LAT Performance

Eric Charles
Fermi Summer School 2013
Lewes, Delaware
May 30, 2013
Outline

- Optimizing the LAT for Science
- Instrument Response Functions (IRFs):
  - Validating and Calibrating the IRFs
    - Background Contamination
    - Calibration Samples and Analyses
    - Effective Area
    - Point-spread Function
    - Energy Dispersion
- Summary of Typical Systematic Uncertainties
Almost every plot in this talk is taken from this paper.

The paper is long (170 pages in preprint format, w/ 90 figures).

There is a good chance that the answers to your questions about LAT data analysis are in the paper.

The arXiv version has a table of contents to make it more useful as a reference.

Liz kindly included it in the packet on your memory sticks.
OPTIMIZING THE LAT FOR SCIENCE
Wide Variety of Analysis Subjects

- **MW Variability**
- **Morphology, Source Extension and Counterpart Identification**
- **SEDs and Spectral Components**
- **Catalogs, Population Studies and Contribution Estimation**
- **DM Searches**
- **Single Photon Studies**

No real “standard” analysis, lots of particular cases.
Fermi-LAT Science Covers Huge Phase-Space

Different data selections for different science cases.
Factor of $>10^5$ in bkg. reduction is achieved in several stages.

About 50% $\gamma$-ray efficiency inside fiducial volume from 1-100 GeV.
INSTRUMENT RESPONSE FUNCTIONS
Decomposing the Gamma-ray Sky

Sky = Galactic Diffuse + Point Sources + Isotropic
Likelihood fitting uses lots of information optimally. This is a double-edged sword. Issues with any of our IRFs can affect fit and can be difficult to disentangle.
LAT Coordinate system
Some other useful angles.
Effective Area from Monte Carlo

Slice in $\theta$ $E$ dependence $A_{\text{eff}}(E;\theta=0 \text{ on axis})$

Slice in Energy $\theta$ dependence $A_{\text{eff}}(\theta;E=1\text{GeV})$

Integrate over $\theta$ Acceptance $A(E)$
**Post Launch MC-Based corrections to $A_{\text{eff}}$**

$A_{\text{eff}}$ is affected by ghost signals and correlates with trigger rate and “deadtime fraction”. “Overlay” periodic triggers from flight data on MC events to estimate scale of effect as a function of energy.

**$A_{\text{eff}}$ v. Deadtime**

![Graph showing $A_{\text{eff}}(f_{\text{dead}})/A_{\text{eff \ mean}}$ vs. $t_{\text{dead}}/t_{\text{elapsed}}$ with Mean $f_{\text{dead}}$ marked.]

**Slope of (left plot) v. Energy**

<table>
<thead>
<tr>
<th>$a_0$</th>
<th>-1.372</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0$</td>
<td>5.437</td>
</tr>
<tr>
<td>$a_1$</td>
<td>-0.7523</td>
</tr>
<tr>
<td>$\log_{10}(E_1)$</td>
<td>2.651</td>
</tr>
<tr>
<td>$a_2$</td>
<td>-0.2397</td>
</tr>
<tr>
<td>$\log_{10}(E_2)$</td>
<td>4.639</td>
</tr>
</tbody>
</table>

**$\phi$ dependence map @ 10GeV**

![Color map showing $A_{\text{eff}}$ values with $\phi$ degrees plotted.]

- $A_{\text{eff}}$ is affected by ghost signals and correlates with trigger rate and “deadtime fraction”.
- “Overlay” periodic triggers from flight data on MC events to estimate scale of effect as a function of energy.
Fit a scaled deviation for the PSF in \((E, \theta)\) bins.

Note that the PSF has non-Gaussian tails, which vary with \(E\) and \(\theta\).
As with PSF, we fit a scaled deviation for the energy dispersion in (E,θ) bins.

Note that the response has non-Gaussian tails, is asymmetric, and varies with E and θ.
VALIDATING AND CALIBRATING THE IRFs
Instrument is very stable: ok to use single IRF set for mission to date.

(Gray region is ~ 2 years data used for these analyses).
Low power budget -> $\mu$s (not ns) electronics.

Sensitive to signals from out-of-time cosmic rays, depends CR rate which varies w/ orbit.
Vela: DEC = -45°, β = -60°

Crab: DEC = +22°, β = -1°

Each point in the sky traces a complicated path in the LAT frame which depends on declination and ecliptic latitude (β)

Observing Profile for Vela

The LAT performance depends primarily on the angle w.r.t. the boresight (θ)

“Observing profile”: observing time as a function of θ
## Flight Data Calibration Samples

### Calibration Sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vela pulsar (2 years)</td>
<td>Phase-gated</td>
</tr>
<tr>
<td>15° ROI, $q_{z, vra} &gt; 85°$</td>
<td></td>
</tr>
<tr>
<td>Very clean bkg. subtraction but cuts off around 3 GeV</td>
<td></td>
</tr>
<tr>
<td>76 Bright, isolated AGN (2 years)</td>
<td>Aperture</td>
</tr>
<tr>
<td>6° ROI, $q_z &gt; 100°$, $E &gt; 1$ GeV</td>
<td></td>
</tr>
<tr>
<td>Need small PSF for bkg. subtraction</td>
<td></td>
</tr>
<tr>
<td>Earth limb (200 limb-pointed orbits)</td>
<td>Zenith Angle cut</td>
</tr>
<tr>
<td>$E &gt; 10$ GeV</td>
<td></td>
</tr>
<tr>
<td>Difficult to model earth limb emission below ~ 10 GeV.</td>
<td></td>
</tr>
<tr>
<td>All Sky</td>
<td>Latitude</td>
</tr>
<tr>
<td>$E &gt; 10$ GeV (also prescaled samples at lower $E$)</td>
<td></td>
</tr>
<tr>
<td>Useful for optimizing selections, but not precise</td>
<td></td>
</tr>
</tbody>
</table>

**Shown for P7TRANSIENT event class**
Any particles misclassified as $\gamma$ rays will decrease the signal to noise for sources, and may affect spectral measurements if unaccounted for.

Since the $\theta$-distribution and front/back ratio in BKG are different to $\gamma$ rays they can also confuse the likelihood fit.
P7SOURCE, P7CLEAN and P7ULTRACLEAN were developed w/ flight data.

Too much background to use this method for P7TRANSIENT.

Energy dependent cut rejects 5% of event at all energies.

Cut rejects larger fraction of events.
Fit signal + background templates (top) to compare bkg. to MC predictions (bottom).

This is needed to disentangle $\gamma$ rays in fitted isotropic components when measuring the Extra-Galactic background intensity.
Background Contamination spectra

**Background Rates for P7SOURCE**

- Total residual CRs
- Primary CR protons
- Primary CR $e^+ + e^-$
- Secondary CRs

**Background Rates for P7CLEAN**

- Total residual CRs
- Primary CR protons
- Primary CR $e^+ + e^-$
- Secondary CRs

**Isotropic Emission Templates**

Spectra of particle background contamination for various event classes.

These are absorbed into the isotropic component when fitting.
Errors in effective area translate directly to errors in Flux.

Critical for measuring spectra, extrapolation to other energies, identifying spectral features, source classification…
Explain method for data/MC efficiency comparison:

a) Counts spectra in signal and background regions
b) Excess in signal region before and after cut
c) Efficiency of cut on data and MC
d) Ratio of $\eta_{\text{data}} / \eta_{\text{mc}}$
Data/ MC efficiency comparison for

a) Track finding & fiducial cuts
b) Trigger primitives
c) Onboard filter
Most consistency checks (top) yield excellent results. Front/Back fraction (bottom left) sets scale for $A_{\text{eff}}$ errors (bottom right).
Simple “Bracketing” functions maximize bias within $A_{\text{eff}}$ error envelope. Example with two point sources.
**A_{eff} induced variability**

**Time series of residuals**

- Use total counts & exposure to predict counts in each 12-hour period.
- Vela (on-off) excess is very stable.
- Scaled residuals are ~ unit Gaussian.
- FFT shows white noise + 53.4 day orbital precession.

---

**Distributions of residuals**

- \( \mu = -0.03 \pm 0.03 \)
- \( \sigma = 1.04 \pm 0.02 \)
- \( \chi^2 = 42.1 / 54 \text{ DOF} \)

---

**Fourier Trans. of Time Series**
Errors in the PSF affect localization, studies of morphology, and to a lesser extent fluxes and spectra

Critical for establishing source extension and morphology
Monte Carlo underestimates PSF above ~1 GeV, particularly for back-converting events.

In-flight PSF based on study of bright AGN with ~11 months of data

Not enough statistics to study \( \theta \)-dependence: Averaged it out

Use phase-subtracted pulsar and AGN samples to compare containment of MC PSF to in-flight PSF

**In-flight PSF fits the core of distribution better, but overestimates tails**
Error band on aperture coming when ignoring \( \theta \)-dependence of PSF for a series of 12 hour observation

Comes from variations in observing profile (inset)

In General: quantify bias on fit as a function parameters using bracketing IRF technique.
Energy Resolution

Errors in the Energy Resolution affect spectral and spectral features

Critical for measuring spectra, extrapolation to other energies, identifying spectral features, source classification…
Reconstruction provides 3 energy estimates.

The likelihood based energy estimation method has sharp features at bin edges. We removed it from consideration and achieve much smoother response.
Use heavy ions (C,N,O...) to calibrate crystal response in high ranges
Use Geomagnetic cutoff and e⁺e⁻ to calibrate energy scale near 10GeV
3% degradation over mission to date

Energy Calibration, Trending and Scale
Use simulations to show effect of ignoring energy dispersion in counts spectra and in fitting (inset).

Also study the effect of bias in energy scale on spectra.
Given the extreme smoothness of the Earth albedo spectrum we can quantify the significance of any residual local (< 1 decade width) features.

The most significant (25σ) is about 4% relative (near 3 GeV, related to Geomag. cutoff)

Highly significant deviation around ±2% relative near 3GeV

Large fractional deviation at high energy with low stats.
These are just rough estimates of systematic errors on commonly measured quantities. (Section number refer to “performance paper”).

It is not meant to replace actually estimating the systematic errors which are relevant for a particular analysis.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$A_{\text{eff}}$</th>
<th>PSF</th>
<th>Dispersion</th>
<th>Energy Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{25}$</td>
<td>$\sim 8%$ ($\S\ 5.7$)</td>
<td>$\sim 8%$ ($\S\ 6.5$)</td>
<td>$\sim 3%$ ($\S\ 7.4$)</td>
<td>$+13% - 5%$ ($\S\ 7.4$)</td>
</tr>
<tr>
<td>$S_{25}$</td>
<td>$\sim 10%$ ($\S\ 5.7$)</td>
<td>$\sim 6%$ ($\S\ 6.5$)</td>
<td>$\sim 2%$ ($\S\ 7.4$)</td>
<td>$+4% - 2%$ ($\S\ 7.4$)</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>$\sim 0.09$ ($\S\ 5.7$)</td>
<td>$\sim 0.07$ ($\S\ 6.5$)</td>
<td>$\sim 0.04$ ($\S\ 7.4$)</td>
<td>-</td>
</tr>
<tr>
<td>Variability</td>
<td>$\sim 3%$ ($\S\ 5.6$)</td>
<td>$\sim 3%$ ($\S\ 6.5$)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Localization</td>
<td>-</td>
<td>$\sim 0.005^\circ$ ($\S\ 8.2$)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
SUMMARY
• LAT data is used to study a many topics in the $\gamma$-ray sky
  – Flexibility is need to account for many types of analysis
  – Huge amount of instrumental phase space to calibrate
• Data reduction to “public” event classes is tremendous effort
  – Lots of places where it can go wrong in subtle ways
• Current analysis and IRFs provide tremendous potential
  – $\sim 10\%$ errors from $100\text{MeV} – 300\text{GeV}$
    • LAT analyses are becoming correspondingly ambitious
  – Ongoing work to expand energy range, reduce systematic errors
    • Needed to support next generation of LAT analyses
For this afternoon

- To follow the derivation of the IRFs please download this file:
  - (Maybe not all at once though)
- Also available on memory stick
- The tar file includes:
  - The IRF files for the P7SOURCE_V6 IRFs
  - A file of simulated events you can use to derive IRFs.