BatAnalysis: A Comprehensive Python Pipeline for Swift BAT Data Analysis

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Outline

• Introduction to Swift and BAT
• BAT Survey Data
  • Overview of the data
  • Past Analyses
  • Usefulness
• The BatAnalysis Python Package
  • How to analyze BAT survey data
  • Verifying with the Crab Nebula Pulsar
• Example Analyses of:
  • NGC 2992
  • MAXI J0637-430
  • GRB 221009A
The Neil Gehrels Swift Observatory

- Launched in 2004
- Overview of operations:
  1. BAT detects a Gamma Ray Burst (GRB)
  2. Autonomous slewing to the GRB
  3. XRT and UVOT observe the field to detect afterglow counterparts
     OR
  1. There is a ToO/many point plan for XRT/UVOT to observe a source
  2. BAT is pointed towards that source too collecting survey data
     OR
  1. BAT is surveying the sky normally, collecting survey data in between slews
- Over 1500 GRBs have been detected
The BAT

• Uses coded mask techniques to maximize:
  • FOV (~60x120°)
  • Localization Capabilities of GRBs (~3 arcmin)
  • GRBs → time tagged event (TTE) data
    • The highest quality data of each photon’s direction and energy
    • Intensive to store and transfer to the ground
  • Event data can be used to localize transients even if they do not trigger BAT or are located outside of the BAT FOV

Barthelmy+ 2005
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Barthelmy+ 2005
The BAT

• When its not triggering on GRBs BAT is surveying the sky in the 14-195 keV energy range

• Cannot store all the event data, therefore we compress it

• Create Detector Plane Histograms (DPHs)
  • 80 channel histograms of photon counts

• Accumulates DPHs in time intervals of ~300 seconds

Barthelmy+ 2005
BAT survey data is >90% of all the data produced by BAT, by volume.

It is the least used and has tons of possibilities

BAT TTE data is collected when:
  1) BAT triggers
     OR
  2) when there is an external trigger and we can tell BAT to save the data around that time period
N-Month Survey Catalog
where N={22, 70, 105, 157}

- Systematic analyses of BAT Survey data
- Analyze known sources to produce
  - Monthly mosaiced light curves
  - N-month mosaiced Spectra
- Discover new sources and (attempt to) identify them based on multi-wavelength follow-up

http://swift.gsfc.nasa.gov/results/bs22mon/
http://swift.gsfc.nasa.gov/results/bs70mon/
http://swift.gsfc.nasa.gov/results/bs105mon/

Tueller+ 2010, Baumgartner+ 2013, Oh+ 2018, Lien+ in Prep
What if we want to analyze a source on a different time scale?

What if we want to look in archival data to place upper limits on a newly detected transient?
The BAT Analysis Package

github.com/parsotat/BatAnalysis
The BatAnalysis Code Reproduces Prior Survey Catalog Results

- 22 month survey:
  - Creates mosaic images from all survey data from Dec 2004 to Oct 2006

- BatAnalysis
  - Queries HEASARC for data
  - Filters data for ones where the Crab is “seen” by 1000 cm$^2$ of the BAT (~19% partial coding)

Tueller+ 2010, Parsotan+ 2023
The BatAnalysis Code Allows for a More Comprehensive Picture

- BatAnalysis
  - Can fit each survey/mosaic spectrum with a simple power law
  - If spectra are not well fit or if a detection is not obtained, the spectra are used to calculate upper limits
BatAnalysis Allows for Custom Mosaicing

AGN NGC 2992

• Analyzed data from Dec 2004 - Dec 2005

• Obtained upper limits for each individual survey dataset and the monthly mosaics

• The year long mosaic image has a detection of SNR~12 in 14-195 keV energy band
BatAnalysis Allows for Custom Mosaicing

AGN NGC 2992

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• Obtained upper limits for each individual survey dataset and the monthly mosaics

• The year long mosaic image has a detection of SNR~12 in 14-195 keV energy band

• The spectral fit show agreement with prior analyses
BETA: BatAnalysis Allows for Custom Event Data Analysis

**BatGUANO Data**

- Currently working on this portion of the package
- The beta version is available for testing with only one example analysis.
- There are notebooks that give a general overview of BAT event data files and ways to manipulate the data.
BatAnalysis Survey Documentation


- Documentation is currently provided as Jupyter notebooks
  - Allow the results to be reproduced
  - Broadly explains what each step of an analysis is doing
  - A word of caution:
    - Some of these analyses can take a VERY large amount of space (e.g., the full 22 month Crab data & BatAnalyses produced files are ~2.5 TB in total)
    - The NGC analysis takes up ~815 GB
    - The MAXI analysis takes up ~330 GB
    - The BOAT analysis takes up ~60 GB of storage
    - The parallelized mosaic analyses capability can use a lot of memory at ~10 GB per process
Documentation is currently provided as Jupyter notebooks.

- 2 Primary Notebooks outlining the imaging capabilities and the traditional rate capabilities.

- This is still the beta version and development is ongoing so be wary of any bugs.
Data Querying and Download Documentation

https://github.com/parsotat/BatAnalysis/blob/main/notebooks/Example_data_download.ipynb

- Various Examples show different ways to query data programmatically
- This notebook walks through the use of swifttools and various files that can be downloaded
- Additional documentation can be found on the swifttools website: https://www.swift.psu.edu/too_api/
Summary

• The BatAnalysis package unlocks the potential of BAT data for a number of different analyses

• The package is open source and can be used by anyone

• Software such as this is dependent on other open source efforts including:
  
  • Swifttools (https://www.swift.psu.edu/too_api/)
  
  • The swift_bat package (https://github.com/lanl/swiftbat_python)
  
  • HEASoftpy
  
  • Astropy & Astroquery

• Feedback from users such as yourselves
  
  • If issues are encountered users should open a GitHub issue outlining the problem and any relevant code
  
  • If the documentation is not clear please let me know by opening a GitHub issue as well so we can clarify things
Survey Observation Processing Steps

1. Raw Data Processing

DPH (Channel i of 80)
Survey Observation Processing Steps

1. Raw Data Processing

[Image: A data matrix labeled DPH (Channel i of 80) with a highlighted area indicated as Disabled Detectors]
Survey Observation Processing Steps

1. Raw Data Processing

[Image: A grid representing DPH (Channel i of 80) with annotations for Disabled Detectors and Hot Pixel?]
Survey Observation Processing Steps

1. Raw Data Processing

DPH (Channel i of 80) Counts
Survey Observation Processing Steps

1. Raw Data Processing

DPH (Channel i of 80)

DPI (Energy Bin i of 8)

• Rebin data into 8 energy bins: 20-24, 24-35, 35-50, 50-75, 75-100, 100-150, & 150-195 keV
Survey Observation Processing Steps

1. Raw Data Processing
Survey Observation Processing Steps

1. Raw Data Processing

- DPH
- DPI

Coded Mask + Detector Mask
Survey Observation Processing Steps

1. Raw Data Processing

- **DPH**
  - DPI Cleaning* + FFT

- **Coded Mask**
  - Detectors Mask

21 DPI

DPI Cleaning* + FFT
Survey Observation Processing Steps

1. Raw Data Processing

- DPH
- DPI
- DPI Cleaning
- Coded Mask
- Detector Mask
- Sky/Background Variance/etc. Images

- Crab Nebula Pulsar

DPI Cleaning* + FFT
Survey Observation Processing Steps

1. Raw Data Processing

DPI Cleaning:
- Cleans counts from bright sources with ray tracing
- Cleans noisy pixels from DPIs

Sky/Background Variance/etc. Images

Crab Nebula Pulsar

DPI Cleaning* + FFT

Detected Mask

Coded Mask

DPI

DPH
Survey Observation Processing Steps

1. Raw Data Processing

DPI Cleaning:
- Cleans counts from bright sources with ray tracing
- Cleans noisy pixels from DPIs

Pattern Noise Map Subtraction:
- Subtracts off persistent detector noise that builds up over time
Survey Observation Processing Steps

2. Image Processing - Individual Survey Datasets

Sky/Background Variance/etc. Images

Crab Nebula Pulsar
Survey Observation Processing Steps

2. Image Processing - Individual Survey Datasets

Sky/Background Variance/etc. Images

Crab Nebula Pulsar

batcelldetect
Survey Observation Processing Steps

2. Image Processing - Individual Survey Datasets

- For Each Source that may be found:
  - Count rate in each energy bin
  - SNR of the detection
  - Local background variation

Sky/Background Variance/etc. Images

Crab Nebula Pulsar

batcelldetect

Count Rate (cts/s)

E (keV)
Survey Observation Processing Steps

2. Image Processing - Individual Survey Datasets

Sky/Background Variance/etc. Images

Crab Nebula Pulsar

Batcelldetect: Uses a sliding annulus to detect sources and measure the local background counts

- For Each Source that may be found:
  - Count rate in each energy bin
  - SNR of the detection
  - Local background variation

Batcelldetect

[Graph showing count rate vs. energy (E) in keV]
Survey Observation Processing Steps

2. Image Processing - Mosaic Survey Datasets

Observation 1

Observation 2

Images

Images

+ ?
Survey Observation Processing Steps

2. Image Processing - Mosaic Survey Datasets

\[ w_{i,j} \times \text{Observation 1} \quad + \quad w_{i,j} \times \text{Observation 2} \]

\[ w_{i,j} \propto \sigma_{i,j}^{-2} \]

This suppresses counts in noisy images
Survey Observation Processing Steps

2. Image Processing - Mosaic Survey Datasets

Observations within some time bin

\[ w_{i,j} \times \]

\[ + \]

\[ w_{i,j} \times \]
Survey Observation Processing Steps

2. Image Processing - Mosaic Survey Datasets

Observations within some time bin

\[ w_{i,j} \times \]

\[ + \]

\[ \rightarrow \]

Sky/Background Variance/etc. Images
Survey Observation Processing Steps

2. Image Processing - Mosaic Survey Datasets

Observations within some time bin

\[ w_{i,j} \times \]

\( \sum \)

\[ w_{i,j} \times \]

\[ \text{Observation 1} \]

\[ \text{Observation N} \]

\[ \text{Images} \]

\[ \text{Images} \]

\[ \text{Time Bin Mosaic} \]

\[ \text{Sky/Background Variance/etc. Images} \]

\[ \text{batcelldetect} \]
Survey Observation Processing Steps

2. Image Processing - Mosaic Survey Datasets

Observations within some time bin

\[ w_{i,j} \times \]

\[ + \]

\[ \rightarrow \]

\[ \text{Time Bin Mosaic} \]

\[ \text{Sky/Background Variance/etc. Images} \]

\[ \text{batcelldetect} \]

\[ \text{Count Rate (cts/s)} \]

\[ E \text{ (keV)} \]

\[ 10^{-3} \]

\[ 10^{-2} \]