Event-by-Event Errors

Using Covariance to Enhance the *Fermi* Sky

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We describe event-by-event, covariant errors in the LAT science analysis and discuss ongoing development and potential scientific gains from using this information.

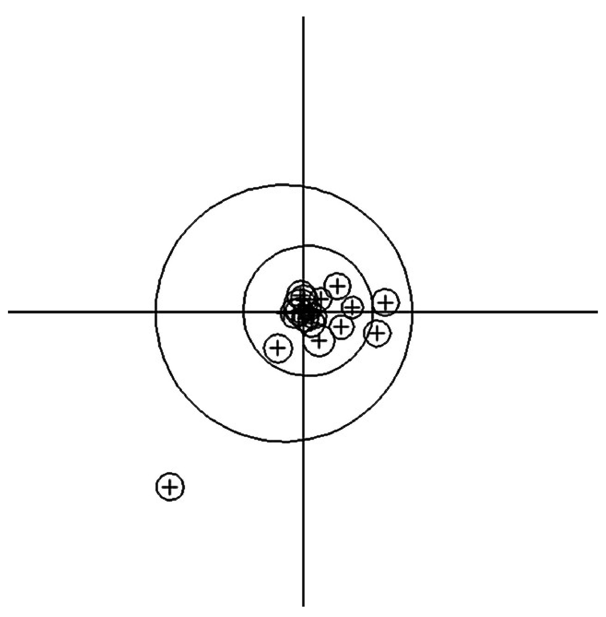
Abstract

In the standard, on-ground processing of *Fermi* Large Area Telescope (LAT) data, detailed track fitting is done for each event. In addition to estimating the incident direction, this reconstruction also provides an estimate of the two-dimensional errors. Although this event-by-event error information in basic form has been included in the standard data release, it is not used in the standard LAT science analysis. We show here the characteristics of these covariant errors when projected onto the sky and discuss the potential science returns, including source finding, localization, and image analysis.

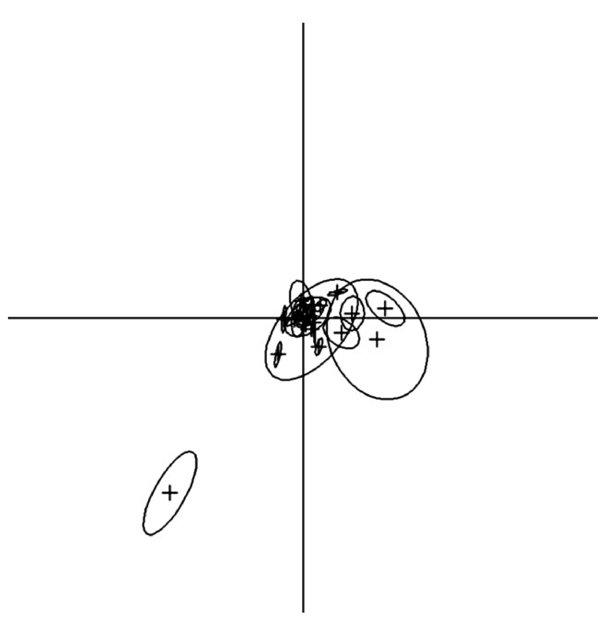
The LAT is a Self-Aware Telescope

To be able to detect high-energy (≥20 MeV) γ-rays, the LAT [1] includes a pair-conversion, silicon-strip tracker which uses well-tested particle-physics technology. We reconstruct both a position **and** an error for every event using a Kalman filter process [2,3], producing a fully-covariant, 2d error matrix. Currently, this information is provided, but it is never used in the standard analysis. Our method improves upon this:

Average PSF [4]: (current method) Monte Carlo detector responses are averaged to give an energy-dependent point-spread-function (PSF) for all events which convert in the the first 12 tracker planes of the detector and a second number for those converting in the last 4. Information about the individual reconstruction quality is lost.



Individual Covariant Errors [5]: (improved method) The errors depend on the full path reconstruction information. Directional information is preserved in the shape and orientation of the error ellipse derived from the covariance matrix. High-accuracy events have smaller ellipses.

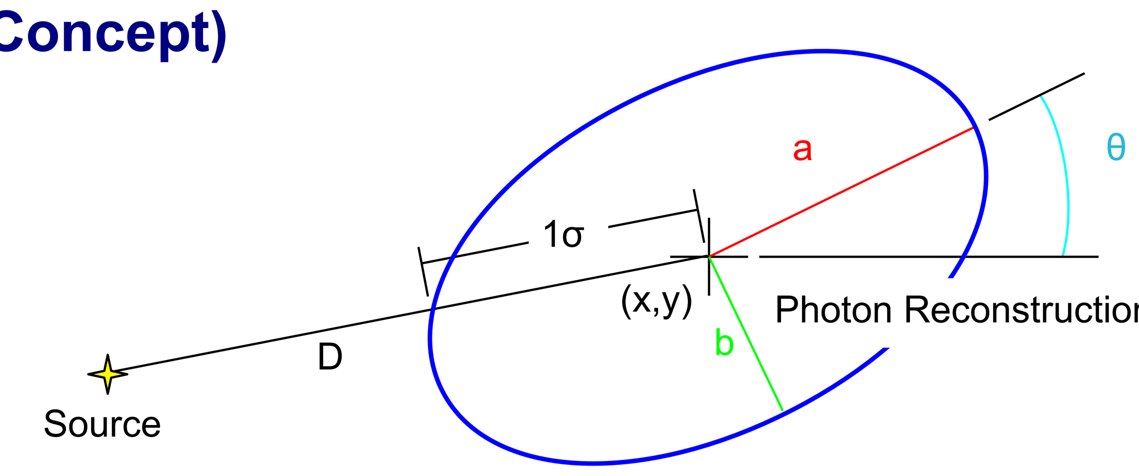


Why we know Individual Covariant Errors are better

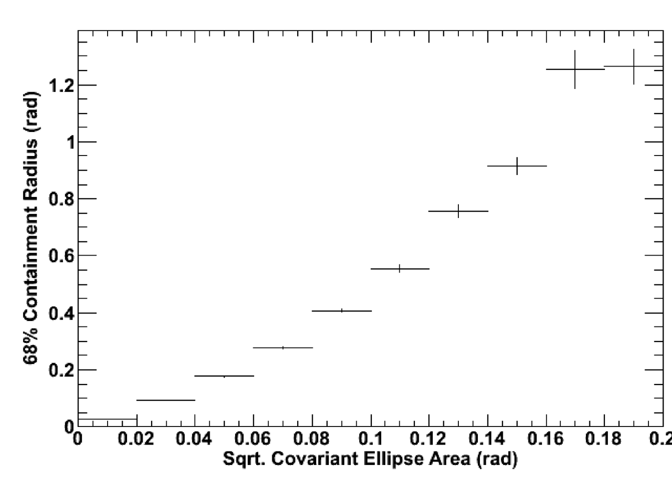
(Proof of Concept)

We use a Monte Carlo (MC) simulation of the LAT to demonstrate that using event-by-event errors provides **more information** and **better results**.

The following studies used photons generated from 100MeV to 18GeV with a $1/E^2$ spectrum.



68% Containment

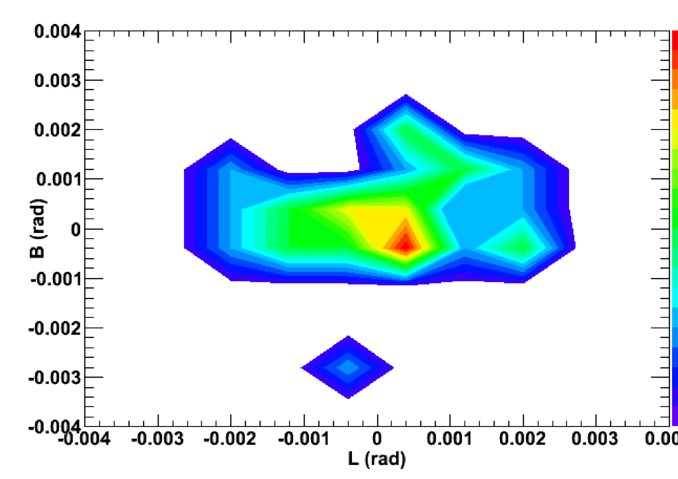


Covariant 68% Containment

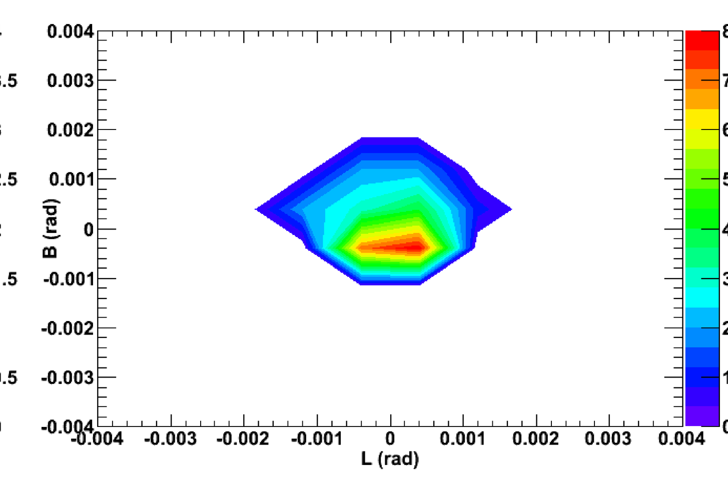
For the above plot, ~100,000 photons were generated and binned by the area of their covariant ellipses. The 68% containment radius for each bin was then measured and plotted.

This demonstrates that there is valid information in the size of the ellipses. In other words: **points with smaller covariant errors are more accurate.**

Localization



Standard PSF Localization



Individual Covariant Localization

Each of the two plots above was generated using 30 sets of 3000 independently generated MC photons which satisfied a set of sanity and quality cuts. Each set was then averaged using the average psf (left) or event-by-event (right) errors and the resulting points were histogramed.

Based on this simulation, covariant errors perform approximately **40-60% better** than the standard ones in RMS localization, an important measure of resolution.

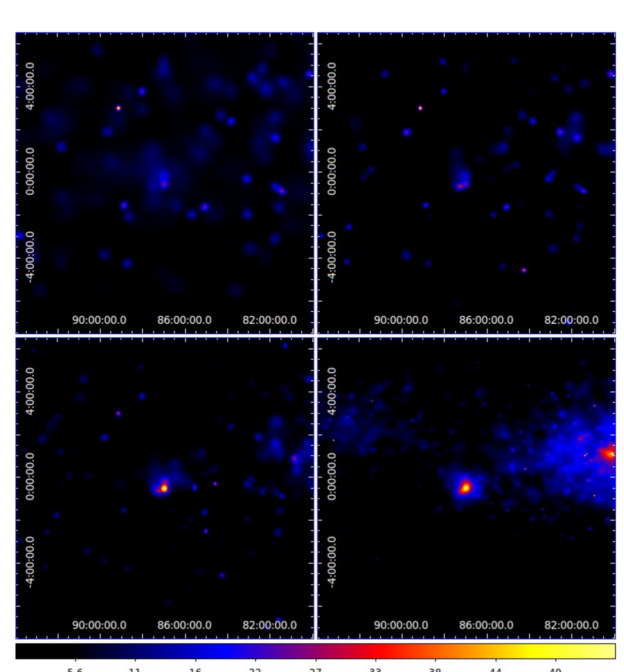
Why don't science analyses already use covariance?

Using event-by-event errors improves results, but thus far it has not been necessary because the existing method performs very well. The use of covariance would also increase the complexity of any analysis and require careful verification.

We now want to extract more information from the data to investigate new science topics, so event-by-event errors are being explored. This will be one of the methods used by the Pass 8 group in building the latest and best version of the analysis software.

See poster 145.18 (Atwood, et. al.) for more information.

Example Transient Localization



To the right, an application of the event-by-event covariance is seen using the transient gamma-ray flare from a nova in the symbiotic binary v407 Cygni [6]. Beginning at the onset of the flare (March 10, 2010 18:00:00), each photon within a 14 x 14 degree square ROI is plotted using a bivariate normal distribution function derived from each event's covariant error matrix. Intervals at 6 hours (upper left), 12 hours (upper right), 1 day (bottom left), and over the full active state (10-25 March 2010) are shown. Event selections include pass 7 source class photons, and a zenith angle cut of < 100 degrees.

Covariant errors allow the source to be seen with relatively little data, because a large amount of information is extracted from each event. The method can have an impact in a wide variety of science applications.

Future Plans

Event-by-event errors show definite promise, but there is more work to be done:

- Difficulty with coordinate transformations may force us to use a 3-dimensional error matrix to eliminate singularities at the poles. This would be akin to using quaternions instead of rotation matrices.
- The analysis code sometimes gives unphysical errors. For now, those events are discarded, but they must be understood before we progress.
- We need to remove several simplifying assumptions, requiring detailed understanding of the method's behavior, and integrate it into the public Science Tools.

References:

1. Atwood, W. B., et al. 2009, ApJ, 697, 1071
2. Kalman, R. E. 1960, *Transactions of the ASME-Journal of Basic Engineering,* 82, 35
3. Jones, B. B. 1998, Ph.D. Thesis, Stanford University. (astro-ph/020288)
4. LAT performance page: <http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm>
5. Johnson, R. P., private communication, 2011.
6. Abdo et al. 2010, Science, 329, 817

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