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MKRMF: Multi-Dimensional Redistribution Matrices

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Abstract. A response matrix is a discrete representation of a given instrument's response to incoming photons. In the case of Chandra, each element (HRMA, gratings, focal plane detectors, etc.) has a specific response to an incoming photon's individual physical characteristics, such as energy or position on the sky. These responses can be encoded in the form of a response matrix file or RMF. This presentation is a preliminary report on MKRMF, a new tool developed by the Chandra X-ray Science Center (CXC), to calculate RMFs appropriate for the variety of science instruments on-board Chandra (Wise 1998). This tool provides a number of innovations including the ability to create RMFs on user defined grids and the use of externally encoded instrument redistribution functions for greater flexibility. These external redistribution functions are stored using a new FITS format developed by the CXC for encapsulating functions.

1. Introduction

Mappings and transformations between any source of photons (S) with physical properties ($\vec{x}$) and the corresponding detected events (D) with properties ($\vec{y}$) can be represented using a response function, (R), expressed as

$$D(\vec{y}) = R[\vec{f}(\vec{x}, \vec{y})]S(\vec{x})$$

where R is potentially a function of several redistribution functions, $\vec{f}$, each of which may depend on $\vec{x}$ or $\vec{y}$. Discrete representations of the response function typically take the form of matrices. Thus, response matrices are inherently multi-dimensional.

The CXC maintains three responses, each of which has a minimum set of redistribution function(s), as described below:

- Detector Response (*energy, pha*) – a traditional 2-D response function which maps the wavelength (or *energy*) of an incoming photon into a detected pulse height amplitude (*pha*). This response is the most familiar and utilized in programs such as XSPEC;

- Grating Response (*energy, pha*, r_d) – a response which maps photon wavelength into both dispersion angle on the detector (r_d) and detected pulse height (*pha*). This response function is inherently 3-D and describes the HETG and LETG on-board Chandra;
- PSF Response (*energy, r*, θ, *x, y*) – a multi-dimensional response which describes the HRMA's scattering properties or point-spread-function (PSF). This response maps photon energy and position on the sky (r, θ) into a detected position in the focal plane (x, y).

MKRMF is designed to work with arbitrary redistribution functions, allow flexibility in defining matrix grids, and provide multi-dimensional matrix solutions to the equation above.

2. Redistribution Function

MKRMF utilizes redistribution functions which are stored externally using FITS Embedded Functions (FEFs)[1], a new CXC standard for storing analytical or tabulated functions in a FITS format. In this manner, the same tool can be used to create multiple response matrices by supplying the appropriate FEF. The FEF file itself is generated using another CXC tool, *dmwritefef*, whose inputs are described below.

script file: contains a description of the functional form (single or combined) and name/dimension/alias that are to be used in the FEF. For example:

```
source = gauss1d[g1]+gauss1d[g2]
```

axes file: specifies the axes of the FEF to be created, as well as their minimum and maximum limits, units, scales, offsets, etc. The following is a sample axes file for a 2-D FEF:

name	min	max	units	scale	offset
ENERGY	0	200	keV	3.6e-3	0.047
PHA	0	4096	ADU	none	none

list file: describes how the parameters of the functional form vary as a function of the other axes.

3. Response Matrix Grids

With MKRMF, the user has three options for defining the matrix grids: command line, FITS binary table, or ASCII table. Each of these is implemented using the SAO parameter file interface[2].

[1] `http://hea-www.harvard.edu/~jcm/asc/fits/func.ps`

[2] `http://asc.harvard.edu/udocs/docs/swdocs/bguide/html/oparam.html`

3.1. Command Line

In this mode, the grid for each axis is specified using five parameters separated by commas, i.e.:

```
axis1 = param1, param2, param3, param4, param5

param1: name of the axis
param2: the low value of the grid array
param3: the high value of the grid array
param4: the number of bins in the grid
param5: flag indicating whether linear or logarithmic
        grids are used
```

For the archetypal case of a CCD response matrix, we might use:

```
% mkrmf axis1 = energy,0.1,10.0,1500,linear \
        axis2 = pha,1,4096,4096,li
```

which specifies that the energy axis is to consist of 1500 linearly spaced bins from 0.1 to 10.0 KeV. Similarly, the pha axis will contain 4096 linear bins from pha values 1 to 4096.

3.2. FITS Binary Table

With this option, matrix grids are read from a FITS format file, which must have at least two columns containing the upper and lower boundaries of each bin in the grid. The syntax for this case is:

```
axis1 = param1, param2

param2: name of an external file where grids are tabulated
```

where `param1` follows the same description above. For example,

```
% mkrmf axis1 = energy,example5_pspc.fits
```

indicates that the external file, `"example5_pspc.fits"`, tabulates matrix grids along the "energy" axis.

3.3. ASCII Table

This mode has a similar syntax to the FITS file interface, but requires 2 or 3 more parameters to specify the column number and the position of each column in the file:

```
axis1 = param1, param2, param3, param4, param5

param3: the total column number (1 or 2)
param4: number of the i_th column in the file
param5: number of the j_th column in the file if param3=2
```

For example,

```
% mkrmf axis1 = energy,example5_pspc.ascii, 2, 2, 3
```

instructs the tool to read the lower boundary of the energy grid from the second column and the upper boundary from the third column.

4. Multi-Dimensional Matrices

The RMF file produced by MKRMF is currently encoded in one of two FITS formats: *legacy* and *cxc*. The 2-D *legacy* format retains the HEASARC OGIP 92-002[3] standard which is appropriate for CCD detector responses and compatible with tools such as XSPEC. This format is not however extensible to higher dimensional response matrices such as those needed to model the HETG and LETG gratings on-oard Chandra. Consequently, the CXC has defined a new FITS standard for storing compressed response matrices which is used by other tools in the data analysis system such as SHERPA (Doe et al. 1998). Using this format, RMFs of arbitrary dimensionality can be stored. In the case of standard 2-D RMFs, such as for X-ray CCDs, the user has the option of creating standard HEASARC format files which are backward compatible with XSPEC/FTOOLS or CXC format RMFs. The form and contents of the CXC RMF format is summarized in the table below.

Table 1. CXC RMF Format

column			
1	2	3	4
contents			
Low cell bound for rows	High cell bound for rows	(non-zero) matrix elements for row	Error for row
E_{low} P^i_{low}	E_{high} P^i_{high}	$Matrix^i$	$Error^i$
format of each column			
4-byte real	4-byte real	4-byte real	4-byte real
column name			
CELL_LO	CELL_HI	MATRIX	ERROR

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References

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Wise, M. 1998, Response Matrix Tool: Design Specification and Data Product Interface Control Document, CXC

[3] `ftp://lheaftp.gsfc.nasa.gov/pub/kaa/cal_gen_92_002.ps`