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# The Chandra X-ray Observatory PSF Library

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**Abstract.** Pre-flight and on-orbit calibration of the Chandra X-Ray Observatory provided a unique base for developing detailed models of the optics and detectors. Using these models we have produced a set of simulations of the Chandra point spread function (PSF) which is available to the users via PSF library files. We describe here how the PSF models are generated and the design and content of the Chandra PSF library files.

## 1. Introduction

The Chandra X-Ray Observatory (Chandra) produces sharper images then any other X-ray telescope to date (less then $1''$ on-axis), and therefore provides a unique opportunity for high-angular resolution studies of cosmic X-ray sources. Crucial to these studies is the understanding of the characteristics of the Chandra Point Spread Function (PSF).

The unprecedented Chandra resolution is mainly due to the innovative design of this observatory, including the guidance systems, the mirror assembly (High Resolution Mirror Assembly, or HRMA), and the science instruments. HRMA consists of four pairs of nested mirrors (a Wolter Type I design), support structures, and additional thermal and optical baffles system. Four science instruments are located in the telescope focal plane (HRC-I, HRC-S, ACIS-I and ACIS-S). The instruments' resolution is well matched to capture the sharp images formed by the mirrors and to provide information about the incoming X-rays: their number, position, energy, and time of arrival.

A set of simulated PSFs is available to the users for data analysis via the standard PSF library files. In addition to these standard PSF libraries, the user may construct their own library files as long as the FITS HDUs and the PSF images conform to the general Chandra PSF library format. The user can extract the desired PSF model image from PSF library files by using the Chandra Interactive Analysis of Observations package (CIAO) tool **mkpsf**.

## 2. Chandra PSFs

The HRMA PSFs vary significantly with source location in the telescope field of view (FOV), as well as with the spectral energy distribution of the source. Because of the Wolter Type I design, the image quality is best in a small area centered about the optical axis. The mirrors were designed to concentrate better than 85% of the energy at 0.277 keV within a 1″ diameter. This is why a substantial pre- and post-launch effort was directed at creating a faithful model of the HRMA's mechanical and optical systems. The detailed modeling and metrology of the optics followed by extensive testing at the X-Ray Calibration Facility at the Marshall Space Flight Center in Huntsville and the on-orbit calibration of the point spread function showed that we are close to reaching the goal of calibrating the optics' performance to 1% (Jerius et al. 2000, Proc. SPIE 4012).

The simulated Chandra PSFs used in the standard PSF library files are generated in two steps:

(1) ray files are generated using SAOsac, a ray-trace code which models the interaction of photons (rays) passing through the HRMA (Jerius et al. 2000). The initial number of rays for these simulations was approximately $10^5$.

(2) PSF model images are made by projecting these rays to the detector surface and then creating images with pixel sizes smaller than the pixel sizes of the detectors.

We produced a large set of PSFs at many off-axis angles covering the field of view of the detectors and at several energies ranging from 0.277 keV to 8.6 keV. Figure 1 shows examples of the HRC-I PSFs at several off-axis angles.

## 3. Chandra PSF Libraries

### 3.1. General PSF Library Definition and Format

The Chandra PSF library consists of two dimensional PSF model image "postage stamps" stored in multi-dimensional FITS images (hypercubes). In the following we summarize the PSF library general format:

**HDU type 1 – the PSF image:** These are n-dimensional images, hypercubes primary array) that extend along a minimum of five coordinates. The known coordinate axes are:

**l** - spatial x-direction of the PSF image (PSFX)

**m** - spatial y-direction of the PSF image (PSFY)

**X** - spatial x-direction offset coordinate (DETX)

**Y** - spatial y-direction offset coordinate (DETY)

**E** - energy (ENERG)

**f** - defocus (DEFOCUS)

Every image is required to have the following axes: (**l**, **m**, **E**, **X**, **Y**, **f**). Each coordinate may be regularly sampled, in which case the sample points are defined by the usual CTYPEi, etc., keywords; or irregularly, in which case the sample points are defined in a table extension (in the same file).

Each coordinate has to have one or more pixels, but one is expressly allowed. If there is only one point along any of the required axes, the axis still needs to be present and its coordinate value is defined in the usual way (CTYPEi, etc.). The

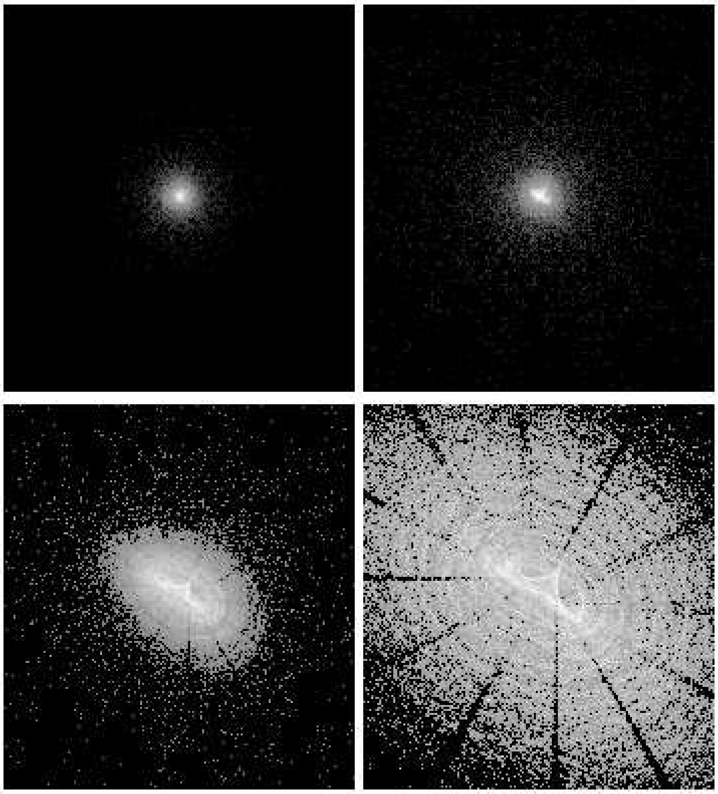

Figure 1. Model PSFs for the HRC-I instrument at 1.4967 keV as a function of off-axis angles (log display); clockwise from the top, off-axis angles 0 (on axis), $1.'5$, $6'$, and $12'$. The size of the FOV is about $0.'5$.

coordinate axes (most notably the spatial ones) have several aliases defined in the header. The headers of these images contain the required Caldb keywords. These images have SUMRCTS=1.0.

**HDU type 2 – the irregularly sampled coordinate definition tables:** These are binary tables which allow an unambiguous translation of "bins" or "pixels" to physical coordinates (e.g., energy, defocus).

**HDU type 3 – SUMRCTS image:** The SUMRCTS images contain the information on how many photons there are per individual PSF data in the PSF hypercubes. These images match the PSF hypercubes exactly, except that the **l** and **m** axes are missing. The image pixels indicate the number of counts used for each PSF image. The SUMRCTS images are kept in IMAGE extensions.

## 4. Standard PSF Library Structure and Content

There are four standard PSF libraries provided per instrument. The standard library files are comprehensive, covering the entire instrument FOV, or a section of the FOV in a regular grid. The HDU for each of those files contains the self-contained PSF data, as a single hypercube (6-D; NAXIS=6) with image extension containing information on the number of photons (weights) needed for normalization of the PSF models, and one or more binary tables containing irregular coordinate definitions.

The PSF models incorporated in the PSF library hypercubes are single size arrays (images) on a fixed, regular grid. They do not contain spreading due to aspect. The PSF model images are made using the nominal aim-point and the nominal SIM-Z position for each detector. Currently, the standard libraries contain PSF models calculated for one defocus position (defocus=0) and 5 energies (0.277 keV, 1.4967 keV, 4.51 keV, 6.4 keV, and 8.6 keV).

When designing the standard library we had to make a compromise between the need for fine spatial and spectral resolution in the PSF grids, and the need for a reasonable file size of each individual library hypercube delivered to the user. In fact, the large size of the individual PSF "postage stamp" image files was a limiting factor on how many can be incorporated in the standard PSF library files, and still provide a useful off-axis angle and energy sampling of the PSFs, and at the same time cover a reasonable FOV. In the following we summarize the current structure of the library files:

*1. High resolution library (I)* with a step of 1 arcminute between images: contains 1 $\mu$m pixel images covering a $-1$ to $+1$ arcminutes grid ($3\times3$) about the optical axis. [NB: ACIS pixel size is 24 $\mu$m; HRC pixel size is 6.4294 $\mu$m). The actual resolution ("effective pixel size") for HRC can be obtained by convolving with a Gaussian with $\sigma$ of 1.5 HRC pixels.

*2. High resolution library (II)* with a step of 1 arcminute between images: contains 2 $\mu$m pixel images covering a $-6$ to $+6$ arcminutes grid ($11\times11$) in azimuth and elevation (in a telescope fixed system) about the optical axis.

*3. Medium resolution library* with a step of 1 arcminute between images: contains 6 $\mu$m pixel images covering a $-10$ to $+10$ arcminutes square grid for ACIS-I and HRC-I ($21\times21$), and a $-10$ to $+10$ arcminutes in elevation and $-5$ to $+5$ arcminutes in azimuth grid ($21\times11$) for ACIS-S and HRC-S about the optical axis.

*4. Low resolution library* with a step of 5 arcminutes between images: contains 12 $\mu$m pixel images covering a $-25$ to $+10$ arcminutes in elevation and $-10$ to $+10$ arcminutes in azimuth ($8\times5$) grid for ACIS-I, a $-25$ to $+25$ arcminutes in elevation and $-5$ to $+5$ arcminutes in azimuth ($11\times3$) grid for ACIS-S, a $-25$ to $+25$ arcminutes in elevation and $-25$ to $+25$ arcminutes in azimuth ($11\times11$) grid for HRC-I, and a $-30$ to $+30$ arcminutes in elevation and $-5$ to $+5$ arcminutes in azimuth ($13\times3$) grid for HRC-S about the optical axis.

The PSF library grids are very coarse (azimuth and elevation angular offsets of $1'$ or $5'$, only 5 energies, and only one defocus position). Therefore, the user needs to interpolate in these grids to get a PSF for the off-axis angle and the energies (spectrum) of the observed source. The standard libraries can be used to view the general distortions and structure of the HRMA PSFs, as well as the PSF variations as a function of off-axis angle and energy. Since the variation in the PSF can be significant even for small off-axis angles, the current PSF library should be used with caution when performing a detailed spatial/spectral analysis or for deconvolution.

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