AXAF Exposure Maps: *Modus Operandi*

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Revision 2.0

May 21, 1998

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Revision Log

Revision Log			
Date	**Version**	**Section**	**Status**
30 Dec 97	0.0	all	first draft; reviewed by D.Dewey, D.W.Kim
15 Jan 98	1.0	all	Revised as per comments on Rev. 0.0.
12 May 98	2.0	all	major revisions: now follow-on to J.Davis theory memo. Big change is implementation via "Instrument Maps"

Open Issues

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

1. 980512: Grating mode not yet included in detail.
2. 980512: Need to update referenced ICD on product (Level 2 imaging, Level 2 grating, for pipeline and analysis modes).
3. 980512: Need referenced ICD on instrument map product.
4. 980512: Need referenced Tool Specs on instrument map creation.
5. 980512: Need to update reference data ICD: HRMA Aeff(x,y,E), detector QE(x,y,E) (re-specify as image, not FITS region).

1 Purpose of This Document

This document is intended to describe typical modes of use of the exposure map and to discuss some issues related to use or implementation. It is *not* a user's guide to software, or reference manual to the software, or specifications for a programmer; these will be provided in other documents. The subtitle, while Latin, is in your English dictionary and translates to "manner of use" and it is this which I wish to communicate to potential users in order to define and refine the content, approximations, and to uncover any issues.

2 Exposure Map Definition

The derivation and definition of the **Exposure Map** is given in detail in "Exposure Maps", an internal memo by John Davis which serves in part as the exposure map specification (Version 0.2, April 29, 1998; see the Relevant Documents, section 10). The imaging-mode map is defined by

$$E_I(h,\, \lambda,\, \hat{p}) \tag{1}$$

which has units of [cm^2 s], and in which h is the detected energy quantity (pulse-height), λ is the incident photon's wavelength, and $\hat{p}$ specifies the sky coordinate — a vector, representing the two spatial coordinates. E_I is essentially a position-dependent redistribution matrix, scaled by the exposure time and the effective area. It most generally includes the mirror efficiency (and vignetting), detector efficiencies, and detector geometry. Alternatively, it can be calculated as exposure time vs. sky position by using unit efficiencies for the mirror and detector. It *does not* contain any PSF information. This map is calculated by integrating (over time) the time-dependent projection of the detector onto the sky, weighting by the total detection efficiency. The relationship between the source spectrum and the counts is given by

$$C(h,\hat{p}) = \int d\lambda\, E_I(h,\lambda,\hat{p})\, S(\lambda,\hat{p}), \tag{2}$$

which (ignoring the spatial dependence) is the "response matrix" multiplication solved by tools such as `XSPEC`. Here, S is a spatially-dependent source spectrum (PSF effects ignored), and C is the pulse-height counts-spectrum vs. sky position.

You must take note of one important fact: the counts depend on the source spectrum and exposure map through an integral. Thus, *application of an exposure map to a counts image without a source model may not be valid!*

At the full spatial and spectral resolutions of AXAF, E_I would be very time-consuming to compute and unmanageable in size. Instead, we will allow its computation over specifiable regions, coarse spatial resolution, or coarse pulse-height or energy (h, λ) resolutions, specifically tailored to the user's analysis. **Hence, the type of analysis to be done will determine what is kind of exposure map is computed.** Some uses are spatial "flat-fielding", background rate prediction, or spectral modeling.

E_I could also be determined as a function of time; that dependence will be implicit unless made explicit for time-dependent applications. Assumptions will be made for pipeline (autonomous) processing.

3 Instrument Map Definition

Davis' theory memo defined an "instrument map." This is an implementation feature similar to that done in previous missions (such as ASCA and ROSAT). The instrument map is a pre-calculated item which makes it easier to compute an exposure map. The instrument map is the product of the mirror effective area, M, (vs. off-axis angle, azimuth, and energy) and the detector response, D, (vs. energy and position), or

$$I(\sigma, \Delta h, \lambda) = D(\Delta h, \sigma, \lambda) M(\sigma, \lambda). \tag{3}$$

Here, σ is used for position since it represents a location in detector coordinates instead of sky coordinates. The pulse-height, h, has been summed over some range, Δh. We can also integrate over wavelength bands to calculate an instrument map of the form (see Davis for details)

$$I(\sigma, \Delta h, \Delta\lambda). \tag{4}$$

The instrument map will be a fundamental input to exposure map computation, since the resultant exposure map will have the same dimensionality as the input instrument map times time.

Though the form of I shown has four dimensions, it can conceptually be considered as a collection of two-dimensional images: $I(x, y)$; the exposure map is derived by sequentially applying the aspect motion to each 2D map to project it onto the sky. The actual files used will be either two- or three-dimensional; the additional dimensions will be implicit. For example, if 2D, then the map is for one wavelength or a wavelength band, and for one pulse-height or pulse-height band. If it is 3D, then the third dimension will be wavelength or wavelength bands, and there will be an implied pulse-height or pulse-height band. (The header of the file will specify the dimensionality and binning.)

There is one necessary assumption made in the definition of the instrument map: that the change in position of the detector relative to the mirror axis during an observation is not significant with respect to QE-position-dependence. This is satisfied by the current expectation of performance, in which the Science Instrument Module (SIM) is predicted to have a 3-standard-deviation displacement in 48-hours of 5 arcseconds; this amplitude is insignificant relative to the slope of the mirror vignetting function with off-axis angle. (It is, however, significant with regard to coordinate transformations, where it will be accounted for.)

There are two other assumptions we make, based on current understanding of the detector responses:

1. Detector redistribution is weakly dependent upon position. That is, the response matrix is constant over large regions. It may change greatly from one large region to the next, but within a detector element (such as the entire HRC-I, or a single front-illuminated CCD, or a back-illuminated CCD quadrant), it is a constant with position. For the CCDs, this is only true for CTI corrected PI values, not for raw PHA.

2. The detector quantum efficiency is strongly dependent upon position, even within a detector element. The QE has sharp boundaries (filter spatial edges, bad pixels). The QE is known on a fairly small scale, relative to a detector element, and as a function of energy.

3.1 "Off-the-Shelf" Instrument Maps

Some instrument maps will be supplied and should be sufficient for most observations. For imaging mode, they will be calculated for nominal aim points on HRC-I, ACIS-I, and ACIS-S. HRC-I will have its map summed over all PHA. ACIS will be in several $\Delta\lambda, \Delta h$ bands (where the PHA band is determined from the wavelength band).

Maps are provided or calculated for a single detector "element". That element is defined by a region of relatively uniform response. It typically corresponds to a physical array element, such as an HRC micro-channel plate, or an ACIS CCD. However, the uniformity of the back-illuminated CCDs is not yet known; for them, a detector element may be a CCD quadrant (as defined by the readout amplifiers) or smaller, depending on how well charge-transfer inefficiency (CTI) can be calibrated and modeled.

The logic of specifying the maps by detector element is so that "photon integrity" can be maintained. During analysis, users may not wish to mix photons seeing markedly different response. They may wish to model BI and FI photons separately, but if not, exposure maps are linear: they can be summed and photons treated as an ensemble.

3.2 "Dynamic" Instrument Map Attributes

The "off-the-shelf" instrument maps may need some further modification before any specific application. They must be masked by any non-standard ACIS windows or sub-arrays which have clipped the spatial region. They must also have any new or "temporary" bad pixels zeroed out. The instrument map creation tool (see Section 6) will support such manipulations.

4 The Fundamental Interface

It is instructive to examine the interface to the low-level driver upon which all other exposure map tools will be based. This driver may be used directly, or may be hidden within scripts which set parameters to appropriate values and manipulate the output. The prototype interface is defined as follows:

```
exp_make_map
                Calculate the imaging-mode response (effective
                exposure time nominally in units of [cm^2 s] ) as
                a function of energy and position by applying
                the observatory aspect solution to instrument
                response and geometry (the instrument map,
                see below).  The fundamental output is a 2D
                image, with two spatial dimensions (the sky
                X,Y --- R.A. and Dec tangent-plane with respect
                to the nominal pointing).  Optionally, if the
                instrument map is 3-dimensional (two spatial
                and one energy dimensions), the output will be a
                3D-map.
Inputs:
                Aspect solution
                Good Time Interval
                Instrument Map
Parameters:
                Sky Grid specification:
                  R.A. min, R.A. max
                  Dec.  min, Dec.  max
                  R.A. resolution [arcsec]
                  Dec.  resolution [arcsec]
                Detector Element ID
                Aspect Tolerance (TBD)
                Anti-aliasing Flag (TBD)
                Coordinate Interpolation Flag (TBD)
Output:
                Exposure Map
Restrictions:
                Sky Region and Sky Resolution must specify one
                or more bins.
```

Aspect Solution: This is the model of the mirror optical axis location on the sky (3 numbers, plus uncertainties) and the orientation of the detector relative to this axis (3 numbers, plus uncertainties) as a function of time. There is an aspect record every 0.256 seconds. There may be several files for any observation.

Good Time Interval (GTI) This is the time-filter to be applied to the Aspect Solution. It is typically an extension on an event file. ACIS may have more than one GTI.

Instrument Map This is what goes in and determines what goes out (it better not be you-know-what). It may be for a single energy, or integrated over an energy band. It may be for a single pulse-height, or may be integrated over a

pulse-height band. See the text for more information. A value of "UNITY" means that an efficiency of 1.00 is used for the region inside the detector boundary, and 0.00 outside.

TBD: UNITY value for parameter

Sky Grid This is the region over which to calculate the exposure map, given in the same units as an event files sky coordinates. It is possible to have different sized bins in R.A. and Dec. It is possible to have only one output bin. It is possible — but not very useful — to specify a sky region which isn't exposed by specified detector element.

The resolution is arbitrary. It can be smaller than a single detector pixel. The higher the resolution (smaller bins), the longer the computation will take.

Detector Element This specifies which array of the detector to process, such as an ACIS chip-ID, or HRC micro-channel plate ID. Note that this could be mutually exclusive with the Sky Grid specification.

Aspect Tolerance This parameter specifies how big a shift in position (combined optical axis and instrument) is significant. The corners of the region are transformed from detector to sky, and if any corner moves by more than this tolerance, then a new projection of the instrument map is calculated and integrated to the sky. Otherwise, the previous calculation is used.

This is effectively a dynamic compression of the Aspect Solution. The Aspect Solution itself cannot be compressed into "stable aspect intervals" a priori, since the magnitude of any shift depends on where you are in the field (consider any rotations).

TBR: Aspect Tolerance flag definition

Anti-aliasing Flag How much do you worry about pixelization of the map? Anti-aliasing will smooth jagged edges by distributing input bin values fractionally over covered output bins. The alternative is nearest-neighbor sampling. Anti-aliasing makes the map look nicer, but may not be quantitatively significant. It is also computationally expensive.

TBR: Anti-aliasing flag definition

Coordinate Interpolation Flag There is a "fast" method, and a "slow" method (and possibly an internal vs external (`pixlib`) method. The "fast" method transforms the corners of an instrument map region to the sky and then uses a bi-linear interpolation to interpolate coordinates within that region. The "slow" method performs full coordinate transformations on each Instrument Map coordinate.

TBR: interpolation modes

Exposure Map An image of the effective exposure time on the sky, for the energy/pulse-height gridding of the input Instrument Map. Its units are time (in seconds) times the units of the Instrument Map, which is nominally in $[\mathrm{cm}^2\,\mathrm{s}]$.

Issue: There may be more than one aspect solution files per observation. There are also Aspect Offsets and SIM Offsets files. There use in place of the Aspect Solution is TBD. The Apspect Solution is preferred, since it contains all information. The SIM Offsets is filtered data.

Issue: We don't yet have any Instrument Map Tools (or tool specs!). Until we get some, We will make some test files for prototyping use, pending development of production tools.

5 Modes of map calculation

As was already mentioned, how you compute an exposure map depends on what you want to do with it. It is just too big an object to calculate at full spatial, wavelength, and pulse-height resolution to post-process as you please. We must specify some spatial and spectral integrals for the Instrument Map set defintion as required for the application, and then compute the corresponding exposure map set. There are two basic modes of use:

1. spatial "flat-fielding", in which one wishes to remove spatial fluctuations due to instrumental affects from a counts image to produce a flux-in-a-band image;
2. spectral flux calibration, in which one wishes to remove instrumental energy-dependent features to produce an incident source spectrum for the pulse-height counts spectrum integrated over a region.

(These cases are not mutually exclusive.) Davis described several approximations in the map for application to a source-model-spectrum to predict counts (his section 6). I will elaborate on those here.

5.1 Diagonal Redistribution Matrix

Consideration of a diagonal redistribution function is a good conceptual starting point, but it will need some subsequent improvements in quality. Under the assumption that the redistribution within a detector element is uniform (which we achieve by definition of an "element"), the redistribution factors from response:

$$I'(\sigma, h, \lambda) = D_R(h, \lambda)\, Q(\lambda, \sigma)\, M(\lambda, \sigma). \tag{5}$$

For the Instrument map, we can use only the $h-$independent part, so

$$I(\sigma, \lambda) = Q(\lambda, \sigma)\, M(\lambda, \sigma). \tag{6}$$

The expression for the counts thus becomes

$$C(h, \hat{p}) = \int \mathrm{d}\lambda\, D_R(h, \lambda)\, E_I(\lambda, \hat{p})\, S(\lambda, \hat{p}) \tag{7}$$

Now, if we had I for many λ, we could define a model spectrum, use the appropriate redistribution matrix, and model the counts spectrum. But we can't easily compute thousands of Instrument Maps over the whole field. Let's pretend the redistribution is diagonal, which means that for $h = \lambda$, $D_R = 1$, and is 0 otherwise. Let us pick some wavelength, λ_0 (to emphasize the fact that we are really 2-dimensionsal). Then we can boldly proclaim that

$$S_{\lambda_0}(\hat{p}) = \frac{C_{\lambda_0}(\hat{p})}{E_{I\lambda_0}(\hat{p})}. \tag{8}$$

We could do this — at one wavelength — at arcsecond resolution fairly efficiently.

5.2 Diagonalized Redistribution Matrix

We can do better than a diagonal response, at least for the CCD detectors, since their response is primarily diagonal. We can integrate the Instrument Map over a wavelength band and a corresponding pulse-height band. Corresponding means the region in pulse-height which is significantly non-zero and near the diagonal for the specified wavelength band. That is, for any $\Delta\lambda = \lambda_+ - \lambda_0$ we define a function $\Delta h(\lambda_-, \lambda_+)$ such that Δh contains most of the power in the redistribution function. We can then define the Instrument Map by summing the redistribution over the pulse-height interval and integrating the wavelength interval. I'll repeat the relevant equations *verbatim* from Davis (around his equations 34-41). Summing over the detector response we have (Davis Eq. 34):

$$D(\sigma, \Delta h, \lambda) = \sum_{h \in \Delta h} D(\sigma, h, \lambda). \tag{9}$$

Given this, the Instrument Map definition temporarily becomes (Davis Eq. 40)

$$I(\sigma, \Delta h, \lambda) = D(\Delta h, \sigma, \lambda) M(\sigma, \lambda). \tag{10}$$

Integrating over the wavelength band we finally get (Davis Eq. 41)

$$I(\sigma, \Delta h, \Delta\lambda) = \frac{1}{\Delta\lambda} \int_{\lambda \in \Delta\lambda} \mathrm{d}\lambda \; I(\sigma, \Delta h, \lambda), \tag{11}$$

We could create these, say, for ten or so ACIS bands. We must be careful, however, to keep our wavelength regions *between* edges, as opposed to straddling them, so that we have a response that is reasonably constant and our integrals over the bandpass define physically meaningful mean values.

We use this definition of I, perhaps creating several I's for different bands; the subscript, i, will represent a $(\Delta h_i, \Delta\lambda_i)$ pair. This definition of I_i is used to compute the exposure map, $E_{Ii}(\hat{p})$, which leads to the expression for counts,

$$C_i = E_{Ii}(\hat{p})\, S(\Delta\lambda_i, \hat{p})\, \Delta\lambda_i. \tag{12}$$

This can be solved for the approximate source flux in the band as

$$S(\Delta\lambda_i, \hat{p}) = \frac{C_i}{E_{Ii}(\hat{p})\ \Delta\lambda_i}. \tag{13}$$

Caveat! While this may be a useful quantity, it must be used with care. In general, the pulse-height bands are not unique. The counts in a band, C_i are the counts in a pulse-height band from a given wavelength band. *This does not mean that other wavelengths do NOT contribute to this pulse-height band!*. The actual contribution depends on the exact spectral energy distribution. Strong spectral features (intrinsic to the source or the response) in a neighboring band could give a significant contribution to the counts, but would not be included in this approximation to the exposure map.

5.3 Non-Diagonal Redistribution Matrix

What do we do if the redistribution is in no way diagonal, such as in the case of HRC? We can sum over all pulse-heights when we create the Instrument map.

Since the redistribution function is normalized, the detector response becomes the quantum efficiency:

$$I(\sigma, \lambda) = Q(\sigma, \lambda)\, M(\sigma, \lambda). \tag{14}$$

This leads to a familiar expression for the counts,

$$C(\hat{p}) = \int \mathrm{d}\lambda\, E_I(\lambda, \hat{p})\, S(\lambda, \hat{p}). \tag{15}$$

This time, however, we don't have the ability to "factor out" the spectrum. We would need E_I as a function of wavelength and a model spectrum in order to predict the counts.

5.4 Spectrally Weighted Instrument Map

Summing over all pulse-heights leaves us with a spectral-model-dependent map, which cannot be applied quantitatively without having a map at many energies and integrating over a spectral model to predict the counts. What we can do is create an Instrument Map which already contains the integral over the spectrum. We will then get an Exposure Map which in units of photons for the assumed input spectrum. This may be useful, for example, for background prediction and source detection. In this case, the determination of faint sources is limited by what the background counts. Such a map could be useful for both ACIS and HRC source detection. The Instrument Map computation will support spectral weighting (see Section 6).

The "Instrument" Map in this case becomes

$$I(\sigma) = \int \mathrm{d}\lambda\, I(\sigma, \lambda) S(\lambda). \tag{16}$$

We have made the simplifying assumption that the spectrum is independent of position; otherwise, we cannot make an Instrument Map in detector coordinates. This map gets integrated over the aspect solution as usual to create the "Exposure" Map, and the counts per unit flux are thus

$$C(\hat{p}) = E_I(\hat{p}). \tag{17}$$

This method could also be used to determine photon fluxes of sources (instead of the background) under the assumption of a fixed spectral energy distribution.

5.5 Mean exposure in a sky region

For spectral analysis of an isolated point source or for photons in any arbitrary shaped region, we want an "ARF": the effective area as a function of energy, and the "RMF", the spectral redistribution function. In this case, we should calculate an exposure map in high spatial and spectral resolution, $E_I(\lambda, \hat{p})$, but over a small region enclosing the source. We can then spatially integrate over a sub-region of interest, such as a circle, and scale by the exposure time and geometric area to produce an ARF, which is the average response over the region. The redistribution matrix is "off-the-shelf", if the source does not cross a response boundary.

If the region, in sky coordinates, contains events from devices of very different response, such as back- or front-illuminated CCDs of ACIS-S, and if *either* of the following is true:

- the response is uniform over the region, or
- the photons are uniformly distributed over the region,

then an average RMF can be used with the ARF generated from merged detector-element exposure maps.

This method could also be used for larger regions and coarser spatial gridding, such as elliptical annuli.

The user must also be aware and correct for PSF affects, if necessary. For example, for an isolated point source, the region should be large enough that approximately the same fractional flux is enclosed at any energy, or an Auxiliary Response File (ARF) generated which contains that information if the assumption isn't valid. For extended sources, regions should be large enough so that contributions from neighboring bins are small.

Note that spatial integration and PSF fraction calculations are not a part of the exposure map computation.

5.6 Exposure Map Energy Interpolation

In order to produce an effective area function for detailed spectral analysis, we need to compute the exposure map on a fine energy grid. To do this directly from as many Instrument Maps would be computationally expensive, especially at high spatial resolution over a wide field. Instead, the energy dependence will be interpolated from mean QE functions, given the map computation at several grid points. The grid-points will be chosen to avoid interpolation across instrumental features. If the QE dependence did not change with energy, this would be trivial. However, for the back-illuminated CCD's and for HRC, the shape of the response changes with position, as well as the normalization. Experience will be needed to determine how many energy points are needed and what kind of interpolation to perform.

5.7 Grating Mode

For grating spectra, an extraction mask is specified by a zero-order position, cross-dispersion width, and PI fraction. These must be consistent with the counts spectrum binned from the Level 1.5 event file. It is assumed that order-sorting has been done via the grating response and CCD response matrix for ACIS.

The spectroscopic map is specified by

$$E_{\hat{p}_0}(\lambda_G, m), \tag{18}$$

in which $\hat{p}_0$ is the zero-order position, λ_G is the detected grating wavelength, and m is the spectral diffraction order. The detected grating wavelength, λ_G, is close to λ, the source wavelength, but is not identical due to the instrumental line spread function.

This map is a two-dimensional object of size $n(\lambda)$ by $n(m)$ (on the order of 3000×20). It is different from the imaging-mode map because for any given detector position, its value depends on the zero-order location. Hence, it can only be made on a per-source basis.

The predicted counts are approximately

$$S_{\hat{p}_0}(\lambda_G, m) = f_{\hat{p}_0}(\lambda_G) E_{\hat{p}_0}(\lambda_G, m) \tag{19}$$

(having equated λ with λ_G in f).

For HRC, since there is no order resolution, the counts-spectrum is given by a sum over orders at each diffraction angle, $\beta \approx m\lambda/P$, where P is the mean grating period:

$$S_{\hat{p}_0}(\beta) = \int_{m=1}^{m=\infty} dm\, E_{\hat{p}_0}(\lambda_G(\beta), m)\, f_{\hat{p}_0}(\lambda(\beta)) \quad (20)$$

$$= \int_{m=1}^{m=\infty} dm\, E_{\hat{p}_0}((P\beta/m), m)\, f_{\hat{p}_0}(P\beta/m) \quad (21)$$

(where $\infty \approx 30$).

5.8 Pipeline Mode

Rigorous detailed analysis of an imaging or spectroscopic observation involves many choices regarding spatial region definition, spatial resolution desired, spectral region of interest, and source model characteristics. These cannot be known *a priori* for purposes of autonomous standard pipeline processing. Pipeline processing should provide a small number of useful diagnostic exposure maps, but not necessarily products for rigorous and detailed source modeling and analysis, since they depend heavily on subjective scientific decisions.

Some source-model-independent products can be derived in certain cases:

- For well-defined point-sources or for a small sky region of interest, a mean response can be calculated.
- For ACIS imaging observations, a moderately source-model-independent map can be made in several pulse-height bins.

For HRC imaging observations, a compromise must be made by assuming simple spectral distributions, such as a power-law.

Pipeline processing will produce low-spatial resolution maps (a few arcseconds, TBD) . for the entire field in several pulse-height bins for ACIS. For HRC, a spectral model (TBD) will be assumed and a sensitivity map calculated for that spectrum.

pipe map resolution TBD

HRC pipe map spectrum TBD

HETGS and LETGS observations (that is, HETG with ACIS-S and LETG with HRC-S) will have exposure maps for the target source and default extraction region for first orders of MEG and HEG. In addition, an imaging-mode response will be calculated for the zero-order region.

Background map products may be made as part of pipeline processing, as well as source-by-source ARFs. .

bkg, ARF products TBD

5.9 Interactive/Custom Mode

A general user will be able to create Instrument Maps and Exposure Maps as desired, within the limits of computing time and file size dictated by the resolutions specified. In fact, the user *should* generate maps for detailed source analysis, and *must* generate Instrument Maps for non-standard aim-points.

5.10 Time-Resolved Mode

Time-resolved maps may be necessary for light-curve investigations, where the response is needed in temporal bins commensurate with the light-curve bins. There is no explicit support for this in the Instrument Map or Exposure Map calculation. It

is implicitly supported in the ability to specify a GTI table. Computation of maps for a large number of time bins may be cumbersome. Utilities to facilitate this are TBD.

TBD light-curve utilities.

6 Instrument Map Interface Specification

Specification of Instrument Map here...

```
inst_make_map
                Calculate the instrument map by multiplying
                the mirror effective area by the detector
                efficiency.  The mirror area is transformed
                to detector coordinates for the given SIM Z
                offset.  If only one band is specified, the
                output is a 2D FITS image.  If multiple bands
                are specified, then the output is a 3D FITS
                image with third axis of energy.  If band-passes
                are specified, then an integral is done over
                the PHA and energy band.  If a spectrum is
                specified, it weights the integral, and the
                output is really a photon/s/unit flux map.
Inputs:
                Detector QE(x,y,E) [optional]
                Detector Redistribution RMF(h,E) [optional]
                Mirror Effective area AE(theta,phi,E) [optional]
                bad pixel file [optional]
                region mask file [optional]
                spectrum [optional; phot/cm^2/s/keV]...
                TBD...
Parameters:
                Detector Element ID [required]
                SIM Z [required]
                PHA bands [optional]
                PHA bin widths [optional]
                Energy bands [optional; keV]
                Energy bin widths [optional]
                Others TBD...
Output:
                Instrument Map
Restrictions:
                The only required parameters are the SIM
                aimpoint (Z) and the detector element ID.
                These are sufficient to define the geometric
                projection of the detector outline onto the sky.
                The rest of the parameters, while optional,
                are interdependent.  Their use depends upon
                what quantity is desired (e.g., monochromatic
                instrument map, vs. integral over an energy
                band, vs. spectrally weighted map).
```

7 Recommended Usage and Products

Pipeline products **ACIS Imaging:** Exposure Map for several PI/E bandpasses, no spectral weighting. Off-the-shelf Instrument Maps will be for a few nominal aim-points (ACIS-I, ACIS-S). For non-standard aim-points (tolerance TBD), Instrument Map calculation will be required.

HRC Imaging: Exposure Map integrated over the entire bandpass, for TBD spectrum (flat, or E^{-2}?).

HETG, LETG Grating Exposure Map vs order (1-5 TBR) vs energy, for target source.

ACIS, HRC Imaging, per source: Exposure Map per source region, for primary target, vs. energy (TBR)

Custom products As desired by the user: monochromatic maps, band-integrated maps, spatially resolved, spectrally resolved. Generally requires generation of Instrument Maps.

7.1 External Dependencies

1. inst_make_map: generate an instrument map
2. Binning, integration tools for processing output.
3. RMF/ARF tools, for creating custom input (TBR).
4. DataModel tools (dmregrid), for merging maps.
5. ...others TBD

8 Miscellaneous issues: Speed, accuracy, implementation, utilities.

8.1 Combining Maps

Maps are made per detector element, or may be made for independent observations with overlapping fields. Since the maps are linear, they may be added, within the limits of compatible coordinate systems. If the coordinate systems are commensurate (i.e., tangent-plane projections with the same tangent-point), then maps may be re-gridded and added.

Re-gridding tools are not a part of the map tools.

8.2 Exposure map gradient utility

The detector arrays are heterogeneous. ACIS-I is comprised of 4 CCDs, each with a unique response. ACIS-S has very different elements: front- and back-illuminated CCDs. HRC-S has several different filter regions, with fuzzy boundaries (they are shadows of the converging cone). If the aspect dither shuffles an interesting source across boundaries, analysis could be difficult. To provide the user with a quick assessment of whether particular region of the sky is likely to be affected by strong gradients in the response (either QE or redistribution), a utility will provide a map of regions exposed by different array or filter elements. For example, if dither exposes

a sky region on two CCDs of ACIS-I, then the utility will outline that sky region. The user should then take particular care analyzing any sources in that region.

This utility will function by comparing the extrema in the projection of detector element boundaries onto the sky and performing the boolean "more-than-one" operation (For example, "more-than-one" for 3 detector elements, A, B, and C, means
$\{ (A \text{ AND } B) \text{ OR } (A \text{ AND } C) \text{ OR } (B \text{ AND } C)\}$). Since the default mode of computation is by detector element, assessing whether a give region is contained in more than one map is straightforward.

8.3 Some Implementation Issues

1. Aspect solution: histogram or time-series?

   The AXAF aspect solution provides a pointing and detector position every 0.256 s. Since the exposure map computation time scales directly with the number of aspect pointings to be processed, it is important to compress the aspect solution into a set of unique pointings.

   The nominally programmed dither pattern is large compared to the on-axis point-spread-function (40 arcsec vs 1 arcsec). Hence, it is not clear that any cell in a 6-dimensional aspect solution will be re-visited, which means that an aspect histogram does not economize over a sequential time integration. Actual performance (and better performance models) will help answer this. For example, SIM motion is expected to be very slow so 3 of the 6 dimensions may compress into a few bins. If roll variation is as small as predicted, it also fits into a small number of bins. Hence, an aspect histogram as used in past missions may be efficient.

   Alternatively, stable aspect intervals may be defined which compress the sequential aspect points into the times during which the mean pointing does not change by more than some fraction of a sky bin. This also has dependencies on the actual aspect performance. For instance, if roll is significant, these intervals depend on the off-axis angle of the detector region.

   Both aspect histogram (via a 64-tree, the 6-dimensional counterpart of the oct-tree of a 3D aspect solution) and sequential options will be available. The time to process TBD aspect bins for map resolutions of TBD is TBD.

J.E.D. review histogram options.

TBD Aspect time scaling.

8.4 Timing Issues

1. Sky grid resolution directly affects the computation time by the number of bins whose response must be computed. A related term is the degree of accuracy to which the mirror vignetting with off-axis angle must be interpolated.

   Optimization trade-offs are TBD.

2. Pixel sub-sampling (also known as anti-aliasing) can be applied to produce a smoother map, but costs computationally. This may be important since the PSF is comparable to a pixel, but may be sufficiently smoothed by the dither. Use is TBD.

3. Detector uniformity resolution and detector size affects computation time. Regions of uniform response are projected to the sky, and sky pixels filled with a constant value. More regions require more time. Optimization trades are TBD.

8.5 Miscellaneous Issues

1. For grating spectroscopy, the regions over which the exposure map is calculated and over which the 1D spectrum is extracted must be consistent. Whether a 2D (wavelength and cross-dispersion coordinate) maps is required is TBD.

2. PSF issues: far off axis, less resolution is required. Spatial grids could be coarser.

9 Some Relevant Special Conditions of AXAF

Previous missions (`ROSAT, ASCA`) made certain approximations which don't work for `AXAF`. The relevant differences are:

- Spatial Resolution: AXAF's PSF is much smaller, relative to the aspect motion. Coordinate transformations must be accurate over a wide field (15 arcmin radius), and handle many pixels.

- Spectral Resolution: AXAF has high (grating), moderate (CCD), and low (HRC) spectral resolutions. The dispersing spectrometers require a completely new form of exposure map.

- Calibration: Instrument response is well characterized in ground-calibration, in terms of spatial and spectral response.

- Non-uniform detectors: Detector arrays have regions of very different response, via filters, energy redistribution, or quantum efficiency.

- Detector modes: ACIS is programmable, and has many modes of operation, each of which has a different calibration.

- Aspect Solution: The AXAF aspect solution includes the detector position relative to the mirror, and so is 6-dimensional, instead of 3. The aspect is specified approximately every quarter second, giving many aspect bins. For the small PSF (which means small changes in pointings are significant), the solution may not compress much as an aspect histogram.

- The aim-point is selectable in one dimension. Unique offsets require independent maps, since the relative mirror-detector position changes.

10 Some Relevant ASC Documents

These are some references to the detailed information required for application and development of exposure map tools:

"Exposure Maps", J.Davis memo derives exposure maps from first principles of the AXAF response, for both imaging and spectroscopic modes. See: `http://space.mit.edu/ASC/analysis/Exposure_Maps/jd_expmap_theory.ps.gz`

exp_make_map is
a top-level interface description of the low-level exposure map engine. See: `http://space.mit.edu/ASC/analysis/Exposure_Maps/exp_make_map.txt`

Level 2 ICD — is where the data exposure map data product (FITS image) is defined in detail. See: `http://space.mit.edu/ASC/analysis/Exposure_Maps/Exp_DP.ps.gz`

Reference Data are also described in an ICD (Interface Control Document). The reference data are those calibration products necessary for computing an exposure map, such as detector QE or mirror effective area. See: `http://space.mit.edu/ASC/docs/ARD_ICD/ARD_ICD.ps.gz`

Instrument Map computation and data product are described in TBD. See: `http://space.mit.edu/ASC/documents/tbd/TBD` tbd tbd link

11 Relationship to previous missions

980115 new section, unreviewed

1. ROSAT HRI used bright-earth data to make a map of size 512×512, blocked 30×30 pixels (to 5.0 arcsec). Vignetting was only done for 0.53 keV. The `FTOOL` is `hriexpmap`, and is based on Snowden et al. 1992 (ApJ, 393 819). `FTOOLS` documentation says that the task can take a "long time" (without further elaboration).

2. ROSAT PSPC (also based on Snowden et al. 1992; `FTOOL pcexpmap`) used a composite detector-source response map derived from all-sky survey data, with known sources removed. This is an empirically determined flat field *for some mean incident background spectrum*. As such, it is an approximation to the instrument response. The output is a 512×512 image with 15 arcsec pixels, which is a blocking by 16 of the detector pixels. It may be calculated in any of several pre-determined PHA ranges.

   The input map dimensions are TBD by TBD spatially, and TBD PHA bins. To create a sky map of size TBD by TBD for TBD PHA bins takes TBD seconds on a TBD computer.

   ROSAT TBD, TBD, TBD benchmark.

3. ASCA: Exposure maps for ASCA (`FTOOL ASCAEXPO`) can be made for just exposure time, exposure time and mirror response, or time with both mirror and detector responses. The detectors are assumed to be uniform. Attitude records may be decimated or a minimum significant step-size set to improve speed, but possibly sacrifice accuracy. A time-independent map may also be made (no attitude file used). Input and output maps may be rebinned (but by the same factor). The `FTOOL` doesn't include GIS dead-time or SIS frame saturation.

   The input instrument map determines PHA regions. This can be created via the `FTOOL`, `ascaeffmap` for either the SIS or GIS. `FTOOLS` documentation indicates that an "extremely long time" can be required for making an instrument map over the entire energy band.

   A timing benchmark is TBD.

   ASCA benchmark TBD.

12 References

1. Examples of extended source analysis in narrow PI bands for ROSAT and ASCA.
   (a) Hwang, U., and Gotthelf, E.V., (1997), Ap.J., 475, 665.
   (b) Snowden, S.L., McCammon, D., Burrows, D.N., and Mendenhall, J.A., (1994), Ap.J., 424, 714.
2. HEASARC resources:
   (a) ROSAT GOF FAQ has some exposure map tips:
   (`http://heasarc.gsfc.nasa.gov/docs/rosat/faqs/pspc_faq_list.html`)
   (b) ROSAT FTOOLS: `HRIEXPMAP`, `PCEXPMAP`
   (c) ASCA Exposure Map and tutorial:
   `http://heasarc.gsfc.nasa.gov/docs/asca/abc/node11.html#SECTION00115000000000000000`
   (d) `ASCAEFFMAP`: ASCA effective area map `FTOOL`.
   (e) `ASCAEXPO`: ASCA exposure map `FTOOL`.
3. SAO Historical resources:
   (a) SAO Special Report #393 (1982), L. Van Speybroeck, "Exposure Map Definitions", p.255.