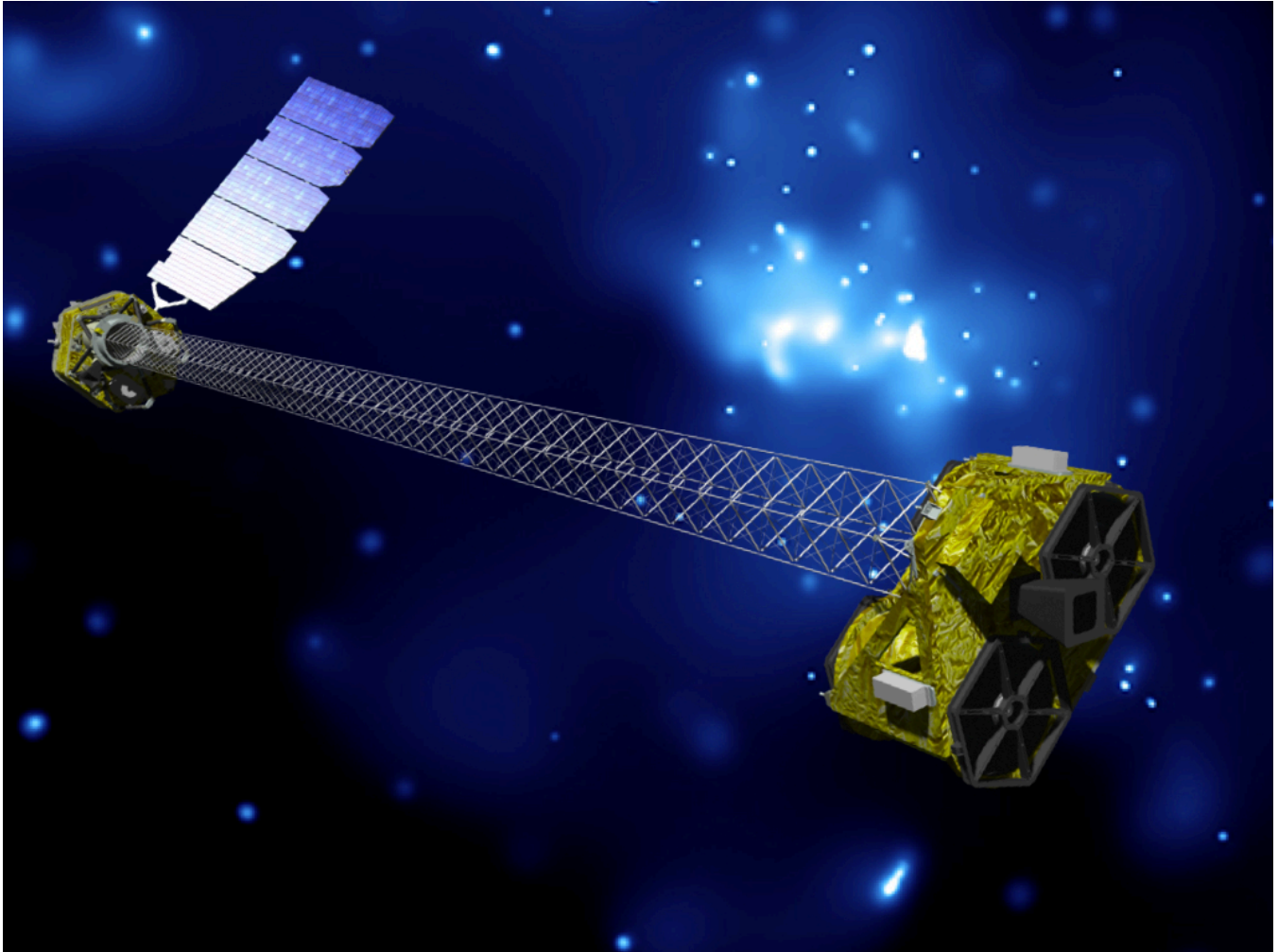# NuSTAR DATA ANALYSIS

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. NuSTAR will probe the hard X-ray sky with a more than one-hundred-fold improvement in sensitivity over collimated or coded-mask instruments that have operated in this bandpass.

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. Once the science quality of completed observations have been validated by the SOC, the observations are then transferred electronically to 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. All data from the NuSTAR satellite will be made publicly available from the HEASARC. The SOC also has responsibility for generating the calibration data and making those data available for transfer to the HEASARC for archiving in the HEASARC's Calibration Database.

A description of the NuSTAR observatory and the primary science mission can be found in Harrison et al., (2013) ApJ 770, 103.   The detailed guide to the **NuSTAR Data Analysis Software** (*NuSTARDAS*) and the **NuSTAR Observatory Guide** can be found on the NuSTAR data archive website hosted by HEASARC (http://heasarc.gsfc.nasa.gov/docs/nustar).

The purpose of this document is to provide users with information that will enable basic scientific analysis of NuSTAR data. For the purposes of this document 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* (v1.2.0 onwards) is integrated in HEASoft release 6.14 onwards.
    - the NuSTAR calibration database (CALDB) (release 20130509 onwards).

- downloaded the NuSTAR observation(s) to be processed from the NuSTAR archive at HEASARC.
    - Note that data is also publicly available at the ASDC multi-mission interactive archive (http://nustar.asdc.asi.it).

- some experience using the *SAOImage DS9* astronomical imaging and data visualization application that can display FITS format images.
    - Freeware available for download from http://hea-www.harvard.edu/RD/ds9/site/Download.html
    - Documentation for *DS9* at http://hea-www.harvard.edu/RD/ds9/site/Documentation.html

- some experience with astronomical X-ray data analysis using the HEASARC *Xanadu* software tools like *XSPEC* and *XRONOS*.

Instructions on how to download and install NuSTAR software and CALDB, and how to download archival data can be found on the HEASARC website. It is possible to process NuSTAR data without downloading the many MBytes of NuSTAR CALDB files. However users are cautioned that some stages of processing may run very slowly while CALDB files are accessed over the internet. We recommend downloading and local installation of the NuSTAR CALDB.

Data analysis overview

NuSTAR data processing using *NuSTARDAS* is organized into three distinct stages:

Stage 1	Stage 2	Stage 3
Data Calibration	**Data Screening**	**Products extraction**
Level 1 & 1a calibrated event files	*Level 2 cleaned event files*	*Level 3 products*

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 (J2000 187.2779154 2.0523883 deg) observed by NuSTAR on 2012-07-13 between 0145 UT to 0440 UT that obtained two orbits of data with a total exposure time of 5150/5161 seconds in Focal Plane Module (FPM) A/B respectively. This 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.

How to run the pipeline using *nupipeline*

As a first step users should run the NuSTAR data analysis pipeline (*nupipeline*) stages 1 and 2. Note that if default calibration and data screening is sufficient, then users may skip ahead to the next section (*nuproducts*).

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 our 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`

Note that the majority of the input parameters of the individual modules within *nupipeline* can also be set. See the *NuSTARDAS* software guide for details, including worked examples. Descriptions of the input parameters are available via extensive help files for *nupipeline* and all of its modules via the "fhelp" command. These can be accessed from the command line by typing:

```
fhelp <module>
```

E.g. for a description of the output files generated by *nupipeline* run:

```
fhelp nupipeline
```

Run *nupipeline* stages 1 and 2 by issuing the command:

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

(where the \ slash is just an indication of command line continuation).

Go to the output directory that was produced:

```
cd ./out
```

The level 2 output files are the calibrated, cleaned, and screened events files from the NuSTAR X-ray telescope. 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
```

The *nupipeline* script can be used to automatically run stage 3 to extract level 3 products, but the default use is to run stages 1 & 2. It is recommended that users run stage 3 separately (via the *nuproducts* script), particularly when first examining an observation.

Extracting a point source spectrum and light-curve using *nuproducts*

X-ray photons from a celestial source observed by NuSTAR should be visible (assuming sufficient exposure time!) in the NuSTAR detected X-ray events image generated by *nupipeline* stages 1 and 2.

Note that level 2 calibrated and screened event files are available for each obsID directly from HEASARC in the archive `/event_cl` directory. These files were generated at the NuSTAR SOC with default parameter settings for *nupipeline* and so users wishing to examine observations generated with default calibration and screening can begin with this step. GIF files of the NuSTAR image, energy spectrum, and light-curve are also available for every obsID in the archive generated with 30 arcsec extraction at the J2000 position of the target (see table 2 below).

All of the following notes are for analysis of point sources in the FPMA telescope and can be repeated for FPMB by replacing `A` with `B` in the file names. 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
```

Assuming that *nupipeline* has been run and files are in the output directory `./out` the image of events can be viewed using *DS9*. Go to the output directory:

```
cd ./out
```

Load the science mode level 2 event file into *DS9*:

```
ds9 nu10012001002A01_cl.evt
```

Make source extraction region files using *DS9* by choosing a circular region of 30 arcsec radius centered on the source.
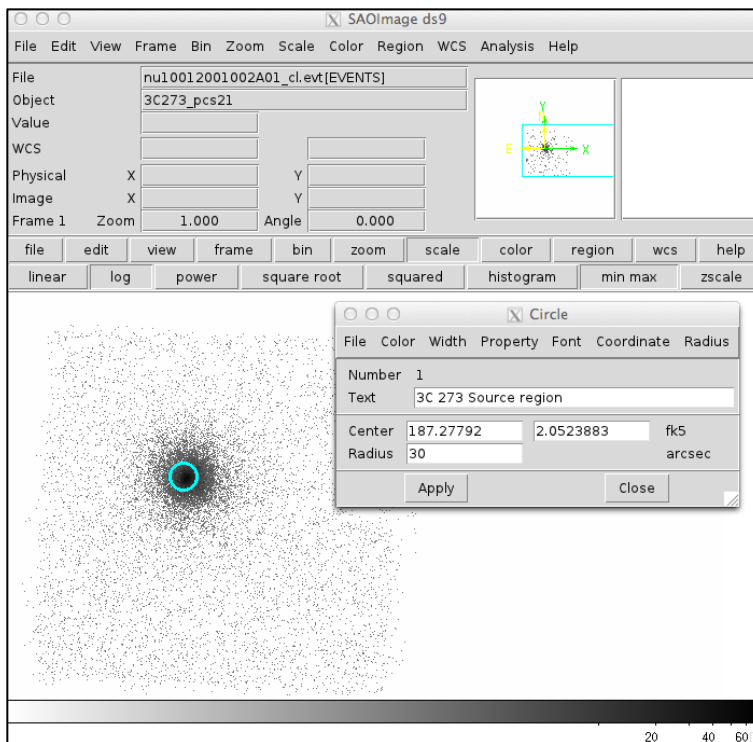

Fig. 2 shows the NuSTAR FPMA image of 3C 273 displayed in *DS9*.

The location of X-ray events has been translated to sky coordinates in the image so the center of the region can be set to the J2000 coordinates of 3C 273 or chosen to be located at the position of peak source brightness.

The blue circle is the 30 arcsec radius source extraction circular region centered on the J2000 coordinates of the target.

Use *DS9* to save this region information in a file called `source.reg` in the `./out` directory. Choose the WCS coordinate system when saving region files.

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. A detailed discussion of NuSTAR background will come in a future document. The most straightforward method is to place the background region as close to the source as possible without including source photons, away from the outer edges of the field of view (which has systematically higher background), and preferably on the same detector.
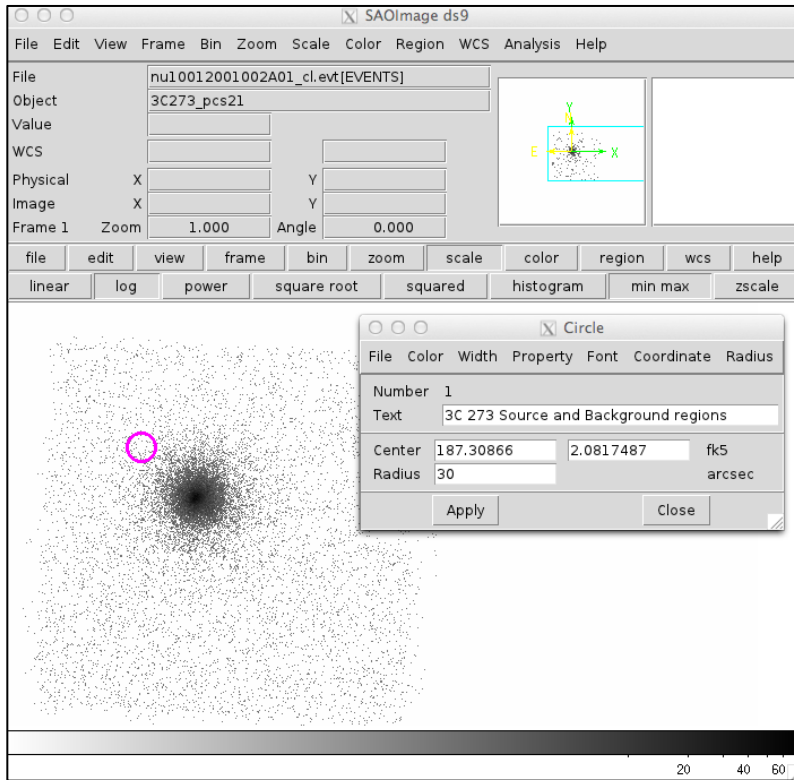

Figure 3 – NuSTAR FPMA event image of obsID 10012001002 (3C 273) with source and background extraction regions displayed in *DS9*

Fig. 3 shows the NuSTAR FPMA image of 3C 273 displayed in *DS9*. The magenta circle is the 30 arcsec radius background extraction circular region. Use *DS9* to save this region information in a file called `bkg.reg` in the `./out` directory.
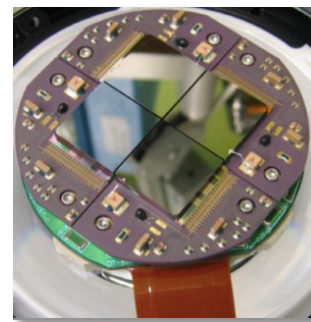

Figure-4 – Photo of the NuSTAR focal plane.

Each NuSTAR focal plane consists of a 2x2 array of CdZnTe pixel detectors, each with 32x32 pixels of 0.6mm (12.3 arcsec) in size, providing a 12 arcmin field of view. See Harrison et al. (2013) for details and Appendix A.

Now you can exit *DS9*.   Users should now run *nuproducts* to extract the level 3 science products.

There are many variables that can be set in *nuproducts*. For details, particularly when examining extended sources, please see the *NuSTARDAS* software guide and/or run:

```
fhelp nuproducts
```

Here is the *nuproducts* command with all of the correct keywords passed to *nuproducts.* If you wish to extract a background PHA file, set the *nuproducts* parameter *bkgextract=yes*. The output directory is called `products` and the \ slashes are the "line continuation" in the shell environment:

```
nuproducts \
   srcregionfile=source.reg \
   bkgregionfile=bkg.reg \
   indir=./out \
   outdir=./products \
   instrument=FPMA \
   steminputs=nu10012001002 \
   bkgextract=yes
```

It is also useful to have XSPEC automatically load the ARF, RMF, and background files. The `ANCRFILE`, `RESPFILE`, and `BACKFILE` keywords are automatically added by *nuproducts* to the FITS header of the PHA file.

Note that if *nuproducts* is run to extract level 3 products directly from data downloaded from the archive then it is also necessary to set the '*attfile*' and '*hkfile*' input parameters as follows:

```
nuproducts \
    srcregionfile=source.reg \
    bkgregionfile=bkg.reg \
    indir=./event_cl \
    outdir=./products \
    instrument=FPMA \
    steminputs=nu10012001002 \
    bkgextract=yes \
    attfile=./auxil/nu10012001002_att.fits \
    hkfile=./hk/nu10012001002A_fpm.hk
```

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.

All of this can be scripted in a way to process multiple OBSIDs and/or both instruments. Stage 3 can also be run to extract products from both FPMA and FPMB by running *nupipeline* and setting the parameter *exitstage=3*:

```
nupipeline  indir=/disk/nustar/archive/10012001002/  steminputs=nu10012001002  \
    outdir=./out  exitstage=3  srcregionfile=./out/source.reg  \
    bkgregionfile=./out/bkg.reg
```

The files generated in the output 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 then coadded. Please review the NuSTAR FAQs on the HEASARC website and if you have any questions about NuSTAR data analysis or technical issues with *NuSTARDAS* or *HEASoft* please contact the HEASARC help desk. The URL for these websites and documentation can be found in the next section (Additional information).

Good luck!

Table 2 - *nuproducts* output files for FPMA

File generated by *nuproducts*	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

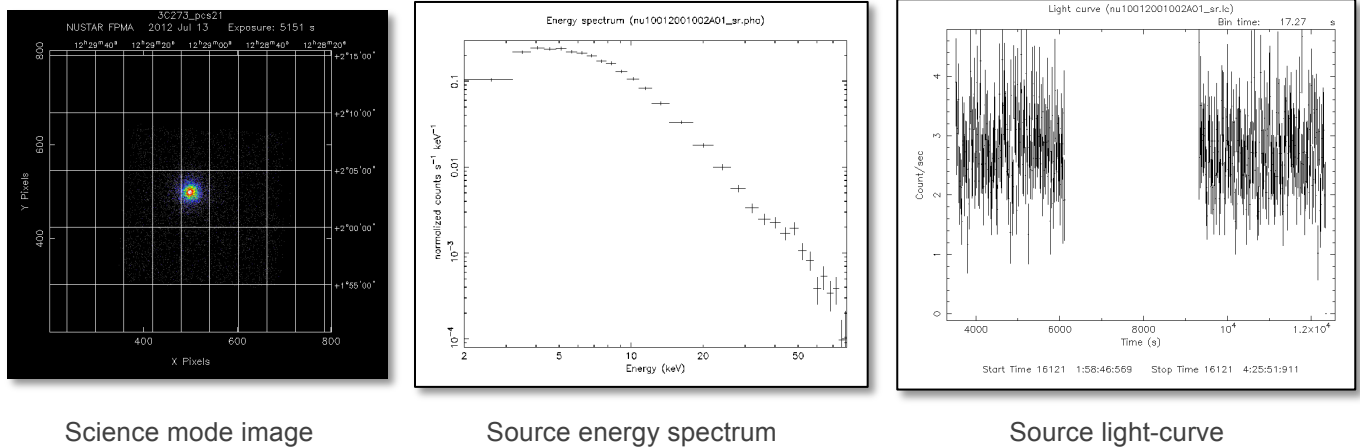| Science mode image | Source energy spectrum | Source light-curve |

Figure 5 - Level 3 FPMA scientific products for 3C 273 calibration observation (obsID 10012001002)

Additional information

NuSTAR website at Caltech – news about the mission and information for proposers
http://nustar.caltech.edu
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://www.srl.caltech.edu/NuSTAR_Public/NuSTAROperationSite/Home.php
NuSTARDAS software guide – Perri et al. (2013)
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
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
NuSTAR CALDB guide – Corcoran, M.F. 2013 – *CAL Memo CAL/NuSTAR/2012-001*
http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/nustar/
The NuSTAR calibration database (CALDB)
http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_intro.html
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 Science Data Center homepage (ASDC)
http://www.asdc.asi.it

Appendix A – NuSTAR observation position angle

The position angle of NuSTAR observation is defined in the standard way as degrees East of North of the direction of the +DET1Y focal plane axis. At PA = 0 degrees the optical axis is approximately 1 arcminute North-East of the center of the focal plane field of view.
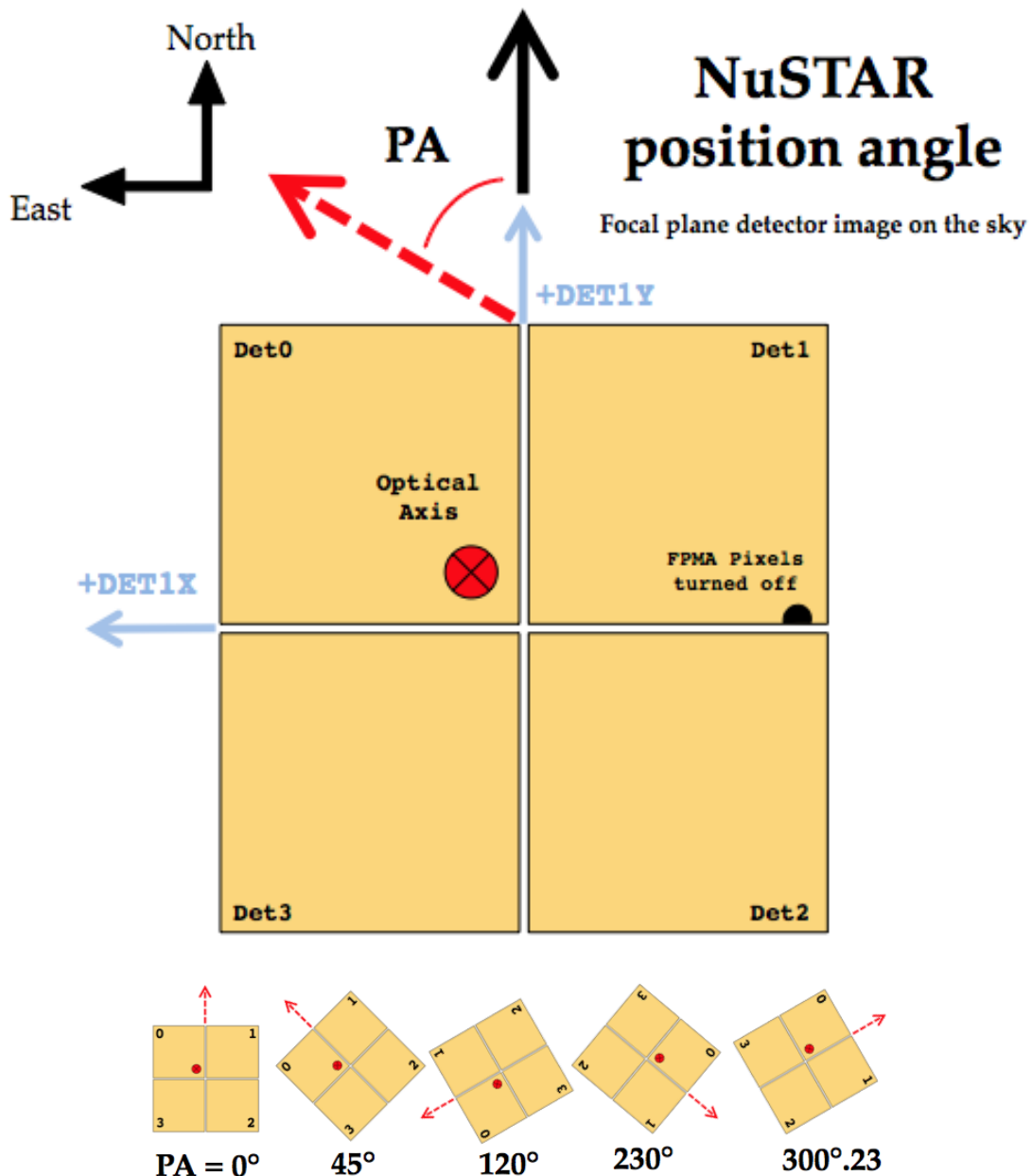

Figure A1 – Definition of NuSTAR observation position angle. Note the location of a group of pixels on FPMA DET1 that are turned off. This position may be visible in images of long (≥ 50 ksec) exposures.

Appendix B – *NuSTARDAS* pipeline modules

NuSTARDAS Pipeline modules

Stage 1 – Calibration
Processing of FITS formatted telemetry

Level 1 Event Files

Module	Function
Metrology Processing	numetrology
Attitude Correction	nuattcorr
Bad Pixel Flagging	nuflagbad
Hot Pixel Search	nuhotpix
Event Reconstruction and grade assignment	nucalcpha
Energy Calibration (gain correction PHA to PI)	nucalcpi
Event Flagging (depth cut correction)	nuflagevt
Coordinate transformation	nucoord nucalcpos coordinator nuskypos

Level 1a Calibrated Event Files

Pipeline script
nupipeline

Stage 2 – Screening
Filtering of calibrated event files by applying conditions from specified attitude/orbit/instrument parameters

Level 2 Cleaned Event Files

Module	Function
SAA passages	nucalcsaa
Filter file generation	nufilter
Data screening	nuscreen
Dead Time	nulivetime

Stage 3 – Extraction
Extraction of high-level scientific products from cleaned event files. Light curves, spectra, exposure map, images

Module	Function
Extraction of high level products	nuproducts
Exposure map generation	nuexpomap
Backscale correction (energy spectra)	nubackscale
Light-curve corrections	nulccorr
ARF file generation	numkarf
RMF file generation	numkrmf

Level 3 Scientific Data Products