Alignment Calibration Observations

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Gamma-ray Source Localization and Pointing Knowledge

- LAT science requirement for source location is < 30 arcsec
  - High latitude source of 10^{-7} cm^{-2} s^{-1} flux at >100 MeV with a photon spectral index of -2.0 above a flat background and assuming no spectral cut-off. 1 sigma radius. 1-year survey.
- Observatory pointing knowledge (<10 arcsec) vs. pointing accuracy (<2°)
- The uncertainty in the measured direction of a single photon by LAT is determined by:
  - single photon PSF
  - end-to-end pointing knowledge
    - GN&C uncertainties
    - mechanical/thermal distortions from the mean
    - alignment calibration uncertainties (residual)

The requirements explicitly specify all of these.

- LAT will measure many photons from a point source. The point source localization is determined by a combination of several factors:
  - Aeff, FOV, single photon direction errors, source characteristics (brightness, emission spectrum, sky region), and exposure
  - The effect of an error in the pointing knowledge will only be noticed to the extent that they don't average out.
- **Intent of the 10 arcsec pointing knowledge requirement is to support source localizations of bright sources to 10 arcsec.**

Calibration Strategy

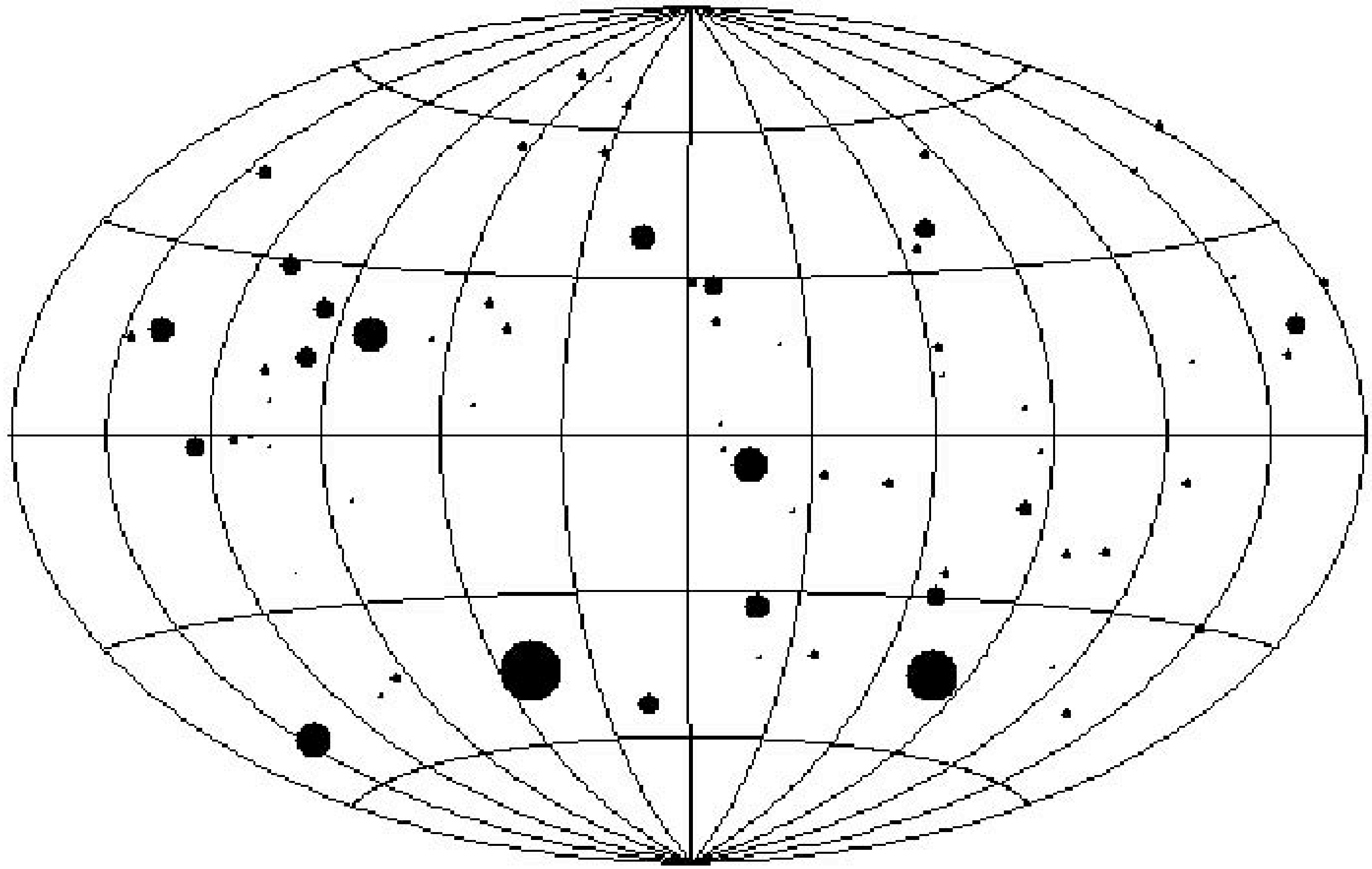
- For science, there is no need to align LAT-SC physically to very high precision prior to launch (or to maintain that mechanical alignment during launch). Requirement: 0.5 deg
  – well-established, bright gamma-ray point sources whose positions on the sky are known (pulsars, AGN) provide a calibration reference
  – the mathematical transformations from instrument coordinates to sky positions can be obtained using photons detected from these sources.
  – the pointing knowledge requirement is thus mainly a stability requirement on orbit.

- Since the system is used to calibrate itself, all the other pointing knowledge components can affect the calibration.
  – our choice: include the residual in the total error decomposition
  – analysis of expected residual size requires a detailed understanding of the mechanical/thermal stability of the system over the timescales needed to accumulate sufficient photon statistics.

- Calibration continuously monitored and refined as data accumulate.
  – During routine operations, calibration residual continues to reduce (see later slides).
  – Earlier data, prior to calibration updates, are still valid and are reprocessed simply.

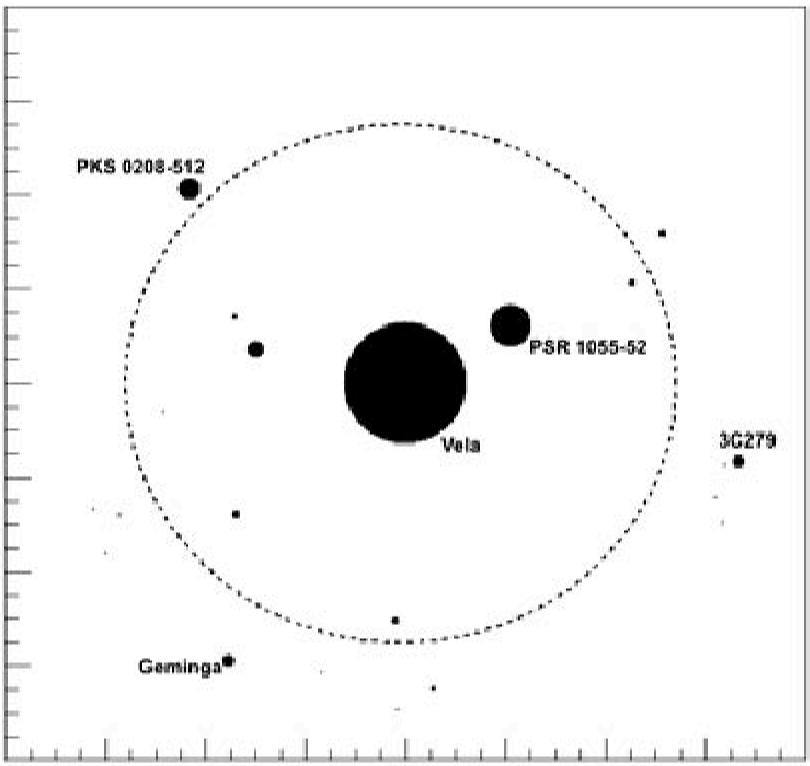
Known Sources for Calibration

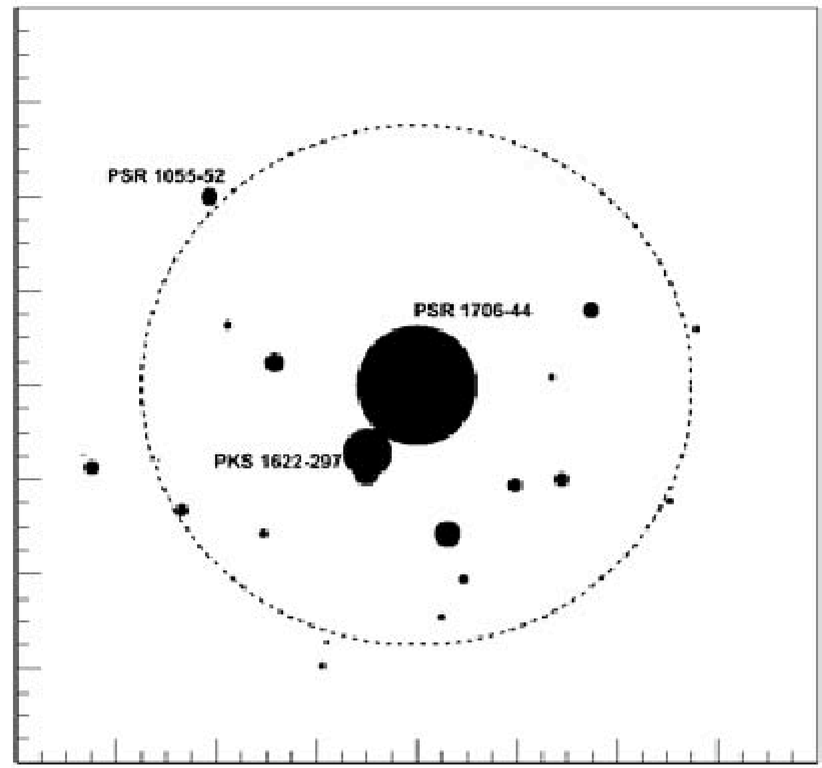
- Locations of 66 known (identified EGRET sources
- Larger circles indicate better LAT localizations
- Many options. The three best steady sources are likely the Vela pulsar, the Geminga pulsar, and PSR 1706-44 However, bright AGN flares would also be excellent calibration sources (not relying on AGN flares!).



Harder spectra (and brighter) sources are localized better. Some uncertainties in the localization potential from uncertainties about the highest-energy spectra (one reason to do the mission!). Details are not critical to calibration plan.

Two Useful Pointed Observations





Known high-energy gamma sources within the field of view of the LAT for an observation pointed at Vela (left) and PSR 1706-44 (right). Larger dot signifies better ability to localize the source. Dotted line is 55 degrees from the center of the field.

LAT Imaging

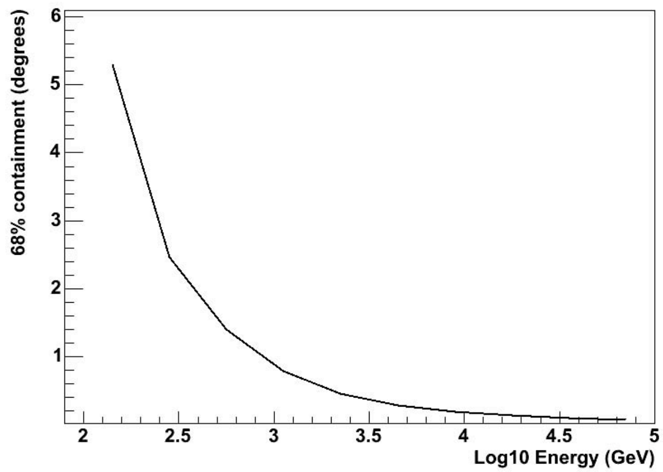
- Somewhat different from other kinds of imaging:
- LAT "shutter time" is a few microseconds for each "frame" = single photon detection ("event").
- Analysis combines a very large number (from a few to millions, depending on source intensity), which can be recorded at any time throughout the mission.
  - scanning the whole sky during most of the mission
  - for many sources, we will collect < 1 photon per orbit
  - combination of events constitutes the exposure
- The calibration is used to place each of the photons of the exposure on the sky correctly.
- Calibration sources are typically in the field of view at all times, so the calibration can be verified and monitored contemporaneously with other source observations.

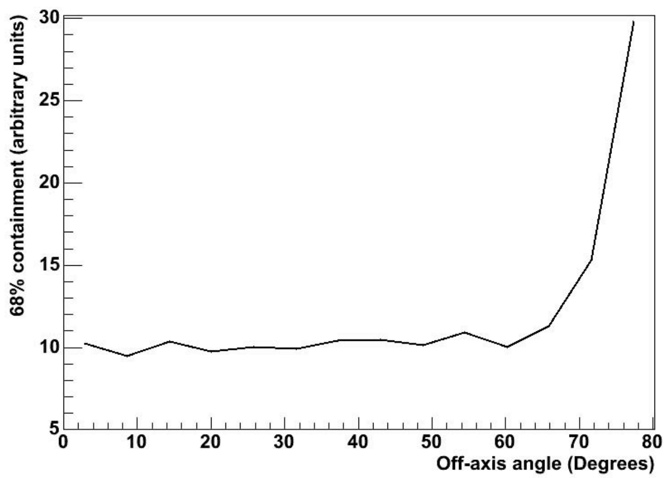
Calibration Residual

- Compare the measured positions with their known positions, photon-by-photon in instrument coordinates.
  - Calibration must be done in instrument coords.
  - Thus, don't think of the calibration as aligning several reconstructed sources (blobs on the sky) with known positions;
  - More like millions of individual sources (each photon) over the full instrument field of view. The true position for each photon is known, and the offset from the measured position is recorded.

- Use these data to extract the three rotation angles (a, b, c) between LAT and spacecraft frames.
  - **The values of (a, b, c) are the calibration.**
  - **The errors (δa, δb, δc) are the calibration residuals.**
  - **Calibration plan results in sqrt($(\delta a)^2 + (\delta b)^2 + (\delta c * \sin(55°))^2$)<4 arcsec.**

Quick and easy LAT source localization

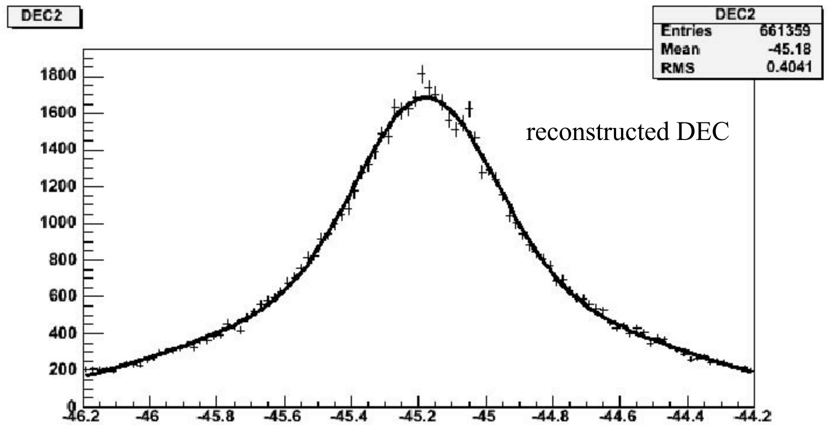


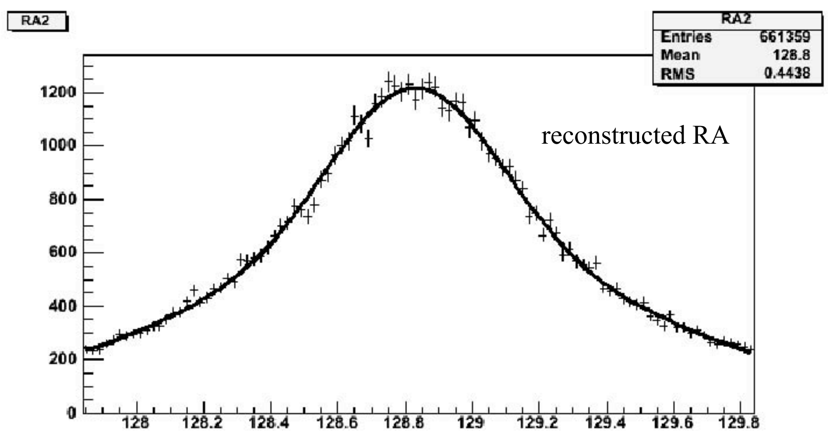


- For each source, make histograms in RA and DEC, for all photons within 5 sigma (sigma = psf) of the true position.
- Each photon was weighted by $1/psf^2$. This accounts for the variation of the angular resolution with energy and conversion layer, but does not use the full information about the shape of the psf.
- Fit the RA and Dec histograms with the sum of two Gaussians (which have the same mean but different sigma).

LAT Localization

Vela one-year sky survey simulation





note: distributions do not yet incorporate our best knowledge of the LAT PSF; along with more careful likelihood analysis, We will do better than this.

- Localization (precision on mean values) much better than width of distribution (shown weighted by $1/PSF^2$), due to high statistics (~660,000 photons)

- any pointing uncertainties that are small compared with the best photon PSF will not affect the localization ability *provided* they average down faster than the intrinsic LAT localization capability.

- Choice: specify error budget using widths of distributions. If they sum to <10 arcsec, guaranteed to meet pointing knowledge requirement; if they are larger, *then* must determine the degree of averaging down expected from the observatory to assess impacts on science.

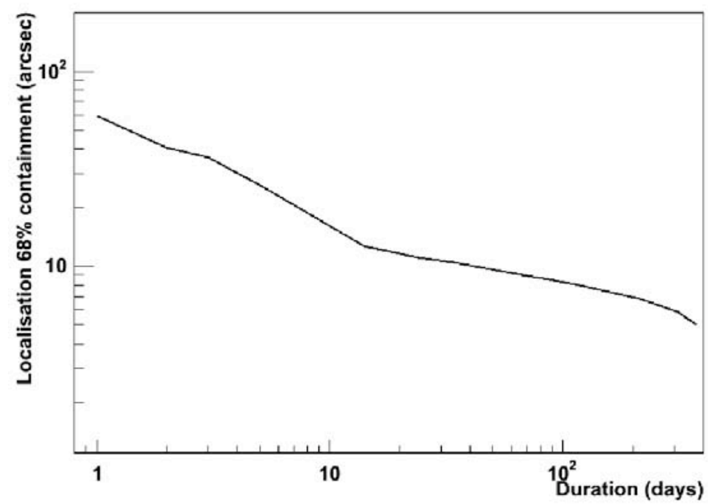
Averaging

- Three important and distinct categories of "averaging down":
  - time (statistics)
  - geometric mechanical-thermal motions (intra-LAT and LAT-spacecraft)
  - geometric orientation with respect to the target (instrument coords vs sky coords)

  All three are affected by the observing plan.

- Illustration of averaging down with time:
  - full simulation of localization of Vela pulsar as a function of time for a two-week pointed observation followed by 365 days in sky survey mode.

  [note: Vela is only one of a sizable number of calibration sources—see later slides.]



- Any thermal-mechanical distortions that are stable will be calibrated out; any distortions or errors that vary rapidly enough (*e.g.*, jitter) and are small compared with the PSF will average down to a mean value that is negligible for GLAST science.

Systematic Uncertainties

- Possible sources considered are typically all small
  - if LAT systematically reconstructs positions of high-energy photons offset relative to low-energy photons, then two sources with very different spectral characteristics would have systematic location shifts in instrument coordinates.
    - no indication this happens, or any reason to expect it, and would anyway average out due to orientation averaging (third kind).
    - will be verified in LAT beam test
  - same conclusion for effects such as the "fisheye" effect (offset dependent on angle of incidence and energy, well-known for pair conversion telescopes).
  - presence of unaccounted point sources and/or non-uniform diffuse emission nearby calibration sources.
    - magnitude difficult to quantify since it depends on the nature of the gamma-ray sky at spatial and energy scales yet to be explored (another reason to do the mission!). Typical magnitude in worst case on reconstructed positions expected to be less than 10 arcsec.
    - effect on the calibration values will be <u>much less</u> than this due to geometric averaging into instrument coordinates!

- Thus, calibration systematic errors will be much smaller than the statistical uncertainties, particularly during year 1. This will be verified by calibration source monitoring throughout the mission.

Calibration Plan: Observations

- First two-week observations to perform initial LAT-SC calibration to better than 15 arcsec (more than sufficient for most year-one science topics).
  - Optimization of initial observing strategy (source selection, optimal orientation, etc.) under investigation. Current plan is Vela and PSR1706 in center of the field of view (two-target mode).
- Then, proceed with sky survey and use known sources to reduce the error over year 1 to the required level.
  - 4 arcsec calibration residual statistically achievable
  - 10 arcsec pointing requirement will be easily verified by end of one year sky survey
- These observations have been simulated using the full LAT instrument simulation.

Detailed Simulations of Observations

- Key calibration source characteristics

Source	α	β	E_{break} (GeV)	E_{cutoff} (GeV)	Flux(>100MeV, 10^{-8}ph $m^{-2}s^{-1}$)
Crab	2.19	-	-	2	226.2
Geminga	1.5	-	-	1.5	352.9
Vela (1)	1.62	2.7	1	30	834.2
Vela (2)	1.69	-	-	2	834.2
PSR 1055-52	1.94	-	-	20	33.3
PSR1951+32	1.74	-	-	30	16.0
PSR 1706-44	1.27	2.25	1	30	112.2

- Spectra in some cases described by broken power law (α is low-energy index, β is high-energy index, with switchover at E_{break}) with a high-energy cutoff (E_{cutoff}).

- Two Vela models are used to illustrate importance of highest-energy spectrum. Vela (1) was used in EGRET in-flight calibration; Vela (2) is much more pessimistic for our purposes , but is consistent with existing gamma-ray data.

- PSR1706 is not as bright as Vela, but it has a spectrum with more high-energy photons, which are reconstructed by LAT with greater accuracy.

Detailed Simulations of Observations

- With the calibration sources, observation scenarios simulated:
  - one year's all-sky survey (+/- 35 degree rock)
  - two week pointed observations centered on Vela and PSR1706-44. Vela is observable when PSR1706 is occulted and vice versa.

- By simulating the observations using the detailed LAT instrument simulation, which supports misalignments, and then passing the simulated data through the full event reconstruction chain and a simple analysis, we can
  - simulate the calibration observations and verify the statistical precision obtained with time;
  - quantify the impacts of thermal-mechanical distortions
  - quantify how much effects average out for different observations

- Several scenarios studied to demonstrate effects clearly:
  - misalignment rotation of all towers about the X-axis 30 arcsec (all in the same direction)
  - 8 towers rotated +50 arcsec, 8 towers rotated -50 arcsec, about the X-axis ("splayed" configuration)

Results

Duration	Source	Error	Deviation	Mode	Offset
1 year	Vela (1)	5.9	6.4	Scan	0"
1 year	Vela (2)	15.6"	13.3"	Scan	0"
1 year	PSR 1706-44	17.0"	22.7"	Scan	0"
1 year	Geminga	20.7"	20.6"	Scan	0"
1 year	Crab	40.0"	52.3"	Scan	0"
1 year	PSR 1951+32	20.6"	25.5"	Scan	0"
14 days	Vela (1)	12.7"	10.5"	Point	0"
100 days	Vela (1)	8.1"	10.1"	Scan	30"
31 days	Vela (1)	8.7"	27.9"	Point	30"
1 year	Vela (1)	5.0"	4.9"	Scan	50"

- Error is the precision of the localization from the fit; deviation is the difference between the reconstructed position and the true position
- The three different averaging effects clearly visible!

Remarks on Results

- All three types of averaging as expected
- All-sky survey is very effective for averaging down
- Pointed observations without observational geometric averaging are the most sensitive to uncalibrated misalignments
  - if the errors stack up to <10 arcsec, guaranteed to support localizations of bright sources to the required precision (GLAST Project approach to management of this requirement);
  - if the errors were to stack up to slightly more than 10 arcsec, science requirement of supporting localizations of bright sources to 10 arcsec can still be met on the relevant timescales but the <u>details matter</u>:
    - averaging must be evaluated (many failed attempts to codify in requirements!) for the peculiar characteristics of the source(s) in question;
    - if calibration sources are in the FOV (and not too far off axis), distortion effects can be monitored *unless* the new source is localizable more quickly than the calibration sources.
  - larger violations would mean the details matter more and the risk of compromising the science is increased.

Verification & Timescales

- Estimate verification of pointing knowledge:
  - after two weeks <12 arcsec
  - after 8 weeks <9 arcsec
  - after one year <4 arcsec

- Impossible to calculate with high accuracy the calibration residual with time, since it depends on currently unknown properties of the gamma-ray sky.
  - estimates are conservative because they use simple analysis techniques and only a fraction of the likely calibration sources are considered.
  - calibration residual is as much a property of the source characteristics and calibration observations as it is a property of the observatory!

- Localization of point sources to <10 arcsec will provide clear evidence that pointing knowledge errors average down to <10 arcsec over the corresponding timescales.

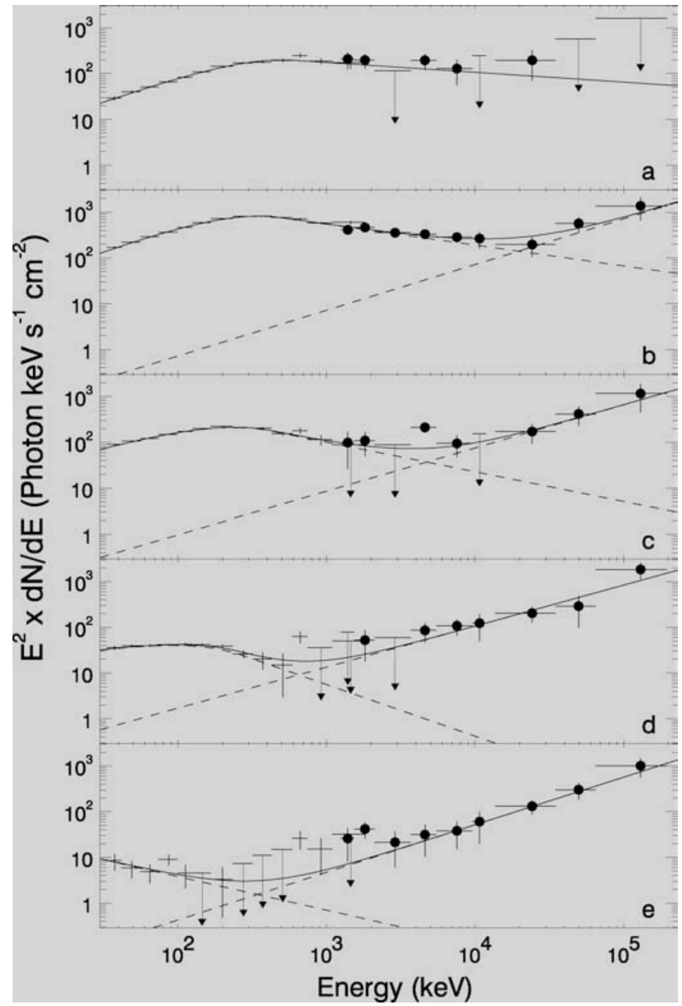
Risk Impacts

- Suppose the calibration residual 4 arcsec requirement is not met. What are the impacts?
- Consider the case that the calibration residual is 10 arcsec, and the rest of the system errors (GN&C uncertainties, thermal-mechanical distortions) also stack up to 10 arcsec. Then:
  - sources can still be localized to <10 arcsec in sky survey, due to geometric averaging down
  - pointed observations that have calibration sources in the FOV can be recalibrated sufficiently precisely, <u>provided</u> the target source is not localizable faster than the calibration sources.
  - WORST CASE: if there are no calibration sources that are more localizable than the target in the FOV in a pointed observation, then the systematic error on the reconstructed position of the target is <u>still bounded from above</u> (since calibration residual from previous observations and other errors for this observation are uncorrelated). This worst case is <u>very unusual</u>:
    - thermal effects do not average down
    - geometric observation effects do not average down
    - strong enough calibration sources not in the field of view
- Risk may be acceptable. Relies on the rest of the system having <10 arcsec performance.

When might misalignments matter?

Pointed observation of a bright unknown source (AGN flare). Some of the time-varying terms may average out (but if we can't quantify this, we can't assign a smaller systematic error). However there are likely to be several known sources within the fov that we could use to calibrate the pointing aligment.

Considered a burst similar to GRB971017 lasting 250 seconds with an E-1 spectrum from 10 MeV to 2 GeV. Achieve source localization of ~50".



Next Steps

- Calibration Plan draft released.
  - flows requirements into planned observations
  - issues documented
- Next step: Calibration Procedures document
  - details of algorithms for extracting a, b, c and evaluating subtle effects
  - may iterate back into plan