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Document Title **LAT Beam Test Rationale**		

LAT Beam Test Rationale

Purpose of Document

The science performance verification strategy uses the Monte Carlo simulations and reconstruction algorithms to verify that the LAT meets the science performance requirements. A beam test provides an experimental reference for the simulations. The existing beam test plan (LAT-TD-00440) and Science Verification and Calibration Plan (LAT-MD-00446) started with the assumption of available resources (beam time, number of towers, etc.) to provide this reference. Schedule pressures have forced a re-examination of the original resource assumptions, and a bottoms-up assessment of what is essential is provided in this document. The document serves as justification for the beam test plan and as input to the team for any further decision process concerning the beam test.

Summary of Findings

We summarize here the findings of the document.

- A minimal beam test of two TKR towers and three CAL modules, exposed to hadron, positron, and tagged photon beams provided at SLAC, will be sufficient to meet the needs of LAT. The items to be checked, along with a required beam configuration, are listed in Table 1.
- While the science verification needs from the beam test are relatively straightforward to asses, it is more difficult to quantify the risk reduction aspects of the beam test. There is no question that exposing the calibration unit to well-defined particle beams over a wide range of energies prior to (or during) flight integration would provide significant risk reduction. However, that risk reduction is due to the early *functional* testing that would be a collateral benefit of the early beam test. If that functional testing can be accomplished by other means around the same time, the essential aspects of the risk reduction can be maintained.
- A superficial assessment of the impact of doing *no* beamtest prior to launch was done. Deleting the beam test entirely would add risk to science, because clearly identifiable information needed for science data interpretation would be more difficult to obtain by other means to the accuracy afforded by doing the test. However, it is also difficult to prove that a beam test is essential to mission success. The main areas of science performance at risk are the background rejection and knowledge of the tails of the point spread function (PSF). Reduced understanding of these performance parameters will have a direct impact primarily on measurements of diffuse emission and emission from the weakest point sources. In general, without a beam test, substantially more effort will be devoted in early operations to understand the basic instrument response instead of doing science; uncertain particle fluxes will have to be used to understand instrument distributions, instead of the other way around.

Science performance verification strategy

Every LAT science performance requirement has a defined test. The LAT energy range and FOV are vast. Testing for science performance will therefore consist of a combination of simulations, beam tests, and cosmic ray induced ground-level muon tests. It is neither practical nor has it been shown to be necessary to verify by direct test the full range of LAT performance. Instead, the beam tests are used to sample the performance space and to verify the detailed simulation; analysis using the simulation is used to verify the full range of performance parameters. The simulation package is built with tools from GEANT4, which is based on widely-used algorithms with a long heritage in particle physics. Germane to GLAST are two underlying physics simulation components: electromagnetic interaction (EM) code and hadronic interaction code.

The EM component of the GEANT4 toolkit is very well tested and understood. It is derivative of the EGS code originally developed in the late 1960's and used in previous space missions, the most notable being EGRET. GLAST LAT photon measurement performance relies on this EM part. The key additional information needed consists of a few well-chosen measurements, to provide a benchmark for tuning simulation parameters (e.g. shower cut-offs, see below), and end-to-end verification that the detector model is correct. The information and the methodology for obtaining the information are described below.

The fidelity of the hadronic code portion is less well understood and certainly not *a priori* known to the precision required for our background rejection. It is important to remember that the background fluxes themselves are not known to better than ~20%, and they vary over the orbit and the lifetime of the observatory by large factors (typically 50% to a factor of 4). In the past, we have demonstrated that there is ample information from the instrument to do the background rejection by using the example of the existing hadronic simulation and identifying additional sources of margin. Additionally, the orbit variation of the background rate can be exploited to verify again the background rejection: the weakest measured photon flux should not vary by more than 10% over the range of orbit conditions if the background rejection requirement is met.

What are the requirements on the beam test for the background rejection? Ideally, the instrument would be exposed to ~10^8 hadrons and electrons from all directions and over the full range of energies, and a simple demonstration performed that an adequate fraction of events is rejected. Unfortunately, such a test is fundamentally impractical because hadron beams have a non-negligible photon contamination that is difficult to measure independently, as well as a halo of muons. Fortunately, by dividing the problem into components and using the simulation, the requirement can be verified, as described below.

Information from the beam test and methodology

Specifically, the components of the simulation verified in the beam test are

1. underlying physics (EM and hadronic); and
2. detector model (geometry, sensor response, electronics response).

This section will provide an explicit list of everything that must be tuned. For each item in the list, the beam configuration and required precision are specified.

There is also end-to-end verification: direct measurement of the photon PSF at selected angles and energies is important as an end-to-end test to ensure something is not missed.

Underlying physics parameters to tune

The electromagnetic interaction section of GEANT4 is based on the EGS4 code which has along heritage and many experimental checks. As such, the basic algorithms used here are believed to be essentially correct and represent the state of the art in this area of physics modeling. However the implementation and transfer of this code must be verified appropriately. Many of these checks can be done internally to the simulation, with direct comparisons to theoretical expectation. The area where we anticipate the largest possible problems is in the production of very soft electromagnetic particles in and around the shower core. The distributions of soft electrons, often referred to as "delta rays" or "knock-on" electrons, depend on the detailed modeling. These particles are important as they both enlarge cluster size for shower core particles as well as create a halo of "noise" hits, which is a source of confusion for the pattern recognition. The energy down to which particles are produced and transported in GEANT 4 is controlled by an effective range cut-off: smaller values result in increased time for simulations while large values run the risk of truncating important effects. Presently we run simulations with this parameter set to 100 μm. The ultimate value will be established by comparing cluster size distributions from beam test data to those from the simulations. This presently is the main "knob" provided in the GEANT 4 package, however it is anticipated that this range parameter in the next release (GEANT4 version 5.1) will be settable region by region to allow for increased efficiency. Our requirement here is driven by the detailed hit pattern in the Tracker.

The multiple scattering in GEANT 4 is verified by direct comparison of tracked particles with known distributions in stand-alone test programs and, as such, is not really in question.

The most questionable part of the simulation is centered on the modeling of the hadronic interactions. Given our dependence on this to determine how best to reject backgrounds, it represents an important challenge to the GLAST simulation model. Comparisons of distributions of hits by layer, numbers of reconstructed tracks and track lengths, and energy deposition patterns are needed to provide confidence in our abilities to simulate backgrounds adequately (see discussion below).

Detector model

In addition to the basic physics modeling in GEANT4, the accuracy of the detector modeling as well as the physical layout of materials (or geometry) must be verified. GEANT4 deposits energies in volumes, and from there it is necessary to generate simulated detector signals.

TKR

Again the issue of cluster size in the silicon strip detectors arises and needs cross checking. Also noise in these detectors and the modeling of the pulse duration (time over threshold, TOT), which is used to estimate the energy deposited, must be checked.

CAL

The determination of the energy centroid from the light asymmetry derived from the diodes at each end of the crystals must be verified. In particular, the distortion caused by the direct deposition of ionization in the diodes, which are often located within the shower volume, should be compared with the simulation. (A direct confirmation of the light yield per MeV of deposited energy is also important; however this will already have been measured in the engineering model heavy ion test.)

ACD

Since the primary requirement on the ACD is to measure the passage of minimum ionizing particles (MIPs) with high efficiency, and since there is a readily-available natural source of MIPs, namely muons from cosmic-ray induced air showers, there are no requirements on a beam test from the ACD alone. The backsplash rate is important to verify, but this has already been measured at several previous beam tests, and additional tests are not necessary.

Quantities used in the background rejection analysis

Although the background rejection required is at the level of 10^6:1, it is not necessary for all aspects of the simulation to be accurate to that precision (nor would it be possible). This is because the background rejection analysis uses information from components of the instrument in different ways. Each selection contributes only a fraction of the total rejection, and there are a sizable number of selections that, when combined, provide the needed rejection. The rejection power of each selection varies by type, but is typically less than a factor ~10. (Simplistically, if each selection provided a factor 10 rejection, then 6 such quantities would be needed if they were all mutually orthogonal. Of course, the real rejection scheme is more complicated.) To the extent that individual quantities afford rejection capability, the agreement with the simulation must match to a corresponding precision. This then sets the required statistics in the verification measurement. Specifically if a variable provides a factor of 10 reduction in background, and if our confidence in this quantity is ~ 1%, then a 10% uncertainly in the residual background will result. Most of our variables (with the noted exception of the ACD distances, which provide much greater rejection) actually give worse discrimination than this, which constitutes the main reason for the large number of them. For planning purposes, then, a requirement of comparisons to 5-10%, with a goal of 1%, will be adequate in most cases.

We present here a list of distributions that have been used in past proofs of background rejection as input to the hadron beam test verification requirements. We divide this list into the following logical categories:

1) ACD variables: These variables are for the most part concerned with the correlation of struck ACD tiles with found tracks. However, neutrals from interactions elsewhere in the LAT (most notably the Calorimeter) do make energy depositions in this system as well ("backsplash"). There are two sub-categories for the ACD:
    a. distribution of hit tiles with respect to a known event axis and
    b. distributions of quantities comparing the projection of found tracks with the locations of hit tiles (for example distance of closest approach to tile center, or distance of tracks for hit tile edges) .

    Item (a) was measured in the CERN beam test in 2002. Item (b) relies primarily on EM physics modeling and the detector model, and is therefore possible to understand to relatively high precision.
2) CAL energy distributions:
    a. topologies and numbers of hit crystals, particularly transverse relative to energy centroids and known event axes
    b. energy depositions per layer
3) TKR topologies. Here we look at track hit distributions at the head of the tracks as well as hit populations about the event axis, both near by as well as outside a given transverse distance.
4) TKR-CAL matching. These variables compare the location as well as the direction of the reconstructed event axis from the tracker to that measured in the Calorimeter. At low energy, only the distance for the projected axis to the energy centroid has merit, however at high energy the Calorimeter provides an independent direction for the event axis.
5) Low Energy Particle Range-outs: Both the Z location of where tracks start and stop as well as the Time-Over-Threshold (TOT) from the tracker (not yet used in the analysis).

The basic goal of the beam test will be to compare the distributions of these variable classes with those found experimentally, as detailed in the last section.

End-to-end direct performance verification

All of the following can, in principle, be accurately predicted by the model after tuning to the distributions described above. However, end-to-end tests are generally important to verify that nothing significant has been missed in the component verification. This represents good experimental practice, and is more risk reduction than science performance verification. Those end-to-end tests should include the following:

1. Photon PSF at 1 GeV, normal incidence and at 30 degrees. The beam test will represent the first opportunity to follow photon events across tower boundaries. While the instrument model can be checked using cosmic rays, photon events provide a more direct test.
2. Fisheye and other small systematic offsets and overall efficiencies (Aeff) at 100 MeV; at normal incidence, 5 degrees, 30 degrees, and 60 degrees.
3. Photon energy reconstruction at 100 MeV at normal incidence and at 30 degrees; electron energy reconstruction at 1 GeV and multi-electron at 100 GeV-effective (4x 25 GeV) at normal incidence and at 30 degrees. Some exploration of energy losses in the gaps between CAL modules should also be performed.

Required elements of the beam test

Much of the above validation work with respect to detector modeling and EM showers can be accomplished using beams of particles closely aligned with the instrument axis. However, in addition, samples of events at angles midway to the edge of the field of view as well as at its limit are highly desirable. Finally, beams impinging on the instrument from the side as well as at angles larger then 90^{o} will be necessary to verify effects of back-entering particles, as will be present from earth albedo. Hadronic beam testing should be mainly focused on that part of the GLAST phase space not covered by the ACD system, and in which the primary incident particle is not tracked, to study the less well-understood effects adequately.

The minimum instrument configuration that provides the essential features of inter-tower gaps is obviously two towers. Since the events LAT will see on orbit are significantly smaller than the size of the instrument, and therefore well-contained in a subset of the towers, a full-LAT beam test is not required for science performance verification (although there are obvious risk reduction benefits of a full LAT beam test, to be weighed against other risks of cost, schedule and handling). With a configuration of two TKR towers and three CAL modules, even at the limit of the tracker 3-in-a-row trigger, approximately 5 x,y pairs of hits will be produced, allowing a measurement of the tracking performance.

Each calorimeter unit when hit from the side is about 0.9 interaction lengths. In the full LAT, particles coming for this direction will encounter $> 3.6\ \lambda$ and fairly well-developed hadronic showers will result. As such we will want to make the hadronic section of the beam test unit as thick as possible. While not ideal, by incorporating the engineering model CAL with two fully functional towers, the test configuration will present $2.7\ \lambda$ and will provide a range of interaction depths and shower developments.

From these considerations we conclude that a calibration unit consisting of two towers plus the CAL engineering model will be adequate to obtain the information described above in a beam test. As is planned in LAT-TD-00440, this configuration arranged horizonally on a table affording rotation about the vertical axis as well as translations perpendicular to the beam direction will be required.

Electron and Photon Beams

Testing with electrons (positrons) will provide much of the information required to validate the electromagnetic modeling. Energies at a few GeV and then at the highest energies possible should be used to gather data at normal incidence as well as at 30^{o} off axis.

The photon beam can be derived from the electron beam in the usual way. Electrons which produce photons by bremsstrahlung, and hence are degraded in energy, can be measured so as to tag the radiated photon energy. The tagger should have acceptance over the full energy range being studied, with ~ 10% energy resolution being adequate. In previous GLAST beam tests, simple scintillating tile hodoscopes followed by lead glass total absorption counters proved adequate for this task. The same or similar instrumentation will be required for these tests.

The hadron running will primarily have the beam incident on the side of the calorimeter. Again three energies, a few GeV, ~ 10 GeV, and the highest energy possible are desirable. A preliminary assessment of the nature of such running suggests that a majority of the incident protons will cause interactions germane to providing data on the lower energy tails in the resulting showers. As such, the presently planned ~200K proton events seems quite adequate to provide distributions at the 1-10% level as we have proposed.

What can be done without a beam test?

To help answer this question, we speculate on the impact of the loss of the information in Table 1. In some cases, partial information is available from other elements of the test program (*e.g.*, ground-level muons from cosmic-ray induced air showers) and on orbit, as well as from previous beam tests. It is possible, for example, to obtain a fairly clean sample of photons from observations of pulsars, using a timing cut. The main problem with obtaining information on orbit, even if a clean sample can be isolated, is that the true particle energy will be unknown.

- TKR cluster sizes. This is obtainable on orbit, over time, probably to about the same precision, but then the details of the performance will have to be iterated.
- TKR pulse durations. Without a good understanding of the TOT behavior from the beam test, it is possible this experimental handle on the event classification will not be used. While it is not mission critical, the loss of TOT as reliable corroborating data adds some risk.
- CAL direct energy deposition. This can be studied using electrons on orbit.
- CAL energy topologies. It is difficult to obtain this information by other means. This is because, on orbit, we will not have certain knowledge of the incident particle type, energy, and direction, especially for those cosmic rays incident on the side of the CAL. For that important class of backgrounds, there is very little direct information available from the instrument about the primary particle; thus, a quantitative and detailed comparison with the simulations will be very difficult, and the tight connection between the data and the simulations will be broken. We note, however, that protons will typically travel through one calorimeter module before interacting; thus, given the combination of coordinate and energy measurements from each crystal, these MIP tracks are findable, in principle, and could be used to provide some of the parameters of the incident particle.
- TKR track topologies. This is obtainable on orbit, but to somewhat degraded precision due to lack of knowledge of the true energy.
- TKR-CAL matching. This distribution is most important for events initiated by side-entering cosmic rays on the calorimeter. As noted above, that information is not directly available on

orbit, but some of it might be "boot-strapable" (*i.e.*, derivable in a self-consistent manner using the some of the same LAT information we are trying to understand).

- Low-energy particle range outs. These distributions can be obtained from the science data, but their interpretation will be difficult because different primary particle fluxes produce different components of these distributions. In that case, unfortunately, it is very likely that these range-out distributions will be used to estimate the sizes of the background fluxes, instead of the other way around.
- End-to-end items (PSF, efficiencies, energy reconstruction). The energy reconstruction test will be particularly compromised. The measured spectrum from a "known" source is a result of a convolution of the energy resolution (and shifts) and the effective area as a function of energy. Normally, we will want to use our knowledge of those performance parameters to extract the flux, not the other way around.

It is difficult to quantify how wrong the untuned simulation might be. For the EM portion of the code, we can adjust the EM cutoff parameter until the results for LAT no longer are affected. Previous experience with beam tests has shown this to be effective, and the basic photon measurement characteristics are probably quite reliable. The biggest uncertainty is in the background rejection. There are a significant number of experimental handles available to run cross-checks on-orbit, however that process will be less accurate and more time consuming. In both cases, however, significant systematic errors could remain.

Of course, all the real effects likely to be uncovered by a beam test can't be fully anticipated.

The importance of the end-to-end testing opportunity of the beam test should not be underestimated. For example, if the predictions from the simulation for one or more of the component distributions in the top section of Table 1 do not match the data to the target precision, for reasons that can not be determined, the direct measurements in the bottom half of the table will allow us to bracket the residual systematic errors.

Finally, the biggest risk to science of not doing a beam test may be the inevitable delays introduced to the post-launch science processing and analysis, while these studies are being performed. Instead of focusing attention on the most subtle performance issues of the instrument, or the details of particular astrophysical sources, the LAT team will be performing basic instrument studies. This will happen at some level even with a beam test, but to a more limited degree.

Summary

In Table 1, we summarize the information needed from the beam test and the methodology to obtain it.

Table 1 Summary of information from beam test. The upper part consists of direct component comarisons while the lower part lists end-to-end tests.

ITEM	***Distributions***	***Beam configuration***	***Target Precision***
TKR cluster sizes	TKR cluster sizes by layer	Positrons (few GeV) and/or tagged gammas (100 MeV, few GeV) at normal incidence and off-axis (~30 degrees)	1%
TKR pulse durations	TOT by layer	Positrons (few GeV) and tagged photons (100 MeV, 1 GeV, 10 GeV) at normal incidence and off-axis (~30 degrees)	5%
CAL nuclear counter effect (direct energy deposition in diodes)	Energy centroid position relative to true particle impact position	Positrons (few GeV or higher) at normal incidence and off axis (~ 30 degrees)	10%
CAL energy topologies	#hit xtals relative to energy centroid and track axis; energy deposition per layer.	Positrons or tagged gammas (100 MeV, few GeV, >10 GeV); side-incident and normal-incident protons	5%
TKR track topologies	Hit distributions at the track vertex; distributions of hits around tracks (inside and outside "roads")	Tagged gammas (100 MeV, few GeV, >10 GeV); at normal incidence and off-axis (~30 deg);protons at normal incidence and off-axis (~30 deg).	1%
TKR-CAL matching	Difference of track projection and CAL energy centroid	Positrons or tagged gammas (100 MeV, few GeV) at normal incidence and off-axis (~30 degrees); side-incident protons	2%
Low energy particle range-outs	Z location of track starts and stops, # tracks, TOT for stubs; fraction of L1Ts produced.	Side-incident protons.	2%
PSF	PSF distribution and 68% and 95% containment values	Tagged gammas (normal incidence and off-axis ~30 degrees)	1%
Systematic photon reconstruction effects (offsets, efficiencies)	Mean reconstructed direction; number of reconstructed photon events compared with tagged rates.	Tagged gammas at 100 MeV and a few GeV, at normal incidence, 5 deg, 30 deg, and 60 deg.	5% on efficiencies
Photon energy reconstruction	Reconstructed energy distributions	Tagged gammas at 100 MeV, normal incidence and at 30 deg, at a few incident positions to explore gaps. Positrons at a few GeV and multi-positron events at 100 GeV effective at normal incidence and at 30 degrees, at a few incident positions to explore gaps.	5%