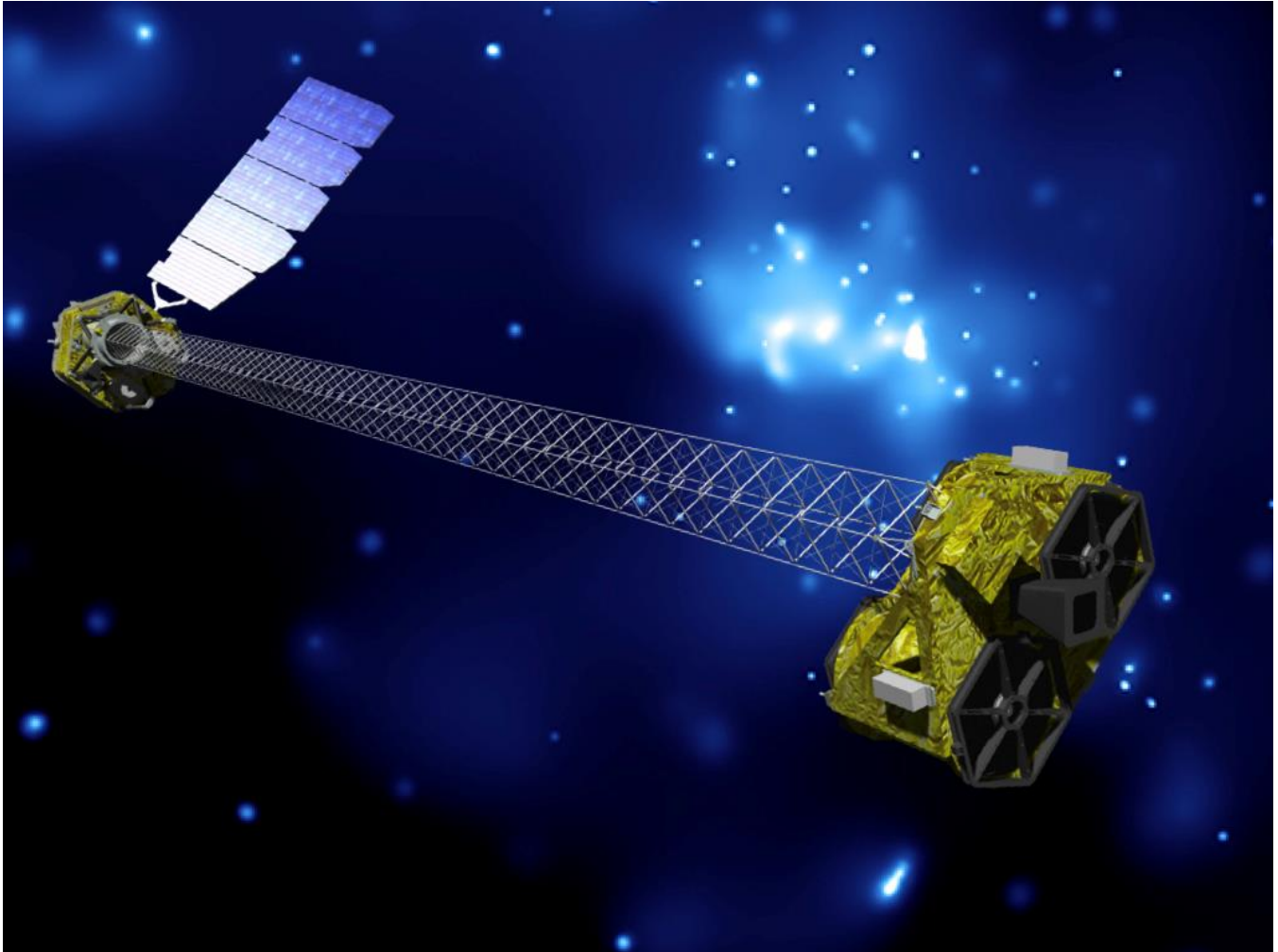


NuSTAR DATA ANALYSIS

Quickstart Guide



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Karl Forster, Brian Grefenstette, & Kristin Madsen
NuSTAR Science Operations Center,
California Institute of Technology

http://www.srl.caltech.edu/NuSTAR_Public/NuSTAROperationSite/Home.php

Introduction

The Nuclear Spectroscopic Telescope Array (NuSTAR) mission, launched in June 2012, is the first focusing high energy (3-79 keV) X-ray observatory. The primary citation for the NuSTAR mission is: [Harrison et al, \(2013\)](#). The detailed guide to NuSTAR Data Analysis Software package (NuSTARDAS) and the NuSTAR Observatory Guide may be found on the [NuSTAR HEASARC page](#).

The purpose of this guide is to provide users with information that will enable basic scientific analysis of NuSTAR data. For the purposes of this guide, it is assumed that users have:

- Downloaded and successfully installed:
 - the latest version of the [HEASoft X-ray data analysis software package](#)
 - Note that NuSTARDAS (v2.1.0 onwards) is integrated in HEASoft release v6.29
 - the [NuSTAR calibration database \(CALDB\)](#) (release 20210210 and later)
- Initialized the command line environment for HEASoft and have some experience with command line tools using the terminal
- Downloaded the NuSTAR observation(s) to be processed from the NuSTAR archive at HEASARC or the mirror at ASDC in Europe:
 - <https://heasarc.gsfc.nasa.gov/docs/nustar/index.html>
 - <http://nustar.asdc.asi.it>
- Downloaded and have some experience using the *SAOImage DS9* astronomical imaging and data visualization application that can display FITS format images.
 - <https://sites.google.com/cfa.harvard.edu/saoimageds9/home>
 - We also assume that the user has set up *DS9* to be invoked from the command line
- Some experience with astronomical X-ray data analysis using the HEASARC *Xanadu* software tools like *XSPEC* and *XRONOS*.

Overview of NuSTAR data processing

NuSTAR science data are processed automatically at the Science Operations Center (SOC) at the California Institute of Technology (Caltech, USA) upon receipt of data transmission from ground stations, typically about four times every day. The processing at the SOC makes use of the NuSTAR Data Analysis Software package (NuSTARDAS), jointly developed by the ASI Science Data Center (ASDC, Italy) and Caltech. NASA's High Energy Astrophysics Science Archive Center (HEASARC) at the Goddard Space Flight Center in Greenbelt, MD. The HEASARC serves as the science archive for NuSTAR data, though data are also publicly available via the ASDC multi-mission archive.

The [NUMASTER FITS table](#) contains relevant information for all NuSTAR observations. This table contains a list of (a) unobserved targets that are planned or have been accepted for observation by NuSTAR in the future and (b) NuSTAR observations which have been processed and successfully validated by the SOC. During the quality assurance process (QA), members of the SOC team examine the data for any issues such as enhanced background due to solar activity or data gaps. If any issues are found, then the "ISSUE" flag is set to "1" in the NUMASTER table.

When the user downloads an observation, they should always check the ISSUE flag to make sure that an observation does not have any known issues before starting analysis.

Overview of NuSTAR Observations

In the NUMASTER FITS table a visit to a given target typically appears as two observation IDs: One of these is a “SLEW” observation and one is listed as a “SCIENCE” observation. This is indicated by the “observation mode” column in the NUMASTER table. For nearly all science use cases, we recommend only using the SCIENCE mode data.

Data analysis overview

NuSTAR data processing using NuSTARDAS is organized into three stages:



Figure 1 - NuSTAR data analysis stages within *NuSTARDAS*

Each processing stage consists of multiple software modules (see Appendix B), including some multi-mission FTOOLS in the HEASoft package, that can be run in sequence using the `nupipeline` script.

The example used in this document is from a calibration observation of the quasar 3C 273 observed by NuSTAR on 2012-07-13 between 0145 UT to 0440 UT that contains two orbits of data with a total exposure time of 5150/5161 seconds in Focal Plane Module (FPM) A/B respectively. These data can be downloaded by following instructions on the HEASARC website, including access via direct FTP:

<http://heasarc.gsfc.nasa.gov/FTP/nustar/data/obs/00/1/10012001002/>

The NuSTAR observationID (obsID) for this data is 10012001002. Information about the file naming convention and the archive directory structure can be found in section 2 of the [NuSTAR Data Analysis Software Guide](#).

Step-by-step analysis of data

In all of our examples below, the commands typeset in Courier (like `nupipeline`) are intended to be entered at the terminal prompt. For simplicity, we have broken terminal commands into individual lines, where the backslash “\” indicates command line continuation. These are designed to be directly copied to a terminal window. However, we do recommend that users copy these commands into scripts in their preferred shell environment.

Step 0: Confirm that HEASoft and NuSTARDAS are initialized

The command

```
nuversion
```

...will return the currently installed version of NuSTARDAS and also confirms that your HEASoft has been initialized. Please check your current versions against the latest release via HEASARC to confirm that you are using the most up-to-date software.

Step 1: Run nupipeline stages 1 and 2

As a first step, users should run the NuSTAR data analysis pipeline (`nupipeline`), which is typically run to process the data through Stage 1 and Stage 2 in Figure 1. For standard pipeline processing, all that needs to be specified is the input path to the top-level directory containing the observation to be processed, the stem name of the data files, and an output directory. In the following example these values are:

Table 1 - nupipeline parameters for analysis of obsID 10012001002

| nupipeline parameter | value | Notes |
|----------------------|--------------------|---|
| indir | <path>/10012001002 | <path> is the full path to the downloaded data directory. E.g. /disk/nustar/archive |
| steminputs | nu10012001002 | File naming convention is nu<obsID> |
| outdir | ./out | Output directory for processed files. Any directory path can be specified (this example is relative to the current location). The standard archival directory name for output is ./event_cl |

There are a large number of other input parameters to the individual modules within `nupipeline` that can also be set from the command line. See the NuSTARDAS software guide for details of the syntax and worked examples. Descriptions of the input parameters are also available via extensive help files for `nupipeline` and all of its modules via the “fhelp” command or via the HEASARC webpages. Once HEASoft is initialized these can be accessed from the command line by typing:

```
fhelp <module>
```

e.g. for a description of the output files generated by `nupipeline` you can access the fhelp page using:

```
fhelp nupipeline
```

or using the [webpage for nupipeline at HEASARC](#).

We recommend directing the output of all processing scripts to a log file by appending ‘> log.txt’ to the end of any command line or scripted calls to FTOOLS. This can then be monitored as the processing runs.

Processing the data in our test case can be done using the command:

```
nupipeline \  
  indir=/disk/nustar/archive/10012001002/ \  
  steminputs=nu10012001002 \  
  outdir=./out > nupipeline_log.txt
```

Go to the output directory that was produced:

```
cd ./out
```

This contains Level 2 output files that are calibrated, cleaned using “good time intervals” (GTIs), and screened for passages through the South Atlantic Anomaly (SAA). This corresponds to the middle bubble in Figure 1. Detailed information about event screening for SAA passages, Earth occultation, valid star tracker periods, etc. can be found in section 4 of the NuSTARDAS software guide.

The following files in the output directory contain the science quality X-ray events:

```
nu10012001002A01_cl.evt    FPMA science quality event FITS file  
nu10012001002B01_cl.evt    FPMB science quality event FITS file
```

Please note that this stage of the data processing may take some time depending on the duration of your observation. NuSTARDAS corrects the position of every X-ray photon based on the real-time reconstruction of the motion of the NuSTAR mast, which means that the volume of data to be processed will depend both on the total exposure time and on the source count rate. The example data above should run within a few minutes since this is a very short exposure (~5-ks).

Note: the `nupipeline` script can be used to automatically run completely through Stage 3 in Figure 1 to extract high level science products. However, this is typically not recommended during the first analysis of science data. The default `nupipeline` behavior is to run Stages 1 & 2.

Final note: Level 2 event files are available for each obsID directly from HEASARC in the archive `event_cl` subdirectory. These files were generated at the NuSTAR SOC with default parameter settings for `nupipeline` and the most recent CALDB at the time the data were processed. For quicklook analysis, users can begin with these data, **though we always recommend reprocessing the data with the latest CALDB.**

Step 2: Extract a source spectrum and light-curve using `nuproducts`

NuSTAR has two similar (but not identical) telescopes focusing onto two similar (but not identical) focal plane arrays, FPMA and FPMB. Analysis of the data from the two telescopes is done separately with a joint analysis of the combined data occurring only at the end during joint spectral fitting.

All of the following notes are for analysis of a point source in the FPMA telescope and can be repeated for FPMB. Extended source extraction and extended ARF generation is more sophisticated and requires the user to make educated choices that can be based on information in section 5 of the NuSTARDAS software guide and also obtained by running:

```
fhelp nuproducts
```

or using the [webpage for nuproducts at HEASARC](#).

Use DS9 to produce a source extraction region file

Event files can be viewed as images using DS9. Go to the output directory:

```
cd ./out
```

Load the science mode level 2 event file into DS9 using the command line:

```
ds9 nu10012001002A01_cl.evt
```

For the example data, use a circular region centered on the source. Choosing the correct region size depends on the particular analysis, how bright the source is, and how sensitive you are to the various sources of background. The user should make the determination of what size source region to use.

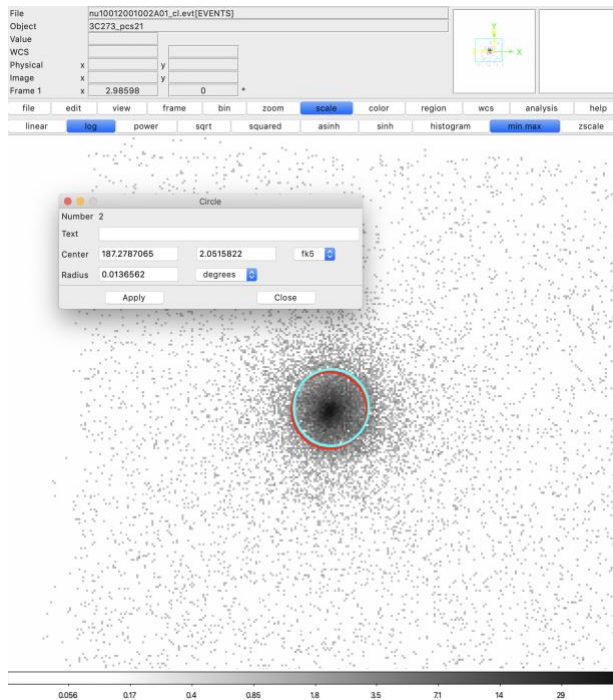


Figure 2 - NuSTAR FPMA event image of obsID 10012001002 (3C 273) and source extraction region displayed in DS9

Use DS9 to produce a background region file

The NuSTAR background varies across the field of view and between the four CZT detectors on each focal plane. How to properly deal with the background contributions to the source region spectrum is an open topic in the community and far beyond the scope of this quickstart guide. Here, we simply extract the background from a nearby region to estimate the background in the source region. Place the background region as close to the source as possible without including source photons. The size of the background region will determine the count rate statistics, but the `nuproducts` FTOOL properly scales the background for the size of the source region via the `BACKSCAL` keyword in the source and background spectral (PHA) files.

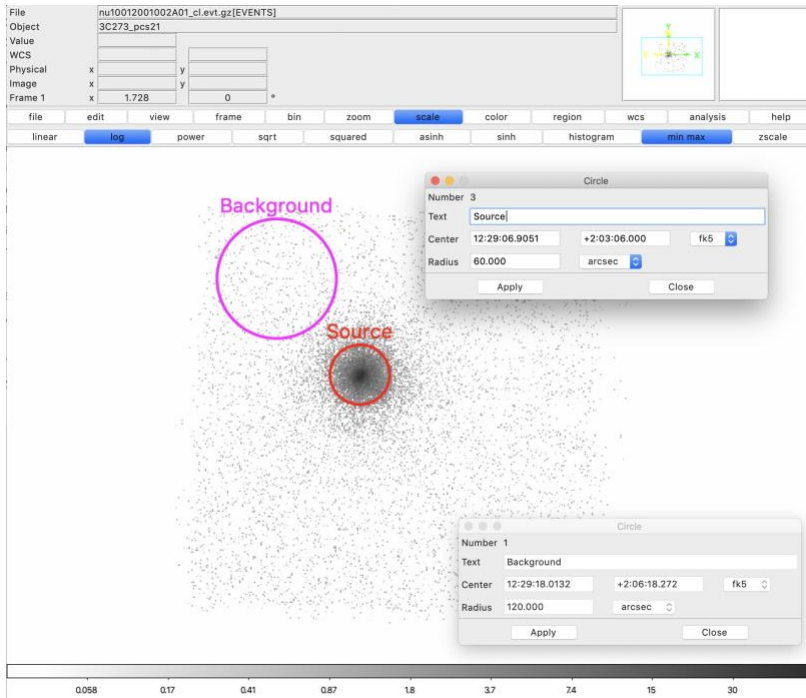


Figure 3 – NuSTAR FPMA event image of obsID 10012001002 (3C 273) with the source and background extraction regions displayed in DS9

Fig. 3 shows the NuSTAR FPMA image of 3C 273 displayed in DS9.

The magenta circle is a 120-arcsec radius background extraction circular region. Similar to the source region file, background region files should typically be chosen for each telescope. Use DS9 to save this region information in a file called `bgdA.reg` in the `./out` directory.

`bgdA.reg` should only contain the background region (not the source and background region).

We note that the size of the background extraction region will affect the number of counts in the background spectrum. The choice of the size and location of the background region are key aspects to understanding the source spectrum. In general, we suggest that the background region be chosen to be as large as possible and from the same detector quadrant (as shown). There are a number of papers that also describe the NuSTAR background (i.e., [Harrison et al. 2013](#), [Wik et al. 2014](#), and [Krivonos et al. 2021](#)) and the potential science impact.

Run `nuproducts` to extract the level 3 science products

The next step is to run `nuproducts` to produce light curves, images, and spectra. There are a large number of input parameters to tune, but by default light-curves and images will be produced using the full NuSTAR bandpass (3-79 keV). The spectrum (PHA) file always covers the full channel range (channels 1 – 4096, or 1.6 – 165 keV).

Below is the `nuproducts` command with the minimum set of input keywords to extract a source and background spectrum from FPMA. We assume that `nuproducts` is being invoked from the directory tier directly above the observation ID (i.e. in the top-level directory containing 10012001002). Quick-look gifs (Figure 5) are produced at this stage, along with the FITS version of the science products (Table 2).

```
nuproducts \
  srcregionfile=./out/srcA.reg \
  bkgregionfile=./out/bgdA.reg \
  indir=./out \
  outdir=./products \
  instrument=FPMA \
  steminputs=nu10012001002 \
  bkgextract=yes > nuproducts_log.txt
```

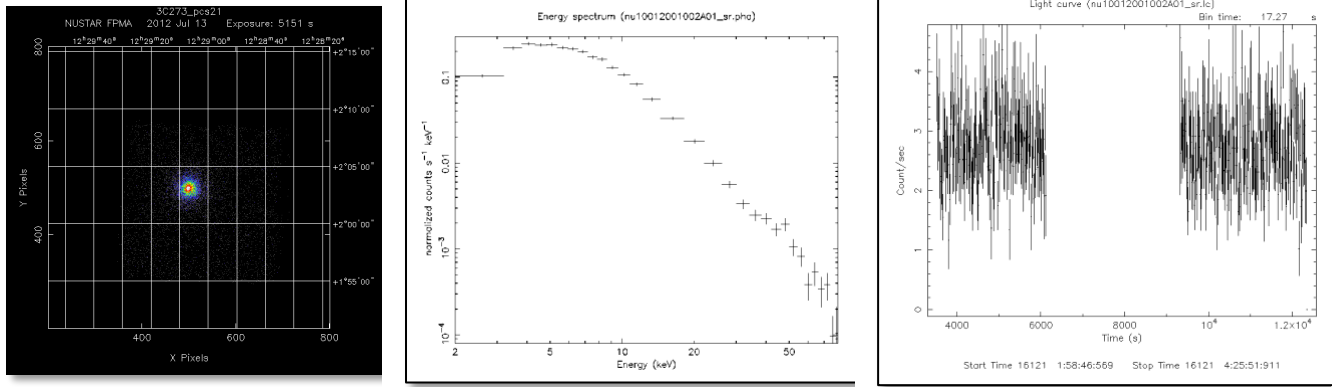


Figure 4 – Sky image

Source energy spectrum

Source light-curve, where the gap is when NuSTAR orbits behind the Earth

The files generated in the output (Table 2) can be loaded into XSPEC, ISIS, or your favorite fitting package. We recommend that data from the two FPM be modeled simultaneously in XSPEC rather than coadded. Note that if the various FTOOLS are run multiple times, then the standard clobber keyword should be set to clobber=yes to enable overwriting of existing files in the output locations.

There are many variables that can be set in `nuproducts`. For details, particularly when the source is extended, please see the NuSTARDAS software guide.

Congratulations, you are now ready to analyze your data! Please also see the “Useful Things to Know” section below.

Table 2 - `nuproducts` output files for FPMA

| File generated by <code>nuproducts</code> | Format | Level 3 file description |
|---|--------|---|
| nu10012001002A01_sk.img | FITS | Science mode image (for use in e.g. XIMAGE) |
| nu10012001002A01_im.gif | GIF | Science mode gif image |
| nu10012001002A01_sr.pha | FITS | Source energy spectrum |
| nu10012001002A01_ph.gif | GIF | Source energy spectrum plot |
| nu10012001002A01_sr.lc | FITS | Source light-curve |
| nu10012001002A01_lc.gif | GIF | Source light-curve plot |
| nu10012001002A01_bk.pha | FITS | Background energy spectrum |
| nu10012001002A01_bk.lc | FITS | Background light-curve |
| nu10012001002A01_sr.arf | FITS | Source ARF file |
| nu10012001002A01_sr.rmf | FITS | Source RMF file |

Non-standard processing

This section includes additional information that may be useful to some users.

Producing high level science products on one line:

If you have already defined your source and background regions, you can also directly produce Stage 3 products for both FPMA and FPMB using `nupipeline` and setting the parameter `exitstage=3`:

```
nupipeline \
  indir=10012001002 \
  steminputs=nu10012001002 \
  outdir=./out \
  exitstage=3 \
  srcregionfile=./out/srcA.reg \
  bkgregionfile=./out/bgdA.reg > nupipeline_log.txt
```

Running analysis on data downloaded from HEASARC without re-running nupipeline

We do not recommend using the data directly downloaded from the HEASARC. These data may have been processed using an out-of-date CALDB. However, this can be done using `nuproducts` to extract level 3 products directly from data downloaded from the archive. In this case it is also necessary to set the 'attfile' and 'hkfile' input parameters as follows since these files will not have been copied into the `./out` directory during the `nupipeline` run.

```
nuproducts \
  srcregionfile=./out/srcA.reg \
  bkgregionfile=./out/bgdA.reg \
  indir=./event_cl \
  outdir=./products \
  instrument=FPMA \
  steminputs=nu10012001002 \
  bkgextract=yes \
  attfile=./auxil/nu10012001002_att.fits \
  hkfile=./hk/nu10012001002A_fpm.hk > nuproducts_log.txt
```

Please note, that for NuSTARDAS version 2.0 there was an additional `obebhkfile` input parameter that had to be specified for these data, otherwise `nuproducts` would return with an error. If you encounter this issue, please upgrade your HEASoft to version 6.29 or later and NuSTARDAS v2.1 or later before proceeding.

Note the use of the `event_cl` directory as the `indir`. See sections 5 & 6 of the NuSTAR data analysis software guide for more details. Also note that the data download directly from the HEASARC may still be compressed, so if you have not yet uncompressed the files the inputs may need to be adjusted (i.e. `nu10012001002_att.fits.gz` rather than `nu10012001002_att.fits`).

Useful things to know

Frequently Asked Questions

Analyzing data from any telescope results in a number of edge cases. If you run into oddities in your data analysis, please check the [NuSTAR FAQ page at HEASARC](#) which contains many answers to common questions for NuSTAR data analysis.

Enhanced background

The NuSTAR SOC produces a “background report” for every observation. These can be accessed via the NuSTAR SOC webpage:

https://nustarsoc.caltech.edu/NuSTAR_Public/NuSTAROperationSite/SAA_Filtering/SAA_Filter.php

...which list various input options that can be used with `nupipeline` to apply the standard background filters in the case of enhanced geomagnetic activity (e.g., after the arrival of a coronal mass ejection from the Sun). We recommend that all users check the background report for their observation before analyzing their data.

The NUMASTER “ISSUE” flag and “solar_activity” flags

The [NUMASTER FITS table](#) contains an “ISSUE” flag (binary 0 == No issue). If your observation has been flagged as having an issue, we recommend examining the table in detail. If enhanced activity was noted during quality assurance checking of the observation, the `solar_activity` flag will be set. Especially in this case, check the background observations linked above.

Clock corrections

The on-board NuSTAR clock can be corrected using the `barycorr` multi-mission FTOOL. The NuSTAR SOC produces a new clockfile every few weeks, which is available here:

https://nustarsoc.caltech.edu/NuSTAR_Public/NuSTAROperationSite/clockfile.php

...along with details on how to apply the clockfile.

MLI corrections

Occasionally there are pathological observations where additional parameters need to be set in `nuproducts` to obtain the correct optics response. The SOC maintains a list of these observations and we recommend that all users check to see if your observation is on this list and see the details of what to do on the following page:

https://nustarsoc.caltech.edu/NuSTAR_Public/NuSTAROperationSite/mli.php

nustar-gen-utils python wrappers

In addition to the NuSTARDAS command line interface, there are a number of python wrappers that provide a useful interface via jupyter notebooks. These can be found here:

<https://github.com/NuSTAR/nustar-gen-utils>

NuSTAR Timing Analysis Code

Beyond the standard XRONOS FTOOLS, NuSTAR timing analysis is a key component of Stingray/HENDRICS. You can find that code here:

<https://github.com/StingraySoftware/stingray>

Additional information and links

NuSTAR website at Caltech – news about the mission and information for proposers

<http://nustar.caltech.edu>

The NuSTAR calibration database (CALDB)

http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_intro.html

NuSTARDAS software guide – Perri et al. (2020)

http://heasarc.gsfc.nasa.gov/docs/nustar/analysis/nustar_swguide.pdf

NuSTAR Observatory Guide

http://heasarc.gsfc.nasa.gov/docs/nustar/NuSTAR_observatory_guide.pdf

NuSTAR mission reference paper – Harrison et al. (2013) ApJ 770, 103

http://www.nustar.caltech.edu/uploads/files/harrison_2013_apj_770_103.pdf

NuSTAR Science Operations website at Caltech – Observing schedules, tools for proposers and as-flown timeline

http://nustarsoc.caltech.edu/NuSTAR_Public/NuSTAROperationSite/Home.php

NuSTAR CALDB guide – Corcoran, M.F. 2013 – *CAL Memo CAL/NuSTAR/2012-001*

<http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/nustar/>

HEASARC NuSTAR home page at GSFC – Access to archival data, data analysis software and calibration files

<http://heasarc.gsfc.nasa.gov/docs/nustar/>

HEASoft X-ray data analysis software package

<http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/>

HEASARC and NuSTAR Frequently Asked Questions

http://heasarc.gsfc.nasa.gov/docs/nustar/nustar_faq.html

<http://heasarc.gsfc.nasa.gov/docs/faq.html> - astronomers

HEASARC help desk

<http://heasarc.gsfc.nasa.gov/cgi-bin/Feedback>

HEASARC *Xanadu* software tools

<http://heasarc.gsfc.nasa.gov/docs/xanadu/xanadu.html>

Interactive Spectral Interpretation System (ISIS) homepage

<http://space.mit.edu/cxc/isis/>

ASI Space Science Data Center homepage (SSDC)

<http://www.ssdsc.asi.it>

Appendix B – NuSTARDAS pipeline modules

NuSTARDAS Pipeline modules

