The *XRISM* Data Reduction Guide

–also known as the ABC Guide–

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Prepared by the *XRISM* Guest Observing Facility (GOF)
and Science Data Center (SDC) on behalf of the *XRISM* mission

Institute of Space and Astronautical Science (ISAS/JAXA),
X-ray Astrophysics Laboratory
NASA's Goddard Space Flight Center (GSFC),
and
European Space Agency (ESA)

Copies of this guide are available in `html` and `pdf` formats.

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Chapter 1

Introduction

This document describes the basics of the analysis of X-ray data obtained using the *XRISM* observatory. It explains the required software, the data download procedure, the data structure and contents, the standard data reduction, and the creation of analysis products. Readers should be familiar with basic astronomical X-ray analysis and the *XRISM* instruments at this stage. If not, please refer to the following *XRISM* Guest Observer Facility (GOF) page for general XRISM satellite information:

https://heasarc.gsfc.nasa.gov/docs/xrism

or the Proposer's Observatory Guide (hereafter, POG) for the *XRISM* Guest Observer's program available at:

https://heasarc.gsfc.nasa.gov/docs/xrism/proposals/POG/

This document does not cover the analysis of data obtained for unusual instrument setups or observing conditions, complex data reduction methods, or advanced data analysis techniques. Please note that a future version of the document may cover them.

Chapter 2 describes information on current caveats and things to watch out for when working with *XRISM* data. Chapter 3 describes the software needed for *XRISM* data analysis, including instructions for downloading and installation. Chapter 4 explains the *XRISM* data directory structure, coordinate systems, and file names and formats. Chapter 5 provides a broad overview of the data analysis flow. Chapters 6 and 7 describe in depth how to analyze Resolve and Xtend instrument data, respectively.

Users who encounter problems reducing *XRISM* data may ask questions at one of the following help desks.

NASA: https://heasarc.gsfc.nasa.gov/cgi-bin/Feedback
JAXA: https://xrism.isas.jaxa.jp/research/
ESA: https://www.cosmos.esa.int/web/xrism

Chapter 2

Updates and Ongoing Issues

2.1 Introduction

This chapter contains information on current caveats and things to watch out for when working with *XRISM* data. Please also check the *XRISM* web page, which is updated more frequently than this guide, for the latest on newly identified issues or solution to previously identified issues.

2.2 Latest Changes and Updates

- 2024 August: *XRISM* software was included in `HEASoft` (version 6.34). First *XRISM* CALDB, version 240815, was released.

2.3 Ongoing Issues

Resolve

- We recommend using Hp events only for spectral analysis because the Hp and Mp events currently have significant gain inconsistencies: merging these two event grades degrades spectral resolution significantly. We expect this issue to be resolved in a near-future update of the software.
- Pixel 27 shows somewhat irregular gain variation. We recommend not using the data for scientific analyses.
- The onboard calibration found more Ls events than expected from the ground study. The so-called anomalous Ls events do not originate from direct X-ray signals from

celestial objects, but the current analysis scheme assumes so. The item ”Removing Ls Events from Cleaned Event Files” in Section 6.3 shows a measure to mitigate this problem for relatively weak sources. The studies for bright sources are underway.

Xtend

- Cosmic ray echo events produce false events at affected pixels at every exposure frame until a daily dark-level initialization. These events show multiple high-count dots in Xtend images. Software released in the near future will efficiently remove these events. For now, we suggest that users avoid analyzing data below $\sim$0.6 keV or running the `HEASoft` tool `searchflickpix` with special parameters to remove the events.
- The Xtend housing blocks the light path near the Xtend FOV edge on CCD_ID=2 (see Figure 6.2 on POG). The current calibration does not include this effective area reduction, causing flux underestimates of sources detected in this tiny area.

Chapter 3

Analyses Tools and Environment

XRISM data analysis requires multiple software packages, which are available for free on the Internet.

3.1 HEASoft

XRISM users reduce the data using the `HEASoft` package developed by the High Energy Astrophysics Science Archive Research Center at NASA's GSFC.

https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/

`HEASoft` is a unified release of the `FTOOLS` software package, a collection of programs and scripts with command-line interface for NASA's space science mission data and their reductions, and the `XANADU` package for image, light curve, and spectral analysis. The *XRISM* instrument teams write all mission-specific tools to recalibrate and analyze *XRISM* data and include them as a part of `HEASoft` after version 6.34, which are collectively called the "*XRISM* `FTOOLS`". *XRISM* users must use *XRISM* `FTOOLS` to recalibrate *XRISM* data and produce their image, light curve, and spectrum products. Users can continue in-depth analyses of those products using `ximage`, `xronos`, and `xspec` in the `XANADU` package. The produced analysis products are OGIP compliant FITS files, so users may use software outside of the `HEASoft` suite (e.g., CIAO). However, *XRISM* GOF supports other tools only if time permits due to limited resources.

`HEASoft` runs on major Unix architectures, Linux, and OS X. `HEAsoft` should run on Cygwin on Windows in principle, but caveats apply (see `HEASoft` website). *XRISM* users are strongly encouraged to use one of the supported Unix systems, listed on the `HEASoft` website. The `HEASoft` package is nominally released approximately once a year, but patches of the *XRISM* `FTOOLS` may be released on a faster timescale as needed. Please check the *XRISM* web page frequently for information.

3.1.1 fhelp

This is arguably the most important but underrated tool in `HEASoft`. Users can look up the detailed usage and the option description of any `HEASoft` tools. After setting up the `HEASoft` environment, type

```
term> fhelp 'command'
```

to find the command description. Users can also list all `HEASoft` tools by typing

```
term> fhelp ftools
```

We recommend that users check fhelp first when encountering a software-related problem. Users can also find the online version on the `HEASoft` web page.

3.1.2 fv

The `FTOOLS`, `fv`, is a handy tool for viewing images or tables inside a FITS file. It can also make plots or basic statistical analyses, which are convenient for checking the observatory's HK or obtaining data. To launch `fv`, type

```
term> fv FITS_file_name
```

or simply

```
term> fv
```

and find a file to open from the menu.

3.1.3 XSELECT

`Xselect` is a multi-mission command-line interface in the `HEASoft` suite, which loads X-ray event data, selects events with various user-defined conditions such as sky areas, time intervals, and photon energies, and outputs image, light curve, and spectral FITS products after filtering data. It works interactively, preserving all filtering conditions and organizing information during a run. Thus, users can focus on data analysis without having to manage tedious command options for running the `FTOOLS extractor` event extraction tool, which does the job behind `Xselect`. It has been widely used to analyze X-ray event data from *ASCA*, *ROSAT*, *BeppoSAX*, *Einstein*, *Suzaku*, and other high-energy missions. *XRISM* GOF recommends that users use `Xselect` to manipulate *XRISM* event data. Users unfamiliar with `xselect` should read the following online manual.

https://heasarc.gsfc.nasa.gov/docs/software/lheasoft/ftools/xselect/xselect.html

3.1.4 HEASoftpy

`Heasoftpy` supports a Python 3 interface to the `HEASoft` tools, allowing users to integrate the `HEASoft` package into their Python codes or other Python libraries publicly available. The details can be found at:

https://heasarc.gsfc.nasa.gov/lheasoft/heasoftpy/

3.2 CALDB

XRISM `FTOOLS` access the observatory's calibration information through Calibration Database or CALDB:

https://heasarc.gsfc.nasa.gov/docs/xrism/calib/index.html

XRISM users may install the whole set of *XRISM* CALDB from HEASARC or access the remote database at NASA/GSFC at each run. The database stores all calibration versions from the mission start, and users can access any of them if needed. However, most users need only the latest CALDB information, so CALDB has a device that provides a file with the newest calibration information for each calibration category. Hence, users only need to specify "CALDB" with appropriate command options or don't even need to select them as they are hidden and their default values are "CALDB". The tools automatically pick the newest calibration files.

The following URL explains the procedures for installing the CALDB database on a local disk or setting up the remote access.

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

The local CALDB installation enables faster access to the calibration data, which may be especially important for users with limited internet connection. The remote CALDB access ensures that users utilize the most up-to-date calibration without monitoring the CALDB update and updating the CALDB data. Users can obtain the *XRISM* CALDB version information from the above web page.

3.3 SAOImage ds9

SAOImage is an astronomical imaging and data visualization application developed by the Harvard & Smithsonian Center for Astrophysics. It is outside the `HEASoft` suite but is a default image viewer of `xselect`, an essential `HEASoft` tool. Users can download the application from the following URL.

https://lweb.cfa.harvard.edu/resources/software.html

3.4 XSLIDE

XSLIDE (X-ray Spectral Line Identification Energy) is a spectral analysis software package that the *XRISM* Science Data Center plans to release. XSLIDE uses a graphical user interface to assist users in *XRISM* spectral analysis, allowing for line identification and basic plasma diagnostics using information stored in external files. It is a powerful line diagnostics tool that particularly helps understand the Resolve data, especially. However, it does not make spectral fittings, so it is suitable for supporting detailed spectral analysis with `xspec`. We will announce the release on the *XRISM* web page.

3.5 Sciserver

`Sciserver` is a cloud computing service maintained by `HEASARC` that allows users to analyze space science data in the `HEASARC` archive with a remote computer. `HEASARC` promptly updates the `HEASoft`, `CALDB`, and archival data in `Sciserver`, so users only need to access the server to analyze data. Anyone can create an account for free and is allotted 10GB of disk space. For the details, please see the following URL.

https://heasarc.gsfc.nasa.gov/docs/sciserver/

Chapter 4

XRISM Data Specifics and Conventions

This chapter describes the *XRISM* observation data, including the directory structure, data files, and their formats. The data format and structure are similar to some X-ray observatory mission data (e.g., *ASCA*, *Suzaku*) with minor variations.

4.1 Data Organization

Unique 9-digit sequence numbers are used to organize the *XRISM* observations. A sequence number is assigned for all data during an observation and during the slew from the previous observation. The initial data processing at JAXA and NASA, hereafter pipeline, collects all relevant data of an observation, calibrates and screens the data, makes standard analysis for quick looks, and stores all products in a package with a sequence number. NASA and JAXA have their own data archives open to the public through the following URLs.

NASA: https://heasarc.gsfc.nasa.gov/FTP/xrism/data/obs/
JAXA: https://data.darts.isas.jaxa.jp/pub/xrism/data/obs/

Users can directly access these URLs to download any packages, but they can find the desired datasets more easily through the archival portal sites (see Section 5.2).

4.2 Directory and Data File Structure

A *XRISM* data package is stored under a directory with its sequence number name. There are four directories under the top directory.

auxil contains auxiliary files not associated with a particular instrument, such as the attitude, orbit, filter, and satellite housekeeping files. These files help assess the satellite condition during the observations. Users may need to explicitly specify some of these files for running downstream software (see Section 5.7),

log contains log files of the pipeline processing,

resolve contains Resolve related data files, and

xtend contains Xtend related data files.

Each of the Resolve and Xtend directories has the following four sub-directories.

hk contains instrument housekeeping data: voltages, temperatures, and other instrument-specific information,

event_uf contains all X-ray event data down-linked from the observatory and calibrated, so-called unfiltered event files,

event_cl contains X-ray event data filtered from unfiltered event data using the standard screening criteria, so-called cleaned event files,

products contains quick-look analysis products (images, light curves & spectra) processed with the pipeline. These products are not suitable for science data analysis.

All science and HK files are in FITS format, while processing logs are in plain text.

4.3 Filenames

Users may use the following files in downstream software commands.

attitude	auxil/xa*OBSID*.att
filter	auxil/xa*OBSID*.ehk
orbit	auxil/xa*OBSID*.orb
unfiltered event	(resolve or xtend)/event_uf/xa*OBSIDiii_P*0*mmmmmm*_uf.evt
cleaned event	(resolve or xtend)/event_cl/xa*OBSIDiii_P*0*mmmmmm*_cl.evt

where

xa short term of `xarm`, the start-up name of the *XRISM* project,

OBSID 9-digit sequence number,

iii	instrument name abbreviation - rsl: Resolve, xtd: Xtend, gen: all instruments,
P	observation mode - p: pointing, s: slew, a: all (p+s),
$m \times N$	instrument mode. (N =6 for Resolve, =8 for Xtend)

The instrument mode describes the applied X-ray filter in use for Resolve. The former 3 digits of the instrument mode describe the applied CCD window and burst mode in use for Xtend.

Resolve

`Sub-string`	`X-ray Filter`
px0000	Undefined
px1000	OPEN
px2000	Al/Polyimide
px3000	Neutral Density (ND)
px4000	Be
px5000	Fe 55 calibration source

Xtend

`Sub-string`	`CCD Window/Burst Mode`
300	all four CCDs in full window mode
311	CCD1 & CCD2 in 1/8 window mode
312	CCD1 & CCD2 in full window + 0.1 sec burst mode
313	CCD1 & CCD2 in 1/8 window + 0.1 sec burst mode
320	CCD3 & CCD4 in full window mode

All files are compressed in gzip, so they have extra .gz extensions. `FTOOLS` software understands gzipped files, so users do not need to unzip them.

4.4 Unfiltered or Screened?

The pipeline produces two types of event files for each instrument: the 'unfiltered' file (*_uf.evt) under the event_uf directory and the 'cleaned' file (*_cl.evt) under the event_cl directory. The unfiltered files contain all events telemetered from the observatory; the events are calibrated but not screened. The pipeline at the data center or the `xapipeline` reprocessing tool feeds these unfiltered files, filters events that satisfy specific conditions (e.g., event type, grades) or time intervals (e.g., outside of South Atlantic Anomaly) and outputs 'cleaned' event files. The screening applied by the pipeline is the minimum set of filters considered to be compatible with all observations, including those of bright sources.

The archival cleaned files and those reprocessed with `xapipeline` with the default setup use the screening criteria defined in Table 5.1 for Resolve data and Table 5.2 for Xtend data, which shows the minimum screening. Users can adjust the screening conditions to optimize for their scientific goals following the guidance of Section 6.3 for Resolve and Section 7.3 for Xtend at their own risk. Users should always use cleaned event files for science analysis.

4.5 Important Reference Values

4.5.1 Image Coordinates

The pipeline uses various coordinate systems (RAW, ACT, DET, FOC, SKY) to map detected event locations on the detectors to celestial coordinates. Event files store all coordinate values for each event, but general users need only the following coordinates for science analysis. See also Fig. 5.1 for Resolve and Fig. 6.2 for Xtend in POG.

SKY: the X/Y coordinates with the same orientation as the world coordinate system (WCS, e.g., FK5) — declination (δ) increases in the +Y direction and Right Ascension (α) increases in the –X direction — incremented every $\sim$1.77 arcsec. Their origin is at the celestial reference coordinates in the HEADER keywords (TCRVL31/TCRVL32), shared between the Resolve and Xtend data of the same observation. A detector pixel can generally be mapped onto multiple `SKY` pixels, so the software picks a `SKY` pixel for each event based on its weighted positional probability and stores the values in the `X/Y` columns of the event FITS files. Standard image viewers such as `ds9` and `Ximage` can automatically convert the SKY coordinates to the world coordinate system.

DET: the coordinate system mapped individually on the Resolve and Xtend detector planes, looking up toward the sky through the X-ray mirror (XMA). The Resolve `DET` coordinate system puts the 6$\times$6 pixel array in the positive quadrant, with the missing corner pixel for calibration at (1, 1), and increments the coordinates by 1 with every pixel. The Xtend DET coordinate system originates at the corner of the CCD array on CCD_ID=1, having the x- and y-axes of the vertical and horizontal CCD pixel directions of CCD_ID=1. The four CCDs do not perfectly align, so the DETX/Y axes are not strictly parallel to the CCD rows or columns of the other CCDs (CCD_IDs = 0, 2, 3). The event FITS files store these values in the `DETX/DETY` columns.

4.5.2 Pulse Height

Each event has a PI (pulse invariant) value that is proportional to the incident photon energy. This value is calculated from the sensor's pulse outputs (pulse height value: PHA for Resolve, PHAS for Xtend) and adjusted to the linear energy scale of the incident photon using the calibration information. `Xselect` produces a PI value histogram (event counts per each PI value or channel) from the selected events for spectral analysis. `Xspec` fits the histogram with physical models with the corresponding detector response.

4.5.3 Detection Time

Each event has a TIME value, which describes the event detection time in seconds from the *XRISM* mission time origin (2019-01-01 00:00:00 UTC). The mission time origin is stored in the MJDREFI and MJDREFF keywords of all *XRISM* FITS file headers, so `HEASoft` or OGIP-compliant timing software can convert the mission time to a human-friendly time system. Users can also convert *XRISM* time to various time systems on the `xTime HEASARC` web page.

4.6 XSELECT Default Parameters

By default, `XSELECT` (see Section 3.1.3) uses the following setups for *XRISM* data analyses[1]. Users can change them during `XSELECT` sessions after loading event data.

- Common for all instruments:
  - The FTOOLS "extractor" is called when extracting events
  - Light curve bin size: 16 sec
  - Image coordinates: the SKY (X/Y) coordinates
  - Event file names: xa*.evt[2].
  - The filter file has the name xa*mkf[2].
  - Image binning: 1
  - WMAP binning: 1
  - "RAWX" and "RAWY" coordinates: "ACTX"/"ACTY". The "set image raw" command creates an ACT coordinate image.
- Resolve:

[1]The pre-defined setup is described in $HEADAS/bin/xselect.mdb, where $HEADAS is the UNIX shell environment variable set by running `heainit`, or an equivalent `HEASoft` initialization.

[2]Implemented from HEASoft 6.35

  - WMAP[3] is not created in the spectral file's primary extension.

- Xtend:
  - WMAP is created in the spectral file's extension
  - WMAP coordinates: the Detector (DETX/DETY) coordinates
  - Pixels on WMAP outside of the selected region have the −1 value.

4.7 Important Values in the Event Files

[3]WMAP is a detector image of the spectrum extraction region, with which `xtdrmf` creates a spectral response.

Table 4.1: Resolve Event Columns for Calibration, Screening, Filtering, and Analysis

Column	**Description**	**Range**
ITYPE/TYPE	Resolution Grade 0/Hp: High-resolution Primary 1/Mp: Mid-resolution Primary 2/Ms: Mid-resolution Secondary 3/Lp: Low-resolution Primary 4/Ls: Low-resolution Secondary 5/Bl: Baseline event (diagnostic) 6/El: Lost event† 7/Rj: rejected events	0−7/Xx
PIXEL	Pixel number	0−35
RISE_TIME	Event pulse time from the baseline to the peak	0−255
PI	Pulse Invariant energy channel	0−59999
STATUS[N]	16 bit Event Flag (14 in use) [1]: outside of all-pixel GTIs [2]: outside of individual-pixel GTIs [3]: coincidence with anti-co event [4]: coincidence with event on any pixel except 12 [5]: coincidence with pixel 12 event [6]: [5] & passed energy test for absorption of electron ejected from 12 [7]: candidate electrical crosstalk event or its source [8]: [7] & largest PHA of coincident group [9]: during pulse of MXS direct source [10]: during afterglow of MXS direct source [11]: during pulse of MXS indirect source [12]: during afterglow of MXS indirect source [13]: event likely contaminated by untriggered electrical crosstalk [14]: [13] & largest PHA of coincident group	b0: no b1: yes

ITYPE/TYPE provides a numerical/adjectival representation of the event grade. It is also conventionally called GRADE.

†The events the onboard software is unable to process within the available computational time.

Table 4.2: Xtend Event Columns for Calibration, Screening, Filtering, and Analysis

Column	Description	Range
GRADE	5×5 pixel pulse height patterns 0: Single† 1: Corner split 2: Vertical split† 3: Left split† 4: Right split† 5: Vertical, left, or right split with a corner 6: 2×2 box split with a low corner pulse-height† 7: 3 pixels vertical or horizontal split with an outer 5×5 pixel above thres. 8: unused 9: 3 pixels vertical or horizontal split with no outer 5x5 pixel above thres. 10: GRADE 2, 4, 5, or 6 with an outer 5x5 pixel above thres. 11: 2×2 box split with a high corner pulse-height	0−11
PI	Pulse Invariant energy channel	0−4095
STATUS[N]	48 bit Event Flag (37 in use) [1]: Bad event based on all other status flags [2]: Inside the calibration source region [3]: Outside of CCD* [4]: Outside of window* [5]: Outside of the area discrimination* [6]: Charge Injection (CI) row* [7]: Bad pixel from CALDB* [8]: Bad column from CALDB* [9]: Hot pixel from pre-pipeline* [10]: Flickering pixel detected by `searchflickpix`* [11]: CCD boundary* [12]: Window boundary* [13]: Segment boundary [14]: Area discrimination boundary [15]: At least one 3x3 surrounding pixel has bad status [16]: CI trailing row* [17]: CI preceding row* [18]: Preceding/following of bad column* [19]: Neighbor of bad/hot pixel and bad column* [20]: Neighbor of flickering pixel*	b0: no b1: yes

Table 4.2: Continue

Column	**Description**	**Range**
STATUS[*N*]	[21]: Neighbor of preceding/following of bad column STATUS [22]: Neighbor of CCD/window boundary [23]: Neighbor of segment boundary [24]: 3x3 info is present but 5x5 is absent [25]: 3x3 is absent* [26]: PHAS[0] < event threshold* [27]: Video temperature is out of range* [28]: Lack of video temp HK at time close to the event* [29]: Correction value is negative [30]: Null value by correction process* [31]: 1st trailing row of the CI rows [32]: 1st preceding row of the CI rows [33]: 2nd trailing row of the CI rows [34]: 2nd preceding row of the CI rows [35]: 3rd trailing row of the CI rows [36]: 3rd preceding row of the CI rows [37]: Cosmic ray echo pixel	b0: no b1: yes

†Grades corresponding to X-ray (as opposed to cosmic ray) events.
*Bad pixel events removed with the standard screening.

Chapter 5

XRISM Data Analysis Overview

This chapter briefly outlines the initial analysis steps common to Resolve and Xtend. Subsequent chapters 6 & 7 describe the following steps specific to each instrument.

This and the following chapters use the *XRISM* first light observation data of the supernova remnant N132D (Obs_ID = 000126000) as command examples. The object is moderately extended by ~1 arcmin, but we sometimes treat the source as a point source. Users can freely change the command options with "N132D" to other arbitrary names while replacing those with 000126000 to the corresponding files in their data packages.

5.1 Setting Up the Environment

Users need `HEASoft` version 6.34 or a later version, *XRISM* CALDB, and the SAOImage ds9 viewer. Read the Software chapter in Section 3 for the details.

5.2 Retrieving *XRISM* Data

Most *XRISM* Guest Observer (GO) data are proprietary for 1 year after being fully processed. During the proprietary period, the data are downloadable but encrypted with `gpg` encryption. Only the observation's contact person receives the instructions for and decrypting the data from the Science Data Center, or SDC. After the proprietary period, all data are decrypted and available to anybody.

Non-GO users can search and access public data through the two web portals at NASA's HEASARC and ISAS/JAXA's DARTS.

https://heasarc.gsfc.nasa.gov/docs/archive.html

https://darts.isas.jaxa.jp

They provide multiple options for data downloads. Below is an example of downloads from NASA and JAXA through Unix terminal commands. Similar commands are in the instructions for GO observers.

```
NASA:
term> wget -nv -m -np -nH --cut-dirs=5 -R "index.html*" --execute robots=off
--wait=1 https://heasarc.gsfc.nasa.gov/FTP/xrism/data/obs/0/000126000/
```

```
JAXA:
term> wget -nv -m -np -nH --cut-dirs=6 -R "index.html*" --execute robots=off
--wait=1 https://data.darts.isas.jaxa.jp/pub/xrism/data/obs/rev3/0/000126000/
```

The last directory but one, with "0" in the above examples, organizes the observation type with a single-digit number (0−9) (2 for GO observations). Users should not omit "/" at the end of the html address, or they copy many empty directories at the same directory level.

5.3 Checking the Operation Logs and Resolve Processing Notes

The *XRISM* operations team makes logs of satellite and instrument anomalies, which are available from the following web page.

https://xrism.isas.jaxa.jp/research/observers/operation_log/index.html

Unusual data are often associated with these events.

The pipeline processing produces the Energy Scale Quality Reports for each observation, which summarizes the Resolve per-pixel and full-array energy resolution and gain accuracy based on Filter Wheel and pixel 12 Fe55 Calibration source data analysis. Users can download the reports from the following site.

https://heasarc.gsfc.nasa.gov/docs/xrism/analysis/gainreports/index.html

Users are advised to check these notes before analyzing the data.

5.4 Browsing the Quick Look Products

The *XRISM* pipeline generates quick-look preview products under each instrument's `products` directory (see Section 4.2). This directory includes images in multiple energy bands and the main target's light curves and spectra (whole sensor for Resolve, within 2.5 arcmin from the on-axis position for Xtend) in FITS or GIF format. These products are handy for checking the quality of the data obtained. However, we strongly discourage using them for detailed science or calibration analysis. The directory does not contain spectral `arf` responses for either instrument, so users cannot perform spectral fits with these products.

5.5 Checking for HEASoft and Calibration Updates

The instrument teams regularly monitor the instrumental responses and their time evolutions and update the results in CALDB, sometimes promptly, if their findings significantly impact the scientific outcome. Data downloded a while ago may well be outdated. Also, the Science Data Center (SDC) does not reprocess archival data for each CALDB release, so archival data placed a while ago may not also use the latest calibration. Users are encouraged to check the calibration information and apply the latest calibration to the analysis dataset.

Users can find the latest *XRISM* calibration information on the following calibration web page.

https://heasarc.gsfc.nasa.gov/docs/xrism/calib/index.html

All FITS files have the following keywords, which record the calibration version applied by the pipeline.

PROCVER:	processing script version
SOFTVER:	software package version used for the pipeline
CALDBVER:	calibration version used for the pipeline

If the calibration is outdated, users should apply the latest calibration to the data with the HEASoft *XRISM* task `xapipeline`. This script runs the following three stages:

1. applying the new calibration to update unfiltered event data,
2. screening the unfiltered event data to create cleaned event data, and
3. creating quick-look final products (images, light curves, spectra).

Here is a command example.

```
term> xapipeline indir=000126000 outdir=000126000_rep
  steminputs=xa000126000 stemoutputs=DEFAULT entry_stage=1
  exit_stage=2 instrument=ALL verify_input=no
```

This command runs in the directory with the downloaded data's top directory (`000126000`) and outputs all reprocessed data to the directory, `000126000_rep`[1]. Users can control the reprocessing stages with the `entry_stage` and `exit_stage` options. For example, a run with `entry_stage`=2 does not re-calibrate data, while a run with `exit_stage`=3 also makes quick-look products. Users can reprocess only one instrument data with the `instrument`

[1] Users can name this as they like, although this directory has 00012600 and not N132D.

option. `xapiepline` has many command options to control all the tasks running under it. To get a list of all the parameters, please check the command line manual by typing

```
term> fhelp xapipeline
```

or visit the online help.

5.6 Standard Screening Criteria

Tables 5.1 and 5.2 show the Resolve and Xtend standard screening criteria the pipeline uses to produce cleaned event files. There are two types of data screening: one with time and one with event characteristics. The time screening excludes intervals not suitable for the target's science study — the slew from the previous target, the Earth occultation of the target, the South Atlantic Anomaly (SAA) passages with high particle background, the Resolve ADR cooling cycles with significant spectral gain uncertainty, and event losses during the onboard data processing and telemetry. The files in the reference column record these time intervals, and the pipeline excludes them to include only "good time interval" or GTI. The data obtained during the GTI intervals still include particle background or spurious events. The event screening selects events that maximize X-ray signals for most objects.

5.7 Setting an Analysis Directory

We recommend that users create a separate directory for analysis, although they can analyze data under the event_cl directory. Hereafter, the analysis directory is called `analysis/`.

Users should copy or link the following files to `analysis/`.

000126000/auxil/xa000126000.ehk
000126000/resolve/event_cl/xa000126000rsl_p0px1000_cl.evt
000126000/resolve/event_uf/xa000126000rsl_px1000_exp.gti
000126000/xtend/event_cl/xa000126000xtd_p030000010_cl.evt
000126000/xtend/event_uf/xa000126000xtd_p030000010.bimg

See Section 4.3 for the file convention. If users run `xapipeline`, all these files are under the `outdir` directory.

5.8 Optimized Screening and Product Extraction

Users perform further data screening or processing optimized for the targets and then produce images, light curves, and spectra. The procedures are more specific to the instruments, so we describe them separately in the next two chapters. The point and diffuse

Table 5.1: Resolve Standard Screening Criteria for the Cleaned Science Event Files

<table>
<tr><th>Screen</th><th>Reference</th><th>Condition</th><th>Comments</th></tr>
<tr><td>Time</td><td>.ehk</td><td>ANG_DIST<1.5
SAA_SXS==0
ELV >5
DYE_ELV >5</td><td>pointing target
outside SAA
above the Earth rim
above the Bright Earth rim</td></tr>
<tr><td>Time</td><td>_gen.gti</td><td>inside GTIPOINT
inside GTIATT</td><td>excl. slew
excl. bad attitude</td></tr>
<tr><td>Time</td><td>.mkf</td><td></td><td>nominal instrument status</td></tr>
<tr><td>Time</td><td>rsl_tel.gti</td><td>inside GTIADROFF</td><td>excl. ADR cycle</td></tr>
<tr><td>Time</td><td>_el.gti</td><td>inside GTILOSTOFF</td><td>excl. lost event interval†</td></tr>
<tr><td>Event</td><td>_uf.evt</td><td>ITYPE<5
(SLOPE_DIFFER==b0||PI>22000)
QUICK_DOUBLE==b0
STATUS[2]==b0
STATUS[3]==b0
STATUS[6]==b0
RISE_TIME <127
PIXEL!=12
−8 < TICK_SHIFT <7</td><td>

excl. antico events
excl. e- from pix 12

excl. calibration pixel
</td></tr>
</table>

The screening formulae connect these conditions with AND unless explicitly stated.
Strings in the Reference column come after "xaOBSID."
†applied to antico events only.

source analyses share most reduction procedures except for the `arf` response creation. We explicitly describe their differences when necessary.

Bright sources need extra care as the instrument's behaviors change at high count rates. The flux definition of bright sources is different between Resolve and Xtend instruments or the applied observation mode (See Chapter 8 in POG for Resolve and Section 6.3 in POG for Xtend) and there are multiple count rate thresholds that change the behaviors. We describe the issue briefly in the last section of each chapter, but the detailed treatment is beyond the scope of this document.

Table 5.2: Xtend Standard Screening Criteria for the Cleaned Science Event Files

Screen	**Reference**	**Condition**	**Comments**
Time	.ehk	ANG_DIST<1.5 SAA_SXI==0 T_SAA_SXS > 277 ELV >5 DYE_ELV >20	pointing target outside SAA Time after SAA passage above the Earth rim above the Bright Earth rim
Time	_gen.gti	inside GTIPOINT inside GTIATT	excl. slew excl. bad attitude
Time	.mkf	SXI_USR_CCDn_OBS_MODE==1 n: appropriate CCD_IDs	nominal instrument status
Time	sxi_tel.gti	inside GTITEL	excl. times of telemetry saturation
Time	_uf.evt	inside GTIEVENT	inc. GTIs of the event data
Event	_uf.evt	GRADE==0,2,3,4,6 STATUS[1]==b0 PROC_STATUS[1,2]==b0†	

The screening formulae connect these conditions with AND unless explicitly stated.
Strings in the Reference column come after "xaOBSID."
†PROC_STATUS reports errors found in the telemetry or during the processing.
PROC_STATUS[1,2]==b0 means that the data in the row was good and processed correctly.

Chapter 6

Resolve Data Analysis

6.1 Introduction

The unprecedented spectral resolution in the hard (>2 keV) band is the hallmark of Resolve data. It can be realized with the High and Mid primary events (Hp and Mp) among five X-ray grade events (Table 4.1. See also POG for details). Users who want to take full advantage of the Resolve instrument should use these events for spectral analysis. The lower-grade events (Ms, Lp, Ls) also have very good energy resolutions, especially compared with X-ray CCD data (cf. Table 6.1)[1]. They may also help obtain the highest statistical significance. Section 6.3 describes how to choose specific grades for analysis.

An essential characteristic of the Resolve data is that the grade branching ratios significantly change at high count rates, above $\sim$1 cts s^{-1} array^{-1} for on-axis point sources (see Figure 5.9 in POG). We categorize these sources as Resolve Bright sources and briefly describe the treatments, including other high count rate features, in Section 6.7. This threshold is not so high among typical Resolve point sources, so users should exercise extra caution in analyzing such data, particularly strongly variable sources, as observed spectral variations can be artificial. Note that this threshold is based on count rate per pixel, so it is much higher for extended sources, and nearly all extended sources are unaffected by this issue.

We strongly encourage users to familiarize themselves with the Resolve detector properties described in Chapter 5 in POG. There are ongoing efforts on the detector response calibration. Currently (November 2024), we recommend using Hp events only for spectral analysis because the Hp and Mp events have significant gain inconsistencies: merging these two event grades degrades spectral resolution significantly. Software released in the future will address this issue. Please check Section 2 and the *XRISM* web page regularly for the

[1] This is especially true for bright sources, where a large fraction of photons will be registered in the lower grades.

latest information.

6.2 Cleaned Event File

The pipeline creates 2 cleaned event files in the `resolve/event_cl` directory.

xa000126000rsl_p0px1000_cl.evt
xa000126000rsl_p0px5000_cl.evt

The first file corresponds to the science data. The digit after `px` can be 1−4, depending on the X-ray filter chosen for the science observation (see Section 4.3). The file is screened with the standard screening condition in Table 5.1 unless users change the screening condition. The second file (px5000) contains the data obtained during the gain calibration. The directory may have one more event file, "*_p0px0000_cl.evt", which includes data not optimal for the primary target.

6.3 Additional Screenings and Processings

We recommend that users consider the following additional processes for the cleaned events. The pipeline does not perform these processes primarily because the applications depend on the science goal, observation condition, or the nature of the target. We recommend running some processes on a Unix terminal while the others are after loading data into `xselect` (Section 6.4.2), partly for historical reasons.

Screening Out Pixel-Pixel Coincident Events

Command line/Highly recommended

When energy is absorbed into the silicon frame around the Resolve array, it pulses the temperature of the heat sink of all of the pixels, resulting in pulses in the temperatures of the pixels themselves. For very large depositions of energy (MeV scale), the resulting pulses on the pixels can produce signals that trigger in the Pulse Shape Processor (PSP). We refer to the resulting clusters of events as frame events. Most of these events have significantly different pulse rise times from regular events, so they can be removed efficiently with a rise time cut. Because Ls events have a very large spread in rise times, Ls events are excluded from the cut.

Frame events can also be identified by pixel-pixel coincidence and removed by screening on STATUS[4]. The rise-time and STATUS[4] cuts largely remove the same events, but coincidence screening is more effective at very low energies for which the determination of rise time is noisy. STATUS[4] also removes more rare background events that can be identified by coincidence, such as secondary events associated with the same primary cosmic ray. For very weak sources for which the probability of two source photons hitting the array within the coincidence window, currently set at ±0.72 ms, is negligible, the STATUS[4] cut is a useful multi-purpose cleaner. However, it is important to consider the false-coincidence probability before applying it to your data. If the ±0.72 ms window will result in excessive data loss due to false coincidence, the STATUS[4] screening may be omitted.

Currently, electrical-crosstalk screening with STATUS[6] is not recommended. By requiring PI>=600, both for analysis and for flagging pixel-pixel coincidence, the only crosstalk events in the data will be associated with very energetic parent events (>12 keV) most of which are background events, and a STATUS[4] cut will remove both events. However, cross talk that is much too small to be confused with an X-ray can still be large enough to contaminate a real pulse if it overlaps with it. Thus, the coincidence of normal events on electrically adjacent channels is flagged (STATUS[13]) so that these events can be removed from spectral analysis. The window of overlap over which such contamination can significantly degrade the determination of the photon energy is large, ±25 ms. For bright sources, consider screening on STATUS[13] and comparing the result to the case of retaining such events.

The Resolve instrument team and the SDC are currently working to refine the various pixel-pixel coincidence definitions (general (STATUS[4]), electrical cross talk (STATUS[6]), and coincident real events that contaminate each other via untriggered crosstalk (STATUS[13])) through criteria based on PI threshold, PI ratio, and group size, to minimize the overlap in the definitions and allow more precise cleaning at the lowest energies.

To apply screening on PI, rise time, and STATUS[4], execute the following `HEASoft` command on the Resolve cleaned event file.

```
term> ftcopy infile="xa000126000rsl_p0px1000_cl.evt[EVENTS][(PI>=600)
&&(((((RISE_TIME+0.00075*DERIV_MAX)>46)&&
((RISE_TIME+0.00075*DERIV_MAX)<58))&&ITYPE<4)||(ITYPE==4))&&
STATUS[4]==b0]" outfile=xa000126000rsl_p0px1000_cl2.evt
copyall=yes clobber=yes history=yes
```

Users use the output cleaned event file (*_cl2.evt) for further analysis.

Removing the Anomalous Ls Events

Command line/Highly recommended for Relatively Weak Sources/Temporary Measure

The onboard calibration found more Ls events than expected from the ground study. These so-called anomalous Ls events do not originate from direct X-ray signals from celestial objects. However, the current analysis scheme assumes that: the `rslmkrmf` response generator divides the X-ray collecting area by the number ratio of the selected grade events

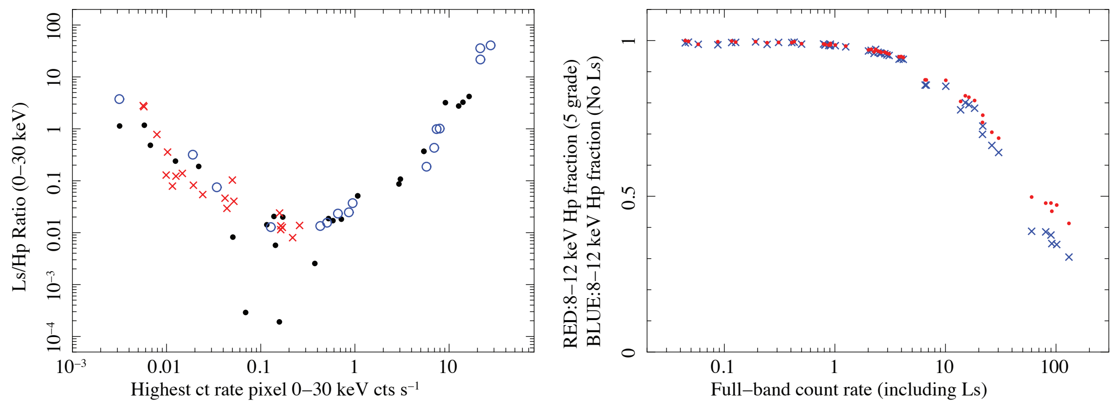

Figure 6.1: *Left*: Ls/Hp ratio over the highest count rate pixel (*black dot*: on-axis point source, *red cross*: extended source, *blue circle*: off-axis or other source). Below 0.2 cts/s/pixel where the first Ls component dominates, the Ls fraction increases as the source count rate decreases. Above 0.2 cts/s/pixel where the second Ls component dominates, the Ls fraction increases strongly as the source count rate increases. *Right*: Hp fraction over the total event counts including (*red*)/excluding (*blue*) Ls events from 48 point source data. The fractions of these two cases do not change until 2-3 cts/s, but then start to deviate.

over the total Grade 0−4 events, which include the Ls events. The produced response systematically has a lower collective area than it should be, which overestimates the total flux.

The anomalous Ls events have two components (See Figure 6.1 *left*). The first component prominent in the low count rate range ($\lesssim$0.4 cts/s/pixel) does not correlate with the source count rate, probably originating from cosmic-ray particles or instrumental X-rays induced by cosmic rays. The second component is more robust with brighter sources, significantly above the 0-30 keV pixel count rate range greater than 1 cts/s/pixel, so it can be related to secondary signals produced by initial (probably energetic) X-rays.

Currently, we have a temporary measure for weak sources whose X-rays do not significantly produce Ls events (maximum pixel count rate below ∼0.4 cts/s/pixel or count rate of ∼1 cts/s for a point source). Since the detected Ls events originate from particle background, users can safely remove them from the event files as non-source origin. The following command produces an event file without Ls events.

```
term> ftcopy infile="xa000126000rsl_p0px1000_cl.evt[EVENTS][ITYPE<4]"
  outfile=xa000126000rsl_p0px1000_wols_cl.evt copyall=yes clobber=yes
  history=yes
```

Users may combine this command with the above command for "Screening Out Pixel-Pixel Coincident Events" by removing the "`||(ITYPE==4)`" part. Users must use the cleaned event file produced for further data reduction or analysis.

Moderately bright sources, up to ∼10 cts/s for a point source, produce the second Ls component events, but not so significantly between 3−10 keV. For such sources, uses may remove Ls events with the above command and analyze only the data between 3−10 keV. The derived source flux should be considered a lower limit, as the source's direct X-rays also produce some Ls events.

The Ls events of brighter sources have complicated behavior, so we do not yet have an effective solution. With currently available response files, their absolute flux and global spectral shape are highly uncertain, so users should limit analyses to narrow energy bands. The instrument team is conducting a comprehensive study to determine the most effective strategy for mitigating this problem.

Selecting Event Grades

Xselect/Highly recommended

The cleaned event files processed with the standard screening include five X-ray grade events [0:4], each having a different spectral resolution.(The High and Mid-primary events (Hp and Mp) achieve the highest energy resolution (see Section 5.3.3 in POG), while the other events have up to ∼6 times worse spectral resolutions. To select only Hp and Mp events for spectral analysis, type on the `xselect` command line,

```
xsel> filter GRADE "0:1"
```

We do not recommend grade selection for image and light curve analysis, particularly of Bright sources, as the grade branching ratios change with the count rate (see Section 6.7 for details). Users should create response matrices matching the selected grades (Section 6.5.1).

Excluding Pixel 27 Data

Xselect/Highly recommended

Pixel 27 at an edge of the array (Figure 5.1 in POG) has significantly different gain variation characteristics from the other pixels. Including its data can degrade the spectral energy resolution. Add the following filtering condition to exclude Pixel 27 events from your data.

```
xsel> filter column "PIXEL=0:11,13:26,28:35"
```

Users must also exclude this pixel from the pixel list or the detector region when generating `rmf` and `arf` response files (see Sections 6.5.1, 6.5.2). Since this pixel is on the edge of the pixel array, an on-axis point source loses only a fraction of events. The above formula also excludes the calibration pixel 12, but the description is redundant as the science cleaned event data do not contain pixel 12 events.

Excluding High Particle Background Periods

Xselect/Depending on source flux or science goal

Particle background in low Earth orbits is roughly inversely correlated to the geomagnetic cut-off rigidity or COR. Excluding low COR intervals may improve the signal-to-noise ratio of relatively faint sources, with a sacrifice of exposure time. If the background contribution is not negligible, users may study the dependence of COR on the signal quality.

The standard screening does not exclude low COR intervals. The HK file, xa000126000.ehk, collects four different COR values during the observation (COR, COR2, COR3, CORTIME). CORTIME is the latest available table, and should best reflect the COR condition on *XRISM* orbit. The following `xselect` command selects only the `CORTIME`>`8` interval.

```
xsel> select mkf "CORTIME.gt.8" mkf_name=xa000126000.ehk
  mkf_dir=path/to/ehk/directory
```

A caveat is that users cannot use the command's prompt mode for this selection; they must type all the command option on an `xselect` command line. Typing only `xselect> select mkf` automatically launches the "FIND MKF" task, which searches for an mkf file in the specified filter file directory. However, the *XRISM* mkf files (xa*OBSID*.mkf) do not contain the COR information, so `xselect` returns an error not finding the COR column.

Applying Barycentric Correction

Command line/Pulse search

With a timing resolution of ∼80μsec, Resolve is also good for pulse searches. With the following command, users can convert the event time to those in the solar system barycenter time system.

```
term> barycen xa000126000rsl_p0px1000_cl2.evt
  xa000126000rsl_p0px1000_bc_cl2.evt xa000126000.orb 81.2596 -69.6441
  orbext=ORBIT
```

Users must specify the `orbext` hidden option at `ORBIT` because the default value, `PAR_ORBIT`, does not work for *XRISM* data. Users must set the precise target position in the `RA` and `DEC` options to get the best timing information for the target.

Excluding Off-Pointing Intervals

Xselect/Spatially-resolved spectral analysis

Some users may divide Resolve FOV into multiple regions for spatially-resolved spectral analysis or exclusion of nearby bright sources. The resolve `arf` generator only supports data in the `DET` coordinates, which does not correct the observatory's attitude fluctuation. XRISM's attitude control switches between the star tracker control and the inertial reference unit (IRU) propagation in every ∼96-minute orbital cycle. During the IRU propagation periods, the attitude typically drifts by around 10−15 arcseconds, about half of the Resolve pixel size. This drift affects approximately 20% of typical Resolve GTIs, so users must be cautious in analyzing data in the DET coordinates. One practical mitigation of spatial contamination is a stricter constraint on the pointing allowance. The following command limits the pointings within 0.1 arcmin from the nominal aim point.

```
xsel> select mkf "ANG_DIST.lt.0.1" mkf_name=xa000126000.ehk
    mkf_dir=path/to/ehk/directory
```

This screening cannot entirely exclude pointing offsets that could remain during the attitude control transition phases, each of which may take up to 4 minutes to converge. We plan to introduce a more straightforward and effective method in a future guide. We note that this drift does not affect the Xtend data analyses using the SKY coordinates.

Relaxing Screening Criteria

Command line (xapipeline)/Expert use only

If users understand Resolve data well and want to relax the screening criteria in Table 5.1 or extract data under a different condition, they may rescreen data with `xapipeline` with appropriate options. In this case, a run starting from stage 2 (`entry_stage=2`) saves processing time (see Section 5.5).

6.4 Extracting Products with Xselect

`Xselect` is the primary tool for extracting Resolve data products. It can filter events with areas, times, energies, or event flags and use the filtered events to create images, light curves, and spectra.

6.4.1 Loading Event Data

Go to the `analysis/` directory, start a new `xselect` session, and read a Resolve cleaned event file with science data:

```
xsel> read events xa000126000rsl_p0px1000_cl2.evt .
```

It may ask if the new mission name is *XRISM*. If so, return for responding yes.

6.4.2 Making Additional Screenings

Type `xselect` commands in Section 6.3 after loading event data for additional screenings.

6.4.3 Extracting Images

The following commands create a 2−10 keV `SKY` image.

```
xsel> set image sky
xsel> filter pha_cut 4000 19999
xsel> extract image
xsel> saoimage
```

The `SKY` images use a much smaller pixel size than the Resolve's physical pixels (see section 4.5.1). They show multiple fine pixels inside a box corresponding to Resolve's physical pixel, but these structures are artificial and should not be considered to reflect the source's spatial distribution.

Users can make images in any energy band by changing the `filter pha_cut` command options. The Energy−PI relation is:

`PI = 2000` × `Energy_in_keV`

Users can also look up the relation in the `EBOUND` extension of a Resolve `rmf` file. To make a `DET` image, change the first command to

```
xsel> set image det
```

To save the image, type:

```
xsel> save image N132D_rsl_sky_020100.img
```

Finally, remove the PI filter for further reductions if necessary.

```
xsel> clear pha_cutoff
```

6.4.4 Region (Pixel) Selection for Light Curve or Spectral Analysis

Resolve's FOV is comparable to the mirror PSF size, so events from a source are spread over all pixels. If users analyze point sources without significant contamination from nearby sources or diffuse sources whose spatial structures are unimportant, they can choose all pixels for light curve or spectral extractions. No spatial selections are necessary.

However, some users may study spatial structures of extended sources within the FOV or need to exclude areas with significant contamination from nearby sources. Then, they need to extract events from a sub-array region. The Resolve spectrum response generator only supports analysis in the `DET` coordinates while Resolve has only 35 imaging pixels. So, we recommend that users define Resolve event extraction regions with pixel numbers. The following example extracts events from all pixels on the positive `DETX` coordinates except for Pixel 27 (see Figure 5.1, Resolve pixel map in POG).

```
xsel> filter column "PIXEL=0:11,13:26,28:35"
```

Users should investigate if attitude fluctuation during the observations is insignificant concerning the sizes of the source extraction regions. Please check "Excluding Off-Pointing Intervals" in Section 6.3.

6.4.5 Extracting Light Curves

The following example extracts a 128 sec bin light curve in the 2−10 keV band.

```
xsel> filter pha_cutoff 4000 19999
xsel> set binsize 128.0
xsel> extr curve exposure=0.0
xsel> save curve N132D_rsl_b128.lc
```

If users do not want narrow light curve bins, increase the exposure option value between 0.0−1.0 (see the `xselect` extract manual).

The grade branching ratios significantly change with the source count rates above ∼1 cts s^{-1} array^{-1} for on-axis point sources (see Chapter 6.7, Figure 5.9 in POG). Above this threshold, the Hp (+ Mp) event rate is nonlinear with the source flux. Users should use all X-ray event grades (Hp, Mp, Ms, Lp)[2] to track the flux variation.

Again, remove the PI filter for further reductions if necessary.

```
xsel> clear pha_cutoff
```

[2] The Ls grade has been considered as an X-ray event grade, but the onboard calibration found that most Ls events originate from background particles or secondary X-ray events, so we do not include Ls in this list. This does not apply for Bright sources. See Section 6.3 for details.

6.4.6 Extracting Spectra

Whole Spectrum

The following commands extract and save a Resolve spectrum of the whole observation. We extract only high-res primary (Hp) events using the grade filter.

```
xsel> filter GRADE "0:0"
xsel> extr spectrum
xsel> save spectrum N132D_rsl_Hp_src.pi
```

Remove the grade filter for further reductions if necessary.

```
xsel> clear grade
```

Time-resolved spectrum

Making a time-resolved spectrum requires a few additional steps. First, users set up a time filter.

```
xsel> filter time file N132D_int0.gti
```

The filter command has a few methods to apply a time filter. Please check the filter time section in the `xselect` user manual.

The `rmf` response generator needs an event file of this time interval. Users make one with the "extr events" command.

```
xsel> extr events
xsel> save events N132D_rsl_int0.evt
> Use filtered events as input data file ? >[yes] no
```

Type "no" to the last question, or users cannot use event data outside of this time interval afterward. Do not apply a grade filter as the event file needs all X-ray Grades (0−3) events.

After this operation, users set a grade filter and extract a spectrum.

```
xsel> filter GRADE "0:0"
xsel> extr spectrum
xsel> save spectrum N132D_rsl_Hp_int0_src.pi
```

Users may repeat this procedure to create spectra at other intervals. Before that, make sure to clear the time and grade filters.

```
xsel> clear time
xsel> clear grade
```

6.5 Generating Response Files

An extracted spectrum needs the corresponding instrument response for spectral analysis. The Resolve spectral response comprises two parts. The `rmf` describes how the detector redistributes X-rays onto the detector PI channels. It is a 2-dimensional matrix that maps photon energy bins to a PI space. The `arf` describes the mirror's energy-dependent effective collecting area, assuming an X-ray source's spatial distribution in the sky. It is a one-dimensional matrix with the `rmf`'s photon energy bins. Resolve and Xtend have nearly identical mirrors and so share the `arf` generation software.

6.5.1 Making an RMF file

The HEASoft *XRISM* tool, `rslmkrmf`, generates Resolve `rmf` files. Below is a command example.

```
term> punlearn rslmkrmf
term> rslmkrmfinfile=xa000126000rsl_p0px1000_cl2.evt
   outfileroot=N132D_rsl_Hp_L_src regmode=DET whichrmf=L
   resolist=0 regionfile=ALLPIX
```

The first command, `punlearn`, initializes any optional parameters of `rslmkrmf` that remain from the previous run. The tool, `rslmkrmf`, obtains the grade branching ratios from the event file fed with the `infile` option and calculates the efficiency for the selected grades specified at the `resolist` option and the region specified at the `regionfile` option. The input event file must contain all events of all X-ray grades 0−3. For a time-sliced spectrum, use the event file produced at the "Time-resolved spectrum" bullet in Section 6.4.6 to match the time interval. If users do not make any region selection for extracting a spectrum, the command option can be `regmode=DET` and `regionfile=ALLPIX`[3]. If the spectrum is extracted from a subset of the pixels, users must specify the pixel list using the `pixlist` option with `regionfile`="NONE". For example, the command for a spectrum without Pixel 27 is:

[3]The `ALLPIX` option includes pixel 12, but since the science event file does not include pixel 12 events, it is equivalent to `pixlist=0-11,13-35`.

```
term> rslmkrmf infile=xa000126000rsl_p0px1000_cl2.evt
   outfileroot=N132D_rsl_Hp_L_src regmode=DET whichrmf=L
   resolist=0 regionfile=None pixlist=0-11,13-26,28-35
```

Make sure to connect the pixel number with "-", not ":" as for `xselect`.

The `resolist` option specifies the grade types used for the spectrum. The above example assumes a spectrum with only Hp events. If users make a spectrum from multiple grade types, list the grade numbers separated by commas (e.g., `resolist=0,1` for Hp+Mp). Please refer to Table 4.1 for the number for each grade type.

A Resolve spectrum has 6×10^4 PI channels, and a physical spectral model needs at least the same 6×10^4 bins to reproduce the data accurately. With 3.6×10^9 elements, a response matrix can be as big as ∼7 GB, which enormously slows spectral fitting processes. So, the tool can generate four types of `rmfs` with different file sizes.

Size	Option	Model Components
small	S	Gaussian core
medium	M	*small* + exponential tail & Si Kα instrumental line
large	L	*medium* + escape peak
x-large	X	*large* + electron loss continuum (ELC)

Users can choose the `rmf` type using the `whichrmf` option. The larger `rmfs` reproduce the response more accurately. For example, if the response matrix does not include ELC, the source may appear to have a soft excess. However, they give progressively heavier loads for spectral fittings, so users might want to consider hybrid approaches in which an "S" matrix is used for exploratory spectral fitting, followed by finer fitting, possibly in restricted energy bands. Since the extra-large (`whichrmf=X`) Resolve `rmfs` are extremely large, users can split them into two matrices, with a coarse grid for ELC and a fine grid for the other components with `splitrmf=yes` and `splitcomb=yes`, and store them in two separate extensions of the output `rmfs` file. `Xspec` can handle such response files as regular response files. See Section Line spread function in POG on the different components of the response and the `rslmkrmf` help file for more details.

6.5.2 Making an `arf` file

There are two steps to make an arf file. The first step is to create an exposure map with `xaexpmap`, which calculates exposure time for each portion of the sky during the observation using the observatory's attitude and instrument FOV information.

```
term> punlearn xaexpmap
term> xaexpmap ehkfile=xa000126000.ehk gtifile=xa000126000rsl_p0px1000_cl2.evt
   instrume=RESOLVE badimgfile=NONE pixgtifile=xa000126000rsl_px1000_exp.gti
```

```
outfile=N132D_rsl.expo outmaptype=EXPOSURE delta=20.0 numphi=1
```

The second step is to calculate the effective X-ray collecting area of the target with `xaarfgen`. The result depends strongly on the X-ray source's spatial distribution and position on the detector plane. `Xaarfgen` can, in principle, handle any X-ray sources in the sky, but that, in turn, means that users need to input multiple parameters to the tool. Below, we introduce examples of a point source and an extended source.

`Xaarfgen` runs a raytracing simulation by calling two tasks: i) `xrtraytrace` calculates the reflection and transmission of raytracing simulation photons from the assumed X-ray source, and ii) `xaxmaarfgen` counts the photons detected in the selected pixels. The simulation is more accurate with more raytracing photons until it hits the calibration or simulation limitation; the `numphoton` option controls the number of simulation photons. For a complete list of parameters and their description, please refer to the command line (`term> fhelp xaarfgen`) or online help.

If multiple sources with various shapes or at different locations significantly contribute to the spectrum, users should make an `arf` file for each source. Some contributions can come from outside the FOV. Users should assess the contributions using the simultaneously obtained Xtend data and/or other observatory data. We note that sources more than a few arcminutes away from the FOV do not significantly contribute to the X-ray event data unless they are extremely bright. `Xaarfgen` simulations of these sources require numerous simulation photons, many of which do not fall onto the detector, and take a long time.

Point Source

The following command shows an example for a point source (`sourcetype=POINT`).

```
term> punlearn xaarfgen
term> xaarfgen xrtevtfile=raytrace_N132D_rsl_pt.fits source_ra=81.2596
   source_dec=-69.6441 telescop=XRISM instrume=RESOLVE
   emapfile=N132D_rsl.expo regmode=DET regionfile=N132D_DET.reg
   sourcetype=POINT rmffile=N132D_rsl_Hp_L_src.rmf
   erange="1.5 18.0 0 0" outfile=N132D_rsl_Hp_L_ptsrc.arf
   numphoton=300000 qefile=CALDB contamifile=CALDB gatevalvefile=CALDB
   onaxisffile=CALDB onaxiscfile=CALDB mirrorfile=CALDB
   obstructfile=CALDB frontreffile=CALDB backreffile=CALDB
   pcolreffile=CALDB scatterfile=CALDB imgfile=NONE
```

- The `source_ra/source_dec` options input the source's `J2000/FK5/ICRS` coordinates.
- The `regmode` and `regionfile` options define the source regions used for the spectrum extraction. Since `xaarfgen` supports only the `DET` coordinates for Resolve,

`regmode=DET`. If users do not have a region file of the selected pixels in the `DET` coordinates, copy and edit the pixel region template in Section 6.8.

- The `rmffile` option specifies the `rmf` file produced with `rslmkrmf`. `Xaarfgen` makes the output `arf` energy grid to match the energy grid of the input `rmf` file. The `arf` works only with an `rmf` that has a matched energy grid.
- The `erange` option consists of four energy values. The first two values are the range in which `arf` values are calculated. The wider the range, the longer it will take for `arf` to be generated. The latter two values are only used in the `IMAGE` mode and are filled with zeros.
- The `emapfile` option specifies the exposure map filename created by `xaexpmap`.
- The `xrtevtfile` option specifies the simulation event file name outputted by `xrtraytrace`. If a named file is in the directory, `xaarfgen` skips the `xrtraytrace` run and uses the existing file for the second step.
- The `numphoton` option specifies the number of raytracing photons allocated to each attitude histogram bin per energy grid point in the exposure map file. If the number of photons is too low, `xaarfgen` complains and fails to provide an `arf`. More raytracing photons improve the quality of `arf`s, but the quality is limited by the calibration accuracy or the simulator's architectural restriction. It does not improve with Poisson statistics near the higher end, while the simulation takes proportionally to the number of raytracing photons.

Extended Source: IMAGE Mode

The point source mode `arf` described above assumes a point-like source placed at RA = 81.2596 deg and DEC = -69.6441 deg in the Resolve array. The case of extended sources is more complicated because the PSF also has a spatially-dependent shape and extent. In addition, the typical width of the PSF is comparable to the size of the Resolve array, meaning that in a large number of cases a significant fraction of photons initially emitted from the source will leak outside the detector region. Conversely, the extracted spectrum inside a given region will also contain photons coming originally from outside the selected region. Whereas these effects are limited in the case of point-like sources, this spatial-spectral mixing (SSM) has a much more important impact in the case of extended sources. This effect, and how to deal with it, is described in detail in POG. Making and using `arfs` appropriately is thus critical for many science cases involving extended sources.

If the user has a high-quality image of the extended source taken with another telescope (ideally *Chandra*/ACIS, otherwise *XMM-Newton*/EPIC), they can use the `arf` generator in IMAGE mode (as opposed to POINT source mode):

```
term> punlearn xaarfgen
term> xaarfgen xrtevtfile=raytrace_N132D_rsl_img.fits source_ra=81.2596
    source_dec=-69.6441 telescop=XRISM instrume=RESOLVE
    emapfile=N132D_rsl.expo regmode=DET regionfile=N132D_DET.reg
    sourcetype=IMAGE imgfile="/path/to/my_chandra_image.img"
    rmffile=N132D_rsl_Hp_L_src.rmf erange="0.3 18.0 2.0 8.0"
    outfile=N132D_rsl_Hp_L_img.arf numphoton=600000
    qefile=CALDB contamifile=CALDB gatevalvefile=CALDB
    onaxisffile=CALDB onaxiscfile=CALDB mirrorfile=CALDB obstructfile=CALDB
    frontreffile=CALDB backreffile=CALDB pcolreffile=CALDB scatterfile=CALDB
```

The two last numbers of the `erange` parameter now represent the energy range in which the provided image has been made. The `source_ra` and `source_dec` coordinates should now be set to the coordinates of the target source within the input image. If there are no obvious source, these coordinates should be set to the center of the image.

Important warning: A parameter that is important in the IMAGE mode is the number of input simulated photons, `numphoton` (see also above). If the user creates an `arf` for a source that is far away from the array, only a small percentage of the input photons simulated from this source will be scattered into the detector. In such a case, the raytracing sub-task `xrtraytrace` will require a large number of photons to create a reliable `arf`. Similarly, if the user uses a too wide input image, a large percentage of the input photons will be used to simulate features that are out of interest (e.g. point sources or residual background too far away from the detector region). These photons will thus be "lost" and the `arf` may be created with poor statistics and/or even biased low. It is strongly recommended to use an input image that is cropped to a moderate size ($\sim$10$-$15 arcmin wide at most). The appropriate image size depends on the brightness and distribution of surrounding sources. For example, if the Resolve FOV is on a dim part of an extended source with a very bright core, the bright core could contribute more to the outer pixels than the local dim emission. One way to check would be to run `xaarfgen` twice, the second time with a slightly larger image, to see what difference it makes.

Extended Source: Alternative Methods

In some cases, users may not have a proper *Chandra*/*XMM-Newton* image of their extended source. Providing that the surface brightness distribution of that source can be approximated with a 2D beta-model or a flat circle with known parameters, users can also make an `arf` using either the BETAMODEL or the FLATCIRCLE mode, respectively:

```
term> punlearn xaarfgen
term> xaarfgen xrtevtfile=raytrace_N132D_rsl_beta.fits source_ra=81.2596
    source_dec=-69.6441 telescop=XRISM instrume=RESOLVE
```

```
        emapfile=N132D_rsl.expo regmode=DET regionfile=N132D_DET.reg
        sourcetype=BETAMODEL betapars="0.50 0.60 5.0"
        rmffile=N132D_rsl_Hp_L_src.rmf erange="0.3 18.0 0 0"
        outfile=N132D_rsl_Hp_L_beta.arf numphoton=600000
        qefile=CALDB contamifile=CALDB gatevalvefile=CALDB
        onaxisffile=CALDB onaxiscfile=CALDB mirrorfile=CALDB obstructfile=CALDB
        frontreffile=CALDB backreffile=CALDB pcolreffile=CALDB scatterfile=CALDB
        imgfile=NONE
```

This beta-model can be parametrized as $N(r) = C[1 + (r/r_c)^2]^{1.5-3\beta}$ and its parameters (`betapars`) are, in order: r_c, β, and the cutoff limit of the profile ($0.5'$, 0.60, and $5'$ in this example).

```
    term> punlearn xaarfgen
    term> xaarfgen xrtevtfile=raytrace_N132D_rsl_flatcircle.fits source_ra=81.2596
        source_dec=-69.6441 telescop=XRISM instrume=RESOLVE
        emapfile=N132D_rsl.expo regmode=DET regionfile=N132D_DETx.reg
        sourcetype=FLATCIRCLE flatradius=10.0
        rmffile=N132D_rsl_Hp_L_src.rmf erange="0.3 18.0 0 0"
        outfile=N132D_rsl_Hp_L_flatcircle.arf numphoton=600000
        qefile=CALDB contamifile=CALDB gatevalvefile=CALDB
        onaxisffile=CALDB onaxiscfile=CALDB mirrorfile=CALDB obstructfile=CALDB
        frontreffile=CALDB backreffile=CALDB pcolreffile=CALDB scatterfile=CALDB
        imgfile=NONE
```

The only parameter relevant to the flat circle model is its radius ($10'$ in this example).

Also, note that the last two parameters of `erange` are set to zero. By definition, these numbers are relevant only for the IMAGE mode as they are set to the lower and upper energy bound, respectively, of the image data.

Although the BETAMODEL and FLATCIRCLE modes can be useful in a few specific cases, using the `arf` generator in IMAGE mode is the recommended procedure for the analysis of most extended sources.

6.6 Generating Non X-ray Background Spectra

Because of the small field of view, users cannot create Resolve background spectra from the same observation data, but must generate them using the *XRISM* tool `rslnxbgen`, which requires sufficient time to have passed since the *XRISM* launch to have a database that it can use. A provisional version of this data base was used during the PV phase and is being made available to GOs. Links to pages describing how to access the data base and use `rslnxbgen` and how to model the background can be found at

https://heasarc.gsfc.nasa.gov/docs/xrism/analysis/index.html

Updates will be reflected in those links as they are made available. If users produce a background spectrum, they should ensure that the keywords BACKSCAL in the source and background spectrum have identical values (both spectra should be drawn from the same Resolve pixels). Note also that the background and the data must be subjected to the same screening.

6.7 Bright Source Analysis

Resolve's detector response changes at high count rates. The following list shows three count rate thresholds for an on-axis point source, above which the performance changes significantly. The thresholds for extended sources are higher as X-ray events spread over multiple pixels more evenly. There are few *XRISM* extended sources that fall in this category. Detailed instructions on such data are beyond the scope of this document. Please, see Chapter 8 in POG for the details.

Cause		Threshold (cts s^{-1})
i	Significant change in the Hp grade branching ratio†	$\sim$1
i′	Anomalous Ls events complicate accounting for the source's Ls events†	
ii	Pulse Shape Processor processing limit	$\sim$200
iii	X-ray pulse contamination by untriggered electrical cross-talk	$\gg 1$

†See Figure 5.9 in POG.

6.8 DET Pixel Region

Below are the pixel positions in the `DET` coordinates. Copy those selected pixels into a region file and feed it into `xaarfgen` through the `regionfile` option (see Section 6.5.2).

```
box(4,3,1,1,0)  # pixel 0
box(6,3,1,1,0)  # pixel 1
box(5,3,1,1,0)  # pixel 2
box(6,2,1,1,0)  # pixel 3
box(5,2,1,1,0)  # pixel 4
box(6,1,1,1,0)  # pixel 5
box(5,1,1,1,0)  # pixel 6
box(4,2,1,1,0)  # pixel 7
box(4,1,1,1,0)  # pixel 8
box(1,3,1,1,0)  # pixel 9
box(2,3,1,1,0)  # pixel 10
box(1,2,1,1,0)  # pixel 11
box(2,2,1,1,0)  # pixel 13
box(2,1,1,1,0)  # pixel 14
box(3,2,1,1,0)  # pixel 15
box(3,1,1,1,0)  # pixel 16
box(3,3,1,1,0)  # pixel 17
box(3,4,1,1,0)  # pixel 18
box(1,4,1,1,0)  # pixel 19
box(2,4,1,1,0)  # pixel 20
box(1,5,1,1,0)  # pixel 21
box(2,5,1,1,0)  # pixel 22
box(1,6,1,1,0)  # pixel 23
box(2,6,1,1,0)  # pixel 24
box(3,5,1,1,0)  # pixel 25
box(3,6,1,1,0)  # pixel 26
box(6,4,1,1,0)  # pixel 27
box(5,4,1,1,0)  # pixel 28
box(6,5,1,1,0)  # pixel 29
box(6,6,1,1,0)  # pixel 30
box(5,5,1,1,0)  # pixel 31
box(5,6,1,1,0)  # pixel 32
box(4,5,1,1,0)  # pixel 33
box(4,6,1,1,0)  # pixel 34
box(4,4,1,1,0)  # pixel 35
```

Chapter 7

Xtend Data Analysis

7.1 Introduction

Xtend inherits data processing architecture from *Suzaku* XIS. It also has a fundamental data structure similar to other imaging (i.e., non-grating) X-ray CCD instruments, such as *Chandra* ACIS or *XMM-Newton* EPIC. Users with experience in X-ray CCD data analysis should be able to analyze Xtend data quickly. One notable difference from the ACIS or EPIC data is that Xtend images show zero-count charge injection rows at regular intervals. *Suzaku* XISs also used the same technique for observations after 2006, but Xtend images shows these lines more clearly because the satellite attitude is remarkably stable. The Xtend software is designed to automatically account for an efficiency deficit with these rows as well as dead columns or pixels for spectral analysis. This feature alleviates users' burden of managing these aspects in their analysis, allowing them to focus on the core tasks.

The X-ray event detection method does not work when two or more X-ray photons fall in 3×3 pixels in a single exposure. Such events, called photon pileups, distort X-ray detection and energy estimates, which is problematic for the flux and spectral measurements. We consider observations with significant photon pileups Xtend Bright source observations. When Xtend observes a point source with a count rate of $\sim$6.3 cts s^{-1} in the full window mode, about 10% of photons suffer pileups. This threshold is higher when an observation chooses a different CCD mode with a short frame exposure time, so Xtend bright source depends on the CCD observing mode (see Section 6.3.1 in POG). We briefly describe how to analyze photon pileup data in Section 7.7.1.

We strongly encourage users to familiarize themselves with the Xtend detector properties described in Chapter 6 in POG. There are ongoing efforts on the detector response calibration, so please check Section 2 and the *XRISM* web page for the latest information.

7.2 Cleaned Event File Content

Since the N132D observation (ObsID: 000126000) chose the full window mode for all four CCDs, the pipeline creates one cleaned event file in the `xtend/event_cl` directory.

xa000126000xtd_p030000010_cl.evt

Another N132D first light observation (ObsID: 000128000) chose the 1/8 window mode for CCD_ID = 1 & 2, so the pipeline creates one cleaned event file for each observing mode, for a total of two cleaned event files.

xa000128000xtd_p031100010_cl.evt (CCD_ID = 0 & 1)
xa000128000xtd_p032000010_cl.evt (CCD_ID = 2 & 3)

An observation that uses the window or window/burst option also has two cleaned event files. See Section 4.3 for the file name convention.

7.3 Additional Screening

The cleaned event file should be suitable for any decent science data analysis, but users can play with additional screening to optimize it for the object of interest. We recommend running some processes on a Unix terminal while the others are after loading data into `xselect` (Section 7.4.2), partly for historical reasons.

Alleviating Cosmic Echo Events

Xselect or Command line/Soft X-ray source analysis/Temporary Measure

A high-signal cosmic ray event produces a pseudo-cross-talk signal in a paired pixel. This echo signal incorrectly decreases the dark level of the pixel, causing non-X-ray signals after the event to rise above the detection threshold. Xtend falsely detects events from the pixel every frame until a daily dark-level initialization. These events show multiple high-count dots in soft band Xtend images, resembling (extreme) frequent flickering pixels. The instrument team is developing a tool to effectively remove these events. In the meantime, we recommend the following measure.

First, these pixels appear mainly on the outer half segments of each CCD chip, so the area near the aiming point is mostly free from these events. Users who analyze the primary target should be able to choose source and background regions without the cosmic echo pixels. Second, these events appear mostly below 0.4 keV and only a fraction up to $\sim$0.6 keV. Users may ignore data below $\sim$0.6 keV unless their interests are in the very soft X-ray band. The following `xselect` command excludes data below 0.6 keV and extracts data between 0.6−10 keV.

```
xsel> filter pha_cut 100 1665
```

Third, users can can effectively remove these events with `searchflickpix` developed for the flickering pixels. See the following section for usage.

Removing Flickering Pixels

Command line/If necessary/Temporary Measure

The flickering pixels occasionally show event signals without actual X-ray or particle events, adding noise to the data (see Section 6.4.3 in POG). The `HEASoft` tool `searchflickpix` searches pixels with abnormally high event rates and records the events as flickering pixel events in a file with the ".fpix" extension. The tool `xtdflagpix` feeds this file and flags the STATUS [10] bit of events detected on a flickering pixel or the STATUS [20] bit detected next to a flickering pixel. The Xtend pipeline is designed to run these tools sequentially to remove the events.

However, the current automated algorithm detects many false positive signals for bright sources, incorrectly removing true X-ray events at the PSF cores. Therefore, the current Xtend pipeline (`HEASoft` 6.34) runs `searchflickpix`, but does not remove events using the result. The *XRISM* team is studying the best method to remove flickering pixels with pipeline processing. Meanwhile, the team introduces a temporary method to eliminate the flickering and cosmic echo events while minimizing false positive events in the appendix of the Quick-Start guide, which can be downloaded from the following web page.

https://heasarc.gsfc.nasa.gov/docs/xrism/analysis/quickstart/index.html

Excluding High Particle Background Periods

Xselect/Depending on source flux or science goal

Particle background in low Earth orbits is roughly inversely correlated to the geomagnetic cut-off rigidity or COR. Excluding low COR intervals may improve the signal-to-noise ratio of relatively faint sources, with a sacrifice of exposure time. If the background contribution is not negligible, users may study the dependence of COR on the signal quality.

The standard screening does not exclude low COR intervals. The HK file, xa000126000.ehk, collects four different COR values during the observation (COR, COR2, COR3, CORTIME). CORTIME is the latest available table, and should best reflect the COR condition on *XRISM* orbit. The following command on `xselect` select only the `CORTIME`>`8` interval.

```
xsel> select mkf "CORTIME.gt.8" mkf_name=xa000126000.ehk
  mkf_dir=path/to/ehk/directory
```

A caveat is that users cannot use the command's prompt mode for this selection; they must type all the command option on an `xselect` command line. Typing only `xselect> select mkf` automatically launches the "FIND MKF" task, which searches for an mkf file in the specified filter file directory. However, the *XRISM* mkf files (xa*OBSID*.mkf) do not contain the COR information, so `xselect` returns an error not finding the COR column.

Applying Barycentric Correction

Command line/Pulse search

With the timing resolution of 0.5−4 sec (0.1-sec accuracy for burst mode observations), Xtend is good for searching moderately fast X-ray pulses. For the study, users should convert the event arrival time to the solar system barycenter time system using the following command.

```
term> barycen xa000126000xtd_p0300000a0_cl.evt
  xa000126000xtd_p0300000a0_bc_cl.evt xa000126000.orb 81.2596 -69.6441
  orbext=ORBIT
```

Users must specify the `orbext` hidden option at `ORBIT` because the default value, `PAR_ORBIT`, does not work for *XRISM* data. Users must set the precise target position in the `RA` and `DEC` options to get the best timing information for the target.

Relaxing Screening Criteria

Command line (xapipeline)/Expert use only

If users understand Xtend data well and want to relax the screening criteria in Table 5.2 or extract data under a different condition, they may rescreen data with `xapipeline` with appropriate options. In this case, a run starting from stage 2 (`entry_stage=2`) saves processing time (see Section 5.5).

7.4 Extracting Products with Xselect

`Xselect` is the primary tool for extracting Xtend data products. It can filter events with areas, times, energies, or event flags and use the filtered events to create images, light curve and spectra.

7.4.1 Loading Event Data

Go to the `analysis/` directory, start a new `xselect` session, and read an Xtend cleaned event file with science data:

```
xsel> read events xa000126000xtd_p0300000a0_cl.evt .
```

It may ask if the new mission name is *XRISM*. If so, return for responding yes.

Users can feed multiple event files by connecting event file names with commas. This operation is convenient for making a combined image of different observation modes (e.g., CCD_ID =1&2 with a 1/8 window mode plus CCD_ID = 2&3 with the full window mode). However, it mixes up the GTI information, so users should load event files separately for producing light curves or spectra.

7.4.2 Making Additional Screenings

Type `xselect` commands in Section 7.3 after loading event data for additional screenings.

7.4.3 Extracting Images

The following commands create a 0.5−10 keV `SKY` image.

```
xsel> set image sky
xsel> filter pha_cut 83 1665
xsel> extract image
xsel> saoimage
```

Users can make images in any energy band by changing the `filter pha_cut` command options. The Energy−PI relation is:

`PI = 166.7` $\times$ `Energy_in_keV`

Users can also look up the Energy − PI relation in the EBOUND extension of an Xtend `rmf` file. To make an image in the `DET` coordinates, change the first command to

```
xsel> set image det
```

To save the image, type:

```
xsel> save image N132D_xtd_sky_020100.img
```

Finally, remove the PI filter for the latter analysis if necessary.

```
xsel> clear pha_cutoff
```

7.4.4 Defining the Source and Background Regions

Users define source and background regions for extracting light curves and spectra. The easiest way is to use the `ds9` image viewer launched internally from `xselect` or launch `ds9` directly on a UNIX command line (see Section 3.3). The `arf` generator `xaarfgen` supports the analysis in the `SKY` coordinates for Xtend, so it would be convenient to define a region in the `SKY` coordinates.

To define a region on `ds9`, click the "edit" tab, the "region" tab, and left-click on the image, then, a region shape appears. The default shape is a circle, but users can choose various shapes through the `Region` > `Shape` pull-down menu. The shape's size, angle, and other property parameters can be adjusted interactively or from a menu that pops up with clicking the shape. Here, we define a source region with a 1.4 arcmin radius circle centered at the source peak, which includes 80% of photons from a point source (see Figure 4.15 in POG).

To save the region in a file, click the bar `Region` > `Save` selection, and choose "format: `ds9`" and "coordinate System: `physical`". Then `xselect` can load the file for a region selection. Check the `ds9` web page[1] for the basic `ds9` usage. A caveat is that `xselect` does not recognize the outer FOV boundary, so users must always define a region enclosure. The corresponding background is obtained best from a source-free region near the source. The background-extraction region should be significantly larger than the source region to collect enough statistics. Once users find a good background region, they can save the region file like the source region and feed it to `xselect` to extract a background light curve or spectrum.

If the source is extended over the Xtend FOV or the data have no appropriate source-free region, the tool `xtdnxbgen` can estimate non-X-ray background using night Earth observations. See section 7.6 for details.

We here name the extracted source and background regions at `N132D_xtd_src.reg` and `N132D_xtd_bgd.reg`, respectively.

7.4.5 Extracting Light Curves

The following example extracts a 500-second bin light curve in the 0.5−10 keV band. The `"xsel> set binsize"` command sets the binning time of the light curve.

First, we extract a source light curve by filtering the source region. Viewing the extracted image with the saoimage command ensures that the region filter is correctly applied. The command `"xsel> plot curve"` shows the extracted light curve.

```
xsel> filter pha_cutoff 83 1665
```

[1] https://sites.google.com/cfa.harvard.edu/saoimageds9

```
xsel> set binsize 500.0
xsel> filter region N132D_xtd_src.reg
xsel> extr "image curve" (or extr all)
xsel> saoimage
xsel> plot curve
```

Users can define a time filtering window from the light curve for spectrum or image analysis. Please see section 7.5 in the `xselect` manual for details.

We can save the source light curve with the following command.

```
xsel> save curve N132D_xtd_src_b128.lc
```

We clear the source region filter and make the background region filter to extract a background light curve.

```
xsel> clear region
xsel> filter region N132D_xtd_bgd.reg
xsel> extr "image curve" (or extr all)
xsel> saoimage
xsel> plot curve
xsel> save curve N132D_xtd_bgd_b128.lc
```

The `FTOOLS` `lcmath` is a handy tool for subtracting the background light curve from the source light curve. The tool requires a scaling factor for the source and background regions. Users can find the areal scales of these regions with the BACKSCAL keyword in spectra extracted from the same regions. Users can make in-depth light curve analysis using `Xanadu` tools such as `lcurve`.

Finally, remove the PI and region filter for further reduction if necessary.

```
xsel> clear pha_cutoff
xsel> clear region
```

7.4.6 Extracting Spectra

The following example extracts Xtend source and background spectra. Again, we recommend viewing the image to check if the region filter is correctly applied.

```
xsel> filter region N132D_xtd_src.reg
xsel> extr "image curve"
xsel> saoimage
xsel> save spec N132D_xtd_src.pi
```

We clear the region filter and make the background region filter to extract a background spectrum.

```
xsel> clear region
xsel> filter region N132D_xtd_bgd.reg
xsel> extr "image curve"
xsel> saoimage
xsel> save spec N132D_xtd_bgd.pi
```

Users who want to perform time-resolved spectral analysis load a time filter before extracting a spectrum.

```
xsel> filter time file N132D_xtd_sn.fits
```

They may keep the time filter made with the light curve analysis. See the `xselect time filter` manual for details.

Check that the `BACKSCAL` values in the source and background spectral files are consistent with the ratio of the source and background regions. Use `fv` to see the header keyword values, or `fkeyprint` and type,

```
term> fkeyprint N132D_xtd_src.pi BACKSCAL
```

to show the `BACKSCAL` value.

7.5 Generating Response Files

7.5.1 Making an RMF file

The `HEASoft` *XRISM* tool, `xtdrmf`, generates Xtend `rmf` files. Here is a command example.

```
term> punlearn xtdrmf
term> xtdrmf N132D_xtd_src.pi N132D_xtd_src.rmf
```

7.5.2 Make an ARF file

This process is the same as the Resolve `arf` generation, except for a few differences. Users first make an exposure map with `xaexpmap`.

```
term> punlearn xaexpmap
term> xaexpmap ehkfile=xa000126000.ehk gtifile=xa000126000xtd_p030000010_cl.evt
pixgtifile=NONE instrume=XTEND badimgfile=xa000126000xtd_p030000010.bimg
outfile=N132D_xtd.expo outmaptype=EXPOSURE delta=20.0 numphi=1
```

The second step is to calculate the effective X-ray collecting area of the target with `xaarfgen`. The result depends strongly on the X-ray source's spatial distribution and position on the detector plane. `Xaarfgen` can, in principle, handle any X-ray sources in the sky, but that, in turn, means that users need to input multiple parameters to the tool. Below, we introduce examples of a point source and an extended source. Please see Section 6.5.2 for a detailed explanation of how `Xaarfgen` works.

Point Source

The following command shows an example for a point source (`sourcetype=POINT`).

```
term> punlearn xaarfgen
term> xaarfgen xrtevtfile=rayt_N132D_xtd_ptsrc.fits
source_ra=81.2596 source_dec=-69.6441 telescop=XRISM instrume=XTEND
emapfile=N132D_xtd.expo regmode=RADEC regionfile=N132D_xtd_src.reg
sourcetype=POINT rmffile=N132D_xtd_src.rmf erange="0.3 15.0 0 0"
outfile=N132D_xtd_ptsrc.arf numphoton=600000 minphoton=100
teldeffile=CALDB qefile=CALDB contamifile=CALDB obffile=CALDB
fwfile=CALDB gatevalvefile=CALDB onaxisffile=CALDB onaxiscfile=CALDB
mirrorfile=CALDB obstructfile=CALDB frontreffile=CALDB
backreffile=CALDB pcolreffile=CALDB scatterfile=CALDB imgfile=NONE
seed=7 clobber=yes mode=h
```

- The `source_ra/source_dec` options input the source's `J2000/FK5/dICRS` coordinates.
- The `regmode` and `regionfile` options define the source regions used for the spectrum extraction. `Xaarfgen` can calculate Xtend `arf` in the `SKY` coordinates as the pixel size is significantly smaller than the mirror PSF. We choose `regmode=RADEC` and use the source region file `regionfile=N132D_xtd_src.reg`. Users can use a region file in the `DET` coordinates with `regmode=DET`.
- The `rmffile` option specifies the `rmf` file produced with `xtdrmf`. `Xaarfgen` makes the output `arf` energy grid to match the energy grid of the input `rmf` file. The `arf` works only with an `rmf` that has a matched energy grid.

- The `erange` option consists of four energy values. The first two values are the range in which `arf` values are calculated. The wider the range, the longer it will take for `arf` to be generated. The latter two values are only used in the `IMAGE` mode and are filled with zeros.
- The `emapfile` option specifies the exposure map filename created by `xaexpmap`.
- The `xrtevtfile` option specifies the simulation event file name outputted by `xrtraytrace`. If the named file is in the directory, `xaarfgen` skips the `xrtraytrace` run and uses the existing file for the second step.
- The `numphoton` option specifies the number of raytracing photons allocated to each attitude histogram bin per energy grid point in the exposure map file. If the number of photons is too low, `xaarfgen` will complain and fail to provide an `arf`. More raytracing photons improve the quality of `arf`s, but the quality is limited by the calibration accuracy or the simulator's architectural restriction. It does not improve with Poisson statistics near the higher end, while the simulation takes proportionally to the number of raytracing photons.

Extended source: IMAGE mode

Whereas the PSF of Xtend is similar to that of Resolve, its large FOV and lower spectral resolution (meaning less subtle spectral features to be mixed) somewhat alleviates the spatial-spectral mixing (SSM) problem. However, there may be cases in the analysis of extended sources where users still want (or need) to take this effect into account. The SSM strategies to adopt here as the same as for Resolve, and are further detailed in the POG. Likewise, extended source users can choose to generate an Xtend ARF based on a *Chandra* (or *XMM-Newton*) input image. Generating Xtend `arf`s in IMAGE mode is done with `xaarfgen` using the same syntax as for the Resolve example above (see Section 6.5.2):

```
term> punlearn xaarfgen
term> xaarfgen xrtevtfile=raytrace_N132D_xtd_img.fits source_ra=81.2596
    source_dec=-69.6441 telescop=XRISM instrume=XTEND
    emapfile=N132D_xtd.expo regmode=RADEC regionfile=N132D_xtd_src.reg
    sourcetype=IMAGE imgfile="/path/to/my_chandra_image.img"
    rmffile=N132D_xtd_src.rmf erange="0.3 18.0 0.3 10.0"
    outfile=N132D_xtd_img.arf numphoton=600000 minphoton=100
    qefile=CALDB contamifile=CALDB gatevalvefile=CALDB
    onaxisffile=CALDB onaxiscfile=CALDB mirrorfile=CALDB obstructfile=CALDB
    frontreffile=CALDB backreffile=CALDB pcolreffile=CALDB scatterfile=CALDB
    mode=h
```

Of course users should not forget to use `instrument=XTEND` and to change the input files (`emapfile`, `imgfile`, etc.) and other parameters (`erange`, etc.) accordingly.

These runs are appropriate for sources that are close to on-axis. The number of photons in runs of `xaarfgen` (the parameter `numphoton`) needs to be larger for larger off-axis angles, but note that the statistics are not Poissonian.

7.6 Generating Non X-ray Background Spectra

Since Xtend has a huge field of view, background data for a point source or a moderately extended source can be obtained from a nearby source free region. However, if a source is extended beyond the FOV, the background must be estimated from other datasets.

The *XRISM* team collects data during the night Earth observations when Xtend detects only particle events. Earlier studies show that the particle (non-X-ray) background is well correlated with the cut-off rigidity value, so the *XRISM* tool `xtdnxbgen` sorts the night Earth data out with the COR values and weights them to match the COR distribution during the source observations.

A provisional version of this database was used during the PV phase and is being made available to GOs. Links to pages describing how to access the database and use `rslnxbgen` and how to model the background can be found at

https://heasarc.gsfc.nasa.gov/docs/xrism/analysis/index.html

The NXB spectra have multiple emission lines and a continuum structure beyond the X-ray-sensitive energy range (see POG Fig. 6.4). These structures can be evident particularly in extended source spectra which tend to be faint. The NXB data do not include sky background such as cosmic X-ray background, local hot bubble, or solar wind charge-exchange emission, so users need to evaluate their contributions to the data.

7.7 Bright Source Analysis

7.7.1 Photon Pile-ups

The *XRISM* mirror PSF has a sharp core and a long tail (ref: X-ray Mirror PSF). Although a bright source has many pileup events in its PSF core, it has significantly fewer in its tail. So, users can take a source region without its PSF core for a pileup-free spectrum or light curve. The PSF core exclusion removes most events, but since such sources are bright, the remaining region should still have significant amounts of events for analysis.

Figure 7.1 simulates the pileup fraction of a crab-like point source for various core exclusion radii. This figure allows users to find an appropriate exclusion radius for their source flux, Xtend mode, and tolerable pileup fraction. The flux measurement with such

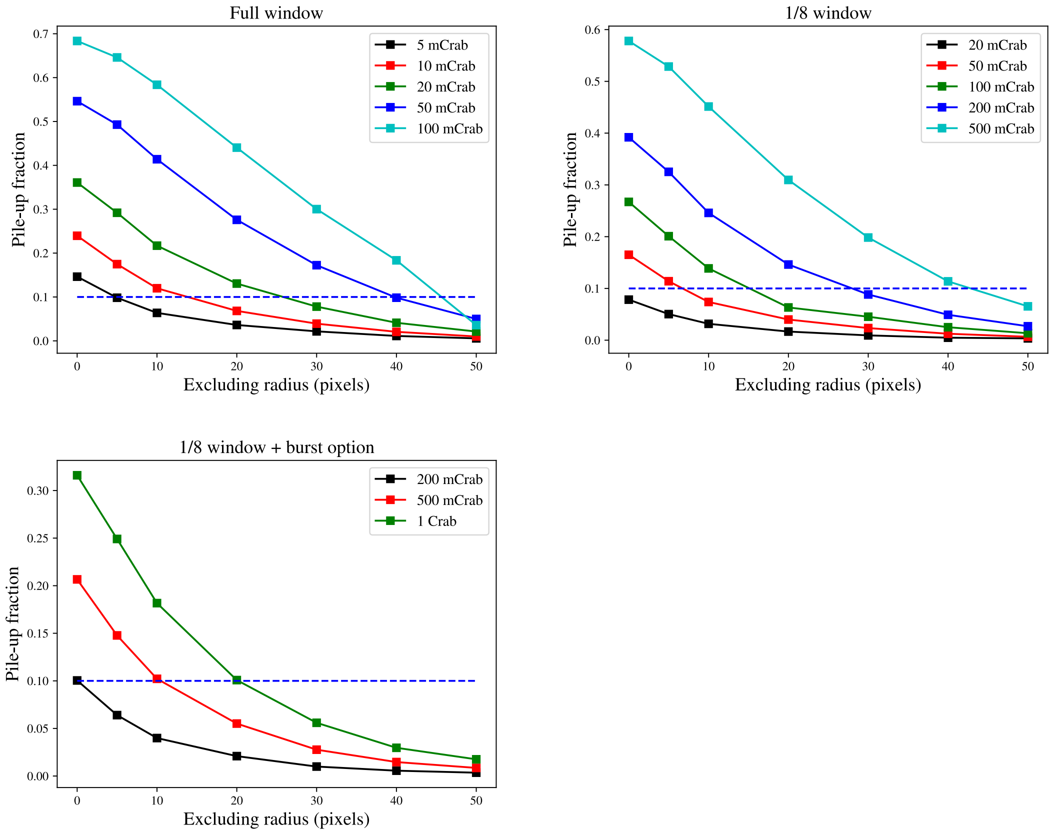

Figure 7.1: Xtend Pile-up fraction of a point source with a Crab spectrum for a source region excluding its PSF core. The x-axis shows the core exclusion radius in the unit of pixels. The blue dashed lines denote a 10% pile-up (Yoneyama et al. 2024, SPIE Proc. 13093, 130935Y).

a source region is sensitive to the accuracy of the source position. The Xtend image can shift by ∼5 arcseconds with the instrument's base plate temperature (BP_TEMP), but this shift is not considered in conversion to the `SKY` coordinates. The effect would be minor in most cases, but users are advised to assess the significance for their analysis.