E>10 GeV, meeting the SRD requirement, with a large

and distinguishable subset of events with 0.074° resolution, surpassing the SRD goal,

- sensitivity of 1.6×10^{-9} cm^{-2} s^{-1} at E>100 MeV for a 2-year survey, surpassing the SRD goal,
- energy resolution of 7% at 1 GeV, surpassing the SRD requirement,
- 2.4 sr FOV with good energy resolution, PSF, and background rejection at all angles,
- point source sensitivity sufficient to detect the weakest EGRET source in one day (see Foldout A, 3a),
- aspect ratio (height/width) of 0.4 that limits edge and fish-eye effects.

The scientific phase of the GLAST mission will begin with a one-year survey of the sky, to be undertaken with the LAT zenith-pointed to maximize the observing efficiency. On alternate orbits the Instrument axis will be rocked above and below the orbital plane by ≈30° to make the survey sensitivity nearly uniform over the sky. LAT will act as an all-sky monitor for transient sources, with a single-orbit sensitivity of 2×10^{-7} cm^{-2} s^{-1}, E>100 MeV. The survey will be interrupted only for extraordinary targets of opportunity, such as searches for delayed high-energy emission from sufficiently bright GRBs. The survey will permit unbiased, long-term flux histories for AGN to be measured. Contemporaneous multiwavelength monitoring of *all* specific sources will be relatively easy to coordinate with the predictable observing coverage of the sky survey. In subsequent years, the scientific observing program for GLAST will be determined by peer review of proposals for key projects and guest investigations.

2.1.4 GLAST LAT Objectives

The sections below describe the science objectives that can be addressed by the LAT through the 1st year survey and the guest observing program. Our collaboration brings enormous breadth and expertise to these pursuits.

The main objectives are categorized into four themes, which are discussed in detail in the following sections. They cover all the science topics discussed in the SRD. Table 2.1.1 lists the LAT characteristics that have the most direct bearing on achieving the science objectives.

LAT will provide overlap (50 GeV to 1 TeV) with ground-based telescopes to explore together a greatly expanded dynamic range with well-matched capabilities. Foldout A (1a) shows the point-source sensitivities of these instruments, compared with a source flux similar to the Crab nebula. The red points in Foldout A (1b) show the precision of the LAT Crab measurement[1] in the overlapping energy range for a five year sky survey.

2.1.4.1 Understand the Mechanisms of Particle Acceleration in AGN, Pulsars, and SNRs

Gamma–ray observations are a direct probe of particle acceleration mechanisms operating in astrophysical systems. The LAT will explore these systems with >50 times better sensitivity than previous missions. We can anticipate how LAT will advance our knowledge of these non-thermal processes by reference to discoveries made with EGRET in three important source categories.

AGN Jets. With its detection of more than 60 AGN, almost all blazars (Hartman 1999), EGRET has strengthened the unified model of AGN as supermassive black holes with accretion disks and jets. Extrapolation of the EGRET Log N-Log S curve (shown in Figure 2.1.1 using values from Stecker & Salamon 1996) indicates that the LAT will detect ~10,000 AGN in two years. This is more than the number of identified blazars and in excess of the SRD recommendation. Population studies with this large sample will allow tests of the unified model, studies of jet formation and evolution with redshift, and studies of jet properties with AGN type and orientation. The likely EGRET detection of Cen A (Sreekumar 1999) suggests that other classes of AGN may be detectable.

With the LAT's sensitivity and broad energy coverage, quiescent emission and spectral transitions to flaring states can be measured. Foldout A (1e) shows how well the LAT will measure AGN spectra. $\gamma\gamma$ transparency calculations can constrain the bulk Lorentz factors of the outflowing plasma and the location of the acceleration and radiation sites in the inner jet.

For many sources, localizations provided by the LAT (Figure 2.1.1b) will permit high-confidence associations with X-ray, optical and radio counterparts for multiwavelength studies. Magnetic field strength can be estimated from com-

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[1] In this plot, to maintain adequate statistics, bins are wider than the intrinsic instrument resolution at the highest energies.

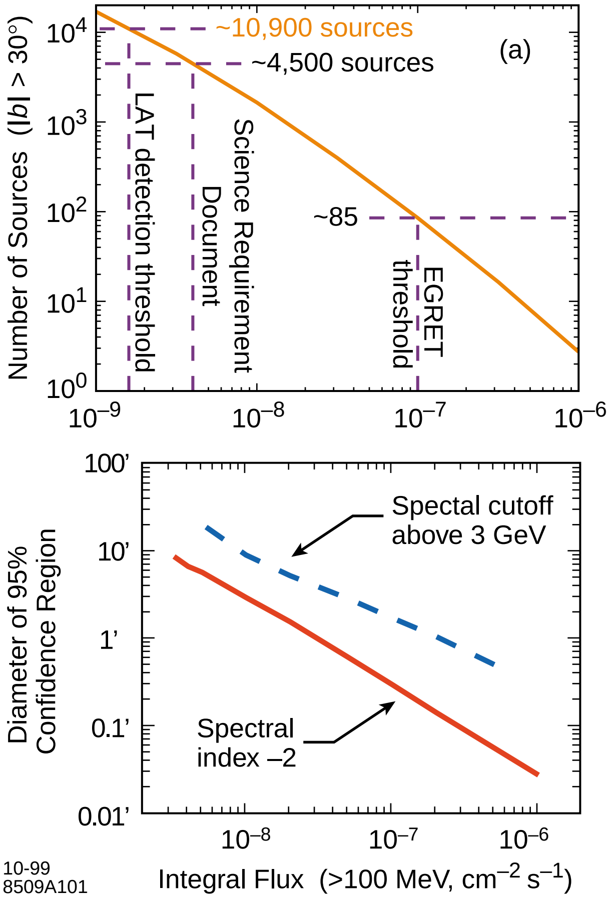

Figure 2.1.1: (a) The expected number of AGN detected with LAT at |b|> 30° and, (b) one year, all sky-survey source localization capability. (Note: s/c systematics will limit capability to ≥ .3′).

bined X-ray and gamma-ray observations (Catanese 1997).

The LAT's wide FOV will allow AGN variability to be monitored on time scales from minutes to years. Flares as bright as that from 3C 279 (Kniffen 1993) will be measurable with a 2-minute resolution (see Foldout A, 3a).

Pulsars. Electric fields generated by charge depletion along open field lines in pulsar magnetospheres are thought to accelerate particles to ~10 GeV and produce the pulsed gamma-rays observed by EGRET from at least six isolated neutron stars (Thompson 1997). Because of its large sensitivity and good spatial and spectral resolution at large angles, the LAT will increase this population database by at least an order of magnitude (see Table 2.1.2) and thereby provide much improved pulsar emission diagnostics: exploring trends between luminosity, period and surface field; gathering large statistics on pulse morphology to constrain beam geometry; searching for periodicities in sources as faint as ~6×10^{-8}cm^{-2}s^{-1} to find radio-quiet/gamma-ray-loud pulsars (i.e., Geminga-like neutron stars).

Table 2.1.2: Detectable Pulsars for the Polar Cap[a] and Outer Gap[b] Models

Pulsar type	EGRET	LAT/Polar Cap	LAT/Outer Gap
Radio	7	150	50
Millisecond	1	20	-
Radio quiet	1	<10	600

a. Zhang & Harding, 1999
b. Romani, 1999

As shown in Table 2.1.2, very different numbers of radio-selected and radio-quiet gamma-ray pulsars are predicted depending on whether the acceleration site resides near the polar cap or close to the light cylinder (outer gap). This is because of the very different gamma-ray beam patterns in the two models. The LAT will definitely test these predictions and provide us with a pulsar sample indepen-

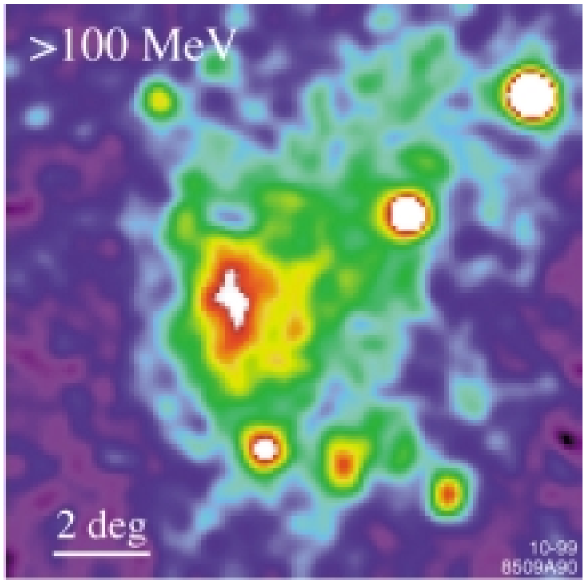

Figure 2.1.2: Simulated map of the interstellar emission from the LMC observed in a 2-year sky survey with the LAT. The simulation is based on a model of the interstellar emission in the LMC by Sreekumar (1999).

dent of radio selection. The increased sensitivity at high energies will also allow detection of older pulsars, intrinsically fainter, but with harder spectra, which could not be detected by EGRET. The good energy resolution of LAT over a broad energy range will allow measurements of the shapes of pulsar spectral cutoffs. Cutoffs, generally well above 1 GeV, relate to the surface magnetic field strength and provide another discriminator between polar cap (e.g., Daugherty & Harding 1996) and outer gap models (e.g., Romani 1996). The LAT data will augment spectral modeling of pulsed emission from X-rays through gamma-rays and constrain the primary radiation and pair creation mechanisms initiating the particle cascades. In particular, phase-resolved spectral index variations will tighten the constraints on model parameters and distinguish between 1- and 2-pole geometries.

Supernova Remnants and Cosmic Rays. Cosmic rays with energy less than 10^{15}eV have long been thought to be shock-accelerated in supernova remnants (SNRs). Recent X-ray and TeV observations have confirmed electron acceleration up to TeV energies by detecting non-thermal bremsstrahlung and inverse Compton emission from a few SNR shells, in particular from plerions (*e.g.,* Tanimori 1998, Koyama 1995). Freshly accelerated protons have not yet been detected through their π^0 decay spectral signature however. EGRET disproved a metagalactic origin of the cosmic rays (Sreekumar 1992; 1993) and found gamma-ray sources toward a few remnants, but its angular resolution would not allow a firm identification.

The LAT's excellent spatial and energy resolutions will separate the extended shell emission of an SNR from a compact source (pulsar, tiny plerion) inside it. It will also spectrally resolve electron and nuclei emission. The LAT will resolve >10 remnants, to establish the location of cosmic ray production. In γ Cygni for example, the central source, coincident with an X-ray source, is suspected to be a pulsar (Brazier 1996). In the simulation shown in Foldout A (1c)-(1d), the EGRET flux was partitioned between the pulsar and a shell segment. The pulsar components can be clearly distinguished from the shell.

2.1.4.2 Resolve the Gamma-Ray Sky: Unidentified Sources and Diffuse Emissions

The interstellar emission of the Milky Way is an intense celestial background that must be modeled in detail in order to build a reliable source catalog and to determine the galactic gamma-ray background. It is a major goal of the LAT investigation to model the interstellar emission from the Milky Way and nearby galaxies.

With a reliable gamma-ray background model, we anticipate finding several hundred or more new Galactic sources in addition to the ~10^4 expected extragalactic sources. LAT's angular and energy resolutions will be critical for determining the origin of the unidentified EGRET sources and the new sources discovered in the sky survey.

Unidentified Sources. Despite the increase in numbers of unidentified sources from ~20 to 170 from COS-B to EGRET, little progress toward identification has come from EGRET observations because of counterpart confusion in large error boxes, as illustrated in Foldout A (2a). The identifications of Geminga and 2CG 342-02 (PSR 1706-44) as pulsars are the lone unambiguous advances. The LAT localizations will be vastly more precise. For example, the Cygnus region, which is very confused for EGRET, even above 1 GeV, will be resolved by the LAT (see Foldout A (2b-2c)). As known from the early days of radio, X-ray and IR astronomy, arcminute localizations do enable firm identifications.

Many sources are related to star-forming sites in the solar neighborhood or a few kpcs away along the Galactic plane (Gehrels 1999). These sites harbor compact stellar remnants, SNRs and massive stars, i.e., many likely candidate gamma-ray emitters. Evidence exists for a correlation with SNRs (Sturner & Dermer 1995) as well as OB associations (Romero 1999), reviving the SNOB concept of Montmerle (1979) or making the pulsar option attractive. Pulsar populations can indeed explain a large fraction of unidentified sources close to the Galactic plane (Yadigaroglu & Romani 1997) and in the nearby starburst Gould Belt (Grenier & Perrot 1999). Other candidate objects among the unidentified sources include binary systems, systems with advection-dominated accretion flows onto a black hole, isolated accreting black holes, and Kerr-Newman black holes.

The LAT will identify the origin of these sources in 3 ways:

1. Provide excellent source localization (95% confidence diameter) for 5σ one-year survey sources and for EGRET sources (Figure 2.1.1b): 14’ and <0.3’ respectively, for an E^{-2} source and 1° and 1.5' respectively, for a source with a spectral cut-off at ~3 GeV, as anticipated for pulsars. This will result in an average chance probability of 0.2 and 7×10^{-5}, resp., for a soft X-ray counterpart; of 0.1 and 6×10^{-5}, resp., for a radio counterpart; and of only 10^{-2} and 8×10^{-6}, resp. for a radio pulsar counterpart.
2. Provide good sensitivity up to 300 GeV, to look for the spectral signature of inverse Compton emission from plerions. Recent studies have indeed found possible associations between X-ray synchrotron nebulae and EGRET sources near the Galactic plane (Roberts & Romani 1998).
3. With high sensitivity, large effective area, and good time resolution, look for periodicities on time scales of milliseconds to seconds, typical of ms pulsars, pulsars and binary systems hosting a neutron star. Extrapolating from EGRET analyses of Geminga (*e.g.*, Mattox 1996), the LAT sensitivity will allow searches in sources as faint as $\sim 5 \times 10^{-8}$ without a prior knowledge from radio data.

Interstellar Emission from the Milky Way, Nearby Galaxies, and Galaxy Clusters. Interstellar emission from the Milky Way is the most prominent feature of the gamma-ray sky. It is produced by the interaction of cosmic rays with nuclei and with low-energy photons. The gamma-rays produced by π^0 decay from nucleon collisions, or by bremsstrahlung and inverse Compton scattering of cosmic-ray electrons, probe the densities of cosmic rays and interstellar matter.

Of particular importance to the study of the extended interstellar emission is the LAT’s excellent rejection of charged particle background while maintaining very large effective area for gamma rays. The 3.1° angular resolution near the pion bump (~100 MeV) is well matched to Galactic structure scales, such as tangents to the spiral arms and inter-arm regions.

A longstanding issue about the Galactic emission is the contribution of unresolved point sources, buried in the highly structured emission at low latitudes. Residuals in the EGRET data (Hunter 1997) above 1 GeV hint at a significant population of unresolved, hard spectrum sources (Pohl 1997). The excellent angular resolution of the LAT above 1 GeV promises great progress in uncovering these sources.

The LAT’s combination of excellent angular resolution and large effective area will allow the study of external galaxies in the light of their interstellar emission. LAT will resolve the LMC in detail and, in particular, map the massive star-forming region of 30 Doradus (Fig. 2.1.2). The LAT will also map M31, thereby inaugurating the study of cosmic rays in spiral galaxies other than the Milky Way (Foldout A, 2e).

Extragalactic Diffuse Emission. An isotropic, apparently extragalactic component of the high-energy gamma-ray flux was discovered by SAS-2 and observed by EGRET (Sreekumar 1998). It is well-fitted by a power law spectrum of index -2.1 over the range 30 MeV - 100 GeV. No large-scale spatial anisotropy is seen.

Calculations show much of the emission may be produced by unresolved blazars (Stecker & Salamon 1996). However, these calculations require extrapolation of the relative contributions from flaring and quiescent blazar emission. EGRET detects most blazars only during their flaring states, so the quiescent emission is not well measured.

The LAT will observe the spectrum with better precision and over a broader energy range than EGRET. Foldout A (2d) shows the integral number of photons the LAT will detect versus energy, assuming the flat distribution of Stecker & Salamon. After 5 years, more than 10 million diffuse photons above 100 MeV and more than 1000 above 1 TeV will be collected! The LAT will also directly measure the quiescent (and flaring) emission from thousands of blazers, allowing a detailed calculation of the AGN contribution. After the blazar component has been resolved, any truly diffuse cosmological flux remaining would be of great interest and would likely rank as one of the most important discoveries of GLAST.

2.1.4.3 Determine the High Energy Behavior of Gamma-Ray Bursts and Transients

There have been recent breakthroughs in our understanding of gamma-ray bursts (GRBs) with the discovery of X-ray, optical, and radio afterglows, and delayed high-energy gamma-ray emission. We now know that GRBs are cosmological and involve extremely powerful, relativistic explosions. What triggers the explosions is not known, but theories suggest that GRBs are signatures of black hole creation and tracers of star formation at early epochs. It is thought that an initial fireball creates a super-relativistic blast wave resulting in an afterglow that cascades down from gamma-rays to radio.

EGRET detected two components of high-energy gamma-ray emission from GRBs: prompt emission, well defined at lower energies, and a delayed component extending to GeV energies that lasted more than an hour in the case of GRB940217 (Hurley 1994). The initial pulsed component was poorly measured by EGRET because of its severe spark chamber dead time (~100 ms/event). The LAT is designed with low deadtime (~20 μs/event) so that even a high-flux burst like GRB940217 will be detected with very little (< few %) dead time during the most intense part of the burst. Foldout A (3b) shows the distribution of times between photon detections, for a relatively bright burst with fluence of 2000 photons (E>10 MeV), assuming that pulse widths scale as $\sim E^{-0.3}$, extrapolated from BATSE (Norris 1999). For reference, the EGRET dead time is indicated in the figure, showing the dramatic improvement the LAT provides for high energy burst science.

The delayed component of GRBs will also be much better measured because of LAT's increased effective area, larger FOV, and low self-veto at >GeV energies. Models of delayed GeV emission, for example, involving production of gamma-rays from ultra-high-energy cosmic rays (Bottcher & Dermer 1998) and interaction with the intergalactic medium (Plaga 1995), can be tested.

Internal and external shock models are currently constrained primarily by spectral and temporal behavior at BATSE energies (Fenimore & Ramirez-Ruiz 1999). The LAT's sensitivity will force comparison of models with observations over a dynamic range in energy $\sim 10^3$-10^4, instead of the factor of ~20 afforded by BATSE.

The LAT will provide spectral diagnostics of bright bursts and can measure exponential high-energy spectral cutoffs expected from moderately high redshift GRBs caused by $\gamma\gamma$ absorption in the cosmic infrared background (complementing AGN probes: see Section 2.1.4.4). LAT will distinguish such attenuation from $\gamma\gamma$ absorption internal to the sources. Internal absorption is expected to produce time-variable breaks in power-law energy spectra. Signatures of internal absorption will constrain the bulk Lorentz factor and adiabatic/radiative behavior of the GRB blast wave as a function of time (Baring 1999).

Detailed simulations show that the LAT will detect ~200 GRBs per year, ~40 times as many as EGRET detected during the entire CGRO mission (Table 2.1.3). See Section 2.1.5.2 for more discussion of GRB localizations and alerts.

More speculatively, simulations show that the LAT could make major discoveries in quantum gravity by detecting an energy-dependent dispersion of light from GRB (Amelino-Camelia 1998). The LAT properties important for this measurement are its broad energy range, sensitivity at high energies, and good timing. The LAT's low deadtime and simple event reconstruction, even for multi-photon events, will enable searches for evaporation of primordial black holes.

2.1.4.4 Probe Dark Matter and the Early Universe

Potentially the most revolutionary discoveries from GLAST will come from searching for signatures of Galactic dark matter or from the use of AGN spectral cutoffs to probe galaxy formation in the early universe.

Searching for Gamma-Ray Signatures of Dark Matter. The rotation curves of galaxies, struc-

Table 2.1.3: Expected Numbers of GRBs and Delayed Emission in the LAT

Instrument	GRBs	Afterglows
EGRET	6	2-3
GLAST	200-250	60-120

ture-formation arguments, and the dynamics and weak lensing of clusters of galaxies all provide strong evidence for the existence of a vast amount of dark matter in the Universe, particularly in galactic halos. The LAT will make important measurements relevant to the search for dark matter.

Baryonic dark matter in the Milky Way may exist in cold molecular clouds (e.g., Sciama 1999; De Paolis 1999). Its signature would be a hardening of the interstellar gamma-ray spectrum above ~1 GeV. Such an excess can be measured by the LAT, with its excellent background rejection and sensitivity. The fine angular resolution will allow precise measurements of the molecular gas emissivity at the periphery of the Milky Way, to set limits on baryonic dark matter (Digel 1996).

Narrow gamma-ray annihilation lines would be a definitive signature of nonbaryonic dark matter (WIMPs) and would determine the WIMP mass. Calculations from SUSY models show that a window exists for the LAT to discover this exotic matter (Ullio & Bergström 1998) beyond the reach of accelerator and energetic-neutrino searches. (e.g., Wells 1998).

For photons incident at > 50°, LAT will have ~4% energy resolution, allowing a sensitive search for WIMP annihilation lines. Foldout A (4b) shows the 95% CLUL for detection of such lines by the LAT, observing a 1 sr cone surrounding the Galactic Center after a five-year all-sky survey. Overplotted on the figure for comparison are two types of SUSY models (Ullio 1999). Both $\chi\chi \rightarrow \gamma\gamma$ and $\chi\chi \rightarrow \gamma Z$ final states are expected. The two narrow photon lines from these states are separable provided the mass of the lightest SUSY particle $M_\chi < M_Z/\sqrt{(4\Delta E/E)}$, or $M_\chi < 230$ GeV for 4% energy resolution.

Probing the Early Universe. Photons above 10 GeV can probe the era of galaxy formation through absorption by near UV, optical, and near IR extragalactic background light (EBL). The latter depends sensitively on star formation rates and the presence of dust (Stecker 1992; Madau & Phinney 1996; MacMinn & Primack 1996). Too few sources have been detected so far to separate intrinsic turnovers from EBL absorption effects.

With as many as 10^4 AGN detectable up to z>4 (Figure 2.1.1), LAT data will yield conclusive results (Salamon & Stecker 1998, Chen & Ritz 1999). Spectra to more than 50 GeV can be determined for several hundred sources. The ratio of integrated flux above 10 GeV to that above 1 GeV as a function of redshift is shown in Foldout A (4a) for one EBL absorption model (Stecker 1999). The large number of detected blazars over a broad energy range will provide the data necessary to evaluate the gamma-ray optical depth as a function of redshift and energy, and will remove peculiar effects of individual sources. The team will work closely with the optical astronomy community to estimate the required redshifts.

2.1.5 Instrument Team Projects

Specific science projects are proposed by our team to complement independent research by other investigators and help guarantee the success of the GLAST mission as a whole.

2.1.5.1 Conduct All Sky Survey

A carefully planned and calibrated all-sky survey will provide a rich database of scientific results and form the foundation of future observations. Simulated results for a one-year survey using LAT performance parameters are shown in Foldout A, (5a–5d). The catalog of ~10^4 sources, each detected with > 5σ significance, highlights the LAT's excellent PSF and large FOV.

The most important goal of the survey is the production of a reliable point source catalog. This requires a well-calibrated, stable instrument. We are committed to producing and maintaining a comprehensive source catalog at the earliest possible stage, and to keeping this catalog up-to-date throughout the mission. We will draw on the experience of our team members who were part of the EGRET catalog efforts. Two keys to producing an optimal catalog are (1) modeling the interstellar and extragalactic diffuse radiation and (2) determining the source locations accurately enough to avoid source confusion. We recognize the critical importance of modeling the highly structured interstellar radiation and will use the expertise on our team to develop this model well before launch. The excellent angular and energy resolutions of LAT are key parameters to

Table 2.1.4: All-Sky Survey Project

Data Product	Updates	Comments
Source Catalog	Available and regularly updated on the web, with major publications after 1, 2, and 5 years.	Includes significance, flux, spectra, locations, and identifications.
All-Sky Maps	1, 2, and 5 years	Intensity, counts, and exposure maps over various energy ranges.
Residual maps	1, 2, and 5 years	A residual map for each all-sky map after subtracting point sources and Galactic emission.
Diffuse Model	Prelaunch, then update as necessary	

Table 2.1.5: GRB and Transients Project

Data Product	Updates	Comments
GRB Catalog	Monthly via WWW, with periodic refereed publications	Includes fluence, durations, time profiles, spectra, and locations.
Transient Alerts	Continuous, on a timescale of days via WWW and IAU circulars for transients. Continuous, on a timescale of seconds for GRBs via GCN.	GRBs and other transient alerts will include flux and locations. Flaring sources will include possible identifications.

reduce the source confusion problems that plagued the EGRET analysis. In addition, the multiwavelength coordinator on our team will work with the astronomy community to provide information on identifications.

With a good diffuse model and point source catalog, residual maps will be constructed to form the basic data for studies of the isotropic background and searches for dark matter.

Table 2.1.4 lists the data products that we will produce for the All-Sky Survey project.

2.1.5.2 Provide Transient Alerts and Catalog of Transients

The excellent short timescale sensitivity of LAT for transients is illustrated in Foldout A (3a) along with a scale of EGRET measurements for comparison.

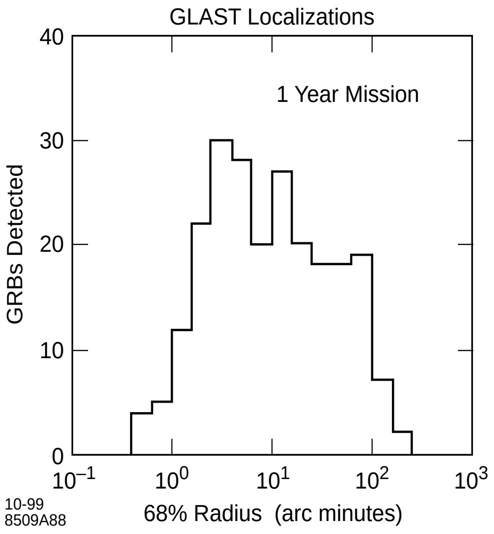

Figure 2.1.3: Distribution of centroided GRB 68% confidence error radii, determined by the LAT over one year.

We will prepare and distribute a catalog of GRB observations and provide the community with alerts for GRBs and other transient sources. A careful study of triggered and untriggered GRB events will produce a comprehensive data set which will be kept up-to-date on the Web. Other transients will be found through a comparison of binned photons over 1–2 orbits with previous observations.

The LAT team is the only group that can efficiently provide this service. To supply the rapid notifications required, reliance on onboard processing, early access to telemetry, knowledge of instrument calibration, and past observation histories are essential. Our team includes experts in both GRB and multiwavelength transient observations.

Simulations (Section 2.1.4.3) show that for ~25% of the bursts, LAT localizations are sufficient for direct optical counterpart searches (see Figure 2.1.3). For these ~50 GRBs per year, LAT will rapidly calculate the absolute position onboard. The information will then be sent to the ground via the real-time TDRSS link and distributed on the GCN network, within ~15 seconds. Fainter high-energy bursts will be detected by subsequent ground analysis.

2.1.5.3 Perform In-depth Analyses of Selected Sources

As part of our science program, we propose to perform in-depth analysis of a limited list of sources chosen to best evaluate our instrument performance, initiate our team's scientific program, and improve all aspects of LAT data analysis and software, thus benefiting the entire community. The proposed sources and scientific goals are listed in Table 2.1.6 on the following page. We intend to make a comprehensive analysis of each source using the sky-survey data and including multiwavelength campaigns where applicable. As noted in the table, a few key flaring sources require multi-year LAT data to constrain their behavior at high energy. Other analyses will take advantage of the team's expertise in modelling the structured Galactic background to resolve extended sources.

2.1.6 Relevance to Other Missions and Ground-based Observations

The scientific return will be compounded by the complementarity of LAT to other space missions and ground-based observations. Starting with the X-ray and gamma-ray measurements from XMM (2000), INTEGRAL (2001), AGILE (2002), and numerous air Cerenkov instruments, these opportunities are of central importance to our science effort.

GLAST will be one of the first NASA missions to forge a link between space-based astrophysics and particle physics. Some of LAT's science focus is unique, *e.g.*, the searches for signatures of nonbaryonic dark matter and quantum gravity. Many other LAT objectives will profit from synergy with contemporaneous NASA missions, especially those designed to explore the high-redshift Universe, such as FIRST (2006) and NGST (2007). GLAST may overlap with SIRTF as well. For GRBs, GLAST may overlap in time with the Swift MIDEX mission, in which case the redshifts and afterglow measurements provided by Swift will calibrate the low to medium redshift range of the GRB distribution. Combined, these observatories provide a powerful probe of the high-energy processes to the farthest reaches of the universe.

Table 2.1.6: Selected Sources for In-depth Analyses

Sources	Characteristics	Science Goals
PARTICLE ACCELERATION in PULSARS and PLERIONS		
PSR1951+32	EGRET pulsar, 39.5 ms, 100 kyr, 2.5 kpc, $B=10^{12}$ G	Study phase-resolved spectra and test LAT absolute timing data and software; measure the cut-off energy E_{cut} above 10 GeV to extend the $E_{cut}(B)$ relation; spatially resolve its remnant CTB80 (∅= 80’)
PSR1617-5055	Radio pulsar not seen by EGRET despite its 8th rank in $\dot{E}/D^2$, 69 ms, 8 kyr, 6.5 kpc	Deeply search for pulsed emission to constrain the beaming fraction in γ rays vs. polar cap and outer gap predictions; search for DC emission from its remnant RCW103 (∅= 10’)
PSR1853+01 plerion	267 ms, 20 kyr, 3.3 kpc, B=2 10^{13} G, high $\dot{E}/D^2$, in 3EG1856+0114 error box	Study DC emission from the X-ray/radio plerion ; search for pulsed emission to extend the $E_{cut}(B)$ relation to high field; spatially resolve the outer shell (W44: ∅ = 30’)
COSMIC-RAY ACCELERATION in SUPERNOVA REMNANTS		
Cas A Kepler	SN II in ~1670, 2.8 kpc, ∅= 5’ SN Ib in 1604, 4.4 kpc, ∅= 3’	Study young shocks in SN II and SN Ib environments: radio to TeV data to separate electron and nuclei emission; long-term monitoring to look for a compact star; higher density for Cas A & increased LAT sensitivity at b=6.8° for Kepler
Cygnus Loop IC443	Sedov phase, 360 pc, 230’x160’ Sedov phase, 1-2 kpc, ∅= 45’, in3EG 0617+2238 error box	Later SNR stage: spatially and spectrally resolve the nuclei emission; study non-linear acceleration; low Galactic background (b=8.5°) for Cyg Loop; enhanced nuclei emissivity expected where IC443 overtakes an H_2 cloud and X-ray and radio spectra harden
RX0852.0-4622 “Vela junior”	680 yr, ∅= 2.1° , closest SNR to Earth, 4.4° away from intense Vela pulsar	Observe using photons from Vela off-pulse time intervals to test source searches and localization in the wings of intense neighbors
NEARBY GALAXIES		
M31 LMC SMC	670 kpc, ∅~ 3° 55 kpc, ∅~ 8° 63 kpc, ∅~ 3°	Spatially and spectrally resolve their interstellar γ radiation to study cosmic rays, magnetic fields; compare energy balance and mass tracers in different metallicity environments
Coma cluster A1656	z = 0.02, ∅~ 1°	Constrain the energy density of cosmic rays inside a cluster; resolve the predicted emission above a low background (b= 89°); study the merging of two clusters
ACTIVE GALACTIC NUCLEI		
PKS0528+134 Mrk 501	EGRET flat spectrum quasar, z = 2.06 TeV BL Lac, z = 0.03	Multiwavelength, multi-year monitoring to explore particle acceleration in blazar jets, in particular γ-ray spectral evolution from quiescent to flaring states
Cen A	Radio galaxy, z = 0.002, 3EG1324-4314	Confirm EGRET detection and study γ-ray emission from AGN jets at large viewing angles (>70°)
UNIDENTIFIED SOURCE REGIONS		
Rabbit region: l= 312° ± 1° b= 0° ±1° Ω region: l= 17.5° ±1.6° b= -0.75°± 0.75°	3EG1420-6038 and 3EG1410-6147 3EG1826-1302 and 3EG1824-1514	Identify the γ-ray sources in complex regions and test source confusion limits; Rabbit : 2 SNRs, 1 candidate pulsar, 1 candidate plerion, and a few non-thermal shells Ω : 2 SNRs, PSR1823-13 (high $\dot{E}/D^2$), and PSR1822-14
Galactic Center l = 0° ±2° b = 0° ±2°	3EG1746-285	Multi-year monitoring of the high-energy activity around SagA* and γ-ray source localization with respect to the giant H_2 clouds and to AXAF, XMM, and INTEGRAL sources
3EG1835+59	brightest high-latitude, unid. source, $E^{-1.7}$ spectrum	Search for a radio-quiet pulsar; test periodicity search software
GALACTIC SOURCES WITH RELATIVISTIC JETS		
GRS1915+105	Micro-quasar, 12.5 kpc jet velocity = 0.9.c	Search for predicted γ-ray emission from relativistic jets at large angles and compare to AGN emission ; multi-year monitoring for flaring activity
SS433	5 kpc jet velocity = 0.3.c	Study termination shocks from jets impacting the remnant shell (120’x60’) and producing non-thermal X-rays

2.2 SCIENCE IMPLEMENTATION

2.2.1 Measurements and Relations to Scientific Objectives

The LAT is designed to measure the direction and energy of gamma-rays incident over a wide field-of-view (FOV), while rejecting background from cosmic rays. Foldout D gives quantitative details of the measurement requirements and how they relate to the scientific goals of the GLAST mission and to the LAT design. Sections 2.2.3 and 2.2.4 further explain how details of the LAT design impact the measurement performance. The remainder of Section 2.2 discusses the design, implementation, and operation of LAT.

2.2.2 Overview of Instrument Characteristics and Performance

2.2.2.1 Design Approach

Our design approach is, first, based upon more than 7 years of detailed simulations of the detector response to signal and background. We have shown that our design achieves the necessary background rejection, and all *performance evaluations for signals include the inefficiency and other effects of the background-rejection filter.*

Second, we identified the technology drivers of the detector system at an early date. Detector technologies were chosen that have extensive history of application in space science and High-Energy Physics (HEP) with demonstrated high reliability. We built relevant test models to demonstrate that our specific requirements, such as power, efficiency, and noise occupancy, can be readily met.

Third, we successfully operated these detector-system models, including all subsystems, in test beams to validate the design and the Monte Carlo programs used in the simulations. Our modular design has allowed us to build, at reasonable cost, a full-scale, fully functional demonstration tower (Beam-Test Engineering Model, or BTEM) for validation of the design concept and technology, including mass, power, and noise budgets.

2.2.2.2 Performance Predictions

The predicted performance of the proposed LAT instrument is summarized in Foldout B (5a–5d), and in Table 2.2.1 (also Section 2.2.8.3). It meets or exceeds all GLAST science requirements from the Science Requirements Document (SRD).

The LAT Tracker is divided into two sections, “front” and “back”, each optimized for different aspects of the science. The front section is designed to exceed the SRD PSF requirements, whereas the back section is designed to exceed the effective area requirement, with about a factor of 2 reduction in angular resolution compared with the front. The scientific justification for the back section is to improve the sensitivity at the high-energy end of the spectrum. In that regime both sections provide excellent angular resolution. Our science simulations show that the LAT point source sensitivity is approximately balanced between the front and back sections.

Consistency of Performance Predictions. All performance predictions shown herein adhere to the GLAST AO stipulation that the demonstrated effective area include all "inefficiencies necessary to achieve the required background rejection." In addition, all performance plots and predictions use only simulated data which have passed all cuts necessary to satisfy the PSF and energy resolution requirements.

Figure 2.2.1b demonstrates how event-reconstruction quality cuts in the analysis program dramatically clean up large tails that exist in the raw data sample. Foldout B (4a), shows how the same analysis serves to take the background rejection from the 10^3:1 level provided by the LAT triggers up to the high level quoted in Table 2.2.1. Figure 2.2.1a shows the effect of this analysis on the effective area and FOV.

The impact of the energy-resolution requirement is that we *do not* include in our performance predictions gamma-ray conversions that exit the side of the Tracker (TKR). This necessarily restricts the FOV, but we have designed the LAT with a low aspect ratio expressly to maintain a large FOV for conversions with good energy measurement

A crude energy measurement for photons that miss the Calorimeter (CAL) can be made by measuring the multiple-scattering angles of the e^+ and e^-. Despite the high precision of the TKR, this only works at the level of 45% for 100 MeV photons and gets worse at higher

Table 2.2.1: Predicted Performance of the GLAST Large-Area Telescope

Parameter	SRD Requirements	GLAST LAT
Energy Range	20 MeV – 300 GeV	10 MeV – 1 TeV
Energy Resolution	10% (0.1 – 10 GeV) 50% (20 – 100 MeV)	10% (0.1 – 100 GeV) < 25% (20 – 100 MeV)
Peak Effective Area	8,000 cm^2	12,900 cm^2
Single-Photon Angular Resolution (68% containment; on-axis)	< 3.5° (E=0.1GeV) < 0.15° (E>10 GeV)	Front: 3.1° (E=0.1GeV) Total: 4.4° (E=0.1GeV) Front: 0.074° (E=10 GeV) Total: 0.10° (E=10 GeV)
Single-Photon Angular Resolution (95%; on-axis)	$< 3 \times \theta_{68\%}$	Front: $2.4 \times \theta_{68\%}$ Back: $2.8 \times \theta_{68\%}$
Single Photon Angular Resolution (off-axis at fwhm)	< 1.7 times on-axis	1.5 times on-axis
Field of View (fwhm)	>2 sr	2.4 sr
Point Source Sensitivity @ E > 100 MeV(2 yr survey)	4×10^{-9} cm^{-2} s^{-1}	1.6×10^{-9} cm^{-2} s^{-1}
Absolute Time Accuracy	10 µs	2µs
Background Rejection	$> 10^5$: 1	2.5×10^5 : 1
Dead Time per event	< 100 µs	20 µs
Mission Life	5 yrs	≥ 5 yrs (no consumables)

energies. Furthermore, side-exiting photon conversions do not reach the required level of background rejection, for which the CAL plays an important role (Section 2.2.8.2). Since the scientific value of these photons has not been established, we have not included them in our effective-area and FOV performance metrics.

Monte Carlo Simulation. The analysis used to derive the performance predictions is based upon detailed Monte Carlo simulations (Section 2.2.8.1), which incorporate all known detector properties and Instrument material, as well as our best understanding of the background fluxes (Section 2.2.8.2). Foldout B (1a–1b), shows some single-event displays of signal and background interactions in the LAT, to illustrate the simulation. Note that events may cross from one tower to another. All material at tower boundaries is simulated.

Validation of Simulations by Beam Tests. An important element of our development program has been a series of beam tests of prototype hardware. One purpose of those tests was to validate the simulation and analysis methods used to establish the performance predictions of the LAT design. As an example, Foldout B (2a–2d) shows PSF measurements made in a tagged photon beam at SLAC, using a silicon-strip tracker with 6 *x*,*y* planes of variable spacing and with variable amounts of Pb converter (Atwood 1999). The tracker employed our custom readout electronics, which meet the LAT noise and power requirements. The measurements are in excellent agreement with simulations made using the same program and procedures as used for the performance plots and the predictions in Table 2.2.1. This strongly supports the validity of the excellent PSF that we predict for the LAT design.[1]

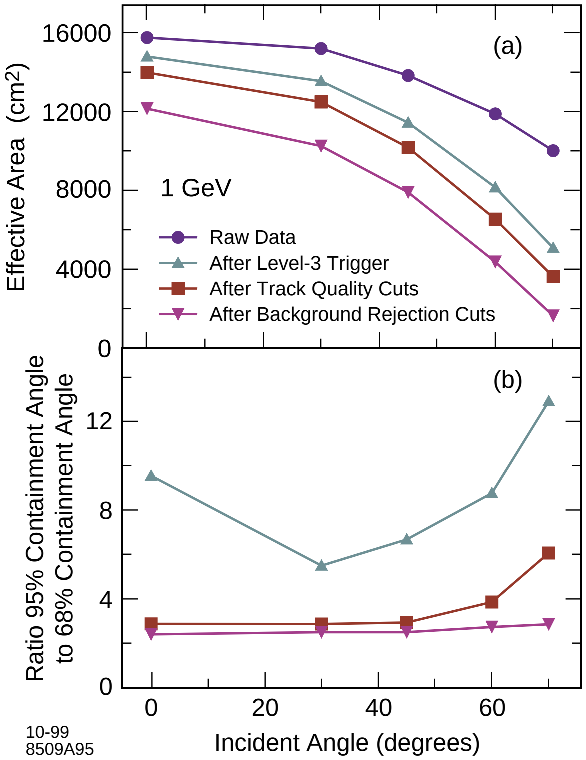

Figure 2.2.1: Impact of analysis cuts on (a) the total effective area, and on (b) tails in the PSF (front section only)

Table 2.2.2: GLAST LAT Subsystems

Subsystem	Principal Functions	Technology	Arrangement
Tracker (TKR)	Direction of Gamma rays. Cosmic Ray Suppression.	Silicon strip Detectors.	Precision "Front" (Low Energy). Efficient "Back" (High Energy). Redundant Readout.
Calorimeter CAL)	Energy of the Gamma rays. Cosmic Ray Suppression.	Cesium Iodide. PIN-Diode Readout.	Hodoscopic Stack: Longitudinal and Transverse Segmentation.
Anticoincidence Detector (ACD)	Veto of Cosmic Rays.	Scintillator Tiles. PMT Readout.	High segmentation: 145 tiles. Redundant Readout.
Data Acquisition System (DAQ)	Triggering. Data Acquisition. Data Reduction. Housekeeping. Spacecraft Interface.	Readout logic: FPGA RTOS: VxWorks. CPU: RISC Processor. Data Switch: Serial LVDS.	Hardware trigger and data capture. Modular Design. Fully redundant—No single point failures.

Similarly, Foldout B (2f–2g) demonstrates, using data from the same beam test, how our hodoscopic CAL design (Section 2.2.7.3) achieves excellent energy resolution at high energy by application of shower leakage corrections. This supports the simulated energy-resolution performance shown in Foldout B (5d).

2.2.2.3 Instrument Design Overview

The LAT, illustrated in Foldout C, is a pair-conversion telescope that includes the same essential elements as EGRET: a tracker-converter followed by a substantial calorimeter and covered by an anticoincidence shield (see Table 2.2.2). However, in addition to increased area with respect to EGRET, the design of each element is refined to improve greatly the sensitivity, resolution, and energy range.

The TKR and CAL are composed of 16 identical modular towers supported by a low-mass grid structure.[2] The TKR utilizes silicon-strip technology for charged-particle detection, providing a precision measurement of the photon direction. The CAL uses a segmented array of CsI crystals read out by PIN diodes for energy measurement and precise three-dimensional shower localization. The ACD is composed of plastic scintillator, segmented into tiles and read out by waveshifting fibers connected to photomultiplier tubes.[3] Each tower also includes an independent data acquisition board, which together are organized in a network with redundant data paths.

The design includes a 3-level trigger based upon information from the TKR, CAL and ACD veto. The trigger is flexible and programmable, to adjust to changing science requirements or unexpected backgrounds.

A grid structure supports the 16 TKR and CAL modules, as well as the ACD, processor boards, and wiring harness. It also acts as the mechanical interface to the Spacecraft. See Foldout D for a block diagram of the LAT, with more details on its interfaces.

The three detector subsystems of the LAT, designed for complementary tasks, have been optimized together as an integrated instrument, to yield a powerful gamma-ray telescope with superior track reconstruction and background-rejection capabilities. It not only exceeds the science requirements, but it also maintains a high degree of redundancy in order to maintain its full capability throughout the mission.

Several principles found to be important to success in the design of large detector systems, both in HEP and in space science, have played a prominent role in our design process. They are listed in Table 2.2.3, along with their impact on the LAT design concept. Our technology development program, partially illustrated in Foldout C by photographs of several prototype components, has played a critical role in bringing this design concept to its present level of maturity.

2.2.3 Instrument Design Issues

Choosing the LAT parameters involved numerous trade studies. The most important parameters are summarized in Table 2.2.4, together with short explanations of the drivers and con-

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[1] Note that the PSF measured in the beam test cannot be applied as a direct prediction of the performance of the LAT, because it was not an identical configuration and had a small 5-cm aperture. In particular, the aperture biased the PSF below about 100 MeV.

[2] A tower is a logical association of a TKR module, CAL module, and DAQ module. The modules, however, integrate separately into the Grid.

[3] The waveshifting fibers absorb light of short wavelengths and re-emit it at longer wavelengths, to which the PMTs have better sensitivity. They do not scintillate.

Table 2.2.3: Principles of the LAT Design Concept

Design Principle	Impact
Proven technology. Advanced progress in simulation and prototyping.	Minimized risk in schedule and cost. Excellent understanding of performance and margins.
High noise margins.	Eliminate risk of reduced scientific yield from gradual detector degradation.
Modularity[a]	Distributed manufacturing and testing. Efficient assembly. Exchangeable parts. Minimal impact from component failures.
High segmentation[a]	Extension of energy reach. Minimization of backgrounds.
Redundant readout paths.	Protection from single-point failures of the electronics.
Flexible, programmable trigger	Adjust to unforeseen background conditions and scientific needs.
No consumables, no moving parts.	Long mission life. No design limitations preclude 10 yr lifetime.

[a] *"Module" refers to a detector assembly with a unique interface to the DAQ. A given module could operate independently of all others. Each module is "segmented" into numerous detector elements.*

straints underlying the decisions. The following discussion highlights some of the considerations involved in optimizing the LAT design for GLAST science.

2.2.3.1 Importance of Energy Reach

To achieve a factor of 50 or more improvement over EGRET in source sensitivity, given only a factor of 3.5 increase in active area allowed by the launch vehicle, it is essential to take full advantage of improved detector technology and experience gained from EGRET. The crucial element is to capitalize on the unprecedented angular resolution that can be achieved for photons in the very interesting regime around 1 GeV and above, while preserving optimal performance in the 100-MeV range.

Because of the $1/E$ dependence of multiple scattering, for a typical source spectrum in the presence of a diffuse background the GeV photons can contribute more to the sensitivity than do the much more plentiful lower-energy photons near the detection threshold. This is illustrated in Figure 2.2.2, *but the advantage is gained only if the Instrument is not limited in the GeV regime by the resolution of the detector technology.*

The TKR angular resolution is determined by the ratio of the detector resolution to the lever arm over which the measurement is made. The lever arm is restricted at high energy by the need for a large FOV and by the fact that the direction measurement must be made before the first bremsstrahlung photon is emitted, *i.e.* before the electron has passed through ≈1 R.L. of material. Therefore, our design emphasizes the excellent position resolution obtainable from silicon strip detectors. Such detectors also have fine two-hit resolution, which enhances the track reconstruction capabilities, as explained in Figure 2.2.4.

Similarly, the CAL is designed to achieve good energy resolution over the full energy range, together with excellent pattern recognition capability. EGRET experience showed that CAL albedo can be a serious problem at high energy, so the ACD is carefully segmented to avoid loss of effective area from self veto.

2.2.3.2 Importance of High Detector Efficiency

Pair conversion trackers contain far more material than would normally be put into a particle tracking device. Multiple scattering and bremsstrahlung production severely limit the obtainable resolution. To get optimal results requires that the electron and positron directions be measured immediately following the conversion. At 100 MeV the penalty for missing one of the first hits is about a factor of 2 in resolution, resulting in large tails in the PSF, as demonstrated in Figure 2.2.3. Figure 2.2.4 illustrates these and other points.

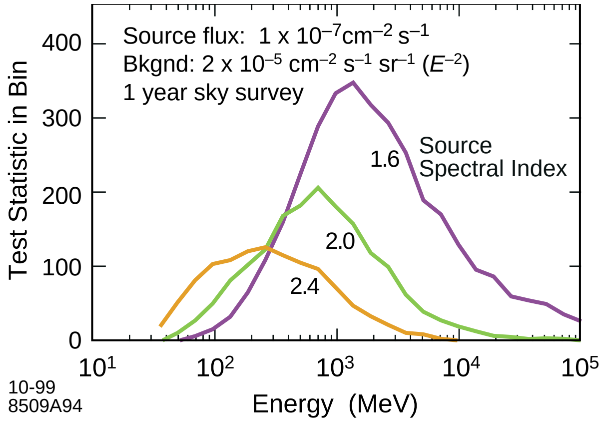

Figure 2.2.2: Maximum likelihood test statistic for detection of point sources, from a simulation of a generic detector that is multiple scattering limited to well above 1 GeV. For typical spectral indices, the sensitivity is maximum in the GeV domain.

Table 2.2.4: Brief Explanations for Choices of Instrument Parameters of the LAT Design

<table>
<tr><th>Parameter</th><th>Value</th><th colspan="2">Performance Drivers and Constraints</th></tr>
<tr><td colspan="4">Tracker</td></tr>
<tr><td>Noise occupancy (fraction of channels with noise hits per trigger)</td><td>$<10^{-4}$</td><td colspan="2">Trigger rate, data volume, track reconstruction. This value is the trigger requirement.</td></tr>
<tr><td>Single-channel efficiency for MIP, within fiducial volume.</td><td>>99%</td><td colspan="2">PSF, especially at low energy. It is crucial to measure the tracks in the first 2 planes following the conversion.</td></tr>
<tr><td>Ratio of Strip-Pitch to vertical spacing between planes.</td><td>0.0064</td><td colspan="2">High-energy PSF (roughly ≥1GeV).</td></tr>
<tr><td>Detector pitch (center-to-center distance between strips)</td><td>201 μm</td><td colspan="2">Small value needed to maintain a small pitch-to-plane-spacing ratio without destroying the FOV.</td></tr>
<tr><td>Aspect ratio (Height/Width)</td><td>0.4</td><td colspan="2">Large FOV for photons with energy determination</td></tr>
<tr><td>Front converter foil thickness (R.L)</td><td>12×0.025</td><td colspan="2">Minimize thickness per plane for low-energy PSF, but not so much that support material dominates.
Maximize total for Aeff.</td></tr>
<tr><td>Back converter thickness (R.L.)</td><td>4×0.25</td><td colspan="2">Aeff and FOV at high energy.</td></tr>
<tr><td>Total converter thickness (R.L)</td><td>1.3</td><td colspan="2">Maximize A_{eff}, but payoff is small much beyond 1 R.L.
Excessive material in front of the CAL will hurt the energy resolution.</td></tr>
<tr><td>Support material and detector material per <i>x,y</i> plane (R.L.)</td><td>1.3%
(should be less than foil R.L.)</td><td colspan="2">Stable mechanical support is needed, but much of this material is in a non-optimal location for the PSF. Minimize to limit PSF tails from conversions.</td></tr>
<tr><td colspan="4">Calorimeter</td></tr>
<tr><td>Depth, including Tracker</td><td>~10 R.L.</td><td rowspan="3">Energy Resolution</td><td>Shower max within instr. up to ~100 GeV.</td></tr>
<tr><td>Sampling</td><td>>90% active (angle dep.)</td><td>Sufficiently high active fraction that resolution is not dominated by sampling statistics.</td></tr>
<tr><td>Longitudinal segmentation</td><td>8 segments</td><td>Segmentation is needed in order to correct for shower leakage out the back. Also helpful for background rejection.</td></tr>
<tr><td>Lateral segmentation</td><td>~ 1 Molière Radius</td><td colspan="2">Background rejection–a gamma-ray shower should match well with the pair conversion in the Tracker.</td></tr>
<tr><td colspan="4">ACD</td></tr>
<tr><td>Segmentation into tiles</td><td><1000 cm^2 ea.</td><td colspan="2">Minimize self-veto, especially at high energy. This value is for the top. Side tiles are smaller, to achieve a similar solid angle, as seen from the CAL.</td></tr>
<tr><td>Efficiency of a tile for a MIP</td><td>>0.9997</td><td colspan="2">Cosmic ray rejection, to meet the 0.99999 requirement when combined with the other subsystems.</td></tr>
<tr><td>Number of layers</td><td>1</td><td colspan="2">Minimize material, mass, and power. Dual readout on each tile for redundancy.</td></tr>
</table>

2.2.3.3 Optimizing the Converter Thickness

One of the most complex LAT trades was the balance between the need for thin converters, to achieve a good PSF at low energy, versus the need to increase converter material to maximize the effective area. We found that the overall science performance is best when the TKR is divided into two regions, "front" and "back." The front region has thin converters to optimize the PSF at low energy, while the converters in the back are 10 times thicker, to maximize the effective area at the expense of only about a factor of two in angular resolution for photons converting in that region.[4]

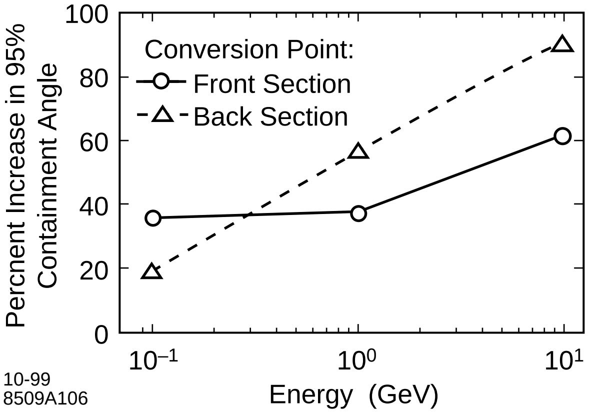

Figure 2.2.3: Effect on the PSF from reducing the TKR detector efficiency from 100% to 90%. (Full LAT Monte Carlo simulation.)

The back region is especially important for achieving good statistics at high energy. Note that the thick-converter planes can work well

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[4] Multiple scattering varies inversely with energy and as the square root of the material thickness, in radiation lengths. Note that structural material and the detectors themselves increase the radiation lengths of the front section by about 40% with respect to the thin converter foils alone.

only with nearly 100% efficient detectors. Because of the large multiple scattering at low energies the photon direction must be measured accurately in the first two detector planes following the conversion.

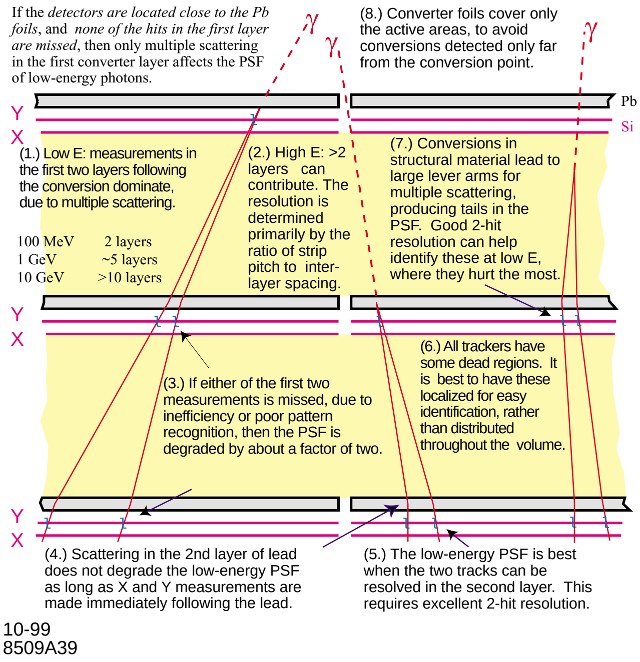

Figure 2.2.4: Qualitative illustration of how the design of a pair-conversion telescope impacts the quality of the PSF. (Not to scale)

2.2.3.4 Importance of a Large Field of View

In addition to excellent PSF at high and low energies, our design emphasizes the importance of a large FOV, particularly for photons that convert in the TKR *and* are measured by the CAL. The large FOV is crucial for monitoring of transient sources and for maximizing the on-source time for *all* of the large number of sources to be studied by GLAST.

The FOV requirement constrains the height of the TKR to be significantly less than the width. It also requires the LAT not to have a time-of-flight system, which is unnecessary for triggering or background rejection in our design.

2.2.4 Flowdown from Science Requirements to Instrument Requirements

The traceability matrix in Foldout D summarizes the SRD specifications, how they relate to the science goals, and how they flow down from the SRD to the LAT requirements and the proposed LAT design. It also shows how the design relates to trades between resources and scientific performance.

2.2.5 Heritage

The LAT design successfully merges the experience gained through EGRET with modern, space-proven technologies. In fact, a large fraction of the EGRET team has played important roles in the LAT development. The large improvements in performance over EGRET are made possible by advanced detector technology, most significantly the silicon-strip detector technology used for the LAT TKR.

Silicon-strip technology already has a successful history of application in space in several relatively small systems and, recently, in the large 2.4 m^2 AMS system (see Table 2.2.5). In HEP research, large silicon-strip systems with specially optimized readout electronics and interconnects are the norm in nearly every modern experiment. This technology allows large areas to be instrumented with high precision, highly efficient, robust detectors.

A similar pattern of parallel application in space science and HEP also holds for the LAT CAL and ACD technologies. CsI calorimeters, very similar to the LAT design, are used in most modern HEP experiments that require precision energy measurements of relatively low-energy gamma-ray photons (*e.g.* the B-Factory experiments at Cornell, SLAC, and KEK). Crystal CALs also have a long history of application in space science, including all four CGRO Instruments. The INTEGRAL IBIS instrument also uses a highly segmented crystal calorimeter with PIN diode readout.

The primary components of the detector systems have substantial heritage. Details may be found in Table 2.3.2**.** The detector subsystems are designed and optimized to yield maximum scientific output from the GLAST mission and therefore, are not identical to previously flown systems. To mitigate this risk, we are presently assembling a full-scale BTEM tower, some components of which are displayed in Foldout C.

Starting in December 1999, the BTEM, which includes a TKR module, CAL module, plus ACD and data acquisition (DAQ) systems, will be thoroughly evaluated in accelerator beam tests, subjected to environmental testing, and flown on a balloon, as described in

Table 2.2.5: Summary of the Tracker Technology Trade Study[a]

		Silicon-Strip Detectors		Scintillation Fibers/PMT readout
Detection Principle		Electron-hole creation from ionization in PIN diode.		Light production by scintillation in plastic fibers.
Readout		Direct VLSI Readout; simple, compact interface. 150 V max.		PMT, Amplifier. Bulky; large dead mass around Tracker; complex interface. High voltage.
# detected primaries	√	80,000 e^-,hole pairs/mm Highly efficient, robust.		5-15 photoelectrons/mm. Low efficiency; high risk from system degradation.
Efficiency/layer	√	>99% in active area.		60-90% in active area (see text).
Minimum Pitch	√	≈0.05 mm. Gives no restriction on capability for GLAST.		≈0.5 mm for MIP detection. Restricts attainable resolution at high energy.
Resolution	√	Predictable: ≤ strip pitch divided by root(12)		Existing HEP implementations have been limited by poor signal/noise and crosstalk.
Dead regions; Distribution	√	Edges of Si detectors. Localized.		Surrounding every fiber (cladding). Distributed over entire Tracker plane.
Ground experience with large system (see text)	√	Extensive. Virtually every modern HEP experiment. Excellent performance for MIPs.		Two relatively small experiments with Multi-Anode PMT readout. Marginal performance.
Space experience with large system	√	AMS experiment; sensitive to MIPs. Double sided, small pitch⇒much more complex than GLAST.		None with PMT readout, some with image-intensifier readout for heavy-ion detection.
Sensitivity of readout to MIPs	√	None.		Could be problematic for PMTs.
Channel Count		Large, due to small pitch and limited strip length.	√	Long fibers allow coverage of a large area with fewer channels.
Cost	√	Detectors now at an acceptable level for large systems.	√	Higher per channel; May be compensated by reduced channel count.
Power Consumption	√	Potentially large, due to large channel count. Addressed by low-power ASIC development	√	Higher per channel; May be compensated by reduced channel count.
Assembly	√	Standard industrial large-scale, precision assembly techniques. Strips within detectors are naturally extremely precise.		Precision assembly and alignment of thousands of individual long fibers. Calibration of misalignments of individual fibers would be very difficult or impossible to implement.
Calibration	√	Insensitive. Small threshold dispersion. Highly stable.		Efficiency is highly sensitive to calibration of each PMT anode. Questionable stability.
Modularity	√	Required by strip length. Helps track reconstruction, redundancy, and I&T.		Long fibers allow construction in single module. Yields favorable channel count but larger pattern ambiguities in complex events.

[a] *We chose silicon-strip detectors because of their high performance and robust operation (low performance risk).*

Section 2.4.3. It will also be used for software and DAQ development and to supply test data for use in engineering of the final design.

2.2.6 Technology Choices

2.2.6.1 Tracker

Gas microstrip detectors, scintillating fibers, and silicon-strip detectors were considered as candidate tracker detector technologies. Table 2.2.5 shows the highlights of our trade study of the latter two technologies. Gas microstrips and scintillating fibers were rejected, firstly because of their marginal single-hit efficiency for minimum ionizing particles (MIPs), a critical quantity for good PSF, especially at low energy. In both cases the primary signal, before amplification, is just a few electrons, leading to inefficiencies from downward fluctuations. Secondly, gas microstrip technology has virtually no heritage, while scintillating fiber technology cannot achieve the hit resolution necessary for optimizing the PSF at high energy.

The concern over detector efficiency with scintillating fibers is strongly reflected in their history of use in particle physics experiments. Recent experiments at FNAL, E835 (Ambrogiani 1998) and D0 (Wayne 1996), employ VLPC readout, which has a very high (60% to 80%) quantum efficiency but requires *cryogenic* operation. They obtain 93% and 90% single-layer hit efficiency, respectively, for MIPs traversing 1.1-mm and 0.8-mm fibers. The DESY H1-FPS obtained only 60% efficiency with multi-anode phototube (MAPMT) readout of 1-mm fibers (Bahr 1996) while the CERN RD-17 R&D program (Agoritsas 1998) improved to 93% efficiency with MAPMT readout, but only by stacking *five* 0.5-mm fibers for each detection

Table 2.2.6: History of Applications of Silicon-Strip Detector Techology[a]

Year	Experiment	Channels in thousand	Resolution (μm)	Read-out	Comments	Reference
Use of Silicon Strips in Particle Physics Experiments						
1986	SLAC Mark-II	10	6	VLSI	1st colliding beam system	NIM A 313 (1992) 63
1989/95	CERN Aleph	74/95	10	VLSI	1st double-sided system	NIM A 409 (1998) 157
1992/00	FNAL CDF	46/405	13	VLSI	single/double sided	NIM A 409 (1998) 112
1994	DESY Zeus LPS	56	30	VLSI	single sided	NIM A 364 (1995) 507
1999	SLAC BaBar	150	10	VLSI	double sided	NIM A 409 (1998) 219
2005	CERN Atlas	5000	24	VLSI	single sided	NIM A 409 (1998) 161
Use of Silicon Strips in Space-Based Experiments						
1978	ISEEC/HIST	0.024	290	IC	heavy ion	IEEE Geo. Sci. E, 6E-16 (1978)3.
1998	NINA	0.5	1000	IC	single-sided	NIM A424(1999)414
1996	ACE/SIS	0.13	290	VLSI	double-sided, heavy ion (He and up)	SSR 86(1998)357
1998	AMS (Shuttle)	58	10	VLSI	double sided	NIM A 409 (1998) 458

a. Virtually all modern particle-physics detectors include a silicon-strip system. Here we list only a few of the experiments in which members of our collaboration have participated. In some experiments, both original and upgraded versions are listed.

layer. Recently, Rielage et al. (1999) reported on a system with MAPMT readout and efficiencies greater than 92% for long 0.75-mm fibers. However, as shown in Figure 2.2.3, even a 10% loss of efficiency significantly compromises the PSF. Furthermore, with Poisson statistics of small numbers, losses in photoelectron yield due to possible system degradation get amplified exponentially in terms of inefficiency, creating an unacceptable risk for a crucial performance parameter.

Silicon strip detectors, on the other hand, have an excellent history of application in large particle-physics and space-based experiments (see Table 2.2.6), and they easily achieve the needed resolution. With their primary signal of tens of thousands of electrons, they can operate at essentially 100% efficiency with very low noise occupancy and little risk from system degradation. They are readily integrated into large systems using standard VLSI technology and commercialized electronics assembly methods. Their cost has steadily decreased in the past decade, making them suitable for very large detector assemblies. The main challenge, reducing the power required for the readout electronics, has been met already by our R&D program, in which we have produced ASICs that meet the LAT power and noise requirements.

2.2.6.2 Calorimeter

For the CAL we considered two technologies over several years, making extensive Monte-Carlo simulations and hardware tests of both:

1. Scintillating fibers between lead sheets. This was pursued in the hope of measuring the direction of high-energy photons that do not convert in the TKR, albeit with poor angular resolution. It was dropped because the required energy resolution could not be obtained at low and intermediate energies in a practical design. The fiber technology also did not integrate well with the silicon-strip TKR, and the possible readout methods were unattractive compared with the PIN diodes that can be used with CsI crystals.
2. CsI scintillation crystals (thallium doped), with PIN diode readout:
   - Excellent heritage.
   - Excellent energy resolution.
   - Good spectral match to PIN diodes.
   - Large signal (≈5000 e/MeV).
   - Low-voltage operation (≈50 V).
   - Rugged and compact system.

The main challenges are the dynamic range needed in the electronics and the integration of the crystals into the mechanical structure. These issues have been successfully addressed in our BTEM prototype development.

2.2.6.3 Anticoincidence Detectors (ACD)

The obvious technology choice for the ACD, given the high efficiency required and the needed scale of segmentation, is a system of scintillator panels read out by photomultiplier tubes. Waveshifting fiber, which has an excellent history of application in large particle-physics experiments, is an economical and effective method of coupling the scintillators with the photomultiplier tubes which allows for uniform response and easy routing through a complex assembly. Photomultiplier tubes, rather than photodiodes or avalanche photodiodes, are necessary in this application to achieve the high efficiency that is required.

2.2.7 Baseline Instrument Description

2.2.7.1 System Engineering

During our technology development program significant preliminary system engineering was accomplished, principally by SU-SLAC, Hytec Inc. and Lockheed on the mechanical/ thermal side and by SU-HEPL and NRL on the electrical side. With the establishment of the project office at SU-SLAC, the system engineering procedures are being elaborated and formalized (see Section 2.3.5).

LAT Instrument Interfaces. See Foldout D for a block diagram of the LAT subsystems and their interfaces. The detector modules—TKR, CAL, and ACD—all integrate mechanically and thermally to the Grid and electrically to the DAQ. The DAQ electronics boards and cables also are supported by the Grid, and their heat flows into the Grid. With the exception of mechanical snubbers on the tops of the TKR modules, which help to support the top of the ACD, there are no direct interfaces between any of the detector modules. All electrical interfaces with the Spacecraft are handled by the DAQ, while the Grid handles the mechanical interface between Spacecraft and LAT. There should be no thermal flow between the Grid and the Spacecraft itself, but the Spacecraft does support the LAT thermal radiators, which receive heat from the Grid via heat pipes.

Preliminary specifications exist for the interfaces between the subsystems and the DAQ and are described in block diagrams in Figures 2.2.12, 2.2.14, and 2.2.15. Functional models of all of those interfaces exist within the BTEM. Preliminary specifications also exist for the mechanical interfaces between the subsystems and the Grid. During the formulation phase all interfaces will be refined, and detailed interface control documents will be generated and placed under configuration control.

Grid. The Grid is the centerpiece for mechanical integration of the LAT and also provides thermal management. Foldout C shows the conceptual design of how the TKR and CAL modules integrate onto the Grid, with the TKR modules bolted to the top and the CAL modules inserted inside the cells of the Grid. This arrangement allows TKR and CAL modules to be integrated independently in any order and serviced or removed, if needed, without disturbing the structure or cabling of neighboring towers. The enclosures for the electronics boards mount below the CAL modules, and the ACD and its phototubes are supported on the outer periphery of the Grid.

Heat produced by the TKR, CAL, and DAQ electronics is conducted outward to radiators through constant-conductance heat pipes in the Grid. Figure 2.2.5 illustrates a preliminary conceptual design of the TKR interface to the Grid and the mounting of the heat pipes. “Keep-alive” heaters will be used to maintain minimum temperature when the electronics are powered off.

The Grid also provides the mechanical interface to the Spacecraft, by way of struts attaching to the underside of the Grid. The LAT will be thermally isolated from the Spacecraft by multilayer insulation and low-conductivity struts.

The structure must be rigid enough to support the LAT modules while keeping the TKR interface sufficiently planar that the tops of the TKR modules are not forced together. However, the webs must be as thin as practical, to minimize material between CAL modules. The baseline is a grid of machined aluminum webs 31 cm high and 0.6 cm thick, with heat pipes integrated into the upper flange, as illustrated in Figure 2.2.5.

Instrument Center of Gravity. We estimate the c.g. of the LAT to lie 23.2 cm above the Instrument Interface Plane. This plane is located 1.0 cm below the bottom surface of the CAL modules and represents the mass boundary of the LAT. The CAL-TKR-TEM enclosures extend below this plane by 7 cm under each tower, and in four towers the SIU and ACD-TEM enclosures extend downward by an additional 10 cm. Our FE modeling assumed that the Instrument Interface Structure (IIS) attaches only along the periphery of the Grid. The electronics enclo-

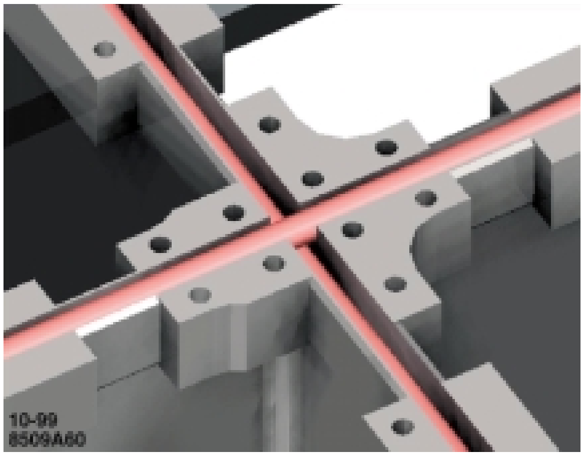

Figure 2.2.5: Conceptual design of the Grid, showing the Tracker interface (mounting flange and cable paths) and the heat pipes.

sures are 10 cm smaller than the towers in the lateral dimensions, making it possible to design the IIS such that it can attach to the Grid without interference. If necessary, attachment points could be designed along inner webs of the Grid while still avoiding the electronics enclosures. The electrical interface cables are readily accessible on the sides of the electronics enclosures that protrude below the Grid.

Mechanical Engineering. The detailed mechanical engineering of the BTEM TKR and CAL modules was accomplished by Hytec Inc. To validate their design concepts, they also did preliminary studies of the overall mechanical integration of the LAT and carried out finite-element and dynamic analyses of the overall structure as well as of the CAL and TKR modules.

Figure 2.2.6 and Figure 2.2.16 show examples of preliminary FEM studies of the LAT as a whole. Frequency response, deflections, and stresses have been studied. The lowest frequency mode (ACD panels) is 57 Hz, and the maximum stresses, 20 MPa, are at the top of the intersections of Grid webs. During the formulation phase we will construct a complete finite-element model of the LAT in IDEAS Master Series format and deliver it electronically to the GLAST project office.

Thermal Engineering. Preliminary thermal engineering studies have been made by SU-SLAC and the Lockheed-Martin Advanced Technology Center. Our requirement is that during normal operations the top of the warmest TKR module should not exceed 25°C, with not more than ≈5°C variation between modules. The driver is the leakage current of the silicon-strip detectors, which begins to contribute noticeably to the noise budget above ≈25°C at end-of-mission. (7% increase in noise from 0°C to 20°C.)

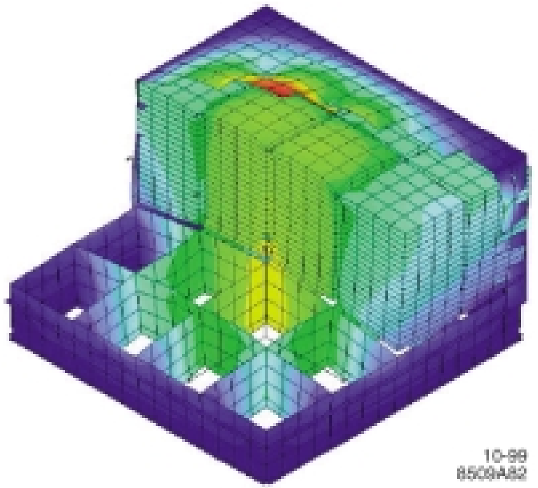

Figure 2.2.6: Lowest global support mode of the LAT. This is the lowest bending mode of the Grid structure. Only half of the TKR modules, the Grid, and a piece of the ACD are shown. The natural frequency is 139 Hz.

Using constant-conductance heat pipes within the Grid, the preliminary studies indicated less than 5°C variation across the Grid and a 12°C drop between the radiator and the top of the warmest tower. Heaters will be present in the Grid but will not be needed during normal operation.

During the formulation phase we will develop a complete thermal model of the LAT in the format specified by the SC-SI IRD, and we will deliver a simplified version to the project office.

LAT Alignment. The internal mechanical alignment precision of an individual TKR module is well understood from measurements made on the mechanical model pictured in Figure 2.2.11. In addition, internal alignment of detectors within a TKR tray (Section 2.2.7.2) can easily be controlled to better than 50 µm rms, requiring no additional corrections. As constructed, a module would yield a pointing precision of better than ≈50 arcsec. This can be improved to better than 10 arcsec by applying corrections obtained from a single day of cosmic-ray calibration data. Relative alignment of the 16 TKR modules will be initially surveyed during I&T. During flight it will be readily calibrated, from high-momentum cosmic rays that pass through multiple towers, to a precision equivalent to the internal module alignment. The alignment of the TKR relative to the star-tracker will be calibrated to better than 10 arcsec statistical precision by a 2-week pointed observation of the bright point sources in the galactic anticenter (or by a ≈2-month scanning-mode observation). The pointing accuracy will also be limited by thermally driven variations in mechanical alignment between the Spacecraft and the TKR. The LAT contribution to this error will come from deformations in the Grid. Our goal is for that contribution to be less than 10 arcsec rms, which requires the temperature difference between the top and bottom of the Grid, during normal operations, not to vary with time by more than 2°C.

Instrument-Spacecraft Interface. Two redundant Spacecraft Interface Units (SIU), based upon the same processor and architecture as the DAQ modules, are located within the Grid, below the electronics modules of two of the towers. They will implement all of the LAT electrical, command, telemetry, and software requirements specified in the SC-SI IRD.

Commands, ancillary data, GRB notification messages, and LAT housekeeping data are relayed between the Spacecraft and the SIU via a standard 1553B (or AS 1773) data bus. The SIU implements a Remote Terminal (RT) interface on the 1553B data bus.

The SIU provides programmable interface support between the LAT and the Spacecraft. The SIU interface will be configured to support the Solid-State Recorder (SSR) using an RS-422 parallel interface (nominally 70 Mbps, or as required following Project definition of the interface). The data packets sent to the telemetry interface will be CCSDS encoded in the SIU as required.

The nominal source of downlink telemetry from the LAT will be the SSR. However, the LAT data switch is capable of supplying the full SSR input bandwidth and has the flexibility of flowing data from any LAT storage location directly to the SSR output of the SIU.

Power Systems and Grounding. The Spacecraft provides a redundant switched service for the +28V power. The LAT provides redundant units for power switching to the internal units (16 TEM and 2 ACD, see Section 2.2.7.6) which operate over the required range of +28 V ± 6 V. The SIU power is internally switched under control of the Spacecraft. The SIU is protected from damage if both SC-A and SC-B are active simultaneously or if power is removed without warning, and the SIU isolates the SC-A and SC-B buses to preclude cross connection.

The LAT utilizes a distributed power supply system with power converters to provide greater than 10 MΩ isolation between primary and secondary returns (see Figure 2.2.7). Secondary loads are referenced to ground at a single connection within each module, and no current is conducted through the chassis. All signals between separate power systems are carried by differential digital links, using LVDS standard devices, in order to maintain isolation and minimize EMI. Separate power converters are used for each detector module and each TEM. Power inputs to each module comply with Mil-STD-461/462. Current and voltage on the input side of the power converters are monitored for each power cable at the SIU switch. The output voltage and current are monitored within each TEM for each voltage on each supply.

Table 2.2.7 lists the voltages needed by the subsystems and their associated power converter ratings. The power requirements, itemized by subsystem, can be found in Table 2.2.11.

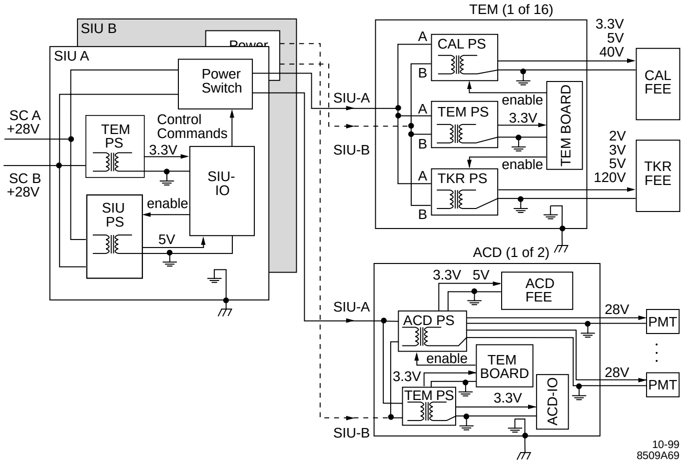

Figure 2.2.7: Power and Grounding Scheme

Table 2.2.7: Power Supply Voltages and Required Power Converter Power Ratings[a]

Subsystem		Voltage (V)	Power Rating (W)	Assumed Efficiency
T	Analog	5	7	87%
K	Analog	2	3	69%
R	Digital	3	6	84%
	Detector Bias	0–150	0.7	n.a.
C	FEB	5	5	87%
A	FEB	3.3	2	84%
L	Diode Bias	0–50	0.5	n.a.
A	FEB	5	7	87%
C	FEB	3.3	8	84%
D	PMT supplies	28	12	87%
D	TEM	3.3	8	84%
A	ACD-TEM	3.3	8	84%
Q	SIU-TEM	3.3	8	84%
	SIU	5	20	87%

a. Efficiencies were taken from a vendor quotation for a high-efficiency design.

2.2.7.2 Tracker Subsystem

The TKR design emphasizes the importance of an outstanding PSF at high as well as low energy, making use of advanced detector technology to minimize all contributions to measurement error beyond the unavoidable multiple scattering. In accordance with the discussion in Figure 2.2.4, the detector layers are held close to the converter foils, the inactive regions are localized and minimized, and the passive material is minimized.

TKR Configuration and Mechanical Design. Each of the 16 identical TKR modules consists of 18 *x*,*y* planes of silicon-strip detectors, converter foils, and the associated readout electronics, all supported by a carbon-composite structure. Figure 2.2.8 illustrates schematically a single *x* or *y* layer.

The support structure for the detectors and converter foils is composed of a stack of 19 composite panels, call "trays," aligned at the four corners and held in compression by cables threaded through the corners. Sidewalls provide additional strength, protect the electronics, and conduct heat to the TKR base. The tray structure is a low-mass carbon-composite assembly composed of a closeout, face sheets, and vented honeycomb core. Carbon-composite is chosen for its long radiation length, high modulus-to-density ratio, and thermal stability. Foldout C (1,3) illustrates the TKR mechanical design and the installation of the electronics and cables.

The tray panel structure is about 3 cm thick and is instrumented with converters, detectors, and front-end electronics. All trays are nearly identical in construction, although the top and bottom ones are special, as they include mechanical interfaces to the Grid and ACD and have detectors on only one face. An *x*,*y* measurement plane consists of a "*y*" layer of detectors on the bottom of one tray together with the "*x*" detector layer on the top of the tray just below, with only a 2-mm separation. The converter layer lies immediately above the "*y*" layer. There are 12 *x*,*y* planes at the top of the TKR with 2.5% R.L. converters ("front section"), followed by 4 *x*,*y* planes with 25% R.L. converters ("back section"). The last two *x*,*y* planes have no converter foils.

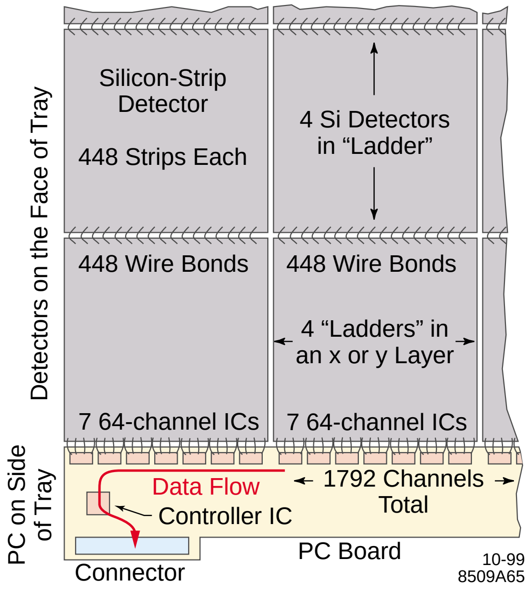

Figure 2.2.8: Schematic depiction of roughly 1/4 of a TKR detector layer, *x* or *y* (not to scale).

The tray and TKR module designs have been extensively studied numerically and by prototyping. Figure 2.2.9 illustrates FE models of the baseline preliminary designs of a tray and a tower module. High stiffness is required in order to prevent collisions between adjacent towers, while maintaining small gaps. A mechanical model with 10 stacked trays, shown in Figure 2.2.10, was constructed and subjected to extensive vibration testing to validate the design and numerical models (Ponslet 1998).

The key requirement in the tray mechanical design is to make the structure sufficiently stiff to avoid tray-tray collisions during qualification testing and launch. This requires the tray's fun-

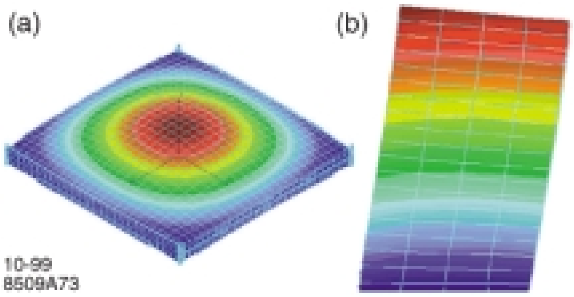

Figure 2.2.9: FEM analysis of deflections of a TKR tray and a complete TKR module. The models show fundamental frequencies above 550 Hz for the tray and 300 Hz for the module, clamped only at its base.

damental frequency to be about 500 Hz or higher. Careful analysis of the thickness of carbon-composite panel components needed to meet this requirement has been carried out and is properly reflected in our mass budget.

A complete, functional tray (aluminum construction) with a full set of wire-bonded silicon-strip detectors and readout electronics was subjected to a random-vibration test to full GEVS qualification levels with no damage (Figure 2.2.11). In particular, not a single wire bond (out of ~10,000), whether encapsulated or not, was broken on this tray or on two other mechanical models. These test data are presently being used to crosscheck the models in development for the carbon-composite tray design.

TKR Cooling. Heat from the electronics flows through the PC boards, into the tray closeout, and into the TKR wall. The thermal resistance between wall and closeout has been measured to be negligible, and the total temperature difference between the top tray and the Grid is calculated to be less than 7° C.

TKR Detector Elements. The detectors are single-sided AC-coupled silicon-strip detectors with polysilicon bias resistors. The thickness is 400 μm, and the strip-to-strip pitch is 201 μm. The bias potential is supplied to the aluminized back of each detector via a flex circuit, and a ground connection is made via wire bonds to the bias ring on the top side.

An *x* or *y* detector plane is composed of 4 adjacent “ladders,” each of which consists of four 9.2 cm square detectors that are edge bonded together. Wire bonds connect the strips of one detector with those of its neighbors, effectively forming 37-cm long strips and reducing the number of detector elements by a factor of 4 to 2,304, each of which integrates 448 strips into a single unit.

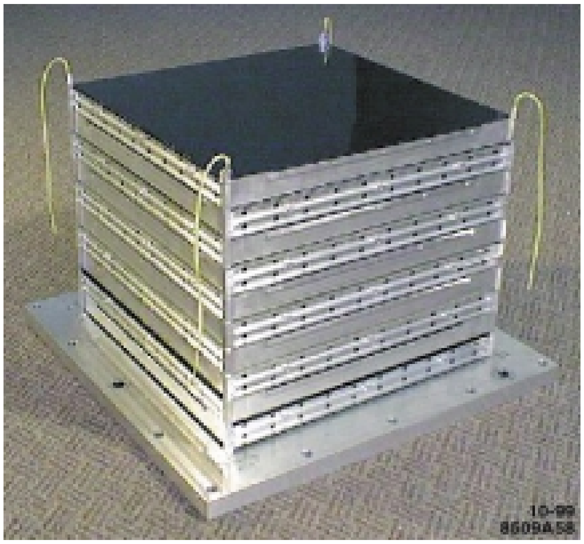

Figure 2.2.10: An aluminum and carbon-fiber mechanical model of 10 stacked TKR trays, used by Hytec, Inc. to validate the design in vibration tests.

TKR Readout Electronics. The TKR readout system encompasses 1,032,200 strips and amplifier-discriminator channels (Johnson 1998). However, that large number is *not* reflected in the parts count. Each VLSI amplifier chip handles 64 channels, and 1792 channels are integrated into each readout section using standard electronics-industry automated assembly techniques.

The readout electronics are mounted on PC boards attached to two sides of the tray, as illus-

Figure 2.2.11: A live BTEM tray undergoing random-vibration testing at GSFC.

trated in Foldout C (6). A flex circuit carries the detector signals and bias currents around the tray corners. This complication is important for minimizing the dead area between towers. Encapsulated wire bonds interconnect the detector ladders with the flex circuit and the amplifier-discriminator readout chips. Twenty-eight such readout chips (GTFE) and two digital readout controller chips (GTRC) populate one PC board and are electrically connected via encapsulated wire bonds.

The two different ASICs are CMOS VLSI chips. In addition to amplifiers and discriminators for each of the 64 channels, the readout chip includes trigger logic, a calibration system, buffering for 8 events, dual redundant control and configuration via serial commands, and LVDS input-output. The readout chips do not interact directly with DAQ. Rather, all communication takes place via the readout-controller chips over LVDS links. In addition to buffering clock, trigger, and command signals, they control the readout sequence, format the data into packets of addresses of hit strips, buffer the data, and handle the readout protocol with the DAQ system. Fully functional prototypes of both chips are already in use in the BTEM TKR module. As shown in Foldout B (3a–3b), the readout system was demonstrated in the 1997 beam test to exceed our noise and efficiency requirements. For the nominal 1.5 fC discriminator threshold, essentially 100% efficiency was obtained with a factor of 100 or more margin on the noise occupancy requirement.

The TKR data acquisition scheme is illustrated in Figure 2.2.12. Via the controller chips, the readout of any layer can be split between any pair of readout chips, with some read out to the left and the rest to the right. This allows the readout to be configured in the case of the failure of a single chip or data link such that at most only 64 channels are lost.

TKR Redundancy Scheme. As shown in Figure 2.2.12, the TKR readout is tolerant of a failure of any single chip or cable. Furthermore, the performance of a TKR module degrades gracefully with the loss of sections of the readout. Loss of a small fraction (≈1%) of individual strips in random locations has a minor effect on performance. Loss of a readout chip, a whole detector ladder, or an *x* or *y* plane results only in a proportional loss of effective area.

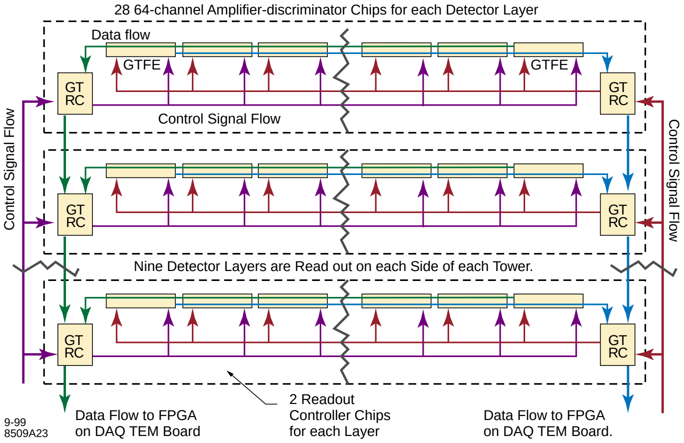

Figure 2.2.12: TKR readout scheme. Each pair of cables connecting to the DAQ handles 9 readout modules, or one side of the TKR Module.

TKR Technology Development Program. A complete, functional model of a TKR module has been fabricated and is currently under test, as part of the BTEM, with cosmic rays and particle beams. It differs from the proposed design in being slightly smaller in cross section (32-cm detector ladders, rather than 37 cm) and having only 17 trays. Also, the tray closeouts and the walls are constructed from aluminum rather than carbon fiber. The detectors and electronics satisfy all of the LAT requirements for power, noise, speed and dead-time, efficiency, and redundancy. Photographs of the front-end electronics and one of the completed trays are shown in Foldout C (6). Foldout B (2a–2d, 3a–3b), features beam test results from an earlier test assembly with 6 small *x,y* planes. The noise measurements were made on a 30 cm-long ladder in that assembly.

2.2.7.3 Calorimeter Subsystem

The CAL design emphasizes good spectroscopy over the full GLAST energy range plus sufficient segmentation to provide the pattern-recognition power needed to assist the TKR and ACD with background rejection. Similar to EGRET, it consists of crystals with a total thickness of 8.5 R.L. (plus 1.6 R.L. in the TKR). But in distinction to EGRET, it is finely segmented in both the longitudinal and transverse directions. Its top-level parameters are summarized in Table 2.2.4.

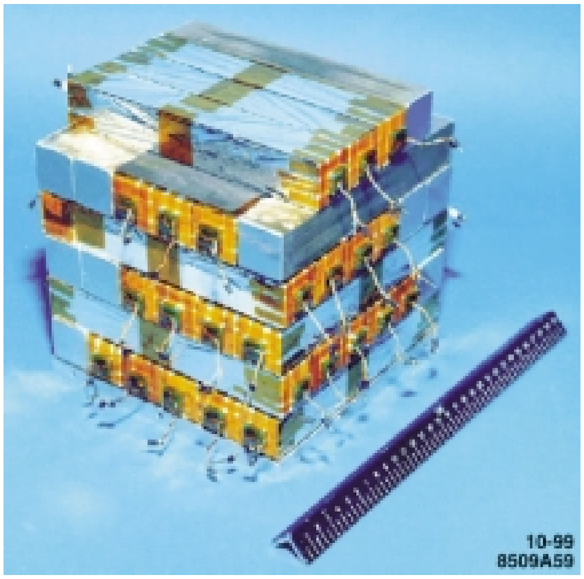

Figure 2.2.13: Example of hodoscopic configuration of CsI crystals in preparation for a beam test at SLAC in 1997.

The energy resolution strongly depends on the CAL depth, sampling, and longitudinal segmentation. Lateral segmentation is necessary in order for the CAL to provide the necessary imaging capability to correlate events in the TKR with energy depositions in the CAL. That is crucial for realization of the required cosmic-ray rejection level. The imaging capability can also be used to measure the direction of high-energy photons that do not convert in the TKR, with a resolution at the level of a few degrees.

The longitudinal segmentation enables energy measurements up to a TeV. From the longitudinal shower profile, we derive an unbiased estimate of the initial electron energy by fitting the measurements to an analytical description of the energy-dependent mean longitudinal profile. Except at the low end of the energy range, the resulting energy resolution is limited by fluctuations in the shower leakage. The effectiveness of this procedure was evaluated in beam tests. Foldout B (2f) shows the measured energy loss in the CAL for electron beams of 2, 25, and 40 GeV. The tails to low energy are clearly evident for the beam energies of 25 and 40 GeV. Foldout B (2g) shows the corrected energies for 25 and 40 GeV runs. Fitting was not performed for the 2 GeV run, and the slight tailing to low energy is still evident. The resolutions, σ_E/E, are 4%, 6%, and 6% respectively, for these three energies.

CAL Configuration and Mechanical Design. We propose a thallium-doped cesium-iodide scintillation crystal CAL with PIN photodiode readouts. It is configured as 16 modules in the 4×4 array of LAT towers. Each module is segmented into discrete detector elements (crystals) and arranged into a hodoscopic, imaging configuration (Figure 2.2.13).

A module contains 96 crystals of size 2.8 cm × 2.0 cm × 35.2 cm. The crystals are optically isolated from each other and are arranged horizontally in 8 layers of 12 crystals each. Each layer is aligned 90° with respect to its neighbors, forming an x,y array. Each CsI crystal provides three spatial coordinates for the energy deposited within: two discrete coordinates from the physical location of the bar in the array and third, more precise, coordinate measured in the long dimension of the crystal.

The PIN photodiodes are mounted on both ends of a crystal and measure the scintillation light that is transmitted to each end. The difference in light levels provides a determination of the position of the energy deposition along the CsI crystal. The position resolution of this imaging method ranges from a few millimeters for low energy depositions (~10 MeV) to a fraction of a millimeter for large energy depositions (>1 GeV). Foldout C (9) demonstrates this method in a 32-cm CsI bar used in beam tests at SLAC and CERN. Simple analytic forms are used to convert the light asymmetry into a position. Positions were determined by the Si Tracker for 2 GeV electrons, which typically deposited 150 MeV in the CsI bar. The rms error in the position, determined from light asymmetry, is 0.28 cm. In the CERN test a successful attempt was made to reduce the light reflected off of the end surfaces and thereby improve the uniformity of the light asymmetry.

The size of the CsI crystals has been chosen as a compromise between electronic channel count and desired segmentation within the CAL. The indicated size is comparable to the CsI radiation length (1.86 cm) and Molière radius (3.8 cm) for electromagnetic showers. This level of segmentation is sufficient to allow spatial imaging of the shower and accurate reconstruction of the incident photon direction, with most of the position information provided by the light-asymmetry measurement.

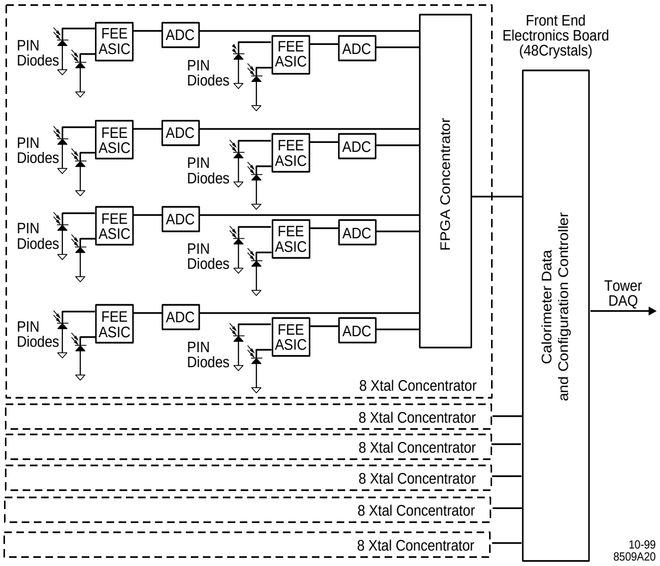

Figure 2.2.14: Block diagram of the CAL readout system for one fourth of one module. The other ends of the same crystals are read out by an equivalent but separate board.

The CAL mechanical structure must support the CsI crystals securely during launch while still allowing for significant thermal expansion and contraction. Two structural designs are being considered. Foldout C (8) illustrates a compression-cell design that has been well tested and used in the BTEM. The crystals are stacked with compliant material between each layer, and the stack is compressed before adding shear panels on all sides. The crystals are prevented from slipping by friction against the compressed compliant layers and, as a backup, by the side panels. The photodiodes are bonded directly to the ends of the crystals, and the front-end electronics boards are integrated into the side-panel structure.

A trade study is in progress to evaluate an alternative CAL mechanical configuration designed to satisfy the same requirements while reducing the dead space between modules. It is based upon a stack of carbon-fiber cells, each of which holds one CsI crystal.

CAL Cooling. The CAL is closely coupled to the surrounding Grid, so the electronics' heat readily flows into the Grid structure. The operational temperature of the crystals and PIN diodes is not critical but will be stable during normal operations due to the very large thermal mass of the CAL.

CAL Readout Electronics. Each CAL module has 96 crystals read out on each end, for a total of 3,072 channels. The major design challenges for the electronics are 1) the large dynamic range (5×10^5) with small nonlinearity (<2%) for spectroscopic measurements, 2) low power consumption, and 3) minimal dead time (<20 μsec per event). We have met these challenges in the prototype CAL developed as part of our technology development program. The dynamic range has been achieved by creating two independent signal chains. The low energy signal chain covers the energy range from 2 MeV to 800 MeV. The high-energy signal chain covers the range from 40 MeV to 100 GeV. The significant overlap between the two ranges permits cross-calibration of the electronics. A custom dual PIN photodiode has been developed for LAT based on the 3590 PIN photodiode from Hamamatsu Photonics. The active areas of the two diodes have a ratio of 4 to 1. The larger area diode covers the low energy band, while the smaller diode covers the high energy band.

A prototype ASIC, developed as part of our technology program for the BTEM, has demonstrated the needed low-power performance. It processes signals from two PIN diodes: one low-energy diode and one high-energy diode from a single end of a crystal. For each PIN diode it contains a preamp, three shaping amps, four discriminators, and two peak-detecting track and holds. The preamp signal feeds two shaping amps, which further divide the energy domain into a total of four energy ranges per CsI log end. These two shaping amps are followed by peak-detecting track and holds, which capture the peak amplitude of the pulse and stretch it for subsequent digitization by the ADC. An additional, faster shaping amplifier with peaking time of 0.5 μsec is used for fast trigger discrimination. Designed-in programmable test pulse generators and in-flight measurements of high-Z cosmic ray energy depositions provide cross-calibration of the four energy ranges, as well as their absolute calibration.

The CAL flight ASIC will be designed and fabricated in the radiation-hard, latchup-free DMILL SOI process. During the formulation phase a complete design will be done that includes all necessary interfaces and that optimizes the overall performance of the readout.

Table 2.2.8: Elements of the ACD

Element	Baseline Concept	Rationale
Sensor	Plastic scintillator tiles (Bicron 408) 1000 cm^2 area (top) Single layer	Good charged particle sensitivity (>0.9997) Low γ-ray sensitivity Rugged, inexpensive, heritage
Light collection	Waveshifting fibers (Bicron 91), 2 sets for each tile	Uniformity, hermeticity, flexibility, redundancy Do not scintillate
Readout	Phototubes, (Hamamatsu R1635 or R5611), 2 each tile	High gain, fairly small, space-qualified, redundancy, heritage, practical in small numbers
Electronics	ASIC front end, two-level trigger, housekeeping data (including PHA)	Low power Fast MIP signal delivered to DAQ High-level trigger for Calorimeter calibration PHA signal available
Mechanical support	Composite structure with scintillator tiles attached	Allows delivery of unit with scintillators tightly packed (gap leakage < 3 x 10^{-4})

To meet the dead-time goal, commercial, off-the-shelf (COTS) successive approximation analog to digital converters (ADCs) digitize the pulse amplitude signals from the ASIC. Each CsI crystal has a dedicated ADC. The organization of the readout electronics is shown in a block diagram in Figure 2.2.14.

CAL Redundancy Scheme. Redundancy in the CAL is achieved by reading out each CsI crystal from both ends. The information from opposite ends does not merge into a common hardware unit until reaching the FIFO in the DAQ TEM. If the readout of one end were lost, then the shower position could not be obtained from light asymmetry in that crystal, but the energy measurement would not be significantly degraded. In most situations the surrounding crystals could still supply the shower position measurement.

CAL Technology Development Program. A complete, functional model of a CAL module has been fabricated and is currently under test, as part of the BTEM. It matches the BTEM TKR in size. Foldout C (7) contains a photograph of the BTEM CAL in assembly with electronics mounted on four sides. The compression-cell structure has been fully implemented, and a second copy was made and has successfully completed GEVS qualification-level random vibration testing and static load testing to the SC-SI IRD specifications. A prototype of the carbon-fiber cell design has successfully passed vibration tests at qualification levels as well. The electronics implement the full design functionality, using the prototype amplifier ASIC and COTS ADC.

2.2.7.4 ACD Subsystem

As for all previous high-energy gamma-ray telescopes, the LAT will use a plastic scintillator ACD. The ACD design emphasizes high efficiency and sufficient segmentation to avoid loss of effective area at high energy due to self-veto, in which albedo from CAL showers fires ACD tiles. It consists of segmented plastic scintillator tiles read out by wave-shifting fibers and photomultiplier tubes. The segmentation is designed to avoid the self-veto problem of EGRET at high energies (50% loss at 10 GeV) while still providing high cosmic-ray rejection.

The ACD is the first line of defense against the enormous charged particle background from cosmic ray primary and Earth albedo secondary electrons and nuclei. However, it is not the only defense. The discussion on background rejection in Section 2.2.8.2 shows how the precise tracking and lateral and longitudinal shower information in the TKR and CAL are used as powerful adjuncts to the ACD. The trigger (Section 2.2.7.7) has a veto over-ride for high-energy photons. This means that GLAST will not lose high-energy photons due to self-veto before the events can be analyzed in more detail, either on-board at Level-3 or on the ground. The cosmic-ray rejection needed by the ACD alone is only about 3×10^3:1.

Table 2.2.4 shows the specific requirements for the ACD, in terms of segmentation, efficiency, and number of layers. They are based on extensive measurements and Monte Carlo simulations to ensure adequate rejection of the backgrounds described in Section 2.2.8.2 and to keep the probability of self veto to less than 10% for even the highest energy gamma rays.

ACD Configuration and Mechanical Design. The proposed design is shown in Foldout C. The choice of a 5×5 array of tiles on the top, compared to the 4×4 TKR tower array, allows the active TKR areas to serve as a back-up for the seams between tiles, where leakage might be possible. The layout reflects careful simulation studies, which show, for example, that the degree of segmentation must be particularly high near the CAL and that there is no benefit in placing ACD tiles around the sides or back of the CAL. There is a total of 145 tiles in the design.

Table 2.2.8 outlines the principal elements of the ACD design, showing how this design meets the requirements. In Foldout C (11) is a photograph of one scintillator tile and its wave-shifting fibers, which are glued into grooves milled into the surface. Each tile is separately wrapped in a light-tight enclosure to avoid crosstalk, and adjacent tiles are either butted together or shingled to minimize dead space.

The ACD tiles will be supported on a frame attached to the Grid and made of composite panels, with carbon-composite face sheets and aluminum honeycomb cores. The frame will be designed and modeled in full scale during the formulation phase. The large top surface of the ACD will also be anchored to the top of the TKR via snubbers located at the tower corners. Figure 2.2.16 shows a preliminary FEM analysis of the LAT under static load, in which the effect of the snubbers is clearly visible. The lowest-frequency mode of the LAT is a 57 Hz drum response of the ACD panels.

ACD Cooling. The ACD is inside of the thermal blanket. Heat from its electronics will flow into the perimeter of the Grid and from there to the radiators.

ACD Readout Electronics. The ACD readout electronics are described by Figure 2.2.15. Following the PMT, an ASIC will handle the amplification and discrimination functions. The low-level discriminator serves the veto function, while the high-level discriminator is used to select highly ionizing particles (primarily for use in CAL calibration). Pulse-height information from the ADC is used only for monitoring and calibration of the ACD system.

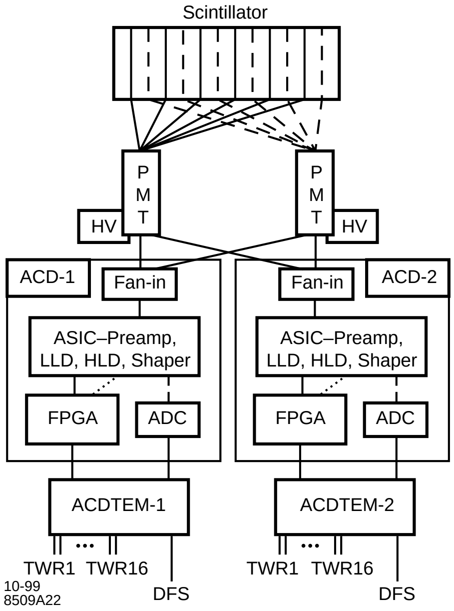

Figure 2.2.15: ACD Readout System

ACD Redundancy Scheme. ACD designs with two layers as well as one were studied. Two layers could improve the cosmic-ray rejection or reduce the self-veto losses due to backsplash, depending on whether they were treated as an OR or AND in the trigger veto. However, a double-layered system adds significant weight, power and cost and greatly increases the complexity of constructing a system without cracks between tiles or at corners. Those costs are too high, and our studies show that the GLAST requirements can be met with a carefully designed single-layer system. A second ACD layer is *not* needed for redundancy.

Our design includes completely separate readout strings for each tile, starting with separate wave-shifting fibers and PMT's, each with individual power supplies and ending with separate electronics strings. The redundancy of the ACD system is illustrated in Figure 2.2.15.

Still, the puncture of a light shield by small meteoroids or orbital debris could render a single tile ineffective. The primary impact of such a failure is a 10% increase of the L1T rate. However the increase is easily handled by the DAQ, and other LAT defenses against the resultant background events are sufficient to remove them to required levels.

ACD Technology Development Program. Measurements of detection efficiency for scintillators

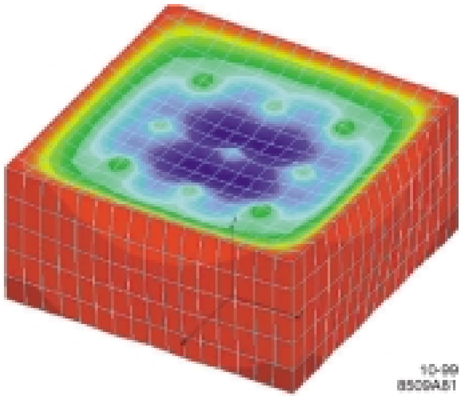

Figure 2.2.16: Static deflection of the LAT under 8.25g in the thrust direction. Only the ACD is shown. The effect of the snubbers between ACD and TKR is clearly visible. The maximum deflection is 162 μm.

with waveshifting fiber readout were made in the laboratory using muons and at the 1997 SLAC beam test (Atwood 1999). Results are shown in Foldout C (10). The requirement of 0.9997 is exceeded at the lowest threshold. Even higher efficiency can be obtained by summing the signals from both phototubes.

Measurements of the backsplash conversion probability for 10-20 GeV photons (and electrons) were made in the 1997 beam test at SLAC and for 150-250 GeV electrons in a subsequent summer 1999 CERN test. These measurements show that segmenting the ACD tiles to of order 1000 cm^2 × (distance from the CAL/ 60 cm)^2 allows us to keep the self-veto probability to less than 10% at 300 GeV.

The BTEM includes an ACD system equivalent to what is described here but sized to fit the single-tower prototype. Beam tests and the balloon flight with this device will provide data for further verification and refinement of the design.

2.2.7.5 Thermal Blanket and Micrometeor Shield

A design element closely related to the ACD is the outer wrapping of the LAT. This wrapping serves three purposes: (1) it forms a light-tight cover for the LAT; (2) it is the thermal blanket for the LAT; and (3) it provides protection against micrometeoroid penetration. At the same time, it must have extremely low mass, because any inert material outside the scintillator is a source of locally produced gamma rays. Our plan is to use a multi-shock shield (Cour-Palais), with four layers of Nextel ceramic fabric separated by spacers made of Solimide foam and with a Kevlar backing sheet. Such a design can achieve good protection for the ACD with a total area mass of less than 0.3 g/cm^2. A single-shock shield of similar design has successfully protected the EGRET ACD for over eight years in orbit. The portion of thermal blanket covering the top of the LAT, the surface through which prime gamma-rays enter, is located inside a "well" formed by extending the side ACD tiles above the top surface. No charged particle capable of creating a π^o or nuclear-decay gamma-ray can reach the inert material on this surface without also passing through an ACD tile.

2.2.7.6 Data Acquisition System (DAQ)

The primary functions of the DAQ are to trigger the LAT to capture an event (the Level-1 Trigger, or L1T), read out the captured event data into memory, and process them into a stream with an average bit rate compatible with the downlink bandwidth. It also performs the functions of command, control, instrument monitoring, housekeeping, and power switching. The DAQ performs the L1T and read out functions in hardware with no direct participation by the processor. The first processing level is the Level-2 Trigger (L2T) and is performed locally at the tower level. Events passing L2T are transmitted to a processor located in the Spacecraft Interface Unit (SIU) for additional filtering (the Level-3 Trigger or L3T). Events passing L3T are sent to the Spacecraft Solid State Recorder (SSR) for later downlink.

During the ATD program, various architectures for implementing the DAQ were considered, including the use of a centralized processor. We concluded that a distributed system, with identical Tower Electronics Modules (TEM) in each tower, plus a similar module for the ACD readout, carries the least risk, offers the best performance, and greatly simplifies the data flow and processing, as well as integration and testing.

The LAT dead time is less than 20 μs per event and is determined by the digitizers used to capture and read out the CAL data.

DAQ Modules. A block diagram of the DAQ system is shown in Foldout D. It consists of 16 Tower Electronics Modules (TEM), with one located under each CAL module, two ACD readout modules (ACD-TEM), and two SIU modules (SIU-TEM). The ACD and SIU units are simple variants of the TEM, with identical CPU and memory components. They are mounted under the TEMs, one in each of four towers.

Data Switch FPGA. The Data Switch FPGA (DSF), illustrated in Foldout D, provides bidirectional serial links between the SIU and TEMs for data flow, command, and telemetry. LVDS technology was selected for the serial links because of its simplicity, low power, and low EMI.

Loss of a CPU in one of the TEMs results in an automatic change for that TEM DSF so that data flows to an external link instead of into local DRAM. The detector data then are written into DRAM in another TEM board. Additional features in the DSF include local registers that provide a means of commanding board level resets and power switching via any link. This means that any processor in the LAT, as well as commanding from the ground, can be used to perform board-level resets or power switching.

Tower CPU. The Tower CPU (TCPU) runs the VxWorks Real Time Operating System (RTOS, see Table 2.3.2). The processor is not required in order to trigger or capture data, but we have chosen to implement it in the TEM to increase the redundancy and margins for on-board processing, command, and control. Other advantages to providing a CPU in each module include simplified design, reduced capability requirements on any one processor, and greatly enhanced testability during development and integration. During the ATD phase, we built a TCPU board using a PowerPC 603E processor, as qualified for flight by the NEMO program at NRL, and wrote a board support package for the RTOS. During the formulation phase, we will select the most suitable processor based on power, performance, cost, and qualification.

Total processing power in the DAQ is 720 Mips, calculated as 40 Mips of available processing power for each of the 18 CPUs (16 TEM + ACD-TEM + SIU-TEM). We require 36 Mips at the peak cosmic ray trigger rate of 9 kHz, which provides a large margin. When CPUs are not active, they can be put in sleep mode to conserve power.

Memory. Each TEM processor is supported by a combination of PROM, FLASH, SRAM, and DRAM memory. The 64-kbyte PROM memory is used for the basic code needed to boot the system and enable external communications. The higher levels of code, including the application code that runs the TEM, reside in 4 Mbytes of FLASH memory, with an option to load from an external source. Code is loadable from any onboard source, which provides a simple method of supplying a high degree of redundancy. After boot, the low activity levels of the PROM and FLASH reduce the power consumption for these devices to a negligible level.

We plan to use a Level-2 (L2) Cache that is an EDAC-corrected 1-Mbyte SRAM. Application code running within the L2 Cache will operate at a higher effective speed than code which must access the DRAM and, in addition, will consume less average power. The main memory on each TEM board is 256 Mbytes of DRAM accessed via a Reed-Solomon EDAC, with 192 MB available for event data and the file system.

Timing. Each event will be timestamped with a 32-bit count of the local clock at the time the L1T signal is received. The SIU receives the GPS sync pulse as well as the local 20 MHz clock from which the timestamp is captured. A "UTC-sync" count is generated by capturing the same clock counter at the time of the GPS sync pulse. The UTC time of each event is calculated from the UTCsync and the GPS UTC time transmitted from the SC. During Level-3 trigger processing this UTC timestamp is added to each event queued for downlink. A trigger count is also attached to each event to identify it across all detector readouts.

The long term stability and accuracy of the GPS time code can be used in conjunction with stable local oscillators to derive event times with µs accuracy. The ultimate limitation in event timing precision will be the jitter in L1T resulting

Table 2.2.9: LAT Instrument Timing

	Noise	Short Term Drift	Long Term Drift	Uncorrected UTC Error
GPS Sync Pulse	1 µs rms	1 µs rms	< 1 µs	< 1 µs
L1T	< 1.3 µs	< 1.3 µs	< 1 us	0–1.3 µs
Clock drift	0.1 ns	0.01 ppm/s	5 ppm/year	< 2 µs

from varying delays in the ACD, CAL, and TKR discriminator inputs to the trigger hardware. Table 2.2.9 lists the contributions to short and long term errors in event timing. Thermal drift of the clock is very low because of its inherent stability and because the temperature of the clock, which is monitored, will change very slowly as a result of the high thermal mass of the CAL.

DAQ Redundancy Scheme. All redundant Spacecraft interfaces are maintained through the redundant SIUs. Within the 16 towers, the detector subsystems have redundant readouts. Single-point failures within a tower are minimized to the few components (LVDS and FPGAs) required for read out and to the power supplies within each tower. The CPU board associated with each tower is not required for data capture and read out.

DAQ Technology Development Program. In addition to developing a detailed conceptual design, the DAQ technology development program has concentrated on design, construction, and testing of DAQ components within a VME-based development system. Custom VME boards designed and prototyped include a TCPU, TKR readout/L1T, CAL readout/L1T, and SIU-IO GPS sync pulse circuit. These boards are also used for the DAQ function in the BTEM.

2.2.7.7 Triggering, Data Flow, and Data Rates

The LAT trigger, summarized in Table 2.2.10, is a three-level system, as commonly found in modern HEP experiments. The primary overall requirements are flexibility for changing experimental conditions and evolving scientific understanding, high-efficiency for all measurable gamma rays, and background reduction to a level that fits within the telemetry capacity. The trigger concept has been refined over several years of simulation work and continues to evolve with the LAT design.

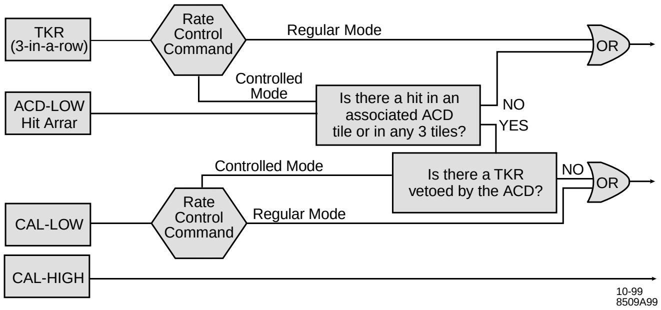

Figure 2.2.17: Schematic of the L1T Logic.

Level-1 Trigger (L1T). The L1T is a hardware trigger that initiates readout of the sensors. Figure 2.2.17 shows a schematic diagram of its logic. Each tower independently forms a trigger, and the L1T is their logical-OR. To ensure a precise knowledge of the effective area at all times, in the event of an L1T all towers are held dead while information from the subsystems is collected into buffers. Two separate conditions may initiate a hardware trigger for a given tower:

(1) Tracker: In each of the 36 layers, the threshold-programmable discriminators for all channels are OR'd together. These asynchronous "Fast-OR" signals are sent to the trigger logic, which looks for coincidences, within *x,y* planes, and then for coincidences between any 3 such *x,y* planes in a row. This is the primary gamma-ray trigger. Simulation studies show that it is

Table 2.2.10: Summary of the LAT Triggers[a]

Level	Type	Location	Components	Function	Pk Rate	Avg. Rate
L1: initiate readout of the detectors.	Hard-ware	OR of independent triggers in each tower.	TKR: coinc. of *x,y* planes CAL-LOW: # of hits CAL-HIGH: energy ACD: high threshold	Two redundant triggers for gamma-rays. Avoid self-veto at high E. Select C,N,O for calibration.	9 kHz (3.4 kHz with ACD veto enabled)	5.5 kHz (2 kHz with ACD veto enabled)
L2: cosmic-ray rejection	Soft-ware	Individual towers + ACD	L1 information. Simple track reconstruction. Extrapolation to ACD.	Reject tracks that point to fired ACD tiles, unless CAL energy is high.	1.7 kHz	1 kHz
L3: final on-board back-ground rejection	Soft-ware	SIU (Full Instrument)	Full event reconstruction (all subsystems). SC ancillary data (attitude information).	Loose cuts to reject background, including Earth albedo, sufficiently for downlink.		<30 Hz

a. Rates are calculated from detailed simulations of the backgrounds, the detector response, and the trigger logic.

highly efficient and redundant even for off-axis photon events. These six-fold coincidences set the noise occupancy requirement for the TKR to be $<1\times10^{-4}$. Below this level, the L1T rate due to stochastic noise is negligible compared with the cosmic-ray background rate. Command controlled masking permits removal of noisy or failed components from the L1T logic.

(2) Calorimeter: The CAL readout electronics supply a count of discriminators firing in coincidence within the module. This provides a trigger (CAL-LOW) that is completely independent of the TKR trigger, enabling crucial efficiency crosschecks and the possibility to collect, for energies above ≈1 GeV, the 30% of the photon flux that does not convert in the TKR. A separate high-energy level (CAL-HIGH), is also formed as an override against ACD vetoes at high energy to prevent the loss of high-energy gamma rays from back-splash. The background rejection for these low-rate events is done offline, on the ground.

The TKR and CAL L1T is formed in the TEM trigger FPGA, allowing great flexibility in its definition. The tower triggers are OR'd in the central ACD-TEM and then fanned out to the individual tower readout electronics to capture the data.

The CAL L1T rate can be reduced by adjusting the thresholds. The ACD information is optionally used to reduce the TKR L1T rate ("controlled mode"). If the low-level discriminator of an ACD tile associated with a TKR L1T fires, or if more than three ACD tile low-level discriminators fire, the global L1T fanout is centrally suppressed.

Finally, a separate ACD high-threshold discriminator is used to prevent a veto of a TKR trigger in case of heavy ion events, which are useful for CAL calibration.

As a housekeeping activity, all of the inputs to the trigger are regularly monitored.

Level-2 Trigger (L2T). The L2T is a tower-based processor trigger, taking place in parallel for all towers. Its principal function is to implement the ACD veto more rigorously than is possible in the L1T. It uses a fast, efficient track finding algorithm and extrapolates track candidates to the ACD tiles to search for vetoes. The veto is not applied to events with a high-energy CAL signature.

Level-3 Trigger (L3T). The L3T carries out a full instrument-wide event reconstruction in the SIU. We plan to make the analysis cuts as loose as possible. In fact, the cuts required in L3T are modest. The vast majority of albedo photon events are removed by comparing the reconstructed photon direction with that of the Earth's horizon. The cosmic-ray event rate is reduced to less than 15 Hz with a loose cut that compares trajectories with the ACD hit pattern and another that requires at least one recognized track *or* a CAL cluster with E>1 GeV. If necessary, the downlink rate of background events could be significantly reduced by implementing in flight more of the analysis cuts described in Section 2.2.8.2.

2.2.7.8 Required Instrument Resources

Table 2.2.11 lists the top-level components of the LAT, their size, and their required mass and power resources. The reserves were calculated according to ANSI/AIAA guidelines. The transverse size of the LAT is 6.7 cm less than the upper limit specified in the SC-SI IRD.

Downlink Rates. The downlink data rates are determined by the trigger rate and the event size. The trigger rate prediction is based upon the background rates discussed in Section 2.2.8.2 and our detailed Monte Carlo simulation of the LAT detector response and trigger logic. As explained in Section 2.2.7.7, the predicted comic-ray background rate is less than 15 Hz, and the gamma-ray event rate is about 15 Hz. The LAT simulation also predicts the event size, including contributions from stochastic noise. The average event size is 4.3 kbits for cosmics and 2.5 kbits for gammas, resulting in an average downlink rate of 100 kbps. Since the raw background and gamma rates have some uncertainty, as does the stochastic noise rate, a reserve of 100% has been assigned to the downlink data rate to give a total that fits within the SC-SI IRD specified limit of 300 kbps with a 50% margin. As explained in Section 2.2.7.7, the flexible, programmable LAT trigger has the capability to further reduce the background trigger rate, if necessary, with minimal loss of efficiency for the gamma-ray signal. This is another source of margin for this resource.

Mass Reserves. In reviewing the mass reserves, it is useful to note that less than half of the mass

Table 2.2.11: LAT Top Level Equipment List and Resource Requirements[a]

Component		Mass + Reserve (kg)		Power (W) + Reserve		# Parts & Size per Part		Status[b]	
								Class	Stage
Total Instrument:		**2558+377**	**15%**	**518 + 121**	**23%**	**1**	**$1.733^2 \times 1.055$ m**		
Grid		143 + 50	35%			1	$1.546^2 \times 0.308$ m	1	Bid
Thermal system (incl. radiators)		50 + 25	50%					1	Bid
Thermal Blanket & Shield		27 + 8	30%					2	Bid
TKR	Mechanical Structures	191 + 67	35%			16	$0.381^2 \times 0.619$ m	1	Bid
	Silicon Strip Detectors	73 + 2	3%			9216	$92.2^2 \times 0.4$ mm	3	CoDR
	Pb Converters (front)	40 + 1	3%			3072	$90.6^2 \times 0.14$ mm	3	CoDR
	Pb Converters (back)	133 + 4	3%			1024	$90.6^2 \times 1.4$ mm	3	CoDR
	Electronics, Cabling, misc.	84 + 25	30%	273 + 35	13%			2,3	Bid
CAL	Mechanical Structures	162 + 49	30%			16		1	CoDR
	Cesium Iodide Crystals	1338 + 27	2%			1536	$35.1 \times 2.8 \times 2.0$ cm	3	Bid
	Electronics & Cabling	32 + 16	50%	118 + 16	13%		$0.374^2 \times 0.239$ m	1,3	Bid
	Other (wrapping, *etc.*)	18 + 9	50%					1	Bid
ACD	Mechanical Structures	51 + 18	35%			1	$1.667^2 \times 0.757$ m	1	Bid
	Scintillators	85 + 17	20%			145	Varies (1 cm thick)	2	CoDR
	PMT, HV supplies, cabling	24 + 12	50%	incl. in DAQ				1	Bid
	Fibers, wrapping, *etc.*	15 + 7	50%					1	Bid
DAQ	TEM modules	32 + 10	30%	88 + 35	40%	16	$28^2 \times 8$ cm	2	Bid
	SIU modules	15 + 7	50%	10 + 9	90%	2	$28^2 \times 10$ cm	1	Bid
	ACD readout modules	5 + 3	50%	29 + 26	90%	2	$28^2 \times 10$ cm	1	Bid
	Harness	40 + 20	50%					1	Bid
Margin w.r.t. SC-SI IRD:		65 kg		11 W					

a. The last dimension in the size column is height. The reserves (contingencies) have been calculated using the methodology of ANSI/AIAA G-020-1992 "Guide for Estimating and Budgeting Weight and Power Contingencies for Spacecraft Systems." The power estimates take into account the efficiency of the power converters. In case of two numbers in the Class column, the first refers to mass

b. Class: 1. A new design which is one-of-a-kind or a first generation device. 2. A generational design that follows a previously developed concept and expands complexity or capability within an established design envelope, including new hardware applications to meet new requirements. 3. A production level development based on an existing design for which multiple units are planned, and a significant amount of standardization exists. Stage: Bid–Concept proposal, RFP response, or a baseline design for future development. CoDR–Conceptual design review level.

of the LAT is in the structures and components that must be engineered. The remaining majority of the mass is "simple" mass making up the detector elements themselves: the CsI crystals, silicon-strip detectors, Pb converter foils, and ACD scintillator tiles. The amount of such simple mass is dictated by the baseline science design and can be firmly fixed early in the formulation phase, with uncertainties due only to the accuracy with which the component dimensions can be machined. Therefore, the margins needed for the simple mass are generally low.

The more uncertain part of the mass budget consists of mechanical structures, electrical components, cables, *etc*. This mass will depend on the detailed engineering design and trades involving cost and performance. The reserves that we assign to this "engineering mass" are relatively high, in adherence to the AIAA methodology. The LAT design shows an average reserve of 3% for the simple mass (CsI, Si, Pb, Scintillator) and an average reserve of 37% for the engineering mass. In addition, the total including reserves has a margin of 65 kg with respect to the SC-SI IRD specification.

Since the LAT mass is dominated by the CsI crystals of the CAL, any future descope that might be needed in the event of a problem with the mass budget would most likely involve the CsI mass. It would be possible even at a very late stage of the design process to eliminate some of the CsI mass. In fact, in case of an emergency, even after completion of the design, some of the crystals at the back of the CAL could be replaced by lightweight filler material to reduce mass, at some expense of energy resolution of high-energy gamma rays. These considerations substantially reduce the risk in the LAT mass budget.

Power Reserves. The LAT power requirements were derived from the baseline designs that exist for all of the electrical hardware required for the LAT. In addition, as shown in the hardware descriptions above, detailed engineering models of the flight hardware have been built for all detector subsystems and for the TEM boards, such that the corresponding power requirements can be assessed with high fidelity.

Of the three detector subsystems, the TKR is the largest consumer of power. Therefore, we have paid particularly close attention to understanding its power needs by building and testing a complete readout system that satisfies all of the performance, size, and weight requirements. The power estimate for the TKR is based upon measurements of complete readout modules made under worst-case trigger-rate and noise-rate assumptions. End-of-life leakage current is assumed for the silicon-strip detectors. Except for the tiny detector leakage current, the front-end-readout and readout-controller ASICs consume all of the power. The Risk Management Plan of Volume 2, Section 1.5 discusses a possible descope option for the TKR power requirements involving an increase in detector pitch (a 17% increase would save 24W).

2.2.8 Performance Characteristics of the Proposed Baseline LAT

2.2.8.1 LAT Simulation and Event Reconstruction

The LAT design is based on detailed Monte Carlo simulations. Because of the complex interplay of detectors and particle interactions, a high-fidelity model of the LAT that includes real-world effects is an essential tool for the design. We use the simulations to:

- demonstrate a cosmic-ray rejection of $>10^5$:1 with high gamma-ray efficiency,
- obtain a solid understanding of LAT performance (effective area, PSF, energy resolution, etc.) *after* all triggers and cosmic ray rejection cuts,
- develop reconstruction algorithms and a practical scheme for triggering,
- determine the requirements on the DAQ system, and
- optimize the design of the LAT.

The LAT simulation uses the GISMO toolkit (Atwood 1992), which incorporates the EGS4 package (Nelson 1985) for electromagnetic particle interactions and the GHEISHA package ((Brun 1989) for hadronic interactions. All mechanical structure, electronics material within the detection volume, the material inherent in the detector elements themselves, detector inefficiencies, cracks and gaps are included in the model. Because gamma rays are produced as byproducts of cosmic ray interactions, we have also included in the computer model an approximate description of the Spacecraft and solar panels, as well as the thermal blanket surrounding the LAT. After the particle simulation has run to completion, code for each detector subsystem generates a response that mimics the properties of the real device (including noise, inefficiencies, *etc*.). Foldout B (1a–1b) shows simulations of a 100 MeV gamma ray interacting in the LAT and a 15 GeV proton (typical of the cosmic rays found in low earth orbit) impinging on the LAT and Spacecraft.

Event Reconstruction. Simulated LAT data are analyzed in exactly the same manner as real data. Digitizations from the CAL photodiodes are used to estimate the location as well as magnitude of the energy deposition in each crystal, and a routine reconstructs clusters and applies leakage corrections to determine the gamma-ray energy. The TKR reconstruction program starts with addresses of hit strips (including noise hits) and reconstructs the electron and positron tracks to find the gamma-ray direction. Finally, the reconstructed tracks are extrapolated to the ACD tiles to search for coincidences with ACD energy depositions that are above threshold.

The TKR reconstruction is initially done in separate x and y projections. The projections are associated with each other whenever possible by matching tracks that pass from one TKR module to another. This significantly improves the power of the reconstruction for complex multi-photon events. A Kalman filter algorithm (Frühwirth 1987) is used to fit tracks to the hits and generate test statistics while taking multiple scattering properly into account.

The primary goals of the existing reconstruction program have been to validate the design and to provide guidance in its optimization. It will continue to improve substantially and become more sophisticated, leading to further improvements in the LAT performance parameters. Modern software-engineering methods are used in the software design to allow us to carry algorithms developed for the reconstruction of simulated data forward into real data analysis tasks such as beam tests, the balloon flight, and finally the flight phase of the mission.

Validation with Beam Test Data. Since the simulation is a cornerstone of the LAT design, it is of great importance to validate it with experimental data. For this reason, and to test many aspects of both the hardware and software design, a com-

Table 2.2.12: List of Cuts Used in the Cosmic-Ray Background Rejection Filter

Cut	Explanation
ACD Veto—reject event if track extrapolates to a hit ACD tile	Only applied to events with less than 20 GeV (adjustable) recorded energy. Bottom row of tiles on sides of LAT are not used at this point.
TKR hit pattern around the best-quality track	Reject the event if the pattern is not consistent with a photon conversion (which generally have more hits than cosmic-ray events). Only applied to events with visible energy less than 5 GeV.
Calorimeter cluster	Require the shape of the energy deposition to be consistent with an EM shower. Require the highest-quality track to point to the energy centroid in the CAL.
Track quality	Three angle and energy dependent cuts (to improve S/N and PSF): • Maximum angle between the best track candidate and the photon direction • Maximum multiple-scattering angle of the best track at the first tracking layer after the conversion layer. • Fit quality of the second-best track used in reconstructing the photon.

Table 2.2.13: Cuts to Reduce Residual Background from Interactions in the Spacecraft

Cut	Explanation
CAL energy deposition. Applied only below 350 MeV	Fraction of energy in top and bottom layers must be consistent with electromagnetic particles incident from above. Transverse development must be consistent with a single shower.
Number of CAL clusters	Energy-dependent maximum number of crystals with >1% of total energy.
Depth of CAL energy centroid	Maximum depth for the longitudinal position of the CAL energy centroid.
TKR track stubs	Track quality cut to remove events with upward-moving low-energy tracks that range out in the TKR.

prehensive and detailed beam test program was initiated early in the development. Tests were done at SLAC in 1995 and 1997, at Michigan State University in 1998, and at CERN in 1998 and 1999. We review here some of the results of the 1997 SLAC beam test, in which reduced-scale versions of all three detector subsystems were assembled together and tested in detail. The main goals of this test were the following:

ACD: Check the efficiency for detecting minimum ionizing particles using fiber readout of scintillating tiles. Investigate the backsplash from showers in the CAL, which causes false vetoes, as a function of energy and angle.

TKR: Demonstrate the merits of a silicon-strip pair-conversion telescope. Validate the computer modeling and optimization studies with respect to converter thickness, detector spacing and SSD pitch. Validate the prototype, low-power front-end electronics used to read out the SSDs. Validate the efficiency and resolution for particles incident at large angles.

CAL: Demonstrate the hodoscopic light sharing concept for coordinate measurement in transversely mounted CsI logs and validate the shower imaging performance. Measure the energy resolution. Study leakage corrections using longitudinal shower profile fitting at high energies.

All these goals were successfully accomplished. Highlights from this test are shown in Foldouts B and C, and details can be found in the comprehensive report from the 1997 beam test (Atwood 1999). Both electron beams (2 GeV to 40 GeV) and tagged photon beams (10 MeV to 20 GeV) were used, as appropriate for efficiency and resolution studies. Careful PSF measurements were made in several different TKR configurations, varying the plane separation (3, 6 cm) and converter thickness (0, 2%, 4% R.L.). The simulation gave an excellent description of the data in all cases, validating the tools that provide the foundation of the LAT design.

A follow-up beam test using the BTEM is in final preparation phases. The main goals of this run are to test systems issues in a data-taking environment using flight-scale detectors, the full chain of custom TKR electronics, the prototype DAQ system and LAT triggers, and the prototype custom front-end electronics for the CAL.

2.2.8.2 Background Rejection Scheme

Although the LAT naturally distinguishes gamma-ray events from cosmic ray events, it is not simple to achieve the required rejection of greater than 10^5:1 while retaining most of the gamma rays. Complex chains of particle interactions, distributions of dead material, and the relatively large flux of background particles impinging on the LAT at all positions and angles conspire to make this a *central issue* in the design of a high-energy gamma-ray instrument. Indeed, without demonstrating adequate background rejection using a high-fidelity model of the instrument (including all significant surrounding material) and realistic reconstruction algorithms, performance parameters such as effective area and FOV are meaningless.

The Radiation Environment. The radiation environment in which GLAST will operate is well understood. The spectra of cosmic ray nuclei from free space are well represented by the CREME model (Tylka 1997). They have a lower energy cutoff that depends on the magnetic latitude and longitude of the Spacecraft in its orbit.

There also are charged albedo particles near the Earth—secondary products made in collisions of cosmic rays with the upper atmosphere. Some of these particles (above the cutoff rigidity) escape immediately to space; others (below cutoff) are trapped on the field lines and reenter the atmosphere. This important component is not included in the CREME model. The fluxes are known from the early days of space observations (Verma 1967), and have been explained by theoretical modeling (Ray 1962). The recent measurements made by AMS give a detailed characterization as a function of latitude (Ting 1999). These fluxes are all built into our simulation package and form the basis of our design of the LAT for background rejection.

Electrons are not included in the CREME model, but a simplified model based on balloon observations (Barwick 1998) is included in our simulations. Although 100 times less abundant than protons, they represent an additional background with different issues. Note that the CAL does not distinguish electrons from photons.

The peak cosmic ray flux incident on GLAST will be under 1,000 particles $m^{-2}\ sr^{-1}\ s^{-1}$, including both cosmic ray protons and helium (≈10% contribution). The orbital average flux is 220 particles $m^{-2}\ sr^{-1}\ s^{-1}$, and the minimum flux is approximately a factor of 2 lower. The albedo energy spectrum of protons extends downward from the local cutoff to about 100 MeV. The integral fluxes are comparable to the orbit-average fluxes just mentioned. These fluxes depend on phase of the solar cycle and are quoted for the solar minimum (worst case). The launch date in 2005 will place GLAST in orbit around the time of the maximum flux, which later will decrease by about a factor of two. The fluxes in the radiation electron belts are sufficiently intense that we cannot operate there. For the most part, the GLAST orbit is below these belts, but in the South Atlantic Anomaly (SAA) the flux is high enough to produce prohibitively high rates in the ACD. In fact, the SAA largely determines the radiation dose that GLAST will see (see Section 2.3.6 and Section 3.3 of the SC-SI IRD).

The Earth is a very bright source of >35 MeV gamma rays, especially near the Earth's limb. These can be distinguished from celestial gamma rays only by their direction of origin.

Radiation will produce significant activation of the LAT materials (particularly the CsI crystals and the Pb converters), resulting in additional background from decays. We have considered this issue and determined that the trigger rates resulting from these decays are low in comparison with other backgrounds. Decays result in a small number of extra random hits in the TKR and ACD, compared with electronics noise rates, and some low-energy CAL signals, but they cannot produce a significant number of LAT triggers.

Simulation of Background Radiation and the Background Rejection Analysis. The background fluxes described above were incorporated in the simulation and allowed to impinge on an imaginary 6 m^2 sphere containing the LAT and Spacecraft.[5] The simulation gives the fraction of these particles causing triggers, allowing a calculation of the absolute expected trigger rate. A sample of 10 million background events, corresponding to about 10 minutes of orbit-average flux in real time, were generated and passed through the LAT simulation and event reconstruction. In the same manner, large samples of gamma-ray events over all relevant angles and energies were generated and analyzed to determine the LAT measurement parameters. The same reconstruction program and background-rejection filters were applied to both the background and gamma ray events.

Note that although the on-orbit proton flux typically peaks around 15-20 GeV, the energy

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[5] The solar panels were not fully contained in this sphere, but separate simulation studies confirmed they are not a significant source of triggers.

deposited by protons in the LAT is typically far less. Thus, the cosmic-ray rejection is most challenging in the 100 MeV to 1 GeV deposited-energy range. Above this range the relative backgrounds are smaller, the tracks are straighter, and the electromagnetic showers in the CAL are more highly developed and distinguishable from hadronic showers. Table 2.2.12 lists the cuts used in the background-rejection filter.

The fraction of remaining background events after each set of cuts as a function of visible energy in the CAL is shown in Foldout B (4a). Examination of the remaining events revealed an important source of background: cosmic rays whose primary interaction is in the Spacecraft material, sending energy up into the LAT from below. The vast majority of these events are removed by the above selections, but pathological cases remain. *This is the largest single source of residual background*, amounting to more than 90% of the remaining sample. Recognizing and rejecting these events is not difficult with the LAT, but requires some care to preserve high gamma efficiency. The cuts listed in Table 2.2.13 are designed specifically to reduce this residual background.

After all cuts, 38 background events remain. Although this demonstrates that the LAT has the capability to meet the background rejection requirements, the analysis is still evolving and will improve further, both in rejection power and in gamma-ray efficiency (increasing the effective area).

Note that almost all of the background rejection analysis will take place on the ground. Only a few loose cuts are required on-orbit (applied in L3T, as described in Section 2.2.7.7) to bring the data rate within the telemetry requirement.

2.2.8.3 Instrument Measurement Parameters

Using the fluxes, simulation, reconstruction, and background rejection analysis described above, it is possible to obtain meaningful LAT performance parameters. These are displayed in Foldout B (5a–5d). Where relevant, we show these separately for the Front and Back TKR sections. These parameters were used as input to the science simulations shown in this proposal. Several features are worth noting:

- All performance parameters include instrumental and trigger effects, realistic reconstruction, and all background cuts.
- The performance parameters meet or exceed all AO requirements.
- The quoted FOV includes only photons that have a meaningful energy measurement in the CAL. These photons are the most important for science and have very low background contamination.
- The good energy resolution extends to the highest energies, where the important overlap with ground-based experiments and, arguably, the biggest discovery potential reside.
- The segmentation of the ACD, together with the inherent ability of the rest of the LAT to reject backgrounds at high energy avoids loss of effective area from splash-back and enables the full acceptance at intermediate and high energies.

2.2.9 Instrument Operations, Data Reduction, and Data Analysis

Instrument operations and level-1 data reduction will be the shared responsibility of the LAT team. The principal objective will be to get the LAT data to the Science Operations Center (SOC) and LAT science team in a useful, well documented form as quickly as possible. The Instrument Operations Center (IOC) will be located at Stanford University. Level-1 data processing will be implemented using facilities provided and maintained by the Stanford Linear Accelerator Center (SLAC). Data for LAT calibration will be distributed to team institutions responsible for the various subsystems. Data from the all-sky survey will be archived at Stanford and at mirror sites at our foreign collaborator’s institutions. Science analysis and observation planning tools will be developed, maintained, and documented by the team and made available to the SOC and for use by the scientific community. A list of the GLAST data products is shown in Table 2.2.14.

2.2.9.1 Instrument Operations

The IOC will monitor LAT health & safety, perform LAT calibration, maintain LAT flight software and configuration control, generate LAT command uploads, and support rapid alert capa-

Table 2.2.14: GLAST LAT Data Products

Data Product	Description	Data Volume (Gbyte)
Instrument Response Functions	Effective area, energy resolution, PSF vs. energy, inclination angle.	<0.1 for each calibration update (infrequent)
Ground Calibration Events	All instrument triggers from accelerator calibration runs.	1000
Flight Events	All instrument triggers that are telemetered to the ground.	1000/year
Gamma Rays	All triggers that are accepted as gamma rays after Level 1 processing.	16/year
Timeline	Location, pointing, and operation mode history for the instrument.	0.1/year
Source Detections	Low-level catalog of detections for all sky coverages analyzed, used to generate the source catalog.	<0.1/year
Source Catalog	High-level catalog of detections, with positions, flux histories, and source identifications.	<0.1/year
Interstellar Emission[a]	Model used in the likelihood analysis of sources near the Galactic plane.	<0.1
Pulsar Ephemerides[a]	From radio observations, for phase folding.	<0.1

[a] The last two data products are probably better considered as inputs to analysis software rather than products, although the interstellar emission model will certainly be refined with LAT data. Also, although the exposure matrices derive from the Timeline, exposure matrices for standard time ranges could be considered a data product in themselves.

bility. The IOC incorporates the broad expertise of GSFC, NRL, and Stanford in operating space science instruments, including the EGRET and OSSE instruments on CGRO, the Michelson-Doppler Imager (MDI) on SOHO, and the USA instrument on ARGOS.

The IOC will be a dedicated operations facility for the LAT and will maximize the use of COTS and Non Developmental Item (NDI) data processing software and hardware. For the Launch and Early Orbit Phase (LEOP) and initial on-orbit calibration period, the IOC will be continuously staffed to monitor LAT health and support LAT commanding by the Mission Operations Center (MOC). Following this period, the IOC staffing will ramp down to a lights-out operations with specified on-call schedule for off-hour support. This workday support will be augmented with 24 hour web-based monitoring by leveraging our worldwide collaboration. This approach has been proven to provide a low-cost means for supporting complex flight operation by MDI-SOHO.

The IOC will be developed by an integrated product team including representation from all major subsystems and will be prototyped to support LAT I&T. The IOC will be capable of performing a limited subset of the off-line data processing to ensure support for the rapid transient alert capability. The IOC will be capable of supporting similar functions for any secondary instrument at minimal additional cost.

2.2.9.2 Coordinated Multiwavelength Observations

We have established a study group to begin planning multiwavelength observations with scientists representing four observational subgroups: AGN, Pulsars, Massive Stars, and GRB.

Our principal efforts will be to keep astronomers informed of GLAST developments, and to encourage them to make early preparations for multiwavelength observations. Some or all of these campaigns may be handled by Interdisciplinary Scientists (IDS) selected by this AO. The instrument team proposes to cooperate with any IDS to whatever extent they wish, to optimize the use of GLAST observations and data for multiwavelength science.

2.2.9.3 Data Reduction and Analysis

Overall Concept. The LAT data system provides a fully automated system that lowers cost and risk by using software created, implemented, and operationally tested during the development of the LAT, leveraging experience and tools developed for handling astronomical (GSFC) and particle (SLAC) data. SLAC has considerable experience and compute resources in place to handle processing and storing event data. The most relevant experience derives from the automated data processing of the SLD experiment, whose data rates and volumes were comparable to those expected from GLAST. The compute resources have been acquired to handle the pres-

Table 2.2.15: Products and Delivery Schedule for the IOC and the SOC

IOC	Schedule	SOC	Schedule
On-line and backed up Level 0 data	1.0 day	Standard all-sky photon maps	Weekly
Photon database entries	1.5 days	Standard flux histories	Weekly
Exposure history database entries	1.5 days	GRB time profiles and spectra	1 day
Calibration tables	Weekly	GRB catalog entries	1 day
Housekeeping	1.0 days	Pulsar catalog entries	1 day
Instrument quick-look health & safety scans	1.0 days	FITS archive products for routing to HEASARC	Weekly
Specialized exposure and photon maps	on demand		
GRB detection and notification services	1.0 days		

Table 2.2.16: Calibration Plan for the LAT Instruments

Mission Phase	Calibration Objective	Calibration Methods	Products
Implementation	CAL response, resolution TKR PSF & Efficiency Hadron rejection ACD efficiency vs. thresh.Alignment.	Optical-mechanical surveys. γ, e, p test beams at SLAC: 2 to 4 towers & ACD tiles	Parameterizations of resolution, PSF, *etc.* Calibration event database. Initial alignment database.
Implementation and Flight.	CAL pedestals and gains. TKR channel & trigger masks. TKR thresholds. ACD pedestals.	Electronic charge injection. Noise-occupancy from random triggers.	Database of pedestals, thresholds, *etc.* for flight operations, and event reconstruction.
Flight	ACD and TKR efficiency. Internal LAT alignment.	Cosmic rays selected by prescaled trigger.	Updated parameterizations. Database updates for ACD and TKR thresholds and LAT alignments.
	CAL resolution, gains, linearity, pedestals.	CNO cosmic rays selected by the ACD HLD.	Database updates for flight operations and analysis.
	Monitor effective area and PSF. LAT alignment with star tracker.	Photons from bright pulsars (*e.g.* 300/day >100 MeV from Vela)	Updated parameterizations for event reconstruction and analysis. Alignment database update.

ently operating BaBar experiment's huge data volumes (≈100 × GLAST). GSFC has considerable experience in all aspects of handling and interpreting astronomical data. Operational experience prior to launch will be gained via the GSE in its support of beam tests and the balloon flight.

Onboard Analysis. The trigger processing (Levels 1–3) is carried out onboard, as described in Section 2.2.7.7. It results in a low-background data stream that fits into the downlink bandwidth.

Post L3T, the flight software will monitor the data stream for transient phenomena such as AGN flares and GRBs (the latter coordinated with the secondary instrument, if applicable). If a flare or burst above a preset fluence threshold is detected, the spacecraft (SC) will alert the ground immediately with direction estimates and timing information (Section 2.2.7.6). If the SC is designed for autonomous slewing, then the LAT software will support use of that mode to maximize the sensitivity to delayed high-energy emission of GRBs and other transients.

Acquiring Data on the Ground. Telemetry arrives at the IOC once daily from the MOC and is processed to "Level 0" using a turnkey system, (e.g. PACOR-in-a-box). Because we use standard CCSDS packets, Level 0 consists only of time-ordering packets, removing incomplete or duplicate packets, and separating housekeeping, calibration, science, and engineering data streams. Variable-length science packets contain LAT status, SC position, attitude, and event time. Level 0 is the fundamental data product and is stored via a hierarchical storage manager (HSM), supplying both rapid access and archive. Table 2.2.15 shows the division of responsibility between the IOC and the SOC and the delivery time for each product in days from arrival of the telemetry.

Analysis of Data: Calibration Strategy. Data arrive at the IOC in NASA standard format. Calibration data for TKR and CAL alignment and response and ACD response are received from the LAT and interpreted to form calibration matrices. Effort is extensive immediately after launch, tailing off during the first year of operations. We expect that updates to calibration matrices will be required weekly at most.

Table 2.2.16 summarizes the calibration work needed for operation of the LAT and analysis of its data. The initial calibration of the detector subsystems will be undertaken at SLAC with gamma, electron, and proton beams. Detailed planning of this test program will be a major emphasis of the formulation phase and will be greatly facilitated by the LAT modularity. One important product will be the establishment of a calibration event database from which background rejection is tuned and response functions are initially calculated and may recalculated if, for example, a plane or a tower is lost during the mission. The LAT is designed such that all calibration can be checked and updated in flight.

The initial detector alignment database will be derived from laboratory surveys. It will then be refined using tracks in cosmic-ray and beam-test data and then monitored and updated during operations using cosmic-ray tracks.

The readout electronics of all subsystems support programmed pulse injection and random triggers, which will be used to calibrate the electronics in flight as well as before launch. In addition, during flight, ordinary cosmic rays, heavy ions selected by the ACD, and gamma rays from bright pulsars will be used to update the calibration and monitor the LAT.

Analysis of Data: Event Reconstruction. Science analysis depends critically on the identification of gamma rays and their energies and directions. The LAT team will further develop the existing Event Reconstruction software (Section 2.2.8.1) for use in flight operations. Tiered results from Event Reconstruction go into the hierarchical storage manager, allowing comparisons each time the data are reprocessed. Event Reconstruction performance is routinely reviewed on a regular basis, both with rote checks and with oversight by scientists. The exposure timeline for each spatial database cell is determined from the housekeeping data and stored.

Analysis of acceptances, backgrounds and corrections requires an ongoing simulation effort. We expect to need MC datasets approximately equal in size to the data. If the science warrants it, much larger MC datasets could be generated.

Data Management

Processing: Data flow from the LAT to the IOC, to be received by a fully automated processing server. Level 0 data are reconstructed to Level 1 and stored in an event database. The database is mirrored with the SOC, where Level 2 processing is done. The PI Teams and Guest Observers access the data via the same presentation layer. Code and algorithms are available to all via the Web.

The emphasis is on reliable and rapid delivery of data, via a fully automated processing server and high capacity disk arrays, tape silos and CPU farms. A clone of the data processing system will be customized to handle the event-simulation production chain. Mirror databases at the SOC and in Europe provide geographically separated storage for a very low probability of data unavailability and fast access for other data centers. All data and calibration tables will be accessible to Guest Observers via the SOC.

Data Retention/Backup: All photon data are kept online. Level 0 and Reconstruction analysis results will be available via a hierarchical storage manager. The IOC maintains copies of all data. Table 2.2.17 shows the planned low level product retention strategy and media.

Table 2.2.17: Low-Level Data Products Retention Strategy

Data Product	Volume daily (GB)	Location	Backup provision	Retention
Telemetry	3.0	Disk	Silo copy	1 year
Level 0	3.0	HSM	Silo copy	Mission
Photons	0.5	HSM	Silo copy	Mission
Housekeeping	0.1	HSM	Silo copy	Mission
Calibrations	0.05	HSM	Silo copy	Mission
Quicklook	.001	HSM	Silo copy	Mission

Database: A commercial relational database (RDB) will be used to manage the processing. A commercial event database will house photon, event, calibration, housekeeping, and Quicklook data, as well as GRB profiles and burst and pulsar catalogs. Trade studies will be used to evaluate and select the event database.

Photon data: We expect approximately 1 billion photons, to be sorted according to spatial and temporal criteria. This methodology has been used for the Sloan Digital Sky Survey, and database/data management tools exist, *e.g.* Informix/ Datablades. Access is by a Web-based GUI that generates tuples (a standard ASCII based format) and/or FITS files. We will exercise this database concept with the EGRET data, tuning access methods and tools.

Exposure Data: We will maintain an exposure timeline for each spatial cell in the database, enabling on-the-fly generation of exposure and intensity maps for arbitrary time intervals.

Event data: Photon data point back to the original event in the database. Events and their processing output will be searchable by time or event-number range. Because event data are stored in a form close to the original packetized state, a translation module unpacks them in the user's choice of familiar formats, including FITS.

2.2.9.4 Supplying Data, Software, and Guidance to the SOC for Public and GI Access

The IOC and SOC will share the event database, which may be physically mirrored at both sites. The IOC posts data, which are immediately available to the SOC for making higher level products. Those products are also stored in the database and available through web-access GUI's after quality checking, subject to access restrictions. A 'presentation' suite integrates tools to create output in familiar forms and offers access to basic analysis capabilities and other community resources, as well as access to routine products like maps and catalogs of pulsars and GRBs. Software is supported by online help files and documentation in HTML format, Email, and phone contacts for individual assistance. Online brochures, manuals and links to FTOOLs and other sites provide additional assistance. The efforts of the IOC and the SOC are integrated through the cooperative design of the shared database.

2.2.9.5 Staffing

The automated processing server, coupled with the robotic tape silos and compute farm, permits lights-out operations. During the high-activity early mission period we will staff the IOC with ~6 FTE's of contract scientist/programmers who will have been engaged in developing software for the mission. After the first three months, they will gradually be reassigned to other projects, leaving a staff of approximately 2.5 FTEs: one database/GUI programmer, one C++ programmer, and 0.5 data technician. It is likely that these individuals may also have SOC or scientific research responsibilities, so that several individuals will be involved and cognizant, important for covering vacations and maintaining continuity with staff turnover.

2.2.10 Descope Options and the Performance Floor

Our descope strategy is an integral part of the Risk Management Plan, which is discussed in Vol. 2, Section 1.5. Descope is an action of last resort in our hierarchical approach to risk mitigation. Our contingency planning is based on the establishment of a performance floor for the LAT. We have considered three performance metrics from which to set the floor: 1) effective area, 2) energy resolution, and 3) a source detection metric that combines both effective area and PSF.

We propose that the metric that sets our Performance Floor should be the effective area, and we set the minimum at 5.5 times that of EGRET (our baseline A_{eff} is 7.5 × EGRET). All other performance parameters of the proposed LAT (Table 2.2.1) are essentially unchanged. As shown in Table 2.2.18, our sensitivity in several science topics depends in different ways upon effective area. With a 25% reduction, the remaining effective area combined with our PSF, FOV, and observational strategy, yields a Performance-Floor sensitivity that is at least a factor of 25 improved over EGRET. Due to the very large effective area of our baseline design, our Performance Floor meets or exceeds all SRD science requirements.

There are several ways in which the proposed development plan could be scaled back if the project encounters a problem with projected costs. Tables 1.5.1 and 1.5.2 in Vol. 2 list many descope options, particularly in the formulation and early implementation phases, that can be tailored to affect schedule, power, mass and/or cost.

Our modular instrument provides a major advantage for descope in the implementation phase—omission of entire towers. Assuming that it is exercised before procurement of the final 25% of the parts, the cost savings is \$1.67M for each tower not built. If cost savings is the only objective, one or both of the two calibration/spare towers could be omitted, yielding no loss of capability but some schedule risk of having to carry out qualification tests with one

Table 2.2.18: Science Impact of Descoping from 16 to 12 Towers

	A_{eff} Dependance	LAT Baseline	LAT Performance Floor	GLAST SRD	EGRET
A_{eff} at 1 GeV (cm^2)		11,400	8,600	8,000	1,600
Source Sensitivity (Photons cm^{-2} s^{-1})	$(A_{eff})^{-1/2}$	1.6×10^{-9}	1.8×10^{-9}	4.0×10^{-9}	5×10^{-8}
Time Study Variable Sources	A_{eff}	$0.13 \times T_{EGRET}$	$0.18 \times T_{EGRET}$		T_{EGRET}
Number of AGN	$A_{eff}^{\ 0.65}$	10,900	9,800	4,500	80

Table 2.2.19: Impact of Descoping by Removal of LAT Towers

Action		Performance Loss	Risk	Science Impact	Resource Impact to NASA		
					Mass	Power	Cost
Omit 2 Calibration Towers		None	Moderate I&T	None	0	0	-$3.35M
Omit Flight Towers	2	12% of A_{eff}	No Additional	Decreased sensitivity at all energies	-263 kg	- 70 W	-$3.35M
	4	25% of A_{eff}			-526 kg	-140 W	-$6.70M

of the flight towers. In addition, other options discussed in Vol. 2 could be used to descope mass or power independently.

Removing entire flight towers cuts mass, power, and production cost as a rate nearly proportional to the number of towers removed. Depending on the descope needs, we would omit up to 4 flight towers, at which point the Performance Floor would be reached with a 3×4 array of towers. This choice permits us to keep the careful optimization of the LAT intact, including the high-energy reach and PSF, while descoping simply the number of photons detected.

The savings incurred by exercising these options are shown in Table 2.2.19. To minimize impact on LAT science, the preferred option to exercise in order to accommodate a $5M reduction for a secondary instrument would be to eliminate 2 towers, including one or both of the calibration/spare towers.

In arriving at the descope plan described here, we have set the ground rule that the plan must not raise risk to an unacceptable level and must reduce the NASA cost by 10%. Because funding for towers is derived from several sources, descoping the number of towers will require some renegotiations of responsibilities between collaborating institutions in order to achieve the desired reduction in NASA costs. Section 2.3.4 and the Risk Management Plan address issues related to the commitments of the non-NASA institutions.

2.3 TECHNICAL APPROACH

2.3.1 Overview

The LAT is an assembly of 16 identical tower modules. This configuration provides significant advantages in prototyping, fabrication, integration and testing. Prototyping can be accomplished at reasonable cost on a full-scale, fully functional module. Fabrication, integration, and testing can proceed in parallel, with lengthy beam tests in progress on the first modules while other completed modules are being integrated and still others are in fabrication. Thus the cost and the schedule risk can be reduced.

A grid structure provides the mechanical and thermal backbone of the LAT. The TKR and CAL will be assembled in separate locations as separate modules, 16 of each, with 2 calibration units, and tested separately with their corresponding prototype tower electronics modules (TEM). After testing, they will be integrated one module at a time onto the flight grid. At the same time, they will be integrated into the data acquisition system (DAQ), with the TEMs, one for each tower module, connected via the data switch. The ACD is a segmented self-supported structure, which will be assembled at GSFC and tested with its own TEM. It will be integrated with the grid and DAQ after integration of all the tower modules.

Our collaboration has carried out an extensive Phase-A hardware R&D effort over the past several years, supported by the DOE, DOD, and the NASA SR&T and ATD programs, to demonstrate the performance of the technologies that we have chosen for the LAT. This program has culminated in the construction of the Beam Test Engineering Model (BTEM), complete with TKR, CAL, and ACD subsystem modules. Table 2.3.1 lists the major components of the LAT subsystems and indicates to what degree they have already been incorporated into the design of the BTEM. This tower corresponds to an earlier instrument design with a 5×5 array of 32-cm square towers, but otherwise it is full-scale and fully functional. This R&D effort has provided an extremely mature design and places us in an excellent position to begin the detailed design of the flight instrument and its assembly procedures.

During the Formulation Phase, we will iterate our existing designs to incorporate the lessons learned from the assembly and test of the BTEM and the results of trade studies identified in Section 2.4.4. This iteration will produce detailed designs and plans for the high fidelity engineering models to be built early in the Implementation Phase.

Our manufacturing, integration and test plans call for the fabrication of 18 tower modules. The first two modules are flight units that

Table 2.3.1: Major Components Developed and Tested in the R&D Program

Component	Status
TKR	
Tray sandwich structure and Module mechanical structure.	17 32-cm BTEM trays exist with Al closeouts and cores and CFC face sheets. A fully functional tray and a full 10-tray nonfunctional mechanical-model TKR have survived full GEVS random-vibration qualification levels.
Silicon-Strip Detectors (single sided, AC coupled, polysilicon bias, 400 micron thick).	High quality prototypes exist in sizes of 6.4 cm square (from 4” wafers) and 6.4 cm by 10.7 cm (from 6″ wafers), all with 194 µm strip pitch. 9.5 cm square prototypes (from 6″ wafers) of the final design have recently been prototyped and tested
Amplifier-discriminator readout ASIC and readout controller ASIC.	Fully functional prototypes exist that meet the LAT power and noise specs. The designs are being ported from the HP 0.8 µm process to the 0.5 µm process.
Front-end electronics components.	Prototypes exist of the hybrid PC board, flex bias circuit, and flex-circuit cables, all for the BTEM 32-cm trays, with 25 readout chips per hybrid.
CAL	
Compression-cell mechanical structure.	Two examples have been built in the 32-cm size: one loaded with CsI and electronics for the BTEM and another loaded with dummy components to use for load and vibration testing. The mechanical engineering model recently passed qualification-level vibration and static-load testing.
Carbon-fiber cell mechanical structure	Prototype passed qualification-level vibration tests.
CsI Crystals hodoscopic stack + PIN diodes.	Proven in beam tests and implemented in the 32-cm BTEM.
Front-end ASIC.	Prototype bulk-CMOS implementation, without some digital control functionality needed in the final design, is used in the BTEM. Final implementation will be in the rad-hard DMILL SOI process.
Readout electronics.	Full functionality in the BTEM with COTS parts.

Table 2.3.1: Major Components Developed and Tested in the R&D Program (Cont.)

Component	Status
Anticoincidence Detectors (ACD)	
Scintillator panels with wave-shifting fiber/PMT readout.	Implemented in the BTEM and proven in beam tests. Detection efficiency and backsplash sensitivity have been verified in beam tests.
Readout electronics.	Functionality implemented in the BTEM, but low-power amplifier ASICs will be designed for the flight instrument.
Support structure.	Conceptual design exists and has been analyzed.
Data Acquisition System (DAQ)	
TKR, CAL, and ACD TEM boards.	Prototypes exist for the BTEM interfaces as VME boards. The final designs will be stand-alone and will interface to the Data Switch FPGA.
Processor board.	Bench tests of PPC603e PowerPC for evaluation of power consumption.
Data Switch FPGA (DSF)	Demonstrated 20Mbps LVDS serial links.
Grid	Conceptual design has been developed and studied. Key interfaces to the TKR and CAL have been developed and mechanical and thermal model analyses have been completed. The TKR interface is modeled in the BTEM tower.
Software	
Simulation Program	Complete model exists for Monte-Carlo simulation of the LAT.
Reconstruction Software	Complete baseline version exists and has been thoroughly tested on simulated data.
Real-time software	Working versions exist for the BTEM VME-based DAQ boards.

will be used in the qualification program and in subsequent detailed calibrations using various accelerator beams. At the end of the calibrations, they will be refurbished for flight spares. The remaining 16 flight units will be fabricated and tested in parallel.

Our LAT design is based on the considerable experience of our collaboration in the key technologies as well as the heritage of the technologies in high energy physics experiments and space experiments. Table 2.3.2 summarizes the flight heritage of LAT components.

2.3.2 Instrument Fabrication Processes

2.3.2.1 Silicon-Strip Tracker-Converter

The TKR fabrication benefits from the modularity of the LAT, from the industrial base for manufacturing the silicon detectors, and from the familiarity of the collaborating institutions in assembling large-scale silicon-strip detector systems. In our manufacturing plan, five institutions with long-term expertise and existing infrastructure will participate in the assembly and testing of the TKR. All have relevant previous experience, as shown in Table 2.3.3, including a large space-based system (AMS). Critical hardware

Table 2.3.2: Flight Heritage of GLAST LAT Components

Component	Heritage	Variation from “build-to-print”
Tracker		
Silicon Strip Detectors	ISEEC/HIST, ACE/SIS, NINA, AMS	Dimension of detectors Simplified design wrt to AMS (see text)
Calorimeter		
CsI crystals	OSO-8, HEAO, OSSE, INTEGRAL/PICsIT, Many others	Dimensions vary.
PIN Photodiodes	INTEGRAL/PICsIT	Custom dual design, comparable size. Same packaging and optical window tested to 200kRad
ACD		
Plastic scintillator	SAS-2, COS-B, EGRET, HEXTE, many others	Dimensions of scintillator tiles
Waveshifter readout	HEXTE	Dimensions (bars instead of fibers)
R1635 and R5611-01 PMT	SAX, ATIC (balloon)	None
Cockroft-Walton HV converters	EGRET	Mechanical configuration
DAQ		
CPU (Thompson TSPC603EMAB/C5LN)	NEMO	Revised design of CPU board.
RTOS- VxWorks	ARGOS, CHeX, SOJOURNER, many others	Latest version as of CDR
Thermomechanical Systems		
Heat Pipes	MILSTAR, SBIRS-HEO, Iridium, IMAGE, others	Mechanical Configuration
Thermal Blanket/ Micrometeoroid Shield	EGRET, ISS	Dimensions of blanket

and the assembly fixtures will be developed and manufactured centrally at SU-SLAC and distributed to the assembly sites. Assembly will be done at the institutions according to the breakdown given in Table 2.3.4, which lists the major components to be fabricated for the TKR subsystem. Integration of trays into the towers will take place at SU-SLAC.

2.3.2.2 Silicon-Strip Detector Procurement

Because the silicon-strip detectors (SSD) are a long-lead item, we have already begun detailed planning for their procurement. There is a strong industrial base, and in our 1998 RFI, seven qualified manufacturers were identified. One manufacturer, Hamamatsu Photonics (HPK), has indicated interest in producing *all* LAT detectors in a single year, while our schedule can, in fact, accommodate a 27-month procurement.

The detector design (single-sided, AC-coupled, *p*-strips on *n*-bulk) was chosen to emphasize reliability and ease of manufacture. Polysilicon-resistor biasing was specified to ensure reproducibility and radiation hardness. To maximize the detector area, our baseline uses the newer 6” wafer technology, for which the projected worldwide yearly production capacity is 8 times the LAT requirements of about 5,000 detectors per year. An international panel of experts reviewed the design in 1997, and we have since established prototyping programs with 3 manufacturers, all ISO9001 registered, as shown in Table 2.3.5. The sensor quality has been very high. In fact, all of the HPK detector runs have improved by more than a factor of 10 upon our tight specifications of leakage current and number of bad channels.

Table 2.3.3: Institutions Participating in the Tracker Assembly

Institutions	Assembly Experience Relevant to SSD Systems
SU-SLAC	Mark2, BaBar, Nomad
UC Santa Cruz	Mark2, Aleph, ZEUS LPS, SDC, BaBar, ATLAS
Hiroshima U./ HPK	SDC, CDF, ATLAS, Belle
INFN	ALEPH, BaBar,L3, AMS

The TKR front-end readout electronics are contained on 576 identical 8-layer printed-circuit boards. In addition to the 28 amplifier-discriminator ASICs and 2 readout-controller ASICs, each board includes a number of surface-mount passive components and 2 miniature connectors, all of which will be space-qualified parts.

Two commercial processes are currently being investigated for the ASIC fabrication: the Hewlett-Packard 0.5 µm AMOS14 bulk CMOS process with the AMI 0.5 µm C5N process as backup. Recent research has shown that these advanced commercial processes can exceed the SC-SI IRD radiation hardness and single-event-latchup requirements with appropriate modifi-

Table 2.3.4: Tracker Subsystem Assembly Parts and Fabrication

Element	Parts & Materials	Fabrication & Assembly
Silicon-strip Sensors.	Custom design (Hiroshima): 9.5 cm square single-sided, AC-coupled, *p*-strip on *n* -bulk, polysilicon bias. Delivery of tested sensors.	Prototypes meeting all specs exist from HPK (Japan) and Micron Semiconductor (UK). Third vendor is STM (Italy). Projected world production capacity: 40,000 sensors/yr. LAT needs: 10,000 in 27 mo.; could be met by HPK in a single year.
Silicon-strip Ladders.	4 silicon-strip sensors.	Edge bonding, automated wire bonding, and encapsulation of wire bonds at HPK and INFN.
Amplifier-Discriminator and Readout Controller ASICs.	Custom design by UCSC.	Fully functional prototypes exist in HP 0.8 µm bulk CMOS process. HP 0.5 µm bulk CMOS process is under investigation for flight parts. Tested on wafer at UCSC, then diced by commercial vendor.
Front-end Electronics printed Circuit Board.	8-layer PC board with gold finish. ASICs, passive surface-mnt parts, Nanonics connectors.	Boards produced by qualified vendor to NASA specs. Assembly and wire bonding by vendor. Testing and encapsulation at UCSC.
Tray Mechanical Sandwich Structure.	Custom design by Hytec Inc. in CFC.	Fabrication by commercial vendor.
Integrated Tray.	Sandwich structure, converter foils, 2 electronics boards, bias and fanout flex circuits, 4 detector ladders.	Assembly at SU-SLAC and INFN, including automated wire bonding, in class-10,000 clean rooms. All electronic components QC’ed, tested, and burned-in, as appropriate, at SU-SLAC/UCSC before assembly.
Tower Walls and Compression Cables.	Custom design in CFC and Vectran, respectively, by Hytec Inc.	Manufactured by commercial vendor. Stacking of trays and integration of Vectran cables, electrical cables, and walls at SU-SLAC.

Table 2.3.5: LAT Silicon-strip Sensor Prototype Development Program

GLAST LAT Manufacturing Run	Year	Lot Size
Beam Test Sensors 4” (HPK)	1998	300
Beam Test Sensors 6” (HPK)	1999	230
Beam Test Sensors 6” (MICRON Semiconductor)	1999	15
Flight Like sensors 6” (HPK)	1999	45
Flight Like Sensors 6” (STM)	In production	100

cations to the design rules and use of guard structures (Osborn 1998).

2.3.2.3 Tracker Tray and Tower Assembly

TKR trays are assembled in clean rooms from prefabricated panels, detector ladders, electronics modules, and the flex circuit used to bias the detectors. Adhesives are generally used in the tray assembly, except that the electronics modules are attached by screws.

Detector ladders are assembled, with 4 tested detectors connected in series by wire bonds, and then tested and encapsulated before mounting onto trays. The tests, carried out by automated probe stations, include leakage-current measurement and strip-by-strip tests for broken capacitors, shorts, and missing wire bonds. This procedure worked well in the BTEM, with only 18 bad strips out of 41,600 strips in 130 ladders mounted on trays. (Bad strips are masked in the readout). The detectors were edge bonded into ladders and the ladders bonded onto trays, with no repairs needed so far. Trade studies of alternative mounting methods with easier reparability are in progress.

The electronics modules are loaded with tested chips in industry and then thoroughly tested and burned in before encapsulation and mounting onto trays. After assembly, the wire bonds between detectors and electronics are made by an automated wedge bonder and then encapsulated.

The trays are stacked and held in compression by Vectran cables while the electronics cabling and sidewalls are attached. The assembled tower is then connected to a TKR data acquisition board and tested and calibrated using the internal charge-injection calibration system and cosmic rays.

2.3.2.4 Calorimeter

The CsI crystal CAL, like the TKR, is composed of 16 modules housed in the 4×4 array of the grid structure. These modules are designed and built by a collaboration among the Naval Research Lab (NRL), CEA/DAPNIA and CNRS/IN2P3 in France, and Royal Institute of Technology (KTH) in Sweden. NRL manages the overall effort. Aspects of the design and fabrication of the baseline CAL have been developed in the fabrication of a full-scale demonstration CAL for the BTEM as part of our ATD program for GLAST.

The responsibilities are assigned according to the special expertise of the institutions and are well defined, as shown in Table 2.3.6. The ATD program qualified two sources for the CsI crystals, both of which meet our technical requirements. Either source alone could provide the crystals at the required rate. The ATD program also developed the custom dual PIN photodiode that was fabricated by HPK. The CsI crystals will be procured and tested by KTH, Sweden. They will be tested and equipped with photodiodes in France.

The CAL electronics is a cooperative effort between NRL and CEA/DAPNIA. The responsibility for the development of a rad-hard analog ASIC with the required functionality is with CEA/DAPNIA. This design will build upon experience with the ASIC fabricated for the BTEM CAL but will add improvements and digital-control functionality and will utilize the DMILL process developed at Saclay. NRL will design and fabricate the ADC, command, control, and digital readout PC boards. Pre-electronics assembly of the equipped crystals into the mechanical structures will be done by CNRS/IN2P3. NRL will complete the module assembly, with integration of the electronics. After installation of the front-end board, the completed modules will be functionally tested and calibrated by NRL and will be delivered in the form of fully functional units to SU-SLAC for final integration and test.

2.3.2.5 Anticoincidence Detector (ACD)

The ACD will be designed, fabricated and tested at GSFC. It is the only LAT detector subsystem that is not modular, so it will be delivered to SU-SLAC for integration as a unit. Table 2.3.7 lists the parts and materials needed in its construction. The assembly procedure is outlined below, based on methods already used for fabrication of the ACD for the BTEM:

Table 2.3.6: Calorimeter Parts and Fabrication

Element	Parts & Materials	Fabrication & Assembly
CsI(Tl)	Two suppliers qualified: Crismatec (France) Amcrys-H (Ukraine)	Crystals pretested and machined to tolerance. Tested at KTH (Sweden).
Photodiodes	Custom PIN Photodiode HPK	Design, assembly, and testing in France.
Analog ASIC	Process DMILL	Rad-hard design in DMILL, fabrication, and testing by CEA/ DAP-NIA.
Digital Electronics	Custom design. Actel FPGA.	Design fabrication, and test by NRL.
Support Structure	Compression cell or CFC cell design (subject to ongoing trade study).	Design, manufacturing, and pre-electronics assembly and test by CNRS/IN2P3.
Module I&T	Electrical-Mechanical I&T	Final module integration of electronics, test, and calibration by NRL. NRL supports CAL integration at SU-SLAC.

- Fabricate support structure, including attachment points for scintillators and PMTs. Because the ACD is a large structure, a full-scale mechanical model will be constructed and tested at GSFC (vibration and acoustics).
- Purchase scintillator tiles with grooves. Bond waveshifting fibers into grooves and gather into bundles for attachment to PMT. Wrap tiles and fibers with Tyvek and light barrier, then attach fibers to PMT interface. Connect PMT power and signal cables to prototype power converters and electronics. Test all assemblies using ground-level cosmic rays and laboratory sources.
- Develop and test electronics board, with ASIC for front-end electronics and FPGA for digital logic.
- Attach tile/fiber/PMT assemblies to the support structure, using Velcro and carbon fiber ribbons. Wire cable harness for all PMTs to power supplies/electronics. Attach thermal blanket/micrometeoroid shield. Conduct full performance test before delivery to SU-SLAC, using sources and cosmic rays.

2.3.2.6 Data Acquisition System (DAQ)

The DAQ is managed by SU-HEPL with support by NRL and SU-SLAC. Responsibilities are indicated in Table 2.3.8. Each TEM is composed of an IO board and CPU board. Therefore, the DAQ is composed of 4 types of boards: 1) CAL-TKR-IO, 2) ACD-IO, 3) SIU and 4) TCPU. The IO boards all have nearly identical components, with the differences being primarily in the interface FPGAs. The SIU and the TCPU boards will be supplied by NRL. The IO boards and power supplies (PS) will be fabricated and assembled by qualified vendors under contract to SU-HEPL. The enclosures will be fabricated by a local vendor and the boards installed at SU-HEPL. The PSs will be mounted on PC boards and interconnect with the DAQ boards through board-mounted connectors, eliminating the need to individually wire these subassemblies. The ACD-TEM (ACD-IO, TCPU, and PSs), will be delivered after test to GSFC for integration into the ACD. The SIU will be fabricated, assembled, and tested by Silver Engineering under contract to NRL.

Field Programmable Gate Arrays (FPGAs) will be used throughout the LAT. They are part of the BTEM and will be part of the Formulation-Phase balloon flight configuration.

2.3.2.7 Grid Support Structure

The Grid is designed to be monolithic, providing the stiffness and heat transfer needed while minimizing the mass and dead area. During the Formulation Phase, a trade study of the material choice for the Grid will be conducted where we will consider stiffness, integration requirements, and cost of carbon-fiber composites (CFC) vs. aluminum.

Flanges on the top of the Grid will accommodate the mounting features for the TKR tower and CAL module and grooves for the heat pipes. The heat pipes carry heat to and down the external sidewalls of the grid to a pair of identical LAT honeycomb radiator panels on each side of the Spacecraft. The heat pipes will be pre-bent and tested before being installed on the Grid.

Heat pipes within the radiators direct heat transfer to cold space. The thermal control system for the LAT is being designed and optimized by the LM-ATC Thermal Sciences group. The LMMS heat pipe product center is baselined to manufacture the heat pipes and radiators. Heat pipes have excellent flight heritage, as

Table 2.3.7: ACD Parts and Fabrication

Element	Parts & materials	Fabrication & Assembly
Scintillators/Fibers	Bicron 408 scintillator. Bicron 91A/MC waveshifting fibers.	Bicron subcontractor cuts high-quality grooves for embedding the fibers into the scintillators. GSFC LHEA bonds the fibers.
Wrapping	Tyvek; Opaque wrap.	Tyvek for light reflection; opaque layer to isolate tiles in case of penetration by micrometeoroid.
PMTs	HPK R1635 or R5611, space-qualified tubes.	Magnetic shielding. HPK can build bases with voltage divider or Cockroft-Walton HV supplies, potted for vacuum.
High Voltage	HPK HV supply or Cockroft-Walton converters.	Purchase as part of phototube assembly or build from design used for EGRET phototubes.
Front-end ASIC and related electronics	Custom design by GSFC	CMOS process. Design based on successful BTEM CAL ASIC developed at GSFC/NRL.
FPGA logic	Actel	Common buy for all subsystems. Some FPGA programming by GSFC engineer, based on beam test experience.
Support Structure	Composite, low-density, high-strength. Space-qualified rigid foam for spacing	Goddard Mechanical Engineering/Composites group design. Parts manufactured by local contractor. Assembly by GSFC in-house.
Outer Shielding (thermal and micrometeoroid protection)	Nextel ceramic fabric Solimide foam Kevlar MLI	High-strength fabric bumper layers, as used on the Space Station. Low-density, flexible foam for spacers, used on Shuttle. Backing shield, good penetration resistance. GSFC blanket group will handle assembly, similar to the EGRET blanket.

Table 2.3.8: DAQ Parts and Fabrication

Element	Parts & Materials	Fabrication & Assembly
CPU Board	Trade studies planned in the Formulation Phase to select processor.	NRL responsible. Custom PowerPC board has been developed in technology program.
Power Supplies (PS)	Modular power supplies with filters mounted on PC Boards	SU-HEPL with Industrial Partners. Vendor or source selection during the Formulation Phase.
CAL-TKR-IO, ACD-IO	FPGA, LVDS	SU-HEPL responsible. Common parts buy for all systems. FPGA programming by SU. VHDL simulation by SU-SLAC.
Electrical Cables	Micro-miniature D connectors with double-shielded cable	SU-HEPL manages vendor fabrication and assembly. Common buy for all subsystems.
SIU	1553B, Telemetry interface, power switching, CPU board.	NRL with Industrial Partners provide design and fabrication of power switching and interface boards

shown in Table 2.3.2.

The flight Grid and radiators will be preassembled and thermally tested, using dummy heat loads, before integration of the detector modules begins. The three stages of Grid development are shown in Table 2.3.9. The Grid design and development will be managed by SU-SLAC and strongly coupled with the design integration function of the Instrument System Engineer (ISE). Detailed structural design and analysis will be subcontracted to LM-ATC.

Table 2.3.9: Grid Development

Stage	Function
Engineering Model	Qualification, test interfaces, clearances, access, cable routing
Mass Model	For use by Spacecraft vendor, I&T
Flight Grid	Thermal balance of radiators and blanket, I&T of Tracker and Calorimeter modules

2.3.2.8 Electrical Wiring Harness

The power distribution and signal cables will be procured from a qualified vendor to SU-HEPL specifications. The power cables will utilize redundant twisted shielded pairs with a shield on two pairs. A separate power cable is used from each SIU to each TEM and each ACD unit. The cable assembly will utilize multiple cables of the same design, differing only in length. This approach provides for a simplified and lower cost procurement by a vendor with simplified testing.

2.3.2.9 Ground Support Equipment

Each subsystem will develop specialized mechanical and electrical ground support equipment that will support the handling, assembly and test of the subsystems. Components of these subsystems GSE will be integrated into the LAT GSE. The ISE will coordinate requirements and control interfaces to permit maximum reutilization of hardware and software modules. Instrument-level mechanical GSE will be developed by the I&T Manager, under direction of the ISE, to ensure full compatibility with all subsystem needs.

2.3.2.10 Software

The LAT software implementation will be led by SU-SLAC. Elements of the software plan were developed during the ATD program and have been reviewed in June 1999.

Flight Software: Flight software will be based on code developed during the ATD phase, including the VxWorks Board Support Package developed by NRL and detector specific code developed by the subsystem teams. Prototype flight software will initially be tested on the BTEM.

Principal components of the flight software are shown in Table 2.3.10. The software runs on TCPUs located in each TEM. All TCPUs will run the same VxWorks RTOS based kernel. The application code for each of the 16 CAL-TKR TEM boards will be identical except for addressing. The ACD and SIU TCPUs will run the same basic code. Each TCPU will run specialized tasks dedicated to the TEM type.

Software modules will be tested and used as available throughout the development process. Simulations using the Tornado and VxSim software programs will be used when hardware is not available. A test bed of multiple TEM boards with hardware detector simulators will be used to test the flight software when the full-up LAT is not available. Since most of the code tasks are performed without external communications, single TEM boards with hardware detector-interface simulators will provide a rigorous test environment for most of the flight code. Application code development has already begun using COTS/VME processor boards running the VxWorks kernel for the BTEM. Flight code will be incrementally built and tested throughout the Formulation and Implementation Phases. Many of the flight code modules have been prototyped and tested in the development TCPU.

Offline Software: Offline software (Table 2.3.11) will be focused around the IOC and SOC. Code and configuration management is already handled with public domain tools. A comprehensive validation mechanism will be put in place.

Simulation and reconstruction deliverables include Level 2 and 3 trigger algorithms that will be developed in an offline environment and then optimally implemented in the flight software. The LAT model is already in place, pending final modifications. Models of cosmic background sources will be improved. A prototype of the reconstruction code exists and has been used to demonstrate the viability of the

Table 2.3.10: Flight Software

Element	Parts and Materials	Lines of Code (Approximate)	Fabrication & Assembly
RTOS Board Support Package	VxWorks	~ 1 Mbyte kernel	NRL , working version exists for VME board. Wind River and SU-HEPL participation in reviews.
Command Interface	’C’ code	6000	SU-HEPL, SU-SLAC
Science Telemetry Interface	’C’ code	1560	SU-HEPL, SU-SLAC
Fault Protection	’C’ code	500	SU-HEPL, SU-SLAC
Level 2 Trigger	’C’ code	2000	SU-HEPL
Level 3 Trigger	’C’ code	10000	SU-SLAC, SU-HEPL
ACD Control and Monitor	’C’ code	500	GSFC
CAL Control and Monitor	’C’ code	500	NRL, France
TKR Control and Monitor	’C’ code	500	UCSC

Table 2.3.11: Offline Software

Element	Parts & Materials	Fabrication & Assembly
IOC Data Processing		SU-SLAC, based on SLD/BABAR models.
IOC Monte Carlo sims		SU-SLAC, based on SLD/BABAR models.
Config. management	CVS	SU-SLAC, Public domain tools; develop validation machinery.
Instrument simulation		UW, Already exists. Update to match final design.
Event Reconstruction		UCSC/SU-SLAC, Refine prototype.
Science	Couple to IOC via mirror	Use GSFC experience.

LAT design. It will be refined to do the production processing in the IOC. Identified photons and backgrounds will be the output products.

The analysis deliverables encompass the infrastructure that will organize the data, interfaces to the analysis tools, and high-level derived quantities. Photons, Level 0 data, and Level 1 data will be stored in a database, which will be mirrored to the SOC and a site to be determined at one of the European team institutions. Interfaces to the database will be created allowing direct access and remote web access. A small number of end-user analysis frameworks, such as IDL and Root, will be supported. Interfaces to the geometry and parameters as well as event displays will be provided for each framework. High-level derived quantities will include models of the sky background and sky maps. Instrument performance measures, such as the point spread function, effective area, and energy response functions will be delivered. These products will be delivered to the SOC.

2.3.3 Manufacture, Integration and Test Plan and Schedule

2.3.3.1 Manufacture and Integration Plan

Manufacturing, integration and qualification will be based on the modular mechanical and electrical design of the LAT. As discussed in detail in Section 2.3.2, subsystem components and subassemblies will be fabricated and integrated at team-member institutions. This distributed manufacturing and assembly model has been proven to work well and leverages the particular expertise of the institutions involved in the project. However, this distributed work model requires tight control of manufacturing planning, throughput, and verification. The following sections outline, and Volume 2 details, the system engineering and performance assurance plans that will be implemented to accomplish this. To ensure adequate coordination of Implementation Phase subsystem manufacturing, integration and testing, all I&T planning and work will be managed by the ISE at SU-SLAC.

As indicated in Figure 2.3.1, most integration and testing of subsystem modules will be completed in parallel assembly lines in the U.S., Italy, and France. Testing during I&T will replicate and confirm functional tests that have already been completed at the subsystem level. This conservative integration method will minimize the risk of technical problems encountered at integration. Integration work is centered on the Grid, which provides the structural support for all subsystems. Mechanical Ground Support Equipment (MGSE) will be designed, fabricated, and tested by one group, which manages Grid design at SU-SLAC, to ensure an optimized integration plan for the LAT. Electrical Ground Support Equipment (EGSE) will be developed by the electrical design integration team in the ISE at SU-SLAC, with technical support from the DAQ subsystem.

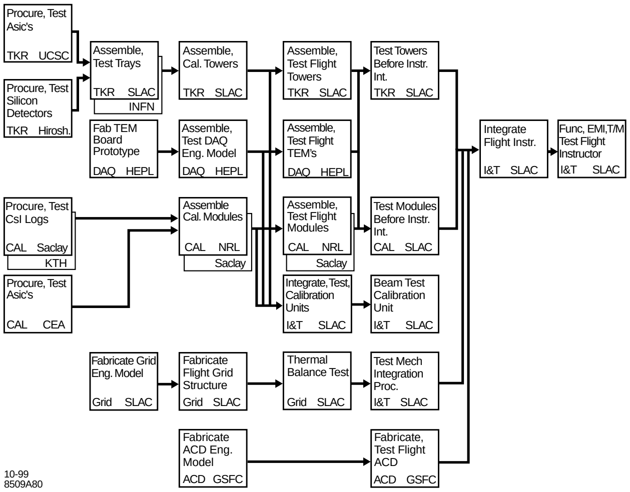


Figure 2.3.1: Manufacturing, integration, and test process flow for GLAST LAT.

The LAT will be integrated at SU-SLAC. Subsystems will be subjected to workmanship qualification and structural and thermal testing prior to delivery for integration as listed in Table 2.3.12. Subsystem-level qualification allows flight integration to proceed in five months, since most subsystem testing will already be completed. Qualification will be done in advance and only for a small number of towers. The first two TKR and CAL modules, called the Calibration Towers, will be integrated onto a dummy Grid and subjected to qualification-level environmental testing. Following the environmental test program, the two Calibration Towers will be calibrated in high-energy electron and gamma-ray beams at SU-SLAC, while the 16 units comprising the flight unit are being integrated.

Following LAT integration and performance testing, a complete environmental test program will take place at an off-site contractor. The environmental test program will include EMI, acoustic, thermal balance, and thermal vacuum tests at acceptance levels to verify LAT readiness for the flight environment. In addition, a modal survey and LAT mass properties assessment will be performed. The IPO has been working with a number of possible sites for this testing (including GSFC, NRL, Lockheed-Martin Missiles and Space, and TRW).

2.3.3.2 Test Plan

Testing will occur at all levels of fabrication, assembly, and integration of the Instrument. Table 2.3.12 shows all key elements of the LAT and the type of testing planned for them. Only the last line shows tests on the integrated Instrument, indicating that most of the testing and design, performance, interface and safety verification will take place before final integration. The Test Plan will follow the relevant sections of the GSFC General Environmental Verification Specification (GEVS-SE).

2.3.3.3 Integration and Test Schedule

Prototyping and development of LAT subsystems has proceeded well during the NASA ATD phase and DOE research and development cycle. During the fall of 1999, a functioning engineering model of one instrument tower (the BTEM) is being installed and tested on an electron/photon beamline at SLAC. A detailed schedule has been developed which shows how the LAT project will proceed from this model, through final Instrument formulation to a second-generation engineering model that uses the flight design. Finally, flight hardware will be designed, procured, and assembled by subsystem, before final integration at SU-SLAC. Figure 2.3.2 shows the top-level mission and Instrument milestones, along with the flow of development activities that support them. This schedule summarizes lengthy subsystem development and fabrication schedules, which are further detailed in Volume 2, Section 1.4.

Mission-level milestones are shown on top, with supporting Instrument milestones detailed on the bottom. Planned dates are August 1, 2001 for the Instrument PDR and July 1, 2002 for the Instrument CDR. The I-PDR is scheduled to occur near the mission NAR (August 17, 2001) just before the start of the Implementation Phase and the development of flight-design engineering models. The I-CDR is scheduled just after the Mission PDR and completion of engineering model testing, but early enough to be able to start production lines for flight hardware.

Table 2.3.12: Instrument Development Testing Strategy

Level of Integration	Screening	Visual/ Dimensional	Functional/ Performance	Burn-in	Radiation/ SEU/Latch-Up	Alignment	Mass Properties	EMI/EMC	Random Vibe -Sine Burst	Acoustic	Thermal-Balance/ Vacuum	Calibration	**Special Tests, Comments**
ASIC's	√		√	√	√							√	
EEE Parts	√				√								
Board Level			√	√									
Silicon Sensors	√	√		√									Leakage current, Bad Channels
Silicon Ladders	√	√											Leakage current, Bad Channels
Tracker Trays		√	√						√	√			
Tracker Modules		√	√			√	√	√	√		√	√	
CsI logs		√	√										Light-output & uniformity
Calorimeter Modules			√	√		√	√	√	√		√	√	
ACD Tiles/Fibers/PMTs		√	√				√	√					Light-output
ACD Ass'y, full-scale model							√		√		√		
DAQ Boards			√	√			√	√	√		√		
Grid/Radiators		√	√			√	√		√		√		Thermal Balance
Qualification/Calibration Unit			√			√	√	√	√	√	√	√	Beam Tests
Instrument			√			√	√	√		√	√	√	

The schedule shown is driven fairly heavily by the funding profile for the LAT. This back-end heavy profile introduces some additional schedule risk, since production, assembly and testing of the TKR and CAL modules must wait for funding, then proceed very rapidly. Our detailed scheduling shows that this is mitigated by parallel production lines.

The critical path for the LAT development and production runs through the TKR subsystem. It is set by the final development of the Tracker CFC tray structure, its prototyping, and then its production and assembly into flight trays. Silicon-strip detector fabrication falls almost ten months off this critical path, even given the relatively conservative detector delivery rate planned.

The scheduled time to integrate the LAT is fairly short:18 weeks for integration of the fully tested tower modules and preliminary functional testing. Electrical integration will follow identical procedures and test protocols used for module testing after assembly. The flight DAQ system will be fully tested using signal simulators before final integration, so this too should integrate smoothly.

On the other hand, we have scheduled 26 weeks of testing on the integrated Instrument. As discussed in Section 2.3.3.2, this will be used for a full array of EMI/EMC tests, cosmic ray and electron beam calibration testing, and thermal and structural testing. This testing is followed by a three month, fully funded schedule reserve, which almost doubles the available integration time, if needed.

The strategy for controlling risk for integration of the LAT to the spacecraft is to simplify and minimize to number and type of interfaces. The SIUs provide a single point for electrical interface to the SC. Each SIU will provide single connections for LAT power, high rate telemetry, low rate command and LAT housekeeping, and a limited set of SC monitors. Mechanical interfaces are limited to support structures for the Grid and the two thermal radiators. No electronics boxes are planned for installation in the SC. Early interface testing with the SC electrical subsystem will be performed. A SC simulator will be provided to the LAT team and will be used to support Instrument I&T. A flight spare SIU will be used to support the Calibration Tower test program and will also be used for interface testing with the SC prior to LAT delivery.

Table 2.3.13 Top Four Program Risks

	Risk	Effect	Mitigation
1	Foreign team institution withdraws from investigation.	Loss of funding source and personnel to accomplish work.	Draw down reserve to mitigate loss of funding source. Redistribute effort within project.
2	Problems or delays during Instrument I&T.	Integration cost and schedule variances.	Holding a 47% cost reserve during I&T, with a fully funded three-month schedule reserve.
3	Under-performing team institution.	Cost and schedule variances eat up reserve.	Maintain 35% reserve during Implementation Phase, and manage subsystems proactively during life of project.
4	Late delivery of Silicon Strip Detectors.	Schedule delay in TKR assembly.	Start SSD development before project start. Procure SSD's starting in Formulation Phase (long lead). Develop multiple suppliers for SSD's.

2.3.4 Potential Risks and Risk Mitigation Plan

Establishment and implementation of a Risk Mitigation Plan, based on a thorough identification and analysis of implementation and product risks, is key to successful risk management. The IPO has been careful in the Concept Study to develop an implementation approach that is low risk and modular in design. This allows flexibility in implementing changes and de-scope options if necessary.

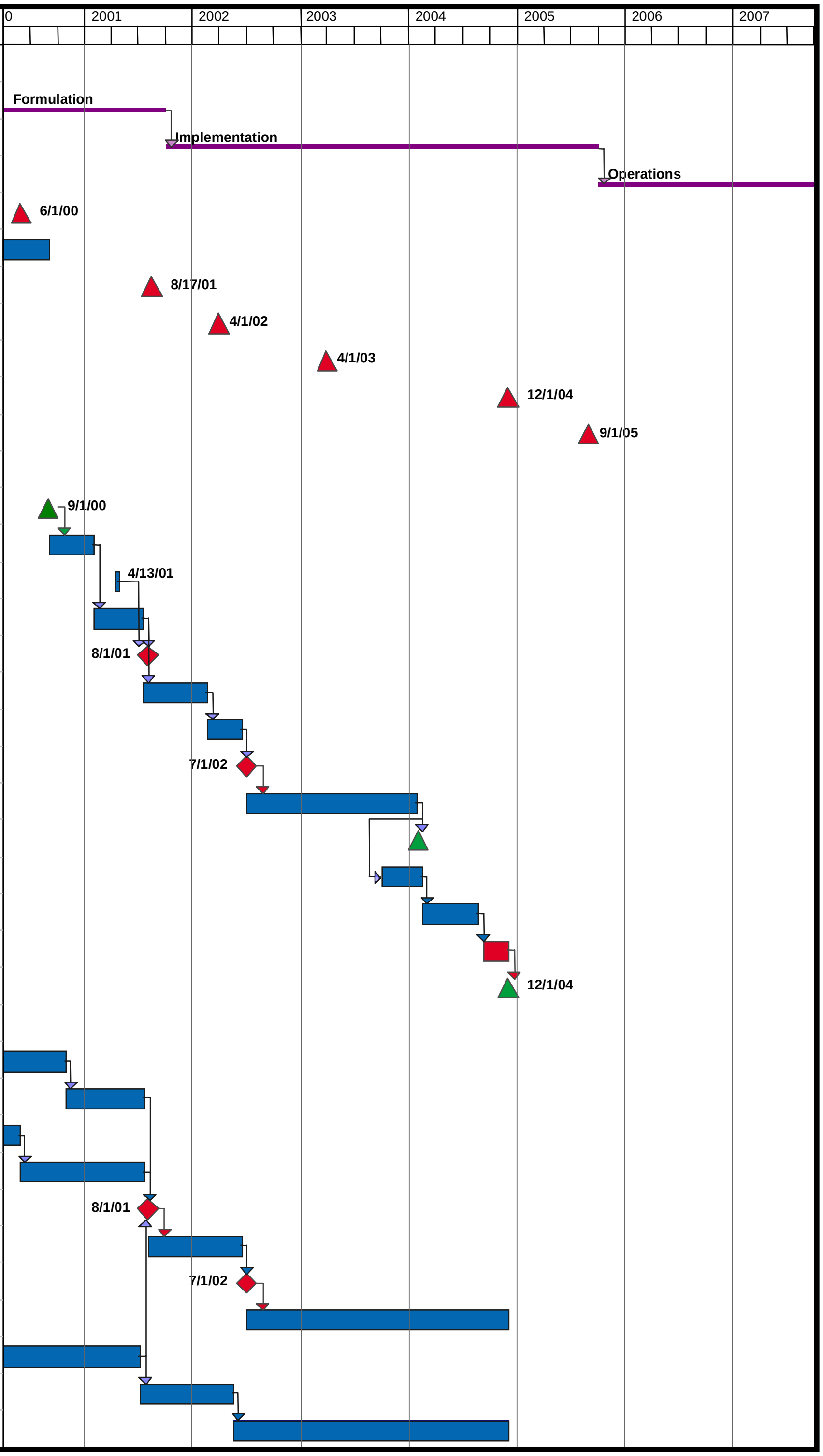
The core of the Risk Mitigation Plan is a descending order decision path for mitigating risk. The baseline plan emphasizes designed-in features to minimize implementation risks. The first level to resolve risks that arise is by the allocation of technical resources and margins. If that is insufficient, then cost and schedule reserves are used. Finally, descoping is a last resort and, if used, will be coordinated with the GSFC Project Office.

Upon completion of identification and analysis of the Risk Management Process discussed in Volume 2 Section 1.5, and assurance that reduction of risk elements was incorporated into the baseline approach, four programmatic risks remain, as summarized in Table 2.3.13.

The following comments explain our mitigation plan of these four risks:

Figure 2.3.2: Development and Implementation Schedule

Task Name	Start	Finish
Mission Milestones	4/1/00	4/1/00
Formulation	4/1/00	9/30/01
Implementation	10/1/01	9/30/05
Operations	10/3/05	9/30/10
System Requirements Review	6/1/00	6/1/00
Independent Assessment	4/1/00	8/31/00
Non-Advocate Review	8/17/01	8/17/01
Mission PDR	4/1/02	4/1/02
Mission CDR	4/1/03	4/1/03
Instrument Delivery	12/1/04	12/1/04
Launch	9/1/05	9/1/05
Instrument Process Flow	4/1/00	4/1/00
Fix Instrument Footprint	9/1/00	9/1/00
Develop Instrument Design	9/4/00	1/31/01
Suborbital Flight Campaign	4/13/01	4/26/01
Procure Eng. Model Matl's	2/1/01	7/16/01
I-PDR	8/1/01	8/1/01
Assemble Engineering Models	7/17/01	2/14/02
Test Engineering Models	2/15/02	6/14/02
I-CDR	7/1/02	7/1/02
Fab, Assemble Flight Modules	7/1/02	1/23/04
Deliver Final Flight Modules	2/2/04	2/2/04
Integrate Instrument	9/30/03	2/12/04
Test Instrument	2/13/04	8/20/04
Schedule Contingency	9/8/04	12/1/04
Ship Instrument	12/1/04	12/1/04
System Engineering	4/1/00	4/1/00
Develop System Architecture	4/1/00	10/26/00
Develop ICD's	10/27/00	7/19/01
Finalize System Specs	4/1/00	5/25/00
Decompose Spec's	5/26/00	7/19/01
I-PDR	8/1/01	8/1/01
Verification Planning	8/1/01	6/11/02
I-CDR	7/1/02	7/1/02
System Validation, Verification	7/1/02	12/1/04
Develop Q.A. Plan	4/1/00	7/5/01
Develop Process Procedures	7/6/01	5/16/02
Implement Q.A. Procedures	5/17/02	12/1/04



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1. The IPO has firm commitments from our European and Japanese collaborators. Their funding authorities have guaranteed the hardware and have allocated funding for scientific involvement. Nevertheless, we carry a relatively large reserve during the Implementation Phase, to deal with unexpected changes in foreign funding. Although this reserve cannot fully replace all activity which the foreign partners would supply, we would be able to proceed while alternate solutions are established or issues resolved.
2. As the LAT is being integrated and tested, unpredictable problems are bound to occur. We have anticipated that such problems might occur even though we will strive to minimize them by extensive testing at the subsystem level, interface verification, and performance verification prior to subsystem delivery. To deal with these events we are holding a 47% reserve during the I&T fiscal year, in addition to a three-month fully funded schedule reserve.
3. The IPO has firm commitments and/or agreements with our team institutions, and our relationship is based upon the established dedication of each institution and the personal commitment of each individual member. We have established excellent communications throughout the concept studies that preceded this proposal, and we have a long track record on past projects showing exemplary performance from all team institutions. The dedicated efforts of the team members will be guided by a pro-active management method which will be implemented in the GLAST project as described in Section 1.5.5 of Vol. 2 on Multi-Institutional Management.
4. The largest single procurement item is the silicon strip detectors. The LAT team has been working on the procurement strategy from the beginning of the R&D phase. Based on our long experience in ground-based applications, we conducted several trade studies of the detector design, in which the more conservative, simpler solution has been chosen. For example, while AMS has flown more advanced, but more complex, double-sided detectors, the LAT team has selected the more robust single-sided configuration, which affords much larger margins in operations, reliability and performance. In addition, this solution is much more economical. The market was surveyed early, and we found that the capacity of qualified vendors exceeds the needs of the LAT by a factor of eight, with no known competition for resources from other experiments. We now have prototyped detectors with three established companies. Our foreign team institutions will procure the detectors, under direct control of the TKR subsystem manager. Together with SU-SLAC, they have funded an aggressive prototyping program in the last years, and their flat funding profile will allow early procurement of the detectors. To establish high visibility of this effort, the TKR subsystem manager has appointed a Detector Coordinator, to directly manage all efforts relating to the detector development and procurement.

2.3.5 System Engineering Plan & Support of Mission Design

The IPO is planning for an intensive System Engineering (SE) activity to complete the Formulation Phase. With the build-up of the BTEM, instrument performance will be verified in a Beam Test prior to the start of the Formulation Phase. Therefore, activity during the Formulation Phase will focus on the formalization of the SE. The process flow is shown in Figure 1.2.1 Volume 2 through I-PDR and Figure 1.2.1 Volume 2 through I-CDR. The key elements of the process are a classical approach to requirements analysis; control of interfaces, systems budgets and intra-system margins; design validation and optimization at key milestones in the design cycle; specifications and verifications requirements and plans; and a thorough I&T Plan.

The SE Process will implement a Distributed Collaborative Engineering Methodology involving systems, science, collaboration, and the GSFC Project Team Members. This results in a thorough integration and optimization of the design. The SE Process will also implement industry lessons learned for better, faster, cheaper solutions for Instrument development. Phase B will end with the Instrument PDR. All designs will be baselined and under configuration control.

We anticipate the economies from using an existing industry SC bus and will work closely with the SC vendor to establish system interfaces and schedules. Our ISE has the primary responsibility for establishing technical interchanges with the SC vendor after award of the SC bus contract. In the early stages of the program we will assist the SC vendor in understanding bus/telescope interface requirements and developing the required ICDs. This contact will also initiate the technical relationships needed during SC integration and launch operations.

Information will be exchanged via face-to-face Technical Interchange Meetings, teleconferencing, and electronic media. We will establish a website to contain ICDs, drawings, plans, schedules, and other information required by the SC team for rapid updating and accessing. This web server will be secure to protect proprietary information and will be accessible to the Project Team. We will install a standard tool for document cataloging and retrieval. We will explore other options for electronic exchange of information, including systems that allow remote participation in technical meetings with the ability to download and print presentation material.

Our ISE and management teams will participate in SC design reviews to further ensure the correct flow of information and will invite representatives from the SC team to our reviews. Adjustments to requirements and schedules resulting from the review process will be made in full-cooperation with the SC vendor and the Project Team.

During Instrument and SC builds our IPM will keep in close contact with the SC vendor management to track schedule performance and anticipate potential delays. Technical personnel from both teams will cooperate in the design of test equipment, procedures, and software to be used during Instrument integration to the SC. This ensures Instrument compatibility with SC ground support equipment and software used during system level testing and launch operations. During flight system integration and test we will provide personnel at the vendor facility and establish electronic connectivity to servers at our home institution. This will also facilitate rapid access to information, Instrument test data reduction, and summoning of technical expertise in case of anomalies. Instrument health will be monitored during specific tests, as needed, from an on-site workstation using telemetry through the SC bus. We will also be able to troubleshoot anomalies from this workstation at the discretion of the vendor’s Test Conductor.

We will support mission simulation tests with the integrated SC from both the vendor facility and our home site. The relationships developed with the SC vendor during integration and test will contribute to successful collaboration during launch vehicle integration activities at the launch site, launch operations, and Spacecraft checkout.

2.3.6 Performance and Safety Assurance

The scope of the LAT Performance Assurance and Safety includes quality assurance (QA), inspection, safety, material and parts selection and control, reliability, problem failure reporting and software validation. The predominant assurance objective is that the LAT will operate in a safe and environmentally sound manner, and will meet the science objectives and corresponding measurement requirements specified in the GLAST SRD. To achieve these top-level objectives, the project will establish formal programs to address the process for achieving safety and mission success.

2.3.6.1 Performance Assurance

The LAT Performance Assurance Program provides guidelines for the quality system of the project to ensure quality consistency for all activity. Project QA is planned, implemented, and managed consistent with the requirements of ANSI/ISO/ASQC Q9001-1994, Standard for Quality Systems Model for Quality Assurance in Design, Development, Production, Installation, and Servicing. Ultimately, the LAT quality assurance program contains elements that:

- Assure quality requirements are identified and implemented through all phases of the GLAST mission.
- Describe a fully integrated and functioning quality organization at all levels.
- Provide practical guidance on implementing a quality plan for critical activities.
- Facilitate the implementation of project-wide quality measures with emphasis on *problem prevention*.

- Integrate all team members assurance activity.

The LAT Performance and Safety Assurance Manager (PSAM) will maintain cognizance of all team member assurance activities. Starting with the Formulation Phase study period, the PSAM shall be an integral part of the development activities and trade studies to ensure that assurance requirements are systematically addressed and, therefore, ensure the system design is compliant with the requirements. The following is a brief description of the LAT product assurance plan. More detail is included in Volume 2 Section 1.6.

2.3.6.2 Quality Assurance

The PSAM will assure that quality requirements are identified and implemented through all phases of the GLAST program.

Quality engineers will be members of the ISE and product development teams, beginning at the Formulation Phase, and will continue their involvement through implementation, test, and delivery. These teams will develop the manufacturing processes, test procedures, and verification requirements to assure producibility, testability, inspectability and verifiability.

Furthermore, the product development teams will determine the critical products and processes within their product scope. That require design review, parts control, inspection, and problem resolution protocols. The quality engineer on the team will assure that LAT QA Program guidelines are met and the appropriate implementing procedures are developed for the subsystem or product element.

Parts Selection and Control: An Electrical, Electronic, and Electromechanical (EEE) Parts Control Program will be implemented to assure that all parts selected for use in flight hardware meet mission objectives for quality and reliability. This program will be developed as part of the larger QA Program prior to I-PDR, and will facilitate the management, selection, standardization, and control of parts and associated documentation. The primary mechanism to accomplish this will be the Program Approved Parts List (PAPL).

All parts will be selected and processed in accordance with GSFC 311-INST-001, Instructions for EEE Parts Selection, Screening and Qualification. The appropriate parts quality level defined in 311-INST-001 will be based on system redundancy or criticality.

Radiation Hardness: The LAT design will meet or exceed the space radiation environment requirements identified in Section 3.3 of the GLAST SI-SC IRD. These requirements have been considered in our current design and will be addressed in detail in the Formulation Phase. In the case of the custom ASICs for the TKR subsystem, a total dose of <8 kRad (Si) is estimated behind the shielding of the micrometeorite shield and ACD (~200 mils Al equivalent) using the design margin of 5. This level of total dose has been verified in lab tests to have no adverse affect on the ASICs of the BTEM. The Tracker flight ASICs will be fabricated in the HP 0.5 μm bulk CMOS process. Recent testing of this process (Osborn 1998) indicates single event latchup immunity to a threshold of 63 MeV/mg-cm^{-2}, which exceeds the SC-SI IRD specifications. The ASICs for the CAL are shielded by a minimum of 500 mils Al (the grid structure) which similarly indicates a total dose of <6 kRad using the design margin of 5 and dose curve in the IRD. These ASICs will be fabricated in the DMILL SOI process which is inherently harder and less prone to latchup.

The ACD and DAQ electronics are also shielded by the grid and the massive CAL so that total doses of <10k Rad are computed. Consequently, many components are available which satisfy the total dose requirements and radiation tolerance of the DAQ components has already received considerable attention. The Thompson PPC603e chip has been tested for the NEMO mission to a total dose of >30k Rad (Si) and showed latchup immunity to 60 MeV/mg-cm^{-2}. Radiation tolerance is a priority in our part design and parts selection process.

The radiation hardness of silicon detectors is well known. Our measurements indicate an end-of-life degradation (including a design margin of 5) of the signal-to-noise ratio from the initial 21 to 18.

Inspections: Flight products, components, piece parts, and material or any item that directly interfaces with flight products will be subject to receiving inspection, in-process inspection, and final acceptance inspection, as determined by the Product Design Team. Inspection procedures and criteria, and approval/rejection protocols will be developed and placed under configuration control concurrent with the product design.

Workmanship: Workmanship standards and procedures will be developed concurrent with inspection procedures. For EEE parts and assemblies, the Instrument QA Program will rely heavily on proven NASA and industry standards, and implement them as needed. For non-EEE parts, NASA and industry workmanship standards will used when possible. For custom processes, new standards will be developed, documented, and implemented as needed.

Problem and Failure Reporting: Problems or failures occurring during ground test of any flight hardware or software will be identified, documented, assessed, tracked and corrected in an approved and controlled manner. The process to assure closure of all such incidents is the Problem/Failure Report (PFR) system. The PFR will be monitored by the PSAM, through a process of data collection, disposition determination, and corrective action planning. Final approval of corrective actions will be given by the ISE, at the recommendation of the PSAM.

For hardware, the PFR system becomes effective with the first application of power at the component or subsystem level, or first test usage of a mechanical item. For software, PFR protocols begin with the first test use of the software with a flight hardware item at the component level or higher.

Reliability: LAT Performance and Safety Assurance will plan and implement a reliability program that interacts effectively with many project disciplines, including safety, systems engineering, hardware design, and performance assurance. The program will be tailored according to the risk level in order to:

- Assure that adequate consideration is given to reliability during design.
- Demonstrate that redundant functions, are independent to the extent practicable.
- Identify and eliminate any single-point failure items.
- Demonstrate that stress applied to parts is not excessive.
- Show that reliability design is in keeping with mission design life.

During the Formulation Phase, reliability analysis will be performed at the system and subsystem level, to identify potential problem areas. At a minimum, a FMEA will be performed to a sufficient depth so that mission critical failures are identified and dealt with effectively.

2.3.6.3 Software Verification and Validation

In general, verification and validation (V&V) activities will be performed to ensure that LAT software will satisfy its functional, performance and quality requirements. The PSAM and ISE are responsible for thorough testing of the code, from unit testing, through integration, to acceptance testing. The role of V&V is to develop analysis procedures and metrics.

2.3.6.4 Safety and Hazard Mitigation

The IPO will plan and implement a system safety program that identifies and controls hazards to personnel, facilities, support equipment, and the flight system during all stages of the Instrument development. System safety requirements will be derived from EWR 127-1, “Eastern and Western Range Safety Requirements”, as well as applicable safety standards of the institutions in the instrument team.

During the Formulation Phase, the Instrument Safety Officer will perform a hazard analysis. This will be a subsystem and system-level qualitative analysis that identifies all potential hazards, develops specific mitigation plans, and assures their resolution.

2.4 FORMULATION PHASE TECHNICAL DEVELOPMENT DEFINITION PLAN

The GLAST ATD program will deliver a Beam Test Engineering Model (BTEM), ready to test at TRL 6 following the December 1999 beam test. The BTEM centerpiece of the Formulation Phase development effort, will be updated as described in Section 2.4.2 and then used for additional instrument testing, culminating in a high altitude balloon flight as described in Section 2.4.3. The lessons learned from the ATD program and the additional testing early in the Formulation Phase will be used to tailor the design of the flight instrument.

A key element of this process will be the definition and refinement of system level requirements and interfaces as part of the System Requirements Review (SRR) in June 2000. The Integrated LAT specifications will be reviewed and baselined at the SRR. Following the SRR, the ISE will begin detailed development of the subsystem project plans, specifications, and ICDs. Subsystem level development and design will proceed in parallel to incorporate lessons learned from the BTEM test program. A detailed plan for high fidelity engineering models to support flight instrument design verification and environmental qualification will be developed.

A schedule showing these Formulation Phase milestones and plans is discussed in Section 2.3.3.3.

2.4.1 Plan to Update Instrument Design for I-PDR

The funding sources available for instrument development provide a funding profile that is not limited by the available NASA funding. First and foremost, this will allow the IPO to be rapidly staffed using DOE funds. All remaining key personnel will be brought onboard and the management system finalized and implemented. The primary focus is to initiate the Integrated Project Schedule (IPS) and establish all budget and cost reporting protocols with subsystem managers and team institutions. Furthermore, the ISE effort will baseline all system and subsystem requirements and implement the change control process.

For the subsystems, the TKR has developed all tracker technologies, and will continue this through validation of all flight processes and technologies, using DOE and foreign funds. The CAL advanced mechanical and electrical engineering models will be developed in a program jointly funded by the French CEA and CNES, while NASA funds will be used to develop the digital electronics design. NASA resources will also be used to integrate the separately developed and demonstrated components that constitute the DAQ and to develop the flight instrument design for the ACD.

During Formulation Phase, we will develop all components that have not been designed, fabricated or tested with the BTEM. All subsystems will evolve existing designs with emphasis on incorporating flight quality parts and materials and producing detailed designs and plans for the high fidelity engineering models to be built early in the Implementation Phase. Figure 2.4.1 shows this progression of design development starting with early prototyping in 1997 and progressing through the BTEM, to the flight-configured EM, completed after I-CDR.

2.4.1.1 System Engineering

An intensive system engineering activity will be implemented and maintained through the Formulation Phase. The emphasis is to maximize the science benefit in the further development of the LAT, to formalize the products and processes needed to deliver the instrument and place them under configuration control, and to design to cost.

This will be accomplished with system trades, decomposition of requirements, developing LAT system specifications and, in conjunction with subsystem engineering staffs, developing the subsystem specifications and design verification plans. All requirements will be formalized, documented, traced, and verified.

During the Formulation Phase, internal interfaces between subsystems will be formalized, and placed under configuration control. A QA Plan will be developed and implemented at all team institutions.

2.4.1.2 Tracker

During the Formulation Phase the LAT instrument geometry will be baselined. The TKR Sili-

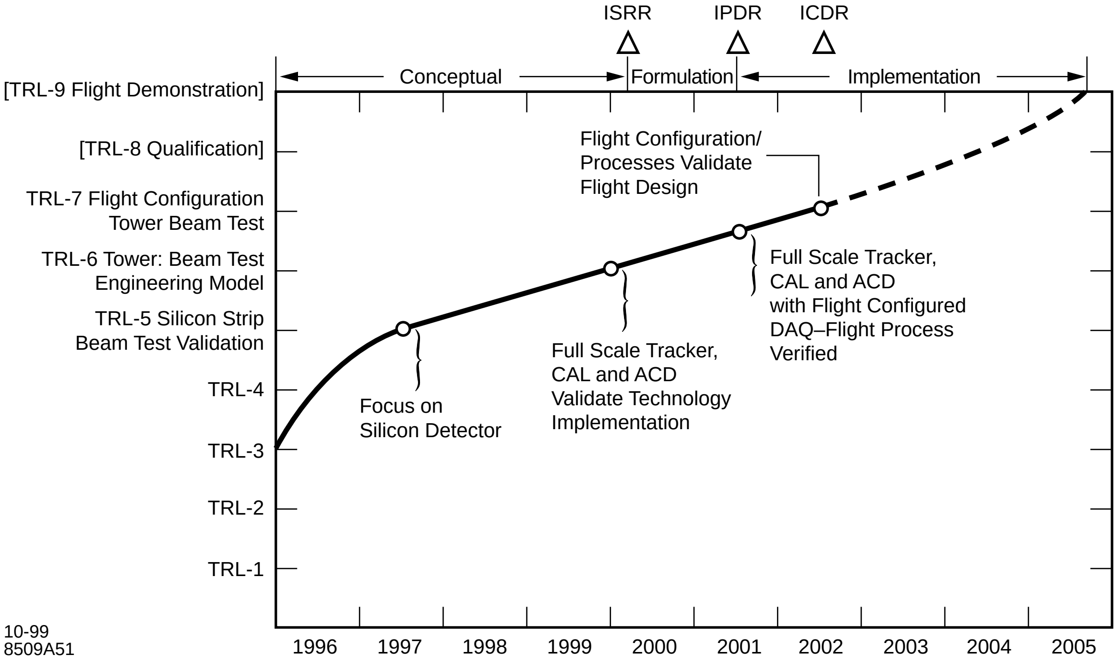

Figure 2.4.1: Technology readiness level progression in engineering model development.

con-Strip Detectors (SSD) are a critical long lead procurement item. Because we have aggressively pursued multiple vendors during the ATD program, we will be able to place the SSD design and dimensions under configuration control by the SRR. This will allow for the procurements needed to support the flight instrument development. The TKR effort will also be focused on evolving the structural design of the C-C tray structure, on radiation testing and EEE parts qualification of the front-end hybrid, and in developing the processes to support the assembly line fabrication and integration of the flight instrument.

2.4.1.3 Calorimeter

The CAL Formulation Phase will focus on a trade study of improvement in the mechanical structure holding the CsI crystal array. CNRS/IN2P3/LPNHE-X will investigate alternate mechanical designs utilizing a carbon fiber composite (CFC) cell structure to house the CsI crystals. This design offers the possibility of less passive material in the calorimeter and ease of assembly.

CEA/DAPNIA/SEI in Saclay will develop the flight version of the CAL front-end ASIC design using the Rad-hard DMILL process. This will use performance results from the current ATD beam test. In support of this design, CEA/DAPNIA, CNRS/IN2P3, and NRL will investigate the light yield measured in the BTEM CAL and investigate the crystal pin diode interface and improvements in light yield.

NRL will create detailed designs of the front-end electronics, incorporating the functionality of the flight ASIC design and assessing the potential changes required by a change in mechanical structure. The CAL (and ACD) ADCs will be qualified, and detailed designs of the interfaces to the DAQ will be completed.

2.4.1.4 Anticoincidence Detector

A Full-scale ACD Mechanical Model (FAMM) of all mechanical components needed for the ACD—structure, frame assembly, standoffs, and PMT mounts—will be designed and some components fabricated. The FAMM will be assembled early in Implementation Phase and will be as close as possible to the flight design, to permit verification by vibration testing and to identify and practice fabrication and integration procedures. In addition, the FAMM will be used to test and select the optimum way to mount and place the tiles onto the ACD structure. It will also allow us to place and route the fibers and PMTs and will assist in cable harness layout.

We will begin the design of the analog

front-end electronics ASIC. The BTEM analog electronics use normal discrete devices for all analog signal-processing chains. We require the power and size savings of an ASIC for the flight design. Therefore an early start on the development of this ASIC is important for the ACD flight development. We will also begin the design of an engineering model HV PS needed for the ACD PMTs.

2.4.1.5 Data Acquisition System

The distributed DAQ architecture has been developed during the ATD program and will be used in the December 1999 beam test. To minimize risk in the ATD program, the DAQ was segmented into subset Printed Wiring Board (PWB) developments for the sensor interfaces and the core CPU which are integrated through a VME back plane. This approach allowed the use of COTS CPUs to support interface development and checkout while allowing Tower CPU (TCPU) development to proceed in parallel. During Formulation Phase, flight qualified parts will be selected. The DAQ team will integrate the components of the DAQ into a flight-like system. This system will be used to verify the power consumption across the range of operations, as well as to support the balloon flight.

2.4.1.6 Grid

The Grid design will be developed during the Formulation Phase with the goal of completing a detailed design for the structural engineering model. Substantial effort will be placed in thermal analysis and design and in the selection of the fabrication technique for the Grid structure. Mechanical and thermal interfaces will be defined, under the direction of the ISE, and placed under configuration control by I-PDR.

2.4.2 Plan to Update Beam Test Engineering Model for Suborbital Flight Test

The TKR, CAL, and ACD portions of the BTEM will be refurbished as required. The VME - based DAQ CPUs and sensor interface boards will be replaced with an integrated unit that includes the TCPU and implements the DSF. The L2T software will be updated to support the higher data rates expected at balloon flight altitudes. A set of balloon flight electronics will be developed to interface between the DAQ and balloon gondola electronics. The GLASTSIM simulation will be used to predict overall data rates.

2.4.3 Suborbital Flight of Beam Test Engineering Model

Testing of the response of the individual subsystems and the entire instrument has been an important part of LAT development. Our approach of validating simulations of the instrument response by testing will continue through the Implementation Phase, as shown in Table 2.4.1. Accelerator beams (photons, electrons, protons and heavy nuclei) will be used at SLAC, CERN and GSI as part of our calibration and testing plan. The remaining performance test that cannot be carried out on the ground is a live demonstration of the instrument's ability to find gamma rays in the presence of a high background of cosmic-ray nuclei and electrons (C.R.). A flight of the BTEM on a balloon launched from Ft. Sumner, New Mexico, in early 2001 will demonstrate that ability, as well as validate the data handling architecture under high background rate conditions. The balloon gondola we will use was developed at GSFC for the Gamma Ray Imaging Spectrometer (GRIS). It can easily meet all the flight specifications (weight, power, pointing).

Due to the background of atmospheric gamma rays we do not expect any statistically significant results on celestial point sources, but instead we will observe the response of the instrument to the albedo photons from the line source of the horizon. The flight will test the triggers, the on-board rejection of background, and the selection of data for telemetry at the appropriate rates. We expect a single tower L1T rate from background at about 1.5 kHz, which is greater than that expected on-orbit. The photon trigger rate will range from 1 to 10 Hz, depending on altitude and the pointing (from the local vertical to looking toward the Earth's horizon). The results of the flight will be compared with GLASTSIM calculated rates at various stages of analysis (*e.g.*, ACD rates; L1, L2 and L3 trigger rates, photon fluxes and some aspects of their detection efficiency, and background rejection probabilities).

Table 2.4.1: Balloon Flight as part of the GLAST Instrument Test Program

	Beam Test 1997	Beam Test 1999	Balloon Flight 2001
Location	SLAC/CERN	SLAC	Ft. Sumner
Device	6 x-y TKR planes 8 Cal layers ACD VME DAQ	BTEM 16 x-y TKR planes 8 Cal layers ACD TEM DAQ	Full BTEM
Objectives	Validation of Simulation	System Test	DAQ Test, C.R. Rejection
Beams	γ, e^-	γ, e^-, p	C.R., Albedo γ
Results	PSF, CAL Resolution, ACD efficiency	PSF, C.R. Rejection. CAL Resolution ACD Efficiency	Albedo γ rates, On-board data selection

2.4.4 Trade studies Planned for Formulation Phase

A number of trade studies have already been done that affect the design of the LAT. They are tabulated in Table 2.4.2. The most important was the choice of TKR technology. We also considered different technologies for the calorimeter, different approaches to the use of the ACD in background rejection, and different architectures for the DAQ. The relevance of these trade studies to the performance of the LAT are discussed in Section 2.2.3.

The completed trade studies targeted performance drivers and constraints from the limited resources (mass, power, dimensions). Planned trade studies, Table 2.4.3, will address increased margins in power and reliability, as well as ease of fabrication and testing.

In the TKR subsystem, we will study the available processes to find the most suitable technology for the tracker flight electronics. An SOI process owned by Peregrine Semiconductor is being investigated as a possible alternative to bulk CMOS. SOI has the potential of providing improved latch-up immunity and better digital-analog isolation. In addition, migration from the current HP 0.8 μm deep submicron CMOS process to HP 0.5 μm will be investigated.

In the CAL subsystem, an alternative to the baseline mechanical design is being investigated, with a goal to minimize the passive material within the calorimeter and to avoid the need for wrapping the CsI.

For the ACD, a trade study will be carried out between a single (redundant) HV power supply for all phototubes and individual converters for each phototube. The single supply potentially has lower power and mass, but less flexibility in supplying a wide range of HV to different tubes. The increased constraints on tube selection may offset the advantages of the simpler single-source HV supply.

In the DAQ, an FPGA flight part selection trade study was initiated during the Basic Contract period and is an ongoing study. The ACTEL 54SX series of FPGAs was identified as a good candidate for implementing the FPGA requirement for the LAT. This series of devices has low power and has been shown to have good radiation tolerance characteristics and to be sufficiently hard against total dose for the GLAST environment.

The data switch design will be studied further. Additional advantages and features of using a switched network approach are continually being recognized. The option to implement the design in an FPGA or possibly an ASIC permits adding features that reduce costs while increasing functionality and reliability of the total instrument.

2.4.5 Process for Interaction among IPI Team Members

There will be varying tiers of reviews and coordination meetings to provide status reporting and guidance to and from the LAT team. These will provide the backbone for coordination. Both the monthly Project Control review and the weekly ISE meeting will be videoconferences, to ensure that all required team members are included. Videoconferencing has been used extensively during the development phase, with the necessary infrastructure already in place at all member institutions.

Communication within the team is now being handled using all media available. Specifically, the team already has web sites in place at most member institutions. These will be expanded significantly at project start. The IPO, in particular, will expand its web presence to include the latest schedule and cost data, as well as all documented and configuration-controlled requirements and design parameters. Action item lists will also be posted on the site along with the status and full explanation as to the resolution of the item. Events will be posted to keep

Table 2.4.2: LAT Trade Studies Completed

Trade	Drivers	Result
Tracker Technology	Performance, Modularity, Heritage	Silicon strip detectors (SSD)
Double/single sided SSD	Noise Performance, Cost, Interfacing, Operation	Single-sided
SSD size	Cost, Coverage, Fabrication	6" wafer
SSD thickness	Performance, Signal/noise ratio, Yield	400micron
SSD pitch	Performance, Signal/noise ratio, Power	200micron
Tracker Converter	Cost	Lead
Tower Geometry	Noise, Performance, Modularity	16 towers, 38cm x 38cm each
Tray Technology	Mass, Stiffness, Cost	Carbon Fiber Composite, Honeycomb core
Converter Thickness	PSF, Aeff @ high vs. low energy	2 Parts: 2.5% front, 25%back
Tracker Length	PSF, Aeff, FOV	1.5R.L., 50cm high
Calorimeter Technology	Resolution, Simplicity, Modularity	CsI
Calorimeter Geometry	Pattern Recognition Shower Corrections	Hodoscope
Calorimeter Pre-Shower	Pattern Recognition	Increase converter thickness in back part to tracker
Coat CsI end faces	Performance	Mask CsI end faces
CsI Wrapping (Comp. design)	Performance, Stability	Tetratek
CAL Dynamic Range	Performance, Power, Parts	Two Diodes with two ranges
ACD Technology	Performance, Mass, Heritage	1cm Scintillator
ACD readout	Flexibility, Mass, Complexity	Waveshifting Fibers into photomultiplier tube
Number of ACD layers	Performance, Mass, Complexity	One layer
ACD Segmentation	C.R. Rejection, Self-Veto	145 tiles
ACD Coverage	C.R. Rejection,	100% Tracker Coverage
ACD Veto	Trigger Rates, Performance	Veto implemented in Software, switchable to Hardware
DAQ Architecture	Data Rates, Redundancy, Power, Triggering	Distributed System
DAQ FPGA Data Switch	Data Rates, Power, Redundancy	Serial, Bidirectional links at 20Mbps, with LVDS.
Tower Support Structure	Mass, Rigidity, Access to Components	Grid between TKR and CAL.

Table 2.4.3 LAT Trade Studies Planned

Trade	Drivers	Choices
Tracker Pitch	Power, Performance, Cost	200-300micron
Tracker Electronics	Power, SEE, Noise	SOI vs. 0.5micron bulk CMOS
Calorimeter Structure	Cost, Mass, Size	Compression Cell vs. CFC cell
ACD Electronics	Power	ASIC vs. FPGA
ACD Power supply	Redundancy, Power	Single vs. Individual Power Supplies
TCPU Processor	Power, Performance, Environment	PowerPC 603e vs. Alternatives
TCPU memory size	Cost, Performance, Power	Number of Mbytes
TEM Configuration	Cost, Schedule, Reliability	Single TEM board or separate IO and TCPU boards
DAQ FPGA Data Switch	Power, Cost, Redundancy, Performance	ASIC vs. FPGA
Power Supplies	Cost, Power, Performance	Vendor selection
DAQ Data Storage	Power, Cost, Reliability	CPU Memory vs. Solid State Recorder
Grid	Mass, Stiffness, Thermal, Cost	Al vs. CFC

the entire team informed as to the latest status. This will be an important tool to keep the entire team, especially our international partners, informed on all of the latest project developments.

The management processes implemented by the IPO will proactively guide the LAT project. These processes have been tailored to fit the international nature of the project team by using the project work breakdown structure for clear definition of projects, and modern media for tight links between geographically diverse parts of the project. Past experience at SU-SLAC and other of the team institutions has proven that these tools can, when applied by a strong and supportive IPO, yield a stable and dynamic team.

2.5 SCIENCE TEAM AND TEAM RESPONSIBILITIES

The LAT science team consists of world experts in high-energy gamma-ray astronomy, instrumentation, data analysis and interpretation, high energy physics, and outreach. The team has members from both the astrophysics and particle physics communities. The team (IPI and co-investigators) is listed in Table 2.5.1 together with their roles and responsibilities.

Table 2.5.1: Science Team and Roles of Team Members

Team Member	Relevant Experience	Role/Responsibility
P. Michelson *+	CGRO/EGRET	Principal Investigator
S. Ritz *	ZEUS, TASSO	Instrument Scientist; Extraglactic Diffuse & AGN
T. Kamae * +	ASTRO-E, TOPAZ, TPC	IDT Lead, Japanese Lead, Catalog, GRBs, & UnIDs
N. Gehrels *	CGRO Proj. Sci.	SSAC Chair; GRBs & AGN
R. Johnson *	BaBar, ALEPH, DELCO	TKR Manager; Extragalactic Diffuse & AGN
H. Sadrozinski *	ZEUS, BaBar, SDC	TKR Detectors – U.S. lead; GRB's & Extra-galactic Diffuse
G. Godfrey	USA, TPC, Crystal Ball	TKR Assembly; dark matter & AGN
T. Kifune	CANGAROO	TKR, Multiwavelength-TeV; AGN and SNRs
T. Ohsugi	VENUS, SDC, CDF	TKR Detectors – Japan lead; Pulsars & SNRs
T. Takahashi	ASTRO-E, TOPAZ, TPC	TKR Integration; AGN & UnIDs
E. Bloom*+	Crystal Ball PI, PEP-II	TKR Integration; dark matter & AGN
G. Barbiellini *+	DELPHI, Wizard	TKR Production – Italy lead; GRBs & dark matter
A. Morselli	NINA, Wizard	TKR Production; dark matter & GRBs
N. Johnson * +	OSSE Inst. Sci.	CAL Manager; extragalactic diffuse & AGN
E. Grove	OSSE Ops. Lead	CAL Integration; pulsars & AGN
B. Phlips	OSSE	CAL Detectors – U.S.; GRBs & transient alerts
I. Grenier * +	COS-B, CAT, CELESTE	CAL French Lead; catalog & diffuse model Co-lead; UnIDs
P. Fleury *	CAT, CELESTE	CAL Dep. French Lead; AGN & SNR
J. Paul	COS-B, SIGMA Co-PI	CAL Detectors; galactic sources & cosmic-rays
A. Djannati-Atai	CAT, DELPHI	CAL Simulations; AGN & SNRs
P. Goret	CELESTE, CAT	CAL – xtal readout; SNRs & pulsars
T. Reposeur	CELESTE, CAT	CAL – GSE/testing; AGN
P. Carlson	CPLEAR	CAL CsI Lead; dark matter
J. Ormes *	ACE P.S., BESS US PI	ACD Manager; cosmic-rays & dark matter
D. Thompson +	SAS-2, EGRET	ACD Design, Multiwavelength Coordinator; catalog & pulsars
A. Moiseev	BESS, GAMMA-1	ACD Assembly & Integration; dark matter
R. Williamson *	CheX, Tether	DAQ Manager; cosmic-ray bkgrd modeling
K. Wood *	USA PI	DAQ Processors; AGN & UnIDs
M. Lovellette	USA Proj. Sci.	DAQ Interfaces/Data flow
R. Dubois *	SLD	Software System Manager
J.J. Russell	SLD, BaBar	Inst. Flight Software Lead
S. Williams	SOHO/MDI, Tether	Inst. Ops. Manager; cosmic-ray bkgrd modeling
T. Burnett *	SLD, D0, ALEPH	Instrument Simulations Lead; GRB catalog & transient alert
T. Schalk	SLD, BaBar	Track Reconstruction Software; GRB's & Extra-galac.Diffuse
S. Digel	GRO SSC, EGRET	Science Analysis Software; Catalog & diffuse model Co-lead
J. Norris	GRO Dep. Proj. Sci.	Data Analysis; GRB catalog & transient alert
L. Cominsky	UHURU, EUVE, Swift	E/PO Lead; cosmic-rays and SNRs
Y. C. Lin	CGRO/EGRET	Science Analysis; AGN
P. L. Nolan	CGRO/EGRET	Science Analysis; pulsars & UnIDs
D. Suson	SSC/SDC	Instrument Simulations;
R. Svensson	JEM-X,INTEGRAL	GRBs & AGN
P. Caraveo	COS-B	Dep. Italian Lead; Malindi Ground Station; pulsars & UnIDs

+ GLAST Science Working Group (SWG) member from LAT team
** Senior Scientist Advisory Committee (SSAC) member*

2.6 REFERENCES

Agoritsas, V., et al. 1998, NIM A 406, 393
Ambrogiani, M.,et al. 1998, NIM A 419, 632
Amelino-Camelia, G., et al. 1998, Nature, 393, 763
Atwood W. B. et al. 1992, Int. Journal of Mod. Phys. C3, 459
Atwood W. B. et al. 1999, NIM A (in press)
Bahr, J. et al., 1996, NIM A 371, 380
Baring, M.G. 1999, Proc. Snowbird TeV Gamma-ray workshop, in press
Barwick, et al. 1998, ApJ, 498, 779
Bignami, G. F. et al. 1975, Space Sci. Instr., 1, 245
Bottcher, M. et al. 1998, ApJ, 499, L131
Brazier, K. et al. 1996, MNRAS, 281, 1033
Brun, R. et al. 1989, CERN Program Library W5103
Catanese, M. et al. 1997, ApJ, 487, L143
Chen, A.W., et al. 1999, AAs HEAD #31, #17.09
Cour-Palais, B. et al. 1990, Int. J. Impact. Eng., 10, 135
Daugherty, J. K. et al. 1996, ApJ, 458, 278
De Paolis, F., et. al. 1999, ApJ, 510, L103
Digel, S. W. et. al. 1996, ApJ, 458, 561
Fenimore, E. E. et al 1999, ApJ, submitted (astro-ph/9906125)
Fichtel, C. E. et al. 1975, ApJ, 198, 163
Frühwirth, R. 1987, NIM A 262, 544
Grenier, I.A. et al. 1999, Proc.26th ICRC.
Hartman, R. C., et al. 1999, ApJS, 123, 79
Hunter, S. D., et al. 1997, ApJ, 481, 205
Hurley, K. C., et al. 1994, Nature 372, 652
Johnson, R. et al. 1998, IEEE Trans Nucl. Sci. 45, 927
Kniffen, D. A. et al. 1993, ApJ, 411, 133
Koyama, K., et al. 1995, Nature, 378, 255
MacMinn, D., et al. 1996, Space Sci. Rev., 75, 413
Madau, P., et al. 1996, ApJ, 456, 124
Mattox, J. R., et al. 1996, A&AS, 120, 95
Montmerle, T. 1979, ApJ, 231, 95
Nelson W.R. et al. 1985 , SLAC-0265
Norris, J. P. et al 1999, ApJ, submitted (astro-ph/9903233)
Norris, J. P., et al. 1999, Proc. 26th ICRC, OG 2.3, 20
Osborn, J.V. et al., 1998, 7th NASA Symposium on VLSI.
Plaga, R. 1995, Nature, 374, 430
Pohl, M. et al. 1997, ApJ, 491, 159
Ray, 1962, JGR, 67, 3289
Rielage, K., et al., 1999, XXVI ICRC, V5, 152
Roberts M. S. E. et al. 1999, AAS HEAD #31, #29.05
Romani, R.R. 1996, ApJ, 470, 469
Romani, R.R. 1999, priv. Comm.
Romero, G. E., et al. 1999, A&A, 348, 868R
Salamon, M. H., et al., 1998, ApJ, 493, 547
Sciama, D. W. 1999, MNRAS, submitted (astro-ph/9906159)
Sreekumar, P., et al. 1992, ApJ, 400, L67
Sreekumar, P., et al. 1993, PRL, 70, 127
Sreekumar, P., et al. 1998, ApJ, 494, 523
Sreekumar, P. 1999, priv. comm.
Stecker, F. W. et al.1992, ApJ, 390, L49
Stecker, F. W. et al.1996, ApJ, 464, 600
Stecker,1999, APh, 11, 83
Strong, A.W. et al. 1999, ApJ, in press
Sturner, S.J. et al. 1995, A&A, 291, L17
Tanimori, T., et al. 1998, ApJ, 497, L25
Thompson, D. J. et al. 1981, JGR, 86, 1265
Thompson, D. J., et al. 1993, ApJS, 86, 629
Thompson, D. J., et al. 1997, Proc. 4th Compton Symp.,ed C.D. Dermer, et al. (New York,AIP), pp.39-51
Ting, S.C.C. et al. 1999, CERN Courier, Vol. X,
Tylka, A. J. et al 1997, IEEE Trans Nucl.Sci. 44, 2150
Ullio, P., et al. 1998, Phys. Rev. D, 57, 1962
Ullio, P. 1999, Ph. D. Thesis Univ. of Stockholm
Verma, S. D. 1967, JGR, 72, 915
Wayne, M.R. et al., 1997, NIM A 387, 278
Wells, J. D. 1998, astro-ph/9808052
Yadigoraglu, I. A.. et al.1997, ApJ, 476, 347
Zhang, B., et al. 1999, ApJ, in press

3.0 GLAST EDUCATION AND PUBLIC OUTREACH PROGRAM

We outline here the Education & Public Outreach (E/PO) program to accompany the LAT-Flight Instrument development. Gamma-ray astronomy is an exciting field for the public as well as the researcher. Both young and old can be engaged by the exotic concepts of black holes and violent explosions seen across the Universe. Thus, we believe that the GLAST E/PO program is well suited to promote inquiry into the origin and structure of the Universe and the fundamental relationship between energy and matter, concepts which are included in the Physical Science Content Standards A, B, & D for grades 9-12.

In this Flight Instrument E/PO proposal, we therefore will focus on the following specific educational goal:

We will utilize the observations and scientific discoveries of the GLAST mission to improve the understanding and utilization of physical science and mathematics concepts for grades 9-12.

Oversight of the E/PO program will be provided by GLAST LAT team member and Sonoma State University (SSU) Professor Lynn Cominsky. Daily coordination of the GLAST-LAT E/PO program, and development of curricular content and teacher training materials will be the main responsibilities of Dr. Laura Whitlock (formerly GSFC LHEA EPO director, now at SSU.) E/PO partners for this flight instrument proposal include Dr. Helen Quinn (SLAC) and GLAST science team member Dr. Hartmut Sadrozinski (UCSC), the NASA Quest project at Ames Research Center, TOPS Learning Systems, Videodiscovery, Incorporated, and assessment specialists WestEd. The GLAST E/PO Management plan, detailed credentials for the E/PO partners and some ideas for an enlarged E/PO program which would utilize project funds, are given in Volume 2. Additional GLAST E/PO partners for the larger, project-funded program include the Great Explorations in Math and Science (GEMS) project at the Lawrence Hall of Science, the Live@The Exploratorium project, and Thomas Lucas Productions. Support letters from all of the above partners are attached in Appendix B.

3.1 FLIGHT INSTRUMENT E/PO PROGRAM

3.1.1 *Web-based Curriculum Materials: Space Mysteries and GLAST Website*

Together with our partner, Videodiscovery Inc., SSU team members Whitlock and Cominsky will develop a series of inquiry-driven interactive Web explorations which take advantage of a person’s natural curiosity to build critical thinking and analytical skills. Each mystery will be constructed to teach at least one of the important physical science standards for grades 9–12, will support a wide range of NCTM Standards 2000 requirements, and will be accompanied by materials for use by classroom teachers. An essential part of each mystery is a video interview with a scientist – in this case, a science team member. The successful SSU LEARNERS Space Mysteries proposal forms the basis of this work and will allow us to do front-end assessment for the GLAST E/PO program during Phase A/B. The LEARNERS program will support the development of 3 Space Mystery Modules (during 2000-2002) and includes plans for GLAST development of additional Mystery Modules. The Swift MIDEX program will support the development of 1 module (in 2003) and we have budgeted two additional modules within the LAT Flight Instrument E/PO program (to be developed during 2004-2005). For further details of the Space Mystery Module development, content standards and evaluation processes, please see the SSU LEARNERS proposal at: http://www-glast.sonoma.edu/learners

SSU team members will also maintain and expand the GLAST outreach website, so that all formal GLAST E/PO materials will be available for download from one place. Informal educational materials and public-oriented information about GLAST will also be available. The GLAST Mission Concept outreach website, developed by Cominsky and SSU student Tim Graves, is located at: http://www-glast.sonoma.edu. After Flight Instrument Team selection, we propose to turn this website into the outreach site for the GLAST mission.

3.1.2 *Printed Curriculum Materials*

Educators consistently respond that while the World Wide Web is a great learning tool and resource, they need to have additional, printed materials that can be used directly in the classroom. The development of printed classroom materials will be led by TOPS Learning Systems, a non-profit education organization dedicated to the development of low-cost, hands-on materials as part of a comprehensive math/science program. During Implementation Phase of the GLAST project, TOPS Learning Systems will create 3 curriculum modules working closely with team members Whitlock, Quinn and Cominsky. TOPS modules are famous for involving students in an inquiry-based study of science using simple, inexpensive materials, many of which are already available in the classroom. TOPS lessons plug directly into the scope and sequence of the National Education Standards, and lessons developed for GLAST will emphasize the Physical Sciences Content Standards A, B & D for grades 9-12. TOPS has their own field-testing and evaluation procedures which they will use in the initial development of the modules and teacher's guides. The materials will then be further evaluated by the Ambassador teachers (see 3.1.3) prior to public distribution, as well as being independently assessed by WestEd (see 3.2).

TOPS modules and teacher's activity guides will be accompanied by the creation of classroom posters, which will provide an in-depth look at an exciting topic related to high-energy astronomy and to the scientific content of the modules. While at GSFC, Whitlock directed a popular program that created annual sets of posters and activity guides for distribution at educator conferences; her most recent set explains the scientific background, recent discoveries, and observations of Gamma-ray Bursts, one of the main scientific targets for GLAST. We will institute a similar effort, producing a new poster annually for students in grades 9-12.

3.1.3 Educator Training: GLAST Ambassadors, Workshops and Conferences

We propose to create a program of 10 educators, who will work in conjunction with GLAST science and E/PO team members at SSU, SLAC, and UCSC to develop workshops and curriculum materials. These educators will be selected via a nation-wide application process and will become "GLAST Ambassadors" for the entire program lifetime. Part of the selection process will include not only the qualifications of the candidates, but their plans to disseminate GLAST materials and information in their local and state areas. In addition, particular attention will be paid to applicants with special abilities to reach underserved communities. These educators, whether formal or informal, will come to SSU for a two-week training period in 2002 and a one-week period in 2004. In the interim, additional training will occur via learning-at-a-distance modules set up on the Internet by the E/PO team members. Each GLAST ambassador is required to have his or her own plans (via teacher in-services, public lectures, museum programs, educator conferences, etc.) to routinely disseminate GLAST materials throughout the year. The GLAST Ambassadors will also attend the launch of the GLAST satellite, so that they may convey that experience to their fellow educators and to their students. Finally, this cadre of educators will serve to field-test any and all materials which the GLAST E/PO team creates and will provide crucial, critical, feedback in the ongoing development of the materials.

GLAST E/PO team members and Ambassadors will interact with and disseminate GLAST curricular materials via workshops and conferences at the national, state, and local levels. Such interactions allow for direct feedback on the quality and effectiveness of the GLAST materials and programs, as well as affording a high-leverage opportunity to teach additional teachers to use GLAST materials in their classrooms. At least one new workshop will be developed each year by E/PO team members and the Ambassadors, targeted at physical science classes for grades 9-12, and will be presented at many educator conferences by the E/PO team and by the Ambassadors.

In addition to presenting workshops, LAT science team and E/PO partners will staff an exhibit at education conferences. This will allow direct interactions with even larger groups of educators and mentors from all over the world, not only to let them know about our efforts, but to get response back from them. Sending a booth filled with GLAST curriculum materials and expert staff will be an important part of our effort to expand the scope of our E/PO activities into the formal and informal education communities.

3.1.4 Informal Education: NASA QUEST Space Scientist Interviews Online

GLAST science team members will regularly participate in NASA Quest's ongoing Space Scientist Online program. Space Scientists Online is a partnership between the NASA Ames Research Center QUEST project and NASA OSS to provide the educational community with new and exciting information from space sciences, as well as collecting relevant information from previous space science projects. Chats featuring GLAST scientists will be organized and moderated by Cominsky. Classrooms of students and teachers sign up to hear project news via live web chats, and read biographical information and field journals from the scientists involved. This popular program is growing and clearly provides an exciting new vehicle to reach directly into the schools.

3.1.5 SLAC's Virtual Visitor Center: Interactive Gamma-ray Detector Exhibit

Dr. Helen Quinn is directing a project now under development as a component of the SLAC Virtual Visitor Center that will facilitate web-based interactive opportunities to allow users to develop their understanding of particles and their interactions (Physical Science Content Standard B for grades 9-12). The website will be targeted for use in formal education settings, and will be grade-appropriate for physics students at the high school and community college level. However, it will also encourage informal exploration by the public. One of the first two modules will allow users to run a simulation program to study the interactions of photons (gamma-rays) and electrons with matter, and to view the output via the World Wide Web. As a part of the LAT project, this tool will be extended to simulate situations encountered in the LAT detector.

3.2 EVALUATION AND ASSESSMENT

WestEd is responsible for the formal program evaluation and guidance of the LAT Flight Instrument E/PO program. Led by Dr. Steven Schneider, WestEd will conduct independent formative and summative evaluations on a regular basis using professionally accepted qualitative and quantitative assessment tools such as questionnaires, telephone interviews, and focus groups. Evaluation will occur not only of the training of the Ambassador teachers, their classroom usage and student learning outcomes, but will include similar metrics for the teachers and students at the second level, i.e., those that are trained by the Ambassadors through educator workshops. Assessment will include each individual part of the GLAST E/PO program as well as measuring the overall effectiveness of the parts working together to quantify the true impact of our efforts in the education and general public communities. The results of the evaluations will be submitted to the LAT PI Peter Michelson as well as to the E/PO Coordinator Cominsky.

The E/PO program proposed here has many milestones which will allow for easy metric evaluation by the E/PO team and the overall NASA education program. For example, the creation and evaluation of individual TOPS curriculum modules or Space Mystery Modules will provide quantifiable mission metrics. Nevertheless, it is also apparent that by coordinating the efforts from GLAST with those of Swift, LEARNERS, DOE, NSF, and other future projects, a large added value will be achieved. The E/PO team proposed here will insure this coordination.

3.3 DISSEMINATION OF MATERIALS/ IMPACT OF E/PO PROGRAM

Dissemination of GLAST materials will take place via a large number of avenues. These include, but are not limited to access through: workshops and exhibits at national, regional, state, and local teachers meetings; the GLAST E/PO website; the NASA OSS Forums and Broker/Facilitators; NASA CORE; NASA Quest website; Videodiscovery website, exhibits, marketing, and catalog and the TOPS Learning Systems website, marketing, and catalog.

The impact and effectiveness of our dissemination will be measured and evaluated by WestEd as part of the independent evaluation. Results from their studies will be used to guide the GLAST E/PO program as it develops over its multi-year lifetime. It is expected that through

Table 3.2.1: LAT Flight Instrument Activities

Activity	Partner/Lead	Formulation Phase Cost (FY 99 $K)	Implementation Phase Cost (FY 99$K)	Schedule
Web Materials	SSU Videodiscovery	65	260	Website ongoing 1 module each in 2004 and 2005
Printed Materials	SSU, SLAC TOPS	0	360	1 module each in 2003, 2004 and 2005
Educator Training	SSU SLAC UCSC	21	240	2001 applications 2002, 2004 training 2005 launch
Informal Education	SSU NASA Quest	0	0	Monthly in 2001-2005
SLAC Exhibit	SLAC	0	25	2004
Assessment	SSU	0	0	Front-end 2001-2002
	WestEd	0	120	2003-2005
Management	SSU	32	165	Ongoing
Total Costs		118	1170	

the workshops given by E/PO team members and by the Ambassadors, over a thousand teachers a year will get hands-on training with our materials. This will allow the materials to be used by over 100,000 students each year. Added to the educators which will find our materials by other means (such as on the Web), we will be able to get information about gamma-ray astronomy and GLAST science into large numbers of classrooms across the country. In this way, educators will be able to teach about energy, matter, the electromagnetic spectrum, and more with exciting, cutting-edge materials.

4.0 NEW TECHNOLOGY PLAN

The NASA Space Science Enterprise Integrated Technology Strategy supports overall NASA Integrated Technology Plan goals. The GLAST mission is featured in the strategy for developing and flight validating mission specific technologies while supporting the goal of joint development with universities, industry, and other Government agencies. We are active participants in the implementation of this strategy through our involvement in the associated GLAST instrument technology development program and earlier SR&T programs.

As shown in Section 2, our GLAST mission is based on technologies with significant heritage in ground-based high energy physics experiments. Our new technology development and demonstration program is based on the adaptation of these mature detector technologies to the GLAST requirements and the rigors of the space environment.

4.1 GLAST INSTRUMENT TECHNOLOGY DEVELOPMENT AND DEMONSTRATION

The GLAST technology development roadmap (SSE Integrated Technology Strategy page 16) delivers sensor technologies tested in a relevant environment (TRL 6) that are mature enough to support down-selection to technology for the flight program. Our on-going GLAST Instrument Technology Development and Demonstration program, initiated in July 1998, will deliver sensor technologies required for GLAST at TRL 6. The technologies we propose have been successfully demonstrated through several high-energy gamma-ray and electron beam tests as shown in Table 2.4.1. These technologies include the tracker large format (6 inch) silicon strip detectors (SSD), hodoscopic readout of CsI crystals in the calorimeter, custom low-power front- end electronics for readout of both the SSDs and calorimeter PIN diodes, a modular stackable tray structure to support the SSDs, and a low power distributed data acquisition system. The SSDs and their associated electronics were developed in partnership with the DOE and UCSC. The modular tracker tray structural design was initially developed by a small business, Hytec Inc., in partnership with the DOE and became the subject of a NASA Small Business Innovative Research (SBIR) grant. The calorimeter front-end electronics, and data acquisition system were developed in partnerships with NRL and GSFC. Each of these technology decisions and approaches were subjected to formal independent peer reviews as shown in Table 1.2.4 in Vol. 2.

4.1.1 New Technology Plan

To control programmatic risk, we plan no additional incorporation of new technology in the LAT.

4.1.2 New Technology Transfer

Stanford University maintains an Office of Technology Licensing (OTL) which has a long track record of successfully transferring new technologies to industry, including those developed under US government funded programs. OTL's 20 member staff processes 3–4 new technology disclosures per week and presently monitors over 450 active technology licenses.

5.0 SMALL DISADVANTAGED BUSINESS PLAN

Our GLAST team fully supports the goals and objectives of NASA's contracting percentages allocated to small and small disadvantaged businesses. Stanford University has a long record of support for small and small disadvantaged businesses (SDB). Stanford's policies and procedures support a successful small business program that fully complies with the expectations of FAR 52.219-8, 52.219-9, and Public Law 95-507.

GSFC, as part of NASA, adheres to the mandate and directives issued by the President and Congress of the United States. GSFC has awarded numerous R&D and training grants to various Historical Black Colleges and Universities (HBCU) and Other Minority Educational Institutions (OMEI) around the country, including a multi-million dollar contract with New Mexico State University, Las Cruces, for the operation and maintenance of the National Scientific Balloon Facility. Additionally, GSFC maintains Co-Op and Internship programs with HBCU's such as Howard University, Morehouse University, and Bowie State University. GSFC also has similar programs with OMEIs such as Gallaudet University, the University of Puerto Rico, and the University of the Pacific. With such programs, GSFC is able to offer students from minority educational institutions valuable hands-on experience on a variety of projects. The GLAST project at GSFC will actively participate in these programs.

NASA's socio-economic goals for SDB Subcontracting are understood and supported at the Naval Research Lab. NRL's SDB goals are developed in accordance with DOD directives. In FY98, NRL's SB goal was 56.5% and it achieved 52.5%. The SDB goal in FY98 was 7.5%. Actual performance on the SDB objective was 10.3%. The combination of these two achievements greatly exceed NASA's SDB goal of 8%. NRL has active contracts with multiple SDBs that are currently supporting NRL's GLAST development program. Examples of SDB participation in the program are:

- Program management support: Praxis, Inc.,
- Mechanical and thermal design: Hytec, Inc.,
- Electrical design and fab: Praxis, Inc. & Silver Engineering, and
- GSE and subsystem software: Software Technology, Inc.

The development program is also supporting research at Texas A&M University in Kingsville (TAMUK), an HBCU.

The selection of Hytec Inc. to support GLAST structural design, while based on merit alone, supports a small business. Hytec is a small business concern in accordance with the FAR 52.219-09 and NASA FAR Supplement 1852-219-76. The total value of the Hytec contract itself will constitute 3% of the overall LATeffort.

SLAC has a small disadvantaged business plan in place with the US Department of Energy.

The University of California at Santa Cruz has in place an effective program to support small disadvantaged businesses.

During the Formulation Phase we will carefully evaluate GLAST subcontract and procurement opportunities for every element of the project, compare the project needs with potential SDB firms, and establish a SDB subcontract plan. All LAT team members will develop plans to achieve the designated SDB subcontracting goal that are practical in view of SDB capabilities, the team member's in-house capabilities, and project risk management goals. We will formulate the subcontracting plans for the LATFlight Instrument program to:

- Support NASA's goal for placinga designated amount of contract dollars with small, small disadvantaged, and women-owned small business concerns and
- Provide opportunities for with small disadvantaged business concerns, women-owned small business concerns, historically Black colleges and universities, and minority educational institutions to participate in the LAT program.

Appendix A

Resumes

WILLIAM E. ALTHOUSE

PRESENT POSITION:	Technical Configuration Manager, LIGO Project, Caltech
EDUCATION:	1968-B.S.E.E., California State Polytechnic University
PROJECTS & RELEVANT EXPERIENCE:	Organize, establish controls & tools for managing the technical configuration of LIGOInvestigate and analyze technical issues and organize meetings of the LIGO Technical BoardResponsible for "holding" the LIGO construction schedule; planning and executing special technical projects
PREVIOUS POSITIONS:	Electronics Technician, Engineer, Technical Manager, Space Radiation Laboratory, Caltech Chief Engineer, LIGO Project, Caltech Deputy Detector Group Leader, LIGO Project, Caltech Technical Configuration Manager, LIGO Project, Caltech

RECENT RELEVANT PUBLICATIONS:

"W. Althouse et al.,"Precision Alignment of the LIGO 4 km Arms Using Dual-Frequency GPS. To be submitted for publication.

A. Abramovici, W. Althouse et al., "Improved Sensitivity in a Gravitational Wave Interferometer and Implications for LIGO, " Phys. Lett. A **218**, 157-163 (1996)

A. Abramovici, W. Althouse et al., "LIGO: The Laser Interferometer Gravitational-Wave Observatory," Science **256**, 325-333 (1992)

W.E. Althouse el al., "First Flight of a New Balloon-Borne Gamma-Ray Imaging Telescope," Proceedings of the 20th International Cosmic Ray Conference, Vol **1**, pp 84 (1987)

W.E. Althouse et al., "A Balloon-Borne Imaging Gamma-Ray Telescope," Proceedings of the 19th International Cosmic Ray Conference, Vol **3**, pp 299 (1985).

W.E. Althouse, W.R. Cook, "Balloon-Borne Video Cassette Recorders for Digital Data Storage", Proceedings of the 19th International Cosmic Ray Conference, Vol **3**, pp
395 (1985)

D.E. Stilwell et al., "The Voyager Cosmic Ray Experiment", IEEE Trans. on Nuclear Science, Vol NS-**26**, pp 513 (1979)

GUIDO BARBIELLINI

PRESENT POSITION:	Full Professor of Physics, University of Trieste
EDUCATION:	1959 - Italian degree of Laurea, University of Rome
PROJECTS & RELEVANT EXPERIENCE:	DELPHI Experiment at CERN, WiZard, CAPRICE, KLOE
PREVIOUS POSITIONS:	Director of the Trieste section of INFN,1991 - 1997 Member of the Scientific Council of the Ecole Politecnique1998

After many years of experience in particle physics laboratories (DESY, CERN), Guido Barbiellini now works on astro-particle physics experiments for the study of cosmic and gamma rays using silicon detectors.

SELECTED RELEVANT PUBLICATIONS

Boezio, M, Barbiellini G. et al. "WIZARD Collaboration, the Cosmic Ray Proton and Helium Spectra Between 0.2 and 200 GeV," INFN-AE-98-06, (1998)

Barbiellini G. et al., "The GILDA Mission: a new technique for a gamma-ray telescope in the energy range 20 MeV - 100 GeV," NIM A 354, 547 (1995)

G.Barbiellini, A.Morselli et al., "A Wide aperture telescope for high energy gamma detection," Nuclear Physics B 43, 253. (1995),

M.Bocciolini, G.Barbiellini et al., "The WiZard/CAPRICE Silicon-Tungsten Calorimeter," Nuclear Instruments and Methods A370, 403, (1996)

LARS BERGSTROM

PRESENT POSITION: Professor, Physics Department, Stockholm University
EDUCATION: 1981 Ph.D. - Physics, Royal Institute of Technology
1976 M.Sc. - Physics, Royal Institute of Technology

AWARDS AND HONORS: 1995, Lindbom Award, Royal Swedish Academy of Sciences

PROJECTS & RELEVANT EXPERIENCE: Member of AMANDA Neutrino Telescope Collaboration

PREVIOUS POSITIONS: Special research scientist, Astroparticle Physics, Swedish Natural Science Research Council

Experience in theoretical model building, computer simulations, and analysis. The group is internationally recognized in the subject of non-baryonic dark matter, in particular as regards its gamma-ray, antiproton and neutrino signatures. Author of university textbook in astroparticle physics. Good in-house support for computers, electronics, etc.

SELECTED RELEVANT PUBLICATIONS

L. Bergstrom and A. Goobar, “Cosmology and Particle Astrophysics,” 350 pp, Wiley/Praxis, Chichester, 1999.

L. Bergstrom, P. Ullio and J. H. Buckley, “Observability of gamma rays from dark matter annihilations in the Milky Way halo,” Astroparticle Physics **9**, 137-162,1998.

L. Bergstrom, “Nonbaryonic Dark Matter,” Nucl.Phys.Proc.Suppl.**70**, 31-42,1999.

ELLIOTT D. BLOOM

PRESENT POSITION:	Professor of Particle Physics, SLAC, Stanford University.
EDUCATION:	1967 Ph.D. - Physics, California Institute of Technology 1962 B.A. - Physics, Pomona College, Claremont, California.
AWARDS AND HONORS:	1985, Fellow of American Physical Society 1982, Senior Scientist Award Alexander von Humboldt Foundation.
PROJECTS & RELEVANT EXPERIENCE	Crystal Ball Experiment, TPC/2γ Experiment. Planning and construction of PEP-II accelerator. USA X-ray Mission and GLAST R&D.
PREVIOUS POSITIONS:	Spokesman (NASA equivalent of PI) Crystal Ball Experiment and TPC/2γ Experiment. Principal SLAC Co-I for the USA experiment Injection System Manager for the PEP-II construction project. Co-PI for the DOE GLAST R&D Group Leader of SLAC particle astrophysics group (EK).

Over the past 25 years I have been part of the leadership/management of a number of large and complex particle physics projects that developed and used state-of-the-art detector and accelerator techniques to advance knowledge in experimental particle physics and particle astrophysics. These projects have typically been international collaborations involving many collaborators. As Injection System manager in the PEP-II construction project I gained considerable experience in the use of management tools and procedures used in large DOE construction projects.

SELECTED RELEVANT PUBLICATIONS

W.B. Atwood et al, "Beam Test of Gamma Ray Large Area Space Telescope Components," SLAC-Pub-8166, 1999. Submitted to Nucl. Instrum. Meth.
C. Chaput et al, "A Search for Aperiodic Millisecond Variability in Cygnus X-1," SLAC-Pub-8039, 1999, Submitted to Astrophys. J.
E.D. Bloom & J.D. Wells (SLAC)," Multi-GeV Photons from Electron-Dark Matter Scattering Near Active Galactic Nuclei," Phys.Rev.**D57**:1299-1302, 1998.
D. Engovatov et al., "GLAST Beam Test at SLAC," SLAC Pub 7323, 1996.
E.D. Bloom, GLAST, Space Science Reviews, **75**, P109-125, 1996.
E. Bloom et al., "The PEP-II Asymmetric B Factory: Design Details and R&D Results," SLAC Pub 6564, Aug. 1994. Proceedings of 4th European Particle Accelerator Conf (EPAC 94, London, Jun-Jul 1994).
E.D. Bloom & C. W. Peck, "Physics with the Crystal Ball Detector," Ann. Rev. Nucl. Part. Sci. 33:143-97, 1983.

THOMPSON H. (TOBY) BURNETT

PRESENT POSITION:	Professor of Physics, University of Washington
EDUCATION:	1968 Ph.D. - University of California, San Diego 1963 B.A. - University of California, Berkeley with high honors
AWARDS AND HONORS:	1977-Alfred P. Sloan Foundation Research Fellow, 1963 Phi Beta Kappa
PROJECTS & RELEVANT EXPERIENCE:	The Crystal Ball, Mark III, SLD experiments at SLAC; theALEPH experiment at CERN
PREVIOUS POSITIONS:	NSF Postdoctoral Fellow, Princeton University (1968-70) Research Associate, University of California, San Diego (1970-75) Assistant Professor, University of Washington (1975-80)Associate Professor, University of Washington (1980-86)

Design, operation, and analysis of High Energy physics experiments, especially the Crystal Ball which involved reconstruction of gamma rays. Emphasis recently on computing aspects, especially control, graphics, and simulation.

SELECTED RELEVANT PUBLICATIONS

The Physics of O++ and 2++ Mesons, T.H.Burnett,
Lectures prepared for the proceedings of the 1995 NATO School on Hadronic Spectroscopy and the Confinement Problem, Swansea Wales, June 1995 Published by Plenum Press.
Further Amplitude Analysis Of J / Psi ---> GAMMA (PI+ PI- PI+ PI-).
By D.V. Bugg, I. Scott, B.S. Zou (Queen Mary - Westfield Coll.), V.V. Anisovich, A.V. Sarantsev (St. Petersburg, INP), T.H. Burnett, S. Sutlief (Washington U., Seattle). 1995. Phys. Lett. B353 (1995) 378-384.
T.H. Burnett, “Gismo: An Object-Oriented Approch To Particle Transport And Detector Modelling”, Proceedings of the Internation Conference of Monte Carlo Simulation in High Energy and Nuclear Physics, Tallahassee, Florida 22-26 February 1993
J.Z. Bai et al, “Measurement Of The Mass Of The Tau Lepton” Phys.Rev.Lett.**69**:3021-3024,1992”
Mark-III Collaboration (J. Adler, et al) “Study Of The Doubly Radiative Decay J / Psi -> Gamma Gamma Rho0” Phys.Rev.D**41**:1410,1990
MARK-III Collaboration (Z. Bai, et al.), “Application of the C++ Standard Library to problems in Pattern Recognition and Reconstruction”, lectures prepared for the 1997 CERN School of Computing.

PATRIZIA CARAVEO

PRESENT POSITION: Senior Staff Scientist, the Istituto di Fisica Cosmica, CNR

EDUCATION: 1977 Italian degree of Laurea full academic honor, U, of Milano

AWARDS AND HONORS: Staff Scientist at the IFCTR/CNR, Milano
Winner of a 2 months NATO senior fellowship
Senior Staff Scientist of Primo Ricercatore at the IFCTR/CNR
Italian Coordinator for the observaing time allocations of the EPIC experiment on XMM.

PROJECTS & RELEVANT EXPERIENCE: COS-B, INTEGRAL, XMM, AGILE

PREVIOUS POSITIONS: Collaborateur Temporaire Etranger
CNR fellow for "Analysis and Astrophysical Interpretation of Gamma-ray astronomy data."
Milano representative of the Data Reduction Group of the Caravane Collaboration for the COS-B satellite
Vice president of the Italian Space Society
Member of the Editorial Board of ApJ & Communications
Co Investigator for the Spectrometer SPI instrument on ESA's Gamma-Ray spectroscopy mission INTEGRAL

P. Caraveo took part from the start to the decade long chase which lead to the discovery and understanding of Geminga through multiwavelength astronomy. This required the use of practically all available means of space and ground based astronomy including: SAS-2, HEAO-1, COS-B, Einstein, EXOSAT, Ginga, ROSAT, EGRET, EUVE,ASCA, HST and Hipparcos. Of special interest is the use of high precision Hipparcos astronomy data for characterizing Geminga's rotational and physical properties. The constant scientific theme is the phenomenology of galactic compact objects, in particular, but not only, isolated neutron stars, their velocity distribution and their relations to supernova remnants. The existing evidence for optical emission of isolated neutron stars is largely the result of the work of her group. In the last few years PAC has further broadened her interests to include work on instrument design and mission planning in the context of ESA, notably within INTEGRAL and XMM.

SELECTED RELEVANT PUBLICATIONS

G.F. Bignami, P. Caraveo, "Geminga: its Phenomenology, its Fraternity and its Physics," Ann. Rev of Astr. And Astrophys 34, 331 1996

P. Caraveo, G.F. Bignami, R. Mignani, L. Taff, "Parallax Observations with the Hubble Space Telescope Yield the Distance to Geminga," ApJ. Lett. 461,L91 1996

P. A. Caraveo, et al, "Bignami Hipparcos Positioning of Geminga: How and Why," A & A Lett. 329, L1, 1998

P. A. Caraveo, R. Mignani, "A New HST Measurement of the Crab Pulsar proper Motion," A & A 344, 1999

PER CARLSON

PRESENT POSITION:	Professor of Physics, Royal Institute of Technology, Stockholm
EDUCATION:	1969 Ph.D. - Physics, Stockholm University
PPREVIOUS POSITIONS:	CERN staff physicist 1975-79 Senior physicist, Stockholm University 1979-86 Full professor of physics 1987-

Long experience from particle physics experiments at CERN, Geneva. Special emphasis on instrumentation developments, e.g. Cherenkov counters and calorimeters. More recently initiated the use of RICH counters in a magnetic cosmic ray spectrometer. Recently studied fundamental symmetry properties in CP-violation experiments at CERN. Also studied cosmic ray antimatter flux and atmospheric muons. Management experience from current position as group leader and department chair (some 200 persons including 14 full professor). Chairing the Royal Swedish Academy of Science Physics class. Member of the Nobel committee for physics.

SELECTED RELEVANT PUBLICATIONS

M. Boezio et al, "The cosmic ray proton and helium spectra between 0.2 and 200 GeV,"
Astrophys. Journal **518** (1999) **457**.

M. Boezio et al, "New measurement of the flux of atmospheric muons,"
Phys. Rev. Letters **82**(1999)4757.

A. Apostolakis et al. (The CPLEAR Collaboration), "Determination of the T- and CPT-violation parameters in the neutral-kaon system using the Bell-Steinberger relation and data from CPLEAR"

GREG CLIFFORD

PRESENT POSITION: Vice President, Systems Engineer - Silver Engineering, Inc.
EDUCATION: 1975 B.S. - Electronics, Florida International University

AWARDS AND HONORS: Graduated with Honors
PROJECTS & RELEVANT EXPERIENCE: GLAST Spacecraft Systems Engineer - IDB, TCPU, SIU, DAQ
NEMO Spacecraft - Systems Lead for CT&DH
JPEX Sounding Rocket - Electrical Interface Manager
ARGOS Spacecraft - Electrical Interface Manager
SSULI DMSP Satellite Sensor - Electrical Interface Manager
MATT - UHF Receiver Section Systems Engineer
ALAGE - Project Engineer
MALABAR AFB - Mount Control System Engineer
Lockheed DSS Telemetry Systems - Systems Engineer
Remote Data & Communication System - Design Engineer
SEALAR Rocket - Software Design
LACE - Software Design

PREVIOUS POSITIONS: Director of Engineering - Mnemonics, Melbourne, FLPresident - Network Engineering, Inc., Palm Bay, FL

Corporate officer duties include responsibilities of company performance and accountability, company polices, technical direction, designation of responsibilities, and assignment of tasks. Engineering efforts included system engineering, digital design, analog design, software design of flight and ground systems. Complete responsibility of product development. Fifteen years experience as a corporate officer. Five years experience as a Director of Engineering and Engineering Manager, managed groups as large as 45 employees. As Director of Engineering, responsibilities included proposal preparation, systems definition, and overall design responsibility for ground and flight based aerospace products. Twenty years experience as a project engineer, managed research and development projects of up to $5M per year

PUBLICATIONS AND PATENTS

Subtracting 4 Digit BCD A/D Converter, Patent Applied For, 1974
Improved DC Clamp, Patent Applied For, 1975

LYNN COMINSKY

PRESENT POSITION: Professor, Physics and Astronomy
EDUCATION: 1981 Ph.D. - Physics, Massachusetts Institute of Technology
1975 B.A. - Physics, Brandeis

AWARDS AND HONORS: Council for Advancement and Support of Education California Professor of the Year
Sonoma State U. Outstanding Professor Award
Excellence in Education Award (from the Santa Rosa Chamber of Commerce)
CSU Meritorious Performance and Professional Promise Awards
PROJECTS & RELEVANT EXPERIENCE: Deputy Press Officer, American Astronomial Society
Press Officer, High Energy Astrophysics Division of the AAS
PI or Co-I on Guest Investigator grants for HEAO A-1,
EXOSAT, ROSAT, BATSE, EGRET, OSSE, ASCA and RXTE

PREVIOUS POSITIONS: Space Sciences Lab, University of California, Berkeley
NASA’s Extreme Ultraviolet Explorer Satellite Project
Systems Development Manager
Science Operations and Data Analysis Administrator

Prior to attending graduate school, Dr. Cominsky worked on producing the Fourth UHURU catalog of X-ray sources, at the Harvard-Smithsonian Center for Astrophysics. She then attended graduate school from 1977-1981 at MIT, where she worked on data from the SAS-3 satellite. In 1983, after two years of post-doctoral work, Dr. Cominsky began to manage various aspects of NASA's Extreme UltraViolet Explorer (EUVE) Satellite project, including the design of the science operations and ground data analysis system, and ultimately the development effort for the entire science payload. In 1986, after the disastrous Challenger explosion which set back the launch of EUVE for many years, she joined the faculty at Sonoma State University, where she is now Professor of Physics and Astronomy. At SSU, she has been PI on over $500,000 of research grants in X-ray and gamma-ray astronomy from NASA and NSF. Since 1992, she has been a collaborator on the GLAST project at the Stanford Linear Accelerator Center. During the GLAST Mission Concept Study, she chaired the Education and Public Outreach working group: as part of this work, she developed the GLAST outreach web site.

SELECTED RELEVANT PUBLICATIONS

L. Cominsky et al, "X-ray/Gamma-ray Observations of the PSR B1259-63/SS2883 System near Apastron," to appear in the Astrophysical Journal, 1999.

X-ray Emission from Compact Sources, a 65-page summary of two invited lectures to be published (1999) in the Proceedings of the Stanford Linear Accelerator Center XXVI Summer Institute on Particle Physics, “Gravity, from the Hubble Length to the Planck Length”

SETH W. DIGEL

PRESENT POSITION:	Research Scientist, Universities Space Research Association, Cooperative Program in Space Sciences, NASA Goddard Space Flight Center
EDUCATION:	1991 Ph. D.- Physics, Harvard University 1987 A. M. - Physics, Harvard University
AWARDS AND HONORS:	1992–1995, NASA Compton GRO Fellow 1985–1988, National Science Foundation Graduate Fellow 1985, Phi Kappa Phi, Sigma Pi Sigma, Tau Beta Pi
PROJECTS & RELEVANT EXPERIENCE:	GRO Science Support GRO Fellow Affiliation with EGRET PI team Millimeter-Wave Astronomy Group
PREVIOUS POSITIONS:	Principal Scientist, Raytheon STX Corp., Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center Senior Scientist, Hughes STX Corp., Astrophysics Data Facility, NASA Goddard Space Flight Center NASA Compton GRO Fellow, Harvard-Smithsonian Center for Astrophysics and NASA Goddard Space Flight Center

Digel has studied the interstellar diffuse emission with EGRET, in particular of local interstellar clouds and of the outer Milky Way. He has extensive experience studying the interstellar medium with radio and millimeter-wave telescopes as well. For GLAST, he has undertaken studies to evaluate the astronomical performance, relating the instrumental response functions to flux limits and source localization regions, for example. He has developed analysis methods to optimize the use of each photon from the scanning sky survey. He has professional experience with data processing and archiving and has helped to define the data system for GLAST.

SELECTED RELEVANT PUBLICATIONS

S. W. Digel et al , "EGRET Observations of the Diffuse Gamma-Ray Emission in Orion: Analysis Through Cycle 6," ApJ, **520**, 196, 1999

G. E. Allen, S. W. Digel, J. F. Ormes, "What Can Be Learned About Cosmic Rays with GLAST?," Proc. 26th International Cosmic Ray Conference (Utah), **3**, 515, 1000

S. W. Digel et al, "Tracing the Interstellar Medium in Ophiuchus Across 14 Orders of Magnitude in Frequency," Proc. IAU Symposium 179, New Horizons From Multiwavelength Sky Surveys, ed. B McLean (Dordrecht: Kluwer), 175, 1996

S. W. Digel et al, "A Large-Scale CO Survey of the W 3 Region," ApJ, **458**, 561, 1996

S. W. Digel et al "Diffuse High-Energy Gamma-Ray Emission Beyond the Solar Circle: The Cepheus and Polaris Flares and the Perseus Arm," ApJ, **463**, 609, 1996

ARACHE DJANNATI-ATAI

PRESENT POSITION: Astrophysicist – CNRS-IN2P3/Collège de France, Paris, France
EDUCATION: 1995 Ph.D. - Physics, Paris University VI
1992 B.S. - Physics, Paris University VI
1988 B.S. - Electronics, Paris University VI

AWARDS AND HONORS: 1994, Distinction for Physics lectures, Paris University VII

PROJECTS & RELEVANT EXPERIENCE: Gamma-Ray Astrophysics :
Analysis and observation program manager of the CAT imaging cherenkov telescope. Consultant for the CELESTE telescope.
Ph.D: THEMISTOCLE cherenkov timing telescope HEP
Forward Vertex detector expert on DELPHI exp. at LEP-CERN.
PREVIOUS POSITIONS: Director of the technical department of T.I.C company (1998-90)

Presently working on the CAT imaging telescope (French Pyrenees) operating in the range 250 GeV to 20 TeV. I'm the manager of the analysis and the observation program. Studies carried out on galactic (plerions, SNRs) and extra-galactic (AGNs) gamma-ray sources. Coordinator and consultant for CAT common observations with CELESTE telescope (French Pyrenees, operating form 30 GeV to 300 GeV) and for multi-wavelength campaigns (mainly ASCA, RXTE, BeppoSAX, EGRET, WEBT and VLBI). Ph. D thesis: Measurement of the TeV spectrum of the Crab nebula with the THEMISTOCLE cherenkov timing telescope. Constraints on acceleration and emission models. High Energy Physics Search for the Higgs Boson at LEP/CERN with the DELPHI detector at 130-172 GeV. Participation in the Forward Vertex silicon detector development and installation for DELPHI.

SELECTED RELEVANT PUBLICATIONS

A. Djannati-Ataï, F. Piron et al., "Very High Enregy Gamma-Ray Spectral Properties of Mkn 501 from Cat Cherenkov Telescope Observations In 1997," Accepted for publication, A&A**.** 1999. (astro-ph/9906060)

The Cat Imaging Telescope for Very High-Energy Gamma Ray Astronomy CAT Collaboration.
Nucl.Instrum.Meth.A**416**:278-292,1998

Gamma-Ray Spectrum of the Crab Nebula in the Multitev Region.
Themistocle Collaboration. Astropart.Phys.**1**:341-356,1993, Erratum-ibid.**5**:79,1996

Search for Neutral and Charged Higgs Bosons in E+ E- Collisions at S (1/2) = 161-Gev and 172-Gev.
DELPHI Collaboration. Eur.Phys.J.**C2**:1-37,1998

RICHARD DUBOIS

PRESENT POSITION:	Staff Physicist, Stanford Linear Accelerator Center
EDUCATION:	1980 Ph.D. - Physics, University of British Columbia
	1978 M.Sc. - Physics, University of British Columbia
	1976 B.Sc. – Physics (Honours), McGill University
PROJECTS & RELEVANT EXPERIENCE:	Initiated North American Linear Collider Detector Simulations facility
	Head of Offline Computing, SLD Experiment at SLAC
	Calorimetry Software Manager, SLD
	Member, SLAC Computer Coordinating Committee and DoE HEP Network Resource Center Advisory Committee
PREVIOUS POSITIONS:	1984-1990 Research Scientist, TRIUMF; Adjunct Professor University of Victoria
	1981-1983 Research Associate, SLAC

Initiated a flexible OO detector simulation facility for the North American Linear Collider studies. It is based on Gismo, the same simulation package used by GLAST. Headed the SLD experiment’s offline software, which involved, among other things, responsibility for processing SLD data from its exit from the acquisition system to physics analysis.

SELECTED RELEVANT PUBLICATIONS

K. Abe et al., Measurement of the Average b Hadron Lifetime in Z Decays Using Reconstructed Vertices, Phys. Rev. Lett. **75,** 3624 (1995).

K. Abe et al, A Direct Measurement of Parity Violation in the Coupling of Z Bosons to b Quarks Using a Mass Tag and Momentum Weighted Track Charge, Phys. Rev. Lett. **81**,942(1998).

K. Abe et al., An Improved Measurement of the Left-Right Z Cross-Section Asymmetry, Phys. Rev. Lett. **78,** 2075 (1997).

K. Abe et al., A Measurement of R_b using a Vertex Mass Tag, Phys. Rev. Lett. **80,** 660 (1998).

PATRICK FLEURY

PRESENT POSITION: High Energy Particle physicist
EDUCATION: 1964 Ph.D. - Physics, Université de Paris
1959 B.A. - Physics, Berkeley University

AWARDS AND HONORS: 1980 Palmes académiques
PROJECTS & RELEVANT EXPERIENCE: Started the CAT experiment
Started CELESTE
Both are earth based gamma astronomy, Thémis (France).

PREVIOUS POSITIONS: 1974-1986 Director of LPNHE lab at Ecole Polytechnique;
1993-1999 In charge of Astrophysics group at LPNHE.

Hadron physics with cryogenic hydrogen bubble chamber of Ecole Polytechnique at CERN. e.g. discovery of the g-meson; Leading a team on electronic detectors at CERN; e.g. baryon exchange reactions; Director of the lab at Ecole Polytechnique (e.g. the onset of “quagma” search at CERN); Works with “Saturne” accelerator (back to direct research); Cosmic ray studies: search of antimatter in cosmic rays using Whipple “10m” air shower telescope. Activity in Gamma Ray Astronomy: I convened for the first Workshop on TeV atmospheric Cherenkov detectors; I initiated the CAT and then CELESTE experiments at Thémis

SELECTED RELEVANT PUBLICATIONS

A. Djannati-Ataï et al., “Very High Energy Gamma-ray spectral properties of Mrk 501 from CAT Cerenkov telescope observations in 1997,” A&A to be published (1999).
A.Djannati-Ataï, C.M.Hoffman et al., “Very High Energy Gamma Ray Astronomy,” Review of Modern Physics V;71 p.897 (999).

NEIL GEHRELS

PRESENT POSITION:	Head, Gamma Ray and Cosmic Ray Astrophysics Branch
	Laboratory for High Energy Astrophysics, NASA/Goddard
EDUCATION:	1981 Ph.D. - Physics, California Institute of Technology
	1976 B.S. - Physics, University of Arizona
AWARDS AND HONORS:	1993, Fellow, American Physical Society
	1993, NASA Outstanding Leadership Award
	1992, Discover Magazine Award for Technology Innovation
PROJECTS & RELEVANT EXPERIENCE:	Project Scientist, Compton Gamma Ray Observatory
	Mission Scientist, INTEGRAL
	Principal Investigator, Swift MIDEX
PREVIOUS POSITIONS:	Visiting Professor of Astronomy, Univ. of Maryland, 1995

I have been active as an experimental physicist working in gamma-ray astronomy since 1981, publishing over 80 papers in the field and giving over 60 invited talks. As Project Scientist of CGRO since 1991, I have scientifically managed a gamma-ray astronomy mission similar in scope to GLAST. My own particular CGRO research interests have been gamma-ray bursts and high-energy emission from AGN. My GLAST involvement dates from 1995, when I joined the Goddard group working with the Stanford team. From 1997 to 1999, I Co-Chaired the GLAST Facility Science Team with P. Michelson.

SELECTED RELEVANT PUBLICATIONS

N. Gehrels, P. Michelson, "GLAST: The Next Generation High Energy Gamma-Ray Astronomy Mission", Astroparticle Phys., **11**, 277, 1999

R. Blandford, N. Gehrels, "Revisiting the Black Hole", Phys. Today, **52**, 40, June 1999.

W. Chen, N. Gehrels, "The Progenitor of the New COMPTEL/ROSAT Supernova Remnant in Vela", ApJ, **514**, L103, 1999

D. J. Macomb, N. Gehrels, "The General Gamma-Ray Source Catalog", ApJS, **120**, 335, 1999

N. Gehrels, J. Paul, "The New Gamma-Ray Astronomy", Phys. Today, **51**, 26, February, 1998

N. Gehrels, "The Use of νF_ν Spectral Energy Distributions for Multiwavelength Astronomy", Il Nuovo Cimento, **112B**, 11, 1997

H. Seifert, B. Teegarden, T. Cline, N. Gehrels, J. int'Zand, D. Palmer, R. Ramaty, K. Hurley, N. Madden, R. Pehl, "TGRS Observations of the Bright Gamma Ray Burst GRB950822", ApJ, **491**, 697, 1997

C. Dermer, N. Gehrels, "Two Classes of Gamma-Ray Emitting Active Galactic Nuclei", ApJ, **447**, 103, 1995

N. Gehrels, W. Chen, "The Geminga Supernova as a Possible Cause of the Local Interstellar Bubble", Nature, **361**, 706, 1993

GARY L. GODFREY

PRESENT POSITION:	Staff Particle Physicist – Stanford Linear Accelerator Center
EDUCATION:	1975 Ph.D. - Physics, University of California Berkeley 1968 B.S. - Physics, California Institute of Technology
PROJECTS & RELEVANT EXPERIENCE:	GLAST USA xray detector (ARGOS satellite) PEPII Ring injection instrumentation TPC and MAC detector at PEP Crystal Ball at DORIS and SPEAR (Accel Ring) Thesis- Measurement of Kaonic xrays
PREVIOUS POSITIONS:	Post Doc Lawrence Berkeley Laboratory

Dr. Godfrey's experience has been in designing, building, and using various instrumentation and electronics to do high energy particle physics experiments. These have included high purity Si and Ge xray detectors, a 672 xtal NaI detector (Crystal Ball), multiwire gaseous vertex detectors (Crystal Ball, MAC,TPC), accelerator beam position monitors (PEPII), and gaseous xray detectors (USA).

SELECTED RELEVANT PUBLICATIONS

W. Atwood, G. Godfrey, et al, "Beam Test of GLAST Components," SLAC-PUB-8166, 1999. Submitted to Nucl. Instrum. Meth.

C. Chaput, G. Godfrey, et al, "A Search for Millisecond Variability in Cygnus X-1," SLAC-PUB-8039, 1999. Submitted to Astrophys. J.

G. Godfrey, "GLAST-A Partnership in Particle and Astrophysics," in proceedings of COSMO 98, Monterey, CA, 1998.

G. Godfrey, "Gamma Large Area Silicon Telescope," in workshop proceedings of Towards a Major Atmospheric Cerenkov Detector, Calgary, Canada 1993.

ISABELLE A. GRENIER

PRESENT POSITION: Professor, Astroparticle Physics, University of Paris VII
EDUCATION: 1988 Ph.D. - Astrophysics, University of Paris VII
1979-1982 - Ecole Normale Supérieure de Cachan

PROJECTS & RELEVANT EXPERIENCE: member of the:
COS-B and GAMMA-I teams
CAT and CELESTE teams
γ-ray astrophysics (unidentified EGRET sources, pulsars, interstellar γ-ray emission, supernova remnants, unbinned likelihood analysis)
Radio astronomy (Columbia CO survey, molecular clouds, mass tracers, Gould Belt)

PREVIOUS POSITIONS: Board of advisors for the Earth and Universe Sciences for the French Minister of Research and Education (1994-98)
PANAGIC “Particle and Nuclear Astrophysics and Gravitation International Committee” of IUPAP (≥1999)
NASA/GLAST Facility Science Team (1998-99)
Secretary of the French Astronomical Society (1996-98)

SELECTED RELEVANT PUBLICATIONS

Grenier I.et al., "The spectral variability of the γ -ray emission from Geminga and Vela and its implications," A&A, **269**, 209, 1993

Chardonnet P., Grenier I.A., Smoot G., "The γ-ray. "diffuse background and Cherenkov telescopes," ApJ, **454**, 774, 1995

Digel S. et al., "Diffuse high-energy γ -ray emission beyond the solar circle: the Cepheus and Polaris Flares and the Perseus arm," ApJ, **463**, 609, 1996

Mukherjee R., Grenier I.A. & Thompson D., "Review at the 4th Compton Symposium, AIP 410, vol. 1, **394**, On the nature of the Unidentified EGRET sources," 1997

Baring M., I. Grenier, P. Goret, in press, Radio to γ-ray emission from shell-type supernova remnants: predictions from non-linear shock acceleration models, ApJ, 1999

Grenier I.A., "γ-Ray sources in the Gould Belt: relics of recent nearby supernovae," A&A, submitted, 1999

A. Djannati-Ataï, Grenier I. et al., "VHE γ-ray spectral properties of Mrk 501 from CAT Cherenkov telescope observations in 1997," A&A, submitted 1999

J. ERIC GROVE

PRESENT POSITION:	Research Astrophysicist Naval Research Laboratory
EDUCATION:	1989 Ph.D. - Physics, California Institute of Technology 1982 A.B. - Physics, University of California, Berkeley
AWARDS AND HONORS:	1999, NRL Alan Berman Research Publication Award 1992, NASA Public Service Group Achievement Award 1989, National Research Council/NRL Research Associateship 1982, Phi Beta Kappa
PROJECTS & RELEVANT EXPERIENCE:	1992-present, Instrument Scientist, Oriented Scintillation Spectrometer Experiment, *Compton* Gamma Ray Observatory.

Grove is the Instrument Scientist for OSSE on the Compton Gamma Ray Observatory. He has been responsible for day-to-day operation of the OSSE instrument, and leads a team of operators and production data processors. His principal CGRO research activities have been centered on spectral and temporal observations of galactic compact objects, especially black hole candidates, and active galaxies, primarily Seyfert AGN. Dr. Grove was a Co-Investigator for the proposed $350M GLAST mission, Gamma-ray Large Area Space Telescope, at its inception as a NASA Mission Concept Study. He remains a Co-Investigator in the on-going Supporting Research and Technology (SR&T) and Advanced Technology Development (ATD) programs for GLAST.

SELECTED RELEVANT PUBLICATIONS

J.E. Grove et al, “Timing Noise Properties of GRO J0422+32," ApJ, **502**, L45. 1998

Grove, J.E.,Johnson, W.N.et al, “Gamma-Ray Spectral States of Galactic Black Hole Candidates,” ApJ, **500**, 899. 1998

P. Grandi, F. Haardt, G. Ghisellini, E.J. Grove et al, “High-Energy Break and Reflection Features in the Seyfert Galaxy MCG+8-11-11," ApJ, **498**, 220, 1998

W.N. Johnson, J.E. Grove, and B.F. Phlips, “A CsI(Tl) Hodoscopic Calorimeter for the GLAST Mission," Proc. IEEE Nuclear Science Symposium, 1997

Grove, J.E “OSSE Highlights of the Low-Energy Gamma-Ray Sky,”.Mem.S.A.It., **67**, 127, 1996

J.E. Grove et al, “Evidence for Shock Acceleration in the Binary Pulsar System PSR B1259-63,” ApJ, **447**, L113, 1995

J.E. Grove et al, “The Soft Gamma-Ray Spectrum of A0535+26: Detection of an Absorption Feature at 110 keV by OSSE,” ApJ, **438**, L25, 1995

GUNTHER HALLER

PRESENT POSITION:	Head of Research Division Electronics Engineering Group
EDUCATION:	1994 Ph.D. - EE, Stanford University 1989 M.S. - EE, Stanford University
PROJECTS & RELEVANT EXPERIENCE:	Chief Electronics Engineer, BaBar detector at SLAC Chief Electronics Engineer, SLD detector at SLAC Chief Electronics Engineer for BaBar detector at SLAC

The BaBar detector is a $85 Million high-energy physics detector consisting of a silicon vertex detector, a drift chamber, a particle identification system, a CsI calorimeter, and a magnet with a flux return. The detector is in full operation as of May 1999. Management; Directed effort of international collaboration (France, Germany, Italy, UK, U.S.) in R & D, design, production, and commissioning of all the electronics. Budget & Schedule; Full budget and schedule responsibility for all the electronics. Detailed budgeting of $12 Million U.S. electronics effort taking place at numerous U.S. universities and laboratories. Technical; Design of architecture of data-acquisition system comprising 200+ Power-PC processors. Design of full-custom integrated circuits, PC boards, and systems including interconnects. Reliability; Full reliability studies undertaken for non-accessible electronics in respect to redundancy and MTBF. Tracker Electronics; The BaBar silicon tracker contains radiation-hard (>10 Mrad) custom integrated circuits and components. Calorimeter Electronics; The BaBar calorimeter consists of 7,000+ CsI crystals with PIN-diode readout and custom electronics performing at 18-bit dynamic range. DAQ; The BaBar DAQ contains 200+ PowerPC processors.

SELECTED RELEVANT PUBLICATIONS

“Electronics for the BaBar Cental Drift Chamber” SLAC-PUB-7996, Nov 1998. 7pp. IEEE 1998 Nuclear Science Symposium (NSS) Toronto, Ontario, Canada, 8-14 Nov. 1998.

“Design and Performance of the SLD Vertex Detector, a 307 Mpixel Tracking System”, Nucl.Instrum.Meth. A400: 287-343, 1997

“Analog Floating-Point BiCMOS Sampling Chip and Architecture of the BaBar CsI Calorimeter Front-end Electronics System at the SLAC B-Factory”, IEEE Trans. Nucl. Sci. 43: 1610-1614, 1996

“A 700-MHz Switched-Capacitor Analog Waveform Sampling Circuit”, IEEE J. Solid State Circuits, vol. 29, No 4, April 94.

“Design of a Trigger and Data-Acquisition System for a Detector at PEP-II”, IEEE Trans. Nucl. Sci. 41:1289-1293,1994

W. NEIL JOHNSON

PRESENT POSITION: Head, Gamma Ray Astrophysics Section Naval Research Lab.
EDUCATION: 1973 Ph.D. - Space Phys & Astron., Rice University
1972 MS. - Space Phys & Astron., Rice University
1967 BA, - Physics & Math, Rice University
AWARDS AND HONORS: 1999 APS Fellow
1999 NRL Alan Berman Research Publication Award
1992 NASA Public Service Group Achievement Award
PROJECTS & RELEVANT EXPERIENCE: Co-I and lead of Calorimeter Team for GLAST Mission Concept Study, SR&T and ATD Programs, NASA
Co-I and Project Scientist on the Oriented Scintillation Spectrometer Experiment (OSSE) on CGRO
PI – Imaging Ge Detector Development, DOE
PI – Silicon Detector Development for Constellation-X ATD Program, NASA

Johnson has over 30 years experience in design, fabrication and operation of gamma ray experiments for space-based platforms. As project scientist, he was responsible for the design, implementation and operation of the Oriented Scintillation Spectrometer Experiment (OSSE) which was launched in 1991 on the NASA's *Compton Gamma Ray Observatory.* His research interests are focused on understanding the spectral characteristics of black holes, both extragalactic (AGN) and galactic. Johnson is head of the Gamma Ray Astrophysics Section in NRL's Space Science Division and directs a broad development program in technology related to the detection and measurement of gamma radiation using both scintillation and solid state detectors.

SELECTED RELEVANT PUBLICATIONS:
W.N. Johnson et al, “Long Term Monitoring of NGC 4151 by OSSE”, ApJ, **482**, 173, (1997).
W.N. Johnson, J.E. Grove, and B.F. Phlips, “A CsI(Tl) Hodoscopic Calorimeter for the GLAST Mission Proc.," IEEE Nuclear Science Symposium. (1997).
W.N. Johnson et al, "OSSE Observations of 3C 273", Astrophys. J. **445**, p. 182 (1995).
W.N. Johnson et al, "The Oriented Scintillation Spectrometer Experiment Instrument Description," ApJ Supplements **86**, p. 693 (1993).

ROBERT JOHNSON

PRESENT POSITION: Associate Professor, University of California at Santa Cruz
EDUCATION: 1986 Ph.D. - Physics, Stanford University
1981 B.S. - Physics, University of Kansas
AWARDS AND HONORS: 1980, Stranathan Award, U. of Kansas
1977, Summerfield Scholarship, U. of Kansas
1977, National Merit Scholar
PROJECTS & RELEVANT EXPERIENCE: GLAST ATD program, Silicon-Strip Tracker subsystem manager
BaBar Experiment, SLAC PEPII accelerator
Aleph Experiment, CERN LEP accelerator
Delco Experiment SLAC PEP accelerator
PREVIOUS POSITIONS: Research Associate, University of Wisconsin
Research Assistant, Stanford University

Johnson has extensive experience with large particle detection systems, especially with regards to electronics, reconstruction software and data analysis. For the Aleph experiment he was in charge of building part of the electronics of the time projection chamber, and he led the development of the track reconstruction software for that device. For the BaBar experiment he led the team that developed the conceptual design of the silicon-strip tracker readout system, and he contributed to the design and testing of the readout ASIC. During the past several years he has led the R&D effort on the GLAST silicon-strip tracker. He made the conceptual design of the front-end readout electronics, designed the amplifiers, and led the team that developed the front-end ASICs. His team built and operated the silicon-strip tracker for the 1997 GLAST beam test and recently completed construction of a full-scale 50,000-channel tracker tower module.

SELECTED RELEVANT PUBLICATIONS

W.B. Atwood, R.P. Johnson et al., “Beam Test of Gamma-ray Large Area Space Telescope Components,” submitted to Nucl. Instrum. Meth., SLAC-PUB-8166 (1999).
V. Re, R.P. Johnson et al., “The Rad-Hard Readout System of the BaBar Silicon Vertex Tracker,” Nucl. Instrum. Meth. **A409**, 354 (1998).
R.P. Johnson et al., “An Amplifier-Discriminator Chip for the GLAST Silicon-Strip Tracker,” IEEE Trans. Nucl. Sci. **45**, 927 (1998).
I. Kipnis, R.P. Johnson et al., “A Time-Over-Threshold Machine: the Readout Integrated Circuit for the BaBar Silicon Vertex Tracker,” IEEE Trans. Nucl. Sci. **44**, 289 (1997).
R.P. Johnson, “BaBar Silicon Vertex Tracker,” Nucl. Instrum. Meth. A383, 7 (1996).
R. Becker, R.P. Johnson et al., “Signal Processing in the Front-End Electronics of the BaBar Vertex Detector”, Nucl. Instrum. Meth. **A377**, 459 (1996).
W. Wiedenmann, R.P. Johnson et al., “Tracking with the Aleph Time Projection Chamber,” IEEE Trans. Nucl. Sci. **38**, 432 (1991).

TUNEYOSHI KAMAE

PRESENT POSITION: Professor
EDUCATION: 1968 Ph.D. - Physics, Princeton University
1962 B.S. - Physics, University of Tokyo
PROJECTS & RELEVANT EXPERIENCE: Astro E Hard X-ray Detector
Japan-Brazil Balloon Experiments (Brazil)
TRISTAN experiment at KEK (Japan)
PEP4 experiment at SLAC
Anti-proton experiments at KEK (Japan)
Kaon decay experiment at CERN
Electron quasi-free scattering exp. at INS (Japan)
PREVIOUS POSITIONS: Principal Investigator, Astro E HXD, TRISTAN, Anti-Proton exp. at KEK
Associate Professor, Univ. of Tokyo

SELECTED RELEVANT PUBLICATIONS

J. P. Finley, T. Kamae et al, "A Broadband X-Ray Study of the Young Neutron Star PSR B1706-44." Astrophys. Journal **493**, 884, 1998
H. Ozawa, T. Kamae et al "Integration of the readout electronics for the Astro-E hard x-ray detector," SPIE Vol.**3115,** 2350, 1997
T. Kamae et al, "Development of the large-area silicon PIN diode with 2 millimeter-thick depletion layer for hard x-ray detector (HXD) on board ASTRO-E," SPIE Vol.**3115,** 244, 1997
N. Yamasaki, T. Ohashi, F. Takahara, S. Yamauchi, K. Koyama, T. Kamae, et al, "Hard X-Ray Emission from the Galactic Ridge," Astrophys. Journal **481**, 821, 1997
Y. Saito, N. Kawai, T. Kamae et al, "Detection of Magnetospheric X-ray Pulsation in Millisecond Pulsar PSR B1821-24," Astrophys. Journal Letter **477**, 37, 1997

TADASHI KIFUNE

PRESENT POSITION: Professor at Institute for Cosmic Ray Research, U. of Tokyo
EDUCATION: 1970 Ph.D. - University of Tokyo, Japan
1965 MS - Physics, University of Tokyo
1963 BS - Physics, University of Tokyo, Japan
PREVIOUS POSITIONS: Research Associate, Dept of Physics, U of Tokyo
Research Associate, U. of Tokyo.
Visiting Research Associate, Columbia University, NY
Associate Professor, Inst. for Nuclear Study, U. of Tokyo
Associate Professor, Inst. for Cosmic Ray Research, U. of Tokyo

Research on cosmic ray physics, ultra high energy gamma-rays by observing extensive air showers. Proton decay experiment and detection of neutrino from supernova explosion. Observation of very high energy gamma-rays from SN1987A in New Zealand. From 1990, research on very high energy gamma-rays by using \v Cerenkov Imaging Telescope, which is located in Australia. Spokesperson on Japan side of the collaboration between Japan Institutions and University of Adelaide in Australia (CANGAROO Project).

SELECTED RELEVANT PUBLICATIONS

T.Kifune, "Invariace Violation Extends the Cosmic Ray Horizon?," AJ Letters, **518**, L21, 1999

T.Tanimori et al., "Discovery of TeV Gamma Rays from SN1006:Further Evidence for the Supernova Remnant Origin of Cosmic Rays," AJ L, **497**, L25, 1998

T.Yoshikoshi et al., "Very High Energy Gamma Rays from the Vela Pulsar Direction," AJL, **487**, L95, 1997

F.A. Aharonian, A.M. Atoyan and T. Kifune, "Inverse Compton Gamma Radiation of Faint Synchrotron X-ray Nebula around Pulsars," Monthly Note of Royal Astronomical Society,291, 162, 1997.

A. Smith, J. Smith, "Solar Activity in RS Cvn Stars", ApJ, 202, 45, 1994

PHILIPPE LAVOCAT

PRESENT POSITION: Head of the Space Equipments Development Group at CEA/DAPNIA/Service d’Astrophysique, France

EDUCATION Engineer in Physics Instrumentation from “Ecole Nationale Supérieure de Physique of Marseille in 1983
Graduated in Physics in 1982.

SPECIALTY : Physics instrumentation engineer

PROJECTS & RELEVANT EXPERIENCE: Design and development of particle physics detector (electromagnetic and hadronic calorimetry) and associated instrumentation, CERN and Fermilab

PREVIOUS POSITIONS:

Project Manager, detector prototypes for the future Large Hadron Collider; CERN; “Quark Top Research” D0 experiment, Fermilab; French Project manager of WALIC warm liquid calorimetry collaboration with Fermilab and Berkeley teams for American SSC accelerator detectors developments.

Project manager, extended cold CCD camera dedicated to Dark Matter Search at ESO Southern Observatory : EROS

Expert on thermal aspects for an IR detector sub-system of the NASA/CASSINI-CIRS instrument

Project Manager of the γ-ray camera ISGRI on the ESA/INTEGRAL satellite

Head of the Space Equipments Development Group (33 people) of Astrophysics Team in Saclay since 1995.

YING-CHI LIN

PRESENT POSITION: Senior Research Scientist

EDUCATION: 1969 Ph.D. - Physics, Cornell University
B.S. - E.E., National Taiwan University

AWARDS AND HONORS: NASA/GSFC Special Act Group Award, 1991
NASA Group Achievement Award, 1992

PROJECTS & RELEVANT EXPERIENCE: Cosmic rays research, University of Arizona
High-energy particle experiments, Fermilab/U. of Arizona
CGRO/EGRET experiment, Stanford

PREVIOUS POSITIONS: Research Scientist

Ying-chi Lin was trained in theoretical nuclear physics and experimental physics at Cornell University. Over the years, he has worked on nuclear structure theories, cosmic rays research, high-energy experiments, and high-energy gamma-ray astrophysics. He joined the EGRET Group at Stanford University in 1983, and was mainly responsible for the NaI (Tl) calorimeter system, the Monte Carlo study of the EGRET detector, the development of the photon beam and a beam monitor at SLAC for EGRET calibration, the EGRET software package, and the analysis of EGRET flight data to produce scientific papers. He has also been involved with the GLAST experiment studies ever since the beginning of the GLAST concept. He has worked on the background radiation environment of the proposed GLAST orbit, the scientific capability of GLAST in observing normal and active galaxies, the property of CsI crystals which can be used for GLAST calorimeter, and the development of application software for the eventual analysis of GLAST flight data.

SELECTED RELEVANT PUBLICATIONS

Hughes, E.B. et al., "Properties of a Large NaI (Tl) Spectrometer for the Energy Measurement of High-Energy Gamma Rays on the Gamma Ray Observatory," IEEE Trans. Nucl. Sci. **33**, 728 (1986)

Lin, Y.C. et al.,"Plastic Scintillator Block as Photon Beam Monitor for EGRET Calibration," IEEE Trans. Nucl. Sci. **38**, 597 (1991)

Lin, Y.C. et al., "Detection of High-Energy Gamma-Ray Emission from the BL Lacertae Object Markarian 421 by the EGRET Telescope on the Compton Observatory," ApJ, **401**, L61 (1992)

Lin, Y.C. et al.,"EGRET Spectral Index and the Low-Energy Peak Position in the Spectral Energy Distribution of EGRET-Detected Blazars," ApJ, 1999 November 1 issue (1999)

MICHAEL N. LOVELLETTE

PRESENT POSITION:	Research Physicist
EDUCATION:	1989 Ph.D. - Physics, Northwestern University 1984 M.Sc. - Physics, Northwestern Univsity 1980 A. B. - Physics, Cornell University
AWARDS AND HONORS:	1989-1992, NRC/NAS Postdoctoral Fellowship, NRL
PROJECTS & RELEVANT EXPERIENCE:	Project Scientist, NRL-801 (Unconventional Stellar Aspect Experiment (USA)) Advanced Space Computing and Autonomy Testbed Space Microprocessor Government Caucus (BMDO) External Advisory Committee on Fault Tolerant Computing (BMDO)
PREVIOUS POSITIONS:	1989 – 1992 NRC/NAS Postdoctoral Fellowship

Dr. Lovellette has been at the Naval Research Laboratory since receiving his Ph.D. in physics from Northwestern University in 1989 and has been a research physicist on the staff in the X-Ray Astronomy Branch, Space Science Division (SSD) since 1992. From 1989 to 1992, he worked on the development of superconducting tunnel junctions for use as X-ray detectors. This project is developing detectors for astrophysical use which will have both high energy resolution and high quantum efficiency. In 1992, he joined the team building the NRL-801 (Unconventional Stellar Aspect , USA) experiment as the project scientist. He has overall responsibility for the design, construction, test, integration, and flight operations of the USA instrument. He is supervising the first direct comparison in flight of a similar radiation hardened, RH-3000, and commercial-off-the-shelf, IDT-3081, processors. This test, which is included as a hitchhiker payload on the USA experiment, will study various strategies for fault-tolerant computation in space.

SELECTED RELEVANT PUBLICATIONS

M. Lovellette et al, “Distributed Data Processing in the GLAST Instrument,” Proceedings of the Nuclear Science Symposium, Albuquerque, 1997

K. S. Wood et al, “The USA Experiment on the ARGOS Satellite: A Low Cost Instrument for Timing X-ray Binaries,” 1994, SPIE 2280, 19.

PETER F. MICHELSON

PRESENT POSITION:	Professor of Physics, Stanford University
EDUCATION:	1979 Ph.D. – Physics, Stanford University 1976 M.S. – Physics, Stanford University 1974 B.S. – Physics, Santa Clara University
PROJECTS & RELEVANT EXPERIENCE:	Co-Investigator, EGRET Instrument Team, Guest Investigator on numerous missions including Ginga, EXOSAT, RXTE, ASCA

Dr. Michelson is Professor of Physics at Stanford University. His current research interests are in the field of high energy astrophysics, particularly X-ray and gamma-ray observations and instrument development. He has also worked on the problem of detecting gravitational radiation from astrophysical sources. His doctoral dissertation, in low-temperature physics, was on high frequency properties of Josephson effect devices. In recent years he has been involved in the analysis and interpretation of observations with EXOSAT, HEAO A-1, *Ginga*., XTE and, most recently, ASCA. Dr. Michelson is also the lead Stanford co-investigator on the EGRET instrument, a high-energy gamma-ray telescope, now flying on the Compton Gamma Ray Observatory. Dr. Michelson is a member of the NASA Office of Space Science Structure and Evolution of the Universe Subcommittee (SEUS), serves on the Committee on Gravitational Physics of the National Research Council, and is currently a member of the High-Energy Astrophysics Panel of the NRC Decadal Astronomy Survey Committee. He was co-chair of the GLAST Facility Science Definition Team and led the team that did the initial study to define the GLAST mission.

RECENT RELEVANT PUBLICATIONS:

Michelson, P.F., “GLAST: A detector for high-energy gamma rays”, invited paper, Proc. SPIE, **2806**, 31 (1996).

Michelson, P.F. et al, “Cygnus X-3 and EGRET gamma ray observations”, ApJ., vol.**476**, no.2, pt.1, p. 842-6 (1997).

Michelson, P.F. et al, “EGRET observations of the diffuse gamma-ray emission from the Galactic plane”, ApJ., vol.**481**, no.1, pt.1, p. 205-40 (1997).

Michelson, P.F. et al, “On the correlation between radio and gamma ray luminosities of active galactic nuclei”, Astronomy and Astrophysics, vol.**320**, no.1, p. 33-40 (1997).

Michelson, P.F. et al, “Comparison of X-ray- and radio-selected BL Lacertae objects in high-energy gamma-ray observations”, Ap. J. Lett., vol.**476**, no.1, pt.2, p. L11-14 (1997).

Michelson, P.F. et al, “EGRET observations of high-energy gamma-ray emission from blazars: an update”, ApJ., vol. **490**, p. 116-135 (1997).

Michelson, P.F. et al, “EGRET observations of the extragalactic gamma-ray emission”, ApJ., vol **494**, p. 523-534 (1998).

Michelson, P.F. et al, “Phase-resolved Studies of the High-Energy Gamma-Ray Emission from the Crab, Geminga, and Vela Pulsars”, ApJ., **494**, p. 734-746 (1998)

Michelson, P.F. et al, “High-Energy Gamma-Ray Emission from the Galactic Center”, Astronomy and Astrophysics, accepted for publication, March 1998.

ALDO MORSELLI

PRESENT POSITION	Permanent Researcher of the INFN, the University of Roma
EDUCATION:	1987 - PhD, Physics, the University of Rome "La Sapienza"
PROJECTS & RELEVANT EXPERIENCE	GLAST instrument, 1994 GLAST Study Team, SLAC-R497 Proposal for GLAST SLAC-R522 Co-Investigator in all the balloon flight campaign of the WiZard collaboration: MASS, MASS91, TS93, CAPRICE, CAPRICE98 and in the satellite experiments NINA, PAMELA Italian-Chinese ARGO project Co-Investigator INTAS project oordinator Si-Eye experiment coordinator

SELECTED RELEVANT PUBLICATIONS

A. Morselli, M. Boezio, "A lead/scintillating fiber calorimeter for the measurement of gamma energy and direction," Frascati Physics Series Vol.VI,(pp.545-552) VI International Conference on Calorimetry in High-Energy Physics, Frascati 1996

G. Barbiellini, A. Morselli, et al.,"The GILDA Mission: A New Technique for a Gamma-ray Telescope in the Energy range 20 MeV - 100 GeV" Nuclear Instruments and Methods, A354, 547,(1995)

M. Candusso, A. Morselli et al. "Neural Networks with Stochastic Preprocessing for Particle Recognition in Cosmic Ray Experiments," Nuclear Instruments and Methods , A360, 371, 1995

G.Barbiellini, A.Morselli et al.,"A Wide aperture telescope for high energy gamma detection," Nuclear Physics B 43, (1995), 253.

A.Morselli, Contribution of the Wizard experiment to the detection of exotic processes, in ’The dark side of the Universe’, 267, Editors: R.Bernabei & C.Tao, World Scientific Co., 1994.

R.Borisyuk, A.Morselli et al. "Gamma-ray determination using neural network algorithms for an imaging silicon detector" Nuclear Instruments and Methods A381, 512, (1996)

R.Bellotti, A.Morselli et al. "Balloon measurements of cosmic rays muons spectra in the atmosphere along with those of primary protons and helium nuclei over mid-latitude" Phys. Rev. D, 60, 052002, 1999

K.Haohuai, A.Morselli, et al. "The Argo Full Coverage Detector, XXV International Cosmic Ray Conference," OG 10.4.16, Vol.5, p.265, Durban 1997

ALEXANDER MOISEEV

PRESENT POSITION: Research Scientist, LHEA, NASA/GSFC

EDUCATION: 1985 Ph.D - Physics, Moscow Engineering Physics Institute
1976 B.S. - Physics, Moscow Engineering Physics Institute

PROJECTS & RELEVANT
EXPERIENCE: GAMMA-1 Russian gamma ray telescope
PAMELA, Antimatter magnetic
BESS, Balloon-borne magnetic spectrometer
GLAST, Design of anticoincidence detector; beam tests

PREVIOUS POSITIONS: NRC Research Associate
Senior Researcher at the Moscow Engineering Physics Institute

Participated in the design of Russian gamma ray telescope GAMMA-1 (1976-1990), where was full time involved in the design and tests of the tracking detector of the instrument spark chambers. The subject of my PhD dissertation (1985) was the experimental study of the gamma-ray background produced in the coded aperture mask of GAMMA-1 for which a special small gamma-ray telescope was built and successfully operated onboard Salute-7 space station. Participated in the design, tests and operation of several Russian space borne astrophysics experiments.

SELECTED RECENT PUBLICATIONS:

James Wells, Alexander Moiseev and Jonathan Ormes, "Illuminating Dark Matter and Primordial Black Holes with Interstellar Antiprotons," ApJ, **518**, **570** (1999)

H.Matsunaga, S.Orito, H.Matsumoto, K.Yoshimura, A.Moiseev, et al, "Measurement of Low Energy Cosmic Ray Antiprotons at Solar Minimum," PRL, **81**, 19, 4052 (1998)

G.Barbiellini, M.Boezio, M.Canduzzo, M.Casolino, M.P.De Pascale, C.Fuglesang, A.Galper, A.Moiseev,et al, "A Fine-grained Silicon Detector for High-Energy Gamma-Ray Astrophysics," Il Nuovo Cimento, b, **5**, 775 (1997)

A.Moiseev, K.Yoshimura, I.Ueda et al., "Cosmic Ray Antiproton Flux in the energy range from 200 to 600 MeV," ApJ, **474**, 489 (1997).

J.Ormes, A.Moiseev, T.Saeki et al., Antihelium in the cosmic rays: a new upper limit and its significance," ApJ, **482**,L187 (1997)

PATRICK NOLAN

PRESENT POSITION:	Senior Research Scientist
EDUCATION:	1982 Ph.D. - Physics, University of California, San Diego 1974 B.S. - Physics, California Institute of Technology
AWARDS AND HONORS:	1992, NASA Group Achievement Award 1991, NASA Special Act Group Award
PROJECTS & RELEVANT EXPERIENCE:	Co-Investigator, EGRET SMM data analysis
PREVIOUS POSITIONS:	NRC Fellow at NRL 1982-84 Graduate Research Assistant at UCSD

My career has been devoted to gamma-ray astronomy. For the last 15 years I have been at Stanford. I worked on the assembly, testing, and calibration of the EGRET instrument. Then I developed data-analysis software for it and took the lead in some of the scientific analysis. I have been involved in GLAST from the beginning, providing technical support and contributing to the simulation effort. Before Stanford I spent a couple of years analyzing data from the SMM gamma-ray spectrometer, doing spectroscopy of gamma-ray bursts. In graduate school I participated in the construction and data analysis of the HEAO A-4 low-energy gamma-ray telescope, with a dissertation on rapid variability of emission from Cygnus X-1 and other black hole candidates.

SELECTED RELEVANT PUBLICATIONS

R. C. Hartman et al., “The Third EGRET Catalog of High-Energy Gamma-Ray Sources,” ApJS, **123**, 79 1999

J. A. Esposito et al., “In-Flight Calibration of the Energetic Gamma Ray Experiment Telescope (EGRET) on the Compton Gamma-Ray Observatory,” ApJS, **123**, 203 1999

P. L. Nolan et al., “EGRET Observations of Pulsars,” A&AS, **120**, C61 1996

J. R. Mattox et al., “The Likelihood Analysis of EGRET Data,” ApJ, **461**, 396 1996

P. L. Nolan et al., “EGRET Observations of Gamma Rays from Point Sources with Galactic Latitude $10^o < b < 40^o$,” ApJ, **459**, 100 1996

C. von Montigny et al., “High Energy Gamma Ray Emission from Active Galaxies: EGRET Observations and their Implications,” ApJ, **440**, 525 1995

P. L. Nolan et al., “Observations of High-Energy Gamma Rays from the QSO CTA 102,” ApJ, **414**, 82 1993

P. L. Nolan et al., “Observations of the Crab Pulsar and Nebula by the EGRET Telescope on the Compton Gamma Ray Observatory,” ApJ, **409**, 697 1993

D. J. Thompson et al., “Calibration of the Energetic Gamma Ray Experiment Telescope (EGRET) for the Compton Gamma Ray Observatory,” ApJS, **86**, 629 1993

E. B. Hughes et al., “Properties of a Large NaI (Tl) Spectrometer for the Energy Measurement of High-Energy Gamma Rays on the Gamma Ray Observatory,” IEEE Trans., **NS-33**, 728 1986

P. L. Nolan et al., “Spectral Feature of 31 December 1981 Gamma Ray Burst Not Confirmed,” Nature, **311**, 362 1984

JAY P. NORRIS

PRESENT POSITION:	Astrophysicist, GS-1330-15 NASA/GSFC, Laboratory for High Energy Astrophysics
EDUCATION:	1983 Ph.D. – Astronomy, University of Maryland 1979 M.S. – Astronomy, University of Maryland 1973 B.S. – Astronomy, University of Arizona
AWARDS:	1995, John C. Lindsay Memorial Award for Space Science 1992, Alan Berman Research Publications Award
PREVIOUS POSITIONS:	Astrophysicist, GM-1330-13, X-ray Astronomy Branch U.S. Naval Research Laboratory, Oct. 1987 – July 1990 Math Analyst, Bendix F.E.C., X-ray Astronomy Branch, U.S. Naval Research Laboratory, Oct. 1985 – Sept.1987 NRC Research Associate, X-ray Astronomy Branch, U.S. Naval Research Laboratory, Oct. 1983 – Oct. 1985

Dr. Norris is Deputy Project Scientist for the *Compton* Gamma Ray Observatory, responsible for: project finances, grants, data systems, and the Science Support Center. During the last 10 years, his primary research focus has been spectral and temporal analysis of cosmic gamma-ray bursts. During the last 4 years, he has contributed to the development of GLAST instrument and science simulations, and to the anticoincidence and calorimeter subsystem designs.

SELECTED RECENT ARTICLES

Norris, J.P., Marani, G.F., & Bonnell, J. T. “Connection between Energy-dependent Lags and Peak Luminosity in GRBs 1999," ApJ, submitted (astro-ph/9903233)

Bonnell, J.T., and Norris J.P.,"'No High Energy Emission’ GRB Class Is Attributable to Brightness Bias,” 1999, ApJ, submitted (astro-ph/9905319)

Norris, J.P., Bonnell, J.T., & Watanabe, K., “Constraints on Association of Single-Pulse GRBs and Supernova," ApJ, **518**, 901. 1999

Marani, G.F., Nemiroff, R.J., Norris, J.P., Kevin, H., Bonnell, J. T., “Gravitationally Lensed Gamma-Ray Bursts as Probes of Dark Matter Objects,” ApJ, **512**, L13, 1999

Bonnell, J.T., Norris, J.P., Nemiroff, R.J., Scargle, “Brightness-Independent Measurements of Gamma-Ray Burst Durations,” J.D., ApJ, 490, 79, 1997

Norris, J.P. et al. “Attributes of Pulses in Long Bright GRBs,” ApJ, **459**, 393, 1996

Norris, J.P. et al. “Detection of Signature Consistent with Cosmological Time Dilation in Cosmic GRBs," ApJ, **424**, 540, 1994

TAKASHI OHSUGI

PRESENT POSITION: Professor of physics, Hiroshima University

EDUCATION: 1972 Ph.D. - Physics, Hiroshima University
1967 B.S. - Physics, Hiroshima University

AWARDS AND HONORS: 1997, High Energy Accelerator Science Award (Foundation for High-Energy Accelerator Science, Japan) PROJECTS & CURRENT AND RELEVANT
EXPERIENCE: KEK, TRISTAN-VENUS experiment, subsystem manager of DAQ and trigger system
SSC-SDC silicon central tracking system, deputy manager
CDF silicon vertex detector up-grade, in charge of development and production of double-sided silicon sensors.

SELECTED RELEVANT PUBLICATIONS:

T. Ohsugi et al., "Radiation damage in silicon microstrip detectors," Nuclear Instruments and Methods in Physics Research, A**265** (1988) 105-111.
T. Ohsugi et al., "Micro-discharges of AC-coupling silicon strip sensors," Nuclear Instrument and Methods in Physics Research, A**342** (1994)22-26.
T. Ohsugi et al., "Micro-discharge noise and radiation damage of silicon microstrip sensors," Nuclear Instruments and Methods in Physics Research, A**383** (1996) 166 - 173.
T. Ohsugi et al., "Optimal design of radiation-hard, double-sided, double-metal, AC-coupled sensors," Nuclear Instruments and Methods in Physics Research, in press.

JONATHAN F. ORMES

PRESENT POSITON: Chief, Laboratory for High Energy Astrophysics, Code 660,
Goddard Space Flight Center, Greenbelt, Maryland 20771

EDUCATION: Ph.D - Physics, University of Minnesota, 1967
B.S. - Physics, Stanford University, 1961

AWARDS: Outstanding Performance Awards, ’83, ’89, ’94, ’95, ’96, ’98
NASA Exceptional Service Medal, 1986
Fellow of the American Physical Society, 1984

PROJECTS and RELEVANT
EXPERIENCE: Project scientist for Advanced Composition Explorer (ACE)
Study scientist for GLAST, ASTROMAG
Visiting Scientist, Stanford Linear Accelerator Center, 2-6/’97
Visiting Scientist, SACLAY, France, 6--9/’81
Acting Discipline Chief, High Energy Astrophysics NASA Headquarters, 10/'83--11/'84

SCIENTIFIC INTERESTS:

Dr. Ormes has concentrated on measurements of cosmic ray spectra at high energies, on isotopic composition measurements, and more recently on measurements of antiprotons and searches for anti-helium in the galactic cosmic rays. He was made a fellow of the American Physical Society for his work on cosmic ray spectra and was the first to report the excess of ^{22}Ne in galactic cosmic rays. He is currently US PI on BESS, conducting balloon-borne searches for anti-nuclei in cosmic rays and measuring antiprotons, and participates in ISOMAX investigation to measure the storage time of cosmic rays in the galaxy. He was the Project Scientist for the Advanced Composition Explorer (ACE), launched August 25, 1997. Recently he has turned his attention to the development of new missions such as GLAST to study high-energy emissions from astrophysical sources of energetic particles and improve on the pioneering studies made by the EGRET on the Compton Gamma-ray Observatory. He has been author and co-author of a number of experimental and theoretical papers about the origin and propagation of galactic cosmic rays, a scientific problem he believes will be solved by the next generation gamma-ray observatory.

SELECTED PUBLICATIONS OF INTEREST:

E.C. Stone et al, "The Advanced Composition Explorer,” Space Science Reviews, **86**, 1-22, '98

J. F. Ormes et al, "Antihelium in Cosmic Rays: A New Upper Limit and its Significance," Astrophysical Journal Letters, **482**, L187, '97

J.F. Ormes, “The NASA Program in Astroparticle Physics," Stockholm, Sweden, Nuc. Phys. B (Proc. Suppl.) **43**, **194**, '95

J.F. Ormes et al, "On the High Energy Gamma Ray Signature of Cosmic Ray Sources," Astrophysical Journal, **334, 722**,'88

JACQUES PAUL

PRESENT POSITION: Head of the Space Gamma-Ray Astronomy Group of the CEA Astrophysics Department
EDUCATION: 1979 Ph.D. - Physics, Paris VII University
1968 DEA - Astrophysics, Paris VII University
AWARDS AND HONORS: 1994, French Atomic Commission Scientific Prize
1980, CNES Bronze Medal
PROJECTS & RELEVANT EXPERIENCE: 1970-1981Co-I of the COS-B satellite
1982-1998French Project Scientist of the GRANAT satellite
1982-1998Co-PI of the SIGMA telescope aboard GRANAT
Since 1994INTEGRAL Mission Scientist

PREVIOUS POSITIONS: Research fellow at the Centre d'Etudes de Saclay
Tenure-track position at CEA (the French Atomic Commission)
Head of the Space Group of the CEA Astrophysics Department

Research in astrophysics concerning the relationship between gas, magnetic fields and cosmic rays in the Galaxy and the spiral structure of the Galactic Disk; the gamma-ray production by the inverse Compton and the Bremsstrahlung processes in the interstellar medium; the structure of the local interstellar medium as traced by gamma rays; the contribution of the spiral and Seyfert galaxies to the gamma-ray background; the cosmic-ray acceleration by stellar winds; the violent interstellar medium associated with the Carina Nebula; the stellar origin of the ^{22}Ne excess in cosmic rays; the identification of the high-energy gamma-ray source Geminga; the nature of the hard source identified by SIGMA in the vicinity of the Galactic Center.

SELECTED RELEVANT PUBLICATIONS

J. Paul, “Gamma-Ray Astronomy,” McGraw-Hill Encyclopedia of Astronomy (New-York: McGraw-Hill), 1999

N. Gehrels, J. Paul, “The New Gamma-Ray Astronomy” Physics Today, **51**, 26, 1998

J. Paul, P. Laurent “Astronomie gamma spatiale,” (Amsterdam: Gordon and Breach Science Publishers), 1998

STEVEN M. RITZ

PRESENT POSITION:	Astrophysicist, NASA Goddard Space Flight Center
EDUCATION:	1988 Ph.D. - Physics, University of Wisconsin-Madison 1981 B.A. - Physics and Music, Wesleyan University (CT)
AWARDS AND HONORS:	1993-97 Alfred P. Sloan Foundation Fellow in Physics 1981 Bertman Prize in Physics, Wesleyan University
PREVIOUS POSITIONS:	1996-98 Associate Professor of Physics, Columbia University 1990-96 Assistant Professor of Physics, Columbia University 1988-90 Post Doctoral Research Scientist, Columbia University

Steven Ritz has extensive experience as an experimental high-energy particle physicist, both in data analysis and the design and fabrication of advanced detectors. As a graduate student on the TASSO experiment at DESY and the ALEPH experiment at CERN, he developed a new kinematic analysis of electron-positron annihilation processes enabling sensitive searches for new massive states that decay predominantly into quarks. During his time at CERN, he collaborated on a number of theoretical papers concerning realistic estimates of particle fluxes from dark matter annihilations in the sun and galactic halo. His interest in the connection between particle physics and high energy astrophysics began then. At Columbia, he played several major roles in the ZEUS experiment at the HERA electron-proton collider. He was responsible for the design, development, production and installation of major elements of the calorimeter readout. The system successfully employs analog pipelines and over 600 embedded digital signal processors (DSPs) working in parallel. Ritz also designed and wrote all the machine code that runs in the DSPs for physics data taking, testing, and calibration. He played central roles in several upgrades to the ZEUS detector, including a scintillator-based tracking detector and a successful proposal for a new silicon strip vertex detector. In addition to measurements exploring a new regime of Quantum Chromodynamics, he did the first ZEUS search for leptoquarks that decay to a neutrino and a quark, which included the isolation of the first charged current deep inelastic scattering events observed at HERA. Ritz is an author of over 130 publications. He has organized sessions and given talks at many international conferences and workshops, and has served on diverse scientific and technical review panels including the GLAST Facility Science Team and, currently, SAGENAP (Scientific Assessment Group for Experiments in Non-Accelerator Physics) for the DoE and NSF. He also has a strong interest in communicating science to the general public: he wrote an article about HERA in the AIP Year in Physics, 1995, and taught “Physics for Poets” for three years at Columbia.

SELECTED RELEVANT PUBLICATIONS

W.Atwood, S.Ritz et al., “Beam Test of Gamma-Ray Large Area Space Telescope Components”, accepted for publication, Nuclear Instruments and Methods A(1999).
A.Caldwell et al., “Design and Implementation of a High Precision Readout System for the ZEUS Calorimeter”, Nuclear Instruments and Methods A321(1992)356.
S.Ritz and D.Seckel, “Detailed Neutrino Spectra from Cold Dark Matter Annihilations in the Sun”, Nuclear Physics B304(1988)877.
J.Ellis, R.A.Flores, K.Freese, S.Ritz, D.Seckel, J.Silk,”Cosmic Ray Constraints on the Annihilations of Relic Particle in the Galactic Halo”, Physics Letters B214(1988)403.

JAMES J. RUSSELL

PRESENT POSITION:	Physicist
EDUCATION:	1980 Ph.D. - Physics, University of Illinois 1972 B.S. - Physics, Ohio State University
PROJECTS & RELEVANT EXPERIENCE:	MARK III. 1980-1982, DAQ and Track Reconstruction SLD 1986-1998, DAQ
PREVIOUS POSITIONS:	Post Doc, California Institute of Technology Staff Physicist, SLAC

I have been involved in various aspects of the data acquisitions through 3 experiments. On SLD I was the lead physicist for the DAQ. This system involved 400 CPUs working in a tightly coupled system. My knowledge spans from front-end systems through systems integration issues to designing processing algorithms used for feature extraction and triggering.

SELECTED RELEVANT PUBLICATIONS

J.J. Russell, R. Claus et al, “Development of A Data Acquisition System for the BaBar CP Violation Experiment,” 11th IEEE NPSS Real Time Conference (Santa Fe 99), Santa Fe, NM, 14-18 Jun 1999.

J.J. Russell, P. Raimondi et al. “Recent Luminosity Improvements at the SLC,” 6th European Particle Accelerator Conference (EPAC 98), Stockholm, Sweden, 22-26 Jun 1998.

J.J. Russell, K. Abe et al., "Design and Performance of the SLD Vertex Detector, A 307 Mpixel Tracking System,” Nucl.Instrum.Meth.A**400**:287-343,1997

J.J. Russell, S. MacKenzie et al., “The Digital Correction Unit: A Data Correction / Compactification Chip”, IEEE TRANS NS-**34**, 250, 1987

HARTMUT F.-W. SADROZINSKI

PRESENT POSITION:	Research Physicist, Univ. of California, Santa Cruz
EDUCATION:	1972 Ph.D. - Physics, Massachusetts Institute of Technology 1968 M.S. Diploma - Physics, University of Hamburg
PROJECTS & RELEVANT EXPERIENCE:	Leading Proton Spectrometer in the ZEUS detector at HERA: Development of a radiation hard silicon strip detector system. SDC detector at the Superconducting Super Collider: Development of radiation hard silicon strip system. ATLAS detector at the Large Hadron Collider at CERN: Development of radiation hard silicon strip system. BaBar detector at the PEP2 B-Factory at SLAC: Development of the SVT silicon detector system Development of the Central Tracking Chamber readout ASIC. Member, Program Committee, IEEE Nucl. Sci. Symposium Reviewer, NSF Small Business Innovation Research Program Contributor, Review of Particle Physics Data

H. Sadronzinski has developed silicon-strip systems for the past 10 years. His constribution has been mainly in radiation hardness and low-power ASIC's. In GLAST, he will work on the specification, procurement, and testing of the silicon detectors, and radiation effects in detectors and ASIC's.

SELECTED RELEVANT PUBLICATIONS

H. F.-W. Sadrozinski, A. Seiden, and A. Weinstein, "Tracking at the SSC/LHC," Nuclear Instruments and Methods **A 279**, 223, 1988
H. F.-W. Sadrozinski, E. Barberis et al., "Design, Testing and Performance of the Frontend Electronics for the LPS Silicon Microstrip Detectors," Nuclear Instruments and Methods **A 364**, 507, 1995
H. F.-W. Sadrozinski, T. Dubbs et al., "Efficiency and Noise Measurements of Non-Uniformly Irradiated Double-sided Silicon Detectors," Nuclear Instruments and Methods **A 383**, 174 1996
H. F.-W. Sadrozinski, "Silicon Microstrip Detectors in High Luminosity Application", IEEE Trans Nucl. Sci. **45**, 295, 1998
H. F.-W. Sadrozinski, R. P. Johnson et al, "An Amplifier-Discriminator Chip for the GLAST Silicon-Strip Tracker," IEEE Trans Nucl. Sci. **45**, 927, 1998

ROLAND SVENSSON

PRESENT POSITION:	Prof. of Astroph., Stockholm Observatory, Sweden since 1990
EDUCATION:	1981 PhD - Astronomy and Astrophysics, UC Santa Cruz 1973 B.S - Physics, University of Lund, Sweden 1973
PROJECTS & RELEVANT EXPERIENCE:	Expert on radiation processes in high energy astrophysics with a number of written reviews, and several papers on their applications to active galactic nuclei. Several refereed papers and one edited conference volume on the prompt emission from gamma-ray bursts. Head of the High Energy Astrophysics Group.
PREVIOUS POSITIONS:	Ass professor, Nordita, Copenhagen, Denmark, 85-90 Postdoc: Nordita, Copenhagen, Denmark, 83-90 ESO, Garching, Germany, 81-83

The High Energy Astrophysics Group at Stockholm Observatory contributes soft-ware and theory support for the X-ray monitor, JEM-X, onboard INTEGRAL. The group participates in the proposal for the mainly Danish micro-satellite, mu-BALLERINA, aimed at studying early X-ray afterglows and determining accurate positions for a large number of gamma-ray bursts. Mainly theory support. The group has analyzed the full 32 GB of CGRO BATSE continous records to search for untriggered gamma-ray bursts thus about doubling the number of bursts useful for statistical studies. A public archive containing the about 1400 new bursts has been created. The average temporal properties of bursts, both in the time-domain and in Fourier space have been analyzed in a number of papers. The spectral evolution of burst pulses has also been studied.

SELECTED RELEVANT PUBLICATIONS

R. Svensson et al, "Gamma Ray Bursts: The First Three Minutes," Proceedings of an International Workshop in Sweden, Feb 1999, ASP Conference Series, vol 190, in press, 1999
R. Svensson, "An Introduction to Relativistic Plasmas in Astrophysics," in Physical Processes in Hot Cosmic Plasmas, (Kluwer), p. 357-381, 1990
A. Zdziarski, R. Svensson, B. Paczynski, "Bursts of Gamma Rays from Compton Scattering at Cosmological Distances," ApJ, 366, 343, 1991
B. E. Stern, R. Svensson, "Evidence for 'Chain Reaction' in the Time Profiles of Gamma Ray Bursts," ApJLett, 469, L109, 1996
R. Svensson, "X-Rays and Gamma Rays from Active Galactic Nuclei", in Relativistic Astrophysics: A Conference in Honour of Professor I. D. Novikov's 60th Birthday, (Cambridge Universisty Press), p. 235-249, 1997
B. E. Stern, J. Poutanen, R. Svensson, "Brightness Dependent Properties of Gamma-Ray Bursts," ApJLett, 489, L41, 1997
A.M. Beloborodov, B. E. Stern, R. Svensson, "Self-similar Temporal Behavior of Gamma-Ray Bursts," ApJLett, 508, L25, 1999

DAVID J. THOMPSON

PRESENT POSITION:Astrophysicist, Laboratory for High Energy Astrophysics
NASA Goddard Space Flight Center, Greenbelt, Maryland

EDUCATION: 1967 B.A. - Physics, Johns Hopkins University
1973 Ph.D. - Physics, University of Maryland, 1973

AWARDS:1992, NASA Group Achievement Award, Energetic Gamma Ray Experiment Telescope (EGRET) Instrument Team

PROJECTS & RELEVANT
EXPERIENCE:Balloon-borne gamma-ray telescopes -- Gamma rays in the Earth's upper atmosphere; Engineering for EGRET prototype.
SAS-2 gamma-ray telescope -- Cosmic sources of high-energy gamma rays, especially diffuse Galactic radiation and gamma-ray pulsars.
EGRET on Compton Gamma Ray Observatory - Calibration; gas refill system, thermal; Pulsars, blazars, gamma-ray bursts, diffuse radiation, and unidentified sources.
GLAST - Anticoincidence Detector; Pulsars, unidentified sources multiwavelength coordination

SELECTED RECENT PUBLICATIONS:

Thompson, D.J. el al.,"Gamma Radiation from PSR B1055-52" May, 1999, ApJ, **516**, 297-306

Zioutas, K., Thompson, D.J., and Paschos, E.A. "Search for Energetic Cosmic Axions Utilizing Terrestrial/Celestial Magnetic Fields," 1998 Dec. 10, Phys. Lett. B, **443**, 201-208

Ramanamurthy, P.V. and Thompson, D.J., "Search for Short-Term Variations in the E>50 MeV Gamma-Ray Emission of the Crab Pulsar," 1998 Apr. 1, ApJ, **496**, 863-868

Fierro, J.M., Michelson, P.F., Nolan, P.L. and Thompson, D.J.,"Phase-Resolved Studies of the High-Energy Gamma-Ray Emission from the Crab, Geminga and Vela Pulsars," 1998 Feb. 20, ApJ, **494**, 734-746

Thompson, D.J., Bertsch, D.L., Morris, D.J., Mukherjee, R., "Energetic Gamma Ray Experiment Telescope High-Energy Gamma Ray Observations of the Moon and Quiet Sun," 1997 Jul. 1, JGR, **102**, 14735-14740

TIM THURSTON

PRESENT POSITION:	Chief Engineer
EDUCATION:	1974 B. S. Mechanical Engineering, Brigham Young University
AWARDS AND HONORS:	1997, NASA Team Achievement Award
	1998, NASA/KSC-State of Florida, Technology Outreach Award
PROJECTS & RELEVANT EXPERIENCE:	Management Systems Re-engineering, KSC BOC 1994-1998
	Solenoidal Detector Collaboration/SSC Project 1990-1994
	Diagnostic Event Management, Nuclear test program,1980-1989
	Control Systems R&D, Aircraft/Missile systems, 1973-1980
PREVIOUS POSITIONS:	Launch Support Systems Consultant, Merritt Island, FL
	Sr. Manager of Engineering, EG&G, Kennedy Space Center, FL
	Deputy Project Manager / Chief Engineer, EG&G, SSC Laboratory, Waxahachie, TX
	Group Leader/Structural Annalist, EG&G, Lawrence Livermore National Laboratory Support
	Senior Development Engineer, AiResearch Manufacturing Co. Phoenix, AZ

As senior manager of engineering, I re-engineered the project management system for the base operations contractor. Administrative, reporting, estimating, and tracking systems were modified and an added level of discipline was maintained. Standard planning, commitment and reserve procedures were modified to allow multi-year budgets and projections to interact. This new feed-forward project control scheme allowed leveling of expenditures and labor resources across the widely fluctuating annual funding. Project cost and schedules variances reduced from over 30 % to less the 5% in a program that complete over 100 projects per year. Engineering resources were stabilized, staffing was to be managed through attrition and controlled hiring, and engineering support of launch operations was sustainable without interruption.

As deputy project manager and chief engineer of the Solenoidal Detector Collaboration Project the major emphasis was on the integration and management of a widely distributed, international workforce. Rigorous system engineering, quality, safety, and project control procedures were specifically designed and fully implemented to design and construct the $600M physics detector. Two years in, the project was on track to ensure the delivery of a detector that fully met the cost, schedule and performance objectives of the physics community and the funding agencies.

As a launch systems consultant and diagnostic systems engineer, I was intimately involved in satisfying the critical requirements of nuclear and launch based systems. This included the design of cryogenics, structural, diagnostic and safety systems for both nuclear testing and launch support systems. I also produced quality control and verifications procedures for the checkout and launch control system, cryogenics systems and life support systems at the Kodiak Island launch center.

LAURA A. WHITLOCK

PRESENT POSITION:	Administrator I, Sonoma State University
EDUCATION:	1989 Ph.D. - Physics, University of Florida 1981 B.S. - Physics, Southwestern at Memphis
AWARDS AND HONORS:	USRA Community Service and Education Outreach Award NASA/GSFC Group Achievement Award (HEASARC) Global Information Infrastructure (GII) Award Semi-Finalist for Education and for Children, StarChild Webby Award for Best Education Web Site, StarChild NASA/GSFC Group Achievement Award (Swift Proposal) Webby Award Judge for Education
PROJECTS & RELEVANT EXPERIENCE:	Education and Public Outreach Co-I for these current projects: NASA LEARNERS Cooperative Agreement
PREVIOUS POSITIONS:	Education/Outreach Projects Coordinator, GSFC Data Archive Scientist at NASA/GSFC Research Scientist, Nichols Corporation

As Education/Outreach Projects Coordinator for NASA/Goddard’s Laboratory for High Energy Astrophysics, I created, developed, and promoted multi-media education and outreach materials, emphasizing the effective use of the World Wide Web to leverage our efforts. This activity focused on the field of high-energy astrophysics, notably on neutron stars, pulsars, black holes, quasars, and other eruptive galaxies. In addition to overseeing, assisting, and coordinating the E/PO efforts of the many missions in the Laboratory, I was the creator, designer, and project leader for the award-winning Imagine the Universe! and StarChild World Wide Web sites (`http://imagine.gsfc.nasa.gov/` and `http://starchild.gsfc.nasa.gov/`). I also wrote and published teacher's guides and educational posters on astronomy and space exploration, and produced CD-ROMs that were used to distribute NASA space science education material. In addition, I organized and presented workshops about high-energy astronomy (X-ray, gamma-ray, and cosmic rays) for educators at local, state, and national education meetings, National Teacher Training Institute workshops, and scientist training workshops.

SELECTED RELEVANT PUBLICATIONS

NSTA National Convention, Boston, Mar 1999, "A Universe of NASA Data: Beyond the Visible"

NSTA National Convention, Boston, Mar 1999, "StarChild: Classroom Applications of a Web Site for Young Astronomers"

NCTM National Convention, San Francisco, Apr 1999, "A Universe of NASA Data: Get the Picture Using Matrices in Your Algebra Classroom!"

SCOTT WILLIAMS

PRESENT POSITION:	Research Manager, W.W. Hansen Experimental Physics Lab
EDUCATION:	1999 Ph.D. - Aeronautics & Astronautics, Stanford 1984 S.M. - Ocean Engineering, MIT
PROJECTS & RELEVANT EXPERIENCE:	Solar Oscillations Investigation (SOI) Shuttle Electrodynamic Tether System (SETS)
PREVIOUS POSITIONS:	Co-Investigator and Program Manager, SETS; Research Engineer, SOI; Research Engineer, LMSC

Scott Williams has 15 years of experience in program management and project engineering for space science instrumentation and mission operations development. . He spent four years with Lockheed Missiles \& Space Co. as an attitude control systems engineer. In 1986, he began research on SETS as part of graduate work at Stanford University. In 1988 he was named Project Engineer for SETS where he directed technical development of the flight hardware. As Deputy Program Manager in 1990 and Program Manager in 1991, he managed the integration, flight qualification, environmental test, and delivery of SETS to KSC for integration into the Tethered Satellite System (TSS-1) mission onboard the Space Shuttle Atlantis (STS-46). In 1992, he supported the TSS-1 flight as lead SETS Replanner and backup Operations Director at JSC. Following the TSS-1 flight, Scott split his time between data analysis and hardware refurbishment as a SETS Co-investigator and Program Manager, and the SOI program. For SOI he developed functional test procedures and software for I &T of the Michelson Doppler Imager (MDI). He developed the mission operations plan and managed the ground system compatibility tests while supporting integration of MDI into the Solar and Heliospheric Observer (SOHO) satellite. He was onsite SOI manager for the first two weeks of MDI on-orbit functional testing following SOHO’s December 1995 launch. In February 1996 he served as SETS Operations Director at MSFC for the TSS-1R mission on the Space Shuttle Columbia (STS-75). Since October 1997, Scott has supported systems engineering and mission concept development for the Gamma-ray Large Area Space Telescope (GLAST) and is presently a Co-Investigator and Program Manager for the GLAST Instrument Technology Development program at Stanford. Scott completed his Ph.D. in Aeronautics and Astronautics at Stanford in August 1999.

SELECTED PUBLICATIONS

A.G. Kosovichev et al., "Structure and Rotation of the Solar Interior: Initial Results from the MDI Medium-L Program,"Solar Physics, **170**, 43, Kluwer, 1997.
D.C Thompson,.S.D. Williams et al, "The Current Voltage Characteristics of a Large Probe in Low Earth Orbit: TSS-1R Results," Geophys. Res. Letters, **25**, 413, 1998.
S. Williams et al, "TSS-1R Vertical Electric Fields: Long Baseline Measurements using an Electrodynamic Tether as a Double Probe," Geophys. Res. Letters, **25**, 445, 1998.
S.D. Williams et al, "Current Collection at the Shuttle Orbiter During the Tethered Satellite System Tether Break," J. Geophys. Res., **104**, 105, 1999.

P. ROGER WILLIAMSON

PRESENT POSITION:	Senior Research Scientist
EDUCATION:	1972 Ph.D. - Physics, University of Denver 1966 M.S. - Physics, University of Denver 1964 B.S. - Physics, Stanford University
AWARDS AND HONORS:	NASA Public Service Group Achievement Award, Spacelab 2 Payload Principal Investigator Team, 1986. NASA Group Achievement Award, JPL/Stanford University Lambda Point Experiment Team, 1993 NASA Group Achievement Award, Confined Helium Experiment Team, 1998

PROJECTS & RELEVANT EXPERIENCE:

Dr. Williamson has 30 years of experience in space flight related work including: NASA advisory and management committees and proposal review panels; flight projects have included Co-investigator, Shuttle Electrodynamics Tether System (1984-1992); Co-investigator, Vehicle Charging and Potential Experiment, Spacelab 2, 1985; Spacelab End to End Data Systems Working Group, NASA, 1984; POCC Operations Manager, SEPAC Experiment, Spacelab 1, 1983; Spacelab Mission Implementation Cost Assessment (SMICA) Experiments Development Working Group, NASA, 1983; Co-investigator, Vehicle Charging and Potential Experiment, STS-3, 1982. In 1980--1981, he was a program scientist at NASA Headquarters supporting the Space Physics branch and had responsibilities in the ISTP and sounding rocket programs. For the last several years, Dr. Williamson has been manager of electronics, computer, and software for the successful Confined Helium Experiment (CHeX), which was launched in November, 1997. He has recently managed the development of the Station Processor and Electronics Controller (SPEC) prototyping project in support of the JPL Low Temperature Facility. Dr. Williamson is an author or coauthor of more than 80 scientific publications and holds one electronics patent.

SELECTED RELEVANT PUBLICATIONS

"Specific energy loss rate measurements in low earth orbit", P.R. Williamson, J.A. Nissen, D.R. Swanson, and J.A. Lipa, 24th International Cosmic Ray Conference, Rome, Vol 4, pp. 1287-1290, August 28 - September 8, 1995, IUPAP.

"Station Processor and Electronics Control (SPEC): New techniques for realtime data acquisition and control of experiments on the external facility of the Japanese Experiment Module", P. Roger Williamson, Robert W. Bumala and John A. Lipa, Proceedings of the 21st International Symposium on Space Technology and Science, May 24-31, 1998, Omiya, Japan (to be published)

KENT S. WOOD

PRESENT POSITION:	Head, X-Ray Astrophysics and Applications Section, NRL
EDUCATION:	1973 Ph.D. - Physics, Massachusstts Institute of Technology 1967 B.S. - Physics, Stanford University
AWARDS AND HONORS:	Phi Beta Kappa, Stanford University, 1966 NAS/NRC Postdoctoral Fellowship (1973 - 1974) NASA Group Achievement Award (1978) NRL Publication Awards (1979, '84, '88, '89,'92)
PROJECTS &RELEVANT EXPERIENCE:	HEAO A-1 Large Area Sky Survey USA (NRL-801) Experiment on ARGOS ASCAT Space Computing Testbed on ARGOS B.M.D.O. Program in Fault Tolerant Computing
PREVIOUS POSITIONS:	Astrophysicist, Space Science Division, NRL NAS/NRC Postdoctoral Fellow (NRL)

Dr. Wood's principal research interests are compact object astrophysics, and instrumentation for X-ray and gamma-ray astronomy, including utilization of computing in space for astronomical purposes. He has been on the GLAST team since 1992 and is the overall lead for the NRL activities on the GLAST program and is on the GLAST Instrument Development Steering Committee. He has been at NRL since 1973. During the lifetime of HEAO-1 he took charge of HEAO A-1 scientific data reduction and analysis. This effort resulted in publication of results on nearly 900 X-ray sources and transients. Currently he is the Head of the X-ray Astrophysics and Applications Section, Space Science Division, in which position he directly oversees NRL's activities in X-ray astronomy, including development of flight instruments, data analysis and theoretical modeling. Dr. Wood is Principal Investigator for the Unconventional Stellar Aspect (USA) Experiment on the ARGOS satellite, an X-ray timing instrument launched in 1999. It includes as a subsystem the first Defense Department testbed for space computing, sponsored by the Navy and the Ballistic Missile Defense Organization. This testbed comprises radiation-hard and commercial MIPS-3000 class microprocessors plus other components that can be used for experiments in reliable computing in space.

SELECTED RECENT PUBLICATIONS

M.N. Lovellette, Wood, K.S., Williamson, R., Michelson, P.F., "Distributed Data Processing in the GLAST Instrument," Proceedings of the Nuclear Science Symposium, Albuquerque, 1997.
K.S. Wood et al., "The USA Experiment on the ARGOS Satellite: A Low Cost Instrument for Timing X-ray Binaries," 1994, Proceedings of S.P.I.E., 2280, 19.
Wood, K.S. et al., "Searches for Millisecond Pulsations," 1990, Ap. J. 1991, 379, 295.
J.P Norris, P. Hertz, K.S.Wood et al, "On Soft Gamma Repeaters," 1990, Ap. J. 366, 240.
Wood , K.S. and Feldman, U. "Fourier Transform Microscope," Pat.ent No. 5,432,439 issued July 11, 1995.

Appendix B

Letters of Endorsement from Participating Organizations

Appendix C

Draft International Agreements

Appendix D

References

Announcement of Opportunity, Gamma-Ray Large Area Space Telescope (GLAST) Flight Investigations, A0 99-0SS-03, NASA, Washington DC, Aug. 1999.

Cockrell, C.E., Lessons Learned from Better, Faster, Cheaper Concepts as Applied to Selected NASA Programs

Eastern and Western Range Safety Requirements, EWR 127-1, USAF, Canaveral, Florida, Oct. 1997.

GLAST Instrument Technology Development: Integrated Instrument Development and Demonstration, NASA Contract NAS5-98039.

GLAST Instrument Technology Development: Integrated Instrument Development and Demonstration, NASA Contract NAS5-98039.

GLAST Integrated Instrument Technology Development and Demonstration Design Concept Report, Basic Period Deliverable 4, NAS5-98039, February 1999.

GLAST Science Requirements Document (SRD), http://glast.gsfc.nasa.gov/SRD

GLAST SI-SC Interface Requirements Document (IRD), http://glast.gsfc.nasa.gov/ao/

Guide for Estimating and Budgeting Weight and Power Contingencies for Spacecraft Systems, ANSI/AIAA, G-020-1992, Apr. 1992.

Mankins, J.C., Technology Readiness Levels, April 1998

NASA Parts Policy, NPD 8730.2, NASA, Washington DC, June 1998.

NASA Program and Project Management Processes and Requirements, NPG 7120.5A, NASA, Washington DC, Apr. 1998.

NASA Quality Management System Policy (ISO 9000), NPD 8730.3, NASA, Washington DC, June 1998.

NASA Software Documentation Standard, NASA-STD-2100-91, NASA, Washington DC, July 1991.

NASA Software Management, Assurance, and Engineering Policy, NMI 2410.10B, NASA, Washington DC, Apr. 1993.

NASA Systems Engineering Handbook, SP-6105, NASA, Washington DC, June 1995.

Office of Equal Opportunity Programs Minority University Research and Education Division (MURED) Home Page, http://mured.alliedtech.com/index.asp

Ponslet, E., S. Ney, and W.O. Miller, “Innovative, Low-Mass, Passively Cooled, All Composite Material Tower Structure for High Resolution Charged Particle Tracking in a Gamma-ray Space Telescope,” NASA SBIR 97-1 17.01-5179, Phase I Final Report, Hytec Inc., Los Alamos, NM, Oct. 1998.

Procedures for Contractor Reporting of Correlated Cost, NPG 9501.2C, NASA, Washington DC, Jan. 1999.

Proposal for GLAST, SLAC-R-522, submitted to the Dept. of Energy, February 1998

Quality Systems - Model for Quality Assurance in Design, Development, Production, Installation, and Servicing, ISO 9001, ANSI/ASQC Q9001, 1994.

Stanford University’s Office of Technology Licensing (OTL) Home Page, http://www.stanford.edu/group/OTL/index.html

The Space Science Enterprise Integrated Technology Strategy, NP-1998-10-243-HQ, NASA, Washington DC, Oct. 1998.

Equal Opportunity - FAR 52.227-11 As Modified NFS 18-52.227-11

S/SDB - FAR 52.219-8; FAR 52.226-2

Subcontracting FAR 52.219-9

OSS - Strategies and Policies

Space Science Enterprise Strategic Plan (Nov 1997)

The Evolving Universe’s Structure and Evolution of the Universe Roadmap 2000-2020 (April 1997)

Partners in Education (March 1995)

Implementing OSS-E/POS (Oct 1996)

OSS-Integrated Technology Strategy (April 1994)

Space Science Supporting Documents
NAS/NRC Report: A new science strategy for space astronomy and astrophysics (1997)

GLAST - Instrument Technology Development Program - NRA 98-217-02 NASA/OSS January 16, 1998
ISO 9000 Series
ANSI/ASQC Q9001-1994
ANSI/ASQC Q9004-1994
ANSI/ASQC Q9000-1-1994
ISO 9000 and NASA Code Q Presentation, April 14, 1995

Procurement-Related Information
Federal Acquisition Regulations (FAR)
NASA FAR - Supplemental Regulations
NASA Financial Management Manual
NPG 5800.1 D Grant and Cooperative Agreement Handbook (July 1996)

Reliability and Quality Assurance Materials and EEE Parts
Office of Flight Assurance, GSFC. URL: http://arioch.gsfc.nasa.gov/
NASA Standards Documents can be found on the Internet at http://standards.nasa.gov/
NASA Technical Standard NASA-STD-8739.3, Soldered Electrical Connections
NASA Technical Standard NASA-STD-8739.4, Crimping, Interconnecting Cables, Harnesses, and Wiring
NAS 5300.4(3J-1), Workmanship Standard for Staking and Conformal Coating of Printed Wiring Assemblies
NASA Technical Standard NASA-STD-8739.7, Electrostatic Discharge Control (Excluding Electrically Initiated Explosive Devices)
NHS 5300.4 (3M), Workmanship Standard for Surface Mount Technology
ANSI/IPC-D-275, Design Standard for Rigid Printed Boards and Rigid Printed Board Assemblies, Class 3
IPC 6011 and IPC 6012, Class 3 as the basic specification requirements with GSFC S-312-P-003B, Procurement Specification for a Rigid Printed Wiring Boards for Space Applications and other High Reliability Uses as a supplement
NASA Technical Standard NASA-STD-8739.5, Fiber Optic Terminations, Cable Assemblies, and installation.
Safety http://arioch.gsfc.nasa.gov/302/Systy.html

Appendix E

Acronyms

ACD	Anticoincidence Detector
ACE	Advanced Composition Explorer
ACS	Attitude Control System
ACT	Atmospheric Cherenkov Telescope
ADC	Analog to Digital Converter
Aeff	Effective Area
AGN	Active Galactic Nuclei
AIP	American Institute of Physics
AMANDA	Antarctic Muon and Neutrino Detector Array
AMI	American Microsystems Inc.
AMOS	Air Force Maui Optical Site
AMS	Alpha Magnetic Spectrometer
ANSI	American National Standards Institute
AO	Announcement of Opportunity
APS	American Physical Society
ARGOS	Advanced Research and Global Observations Satellite
ASI	Italian Space Agency
ASIC	Application Specific Integrated Circuit
ATD	Advanced Technology Development Program (NASA)
ATIC	Advanced Thin Ionization Calorimeter
ATLAS	Atmospheric Laboratory for Application and Science Also: A Toriodal Large Acceptance Spectrometer

BDC	Backgrounds Data Center
BSP	Board Support Package
BTEM	Beam Test Engineering Model

C&DH	Command and Data Handling Subsystem
C.R.	Cosmic Ray
CAL	Imaging Calorimeter
CANGAROO	Collaboration between Australia and Nippon for a Gamma-Ray Observatory in the Outback
CAPRICE	Cosmic Antiparticle Ring-Imaging Cherenkov Experiment
CAT	Cherenkov Array at Themis
C-C	Carbon Composite
CCB	Change Control Board
CCHP	Constant Conductance Heat Pipes
CCSDS	Consultative Committee for Space Data Systems
CDF	Collider Detector at Fermilab
CDR	Critical Design Review
CEA	Commissariat à l'Energie Atomique
CENBG	Centre d'études Nucléaires de Bordeaux Gradignan
CERN	Centre Europeen pour la Recherche Nucleaire
CFC	Carbon-Fiber Composite
CGRO	Compton Gamma Ray Observatory
CheX	Confined Helium Experiment
CLUL	Confidence Level Upper Limit
CM	Configuration Management Also: Center of Mass

CMOS	Complementary Metal Oxide Semiconductor
CNO	Carbon-Nitrogen-Oxygen
CNRS	Centre National de la Recherche Scientifique
COTs	Commercial Off the Shelf
CPU	Central Processing Unit
CsI(Tl)	Cesium Iodide crystal doped with Thallium
CSSR	Cost/Schedule Status Reports
CTE	Coefficient of Thermal Expansion
DAC	Digital to Analog Converter
DAPNIA	Département d'Astrophysique, de physique des Particules, de physique Nucleaire et de L'Instrumentation Associée
DAQ	Data Acquisition System
DESY	Deutsches Electron-Synchrotron
DMILL	Durci Mixte Isolant Logico Linéaire
DOE	Department of Energy
DOD	Department of Defense
DRAM	Dynamic Random Access Memory
DRB	Design Review Board
DRL	Data Requirements List
DRT	Design Review Team
DSF	Data switch FPGA
DSP	Digital Signal Processor
EDAC	Error Detecting and Correcting
EEE	Electrical, Electronic and Electromechanical
EEPROM	Electrically Erasable Programmable Read Only Memory
EGRET	Energetic Gamma Ray Experiment Telescope on CGRO
EGS	Electron Gamma Shower
EGSE	Electrical Ground Support Equipment
EM	Engineering Model
EMC	European Muon Collaboration
EMI	Electro Magnetic Interference
EPO	Education and Public Outreach
ESA	End Station A
eV	Electron Volt
EWR	Eastern and Western Range
FAMM	Full Scale ACD Mechanical Model
FAR	Federal Acquisition Regulation
FCDI	Flex-Circuit Detector Interconnect
FEA	Finite Element Analysis
FEE	Front-End Electronics
FEM	Finite Element Model
FERC	Front End Readout Chip
FIFO	First In, First Out
FITS	Flexible Image Transport System
FMEA	Failure Models and Effects Analysis
FNAL	Fermi National Accelerator Laboratory

FOM	Figure of Merit
FOV	Field of View
FPGA	Field Programmable Gate Array
FTOOL	FITS TOOL
FWHM	Full Width Half Maximum
FY	Fiscal Year
γ	Gamma Ray
GCN	Global Communications Network
GEVS	General Environmental Verification Specifications
GIDEP	Government-Industry Data Exchange Program
GLAST	Gamma Ray Large Area Space Telescope
GPS	Global Positioning System
GRB	Gamma Ray Burst
GRIS	Gamma Ray Imaging Spectrometer
GRO	Gamma Ray Observatory
GSE	Ground Support Equipment
GSI	Gesellschaft for Schwer-Ionen Forschung
GSFC	NASA’s Goddard Space Flight Center
GUI	Graphical User Interface
HBCU	Historical Black Colleges & Universities
HEAO	High Energy Astrophysics Observatory
HE	High Energy
HEO	High Earth Orbit
HEP	High Energy Physics
HEPL	W. W. Hansen Experimental Physics Laboratory at Stanford University
HEXTE	High Energy X-ray Timing Experiment
HP	Hewlett Packard
HPK	Hamamatsu Photonics K (Japan)
HSK	Housekeeping
HSM	Hierarchical Storage Manager
HST	Hubble Space Telescope
HV	High Voltage
I&T	Integration & Test
I/F	Interface
I/O	Input/Output
IAU	International Astronomical Union
IC	Integrated Circuit
ICD	Interface Control Document
I-CDR	Instrument Critical Design Review
IDB	Instrument Data Bus
IDL	Interactive Data Language
IDS	Interdisciplinary Scientist
IDT	Instrument Design Team
IEEE	Institute of Electrical and Electronics Engineers
IIS	Instrument Interface Structure
IN2P3	Institut National de Physique Nucléaire et de Physique des Particules

INFN	Istituto Nazionale Di Fisica Nucleare, (Italy)
IOC	Instrument Operations Center
I-PDR	Instrument Preliminary Design Review
IPI	Instrument Principal Investigator
IPM	Instrument Project Manager
IPO	Instrument Project Office
IPS	Integrated Project Schedule
IRD	Interface Requirement Document
IS	Instrument Scientist
ISAS	Institute for Space and Astronautical Science, Japan
ISE	Instrument System Engineer
ISEE	International Sun-Earth Explorer
ISET	Instrument System Engineering Team
ISM	Inter-Stellar Medium
ISS	International Space Station
ITM	Instrument Technical Manager
JPL	Jet Propulsion Lab
KEK	National Laboratory for High Energy Physics, Japan
KSC	NASA’s Kennedy Space Center
KTH	Royal Institute of Technology, Sweden
L1T	Level One Trigger
L2T	Level Two Trigger
L3T	Level Three Trigger
LASCO	Large Angle and Spectrometric Coronagraph Experiment
LAT	Large Area Telescope
LED	Light Emitting Diode
LEOP	Launch and Early Orbit Phase
LHA	Layer Hit Address
LHEA	Laboratory for High Energy Astrophysics at NASA’s GSFC
LLI	Long Leadtime Items
LLIS	Lessons Learned Information System
LM-ATC	Lockheed-Martin Advanced Technology Center
LMMS	Lockheed Martin Missiles and Space Corporation
LPNHE-X	Laboratoire de Physique Nucléaire des Hautes Energies de l’Ecole
LVDS	Low Voltage Differential Signaling
MAPMT	Multi-Anode Phototube Multiplier
MCM	Multi Chip Modules
MDI	Michelson-Doppler Imager
MGSE	Mechanical Ground Support Equipment
MIP	Minimum Ionizing Particle
MLI	Multi-Layered Insulation
MOA	Memorandum of Agreement
MOC	Mission Operation Center
MODA	Mission Operations and Data Analysis
MSFC	NASA’s Marshall Space Flight Center

MSSM	Minimum Super Symmetry Model
NAO	National Astronomical Observatory
NAR	Non Advocate Review
NASA	National Aeronautics and Space Administration
NCST	Naval Center for Space Technology
NDI	Non-Development Item
NEMO	Naval Earth Map Observer
NIM	Nuclear Instruments and Methods in Physics Research
NRL	Naval Research Laboratory
NSF	National Science Foundation
OMEI	Other Minority Educational Institutions
ORU	Organized Research Units
OSSE	Oriented Scintillation Spectrometer Experiment on CGRO
OTL	Office of Technology Licensing
PA&S	Performance Assurance and Safety
PAM	Performance Assurance Manager
PAN	Polyacrylonitrile
PAPL	Program Approved Parts List
PASM	Performance Assurance and Safety Manager
PAT	Pointing Accuracy per Tray
PCB	Printed Circuit Board
PCC	Laboratoire de Physique Corpusculaire et Cosmologie
PCM	Project Control Manager
PCS	Pointing Control Subsystem
PDR	Preliminary Design Review
PFR	Problem/Failure Report
PGA	Programmable Gate Array
PHA	Pulse Height Analysis
PIN	Positive, Intrinsic, Negative - a type of semiconductor
PMCS	Project Management Control System
PMT	Photo-Multiplier Tube
PPL	Preferred Parts List
PROM	Programmable Read Only Memory
PS	Power Supply
PSAM	Performance and Safety Assurance Manager
PSF	Point Spread Function
PSR	Pulsar
PWB	Printed Wiring Board
QA	Quality Assurance
R&D	Research and Development
RDB	Relational Data Base
R.L	Radiation Length
RFI	Request For Information
RFP	Request For Proposal

RHA	Resolved Hit Address
RI	Required Instrument
RMS	Root Mean Square
RT	Remote Terminal
RTOS	Real Time Operating System
SAA	South Atlantic Anomaly
SAC	Science Advisory Committee
SAP	Service d’Astrophysique
SBIR	Small Business Innovation Research
SC	Space Craft
SciFi	Scintillating Fiber
SCIPP	Santa Cruz Institute of Particle Physics at UCSC
SDB	Small Disadvantaged Business
SE	System Engineering
SEE	Single Event Effects
SED	Service d’Etude des Détecteurs
SEI	Service d’Electronique & Informatique
SEP	Solar Energetic Particles
SEU	Single Event Upset
SEU	Structure and Evolution of the Universe
SI	Science Instrument
SIS	Solar Isotope Spectrometer
SI-SC	Science Instrument Spacecraft
SIU	Spacecraft Interface Unit
SLAC	Stanford Linear Accelerator Center
SLD	SLAC Large Detector
SNR	Super Nova Remnant
SNOB	Super Novae OB Star Association
SOC	Science Operations Center
SOHO	Solar and Heliospheric Observatory
SOI	Silicon On Insulator
SQA	Software Quality Assurance
SR&T	NASA’s Supporting Research and Technology Program
SRAM	Static Random Access Memory
SRD	Science Requirements Document
SRR	Site Recommendation Report
S-S	Subsystem
SSAC	Senior Scientist Advisory Committee
SSC	Synchrotron Self Compton
SSD	Silicon-strip Detector
SSE	Space Science Enterprise
SSR	Solid State Recorder
SSU	Sonoma State University
STM	STMicroelectronics, (Italy)
STP	Space Test Program
SU	Stanford University
SU-HEPL	Stanford University Hansen Experimental Physics Lab
SUSIM	Solar Ultraviolet Spectral Irradiance Monitor

SU-SLAC	Stanford University Stanford Linear Accelerator Center
SV	Space Vehicle
SWG	Science Working Group
TAMUK	Texas A&M University in Kingsville
TBR	To Be Resolved
TCPU	Tower CPU
TCS	Thermal Control Subsystem
TDSP	TEM Digital Signal Processor
TEM	Tower Electronics Module
THA	Tower Hit Address
TKR	Tracker
ToO	Target of Opportunity
TOT	Time Over Threshold
TPG	Thermal Pyrolytic Graphite
TPM	Technical Performance Measure
TRC	Tower Readout Cable
TRL	Technology Readiness Level
UARS	Upper Atmospheric Research Satellite
UCSC	University of California at Santa Cruz
UnID	Unidentified Sources
UTC	Universal Time Coordinated
UW	University of Washington
V&V	Verification and Validation
VCHP	Variable Conductance Heat Pipes
VLPC	Visible Light Photon Counter
VLSI	Very Large Scale Integration
VME	Versa Module Eurocard
WBS	Work Breakdown Structure
WIMP	Weakly Interacting Massive elementary Particle
X0	Radiation Length