Fermi LAT Instrument Response Functions

Fermi Summer School
June 2011
• Context of IRFs
  – Likelihood formalism
• Effective Area
• Point Spread Function
• Energy Dispersion
• Validation & Correction of IRFs
CONTEXT OF IRFs
Recall that IRFs are designed in the context of Likelihood fitting, for example:

\[ A_{\text{eff}}(p, E, t) \]

where \( p \) is the celestial direction and the time dependence is there for 2 reasons:
1. Changing instrument (configuration, degradation, etc.)
2. Instrument pointing

In practice we work in the instrument frame, so we have, for example:

\[ A_{\text{eff}}(v, E, t) \]

where \( v \) is the direction in the instrument frame and the time dependence only reflects changes in the instrument.

In fact, this is why we build “livetime cubes” which give us the viewing profile for each direction in the sky:

\[ t_{\text{live}}(v; p) \]

Which we can use to derive the exposure for each direction and energy band

\[ E(E, p) = \int A_{\text{eff}}(v, E) \, t_{\text{live}}(v; p) \, d\Omega \]

\( \int \) = Integral symbol in Microsoft Power Point
We also define the PSF and $E_{\text{disp}}$ in instrument coordinates, for example:

\[ P(v';v,E,t) \]
\[ D(E';v,E,t) \]

Where $v'$ and $E'$ are observed direction and energies (as opposed to true ones).

Then with the “livetime cubes” we can do the current convolution integrals to get the expected counts distribution $M(E',p')$ from a flux model $F(p;E)$ which is what we need for the likelihood fit:

\[ M(E',p') = \int t_{\text{live}}(v;p) A_{\text{eff}}(v,E) P(v';v,E) D(E';v,E) F(p,E) \, d\Omega_v \]
EFFECTIVE AREA: $A_{\text{eff}}$
Effective Area \((A_{\text{eff}})\)

- \(< 100\ \text{MeV}\) limited by 3-in-a-row requirement
- \(< 1\ \text{GeV}\) limited discriminating information
- \(> 100\ \text{GeV}\) self-veto from backsplash

Off-axis: more material, less cross section

Shift from front/back events as we go off-axis
Generate known “isotropic” incoming flux: (200M events, 1/E spectrum)
Count how many events pass cuts in each bin
Normalize to input flux
Understanding $A_{\text{eff}}$ Behavior

$A_{\text{eff}}$ (logE,cosθ) tables: generate uniform event set and count how many pass cuts

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

Integrate over cosθ Acceptance $A(E)$

Front Events
Back Events
Using the $A_{\text{eff}}$ tables

Recall that the likelihood interface expects:

$$A_{\text{eff}}(v,E,t)$$

What we have produced is a table of values:

$$A_{\text{eff}}(\cos \theta, \log E)$$

Clearly a bit of work is required to do interpolations, verify that errors for interpolations are not significant.

Also, we have ignored $\phi$-dependence. Need to quantify how much of a problem this might be for particular studies.
POINT SPREAD FUNCTION
Low energy: dominated by MS

High energy: dominated by strip pitch

Off-axis: more material, more MS at low energy

More pattern recognition confusion off-axis at high energy
Use same simulated event sample as for $A_{\text{eff}}$
Calculate delta between generated (true) and reconstructed directions
$\delta v = v' - v$
Describe distribution as a function as of Energy, incident angle
Describe (on-axis) angular resolution scale as a function of energy

$$SP(E) = (c_0^2 + c_1^2 \frac{E}{100\text{MeV}})^{2\gamma} \frac{E}{100\text{MeV}}$$

Note that $A_{\text{eff}}$ weighted containment (points) can be somewhat larger
Scaling takes away much of energy dependence

However, behavior of tails varies with energy and incidence angle
Fit a reasonable functional form to scaled angular deviation distribution in each bin of logE, cosθ

\[ x = \frac{\delta \alpha}{\text{SF}(E)} \]

\[ P_{\text{king}}(x; \sigma, \gamma) = (1 - \frac{1}{\gamma})(1 + \frac{x^2}{2\sigma^2})^\gamma \times dx \]
Recall that the likelihood interface expects:
\[ P(v', v', E, t) \]

What we have produced is tables of parameters for
\[ K((v' - v)/S_P(E), \sigma_c, \gamma_c, \sigma_t, \gamma_t, f_c; \cos \theta, \log E) \]

Clearly a fair amount of work is required to do interpolations, verify that errors for interpolations are not significant
ENERGY DISPERSION
Energy Dispersion (D)

Low energy: energy lost in TKR

High energy: energy lost out back of CAL

Off-axis: more material, more MS at low energy

More pattern recognition confusion off-axis at high energy
Scaling (with paraboloid) takes away much of energy and angular dependence.

However, as with PSF, behavior of tails varies with energy and incidence angle.
Fit a reasonable (?) functional form to scaled energy dispersion distribution in each bin of logE, cosθ
Recall that the likelihood interface expects:
\[ D(v', v', E, t) \]

What we have produced is tables of parameters for
\[ R(\Delta E/ES_D(E), \sigma_{l1}, \sigma_{l0}, \sigma_{r0}, \sigma_{r1}, x_0, \cos\theta, \log E) \]

Clearly a fair amount of work is required to do interpolations, verify that errors for interpolations are not significant.
VALIDATING THE IRFs WITH FLIGHT DATA
Validating the IRFs with flight data

• To validate $A_{\text{eff}}$
  – Standard candles? No!
  – Step by step analysis of event selection efficiency
    • Need “clean” photon samples
  – Consistency checks
• To validate PSF
  – Known point sources? Sort of.
    • Pulsars.
• To validate $E_{\text{disp}}$
  – Known spectral features? DM lines? We wish…
**Flight Data Calibration Samples**

<table>
<thead>
<tr>
<th>Calibration Sample</th>
<th>Method</th>
</tr>
</thead>
</table>
| Vela pulsar (2 years)  
15° ROI, \(q_z,_{vela} > 90°\)  
Very clean bkg. subtraction but cuts off around 3 GeV | Phase-gated |

| 30 Bright, isolated AGN (2 years)  
6° ROI, \(q_z > 105°, E > 800\text{MeV}\)  
Need small PSF for bkg. subtraction | Aperture |

| Earth limb (200 limb-pointed orbits)  
E > 8 GeV  
Difficult to model earth limb emission below \(~ 10\text{ GeV} \) | Zenith Angle cut |

Calibration samples showing signal (grey) and background (red) regions for the P7TRANSIENT event class. These are used as starting point for testing P7SOURCE event selection criteria.

Statistics of the calibrations samples after background subtraction.
WORK (FOR YOU) TO DO
Some (Open-Ended) Projects

- Have a go at deriving your own IRFs
  - Simulated data provided in extended FITs format
- Compare them to publically released ones
- Take a look at some data from calibration sources, design tests for IRFs
  - Pre-skimmed data with some additional variables
    - Vela Pulse Phase
    - Angular separation from nominal AGN position
    - Zenith Angle