Calibration of the ROSAT HRI Spectral Response

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Spectral Calibration of the ROSAT HRI

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1 Introduction

The ROSAT High Resolution Imager has a limited (2-band) spectral response. This spectral capability can give X-ray hardness ratios on spatial scales of 5 arcseconds. The spectral response of the center of the detector was calibrated before the launch of ROSAT, but the gain decreases with time and also is a function of position on the detector. To complicate matters further, the satellite is "wobbled", possibly moving a source across several spatial gain states. These difficulties have prevented the spectral response of the ROSAT HRI from being used for scientific measurements. We have used Bright Earth data and in-flight calibration sources to map the spatial and temporal gain changes, and written software which will allow ROSAT users to generate a calibrated XSPEC response matrix and hence determine a calibrated hardness ratio. In this report, we describe the calibration procedure and show how to obtain a response matrix. In Section 2 we give an overview of the calibration procedure, in Section 3 we give a summary of HRI spatial and temporal gain variations. Section 4 describes the routines used to determine the gain distribution of a source. In Sections 5 and 6, we describe in detail how the Bright Earth database and calibration sources are used to derive a corrected response matrix for a given observation. Finally, Section 7 describes how to use the software.

2 Overview of Calibration Procedure

The goal of the calibration procedure is to produce a response matrix valid for a given observation. We assume that the response matrix derived from the ground calibration measurements is valid throughout the mission and for all regions of the detector *except that the gain has changed.* ie. we assume that the redistribution matrix (the probability that a photon of a particular energy will fall in a given channel) is constant. The problem then reduces to shifting the ground based response matrix in channel space to match the gain of the observation.

The gain is derived from Bright Earth (BE) data. The Bright Earth is dominated by scattered solar X-rays at 525 eV, and is effectively a monochromatic flat-field. BE data has been routinely obtained throughout the mission. Hence the BE data can be used to monitor the gain, both as a function of time and position on the detector, by determining the PHA channel corresponding to the maximum of the BE distribution (the "BE gain"). The relationship between the BE gain and the response matrix shift (ie. the number of PHA channels the ground-based response matrix is shifted) is determined from calibration sources. The PHA distribution of sources with known (from ROSAT PSPC) spectra were fit within XSPEC, changing the gain of the response matrix until the χ^2 is minimised. This shift (in channels) is then plotted against the BE gain (Figures 2 and 3) to give a linear "response matrix shift-BE gain" relationship.

The steps to acquiring a calibrated response matrix are as follows. Determine the BE gain of the source, use the linear relationship in Figures 2 and 3 to calculate the response matrix shift, and create the appropriate response matrix. This is complicated by the wobble, whereby a source may be moved over regions of the detector with different BE gain. In this case, a single response matrix is not appropriate. This problem is solved by de-aspecting and calculating the number of gain states a source experiences during an observation. A response matrix is then created from the mean gain, or constructed from the time-average of several gain states.

3 ROSAT HRI gain variations

The variations in gain can be seen from ground-based and in-flight calibration observations. The change in gain across the detector surface is shown in Figure 17 of the HRI Calibration Report (David *et al.* 1995). This map was produced from flat-field observations from six different energies spanning 0.18 to 1.74 keV. The temporal gain variation is monitored from on-axis monthly observations of the supernova remnant N132D (Figure 1; http://hea-www.harvard.edu/rosat/rsdc_www/hri_status.html). To a first-order approximation, the mean pulse height channel decreases 0.5 channels/year. To compensate for this decline, the gain of the instrument was increased in June of 1994. This restored the pulse height distribution to the position in channel space as seen right after launch. Further changes in the High Voltage level were implemented in March and May 1997 (see Table 2).

4 The XGAIN program

The XGAIN program evaluates the gain distribution for a source, using the basic events file and the aspect solution. The position of the source must be provided by the user in sky pixel coordinates; extended sources may also be handled, by providing a file containing a list of pixels to be averaged over. The basic problem is that as the ROSAT satellite wobbles, a given source illuminates different parts of the detector, with different gain values. The program derives a time weighted histogram of these values, with a resolution specified by the user. The overall mean gain is also returned.

For each record in the aspect solution whose time lies within the Good Time Intervals of the events file, we take the sky coordinates of the source and de-apply the aspect transformation to obtain the linearized detector coordinates. This calculation requires the nominal pointing direction and the pixel size, which are read from the header of the events table. We note here the important differences between Rev0 and RDF format for both the aspect solution file and the events file. In particular, the Rev0 archival data stores its aspect information as offsets from the nominal direction, in multiple tables which must be concatenated. The RDF archival data stores the aspect solu-

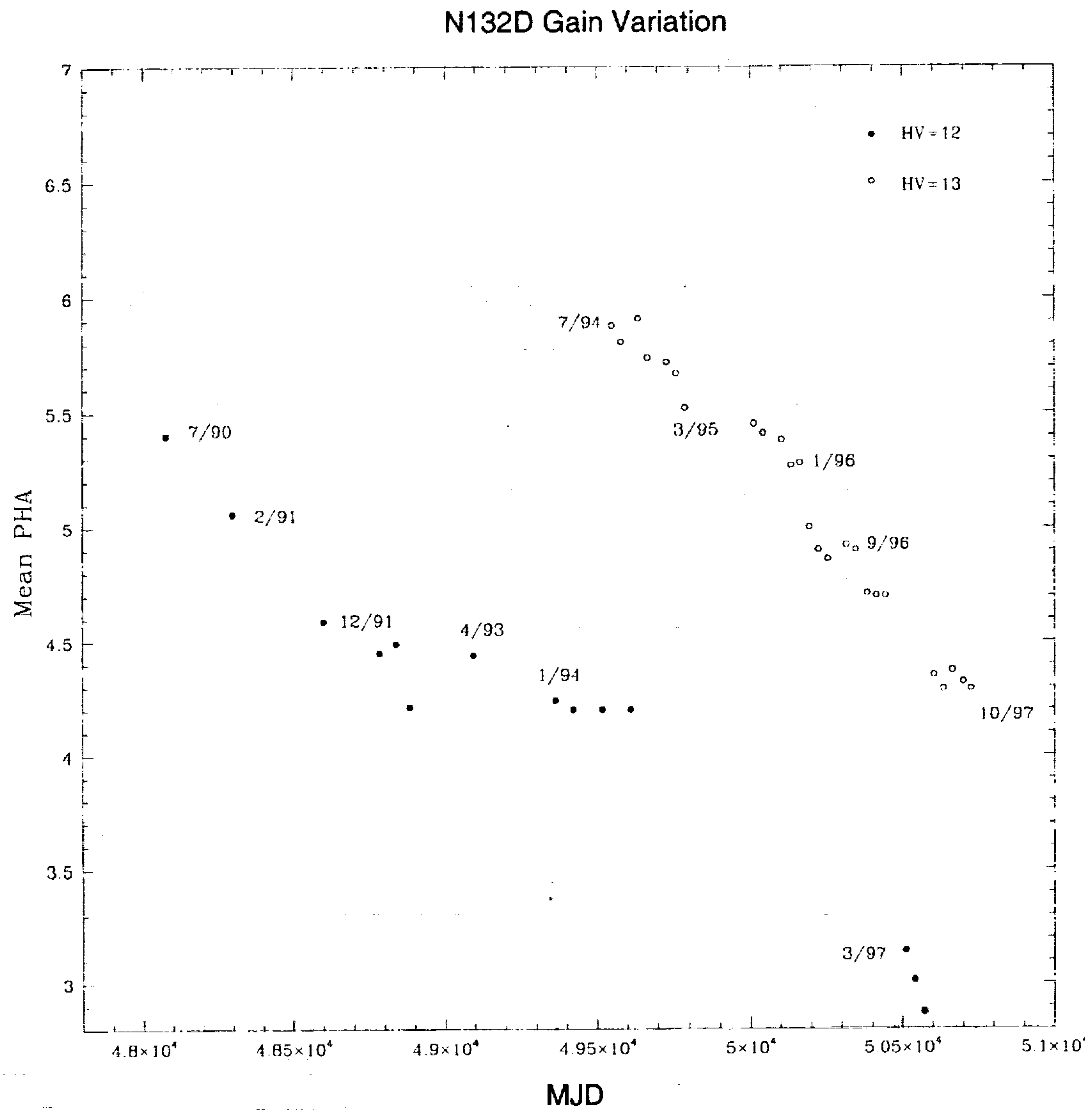

Figure 1: Temporal gain monitoring of the ROSAT HRI using monthly on-axis observations of N132D. The discontinuities in the graph show the high voltage changes in June of 1994, April of 1997 and December of 1997.

tion as absolute pointing directions in a single table. The XGAIN program handles these different formats, at some cost to the complexity of the user interface.

The gain calibration file (gain.fits) contains a sequence of low (2 arcmin) resolution maps of the spatial gain variation on the detector, time-tagged with the Modified Julian Date (MJD). Each gain map pixel corresponds to 256 x 256 full resolution detector pixels. XGAIN will linearly interpolate in time and position to obtain the gain value appropriate for the time of the aspect interval and the calculated detector position. (Since the time interpolation is done repeatedly rather than once per observation, the program will work correctly for combined observation intervals spanning a long period; the extra computation is a small overhead). An optional ASCII 'steps calibration file' gives the MJD dates of discontinuities in the detector gain (for instance because of commanded high voltage changes); XGAIN will avoid interpolating across such boundaries.

The program prints a summary of results to the screen and writes the results to a FITS binary table file suitable for further processing. On the screen, only the nonzero elements of the histogram are displayed, while in the FITS table there is one row for each histogram bin. The three columns written out are the bin center gain value, the relative weight of the bin, and the total time exposure on that bin in seconds. The mean gain is written to the header parameter AVG_GAIN. For the case of a single pixel source, the screen output also includes, for each gain bin, the time filters which could be applied to the events file to get data only in that bin, if the filter is simple enough to be conveniently printed. This information is not, however, written to the FITS file.

The program, written in ANSI C and ported to a variety of Unix machines, uses the SAO IRAF-style parameter interface and the CFITSIO library. The full list of parameters is given in Table 1. The EVENTS, ASPECT, OUTFILE, MAPS and STEPS parameters specify the various data files used by the program.

Due to the wobble of the satellite, photon events are recorded over a 5 arcmin path on the detector. This wobbled path can encompass areas on the detector with varying gain levels. Gain levels for an observation can span as much as one channel.

The program will attempt to guess the data format from the name of the aspect file; if it ends in '.ao' it is a Rev0 dataset, otherwise it is an RDF dataset; however, the MODE parameter may be used to override this guess. If MODE is RDF, the event list table name is assumed to be STDEVT, otherwise it is assumed to be EVENTS. The MODE parameter is also used to decide whether the data in the aspect solution are offsets or absolute aspect.

ASPCOLS is the trickiest parameter; unfortunately different versions of the REV0 aspect data have used different column names in the aspect table. To help XGAIN out, we provide it with the names of the columns containing time, RA, Dec and the roll angle. The example values given above are for RDF data; for REV0 you may check the values in your actual data using any FITS printing software, although "TIME,XOFF,YOFF,ROFF" is a common example.

If the POS parameter is not blank, it is assumed to be the name of an ASCII file containing a list of pixel X,Y pairs, one pair per line for extended sources. Otherwise, the source position is read from the XPOS and YPOS parameters.

The three values read by the gain histogram binning parameter GHIST are the center gain value for the lowest bin, the center gain value for the highest bin, and the bin size.

The boresight offsets, BSO are a correction applied to the aspect solution; unfortunately, they are not stored in a consistent way in the ROSAT aspect solution files. The three numbers required are pixel offsets in the X and Y detector axes and a roll offset in degrees. We recommend the default values be used unless you are an expert on the ROSAT aspect solution.

5 Bright Earth Database

Bright Earth data has been obtained throughout the lifetime of the ROSAT mission. Bright Earth observations spanning approximately two week segments were coadded to produce N ($\sim$ 32) maps. Each map is binned to produce 32 arcsec pixels. In each spatial bin, the PHA spectrum was ex-

Table 1: XGAIN parameters

Parameter	Example value	Meaning
EVENTS	bas.fits	Events (Basic) FITS file name
ASPECT	anc.fits	Aspect (ANC or AO) FITS file name
OUTFILE	xgain.fits	Output FITS file name
MAPS	gain.fits[RHRI_GAIN]	Gain map file and FITS binary table name
STEPS	hv.dat	Gain discontinuities table
ASPCOLS	TIME,RA_SC,DEC_SC,ROAN_SC	Names of columns in aspect file
MODE	RDF	Type of data
XPOS	4096.0	X sky pixel position
YPOS	4097.0	Y sky pixel position
POS		ASCII pixel list file
GHIST	3.0,7.0,0.05	Gain histogram binning
BSO	48.0,40.0,0.0	Boresight offsets

tracted and fitted with a Pearson function with an exponential tail. The Bright Earth Gain (BE gain) is assigned the value of the mean from fitted pulse height distibution. This value typically ranges from pulse height channel 3 to 8. The end result of this Brigh Earth "build" is therefore a $32 \times 32 \times 32$ data cube, with BE gain as a function of time during the mission and position on the detector. The data cube is stored as a single FITS file. This file is updated periodically and is included in this distribution. The FITS file is used by the program 'xgain' to determine the gain state histogram.

To acquire a gain state from the bright earth build, an interpolation occurs according to the two submaps with time signatures immediately before and after the observation time. A gain value is derived from the functional form for the spatial variation of the gain for each of the submaps and then averaged to find the gain at the time of the observation. Discontinuities in the gain curve exist for changes in the high voltage level (HV) for the instrument. These gain shifts are evident in Figure 1. Observation times for sources near these HV changes will be extrapolated to produce an accurate gain level since the gain near these transitions will reflect an average of the two states. Table 2 lists the times of the HV changes during the ROSAT lifetime.

Table 2: HRI Gain History

Begin date	End date	High Voltage Level (HV)
Launch	June 21, 1994 8:59 GMT	12
June 21, 1994 8:59 GMT	March 3, 1997	13
March 3, 1997	May 6, 1997 12:40 UT	12
May 6, 1997 12:40 UT	December 1997	13
December 1997	——	14

Table 3: Calibration Sources

Object	Number of Observations	Spectral Model	Gal. N_H (10^{22} cm^{-2})	Temp (keV)	Photon Index
HZ43	29	BB	–	0.02	–
AR LAC	12	ABS×RS×PL	–	0.88	1.52
LMC X−1	25	ABS×PL	0.68	–	1.24
N132D	3	ABS×RS×RS×RS	0.38	1.10×10^{-2}; 0.18; 0.79	–
EPS_ERI	1	RS×RS	–	0.20; 0.77	–
61_CYG_AB	1	RS×RS	–	8.02×10^{-2}; 0.40	–
70_OPH	1	RS×RS	–	0.11; 0.55	–

Notes:
- A cosmic abundance of 100% is used for each Raymond-Smith model.

6 The response matrix shift vs. gain relation

As described in Section 2, the displacement of the PHA distribution of an observation from prelaunch conditions can be compensated by shifting the (ground-based) spectral response matrix accordingly. Calibration sources have been analyzed to quantify the relationship between the response matrix shift and the bright earth gain state. The calibration sources are listed in Table 3. The PHA distribution of each calibration observation was fitted (in XSPEC) with a spectral model derived from PSPC observations, initially using the ground-based (unshifted) response matrix. The normalization was the only free parameter, and a minimum χ^2 derived. This procedure was repeated using response matrices shifted in channel space (generated using the FTOOL "gcorrmf"). Multiple response matrices were used with incremental shifts of one-tenth of a channel. These matrices covered the whole range of possible shifts between -1 and +4. This best fit incremental shift was recorded. The corresponding gain state was determined from the bright earth data for this detection position and observation time. From 72 calibration observations, a direct correlation has been shown to exist between the channel shift of the response matrix and bright earth mean PHA channel (Figure 2 and 3).

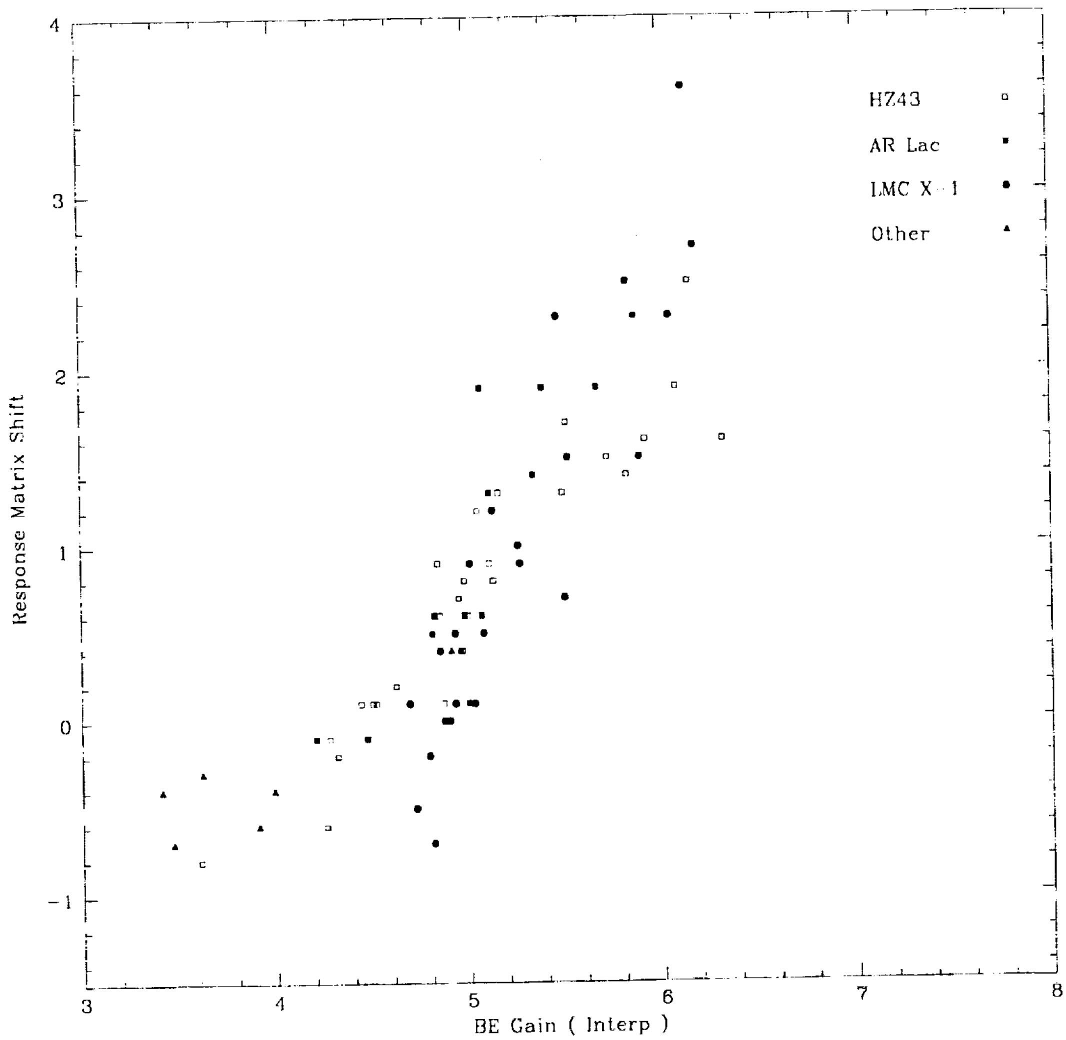

Figure 2: The weighted bright earth gain level is plotted against the response matrix shift which produces the minimum reduced X^2 value. The PHA channels 2-10 were included in the spectral fits.

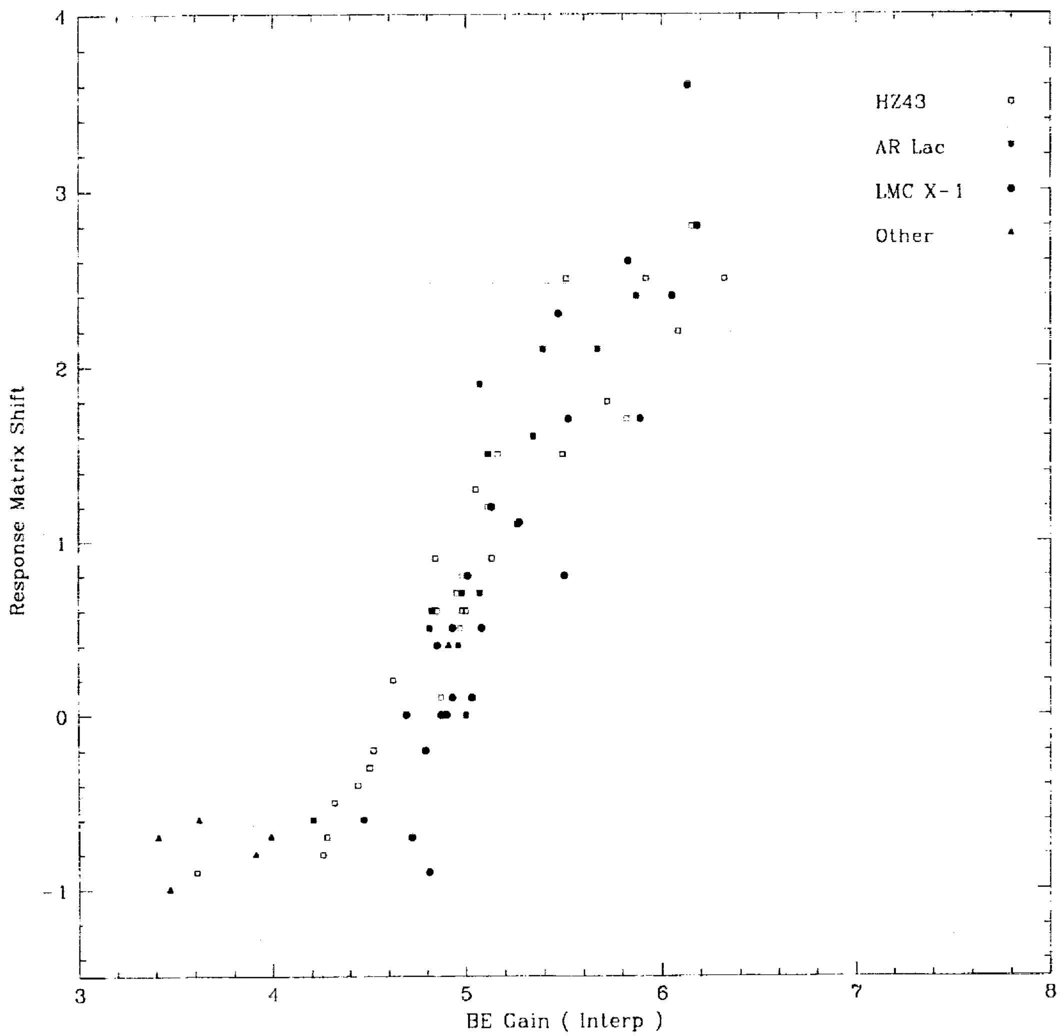

Figure 3: The weighted bright earth gain level is plotted against the response matrix shift which produces the minimum reduced X^2 value. The PHA channels 4-10 were included in the spectral fits.

7 Calibration Example

In this section we give an example of how to find the hardness ratio for a source (61 Cyg) in the center of the field, and show how this can be used to constrain the spectrum. We assume that the user is familiar with PROS, FTOOLS and XSPEC.

1. **You will need standard ROSAT archival data products** (events and aspect fits files). Run IRAF/PROS and convert them to PROS format.

2. **Use the PROS task qpspec to extract a spectrum from the source of interest.** The output of qpspec is 3 files – in the case of 61 Cyg these are rh201950n00_obs.tab, rh201950n00_boh.tab, rh201950n00_soh.tab.

3. **Create a FITS file which can be read into XSPEC** by running the task hrifits.cl provided with this distribution. From within IRAF and in the same directory containing the script hrifits.cl type:

   ```
   xs> task hrifits=hrifits.cl

   fu> hrifits  rh201950n00_obs.tab  rh201950n00
   ```

   Here rh201950n00_obs.tab is the input file from qpspec, and rh201950n00 is the root of the output file ("_pha" will be appended). Note: you must have run the FTOOLS package futils for this script to work. You must have the files "fitscol" and "head" (part of this distribuion.) The task hrifits will create an output file rh201950n00_pha.fits which can be read by XSPEC. The unshifted ground-based response matrix (hri_dtmat_15.fits) is hard-wired into the FITS header, as is the HRI Ancillary Response File (hri_arf.fits).

4. **Run xgain program to determine BE gain.**

   Fill in the parameter file xgain.par:

   ```
   # good pars: 48.0 -40.0 0.0  rev0
   #            48.0 -40.0 -0.4 rdf
   #
   EVENTS rh201950n00_bas.fits
   ASPECT rh201950n00_anc.fits
   ASPCOLS TIME,RA_SC,DEC_SC,ROAN_SC
   MAPS   /data/andrea/HRI/jds/gain.fits
   MODE RDF
   BORESIGHT 48.0 -40.0 -0.4
   TDELAY -0.65
   ```

```
XPOS 4168
YPOS 4056
GHIST 2.0 7.0 0.1
steps /proj/jcm/Science/hri/hv.dat
```

and run xgain. You will need to edit the parameters EVENTS, ASPECT, MAPS, XPOS, YPOS, steps. It may be necessary to edit the other parameters if you are not using RDF files, or are doing more detailed analysis (see Section 4. For 61 Cyg, rh201950n00_bas.fits and rh201950n00_anc.fits are the names of the event and aspect files. These are the FITS files obtained from the HEASARC archive. MAPS contains the location of the gain.fits file your local system, XPOS and YPOS are the coordinates of the source in sky pixels obtained from visual inspection of the image displayed in SAOimage. Finally, steps is the location of the hv.dat file on your local system.

The output of xgain is displayed to the terminal and written to a file xgain.fits.

5. **Run the script shift_matrix.sh.**

   This script shift_matrix.sh uses the output of xgain to construct two response matrices. The first is a matrix derived from the ground-based response matrix by shifting it by the ammount corresponding to the mean BE gain of the observation (default name "new_mean_resp.fits". The second is a matrix composed of several shifted response matrices, weighted by the time spent in each corresponding gain state (called "new_resp.fits".) If the source was not wobbled over too many gain states, the response matrix corresponding to the mean gain is fine. If the source was wobbled over a wide range of gain states the time-weighted response matrix should be used. Note that the spectral resolution can be degraded still further if the source exposure covers many gain states.

7.1 Read spectrum into XSPEC OR calculate a hardness ratio

At this point you have a response matrix and a PHA file. It is therefore possible to read the spectrum directly into XSPEC and fit as usual. Since the spectral resolution is low parameters are often not well constrained within XSPEC, it is often more useful to create simulated spectra to determine whether a given model is consistent with the hardness ratio. Here we describe both these options.

7.1.1 XSPEC Analysis

Read the PHA spectrum (created by hrifits.cl) into XSPEC. Change the response matrix to "new_mean_resp.fits" or "new_resp.fits" using the "resp" command. Ignore the first two channels and channels where the count rate is zero, and fit as usual. Using this method, we find that the best-fit Raymond-Smith plasma temperature for 61 Cyg is 0.35 keV, and the reduced $\chi^2 = 1.09$ for 7 PHA bins (channels 3-9). The PSPC spectrum between 0.5-2 KeV is well fit by a single temperature Raymond-Smith model of tempretaure 0.368 keV. The agreement is good (and may be fortuitous!)

NOTE: when displaying HRI spectra in XSPEC, do not use the "set plot energy option". The channel boundaries are not updated.

7.1.2 Simulations

The first step is to determine the best channels to use for the hardness ratio. In his initial report on the HRI spectral response Fraser concludes that the ratio (counts in channel 1-5)/(counts in channel 6-11) is the most senstive energy indicator. This is true for most sources. However, the optimal channel selections should be checked for each observation. The optimal ratio is one in which the two bands (hard and soft) are seperated as cleanly as possible. An example is given in Figure 4. Here we show three plots. The top left panel shows the probability that a photon will be detected in channels 1-5 as a function of energy (solid line) and the probablity that a photon will be detected in channels 6-15 (dashed line) for the 61 Cyg sequence rh201950n00. The other two panels show the same plot, except that probability is shown for channels 1-6/7-15 and channels 1-4/5-16. These values were derived from the response matrix new_resp.fits. This plot shows that the most senstive indicator is channels 1-4/5-15, which corresponds to a ratio of counts above and below 0.6 keV. A recipe for creating channel boundary plots is given in Appendix A

The next step is to produce simulated data files. This can be done within XSPEC using the "fakit" command. Required inputs are parameters of the spectral model and the response matrices. To ensure that the counting statistics are the same for the simulated data files as for the real data, input a model normalization/exposure time combination that produces an overall countrate in the simulated files approximately equal to that in the real data file. It is then possible to compare the distribution of simulated hardness ratios with that of the real data.

Figure 5 shows the results of 4 simulations for 61 Cyg. The models used in the simulations were Raymond-Smith plasmas with temperatures of 1.0, 0.3, 0.4, and 0.5keV. One hundred fake data files were produced for each model. The ratio of counts in channels (1-4)/(5-15) for the real data was 0.86. The hardness ratios of an 0.4 keV plasma group around 0.85, as might be expected from the fit to the HRI spectra and the PSPC results. However, the hardness ratio is also consistent with an 0.5 and 1keV plasma. Without prior knowledge of the source, we would conclude that the spectrum was consistent with a temperature of 0.4keV, but could not rule out a temperature as high as 1keV.

A Channel Boundary Plots

We do not yet have a script to create channel boundary plots. The following recipe works:

1. **Create an ascii file with the channel probabilities as a function of energy** (this is the MATRIX column of the response matrix) using fdump with parameters as follows

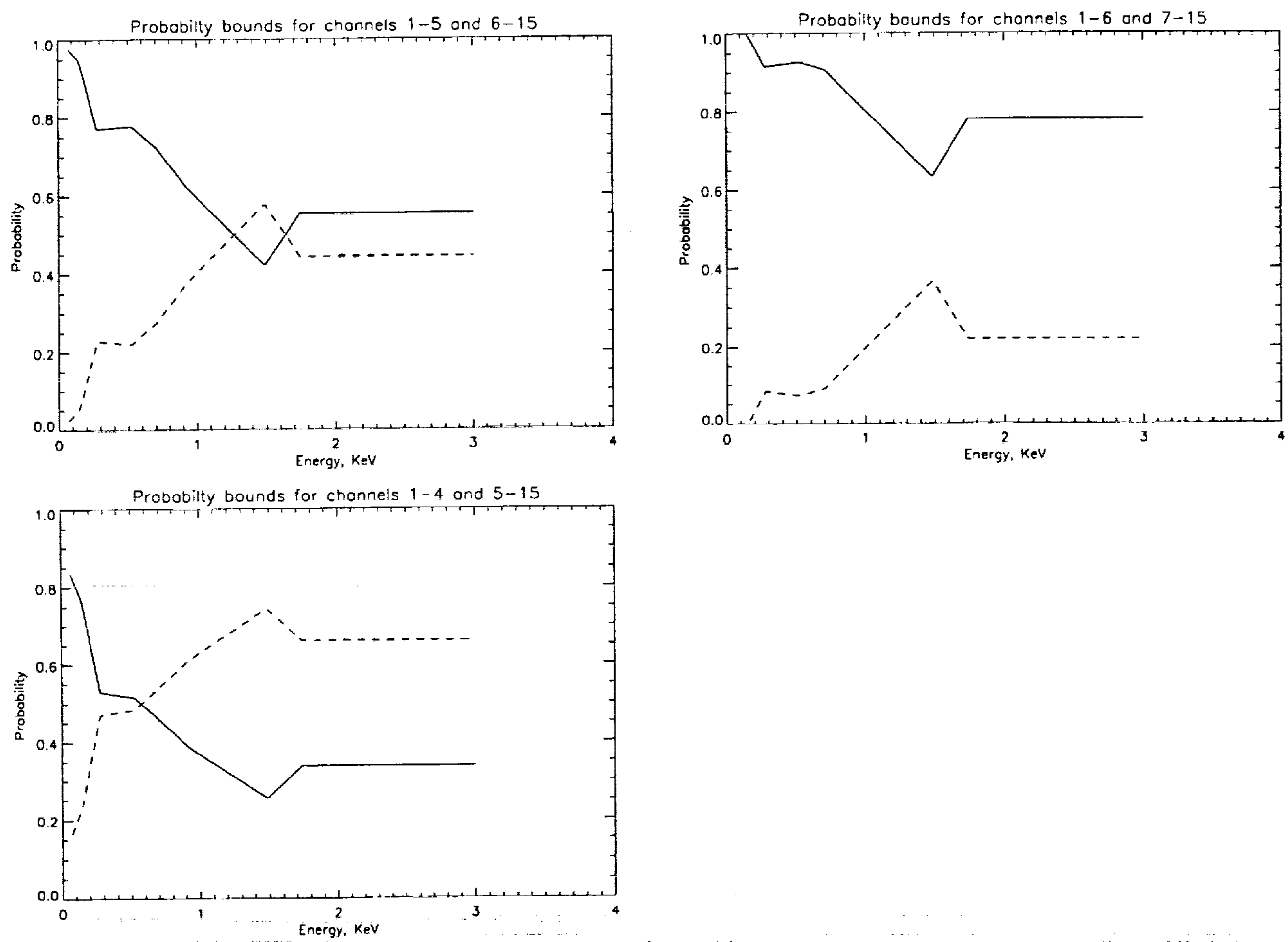

Figure 4: The top panel shows the probability that a photon will be detected in channels 1-5 as a function of energy (solid line) and the probablity that a photon will be detected in channels 6-15 (dashed line) for the 61 Cyg sequence rh201950n00. The other two panels show the same plot, except that probability is shown for channels 1-6/7-15 and channels 1-4/5-16.

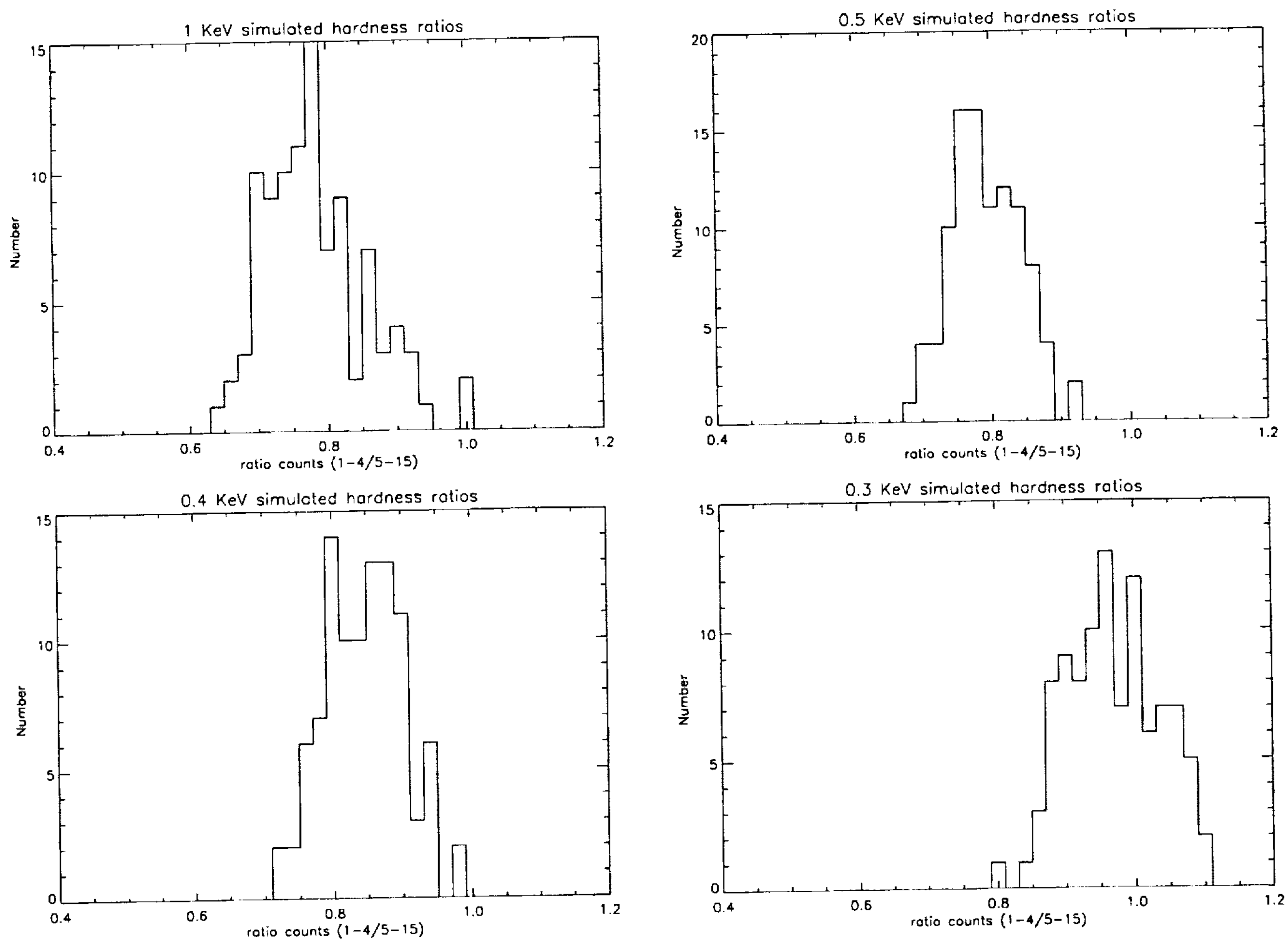

Figure 5: Histograms of hardness ratios produced from simulated data files. From top left to bottom right the models are; 1 keV, 0.5keV, 0.4keV, and 0.3keV RS plasma. The real spectrum has a ratio of 0.86.

```
fdump infile="new_resp.fits[2]" outfile=new_resp.txt clobber=yes
prhead=no showcol=no showrow=no showunit=no rows="-" column=MATRIX
```

2. **Use the awk script awk_chan (included with this distribution) to shuffle the matrix elements** so that the first 729 lines are the probablitity that a photon of a given energy will fall in channel 1, the next 729 lines are the probablitity that a photon of a given energy will fall in channel 2 etc.

3. **Read the file created by awk_chan and the corresponding energy array (the file "energies" supplied with this distribution) into IDL.** Within IDL it is possible to define 15 channel arrays. For example, c1=MATRIX(0:728) will define a new array, c1, which contains the first 729 elements of the array MATRIX. It is then possible to add channel probabilities in any desired combination.

B Creating Simulated Datasets with XSPEC

We do not yet have a script to create simulations. The following recipe works:

1. Create a shell script to provide inputs to xspec. The following is an example used to create the 0.4 keV pha files for 61 Cyg:

```
#! /bin/tcsh -f

echo "mo ray"
echo "0.4 1.0000E-02  8.0000E-03  8.0000E-03 64.00        64.00"
echo "1.0      -1.0000E-03      0.           0.         5.000        5.000"
echo "0.     -1.0000E-03      0.           0.         2.000        2.000"
echo "1e-3       1.0000E-02      0.           0.        1.0000E+24  1.0000E+24"


set comlist = 'cat $1'

foreach file ($comlist)

echo "fakeit none"
echo "new_resp.fits"
echo " hri_arf.fits"
echo "y"
echo "\n"
echo $file
echo "6688,  1.0000 , 1.0000 , 0."
```

```
end
```

The script will output the model parameters, ie. the first 5 lines of the script. The script will then read in a list of file names and output a set of instructions to xspec to create multiple fake pha files. If the list of file names is as follows:

```
pha1
pha2
```

the output of the script will be:

```
mo ray
0.4 1.0000E-02  8.0000E-03  8.0000E-03 64.00        64.00
1.0     -1.0000E-03      0.           0.        5.000        5.000
0.     -1.0000E-03      0.           0.        2.000        2.000
1e-3      1.0000E-02      0.           0.        1.0000E+24  1.0000E+24
fakeit none
new_resp.fits
 hri_arf.fits
y
\n
pha1
6688,  1.0000 , 1.0000 , 0.
fakeit none
new_resp.fits
 hri_arf.fits
y
\n
pha2
6688,  1.0000 , 1.0000 , 0.
```

2. **Run xspec to generate fake pha files.** If the output of the script in item 1 was piped to a file called xinput, run xspec with the command

   ```
   > xspec xinput
   ```

   The result will be 2 fake pha files, pha1.pha and pha2.pha. A larger number will be needed to obtain a statistically meaningful result!

3. Obtain the hardness ratios of the fake data files. The following is an IRAF script to do this in an automated way.

```
procedure ratio (scanfile,output)

char *list
char scanfile {prompt ="Enter simulation list"}  #image list
char output {prompt="Output file"}

begin

#declare local variables

char spect,outfile
real h,r,e,s

list=scanfile
outfile=output

#read file

while (fscan (list,spect) !=EOF){

fstatistic(infile=spect,colname="counts",rows="1-4")
s=fstatistic.sum
fstatistic(infile=spect,colname="counts",rows="5-15")
r=s/h
e=r*(s**(-1)+h**(-1))**(0.5)
print(h,s,r,e, >> outfile)

}
end
```

The parameters for this script are a file containing a list of fake pha files and the name of the output file. The output file is an ascii file with columns containing the number of "hard" counts (channels 5-15 in this case), the number of "soft" counts (channels 1-4), the ratio soft/hard and the ratio error.

4. **Read the file with counts and ratios into IDL** or other plotting/analysis package and plot a histogram.

C Files in this Distribution

hrifits.cl IRAF/PROS script to convert output from qpspec to a fits PHA file

head ASCII file containing FITS header for PHA file. Used by hrifits.cl

fitscol ASCII file containing FITS column names for PHA file. Used by hrifits.cl

hri_dtmat_15.fits,hri_dtmat_15_cs01.fits etc. HRI response matrices. hri_dtmat_15.fits is the original matrix derived from ground-based data. Files with "_cs*" appended have been shifted in channel space. "hri_dtmat_15_cs01.fits" has been shifted by 0.1 channels, "hri_dtmat_15_cs02.fits", has been shifted 0.2 channels, "hri_dtmat_15_cs12.fits" has been shifted 1.2 channels and "hri_dtmat_15_csm01.fits" has been shifted minus 0.1 channels.

hri_arf.fits FITS Ancillary Response File.

xgain Binaries for xgain program.

xgain.par Template input parameter file for xgain.

hv.dat ASCII file containing dates with high voltage changes. Used by xgain.

gain.fits Data cube containing BE gain information. Used by xgain.

shift_matrix.sh Perl script to produce shifted response matrices. Uses output from xgain.

energies ASCII file containing energy points (in keV) from RMF file.