Chandra X-Ray Center

Exposure Map Data Products to Archive Interface Control Document

(http://space.mit.edu/ASC/docs/ARD_ICD.ps.gz)

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6 March 98	0.0	all	Initial Draft
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18 Feb 99	1.0	all	Misc. edits as per review. Added instrument map section Conformance w/ "content.txt" (type, content, hduname, etc.)

Unresolved Issues

The following is a list of unresolved, un-reviewed, or un-implemented items:

1. 990219 Pixel list format is unspecified (page 15).
2. 990219 Need update to "content.txt" for instrument map type, "imap".
3. 990218 Need alternate coord sys keywords (page 10.
4. 990218 Need update to "content.txt" for ARF types, content, etc. (pages 14, 19).

Contents

List of Tables

1 General Description

This document describes the interface to be employed in transferring the CXC Data Products (DP) generated by CXC processing pipelines and tools to the CXC Data Archive, according to the requirements stipulated in the "ASC Data System Requirements" (Applicable Document 1).

Together with processing parameters and the Analysis Reference Data, the documents comprise a Data Dictionary.

1.1 Purpose

AXAF processing, described in Document 1, consists of processing calibration reference products, event files, aspect products, or other derived products into new products suitable our necessary for supporting scientific analysis. This document describes the structure and content of the data produced by exposure map calculation.

1.2 Scope

This interface shall apply to Exposure Map data products that are produced by CXC Level 2 pipelines or analysis tools and distributed to the CXC Data Archive (see Applicable Document 1 and the "ASC Data System Software Design," Applicable Document 2) during the course of the AXAF mission.

1.3 Applicable Documents

The Applicable Documents required for background and detail on exposure map products are as follows:

1. ASC AMO-2400 (SE03)
   ASC Data System Requirements (ASC.302.93.0008)
2. ASC AMO-2401 (DS01)
   ASC Data System Software Design (ASC.500.93.0006)
3. ASC FITS File Designers' Guide
   `http://hea-www.harvard.edu/ãrots/asc/fits/ascfits.ps`
4. Grating Data Products:
   Level 1.5 to ASC Archive Interface Control Document (v1.4)
   `http://space.mit.edu/ASC/docs/ICD_L1.5.ps.gz`
5. Grating Data Products:
   Level 2 to ASC Archive Interface Control Document (v1.2)
   `http://space.mit.edu/ASC/docs/ICD_TGL2.ps.gz`
6. Aspect Histogram:
   Processing and Data Products
   `http://space.mit.edu/ASC/docs/AspHist_ICD.ps.gz`
7. PSF tools:
   TBD.
8. "Guide to AXAF Data Products" (`content.txt, v 1.5`)
   `http://hea-www.harvard.edu/~arots/asc/fits/content.txt`

1.4 Functional Description

1.4.1 Data Content Summary

Data sets read by the processing pipelines shall consist of data files conforming to the FITS format (See the "ASC FITS File Designers' Guide", Document 3) and references therein.) These files contain header keyword entries and binary table (BINTABLE) extensions. Following rules outlined in Document 3, all these files will contain a possibly null primary header followed by a main binary table (the "principal HDU") and auxiliary extensions ("auxiliary HDU").

Any other types of files will either be of types in common use (e.g., PostScript), or fully described here (e.g., ASCII region files of IRAF/PROS), or parameter files conforming to the SAO parameter interface.

1.4.2 Recipients and Utilization

The primary recipients of reference data products, via distribution from the archive, are AXAF observers, who will utilize these data products for scientific data analysis.

1.4.3 Pertinent Relationships with Other Interfaces

Changes to the definition of CXC FITS files as described in the ASC FITS Guide (Document 3), may affect the data products described in the current document.

1.4.4 Assumptions and Constraints

1.4.5 Products Not Covered

Products that are used for maintenance and diagnostic purposes (those that are not supplied to the user for scientific data analysis) are not currently included within the interface defined by this document.

1.4.6 Substructure Definition and Format

The "ASC FITS Designers' Guide" (Applicable Document 3) defines and lists header components for the primary header and for all binary table extensions. These will be followed with any appropriate modifications noted.

In general, when FITS headers are shown, column or row numbers are arbitrary unless otherwise indicated. It is the *column name and its attributes* which specify the requirement. **Additional columns or extensions not specified here are permitted in the file without violating the interface.** Processing software can ignore them, pass them through, or use them if they are "known" quantities. (Example usage of this are columns derived from simulation containing *a priori* known values, to be directly compared with specified columns containing derived values.) Likewise, **HDU order is arbitrary,** except for the primary HDU. HDU are intended to be referenced by name, not position.

Unless otherwise noted, the `HDUNAME` and `EXTNAME` keywords will be identical.

2 Instrument Map

Data Product Summary

CXC Data Product	Instrument Map
Instrument(s)	HRC, ACIS
Level	2
Scientist/SDS	D. Huenemoerder, J. Davis
Filetype	FITS 2D image
Created by tool	mkinstmap
Used by tool(s)	mkexpmap
Sample file	TBD

990217 New section

The instrument map file for imaging mode is a 2-dimensional FITS image in which the dimensions are the detector pixel coordinates. This image is one of the efficiency or effective area vs. position. The map may be calculated for unit mirror or unit detector efficiencies. The map may also be calculated for a single energy, or over an energy band with optional spectral weighting. The map is also only made for a single detector element, or a sub-region thereof (for example, a single ACIS chip, or an HRC plate). These modes are determined by the input parameters of the generating tool and will be encoded into the file header. The processing specifications are described in detail in Document ??.

2.1 File Naming Convention

Default file names will be assigned as described in the "Guide to AXAF Data Products" (Document 8). The appropriate "type" is `imap`, and the processing level is 2. Since there are a multiplicity of instrument maps which can be computed, the "optional discriminator" or "processing run" may be used liberally to encode attributes into the filename (for examples: energy limits, spectral weighting, detector chip). The user may, of course, assign any arbitrary name at will.

TBR: type "IMAP" - needs to be in "`content.txt`"

2.2 File Structure

The following table describes the file structure by Header-Data Unit number, type, extension name, content, and HDU classes. An asterisk (*) denotes the CXC principal HDU.

HDU	Type	EXTNAME	CONTENT	HDUCLASS	Description
1 (*)	imap	IMAP	IMAP	OGIP IMAGE IMAP (EFFIC | AREA)	Instrument Map - either efficiency or area ([cm^2]) vs. detector position, possibly integrated over an energy region with spectral weighting. The map is calculated for a specific detector element and also for a SIM Z-offset if the mirror area is included. The `HDUCLASS` indicates whether the map is of efficiency or area.

2.2.1 Required Header Components

Header components are described in the "ASC FITS Designer's Guide" (Document 3), but appropriately modified since the map is not an observed quantity (many "timing" and "observation" fields are not relevant). Header components will largely be inherited from input or reference files. The components are:

- IMAGE Primary HDU:

  image mandatory
  image coordinates
  full configuration control
  modified timing (only `DATE`)
  non-SI observation

- Auxiliary table HDU:

  bintable mandatory
  table coordinates
  short configuration control
  non-SI observation
  modified timing

2.3 Column/Image Descriptions

The principal HDU holds an image of the instrument map. It is two-dimensional and in detector pixel coordinates. Since the image may be a region of a detector element or have blocked detector pixels, image coordinate system keywords are necessary (`CRVAL`n, `CDELT`n, `CRPIX`n). In making an instrument map, one may specify the starting chip x and y pixels, the number of chip x and y pixels, and the number of output map pixels in map X and Y. These parameters specify a rectangular region of the chip and blocking factors on each axis. Typically, the x and y blocking factors are equal and unity, and the entire chip is mapped, but this is not required. Also note that the blocking is not necessarily integral. In detector space, define (x_{min}, y_{min}) to be the minimum chip coordinates (lower left corner of the input rectangle), and (n_x, n_y) to be the number of input pixels on each axis. (Note that in the FITS convention, the *center* of the first pixel has the coordinates, $(1.0, 1.0)$.) The number of map pixels is given by (N_x, N_y), and defines *blocking factors*, $(b_x, b_y) = (n_x/N_x, n_y/N_y)$. Thus, the transformation from detector pixel to map pixel, (X, Y), is

JED: does mkinstmap enforce integral blocking?

$$\begin{aligned} X &= (x - x_{min} + 1/2)/b_x + \tfrac{1}{2} \\ Y &= (y - y_{min} + 1/2)/b_y + \tfrac{1}{2} \end{aligned} \quad (1)$$

Rounding the result gives the integer pixel coordinates. The coordinate system attached to the instrument map, and given in the following table, is derived from the inverse transformation, using $(X, Y) = (1.0, 1.0)$ for the reference pixel.

Axes for *Principal Image HDU: IMAP*

CTYPE	CUNIT	CRPIX	CRVAL	CDELT	Description
CHIPX	pixel	1.0	$x_{min} + (b_x - 1)/2$	b_x	Map-to-Chip pixel x-coordinate axis transformation.
CHIPY	pixel	1.0	$y_{min} + (b_y - 1)/2$	b_y	Map-to-Chip pixel y-coordinate axis transformation.

2.4 Special Header Keywords

There are several parameters which control the type of instrument map computed. For instance, the map could be mono-energetic, or it could be integrated over a band-pass weighted by a spectral energy distribution. These, and other conditions, will be encoded into the header, preferably in a machine-readable form, as opposed to free-form `COMMENT` or `HISTORY` fields (which are *technically* machine-readable, but not of standardized formats).

The following list is our current knowledge of required descriptive fields. The list may grow with experience.

SPECTRUM: This is a string which should describe any spectral weighting applied. It may have the null value `NONE` or `FILE` if a file of weights were used.

WGTFILE: This is an optional string keyword which gives the filename of the spectral weighting file used, if `SPECTRUM` = `FILE`. The weights may also be attached as an binary table extension.

IMAPTYPE: This will indicate what components of the effective area are included in the calculation, since it is possible to have only the mirror (e.g., for vignetting), only the detector, both, or neither. The useful combinations are both (for the effective area), or neither (for the geometric exposure time, useful for background prediction).

The map type could be parsed from the `TELESCOP`, `INSTRUME`, and `DETNAM` keywords. Having an explicit `MAPTYPE` keyword makes the type more easily determined.

The allowed values will be:

There may be definitions for these already. TBR

- **EFFAREA:** Includes mirror area and detector efficiencies, suitable for modeling flux from counts.
- **MIRROR:** Mirror only, and unity QE for the detector. This would show the vignetting function directly.
- **DETECTOR:** Detector QE only, mirror area set to unity.
- **GEOM:** Geometric only, both mirror and detector efficiencies are unity. This is useful for internal (un-vignetted) background modeling.

ENERG_LO: If weighted by a spectral energy distribution, a band-pass is required. This is the low-energy limit over which the map was spectrally integrated. If the map is monochromatic, then this field indicates that energy.

ENERG_HI: If weighted by a spectral energy distribution, a band-pass is required. This is the high-energy limit over which the map was spectrally integrated. If the map is monochromatic, then this field indicates that energy.

CHIPNAME: A map may be calculated for a specific detector element, or "chip". If you are particularly paranoid (or careful) about the calibration, you may wish to keep events from each detector chip separate, and apply each instrument and exposure map by chip. In fact, the instrument and exposure maps are calculated by chip before merging into a full-field image. This keyword, which is a parameter on the low-level instrument map tool, will be present if the map is for a single detector chip.

Valid values are:

HRC-I
HRC-S1, HRC-S2, HRC-S3
ACIS-I0, ACIS-I1, ACIS-I2, ACIS-I3
ACIS-S0, ACIS-S1, ACIS-S2, ACIS-S3, ACIS-S4, ACIS-S5

`AIMPOINT:` The aim-point is important if the mirror area is included in the map because it determines where the center of the mirror vignetting function is on the detector. The aimpoint is specified as a string using the syntax: "(X, Y, Z)", where X, Y, and Z are numbers that represent SIM offsets in mm. Alternatively, nominal aimpoints can be indicated using one of the following strings:

"AI1" — aimpoint on ACIS-I1 → "(0.00,0.00,-237.400)"
"AI2" — aimpoint on ACIS-I3 → "(0.00,0.00,-233.900)"
"AS1" — aimpoint on ACIS-S3 → "(0.00,0.00,-190.500)"
"HI1" — aimpoint on HRC-I → "(0.00,0.00,126.600)"
"HS1" — aimpoint on HRC-S2 → "(0.00,0.00,250.10)"

(The actual values will be maintained to represent actual flight values for a given epoch.)

2.5 Size Estimate

The size of the instrument map product in bytes is specified by $NAXIS1 \times NAXIS2 \times 4$. The resolution is user-specifiable. Nominal values may be of order 1024, and 1024, for axes 1, and 2, respectively, yielding a 4 MB file. Hence, and ACIS-I single-energy (or spectrally integrated) map would be 16 MB. It is reasonable to assume that HRC-I maps will be blocked by about 16 times, yielding a 1024 by 1024, yielding a 4 MB map.

3 Exposure Map (Imaging Mode)

Data Product Summary

CXC Data Product	Exposure Map (Imaging Mode)
Instrument(s)	HRC, ACIS
Level	2
Scientist/SDS	D. Huenemoerder, J. Davis
Filetype	FITS 2D image
Created by tool	mkexpmap
Used by tool(s)	TBD
Sample file	TBD

The exposure map file for imaging mode is a 2-dimensional FITS image in which the dimensions are the sky X, Y spatial dimensions (right-ascension and declination tangent-plane projection). This image is one of the effective area vs. position, in which the effective exposure, in units of [$\mathrm{cm}^2\,\mathrm{s}$], has been normalized by an exposure time quantity (such as `ONTIME`, or `EXPOSURE`). The map may be calculated from an input *instrument map* which has several options: unit mirror and/or detector efficiencies for "geometric" exposure time onto the sky, as bounded by detector geometry and the aspect motion; single energy; or for an energy band, with optional spectral weighting. These modes are determined by the input parameters of the instrument map generating tool, and will be encoded into the instrument map file's header. The processing specifications are described in detail in Document **??**.

Sub-elements of the final exposure map, such as created per detector element, also have the same format. The merged product (via mosaicing within an enclosing region) will differ only in header image coordinate values.

3.1 File Naming Convention

Default file names will be assigned as described in the "Guide to AXAF Data Products" (Document 8). The appropriate "type" is `exp`, and the processing level is 2. Since there are a multiplicity of exposure maps which can be computed, the "optional discriminator" or "processing run" may be used liberally to encode attributes into the filename (source number, energy limits, etc.). The user may, of course, assign any arbitrary name at will.

3.2 File Structure

The following table describes the file structure by Header-Data Unit number, type, extension name, content, and HDU classes. An asterisk (*) denotes the ASC principal HDU.

HDU	Type	EXTNAME	CONTENT	HDUCLASS	Description
1 (*)	exp	EXPMAP	EXP	OGIP IMAGE EXPOSURE	"Effective" effective area [cm^2] vs sky position, which is the temporally, and possibly spectrally, averaged mirror and detector efficiency, (as per input instrument map). The map has been normalized by the value indicated by `EXPOSURE`.
2		GTI	GTI	OGIP GTI STANDARD	The Good Time Interval table used to create the exposure map. This is a crucial piece of processing history.

3.2.1 Required Header Components

Header components are described in the "ASC FITS Designer's Guide" (Document 3). They will largely be inherited from input or reference files, such as the relevant event file and aspect file. In summary, the components are:

- IMAGE Primary HDU:

    image mandatory
    full configuration control
    full timing
    full observation
    image coordinates

- Auxiliary IMAGE HDU:

    image mandatory
    image coordinates
    short configuration control
    short observation
    short timing

- Auxiliary table HDU:

    bintable mandatory
    table coordinates
    short configuration control
    short observation
    short timing

Since we currently envision no auxiliary image extensions to the imaging-mode exposure map, only the Primary HDU and Auxiliary Table components are relevant.

3.3 Column/Image Descriptions

The exposure map is an image in sky tangent-plane pixels and will have a sky coordinate system specified. In addition, a single map pixel may represent many detector-sized pixels (in projection) if the map has been blocked. To indicate any blocking, an alternate coordinate system will be specified to indicate the relative "detector" coordinate pixel (as defined by projecting detector physical pixels onto the sky for one instantaneous aspect offset).

3.3.1 Primary Image Coordinates

Completely revised section

The principal HDU holds an exposure map image. It is two-dimensional and in sky tangent-plane pixel coordinates. Since the image may be a region of a detector element or have blocked detector pixels, image coordinate system keywords are necessary (`CRVAL`n, `CDELT`n, `CRPIX`n). In making an exposure map, one may specify the starting sky x and y pixels, the number of sky x and y pixels, and the number of output map pixels in map X and Y. These parameters specify a rectangular region of the sky and blocking factors for each axis. Typically, the x and y blocking factors are equal and unity, and the entire field defined by an instrument map and aspect offsets is mapped, but this is not required. Also note that the blocking is not necessarily integral. In sky space, define (x_{min}, y_{min}) to be the minimum sky coordinates (lower left corner of the input rectangle), and (n_x, n_y) to be the number of input pixels on each axis. (Note that in the FITS convention, the *center* of the first pixel has the coordinates, $(1.0, 1.0)$.)

JED: does mkexpmap enforce integral blocking?

We are using lower-case symbols for the "physical" pixels (projections of detector physical pixels), and upper-case for blocked pixels.

The number of map pixels is given by (N_x, N_y), and defines *blocking factors*, $(b_x, b_y) = (n_x/N_x, n_y/N_y)$. Thus, the transformation from sky pixel to map pixel, (X, Y), is

$$\begin{aligned} X &= (x - x_{min} + 1/2)/b_x + \tfrac{1}{2} \\ Y &= (y - y_{min} + 1/2)/b_y + \tfrac{1}{2}. \end{aligned} \quad (2)$$

Rounding the result gives the integer pixel coordinates.

We also have physical coordinates on the sky. Using the same notation, we can transform from sky pixels to the sky coordinate via

$$\begin{aligned} RA &= -(x - x_{ref})\Delta_s + RA\_NOM \\ DEC &= (y - y_{ref})\Delta_s + DEC\_NOM. \end{aligned} \quad (3)$$

RA and DEC are the sky equatorial coordinates (in degrees), RA_NOM and DEC_NOM are the nominal coordinates for the observation, and (x_{ref}, y_{ref}) is the coordinate of the reference sky pixel (denoted by `CRPIX`n FITS keywords, whose counterparts, `CRVAL`n, would be the nominal pointing). The image scale is given by Δ_s in degrees per sky pixel (that is, the change in degrees for $\Delta x = 1$). The negative sign on RA is due to the inverted direction of increasing RA.

We can compute blocked reference values, (X_{ref}, Y_{ref}), by substituting (x_{ref}, y_{ref}) into Equations 2 (and *not* rounding the result). Then in terms of blocked pixels, we have

$$\begin{aligned} RA &= -(X - X_{ref})b_x\Delta_s + RA\_NOM \\ DEC &= (Y - Y_{ref})b_y\Delta_s + DEC\_NOM. \end{aligned} \quad (4)$$

The coordinate system attached to the exposure map, and given in the following table, is derived from the inverse transformations, using $(X, Y) = (1.0, 1.0)$ for the reference pixel.

Axes for *Principal Image HDU: EXPMAP*

CTYPE	CUNIT	CRPIX	CRVAL	CDELT	Description
RA—TAN	deg	X_{ref}	RA_NOM	$b_x\Delta_s$	Map-to-Sky pixel X-coordinate axis transformation. Δ_s is the sky pixel scale, in degrees per pixel; b_x is the blocking factor.
DEC–TAN	deg	Y_{ref}	DEC_NOM	$b_y\Delta_s$	Map-to-Sky pixel Y-coordinate axis transformation. Δ_s is the sky pixel scale, in degrees per pixel; b_y is the blocking factor.

An alternate coordinate system will specify how sky pixels (x, y) are transformed into blocked sky pixels (X, Y). The transformations are analogous to those of the instrument map given in Section 2, but since we already have a primary coordinate system specified with FITS keywords, we need alternate keywords for each column..

Used proposed convention for placeholder. The notation used represents column n, alternate coordinate α, in which n is a digit, and α is an uppercase Roman letter, excluding P, using A for the first alternate coordinate on axis n, B for the second, and so forth.

Alternate coord keywords TBD by JCM. Used proposed convention.

Alternate Axes for *Principal Image HDU: IMAP*

CTYP$n\alpha$	CUNI$n\alpha$	CRPX$n\alpha$	CRVL$n\alpha$	CDLT$n\alpha$	Description
x	pixel	1.0	$x_{min} + (b_x - 1)/2$	b_x	Map-to-sky pixel x-coordinate axis transformation, which transforms from blocked pixel, X, to unblocked pixel, x.
y	pixel	1.0	$y_{min} + (b_y - 1)/2$	b_y	Map-to-sky pixel y-coordinate axis transformation, which transforms from blocked pixel, Y, to unblocked pixel, y.

3.4 Special Header Keywords

The type of exposure map computed is determined entirely by the input instrument map. Other characteristics are determined by the associated aspect offsets histogram.

The following list is our current knowledge of required descriptive fields. The list may grow with experience.

IMAPFILE: The instrument map file. It contains keywords which determine the type of exposure map (see Section 2).

ASPFILE: The map is calulated with an aspect histogram. This keyword points to the file used to perform the transformations. This file must also contain any appropriate GTI (Good Time Intervals) applied. The following keywords are completely determined by the Aspect Histogram:

- **ONTIME:** This quantity is the sum of the GTI, or in other words, the number of seconds out of the elapsed time during which conditions were such that useful photons *could* have been detected.
- **LIVETIME:** This is the ONTIME times the dead-time-correction factor.
- **EXPOSURE:** This is the total exposure time (not *elapsed* time), with all time efficiency corrections applied, as for any duty-cycle.

  This factor is typically *NOT* included in the exposure map values; if it has a value other than 1.0, it should multiply the exposure map to arrive at the proper "effective" exposure ($[cm^2\, s]$).
- **RA_NOM, DEC_NOM:** These specify the tangent-point of the projection. They are *NOT* necessarily the same as the nominal pointing of the aspect history.

3.5 Size Estimate

The size of the exposure map product in bytes is specified by $NAXIS1 \times NAXIS2 \times 4$. The resolution is user-specifiable. Nominal values may be of order 1024, and 1024, for axes 1, and 2, respectively, yielding a 4 MB file. Hence, and ACIS-I single-energy (or spectrally integrated) map would be 16 MB.

4 Approximate Exposure Map (Imaging Mode)

Data Product Summary

CXC Data Product	Approximate Exposure Map (Imaging Mode)
Instrument(s)	HRC, ACIS
Level	2
Scientist/SDS	D. Huenemoerder, J. Davis
Filetype	FITS 2D image
Created by tool	expmap
Used by tool(s)	TBD
Sample file	TBD

The approximate exposure map is computed without explicit observation information. It is computed with a nominal aspect histogram with an unspecified aim-point. For application to a specific observation, it will require scaling by the proper exposure time and transformation to a specific pointing. Otherwise, it is similar to the map described in Section 3. Only differences are described below.

4.1 Required Header Components

Header components are described in the "ASC FITS Designer's Guide" (Document 3). They will largely be inherited from input or reference files, such as the relevant event file and aspect file. Since there is no observation specified, the header components have been modified from the standard set.

In summary, the components are:

- IMAGE Primary HDU:

  image mandatory
  full configuration control
  short timing (only file creation date)
  short observation (with null OBS_ID)
  image coordinates

4.2 Special Header Keywords

4.2.1 Image Coordinates

Image coordinates are similar to the regular exposure map, but for an arbitrary pointing direction. For that direction we will choose the following:

$$RA\_NOM = 0.0,$$

$$DEC\_NOM = 0.0,$$

$$ROLL\_NOM = 0.0,$$

with the reference pixel being the central pixel (approximately $(n_x/2, n_y/2)$).

4.2.2 Map Descriptive Keywords

See Section 3.4.

4.3 Size Estimate

The size of the exposure map product in bytes is specified by $NAXIS1 \times NAXIS2 \times 4$. The resolution is user-specifiable. Nominal values may be of order 1024, and 1024, for axes 1, and 2, respectively, yielding a 4 MB file. Hence, and ACIS-I single-energy (or spectrally integrated) map would be 16 MB.

5 Exposure Map: Effective ARF (Imaging Mode)

Data Product Summary

CXC Data Product	Exposure Map: Effective ARF (Imaging Mode)
Instrument(s)	HRC, ACIS
Level	2
Scientist/SDS	D. Huenemoerder, J. Davis
Filetype	FITS ARF
Created by tool	expmap
Used by tool(s)	TBD
Sample file	TBD

The exposure map described in Section 3 is useful for "flat-fielding" an image, or for predicting the background signal. For source spectral analysis, we wish to maintain the average the spectral response over a region, instead of maintaining the spatial response but integrating over a spectrum. The spectral respose is commonly known (to X-ray astronomers) as an ARF, for "Auxiliary Response Function" (or "File", but "Function" is preferred as more general).

The imaging-mode averaged ARF calculation is an exposure map computation in which the spectral response averaged over a given sky region is integrated over the aspect history. The file is written as a standard OGIP ARF with appropriate AXAF header fields. The units are [$\mathrm{cm}^2\,\mathrm{bin}^{-1}$], and is normalized by an exposure time quantity (`EXPOSURE`). The processing specifications are described in detail in Document **??**.

Since knowledge of the region over which the response is averaged is critical to spatial and spectral analysis, the region is appended as a FITS extension.

5.1 File Naming Convention

Default file names will be assigned as described in the "Guide to AXAF Data Products" (Document 8). The appropriate "type" is `rsp`, and the processing level is `2`. Since there are a multiplicity of averaged ARFs which can be computed, the "optional discriminator" may be used liberally to encode attributes into the filename (e.g., for various regions). The user may, of course, assign any arbitrary name at will.

5.2 File Structure

The following table describes the file structure by Header-Data Unit number, type, extension name, content, and HDU classes. An asterisk (*) denotes the ASC principal HDU.

HDU	Type	EXTNAME	CONTENT	HDUCLASS	Description
1	NULL				NULL Primary.
2 (*)	arf	SPECRESP	RSP	OGIP RESPONSE SPECRESP	Effective area [cm^2] vs energy; the temporally- and spatially-averaged mirror and detector efficiency. Exposure has been normalized by the value indicated by the `EXPOSURE` keyword.
3	REG	REGION	REG	ASC REGION PIXLIST	Pixel list. The pixels enumerated define a region.
4		GTI	GTI	OGIP GTI STANDARD	The Good Time Interval table used to create the effective ARF. This is a crucial piece of processing history.

5.2.1 Required Header Components

Header components are described in the "ASC FITS Designer's Guide" (Document 3). They will largely be inherited from input or reference files, such as the relevant event file and aspect file. In summary, the components are:

- NULL Primary HDU:

  image mandatory
  null configuration control
  short timing
  short observation

- Principal table HDU:

  BINTABLE mandatory
  full configuration control
  full timing
  full observation
  table coordinates

- Auxiliary table HDU:

  bintable mandatory
  short configuration control
  short observation
  short timing
  table coordinates

5.3 Column/Image Descriptions

Columns for *primary* HDU: SPECRESP

TTYPE	TUNIT	TFORM	TLMIN	TLMAX	TDBIN	TNULL	Comment
ENERG_LO	keV	1E	0.0	20.0	N/A	*NaN*	Low energy of response bin.
ENERG_HI	keV	1E	0.0	20.0	N/A	*NaN*	High energy of response bin.
SPECRESP	cm**2	1E	0.0	N/A	N/A	*NaN*	Effective area, averaged over aspect and sky region.

Note: addtional columns are allowed in an ARF. The interpretation is as multiplicative factors (such as mirror, filter, detector), whose product gives the SPECRESP column. I don't think we have any use for this here, since the input efficiency is the full product.

Columns for *auxiliary* HDU: REGION

TTYPE	TUNIT	TFORM	TLMIN	TLMAX	TDBIN	TNULL	Comment
TBD TBD TBD							Pixel list format TBD

Pixel list format TBD. Check IRAF specification, ASC-DM-specification.

5.4 Special Header Keywords

5.4.1 Effective ARF Descriptive Keywords

There are several parameters which control the ARF computation. The conditions *must* be encoded into the header

The following list is our current knowledge of required descriptive fields. The list may grow with experience.

ASPFILE: The file containing the aspect offsets histogram. The aspect file also completely specifies the following:

- **ONTIME:** This quantity is the sum of the GTI, or in other words, the number of seconds out of the elapsed time during which conditions were such that useful photons *could* have been detected.
- **LIVETIME:** This is the ONTIME times the dead-time-correction factor (really 1 minus the dead-time fraction, or times the live-time fraction).
- **EXPOSURE:** This is the total exposure time (not *elapsed* time), with all time efficiency corrections applied, as for any duty-cycle.

  This factor is typically *NOT* included in the exposure values; if it has a value other than 1.0, it should multiply the area to arrive at the proper "effective" exposure ($[cm^2\, s]$).

CHIPID: An effective ARF may be calculated for a specific detector element, or "chip". If you are particularly paranoid (or careful) about the calibration, you may wish to keep events from each detector chip separate, and apply each average response by chip. In fact, the effective ARF is calculated by chip before merging into a full-region product. This keyword, which is a parameter on the low-level exposure ARF tool, will be present if the ARF is for a single detector chip. (It comes from the instrument map generation.)

5.5 Size Estimate

The size of the effective ARF product in bytes is approximately $NAXIS1 \times NAXIS2 \times 4$. Nominal values may be of order 4096 energies by 3 columns, for about 50 kB per region.

5.6 Unresolved Issues

5.7 External Dependencies

For a point-source, the ARF is modified according to the enclosed energy fraction vs. energy given the source position and the ARF region. A description of PSF tools can be found in Document 7.

6 Exposure Map: Effective ARF (Grating Mode)

Data Product Summary

CXC Data Product	Exposure Map: Effective ARF (Grating Mode)
Instrument(s)	ACIS, HESF, HETG, HRC, LETG
Level	2
Scientist/SDS	D. Huenemoerder, J. Davis
Filetype	FITS ARF
Created by tool	mktgarf (TBR)
Used by tool(s)	TBD
Sample file	TBD

The spectral respose is commonly known (to X-ray astronomers) as an ARF, for "Auxiliary Response Function" (or "File", but "Function" is preferred as more general). It is the effective area as a function of energy. For AXAF in grating spectroscopic mode, the ARF is a function of grating type, spectroscopic order, zero-order position (through vignetting and chip gap locations in the spectrum), cross-dispersion region, and pulse-height-region used in order-sorting. The ARF, or response at any wavelength (the linear coordinate for gratings) at any wavelength is the time-average of the response over the aspect history.

Since the ARF for gratings has a multiplicity of orders, and for HETG, two grating types, we will define a "Type II" ARF, in analogy with the OGIP Type II PHA file, a format adapted for the grating binned spectra (see Document 5).

The processing specifications are described in detail in Document **??**.

Knowledge of the region over which the response is averaged is critical to spatial and spectral analysis. The region applied is taken directly from the Level 2 spectrum (to which it is appended as an extension) for which the response is generated.

6.1 File Naming Convention

Default file names will be assigned as described in the "Guide to AXAF Data Products" (Document 8). The appropriate "type" is `rsp`, and the processing level is 2. The user may, of course, assign any arbitrary name at will. However, since the structure is similar to the Level 2 spectrum, the same root-name would be appropriate.

6.2 File Structure

The following table describes the file structure by Header-Data Unit number, type, extension name, content, and HDU classes. An asterisk (*) denotes the ASC principal HDU.

HDU	Type	EXTNAME	CONTENT	HDUCLASS	Description
1	NULL				NULL Primary.
2 (*)	rsp	SPECRESP	RSP	ASC RESPONSE SPECRESP TYPE II TG	Effective area [cm^2] vs energy, order, grating, and source; the temporally- and spatially-averaged mirror, grating and detector efficiency. Exposure has been normalized by the `EXPOSURE` value.
3	tgm	REGION	TGMASK2	ASC REGION TG	Diffraction coordinate region, from which photons were binned.
4		GTI	GTI	OGIP GTI STANDARD	The Good Time Interval table used to create the effective ARF. This is a crucial piece of processing history.

6.2.1 Required Header Components

Header components are described in the "ASC FITS Designer's Guide" (Document 3). They will largely be inherited from input or reference files, such as the relevant event file and aspect file. In summary, the components are:

- NULL Primary HDU:

  image mandatory
  null configuration control
  short timing
  short observation

- Principal table HDU:

  BINTABLE mandatory
  full configuration control
  full timing
  full observation
  table coordinates

- Auxiliary table HDU:

  bintable mandatory
  short configuration control
  short observation
  short timing
  table coordinates

6.3 Column/Image Descriptions

The contents of the FITS columns of the spectral respose extension are given in the following table. These generally are a subset of analogous to those of the binned Type II PHA spectrum.

The length of the vector columns (specified by `TFORM`n, such as for "BIN_LO" or "SPECRESP") is given in the table as n. This is to be replaced with the actual length of the array. For LETGS, for example, binning at a single resolution element per bin will give about 6700 bins, and HETGS about 3400. Analysis tools can specify arbitrary binning. Pipelines will default to 0.5-1.0 resolution-element bins for the data. Custom analysis may produce files only containing a few bins around lines of interest, or even arrays discontinuous in wavelength to hold several regions of interest. The respose should in general have smaller bins than the data.

The spectral response will be by default calculated in units of [$\mathrm{cm}^2\,\mathrm{counts}\,\mathrm{photon}^{-1}$] *vs.* [Å] (note that [$\mathrm{counts}\,\mathrm{photon}^{-1}$] is a unitless quantity). Custom analysis may convert wavelengths to energy units, or analysis could produce flux in units of ergs instead of photons, and a response in commensurate units. These are all permitted in a valid response file as long as consistency is maintained within the grid columns (BINLO, BINHI) and units column.

TTYPE	TUNIT	TFORM	TLMIN	TLMAX	TDBIN	TNULL	COMMENT
RESP_NUM		1I	1	n	1	0	Response number (running index).
ROWID		64A	N/A	N/A	N/A	NONE	Arbitrary string identifier
TG_M		1I	-62	62	N/A	99	Diffraction order (m)
TG_PART		1I	0	99	N/A	N/A	Spectral component (HEG, MEG, LEG, HESF)
TG_SRCID		1I	1	TBD	N/A	0	Source ID, from detect.
CHANNEL		nI	1	n	1	0	Vector of spectral "channel" numbers.
QUALITY		nI	0	5	N/A	TBD	Quality flag; key: 0-good 1-bad 2-dubious 3,4-spare 5-user bad
GROUPING		nI	-1	1	N/A	16	Grouping vector. key: +1-channel is new bin -1-continuing bin 0-undefined
BIN_LO	angstrom	nE	0.0	400.0	1.0E-04 (TBR)	NaN	Bin boundary, "left" coordinate.
BIN_HI	angstrom	nE	0.0	400.0	1.0E-04 (TBR)	NaN	Bin boundary, "right" coordinate
SPECRESP	cm**2	nE	0.0	N/A	N/A	NaN	Effective ARF.
RESP_ERR	cm**2	nE	0.0	N/A	N/A	NaN	Uncertainty on response.

6.4 Special Header Keywords

6.4.1 Effective ARF Descriptive Keywords

Knowledge of the generating parameters for the spectral response are crucial to its application to a counts spectrum. The response is determined by the calibration data, by the zero-order position, by the good-time-intervals and aspect history, and by filtering conditions. When Level 1.5 events are resolved to orders and binned, both spatial and PHA regions are clipped, and both affect the effective area. All these must be accounted for in generating the response and stored in header keywords.

The following list is our current knowledge of required descriptive fields. The list may grow with experience.

SPECFILE: The Level 2 spectrum file which was used to obtain the orders, source IDs, and region.

ASPFILE: The file containing the aspect solution. This file must also contain any appropriate GTI (Good Time Intervals) applied. The Aspect Histogram specifies the following items:

- **ONTIME:** This quantity is the sum of the GTI, or in other words, the number of seconds out of the elapsed time during which conditions were such that useful photons *could* have been detected.
- **LIVETIME:** This is the ONTIME times the dead-time-correction factor (really 1 minus the dead-time fraction, or times the live-time fraction).
- **EXPOSURE:** This is the total exposure time (not *elapsed* time), with all time efficiency corrections applied, as for any duty-cycle.

  This factor is typically *NOT* included in the exposure values; if it has a value other than 1.0, it should multiply the area to arrive at the proper "effective" exposure ($[cm^2\,s]$).

CHIPID: An effective ARF may be calculated for a specific detector element, or "chip". If you are particularly paranoid (or careful) about the calibration, you may wish to keep events from each detector chip separate, and apply each average response by chip. In fact, the effective ARF is calculated by chip before merging into a full-region product. This keyword, which is a parameter on the low-level exposure ARF tool, will be present if the ARF is for a single detector chip.

ACISDE: ACIS Energy-table limit filename. This is the table used to specify photon detector energy (scaled PHA) limits vs. energy for order-sorting. It is important because it truncates the CCD response to some integrated probability, which must eventually be factored into the effective ARF.

6.5 Region Extension

Generally, the response is averaged over the same region for which a particular spectrum has been binned. In this case, the region extension will match that in the binned spectrum file. It is possible, however, to create the response for an assumed position, independent of any observed source. In this case, the TG_SRCID will have a null value, but we still need to specify the zero-order reference point and spectral region. The region extension is otherwise as given in the specification of the binned spectrum (Document 5).

6.6 Size Estimate

The size of the effective Type II ARF, for HETGS, one source, 12 orders (typical MEG plus HEG, -3 to +3 orders, excluding zeroth), 12000 pixels each (to provide some oversampling), is approximately 500 kB.

(Note that even though LETGS cannot produce resolved orders, the response must be produced by order to allow proper modeling.)

6.7 External Dependencies

After creating an effective ARF, two energy-dependent "PSF"-fractions are applied. First, the fractional energy in the cross-dispersion (spatial) region from which the spectrum was extracted. Secondly, the pulse-height fractional energy enclosed in the windows used for order resolution (if ACIS). A description of spatial PSF tools can be found in Document 7. A description of the pulse-height fraction can be found in the grating products (Document 4). This order-sorting region table name is already recorded in the Level 1.5 header and is inherited by the grating effective ARF.