Initial Results of New Tomographic Imaging of the Gamma-Ray Sky with BATSE

Gary L. Case[1], Michael L. Cherry[1], James C. Ling[2], Martin Lo[2], Thomas Shimizu[2], Wm. A. Wheaton[3]

[1]Louisiana State University – [2]Jet Propulsion Laboratory/Caltech – [3]Infrared Processing and Analysis Center/Caltech

Summary

New results are shown of tomographic imaging of the soft gamma-ray sky using BATSE from 23-595 keV.

Earth Occultation

The BATSE instrument was one of the four instruments on the Compton Gamma Ray Observatory (CGRO). It consisted of 8 NaI large area detectors (LADs) located on the corners of the spacecraft. The detectors are non-imaging. However, it is possible to monitor known gamma-ray sources using the Earth occultation technique. Figure 1 demonstrates how the occultation technique works. When a source is occulted by the Earth, the count rate in the detector drops, producing a step-like feature. When the sources reappears, an upward step is produced.

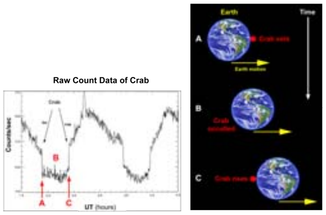


Figure 1. Left: Time history from a BATSE detector. 'A' marks the time at which the Crab is occulted, 'B' marks the time the Crab is blocked by the Earth, and 'C' marks the time the Crab reappears. Right: Schematic of the Earth occultation process.

The Enhanced BATSE Occultation Package was developed at JPL (Ling et al. 2000) to fit the all of the steps that occur during a single day for all of the sources in the input catalog along with a semi-physical background model. The output consists of the average daily count rates in 16 energy bands.

The Radon Transform

The Linear Radon Transform (LRT) is the integral transform of an image I in the (x-y) plane across all lines L into the (ρ-θ) plane, where θ is the angle that the line makes with respect to the x-axis and ρ is the perpendicular distance from the line to the origin.

$$\Re(I) = \int_L I(x,y)\, dm = F(\theta, \rho), \quad \text{where } L = \{ y = \tan\theta\, x + \rho/\cos\theta \}$$

In Figure 2, the LRT is demonstrated for a sample image. The middle image shows how the features in the x-y plane are transformed into the curves in the ρ-θ plane. The Inverse LRT transforms the integrate curves back into the x-y plane.

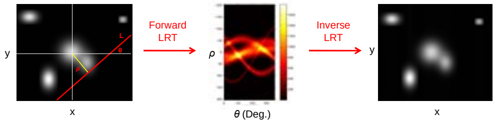


Figure 2. The Forward LRT and Inverse LRT

This technique was first applied to the Earth occultation using BATSE data by Zhang et al. (1994). We implement it as follows. The difference in the counts measured by a detector in two adjacent time bins gives the integrated number of counts from the arc defined by the position of the Earth's limb at that time. Thus the Earth occultation performs a LRT of the sky across a single "line". The LRT assumes a straight line, so the image patch must be restricted to small enough regions that the Earth's limb can be approximated as a straight line. As the plane of the CGRO orbit precesses (with a period of ~51 days), the Earth's limb will be oriented at different angles with respect to the image patch. Performing the Inverse LRT on all of the limbs in one precession period produces an image as shown in Figure 3.

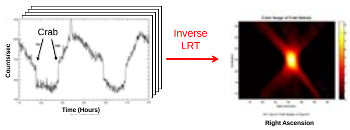


Figure 3. Image of the Crab produced from the Inverse LRT of all of the available limb orientations during one full precession cycle. The image size is 15 degrees and the intensity is in arbitrary units.

Limb Geometry and the PSF

The point spread function (PSF), and hence the expected shape of the image, depends on the declination of the source. For a source at low declination, fewer limb orientations (that is, fewer of the θ angles) are sampled resulting in a PSF that is elongated in the north-south direction. For sources at modest declination, about half of the possible limb orientations are sampled, resulting in a PSF that is slightly elongated in the north-south direction with an 'x' pattern in the wings. For sources above about |60°|, nearly all of the limb orientations are sampled and the PSF is roughly circular. Figure 4 shows the limb orientations, drawn as lines, that are sampled during a complete orbit plane precession cycle for sources at three different declinations, along with the simulated PSFs and the actual images.

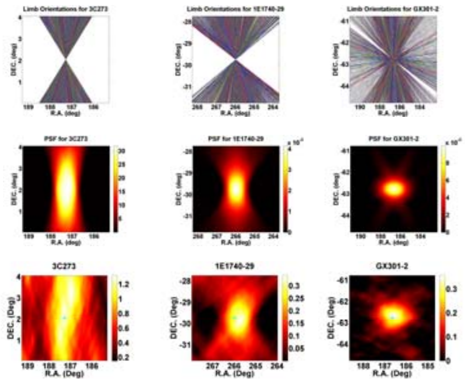
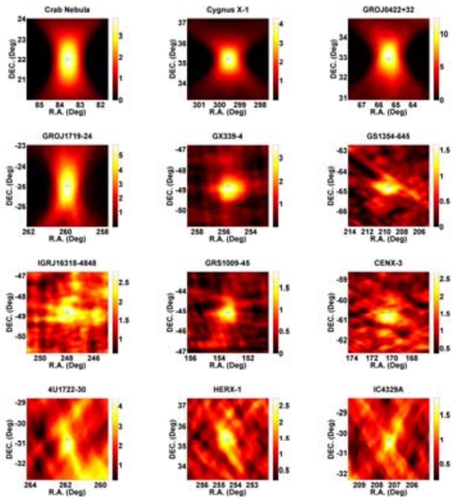


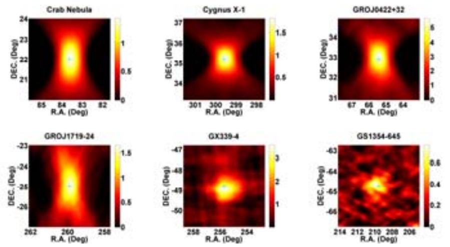
Figure 4. Top: Orientation of limbs during one precession cycle for 3 sources at different declinations. The colors of the lines have no meaning and are used to distinguish individual lines.. Middle: Simulated PSFs for the same 3 sources. Bottom: Actual images of the 3 sources averaged over 20 precession cycles..

Images

23-98 keV



98-230 keV



230-595 keV

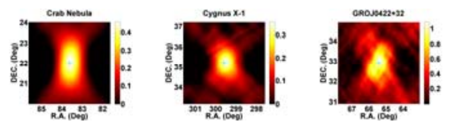


Figure 5. Selected images from those created using the Inverse LRT with the BATSE occultation data in three broad energy bands (Ling et al. 2010). The intensity scales are in arbitrary units, although within a particular energy band the scales are all relative. Note especially that images can be produced at energies above 200 keV.

Future Work

We have shown preliminary images of gamma-ray sources using BATSE and the Earth occultation technique coupled with the Inverse LRT at energies up to 600 keV. Future work will include quantifying the significance of the images and defining sensitivity limits for this imaging method. We are also working on image deconvolution techniques in order to more accurately locate the positions of the sources. This work is part of a larger project to image the entire sky and look for new sources. These sources will be added to our EBOP catalog and the EBOP analysis system will be rerun in an effort to obtain fluxes for the new sources and to get more reliable fluxes for the previously known sources by reducing the systematic errors currently present due to unaccounted for sources in the sky.

References and Acknowledgements

Ling et al. 2000, ApJS, 127, 79
Zhang et al. 1994, Nature, 366, 245
Ling et al. 2010, in preparation