Calibration Requirements and Present Status

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1.0 Introduction

A broad range of scientific requirements for the Chandra observatory was presented in MSFC-RQMT-2229. These requirements covered the full scope of scientific studies expected to be carried out during the nominal 5 year mission of the Chandra observatory. Simulated Chandra observations of well known targets (e.g., M87, 3C273, Coma cluster, Cas A, and Capella) were performed with a full error budget analysis. Calibration requirements were then derived based on these scientific goals. Below is a summary of the scientific areas of study along with the calibration requirements necessary to achieve these scientific goals at a high significance.

2.0 Scientific Requirements

2.1 Extended Source Mapping

2.1.1 AGN Jets

Science: Compare the X-ray structure of AGN jets with their radio images.

*Requirements:*The PSF should be known to within 0.1% of peak within 1 arcsec annuli out to a radius of $16''$. Within an annulus between $16''$ and $20''$ the PSF should be known to within 0.001% of peak.

2.1.2 Clusters of Galaxies

Science: Establish the nature of intensity enhancements in clusters of galaxies.

Requirements: The relative efficiency should be known to 1% on scales of $1'$

2.1.3 Clusters surrounding quasars

Science: Detect and map extended emission around quasars.

Requirements: Same criteria as in 2.1.1

2.2 Motion

2.2.1 Expansion of Supernova Remnants

Science: Measure the expansion rate of young supernova remnants.

Requirements: Relative spatial positions should be measurable to $\leq 0.1''$

2.2.2 Bulk Radial Motion in Supernova Remnants

Science: Determine shock velocities and bulk motions in supernova remnants.

Requirements: Absolute energy scale of HETG/ACIS-S data should be known to 0.005%

2.2.3 Velocity broadening in Supernova Remnants

Science: Measure the velocities responsible for line broadening in supernova remnants.

Requirements: FWHM of gratings LRF should be known to within 3%.

2.2.4 Kinetic Energy of Supernova Remnants

Science: Determine the kinetic energy in supernova remnant lines.

Requirements: Absolute efficiency vs. energy should be known to 10%.

2.3 Plasma Diagnostics

2.3.1 Temperature and Ionization Age in Supernova Remnants

Science: Establish the temperature and ionization age of the plasma in supernova remnants.

Requirements: The relative efficiency should be known to 3% and the wings of the LRF to 1% of its peak value.

2.3.2 Relative Elemental Abundances in Supernova Remnants

Science: Determine relative abundances in supernova remnants.

Requirements: Same criteria as in 2.3.1

2.3.3 Temperatures in Stellar Coronae

Science: Determine the temperatures of bright stellar coronae.

Requirements: Relative efficiency vs. energy should be known to 3% on 0.05A wavelength scales.

2.3.4 Electron Densities in Stellar Coronae

Science: Determine the electron densities of bright stellar coronae.

Requirements: Same as 2.3.3

2.3.5 Loop Structures in Stellar Coronae

Science: Establish the length of loop structures.

Requirements: Gratings absolute effective areas should be known to 10% on 0.05A wavelength scales.

2.3.6 Line Identification in Stellar Coronae

Science: Identify spectral lines and study their profiles.

Requirements: LETG/HRC-S absolute energy scale should be known to 0.02A. HETG/ACIS-

S absolute energy scale should be known to 0.05%.

2.4 Source Identification

Science: Identify the counterparts of X-ray sources.

Requirements: Absolute positions should be known to $1''$ over the entire field-of-view.

2.5 Sunyaev Zel'dovich Effect

Science: Determine the distance to clusters of galaxies.

Requirements: The absolute ACIS effective area should be known to 2% on 0.1 arcmin scales.

3.0 Summary of Calibration Requirements

Characteristic	Det/Grat	Requirement (1σ)	Present (June 2003)	Projection (June 2004)
Relative Spatial Positions	ACIS-I	$0.1''$	$0.1''$	$0.1''$
	ACIS-S3		$0.1''$	$0.1''$
	HRC-I		$0.3''$	$\lesssim 0.3''$
Absolute Positions	HRC/ACIS	$1.0''$	$0.6''$	$0.6''$
Point Spread Function	HRC/ACIS	0.1% of peak within $1''$ annuli out to $16''$	0.004%	0.004%
		0.001% of peak between $16''$ and $20''$	0.00008%	0.00008%
Energy Resolution (FWHM)	ACIS	3%	12%	12%
	LETG/HRC-S	3%	20%	10%
	HETG/ACIS-S	3%	15%	10%
Absolute Energy Scale	ACIS	1 eV	5 eV at 1.5keV	5 eV
	LETG/HRC-S	0.02A	0.05A	0.03A
	HETG/ACIS-S	0.005%	0.004% (MEG)	0.002%
			0.004% (MEG)	0.002%
Relative Efficiency	ACIS	1% on scales of $1'$	0.8%	0.8%
	HRC	1% on scales of $1'$	0.7%	0.7%
	LETG/HRC-S	3% on scales of 0.05A	6%	4%
	HETG/ACIS-S	3% on scales of 0.05A	10%	5%
Absolute Efficiency	ACIS	2%	12%	7%
	HRC	7%	10%	7%
Absolute Efficiency 1st order	LETG/HRC-S	10%	15%	10%
	HETG/ACIS-S	10%	15%	10%
Relative Time Precision	ACIS	$54\mu s$		
	HRC	$16\mu s$	$15.625\mu s$	$15.625\mu s$
Barycentric Time Accuracy	HRC	$100\mu s$	$200\mu s$	$200\mu s$

4.0 In-Flight Calibration Observations

4.1 Relative Spatial Positions

Calibration Targets: The open star cluster NGC2515 and serendipitous targets.

Results:

4.2 Absolute Spatial Positions

Calibration Targets: NGC2515, raster scans of LMC X-1, and serendipitous targets.

Results:

4.3 Point Spread Function

Calibration Targets: ArLac, 3C273, HR1099, Her X-1, the white dwarf RE J1032+53, and serendipitous targets.

ArLac Photon Statistics

Annuli (radii in arcsec)	error in surface brightness
0.5-1.5	0.05257
1.5-2.5	0.00423
2.5-3.5	0.00108
3.5-4.5	0.00056
4.5-5.5	0.00036
5.5-6.5	0.00025
6.5-7.5	0.00019
7.5-8.5	0.00015
8.5-9.5	0.00013
9.5-10.5	0.00010

Note: The errors in the surface brightness are given in terms of the percentage of the peak surface brightness.

Results:

• Her X-1 was observed for 50 ksec with ACIS-S on July 2, 2002. The observation was planned for the high state of Her X-1 and between eclipses. The observation was performed in VF mode to allow further reduction in charged particle background. Because of X-ray dosage concerns, the aim-point was positioned near the top corner of the S3 chip, so S3 captured a full quadrant of the wings. Counting statistics better than 10% were obtained within 500 eV energy bins and angular bins with widths increasing from $2''$ (at $20''$) to $50''$ (at $9'$). Below 7 keV, the profiles can be extracted out to $9'$. Above 7 keV, the background contribution becomes increasingly important. At the highest energies (8-10 keV), the profile can be extracted out to $2'$.

Links:

4.4 Energy Resolution

Calibration Targets: Cas A, E0102-72, Capella, and ACIS cal source.

Results:

4.5 Absolute Energy Scale

Calibration Targets: Cas A, E0102-72, Capella, and ACIS cal source.

Results:

4.6 Relative Efficiency

Calibration Targets: Raster scans of G21.5-09 and E0102-72, 3C273, PKS2155-304, HZ43, and ACIS cal source.

Results:

• In addition to ACIS observations of the external calibration source, the contamination build up on ACIS is monitored with a 30 ksec LETG/ACIS-S observation of PKS2155-304 every 6 months. The PKS2155 observation yields statistical errors in the optical depth at the carbon and oxygen K-edges of 0.020 and 0.010, respectively. At present, the optical depth at the carbon K-edge is increasing at a rate of 0.40 per year.

• G21.5-09 is observed by all 4 focal plan detectors every six months to monitor the broad band efficiency of the detectors.

G21.5-09 Photon Statistics

Energy band (keV)	ACIS-I3	ACIS-S3
< 1.0	6%	4%
1.0-2.0	1.3%	1.1%
2.0-3.0	1.3%	1.1%
3.0-4.0	1.3%	1.2%
4.0-5.0	1.6%	1.5%
5.0-6.0	2.0%	2.2%
6.0-7.0	3.2%	3.4%
7.0-8.0	5.7%	5.8%
8.0-10.0	7.0%	8.1%

• A raster scan of 14 pointings of E0102-72 is carried out every 6 months. E0102-72 is positioned on at least one node of each CCD, along with additional pointings on S3 and I3 at a range of distances from the read-out.

E0102-72 Photon Statistics

Energy band (keV)	ACIS-I3	ACIS-S3
< 0.5	5.7%	1.8%
0.5-0.75	1.4%	0.7%
0.75-1.0	1.0%	0.7%
1.0-1.5	1.1%	1.0%
1.5-2.0	2.9%	2.5%
2.0-3.0	6.5%	5.0%

• Cas A is observed every 6 months with all 4 focal plane detectors.

Cas A Photon Statistics

Energy band (keV)	ACIS-I3	ACIS-S3
< 0.5	3.9%	2.5%
0.5-0.75	2.4%	1.7%
0.75-1.0	0.9%	0.7%
1.0-1.25	0.5%	0.4%
1.25-1.5	0.5%	0.4%
1.5-1.75	0.5%	0.5%
1.75-2.0	0.4%	0.4%
2.0-2.5	0.5%	0.5%
2.5-3.0	0.7%	0.8%
3.0-4.0	0.8%	0.8%
4.0-5.0	1.1%	1.2%
5.0-6.0	1.8%	2.0%
6.0-7.0	2.1%	2.5%
7.0-8.0	4.7%	5.8%
8.0-10.0	7.0%	8.0%

5.0 Calibration Priorities

5.1 HRMA

- Improve the effective area near the IR M-edge
- Refine the PSF/Wing profiles
- Access telescope positional accuracy
- Refine optics alignment model to improve deconvolutions using the on-axis PSF
- Incorporate new surface scattering model; fold in PSF wing data to improve model inputs.
- Investigate scattering profile of off-axis sources

5.2 ACIS

- Time dependent responses for the FI chips at -120
- Improve launch QE
- Correction for the spatial dependence of the contaminant
- Assessment and calibration of ACIS after bake-out
- Improved FEFs for the BI chips at -120
- Improved responses at -110

5.3 HRC

• Testing/Updating the latest QE model with recent LETG/HRC-I data on PKS2155.

• Update the low energy QE map.

• Continue investigation of the gain degradation at the aim points of the HRC-I and HRC-S.

5.4 LETG

• Reduce the residuals in the dispersion relation.

• Improve the accuracy of the first order efficiency

• Improve the accuracy of the higher order efficiencies

• Reduce the residuals in the LRFs

• Improve the HRC-S QE uniformity map - possibly 2-D

• Improve HRC-S gain uniformity map

5.5 HETG

6.0 Planned Updates to the CALDB

• Complete analysis of relative efficiencies of HETG/ACIS-S and compare MEG and HEG efficiencies.

• Use cross-calibrations with XMM to verify absolute efficiencies.

• Quantify comparison of line response functions from flight data with raytrace simulations.

• Quantify effects of pile-up in dispersed spectra and determine the accuracies of correction methods.

• Improve accuracy of dispersion relation.

• Verify high order efficiencies.

Calibration Plans for ACIS Bake-Out

Before Bake-Out

Target	Grating/Detector	Time (ksec)
PKS2155	LETG/ACIS-S	70
PKS2155 (near read-out)	LETG/ACIS-S	70
E0102	ACIS-S and ACIS-I	144
Abell 1795	ACIS-S and ACIS-I	30
Cal Source		

After Bake Out

Target	Grating/Detector	Time (ksec)
PKS2155	LETG/ACIS-S	70
PKS2155 (near read-out)	LETG/ACIS-S	70
PKS2155 (with y off-sets)	LETG/ACIS-S	16
PKS2155 (with y off-sets)	LETG/ACIS-I	24
E0102	ACIS-S and ACIS-I	144
Abell 1795	ACIS-S and ACIS-I	30
Cal Source		

Notes: The exposures in the PKS2155 observations have been increased from our nominal 30ksec to 70ksec to provide better statistics in the O and F edges. Our nominal raster scan of E0102 consists of 15 observations, each with an exposure of 8 ksec. The above plan includes an additional 12 ksec (for a total of 20 ksec) for the E0102 observations at the ACIS-I and ACIS-S aim points. To measure the spatial distribution of the contaminant before and after bake-out, additional LETG/ACIS-S observations of PKS2155 will be taken near the read-out of ACIS-S. Possible changes in the low energy gain will be measured with LETG/ACIS-S observations of PKS2155 at different y off-sets.

Bookkeeping issues

The last AO4 observation for PKS2155 is in June 2003 and the last raster scan of E0102 is in August 2003. If we delay the AO4 E0102 observations until just before bake-out and carry out the first AO5 raster scan of E0102 immediately after bake-out, then the above plan includes an additional 398 ksec of calibration time.