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DRAFT

Gamma-ray Large Area Space Telescope (GLAST)
 Large Area Telescope (LAT)
 Integration and Test Subsystem
 Survey and Alignment Test Plan

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1. PURPOSE

This document describes implementation of survey and alignment tests during LAT I&T.

2. SCOPE

This document covers the survey and alignment test activities during LAT I&T in SLAC Building 33 and NRL Building A59. This document clarifies the configuration and the test methodologies which satisfy the LAT Surveying Plan (LAT-MD-00895) in accordance with the LAT Test Plan Directive (LAT-MD-01312).

The document is divided into sections defining the components required to survey and align the LAT and the survey and alignment tests that are planned. An overview of the test program is given in section 5. The required components are described in Section 6 along with which organization will provide the components. Optical survey tests are described in Section 7, feeler gauge tests are described in section 8, MIP survey tests are described in Section 9, on-orbit survey and pointing tests are described in section 10.

3. ACRONYMS / DEFINITIONS

3.1. ACRONYMS

ACD	Anticoincidence Detector
GLAST	Gamma-ray Large Area Space Telescope
I&T	Integration and Test
LAT	Large Area Telescope
MGSE	Mechanical Ground Support Equipment
MIP	Minimum Ionizing Particle
SSD	Silicon Strip Detector
SVAC	Science Verification Analysis and Calibration
TBD	To Be Determined
TKR	Tracker

3.2. DEFINITIONS

Minimum Ionizing Particle (MIP): Cosmic ray particle which leaves a straight line (or “track”) of ionization hits through the LAT sensor array. MIPs are primarily muons on the ground and protons in LEO.

4. APPLICABLE DOCUMENTS

Documents relevant to the LAT I&T Survey and Alignment:

4.1. LEVEL 2 DOCUMENTS

- LAT-SS-00010 LAT Science Requirements Document

4.2. LEVEL 3 DOCUMENTS

- LAT-SS-00017 LAT Tracker Subsystem Level-III Specification
- LAT-SS-00115 LAT Mechanical Systems Subsystem Level-III Specification
- LAT-MD-01312 LAT Test Plan Directive
- LAT-MD-00895 LAT Surveying Plan
- LAT-MD-00446 Science Verification Analysis and Calibration Plan
- LAT-MD-00676 LAT Assembly Sequence

4.3. LEVEL 4 DOCUMENTS

- LAT-SS-00134 LAT TKR Detailed Subsystem Specification – Level IV Specification
- LAT-TD-00573 SAS I&T Interface Control Document for the LAT
- LAT-TD-01590 Calibration Algorithms for the LAT
- LAT-TD-01340 SAS Calibration Infrastructure

5. OVERVIEW

The purpose of surveying the LAT is:

- Ensure proper spacing and orientation of TKR flight towers on the flight grid during integration
- Verify proper seating of the ACD on the flight grid
- Determine the as-built internal alignment of LAT particle sensors on the ground and on-orbit
- Determine the as-built pointing accuracy of LAT on the ground and on-orbit

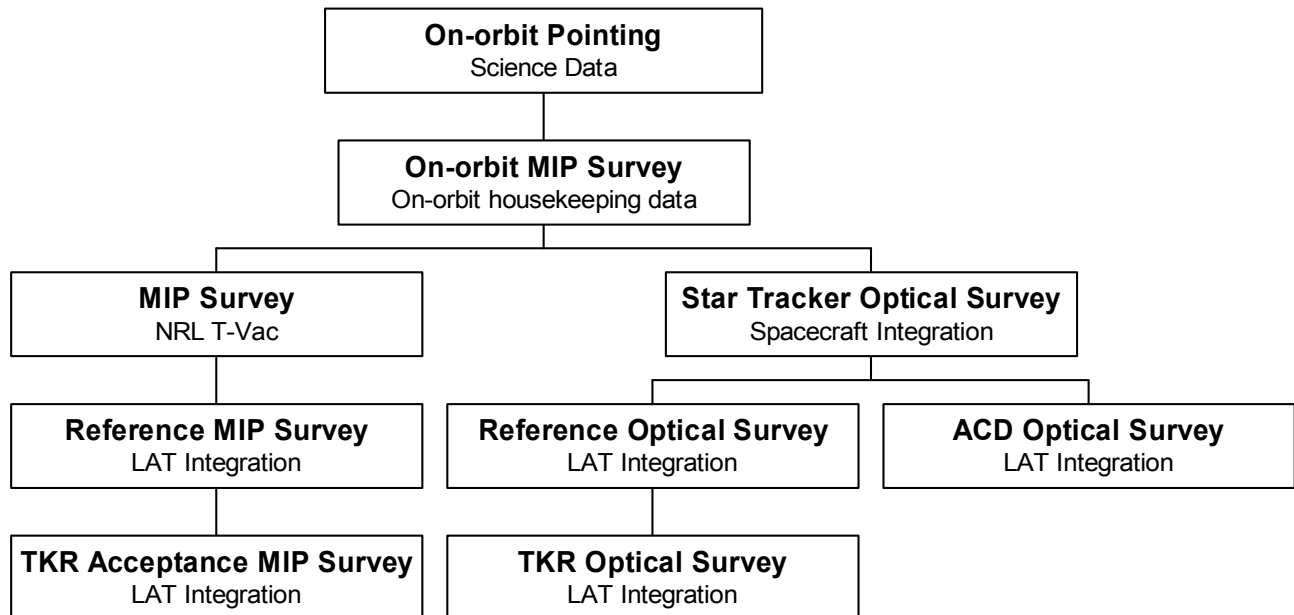
Two types of survey will be performed on the ground: optical and MIP. In addition, tower-to-tower wall separation data from feeler gauges will be recorded during assembly of LAT. Two types of survey will be performed on-orbit: proton and MIP. In addition, pointing accuracy of LAT is verified with celestial gamma-ray point sources.

The tests which implement the surveys required by LAT-MD-00895 are summarized in the following table according to survey number defined in LAT-MD-00895, test name, and subsection in this document:

Survey	Test	Orientation	Temperature	Pressure	Section
1A, 1B	TKR Optical Survey	+Z up	Room temperature	1 atm	7.1
1C	LAT Reference Optical Survey	+Z horizontal	17 deg C	1 atm	7.2
1C	LAT MIP Survey	+Z horizontal	17 deg C	1 atm	9.3
2A	ACD Optical Survey	+Z up	Room temperature	1 atm	7.3
2B	LAT MIP Survey	+Z horizontal	17 deg C	1 atm	9.3
2C	LAT MIP Survey	+Z up	17 deg C	1 atm	9.3
3A	LAT MIP Survey	+Z horizontal	17 deg C	1 atm	9.3
4A	LAT MIP Survey	+Z horizontal	-5 deg C	Vacuum	9.3
4B	LAT MIP Survey	+Z horizontal	8 deg C	Vacuum	9.3
4C	LAT MIP Survey	+Z horizontal	17 deg C	vacuum	9.3

The organization of survey and alignment tests is given in the following chart:

LAT I&T Survey and Alignment Test Organization



6. REQUIRED COMPONENTS

This section describes the required components and is organized by the subsystem who will contribute the items. The required equipment and tooling for survey are summarized in the following table:

Equipment/Tool	Quantity/Unit	Supplier
Laser tracker	1 portable unit	SLAC Metrology Dept., Alignment Engineering Group
1-1/2" sphere mounted reflectors	66 reflectors w/ bushings	SLAC Metrology Dept., Alignment Engineering Group
3/4" sphere mounted reflectors	18 reflectors w/ bushings	SLAC Metrology Dept., Alignment Engineering Group
Surveyor	2 workers x 11 times x 4 hrs	SLAC Metrology Dept., Alignment Engineering Group
Tracker top tray "hat"	17 units	TKR subsystem
Flight grid reamed holes	4 holes x 4 sides	Mechanical subsystem
ACD mounting points	3 points x 4 sides	ACD subsystem
Feeler gauges	2 units	I&T

6.1. TRACKER SUBSYSTEM CONTRIBUTION

The Tracker Subsystem will provide 17 top tray alignment "hats" (one for each tower plus one spare). Each TKR tower top tray surface will provide 4 mounting points for 1-1/2" sphere mounted reflectors. The sphere mounted reflectors have 1/4" stems which will be placed by the surveyor into holes in a portable "hat" which will be accurately placed on each TKR tower top tray surface to be surveyed. TKR subsystem will provide the portable "hat" and calibrate the "hat" location on each TKR module.

6.2. MECHANICAL SUBSYSTEM CONTRIBUTION

Each side of the flight grid will provide 4 mounting points, spaced as widely as possible on each of 4 sides, for 3/4" sphere mounted reflectors. At least 3 reflectors on the flight grid and at least 3 reflectors on each TKR tower must be visible simultaneously to the laser tracker. In addition, all 16 reflectors on the flight grid must be viewable for a given configuration to determine the deformation state of the grid. The flight grid will support the survey needs by providing 1/4" reamed holes in the corners of the grid which allow placement by the surveyor of the sphere mounted reflectors. The grid must be oriented so that gravity does not pull the sphere-mounted reflectors out of the reamed holes.

6.3. ACD SUBSYSTEM CONTRIBUTION

Each side of the ACD will provide 3 mounting points for 1-1/2" sphere mounted reflectors. At least 3 reflectors on the flight grid and 3 reflectors on the ACD must be visible simultaneously to the laser tracker. In addition, all 16 reflectors on the grid and all 12 reflectors on the ACD must be viewable for a given configuration to determine the simultaneous deformation state of the grid and ACD.

6.4. SLAC METROLOGY DEPARTMENT CONTRIBUTION

The SLAC Metrology Department, Alignment Engineering Group, will perform survey measurements using at least one laser tracker and sphere mounted reflectors mounted at points on the LAT. SLAC Metrology, Alignment Engineering Group, will provide the surveyors, laser tracker(s), and 66 1-½” sphere-mounted reflectors (4x16 towers + 2 spares) and 18 ¾” sphere-mounted reflectors (4x4 sides + 2 spares). All equipment will be calibrated and NIST certified prior to surveys.

6.5. I&T SUBSYSTEM CONTRIBUTION

The SLAC Metrology Department laser tracker(s) require continuous line of sight to the sphere mounted reflector as it is moved from the laser tracker test point to the measurement point. The laser tracker will be mounted on stands provided by I&T MGSE to allow the laser tracker to view all reflectors. All surveys will be performed in the SLAC Building 33 LAT integration facility.

In addition, I&T will provide the MIP Survey Scientist for analysis of data from surveys.

6.6. SAS SUBSYSTEM CONTRIBUTION

As described in LAT-TD-00573, the Science Analysis Subsystem will deliver the following products:

6.6.1. *Reconstructed files*

Digis and recon files from MIP data-taking.

6.6.2. *Calibration software algorithms*

Described in LAT-TD-01590.

6.6.3. *Software infrastructure*

Calibration infrastructure with appropriate documentation to read alignment constants into reconstruction programs, described in LAT-TD-01340.

7. OPTICAL SURVEY TESTS

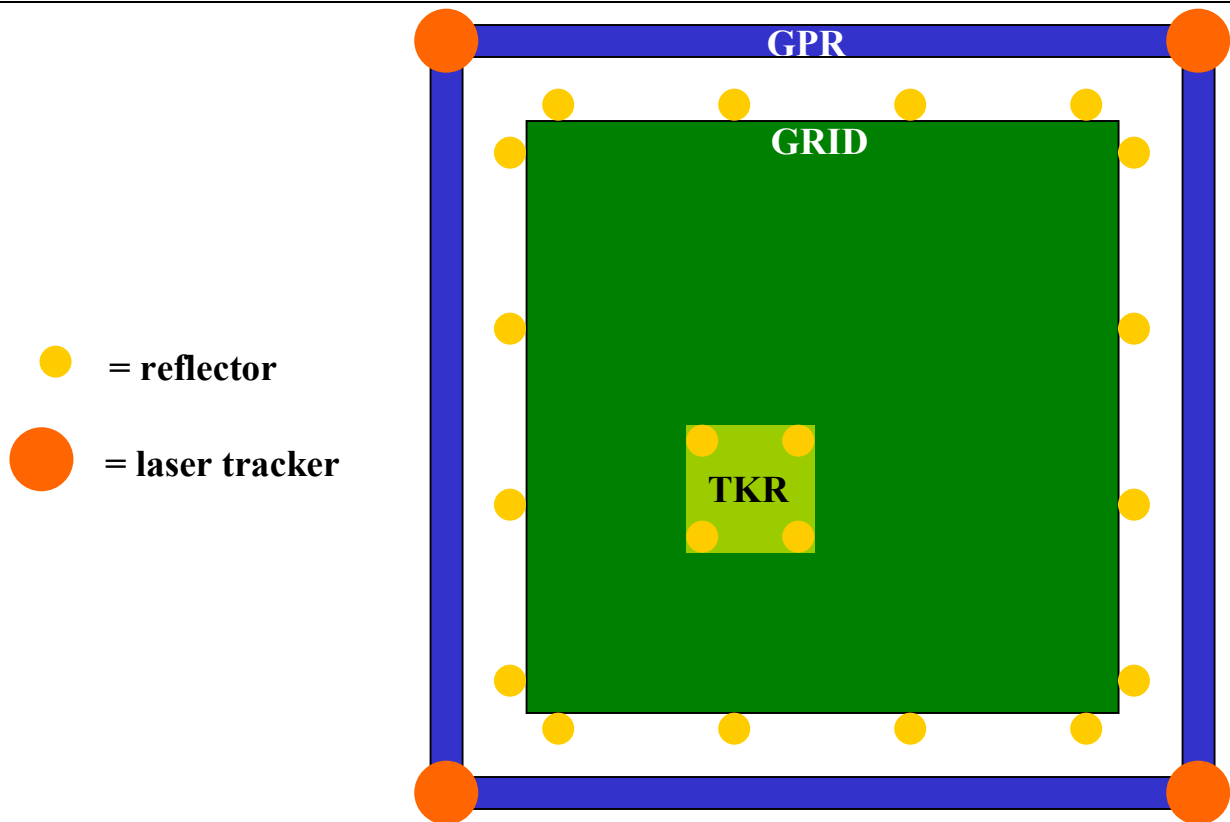
The optical survey tests are described in this section:

7.1. TKR OPTICAL SURVEY TESTS

After each of first 8 TKR modules are integrated into the bays 4-11 we will perform optical survey of TKR module(s) + Grid; TKR module(s) will be re-seated and re-surveyed if necessary.

7.1.1. *TKR Optical Survey Test Configuration*

The setup for TKR optical survey in Room 104, Building 33, SLAC is shown in the following diagram:



7.1.2. TKR Optical Survey Test Analysis

The SLAC Metrology Department, Alignment Engineering Group, maintains and operates the Laser Tracker optical survey test analysis software.

7.1.3. TKR Optical Survey Test Data and Reports

The SLAC Metrology Department, Alignment Engineering Group, analyzes the test data obtained from the laser tracker and produces the optical survey report. The optical survey report contains relative X-Y-Z locations of each module to an accuracy of 25 microns in each direction. The report also gives some quantitative information on deformation.

7.2. LAT REFERENCE OPTICAL SURVEY TEST

After all 16 TKR modules are integrated we will survey all 16 TKR modules + Grid; TKR modules will be re-seated and re-surveyed if necessary; data will be recorded as reference survey

7.2.1. LAT Reference Optical Survey Test Configuration

The setup for LAT Reference optical survey in Room 104, Building 33, SLAC is shown in the following diagram:

TBD

7.2.2. LAT Reference Optical Survey Test Analysis

As in section 7.1.2.

7.2.3. LAT Reference Optical Survey Test Data and Report

As in section 7.1.3.

7.3. ACD OPTICAL SURVEY TEST

After integration of the ACD we will survey ACD + Grid; ACD will be re-seated and re-surveyed if necessary.

7.3.1. ACD Optical Survey Test Configuration

The setup for TKR optical survey in Room 104, Building 33, SLAC is shown in the following diagram:

TBD

7.3.2. ACD Optical Survey Test Analysis

As in section 7.1.2.

7.3.3. ACD Optical Survey Test Data and Reports

As in section 7.1.3.

7.4. STAR TRACKER OPTICAL SURVEY TEST

7.4.1. Star Tracker Optical Survey Test Configuration

The setup for Star Tracker optical survey in Spectrum Astro is shown in the following diagram:

TBD

7.4.2. Star Tracker Optical Survey Test Analysis

As in section 7.1.2.

7.4.3. Star Tracker Optical Survey Test Data and Reports

As in section 7.1.3.

8. FEELER GAUGE TESTS

After each subsequent TKR module installation, feeler gauges will be used to measure the minimum distance between adjacent TKR module walls at predefined levels on the Z-axis.

8.1. TKR STAYCLEAR TEST

8.1.1. TKR Stayclear Test Configuration

TBD

8.1.2. TKR Stayclear Test Analysis

TBD

8.1.3. *TKR Stayclear Test Data and Reports*

TBD

9. MIP SURVEY TESTS

There is currently a requirement on the knowledge of pointing accuracy to be better than 7 arcsec. Since the height of the tracker is about 650 mm, this corresponds to the alignment precision of 20 micron or better. Precision (~10 micron accuracy) tracker surveys will be performed on the ground and in orbit using cosmic ray MIPs tracks. MIP particles travel through the LAT at a rate of 400 Hz on the ground. MIP particles traverse the LAT and deposit charge. Charge is collected and the MIP trajectory is reconstructed producing “tracks” which must be recorded and analyzed to extract the precision survey results. Ground data collection of 10,000 tracks per tower requires 12-hrs for LAT in an upright orientation and 36-hrs in a sideways orientation relative to gravity. Analysis time for the MIP Survey Scientist is 1-day. Due to high data rate the ground test stand must be through the LAT Test Point, which allows full access to LAT data acquisition. On-orbit internal alignment is discussed in the SVAC Plan LAT-MD-00446 in which a dedicated calibration mode is required.

The MIP survey sequence is summarized as follows:

9.1. MIP ANALYSIS ACCEPTANCE TEST

MIP survey analysis method verified using simulation. Blind analysis for given alignment parameters is performed and cross-checked with truth.

9.2. TKR ACCEPTANCE MIP SURVEY

Before acceptance of each TRK module we will perform MIP survey on each single tower to measure tray deformation (see LAT-MD-00446); in case of non-conformance, we will request replacement of non-conforming tray(s). The required precision for the assembly of tracker trays is defined in LAT-SS-00017. The precision with which one measures the projected angle in two adjacent planes of a single tray, or Pointing Accuracy of Single Tray (PAT), is a function of incident angles. The required tolerance on the separation between detectors in the same tray should be better than 200 microns (defined in LAT-SS-00134) as the PAT is dominated by multiple-Coulomb scattering. With a large sample of tracks and assuming the tolerances within which the trays have been built, we cannot achieve desired pointing accuracy without track-based alignment.

9.2.1. *TKR Acceptance MIP Survey Test Configuration*

The MIP acceptance survey will be performed in the Building 33 controlled area. The thermal requirement for the survey is to hold temperature constant to within +/-5 degrees C.

9.2.2. *TKR Acceptance MIP Survey Test Analysis*

Now we describe the single tower tray-to-tray analysis. We need to reduce the 20 micron uncertainty in Z position of silicon to better than 10 microns (3 arcsec) including the safety factor. As described above, we need to divide the silicon wafer to smaller regions as an alignment unit. As a starting point, we assume that we need to divide the silicon wafer in 4x4=16 regions. This is not an accurate estimation, but is sufficient for this note. We no longer require 6 degrees of freedom but 3 per wafer (factor of 2 less in the number of cosmic rays).

The z resolution is calculated as

$$\sigma_z^2 = 2 \left(\frac{0.0136 \cdot E \cdot z_{\text{tray}}}{(E^2 - m_\mu^2) \sin \theta} \right)^2 X_{\text{tray}} + 6 \left(\frac{\sigma_{\text{SSD}}}{\tan \theta} \right)^2$$

We have a factor of two for both terms to account for errors in the 3D space, not 2D plane. Additional factor of three in the second term originated from the three planes involved in the alignment procedure. (Two planes are used to form a line and compared with the position in the third plane.) We obtain the effective z resolution of 150 microns in a similar manner as above. This leads to the number of track required to get 10 micron resolution, $(150/10)^2 \times 3 = 2000$ for each region.

9.2.3. TKR Acceptance MIP Survey Test Data

Cosmic ray flux is calculated to be $0.01 \text{ cm}^{-2}\text{s}^{-1}$ assuming that one-quarter of ϕ can be used for the alignment. This is the worst case for the corner of the detector. Since the area of the region is $2.1 \text{ cm} \times 2.1 \text{ cm}$, the cosmic ray rate is 0.04 Hz and it takes 0.5 day to accumulate 200- tracks.

Pass-fail criteria for test are:

- <200 microns on SSD flatness and/or non-planarity within a tray (TBR)
- <200 microns on parallelism between any two SSD layers (TBR)

9.3. LAT MIP SURVEY TESTS

After all 16 TKR modules are integrated we will survey all 16 TKR modules; MIP survey will be verified with optical survey; data will be recorded as reference survey and compared with results from optical survey.

In addition, relative location of as-installed CAL logs and ACD tiles will be surveyed with MIPs.

At LAT hot and cold plateau during thermal vacuum chamber test at NRL; data will be recorded as reference survey and compared with results from LAT thermo-mechanical model.

Simulations lead to the conclusion that we cannot directly measure the transient effect of GRID deformation due to temperature difference. We still can measure the indirect effect of the temperature cycling by comparing the tower alignment with and without the temperature cycling, which is more close to the real effect on the orbit.

9.3.1. LAT MIP Survey Test Configurations

The instrument is oriented in a sideways configuration in the thermal vacuum test chamber to allow operation of the LAT thermal system. This creates asymmetries in the ability to align two towers and also reduces the triggering rates as compared to an upright orientation. When the towers are located up and down, the rate increases to 8.7 Hz while retaining the effective resolution of 4.8 mrad . This corresponds to 0.3 days of data taking to achieve 5 arcsec accuracy. One the other hand, when the towers are located side-by-side, the rate decreases to 1.6 Hz though the effective resolution is improved to 4.5 mrad . This requires 1.7 days of data taking to achieve the goal.

9.3.2. LAT MIP Survey Test Analysis

From the acceptance survey we know that the knowledge on the Z position of the silicon wafers in a given layer is better than 50 microns. The tracker tower consists of 18 silicon planes (2 layers = 1 plane) corresponding to an overall height of about 650 mm. Since the angle is small we can take 0.05

mm/ 650 mm to obtain 7.8×10^{-5} radians which corresponds to about 16 arcsec. We conclude that the track-based alignment is required to achieve the pointing accuracy better than 7 arcsec.

The major systematic uncertainty in the alignment precision is expected to originate from deformation of the silicon wafer that could be as much as 20 micron. Please note that this affects the track with normal incidence because the alignment is performed using angles track, which may cause systematic shift due to the wafer deformation. In order to minimize the effect of the wafer deformation, each silicon wafer is divided into smaller regions and individually aligned, (Note that the X and Y displacements and the rotation around Z axis will be common to all regions in the same wafer to minimize the degree of freedom.) In this way we can smooth out the height differences of the wafer. This approach requires a larger number of cosmic rays than what we previously estimated.

We start from the calculation for the tower-to-tower alignment assuming that single tower tray-to-tray alignment is performed in sufficient precision. Cosmic ray flux is modeled as

$$\frac{dN}{dEd\theta d\phi} = 0.12 e^{\frac{-d_{air} m_{\mu}}{c\tau_{\mu} E \cos\theta}} E^{-2.8} \left(\frac{1}{1 + \frac{1.1E \cos\theta}{115}} + \frac{0.054}{1 + \frac{1.1E \cos\theta}{850}} \right) \left[cm^{-2} s^{-1} sr^{-1} GeV^{-1} \right]$$

where $E = E + E_{loss}/\cos\theta$ to account for the energy loss of 2 GeV in the air. This formula is obtained from Phys.Rev.D66, 010001 (2002) and is modified to account for the decay and energy loss. If this formula is integrated over all solid angle and $E > 1$ GeV, the rate is obtained to be $0.9 \text{ cm}^{-2} \text{ min}^{-1}$, which is in good agreement with the nominal value of $1 \text{ cm}^{-2} \text{ min}^{-1}$. The angular resolution of the track is dominated by multiple Coulomb scattering and calculated as

$$\sigma_{space}^2 = 2 \left(\frac{0.0136E}{E^2 - m_{\mu}^2} \right)^2 \left(\frac{X_{side}}{\sin\theta \sin\phi} + \frac{2X_{tray}}{\cos\theta} \right) + \frac{2\sigma_{SSD}^2}{z_{tray}}$$

where X_{side} (=2.5%) and X_{tray} (=4.3%) is the radiation length of the side wall and tray. (super-GLAST layers and below are ignored.) Please note that the factor of two is included to account for space resolution, not plane resolution. Also note that we use only two planes since additional layer does not improve the resolution when the scattering is dominant. The resolution dependence on θ and ϕ is relatively mild as shown in figure 1.

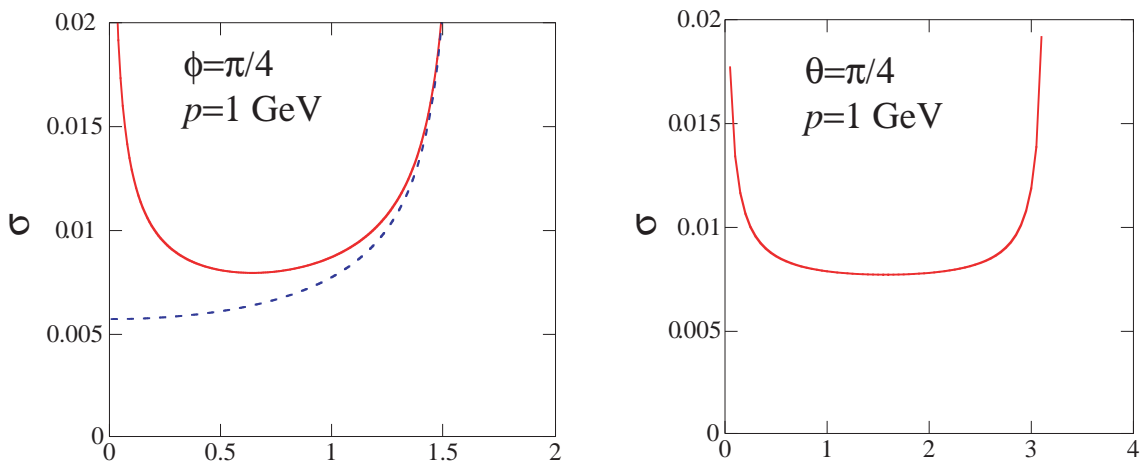


Figure 1 Track angular resolution as a function of θ and ϕ .

Effective angular resolution is calculated as

$$\sigma_{\text{eff}} = \sqrt{\frac{\int_{0.5}^{1.0} \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \frac{dN}{dEd\theta d\phi} \sin\theta d\theta d\phi dE}{\int_{0.5}^{1.0} \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \frac{1}{\sigma_{\text{space}}^2} \frac{dN}{dEd\theta d\phi} \sin\theta d\theta d\phi dE}} = 4.7 \times 10^{-3} \text{ [rad]}$$

Please note that this calculation assumes that the error of each track is properly weighted which is difficult for low momentum tracks. It is best to remove low momentum tracks using the calorimeter information.

9.3.3. LAT MIP Survey Test Data

Now we calculate the rate. We require that the cosmic ray go through the tower sidewall between the 4th tray and the 9th tray so that each tower has at least 4 planes of hits. Useful area is dependent on θ and ϕ and calculated as

$$A = 5z_{\text{tray}} \tan\theta \sin\phi \left(\frac{w_{\text{tray}}}{2} - 3z_{\text{tray}} \tan\theta \sin\phi \right).$$

The rate is calculated as

$$R = 4 \int_{0.5}^{1.0} \int_0^{\frac{\pi}{2}} \int_0^{\theta_{\text{max}}} A \frac{dN}{dEd\theta d\phi} \sin\theta d\theta d\phi dE = 4.6 \text{ [Hz]},$$

$$\theta_{\text{max}} = \tan^{-1} \left(\frac{w_{\text{tray}}}{6z_{\text{tray}} \cos\phi} \right).$$

In order to achieve the angular resolution of 5 arcsec (=0.024 mrad) for 6 degree of freedom for tower alignment, we need $6 \times (0.0047/0.000024)^2 = 230000$ tracks which corresponds to 0.6 days of data taking. Since the above calculation does not account for any loss due to inefficiency and track selection loss, we need 400000 tracks, 1 day of data taking.

10. ON-ORBIT SURVEY AND POINTING TESTS

The tower-to-grid and grid-to-spacecraft alignment will be cross-checked by on-orbit alignment measurements using celestial point sources. Tray-to-tray and tower-to-tower alignment will be cross-checked by on-orbit MIP surveys. On-orbit alignment will be implemented with proton surveys and MIP surveys. LAT pointing accuracy will be verified with celestial point sources which radiate in the optical and gamma-ray bands (pulsars Vela and Crab).

10.1. ON-ORBIT MIP SURVEY TEST

10.1.1. On-orbit MIP Survey Test Configuration

TBD

10.1.2. On-orbit MIP Survey Test Analysis

TBD

10.1.3. On-orbit MIP Survey Test Data

MIPs traverse the LAT at a rate of 400 Hz on the ground and 8 kHz in Low Earth Orbit (LEO). On-orbit data collection is limited by low bandwidth of spacecraft downlink. Thus, on-orbit requires filtering of MIP candidates and downlink of the most useful MIPs in compressed data format. Flight software is capable of down linking 5% of MIP data to earth for LEO in-situ precision survey of LAT. The total numbers of the track required for the single tower tray-to-tray and tower-to-tower alignments are $2000 \times 16 \times 16 \times 16 = 8.0\text{M}$ tracks and $230\text{K} \times 16 = 3.7\text{M}$ tracks, respectively (see LAT-MD-00446 for details). The total data size is $(8.0\text{M} + 3.7\text{M}) \times 2 \text{ kB/event} = 23.4 \text{ GB}$ (2kB/event is tentative number and to be determined). Assuming 300kbps, it takes 9 days to send data to the ground.

As pointed out above, the low momentum tracks are not very useful for the alignment due to the scattering effect. For the effective use of the bandwidth, it is a good idea to get rid of low momentum tracks. For this reason, we should require that the track should penetrate all calorimeter logs. For the tower-to-tower alignment, we should require that two or more towers fire the 3-in-a-row trigger at different layers.

10.2. ON-ORBIT POINTING TEST

10.2.1. On-orbit Pointing Test Configuration

TBD

10.2.2. On-orbit Pointing Test Analysis

TBD

10.2.3. On-orbit Pointing Test Data

TBD