OGIP Calibration Memo CAL/GEN/92-020

THE OGIP FORMAT FOR RADIAL POINT SPREAD FUNCTION DATASETS

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SUMMARY

Ths document describes the standard formats adopted by the OGIP for the storage of the Radial Point Spread Function (RPSF) and Radial Encircled Energy Function (REEF) datasets, which describe the radial angular/spatial response of an instrument as a function of energy, and position.
Intended audience: primarily HEASARC programmers & hardware teams.

Log of Significant Changes

Release Date	Sections Changed	Brief Notes
1992 Jul 24	First Draft	(within memo CAL/GEN/92-003)
1993 Oct 03	All	Separation from CAL/GEN/92-003
1994 Jan 12	All	Revised & added HDUCLASn info
1995 Jan 19	All	Made compatible with `LaTeX2HTML` software
1995 Feb 10	All	Fixed typos & ambiguities

RELATED DOCUMENTATION

The following documents may also be of use:

- *BCF & CPF Calibration File Guidelines*
  CAL/GEN/92-003 (George & Zellar)
- *Calibration Index Files*
  CAL/GEN/92-008 (George, Pence & Zellar)
- *Mandatory FITS Keywords for Calibration Files*
  CAL/GEN/92-011 (George, Zellar & Pence)
- *Virtual Calibration Files*
  CAL/GEN/92-013 (George, Zellar & White)
- *The OGIP format for 2-d PSFs*
  CAL/GEN/92-027 (George & Yusaf)

1 Introduction

Within the HEASARC caldb the term *"Point Spread Function"* (*PSF*) is used to refer to the spatial/angular spreading of incident photons from a point source caused by the instrument (detector and/or mirror). In the most common and simple case, imperfections in the surface smoothness and shape of the mirrors result in incident photons from cosmic sources not being perfectly focussed on the focal plane. Thus the number of events detected as a function of position in the focal plane is not the idealized delta-function at the expected position, but has a characteristic shape (depending upon the optics and detectors in use) with a finite "width". More generally, the *PSF* also can include spreading of events due to "geometrical" effects (*eg* obscuring structures, the detector surface not laying exactly on the focal plane, including coma), and effects within the detector (*eg* lateral charge-cloud drift in gas experiments), *etc*.

Thus, generally a point-source at infinity gives rise to a 2-dimensional image of finite size. Within the the HEASARC caldb such a dataset is refered to as a *2DPSF*, and the FITS file format for such calibration datasets are described in CAL/GEN/92-027 (George & Yusaf). In this memo we concentrate on the 1-dimensional (spatially) calibration datasets, commonly refered to as *Radial Point Spread Functions*, representing azimuthally averaged values of a *2DPSF*, centred on the theoretical point of focus based on an idealized optical path. In practice the centroid of the *2DPSF* is often used instead of the theoretical position of focus.

The HEASARC CALDB currently recognizes two types of datasets relating to the storage of the **radial** point spread function of an instrument:

- *Radial Point Spread Function* (*RPSF*) datasets; each element of which essentially describes the probability of an event (which **was** successfully detected by the detector) being detected at a position which lies within a given annulus centred on the theoretical position of focus. The dataset is normalized to either a single event (giving the true probability per unit area for each annulus – the prefered method for calibration datasets), or a given number of 'total' events (giving the expected/observed number of counts per unit area for each annulus – often useful for observational datasets).
- *Radial Encircled Energy Function* (*REEF*) datasets; each element of which describes the fraction of the 'total' events (when integrated out to a large/infinite radius) contained within circles of increasing radii centred on the theoretical position of focus.

It is hopefully clear that both types are intimately related, and indeed historically both have sometimes both been refered to as *radial point spread functions.* However the HEASARC CALDB makes a clear distinction.

Finally, it should be noted that for most instruments, the azimuthal averaging involved in their construction means that neither *RPSF* nor *REEF* (calibration datasets) are suitable for a detailed scientific investigation as to how an observed image of a given source is extended. Rather, both types of dataset provide:

- a 'first-look' indication as to whether a given observational image is spatially extended beyond that expected due to the instrumental response, and/or
- (assuming an image is indeed due to a point source)
  - a method of determining what fraction of the (source) counts lie within a given radius,
  - how to correct a count rates for this fact,
  - where the background starts to dominate,
  - what size 'detection cell' to use to be most sensitive to detecting sources,
  - *etc*

Detailed image-reconstruction of non-point-source targets should instead use full 2-dimensional *2DPSF* calibration datasets described in CAL/GEN/92-027 (George & Yusaf).

1.1 Storage Options

Due to the range of effects refered to above, in the general case, both *RPSF* and *REEF* datasets consist of a 4-dimensional grid, with 1 axis giving the "radius" (R, the angular distance from the theoretical point of focus), 1 axis giving the photon energy (E), and 2 axes defining the position relative to the optical axis — invariably the off-axis angle (θ_{XMA}) & azimuthal angle (ϕ_{XMA}) — at which each *RPSF* dataset is valid.

1.2 Dataset Origins & Storage Recommendations

The construction, format used (within the limitations discussed here) and delivery of the data to the HEASARC (including any updates) is the responsibility of the h/w teams and/or GOF. However, below, are the recommendations of the HEASARC calibration team based on their experience. Obviously emphasis is placed on 'calibration' *RPSF* or *REEF* datasets (*ie* datasets which are likely to be used as 'standard calibrations' by users and/or software, and/or are likely to be delivered to the HEASRAC caldb). Consequently, a number of the issues discussed here and in the document as a whole are not/less applicable to observational datasets (*ie* datasets derived from non-calibration, Guest Observer observations — particularly in the case of *RPSF* datasets).

<u>*General*</u>
In both the case of *RPSF*s and *REEF*s, virtual calibration files are recommended (see Sections 1.3 & 4).

<u>*Pre-launch*</u>
Prior to launch, the spatial/angular spreading of a point source is usually measured at a (limited) number of positions and/or photon energies during ground calibration experiments and/or combined with theoretical (*eg* ray-tracing) models to produce the datasets. In many case these

results can be parameterized such that a virtual calibration file (Sections 1.3 & 4) can be produced.

Post-launch
In orbit, the pre-launch datasets are usually confirmed by making a limited number of pointings/raster-scans of a known bright point-source. Again, often the results from these datasets can be parameterized such that a virtual calibration file (Sections 1.3 & 4) can be created.

1.3 Dataset vs Task Summary

As stated above, it is often fairly straightforward to parameterize both a *RPSF* and *REEF* dataset of an instrument. As a result such a calibration dataset may often be more easily and economically storted as a virtual calibration file, and an associated standalone s/w task (see CAL/GEN/92-003). Wherever possible, this is recommended. The requirements for such virtual calibration files are discussed in Section 4.

1.4 Software Considerations

Data Files:
In the case of both *RPSF* and *REEF* datasets, interpolation between the θ_{XMA}, ϕ_{XMA} grid points is usually required. By default, downstream software will use a simple 2-dimensional **linear** interpolation when calculating the *RPSF*/*REEF* between θ_{XMA}, ϕ_{XMA} grid points. Thus the θ_{XMA}, ϕ_{XMA} grid should be of sufficient resolution to enable this to be reasonable approximation.

As discussed in CAL/GEN/92-003, it is strongly recommended that the energy grid is of sufficient resolution and carefully chosen such that interpolation of this parameter is not required. However, in cases where interpolation is required, as simple 1-dimensional linear interpolation will be performed (which will clearly be inaccurate close to sharp features).

Virtual Files:
No specific issues.

1.5 Relationships to Other Calibration Datasets

... section incomplete

2 RPSF Data File Formats

The HEASARC FITS Working Group (HFWG) Header-Data Unit (HDU) keywords and values for this type of dataset are:

- `HDUCLASS = 'OGIP'`
  - the name of the organization that defined this file format.
- `HDUDOC   = 'CAL/GEN/92-020'`
  - the name of the document describing the format (*ie* this document)
- `HDUCLAS`n
  - giving the HDUCLAS hierarchy for this format.
  - `HDUCLAS1 = 'RESPONSE'`
  - `HDUCLAS2 = 'RPRF'`
  - `HDUCLAS3 =` (*see below*)
  - `HDUCLAS4 =` (*see below*)

These are valid for all datasets described in this section, and should be present in the **header of the extension** containing the *RPSF* dataset.

2.1 Summary of RPSF file formats versions

The following versions of file formats for a *RPSF* dataset have been defined:

- `HDUVERS  = '1.0.0'` (Section 2.2)
  This format is currently still **VALID**.
  It was designed primarily for calibration datasets, but can be used for GO datasets.
- `HDUVERS  = '2.0.0'` (Section 2.3)
  This format is currently still **VALID**.
  It was designed primarily for GO datasets, but can be used for calibration datasets.

2.2 The Radial PSF Extension (HDUVERS = '1.0.0')

Description:
One file for each telescope/instrument combination containing a single BINTABLE FITS extension. The BINTABLE only has a single row, using arrays for the 8 necessary columns.

Note: this format was formally known as RPSFVERS = '1992a', and is still occasionally refered to as such.

Extension Header
Beyond the standard FITS keywords required, and the HDU keywords/values given in Section 2, the following keywords/values are mandatory:

- `TELESCOP` - the name of the satellite/mission.
  Allowed values are given in CAL/GEN/92-011.
- `INSTRUME` - the name of the telescope mirror/detector assembly.
  Allowed values are given in CAL/GEN/92-011.
- `HDUVERS  = '1.0.0'` - giving the version of the format.
- `HDUCLAS3` - further describing the scientific content of the dataset, specifically regarding the origin of the dataset. The allowed values are:
  - `HDUCLAS3 = 'OBSERVED'` - indicating the *RPSF* dataset has been generated from an observational dataset.
  - `HDUCLAS3 = 'PREDICTED'` - indicating the *RPSF* has been generated using a theoretical model.
- `HDUCLAS4` - further describing the scientific content of the dataset, specifically regarding the contents of the dataset. The allowed values are:
  - `HDUCLAS4 = 'TOTAL'` - indicating the *RPSF* dataset includes counts from the 'source' as well as any counts from the 'background'
  - `HDUCLAS4 = 'NET'` - indicating the *RPSF* dataset has been background-subtracted
- `TDIM`*nnn* - the number of elements and ordering (see CAL/GEN/92-003) of each multi-dimensional array.
  Only the `RPSF`, `AREA_WGT` & (if present) the `RPSF_ERR` columns here (with *nnn*=7,8 & 9 in the example below).
- *i*`CTYP`*nnn* - The axis labels for dimension i (i = 1, 2, 3, 4) of the `RPSF`, `AREA_WGT` & (if present) the `RPSF_ERR` columns. In the example given below, *nnn* = 7, 8 & 9 respectively, and
  - `1CTYP7  = 'SPATIAL_OFFSET'`
  - `2CTYP7  = 'COORD-1'`
  - `3CTYP7  = 'COORD-2'`

  - 4CTYP7 = 'ENERGY'
  - 1CTYP8 = 'SPATIAL_OFFSET'
  - 2CTYP8 = 'COORD-1'
  - 3CTYP8 = 'COORD-2'
  - 4CTYP8 = 'ENERGY'
  - 1CTYP9 = 'SPATIAL_OFFSET'
  - 2CTYP9 = 'COORD-1'
  - 3CTYP9 = 'COORD-2'
  - 4CTYP9 = 'ENERGY'

  (see CAL/GEN/92-003 for further details).

- `CREF`*nnn* = The column referencing keyword for each multi-dimensional array.
  Only the `RPSF`, `AREA_WGT` & (if present) the `RPSF_ERR` columns here (with *nnn*=7,8 & 9 in the example below) giving:

  - CREF7 = '(RAD_LO:RAD_HI,THETA,PHI,ENERG_LO:ENERG_HI)'
  - CREF8 = '(RAD_LO:RAD_HI,THETA,PHI,ENERG_LO:ENERG_HI)'
  - CREF9 = '(RAD_LO:RAD_HI,THETA,PHI,ENERG_LO:ENERG_HI)'

  in the example below.

- `CSYSNAME` - the spatial coordinate system in use
  Allowed values are given in CAL/GEN/92-003)
  (`CSYSNAME = 'XMA_POL'` is assumed in the example below)

- `PIXSIZE` - the angular size of (one side) of the pixels in units of decimal degrees.

- `BACKGRND` - the background count rate in units of counts per pixel (where the pixel size is definded by `PIXSIZ`). If no underlying instrument or cosmic background is expected, then a value of zero should be entered.

- `ENERG_LO` - the minimum energy (in keV) for which the the *RPSF* dataset was constructed or is valid. The value `-99.0` indicates that the value is unknown.

- `ENERG_HI` - the maximum energy (in keV) for which the the *RPSF* dataset was constructed or is valid. The value `-99.0` indicates that the value is unknown.

- `CHANMIN` - the minimum detector channel number for which the the *RPSF* dataset was constructed or is valid. The value `-99.0` indicates that the value is unknown.

- `CHANMAX` - the maximum detector channel number for which the the *RPSF* dataset was constructed or is valid. The value `-99.0` indicates that the value is unknown.

- `CHANTYPE` - the type of detector channels `CHANMIN` & `CHANMAX` are expressed in, with the allowed values:

  - `CHANTYPE = 'PHA'` - for 'raw' detector channels

  - `CHANTYPE = 'PI'` - for (corrected) 'Pulse Invariant' detector channels

- `SUMRCTS` - the sum of the raw counts 'under' the *RPSF* dataset. Essentially the value of this keyword can provide the 'normalization' of an observed dataset. It is **strongly** urged that the *RPSF* supplied to the HEASARC caldb be normalized to 1 count (*ie* `SUMRCTS = 1.0`).

and the following keywords/values are mandatory for CIF purposes **ONLY** if the dataset is ever to be included as a calibration file within the HEASARC caldb (see CAL/GEN/92-011):

- `CCLS0001` - the OGIP class of this calibration file, with allowed values:
  - `CCLS0001 = 'BCF'` - for Basic Calibration datasets
  - `CCLS0001 = 'CPF'` - for Calibration Product datasets
- `CDTP0001` - the OGIP class of the data type, with allowed values:
  - `CDTP0001 = 'DATA'` - for 'true' datasets
  - `CDTP0001 = 'TASK'` - for 'virtual' calibration datasets
- `CCNM0001 = 'RPSF'` - the OGIP codename for the contents
- `CBD`*n*`0001` - the parameter-space limitations of the dataset (see below)
- `CVSD0001` - calibration validity start date
- `CVST0001` - calibration validity start time
- `CDES0001` - a descriptive string of the calibration dataset

and the following mandatory to supply further information:

- `RPSFVERS = '1992a'` - the OGIP version of the FITS format in use

Data Format:
The data within the extension is organised as a BINTABLE with the following columns:

1. R_{low}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the lower radial bounds of the annular bins as measured from the nominal point of focus. The FITS column name is **RAD_LO**.
   The recommended units are arcmin.
2. R_{high}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the upper radial bounds of the annular bins as measured from the nominal point of focus. The FITS column name is **RAD_HI**.
   The recommended units are arcmin.

3. θ_{XMA}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the off-axis angles.
   The FITS column name is **THETA** (but see below).
   The recommended units are arcmin.

4. ϕ_{XMA}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the azimuthal angles.
   The FITS column name is **PHI** (but see below).
   The recommended units are arcmin.

5. E_{low}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the lower energy bounds of the energy bins.
   The FITS column name is **ENERG_LO**.
   The recommended units are keV.

6. E_{high}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the upper energy bounds of the energy bins.
   The FITS column name is **ENERG_HI**.
   The recommended units are keV.

7. *RPSF*, a fixed-length REAL vector (array, each element within which is 4-byte) containing the *RPSF* measurement at each $R, \theta_{XMA}, \phi_{XMA}, E$ grid point.
   The FITS column name is **RPSF**.
   The order of data storage is $RPSF(R, \theta_{XMA}, \phi_{XMA}, E)$, where R & E represent the R_{low} and R_{high} E_{low} and E_{high} arrays respectively (see below).
   The recommended units are per square arcmin.

8. A_{wgt}, a fixed-length REAL vector (array, each element within which is 4-byte) containing an area weighting factor at each $R, \theta_{XMA}, \phi_{XMA}, E$ grid point.
   The FITS column name is **AREA_WGT**.
   The order of data storage is $A_{wgt}(R, \theta_{XMA}, \phi_{XMA}, E)$, where R & E represent the R_{low} and R_{high} E_{low} and E_{high} arrays respectively (see below).
   No units (dimensionless)

These are summarized in Table 1.

Points to Note & Conventions

- The ordering of the columns is of course arbitrary, however that used here is recommended.
- The rules and conventions concerning the energy grid (E_{low} & E_{high}) given in CAL/GEN/92-003 apply.
- An alternate spatial coordinate frame may be used, in which case
  - the values of the CSYS*nnn* keywords should be replaced by the appropriate string listed in CAL/GEN/92-003.

Table 1: Summary of the OGIP format for Radial PSFs (HDUVERS = 1.0.0).

Extension **to** *(filename).(ext)*

HDUCLASS: OGIP
HDUDOC: CAL/GEN/92-020
HDUVERS: 1.0.0
HDUCLAS1: RESPONSE
HDUCLAS2: RPRF
HDUCLAS3: *see text*
HDUCLAS4: *see text*
EXTNAME : RPSF (suggested, not required)
Description: Radial Point spread Function datasets (including errors, if required) as a function of radial angular distance from centroid, energy, off-axis & azimuthal angle.
An alternate spatial coordinate frame may also be used (see text).
Format: BINTABLE

column 1	2	3	4	5	6	7	8
contents							
Inner Radius	**Outer Radius**	**Off-axis angles**	**Azimuthal angles**	**Low energy bounds**	**High energy bounds**	**Radial PSF data**	**Area Weigthing**
R_{low}	R_{high}	θ_{XMA}	ϕ_{XMA}	E_{low}	E_{high}	$RPSF$	A_{wgt}
format of each column							
4-byte real array	4-byte real array	4-byte real array	4-byte real array	4-byte real array	4-byte real array	4-byte real array	4-byte real array
total number of elements per row							
i	i	j	k	m	m	$i \times j \times k \times m$	$i \times j \times k \times m$
column name							
RAD_LO	RAD_HI	THETA	PHI	ENERG_LO	ENERG_HI	RPSF	AREA_WGT

  - and/or (if necessary) the THETA & PHI column names replaced by more suitable alternatives if a different coordinate notation is employed. In this case the CSYSNAME keyword is mandatory and should give the column names used (see CAL/GEN/92-003).

  Spatial coordinate frames cannot be mixed within a given dataset.

- The parameter-space limitations on the dataset involving the following *pname* strings are recommended to be specified via the CBDn0001 keywords (see CAL/GEN/92-003):
  - *pname* = THETA - giving the range of off-axis angle for which the dataset is valid;
  - *pname* = PHI - giving the range of azimuthal angle for which the dataset is valid;

  (or corresponding alternate values of *pname* if a different coordinate notation is employed) along with any other limitations the authors of the dataset consider necessary.

- Datasets in which *RPSF* is independent of ϕ_{XMA} (or θ_{XMA}) should contain PHI = 0.0 (or THETA = 0.0) as a header keyword (or a corresponding alternate keyword if a different coordinate notation is employed).
- Alternative physical units are allowed for all columns of the table as long as they conform to the rules given in OGIP/93-001. The same is true for the physical units associated with the CBDn0001 keywords.
- The order of $RPSF(Rad, \theta_{XMA}, \phi_{XMA}, E)$ whereby the radial parameters change fastest, and the energy parameters slowest was chosen to facilitate access for the most common applications: interpolation in θ_{XMA}, ϕ_{XMA}-space of *RPSF* vs R_{low}, R_{high} arrays. This ordering is further confirmed by the value of the mandatory TDIM*nnn* keyword for this array (where $nnn = 7$ in the above example).
- An optional array containing the 1σ statistical error associated with each element of *RPSF* (if required) should be contained in an additional column named **RPSF_ERR**.

2.3 The Radial PSF Extension (HDUVERS = '2.0.0')

Description:
One file for each telescope/instrument combination containing a single BINTABLE FITS extension.

THIS SECTION HAS BEEN REMOVED *since the format is yet to be officially released*

This format was designed primarily with GO datasets in mind, though (accepting the limitations given above) can be used for calibration datasets.

3 REEF Data File Formats

The HEASARC FITS Working Group (HFWG) Header-Data Unit (HDU) keywords and values for this type of dataset are:

- `HDUCLASS = 'OGIP'`
  - the name of the organization that defined this file format.
- `HDUDOC   = 'CAL/GEN/92-020'`
  - the name of the document describing the format (*ie* this document)
- `HDUCLAS`n
  - giving the HDUCLAS hierarchy for this format.
  - `HDUCLAS1 = 'RESPONSE'`
  - `HDUCLAS2 = 'REEF'`
  - `HDUCLAS3 =` (*see below*)
  - `HDUCLAS4 =` (*see below*)

These are valid for all datasets described in this section, and should be present in the **header of the extension** containing the *REEF* dataset.

3.1 Summary of REEF file formats versions

The following versions of file formats for a *REEF* dataset have been defined:

- `HDUVERS  = '1.0.0'` (Section 3.2)
  This format is currently still **VALID**.
  It was designed primarily for calibration datasets, but can be used for GO datasets.

3.2 The Radial Encircled Energy Fraction Extension (HDUVERS = '1.0.0')

Description:
One file for each telescope/instrument combination containing a single BINTABLE FITS extension. The BINTABLE only has a single row, using arrays for the 8 necessary columns.

Note: this format was formally known as REEFVERS = '1992a', and is still occasionally refered to as such.

Extension Header
Beyond the standard FITS keywords required, and the HDU keywords/values given in Section 3, the following keywords/values are mandatory:

- `TELESCOP` - the name of the satellite/mission.
  Allowed values are given in CAL/GEN/92-011.
- `INSTRUME` - the name of the telescope mirror/detector assembly.
  Allowed values are given in CAL/GEN/92-011.
- `HDUVERS  = '1.0.0'` - giving the version of the format.
- `HDUCLAS3` - further describing the scientific content of the dataset, specifically regarding the origin of the dataset. The allowed values are:
  - `HDUCLAS3 = 'OBSERVED'` - indicating the *RPSF* dataset has been generated from an observational dataset.
  - `HDUCLAS3 = 'PREDICTED'` - indicating the *RPSF* has been generated using a theoretical model.
- `HDUCLAS4` - further describing the scientific content of the dataset, specifically regarding the contents of the dataset. The allowed values are:
  - `HDUCLAS4 = 'TOTAL'` - indicating the *RPSF* dataset includes counts from the 'source' as well as any counts from the 'background'
  - `HDUCLAS4 = 'NET'` - indicating the *RPSF* dataset has been background-subtracted
- `TDIM`*nnn* - the number of elements and ordering (see CAL/GEN/92-003) of each multi-dimensional array.
  Only the `REEF` & `AREA_WGT` columns here (with *nnn* = 7,8 in the example below).
- *i*`CTYP`*nnn* - The axis labels for dimension i ($i = 1, 2, 3, 4$) of the `REEF` & `AREA_WGT` columns. In the example given below, *nnn* = 7 & 8 respectively, and
  - `1CTYP7  = 'SPATIAL_OFFSET'`
  - `2CTYP7  = 'COORD-1'`
  - `3CTYP7  = 'COORD-2'`
  - `4CTYP7  = 'ENERGY'`
  - `1CTYP8  = 'SPATIAL_OFFSET'`

  - `2CTYP8  = 'COORD-1'`
  - `3CTYP8  = 'COORD-2'`
  - `4CTYP8  = 'ENERGY'`

  (see CAL/GEN/92-003 for further details).

- `CREF`*nnn* = The column referencing keyword for each multi-dimensional array.
  Only the `REEF` & `AREA_WGT` columns here (with *nnn*=7 & 8 in the example below) giving:
  - `CREF7    = '(RAD_LO:RAD_HI,THETA,PHI,ENERG_LO:ENERG_HI)'`
  - `CREF8    = '(RAD_LO:RAD_HI,THETA,PHI,ENERG_LO:ENERG_HI)'`

  in the example below.

- `CSYSNAME` - the spatial coordinate system in use
  Allowed values are given in CAL/GEN/92-003.
  (`CSYSNAME = 'XMA_POL'` is assumed in the example below)
- `PIXSIZE` - the angular size of (one side) of the pixels in units of decimal degrees.
- `BACKGRND` - the background count rate in units of counts per pixel (where the pixel size is definded by `PIXSIZ`). If no underlying instrument or cosmic background is expected, then a value of zero should be entered.
- `ENERG_LO` - the minimum energy (in keV) for which the the *REEF* dataset was constructed or is valid. The value `-99.0` indicates that the value is unknown.
- `ENERG_HI` - the maximum energy (in keV) for which the the *REEF* dataset was constructed or is valid. The value `-99.0` indicates that the value is unknown.
- `CHANMIN` - the minimum detector channel number for which the the *REEF* dataset was constructed or is valid. The value `-99.0` indicates that the value is unknown.
- `CHANMAX` - the maximum detector channel number for which the the *REEF* dataset was constructed or is valid. The value `-99.0` indicates that the value is unknown.
- `CHANTYPE` - the type of detector channels `CHANMIN` & `CHANMAX` are expressed in, with the allowed values:
  - `CHANTYPE = 'PHA'` - for 'raw' detector channels
  - `CHANTYPE = 'PI'` - for (corrected) 'Pulse Invariant' detector channels

and the following keywords/values are mandatory for CIF purposes **ONLY** if the dataset is ever to be included as a calibration file within the HEASARC caldb (see CAL/GEN/92-011):

- `CCLS0001` - the OGIP class of this calibration file, with allowed values:
  - `CCLS0001 = 'BCF'` - for Basic Calibration datasets

  - `CCLS0001 = 'CPF'` - for Calibration Product datasets
- `CDTP0001` - the OGIP class of the data type, with allowed values:
  - `CDTP0001 = 'DATA'` - for 'true' datasets
  - `CDTP0001 = 'TASK'` - for 'virtual' calibration datasets
- `CCNM0001 = 'REEF'` - the OGIP codename for the contents
- CBDn0001 - the parameter-space limitations of the dataset (see below)
- `CVSD0001` - calibration validity start date
- `CVST0001` - calibration validity start time
- `CDES0001` - a descriptive string of the calibration dataset

and the following mandatory to supply further information:

- `REEFVERS = '1992a'` - the OGIP version of the FITS format in use

Data Format:
The data within the extension is organised as a BINTABLE with the following columns:

1. R_{low}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the lower radial bounds of the annular bins as measured from the nominal point of focus.
   The FITS column name is **RAD_LO**.
   The recommended units are arcmin.
2. R_{high}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the upper radial bounds of the annular bins as measured from the nominal point of focus.
   The FITS column name is **RAD_HI**.
   The recommended units are arcmin.
3. θ_{XMA}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the off-axis angles.
   The FITS column name is **THETA** (but see below).
   The recommended units are arcmin.
4. ϕ_{XMA}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the azimuthal angles.
   The FITS column name is **PHI** (but see below).
   The recommended units are arcmin.
5. E_{low}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the lower energy bounds of the energy bins.
   The FITS column name is **ENERG_LO**.
   The recommended units are keV.

6. E_{high}, a fixed-length REAL vector (array, each element within which is 4-byte) containing the upper energy bounds of the energy bins.
   The FITS column name is **ENERG_HI**.
   The recommended units are keV.

7. *REEF*, a fixed-length REAL vector (array, each element within which is 4-byte) containing the *REEF* measurement at each $R, \theta_{XMA}, \phi_{XMA}, E$ grid point.
   The FITS column name is **REEF**.
   The order of data storage is $REEF(R, \theta_{XMA}, \phi_{XMA}, E)$, where R & E represent the R_{low} and R_{high} E_{low} and E_{high} arrays respectively (see below).
   No units (dimensionless)

8. A_{wgt}, a fixed-length REAL vector (array, each element within which is 4-byte) containing an area weighting factor at each $R, \theta_{XMA}, \phi_{XMA}, E$ grid point.
   The FITS column name is **AREA_WGT**.
   The order of data storage is $A_{wgt}(R, \theta_{XMA}, \phi_{XMA}, E)$, where R & E represent the R_{low} and R_{high} E_{low} and E_{high} arrays respectively (see below).
   No units (dimensionless)

These are summarized in Table 2.

Points to Note & Conventions

- The ordering of the columns is of course arbitrary, however that used here is recommended.
- The rules and conventions concerning the energy grid (E_{low} & E_{high}) given in CAL/GEN/92-003 apply.
- An alternate spatial coordinate frame may be used, in which case
  - the values of the CSYS*nnn* keywords should be replaced by the appropriate string listed in CAL/GEN/92-003.
  - and/or (if necessary) the THETA & PHI column names replaced by more suitable alternatives if a different coordinate notation is employed. In this case the CSYSNAME keyword is mandatory and should give the column names used (see CAL/GEN/92-003).

  Spatial coordinate frames cannot be mixed within a given dataset.
- The parameter-space limitations on the dataset involving the following *pname* strings are recommended to be specified via the CBD*n*0001 keywords (see CAL/GEN/92-003):
  - *pname* = THETA - giving the range of off-axis angle for which the dataset is valid;
  - *pname* = PHI - giving the range of azimuthal angle for which the dataset is valid;

  (or corresponding alternate values of *pname* if a different coordinate notation is employed) along with any other limitations the authors of the dataset consider necessary.

Table 2: Summary of the OGIP format for Radial EEFs (REEFVERS = 1992a).

Extension **to** *(filename).(ext)*

HDUCLASS: OGIP
HDUDOC: CAL/GEN/92-020
HDUVERS: 1.0.0
HDUCLAS1: RESPONSE
HDUCLAS2: REEF
HDUCLAS3: *see text*
HDUCLAS4: *see text*
EXTNAME : REEF (suggested, not required)
Description: Radial Encircled Energy Function datasets (including errors, if required) as a function of radial angular distance from centroid, energy, off-axis & azimuthal angle.
An alternate spatial coordinate frame may also be used (see text).
Format: BINTABLE

column 1	2	3	4	5	6	7	8
contents							
Inner Radius	**Outer Radius**	**Off-axis angles**	**Azimuthal angles**	**Low energy bounds**	**High energy bounds**	**Radial PSF data**	**Area Weighting**
R_{low}	R_{high}	θ_{XMA}	ϕ_{XMA}	E_{low}	E_{high}	*REEF*	A_{wgt}
format of each column							
4-byte real array	4-byte real array	4-byte real array	4-byte real array	4-byte real array	4-byte real array	4-byte real array	4-byte real array
total number of elements per row							
i	i	j	k	m	m	$i \times j \times k \times m$	$i \times j \times k \times m$
column name							
RAD_LO	RAD_HI	THETA	PHI	ENERG_LO	ENERG_HI	REEF	AREA_WGT

- Datasets in which *REEF* is independent of ϕ_{XMA} (or θ_{XMA}) should contain PHI = 0.0 (or THETA = 0.0) as a header keyword (or a corresponding alternate keyword if a different coordinate notation is employed).

- Alternative physical units are allowed for all columns of the table as long as they conform to the rules given in OGIP/93-001. The same is true for the physical units associated with the CBD*n*0001 keywords.

- The order of $REEF(Rad, \theta_{XMA}, \phi_{XMA}, E)$ whereby the radial parameters change fastest, and the energy parameters slowest was chosen to facilitate access for the most common applications: interpolation in θ_{XMA}, ϕ_{XMA}-space of *RPSF* vs R_{low}, R_{high} arrays. This ordering is further confirmed by the value of the mandatory TDIM*nnn* keyword for this array (where $nnn = 7$ in the above example).

- An optional array containing the 1σ statistical error associated with each element of *RPSF* (if required) should be contained in an additional column named **REEF_ERR**.

4 Virtual File Formats & Allowed Standalone Tasks

Standalone tasks to perform the following tasks are currently allowed:

- Calculate the Radial Point Spread Function, $RPSF(R, \theta_{XMA}, \phi_{XMA}, E)$ as a function of radius from the nominal point of focus (R), for a given off-axis position θ_{XMA},ϕ_{XMA} and (range of) photon energy (E).
  Output:
  The format of the o/p file should be one of the allowed data formats given in Section 2.
  Notes:
  None
- Calculate the Radial Encircled Energy Fraction, $REEF(R, \theta_{XMA}, \phi_{XMA}, E)$ as a function of radius from the nominal point of focus (R), for a given off-axis position θ_{XMA},ϕ_{XMA} and (range of) photon energy (E).
  Output:
  The format of the o/p file should be one of the allowed data formats given in Section 3.
  Notes:
  None

4.1 VCF Requirements

Description:
See CAL/GEN/92-003 & CAL/GEN/92-013. *Extension Header*
Beyond the standard FITS keywords required, the following keywords/values are mandatory:

- `CSYS`*nnn* - the spatial coordinate system used by the standalone task

along (if desired) with those keywords/values mandatory for CIF purposes as given in within the appropriate sub-section of Sections 2 & 3, with the exception of:

- `CDTP0001` (=TASK) - the OGIP class of the data type

plus those required for all virtual files listed in CAL/GEN/92-013, and the following mandatory keyword to supply further information:

- `VIRVERSN` - the OGIP version of the virtual FITS format in use (in this case 1992a)

Data Format:
See CAL/GEN/92-003 amd CAL/GEN/92-013. The number and type of parameters specified depends solely on the requirements of the associated standalone task.

5 Related Software

The following list of subroutines/tasks are available:

- FORTRAN subroutine `wt???.f` (callib)
  writes an RPSFVERS = 1992a dataset (Section 2.2)

6 Example FITS headers

Here we give an example of keywords used in files currently within the CALDB.

6.1 *ROSAT*

Example 1

WARNING: This dataset has a number of keywords missing.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                  200 / width of table in bytes
NAXIS2  =                    1 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    5 / number of fields in each row
TTYPE1  = 'RAD_LO  '           / label for field   1
TFORM1  = '10E     '           / data format of the field: 4-byte REAL
TUNIT1  = 'arcmin  '           / physical unit of field
TTYPE2  = 'RAD_HI  '           / label for field   2
TFORM2  = '10E     '           / data format of the field: 4-byte REAL
TUNIT2  = 'arcmin  '           / physical unit of field
TTYPE3  = 'RPSF    '           / label for field   3
TFORM3  = '10E     '           / data format of the field: 4-byte REAL
TUNIT3  = 'count/arcmin**2'    / physical unit of field
TTYPE4  = 'RPSF_ERR'           / label for field   4
TFORM4  = '10E     '           / data format of the field: 4-byte REAL
TUNIT4  = 'count/arcmin**2'    / physical unit of field
TTYPE5  = 'AREA_WGT'           / label for field   5
TFORM5  = '10E     '           / data format of the field: 4-byte REAL
EXTNAME = 'OBS RPSF'           / name of this binary table extension
TDIM1   = '(10)    '           /  Column dimension
TDIM2   = '(10)    '           /  Column dimension
TDIM3   = '(10,1,1)'           /  Column dimension
TDIM4   = '(10,1,1)'           /  Column dimension
TDIM5   = '(10,1,1)'           /  Column dimension
TELESCOP= 'ROSAT   '           / Name of Mission/Telescope
INSTRUME= 'PSPCB   '           / Name of Instrument/Detector
HDUCLASS= 'OGIP    '           / format conforms to OGIP standard
HDUCLAS1= 'RESPONSE'           / dataset is a response function
HDUCLAS2= 'RPRF    '           / dataset is a radial point response function
```

```
HDUCLAS3= 'NET     '           / Source only radial point spread function
HDUVERS1= '1.0.0   '           / Version of family of formats
HDUVERS2= '1.0.1   '           / Version of format
RPSFVER = '1993a   '           / OGIP FITS format version
THETA_LO=      -9.90000000E+01 / Value not defined
THETA_HI=      -9.90000000E+01 / Value not defined
ENERG_LO=      -9.90000000E+01 / Value not defined
ENERG_HI=      -9.90000000E+01 / Value not defined
DATE    = '14/04/94'           / FITS file creation date (dd/mm/yy)
HISTORY   ST2RPSF converts from STW -> RPSF format
HISTORY   STW FILE : pros2_3b_cnt.fits
HISTORY   EXTENSION WRITTEN BY WTRPF1 Ver 1.0.1
CREATOR = 'ST2RPSF 1.0.5'      / s/w task which wrote this dataset
PIXSIZE =           1.3889E-04 / In decimal degrees
BACKGRND=       0.00000000E+00 / In counts per pixel
CHANMIN =                   20 / Minimum PI channel for image
CHANMAX =                  100 / Maximum PI channel for image
SUMRCTS =         1.496935E+04 / Sum of raw counts
END
```

Example 2

WARNING: This dataset has a number of keywords missing.

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                  120 / width of table in bytes
NAXIS2  =                    1 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    5 / number of fields in each row
TTYPE1  = 'RAD_LO  '           / label for field   1
TFORM1  = '6E      '           / data format of the field: 4-byte REAL
TUNIT1  = 'arcmin  '           / physical unit of field
TTYPE2  = 'RAD_HI  '           / label for field   2
TFORM2  = '6E      '           / data format of the field: 4-byte REAL
TUNIT2  = 'arcmin  '           / physical unit of field
TTYPE3  = 'RPSF    '           / label for field   3
TFORM3  = '6E      '           / data format of the field: 4-byte REAL
TUNIT3  = 'count/arcmin**2'    / physical unit of field
TTYPE4  = 'RPSF_ERR'           / label for field   4
TFORM4  = '6E      '           / data format of the field: 4-byte REAL
TUNIT4  = 'count/arcmin**2'    / physical unit of field
TTYPE5  = 'AREA_WGT'           / label for field   5
```

```
TFORM5  = '6E      '           / data format of the field: 4-byte REAL
EXTNAME = 'OBS RPSF'           / name of this binary table extension
TDIM1   = '(6)     '           /  Column dimension
TDIM2   = '(6)     '           /  Column dimension
TDIM3   = '(6,1,1) '           /  Column dimension
TDIM4   = '(6,1,1) '           /  Column dimension
TDIM5   = '(6,1,1) '           /  Column dimension
TELESCOP= 'ROSAT   '           / Name of Mission/Telescope
INSTRUME= 'PSPCB   '           / Name of Instrument/Detector
HDUCLASS= 'OGIP    '           / format conforms to OGIP standard
HDUCLAS1= 'RESPONSE'           / dataset is a response function
HDUCLAS2= 'RPRF    '           / dataset is a radial point response function
HDUCLAS3= 'NET     '           / Source only radial point spread function
HDUVERS1= '1.0.0   '           / Version of family of formats
HDUVERS2= '1.0.1   '           / Version of format
RPSFVER = '1993a   '           / OGIP FITS format version
THETA_LO=      -9.90000000E+01 / Value not defined
THETA_HI=      -9.90000000E+01 / Value not defined
ENERG_LO=      -9.90000000E+01 / Value not defined
ENERG_HI=      -9.90000000E+01 / Value not defined
DATE    = '18/10/94'           / FITS file creation date (dd/mm/yy)
HISTORY   EXTENSION WRITTEN BY WTRPF1 Ver 1.0.1
COMMENT   DATA OBTAINED FROM RADIAL PROFILE : pros2_3b_cnt.st
COMMENT   THE RADIAL PROFILE DATA IS REBINNED
COMMENT   USING (USER DEFINED) MINIMUM COUNTS/BIN :    20.
COMMENT   LAST BIN CONTAINS LESS THAN MINUMUM COUNTS/BIN
COMMENT   WARNING : INPUT DATASET CONTAINS NEGATIVE COUNTS
PIXSIZE =         1.388900E-04 / pixelsize in deg
BACKGRND=         0.000000E+00 / Background count rate in cts/pixel
CHANMIN =                   10 / Minimum PI channel for image
CHANMAX =                  200 / Maximum PI channel for image
SUMRCTS =         1.496935E+04 / Sum of raw counts
CREATOR = 'RBNRPSF 1.1.1'      / s/w task which wrote this dataset
END
```

6.2 *ASCA*

Example 1

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =               733064 / width of table in bytes
NAXIS2  =                    1 / number of rows in table
```

```
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    7 / number of fields in each row
TTYPE1  = 'RAD_LO  '           / label for field   1
TFORM1  = '502E    '           / data format of the field: 4-byte REAL
TUNIT1  = 'arcmin  '           / physical unit of field
TTYPE2  = 'RAD_HI  '           / label for field   2
TFORM2  = '502E    '           / data format of the field: 4-byte REAL
TUNIT2  = 'arcmin  '           / physical unit of field
TTYPE3  = 'THETA   '           / label for field   3
TFORM3  = '11E     '           / data format of the field: 4-byte REAL
TUNIT3  = 'arcmin  '           / physical unit of field
TTYPE4  = 'PHI     '           / label for field   4
TFORM4  = '3E      '           / data format of the field: 4-byte REAL
TUNIT4  = 'deg     '           / physical unit of field
TTYPE5  = 'ENERG_LO'           / label for field   5
TFORM5  = '11E     '           / data format of the field: 4-byte REAL
TUNIT5  = 'keV     '           / physical unit of field
TTYPE6  = 'ENERG_HI'           / label for field   6
TFORM6  = '11E     '           / data format of the field: 4-byte REAL
TUNIT6  = 'keV     '           / physical unit of field
TTYPE7  = 'RPSF    '           / label for field   7
TFORM7  = '182226E '           / data format of the field: 4-byte REAL
TUNIT7  = '        '           / physical unit of field
EXTNAME = 'ASCA_PSF'           / name of this binary table extension
TDIM7   = '(502,11,3,11)'      /  Column dimension
1CTYP7  = 'SPATIAL_OFFSET'     /  Axis label
2CTYP7  = 'COORD-1 '           /  Axis label
3CTYP7  = 'COORD-2 '           /  Axis label
4CTYP7  = 'ENERGY  '           /  Axis label
CREF7   = '(RAD_LO:RAD_HI,THETA,PHI,ENERG_LO:ENERG_HI)' /  Column referencing
TELESCOP= 'ASCA    '           / Name of Mission/Telescope
CSYSNAME= 'XMA_POL '           / The spatial coordinate system in use
PIXSIZE =       8.18500004E-04 / The pixel size in decimal degrees
BACKGRND=       0.00000000E+00 / The background count rate in counts/pixe
SUMRCTS =                  1.0 / Sum of counts within a 6 arcmin radius
INSTRUME= 'XRT     '           / Name of Instrument/Detector
HDUCLASS= 'OGIP    '           / format conforms to OGIP standard
HDUCLAS1= 'RESPONSE'           / dataset is a response function
HDUCLAS2= 'RPRF    '           / dataset is a radial point response function
HDUCLAS3= 'PREDICTED'          / Predicted (theoretical) dataset
HDUCLAS4= 'NET     '           / Source only radial point spread function
HDUVERS1= '1.0.0   '           / Version of family of formats
HDUVERS2= '1.0.1   '           / Version of format
AREA_WGT=       1.00000000E+00 / Area Weighting Factor
DATE    = '19/09/95'           / FITS file creation date (dd/mm/yy)
```

```
HISTORY   EXTENSION WRITTEN BY WTRPF1 Ver 1.1.0
HDUDOC  = 'CAL/GEN/92-020'     / OGIP memo for File Format definition
RPSFVERS= '1992a   '           / OGIP FITS format version
CCLS0001= 'BCF     '           / OGIP class for this dataset
CCNM0001= 'RPSF    '           / OGIP codename for this dataset
CDTP0001= 'DATA    '           / OGIP datatype for this dataset
CVSD0001= '20/02/93'           / Date when data becomes valid
CVST0001= '02:00:00'           / Time when data becomes valid
CDES0001= 'XRT Radial Point-Spread-Function dataset from Nagoya ray-tracing' /
CBD10001= 'THETA(0,25)arcmin'  /
CBD20001= 'PHI(0,45)deg'       /
CBD30001= 'ENERG(1,10)keV'     /
END
```

REFERENCES

Information regarding on-line versions of any of the following references with an OGIP Memo number (*ie* documents starting `OGIP/..` or `CAL/..`) can most easily be found via the WorldWide Web by following the links from the URL:
`/docs/heasarc/caldb/caldb_docs_index.html`

Most OGIP Calibration Memos of general community interest will eventually appear as articles in *Legacy*, but are also available on request from The Office of Guest Investigator Programs, Code 668, NASA/GSFC, Greenbelt, MD 20771, USA.

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