MSFC-RQMT-2229

Scientific Requirements for the Calibration of AXAF

August 2, 1995

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1List of Acronyms

ACA	Aspect Camera Assembly
ACIS	AXAF CCD Imaging Spectrometer
ACIS-I	AXAF CCD Imaging Spectrometer – Imaging detector
ACIS-S	AXAF CCD Imaging Spectrometer – Spectroscopy detector
ADS	Aspect Determination System
ADC	Analog to Digital Converter
AGN	Active Galactic Nucleus
ASC	AXAF Science Center
AXAF	Advanced X-ray Astrophysics Facility
BND	Beam Normalization Detector
CCD	Charge-Coupled Device
CIDS	Circularity and Inner Diameter Station
CIT	Calibration Implementation Team
CTI	Charge Transfer Inefficiency
CTT	Calibration Task Team
DCM	Double Crystal Monochromator
EIPS	Electron Impact Point Source
FLS	Fiducial Light System
FPC	Flow Proportional Counter
FOV	Field of View
FPSI	Focal-Plane Science Instrument
FTS	Fiducial Transfer System
FWHM	Full Width at Half Maximum
GESS	Grating-Element Supporting Structure (LETG)
GSE	Ground Support Equipment
HESS	HETG Element Supporting Structure
HEG	High-Energy Grating
HETG	High-Energy Transmission Grating
HETGS	High-Energy Transmission Grating Spectrometer
HRC	High-Resolution Camera
HRC-I	High-Resolution Camera – Imaging detector
HRC-S	High-Resolution Camera – Spectroscopy detector
HRMA	High-Resolution Mirror Assembly
HSI	High-Speed Imager
HXDS	HRMA X-ray Detector System
IRU	Inertial Reference Unit
LETG	Low-Energy Transmission Grating
LETGS	Low-Energy Transmission Grating Spectrometer
LRF	Line Response Function
MCP	Micro-Channel Plate
MDS	Motion Detection System
MEG	Medium-Energy Grating
MPMI	Micro-Phase Measurement Interferometer

MSFC	Marshall Space Flight Center
OLR	Observatory-Level Requirement
OTG	Objective Transmission Grating
PGDS	Penning Gas Discharge Source
PHA	Pulse-Height Analyzer
PMM	Precision Metrology Mount
PMS	Precision Metrology Station
PRF	Point Response Function
PSD	Power Spectral Density
RAS	Rotating Anode Source
RGM	Reflection Grating Monochromator
SAO	Smithsonian Astrophysical Observatory
SI	Science Instrument
SIM	Science Instrument Module
SIMSS	Science Instrument Module Support Structure
SNR	Supernova Remnant
SSD	Solid-State Detector
TBD	To Be Determined
TGS	Transmission-Grating Spectrometer
UV	Ultraviolet
XGSE	X-ray Ground Support Equipment
XRCF	X-Ray Calibration Facility

1INTRODUCTION

1.1AXAF OBSERVATORY

1.1.1Scientific Subsystems

The following scientifically critical subsystems comprise the Advanced X-ray Astrophysics Facility (AXAF) Observatory:

- High-Resolution Mirror Assembly (HRMA)
- Objective Transmission Gratings (OTGs)
    - Low-Energy Transmission Gratings (LETG)
    - High-Energy Transmission Gratings (HETG)
- Focal-Plane Science Instruments (FPSIs)
    - High-Resolution Camera (HRC)
        - HRC Imaging (HRC-I) detector
        - HRC Spectroscopy (HRC-S) detector
    - AXAF CCD Imaging Spectrometer (ACIS)
        - ACIS Imaging (ACIS-I) detector
        - ACIS Spectroscopy (ACIS-S) detector
- Aspect Determination System (ADS)
    - Aspect Camera Assembly (ACA)
    - Fiducial Transfer System (FTS)
    - Inertial Reference Unit (IRU)

1.1.2Scientific Capabilities

The AXAF Observatory provides powerful scientific capabilities:

- High-angular-resolution (sub-arcsecond) imaging
- Moderate-spectral-resolution (resolving powers $R \approx 50$) imaging spectrometry
- High-spectral-resolution ($R \approx 1000$) dispersive spectroscopy

1.1.3Scientific Objectives

The scientific objectives of AXAF include the following:

- Determine the nature of celestial objects.
- Understand the physics of fundamental processes in the universe.
- Investigate the history and evolution of the universe.

1.1.4Importance of Calibration

To utilize effectively the exceptional capabilities of the AXAF Observatory requires a calibration of exceptional accuracy. Accomplishing many of the specific scientific objectives of AXAF depends upon these capabilities and thus upon the calibration. In addition, the calibration activities serve as a verification of the capabilities of the AXAF Observatory.

1.2AXAF CALIBRATION

1.2.1Requirements

Goals

Level-1 requirements recognize the importance of the precise calibration of AXAF, through stating a symbolic goal of 1% accuracy. Although valid in an abstract sense, this Level-1 requirement is too vague and, in some cases, misleading. It is the purpose of this document to establish and specify the detailed requirements for scientific calibration.

Approaches

There are two extreme approaches to establishing calibration requirements — "bottom–up" and "top–down".

Bottom–Up Approach

The "bottom–up" approach lists all parameters to be calibrated and then requires a precision much smaller than the expected nominal value. The difficulty with such an approach is that, for extremely complicated measurements requiring long times or inordinate resources, there is no mechanism for rational trade-offs.

Top–Down Approach

The "top–down" approach uses science observing programs to drive the calibration requirements. However, it faces 2 complications. First, it requires detailed performance models to simulate observations and determine the affect of calibration uncertainties upon the result. Generally, during the early stages of a project, such models are unavailable; indeed, key flight instrumentation may not yet have been designed. Second, because it is impossible to identify all potential experiments, some important calibration might be overlooked.

Pragmatic Approach

To facilitate planning, design, development, procurement, etc. of equipment to support activities at the Marshall Space Flight Center (MSFC) X-Ray Calibration Facility (XRCF), we adopt a pragmatic approach. When possible, we use anticipated scientific observations (§3) to drive the calibration requirements (§4); otherwise, we employ a bottom–up approach.

1.2.2Objectives

Response Function

The objective of a calibration is to determine a *response function* which maps a known *input function* into a precisely measured *output function*. Knowledge of this calibrated response function will then allow use of output data (on-orbit observations) to deduce the input data (x-ray properties of cosmic sources).

Imaging with the HRC

As an example, consider imaging observations with the HRC. The output function is $C(\vec{r}_d', Ph, t_d)$ — i.e., counts at location $\vec{r}_d'$ (in detector coordinates), with pulse amplitude *Ph,* detected within a time interval dt_d about time t_d. If the probability of this event arising from more than one x-ray interaction in the detector were not vanishingly small, it would be necessary to modify this approach.

The input function is the intensity $I(\hat{k}_s, E, p, t_s)$ — i.e., photons cm^{-2} s^{-1} str^{-1} keV^{-1} — with $\hat{k}_s$ the direction of the incident photon, *E* its energy (in keV), $\vec{p}$ its polarization, and t_s the arrival time. The response function *M* relates *C* and *I* through a convolution $C = M \otimes I$, supplemented by appropriate coordinate transformations. It is useful to decompose $M = R \otimes H$, where *R* and *H* are instrument and HRMA response functions.

The Instrument Response Function R

The instrument response function $R(r_d', E, \hat{k}_d, p, T, t_d', r_d, Ph, t_d)$ is the probability that a photon of energy *E* and polarization $\vec{p}$, incident on the detector in direction $\hat{k}_d$ at time t_d' at location $\vec{r}_d'$, is detected at time t_d at location $\vec{r}_d'$ with pulse amplitude *Ph* for the instrument at temperature *T*.

The HRMA Response Function H

The HRMA response function $H(r_h', E, \vec{k}_h', p_h', t_h', \delta, T, r_h, E, p_h)$ is the probability that a photon of energy E and polarization $\vec{p}_h'$, incident on the HRMA in direction $\hat{k}_h$ at time t_h' at location $\vec{r}_h'$, appears at time t_h at location r_h with polarization $\vec{p}_h$ for the HRMA at temperature T and under any distortions characterized by δ.

Coordinate Transformations

This example involves 3 distinct coordinate systems *(s, h, d)* for space and time (although the distinction between t_d and t_h is purely pedagogical). To accomplish the convolution requires appropriate coordinate transformations. During on-orbit operation of AXAF, this involves 2 additional coordinate systems — one associated with the aspect camera *(a)* and the other with the periscope assembly *(p)*. The relationship between the coordinate mappings (following photon flow) are $s \rightarrow h \rightarrow d$ for x rays and $s \rightarrow a \leftarrow p \leftarrow d$ for visible light.

Imaging with the ACIS

The previous discussion is not directly applicable to ACIS because the raw data are pulse amplitudes within an "island" of pixels at given positions at a given time. To the extent that the probability of two events is vanishingly small, these are "split" events that have simply registered their presence in multiple adjoining pixels. Thus raw data are of the form $C'(\vec{r}_d', Ph, t_d)$, which are used to construct an image $C(\vec{r}_d', Ph, t_d)$.

Dispersive Spectroscopy

For dispersive spectroscopy, the presence of an Objective Transmission Grating (OTG) between the HRMA and the Focal-Plane Science Instrument (FPSI), interposes another response function — namely, G for the OTG — into the system response function. Thus for dispersive spectroscopy, $M = R \otimes G \otimes H$. The output function is again an image $C(\vec{r}_d, Ph, t_d)$. However, the image is more complicated owing to the strong coupling between wavelength and direction (hence, detected position) and to the presence of multiple spectral orders.

1.2.3Framework

This document provides a framework for the already active AXAF calibration process. The final release of this document will complete the process of establishing requirements, the purposes of which are:

1. Establish sufficiently detailed requirements for equipment, to permit development or procurement with relatively high confidence.
2. Determine planning requirements, to allow allocation of resources.
3. Initiate requirements traceability, to enable the evaluation of potential modifications to low-level requirements in terms of mission goals.
4. Identify the function of each required model and measurement.
5. Specify the mechanism for developing more detailed plans.

1.3OUTLINE OF DOCUMENT

1.3.1Introduction

In §1, we have given a brief overview of the AXAF Observatory and described the critical role of calibration.

1.3.2Reference Documents

In §2, we list applicable documents, supporting references, instrument specifications, and measurement references.

1.3.3 AXAF Science Objectives

In §3 we illustrate how science objectives drive requirements for calibration accuracy. We examine (§3.2) some specific science investigations which drive the required calibration accuracy of each response function or characteristic thereof: These are Observatory-Level Requirements.

1.3.4 Observatory Level Requirements

In §4, we group the Observatory-Level Requirements by instrument configuration and state required calibration accuracies..

1.3.5 Modeling

In §5, we discuss the general modeling approach, indicating how on-orbit response models rely on specific measurements for pre-delivery, XRCF, pre-launch, and on-orbit calibration. We specify requirements for these models and associated planning.

1.3.6 Calibration Measurements

In §6, we describe specific requirements for measurements and associated planning. Also in this section, we identify necessary equipment.

1.4 STYLE FOR STATING REQUIREMENTS

The style of this document differs from that of usual MSFC requirements documents. This is a deliberate experiment in "new ways of doing business". We feel that adding explanatory prose serves to clarify intent (thus avoiding confusion as to interpretation) and makes the document more useful to informed participants. For emphasis, we highlight requirements and key phrases in boxes; we identify requirements with "**Req**" followed by the paragraph number in which the requirement appears.

2REFERENCE DOCUMENTS

2.1APPLICABLE DOCUMENTS

6. AXAF 101, Advanced X-Ray Astrophysics Facility – Imaging (AXAF-I) Level-1 Requirements
7. MSFC-SPEC-1836, Advanced X-Ray Astrophysics Facility – Imaging (AXAF-I) Level-2 Project Requirements Document (PRD)

2.2SUPPORTING REFERENCES

8. A. C. Brinkman, memo to M. C. Weisskopf and M. Joy, "AXAF Calibration Requirements Science Investigation Questions", 26 April, 1991
9. S. S. Murray, memo to E. Cothran, "HRC Calibration Requirement", 2 May, 1991
10. HETG group, memos to CTT dated 5/3/91 and 10/7/91.
11. L. P. Van Speybroeck, AXAF Telescope Scientist Proposal, SAO, P-1394-2-84, February, 1984.
12. TRW 52100.200.92.0015, X-Ray Calibration Facility Interface Definition, HRMA, DPD 692 XC05, Contract NAS 8-37710
13. TRW 52100.200.92.0078, HRMA & SI X-ray Calibration Plan, DPD 692 XC01, Contract NAS 8-37710
14. Science Instrument Notebook, AXAF Science Center, 30 December, 1992

2.3INSTRUMENT SPECIFICATIONS

15. SAO-AXAF-DR-92-017, AXAF Contract End Item (CEI) Specification for the High Resolution Mirror Assembly X-Ray Detection System (HXDS), Data Requirement No. GCM01, contract NAS 8-36123
16. ACIS-DD-003, Contract End Item (CEI) Specification for the Advanced X-Ray Astrophysics Facility – Imaging (AXAF-I) CCD Imaging Spectrometer (ACIS), Data Requirement No. SCM-02, Contract NAS 8-38749
17. SAO-HRC-DR-92-011, Contract End Item (CEI) Specification for the Advanced X-ray Astrophysics Facility – Imaging (AXAF-I) High Resolution Camera (HRC), Data Requirement No. SCM-02, Contract NAS 8-38248
18. Contract End Item (CEI) Specification for the Advanced X-Ray Astrophysics Facility – Imaging (AXAF-I) Low-Energy Transmission Grating (LETG), Data Requirements No. SCM-02
19. Contract End Item (CEI) Specification for the Advanced X-Ray Astrophysics Facility – Imaging High-Energy Transmission Grating (HETG), Data Requirements No. SCM-02, Contract NAS 8-38249
20. MSFC-SPEC-2401 End Item Specification for X-ray Source System (XSS)

2.4MEASUREMENT REFERENCES

21. E. Kellogg, Interim Report: Summary of AXAF Calibration Requirements, SAO-AXAF-DR-93-058, November, 1993.
22. C. Jones, memos listing tables of calibration requirements for ACIS, HRC, HETG and LETG, Spring 1992.
23. Presentation material and supplements from the AXAF-I Calibration Workshop, January, 1993, MSFC.
24. G. Chartas and E. Kellogg, HXDS Error Budget and HXDS Sensitivity Analysis, HXDS PDR, SAO-AXAF-DR-93-056. October, 1993.

3AXAF SCIENCE OBJECTIVES

3.1SCIENCE INVESTIGATION FLOWDOWN

This section outlines the approach for proceeding from a scientific investigation to the required calibration accuracy. Figure 3.1-1 illustrates an example: The scientific objective is to determine the Hubble parameter, via the Sunyaev-Zel'dovitch effect, to a precision of 5%. This requires measuring the absolute flux from a cluster to an accuracy of 2%. Selecting a target (the Coma cluster), an instrument (ACIS-I), and an integration time defines an observation. Selecting an analysis approach (fitting the data to an isothermal β-model), allows one to simulate the observation and, assuming uncertainties in the ACIS absolute response function over the appropriate field of view, determine the accuracy of the measurement. The process is clearly iterative: If the calibration uncertainty is inconsistent with the scientific objective, the calibration accuracy must be modified.

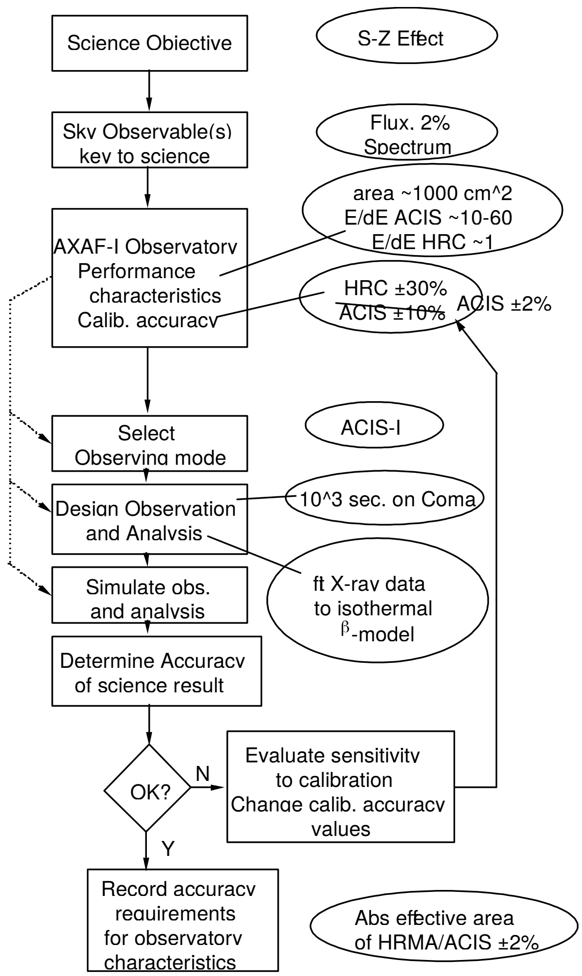

Figure 3.1-1 — Science investigation flowdown to calibration requirements. Boxes identify general activities carried out; ovals give an abbreviated example (Sunyaev-Zel'dovich effect).

3.2SCIENTIFIC INVESTIGATIONS AND THEIR REQUIREMENTS

The following summarizes scientific investigations and AXAF configurations that have been examined in establishing Observatory-Level Requirements (§4).

3.2.1Extended Source Mapping

Jets in Active Galactic Nuclei (AGNs)

Low-Energy Mapping

Reference: S. S. Murray's memo "HRC Calibration Requirement", of 1991 May 2

Investigation: Compare the x-ray structure of AGN jets with their radio images. Investigation of M87 requires knowledge of the Point Response Function (PRF) to 1% of its peak value on 1-arcsec^2 scales out to 2-arcsec radius, and on 10-arcsec^2 scales out to 20-arcsec radius. Investigation of 3C273 requires knowledge of the PRF to 0.1% of its peak value on 1-arcsec^2 scales out to 16-arcsec radius.

Conclusion: Calibrate the PRF to ±0.1% of its peak value on 1-arcsec^2 scales within 16-arcsec radius, and to ±1% of peak on 10-arcsec^2 scales. (HRC-I)

Clusters

Coma Cluster Mapping

Reference: S. S. Murray's memo "HRC Calibration Requirement", of 1991 May 2

Investigation: Establish the nature of intensity enhancements in clusters of galaxies. This requires knowledge of the relative efficiency. An analysis of the Coma cluster, whose central core will produce ~5000 HRC counts arcmin^{-2} in 5x10^4 s, leads to a requirement of knowledge of the relative efficiency to an accuracy of ±1% on 1-arcmin^2 scales over the field of view.

Conclusion: Calibrate the relative efficiency to ±1% on 1-arcmin^2 scales over the entire field of view. (HRC-I)

Clusters surrounding Quasars

Low-Energy Mapping

Reference: S. S. Murray's memo "HRC Calibration Requirement", of 1991 May 2

Investigation: Detect and map a z=1 cluster of luminosity 10^{44} erg s^{-1} centered on a quasar of luminosity 10^{46} erg s^{-1}. Accurate determination of the luminosity requires knowledge of the PRF to 0.001% of its peak value out to 15-arcsec radius.

Conclusion: Calibrate the PRF to ±0.001% of its peak value on 10-arcsec^2 scales within 15-arcsec radius. (HRC-I)

Supernova Remnants (SNRs)

Expansion Rate

Reference: S. S. Murray's memo "HRC Calibration Requirement", of 1991 May 2

Investigation: Measure the expansion rate of young supernova remnants (SNRs). Cas A expands at 0.5 arcsec yr^{-1}. Measurement of the expansion rate to 10% over 3 years requires a relative positional accuracy of 0.1 arcsec.

Conclusion: Calibrate the relative positional accuracy to within 0.1 arcsec. (HRC-I)

3.2.2Motion

Supernova Remnants (SNRs)

Bulk Motion

Reference:	HETG team's memos "Re Science Investigation Proposal", of 1991 May 3 and Aug 7
Investigation:	Determine shock velocities and bulk motions in SNRs. Shock velocities may be as low as 300 km s^{-1}; bulk motions, as low as 45 km s^{-1}. The latter drives the accuracy requirement for the absolute energy scale.
Conclusion:	Calibrate the absolute energy scale to 0.005%. (HETG–ACIS-S)

Velocity Broadening

Reference:	HETG team's memos "Re Science Investigation Proposal", of 1991 May 3 and Aug 7
Investigation:	Measure the velocities responsible for line broadening in SNRs. Detection (3σ) of line broadening for velocities as low as 200 km s^{-1} requires accurate determination of the Line Response Function (LRF).
Conclusion:	Calibrate the Full Width at Half Maximum (FWHM) of the LRF to within 3% (1σ) of its FWHM. (HETG–ACIS-S)

Kinetic Energy

Reference:	HETG team's memos "Re Science Investigation Proposal", of 1991 May 3 and Aug 7
Investigation:	Determine the kinetic energy in SNR lines. Estimating the kinetic energy (to better than 25%) requires measurement (to 10%) of the absolute flux in various lines, velocity information (§), and knowledge of the state of the plasma. (§3.2.3).
Conclusion:	Calibrate the absolute efficiency as a function of energy (at the HETG energy resolution) to 10%. (HETG–ACIS-S)

3.2.3Plasma diagnostics

Supernova Remnants (SNRs)

Temperature and Ionization Age

Reference:	HETG team's memos "Re Science Investigation Proposal", of 1991 May 3 and Aug 7
Investigation:	Establish the temperature and ionization age of the plasma in SNRs. Measurements of the temperature and ionization age to 5% and 10%, respectively, require determination of the relative efficiency to 3% and the wings of the LRF to 1% of the peak value.
Conclusion:	Calibrate the relative efficiency to 3% and the LRF to 1% of its peak value. (HETG–ACIS-S)

Ionization Age

Included in § above.

Relative Elemental Abundances

Reference:	HETG team's memos "Re Science Investigation Proposal", of 1991 May 3 and Aug 7
Investigation:	Determine relative abundances in SNR. Measurements of temperature and ionization age (§) also provide data for measuring relative abundances to 50% — sufficient to distinguish among several SNR models.
Conclusion:	See §. (HETG–ACIS-S)

Stellar Coronae

Temperature

Reference: A. C. Brinkman's memo "AXAF Calibration Requirements Science Investigation Questions", of 1991 Apr 26

Investigation: Determine the temperatures of (bright) stellar coronae. For an accuracy approaching 1% in 10^5 s with LETG–HRC-S, this requires measurement of the O VII to O VIII line ratio to better than 3%.

Conclusion: Calibrate the relative efficiency (0.05-Å scale) to 3%. (LETG–HRC-S)

Electron Density

Reference: A. C. Brinkman's memo "AXAF Calibration Requirements Science Investigation Questions", of 1991 Apr 26

Investigation: Determine the electron densities of bright stellar coronae. For an accuracy of 20% in 10^5 s with LETG–HRC-S, this requires measurement of the OVII intercombination to forbidden line ratio to better than 6%.

Conclusion: Calibrate the relative efficiency versus energy (0.05-Å scale) to 6%. (LETG–HRC-S)

Loop Structures

Reference: A. C. Brinkman's memo "AXAF Calibration Requirements Science Investigation Questions", of 1991 Apr 26

Investigation: Establish the length of loop structures. Uncertainties in temperature, electron density, and absolute line intensity govern uncertainties in loop lengths. For a 10^5-s observation of a bright source, the former would produce an uncertainty of 12%; thus, knowledge of the absolute line flux to within 10% would lead to an overall uncertainty in the loop length of 15%.

Conclusion: Calibrate the absolute efficiency (0.05-Å scales) to 10%. (LETG–HRC-S)

Line Identification

Reference: A. C. Brinkman's memo "AXAF Calibration Requirements Science Investigation Questions", of 1991 Apr 26

Investigation: Identify lines and study their profiles. Such studies require knowledge of the absolute energy scale to within ±0.02 Å.

Conclusion: Calibrate the absolute energy scale to ±0.02 Å. (LETG–HRC-S)

3.2.4Source identification

Counterpart ID

Reference: S. S. Murray's memo "HRC Calibration Requirement", of 1991 May 2

Investigation: Identify the counterparts of x-ray sources. Source identifications require absolute position accuracies of 1 arcsec.

Conclusion: Be able to determine the celestial positions of imaged sources (anywhere in the field of view) to within ±1 arcsec. (HRC-I)

3.2.5Sunyaev-Zel'dovich Effect

Reference: L. P. Van Speybroeck's *AXAF Telescope Scientist Proposal* (SAO P-1394-2-84) of 1984 Feb

Investigation: Determine the distance to a cluster of galaxies. Limiting the x-ray contribution to <10% of the uncertainty, requires measuring the absolute flux to better than 2% on scales <0.1 arcmin^2.

Conclusion: Calibrate the absolute effective area (0.1-arcmin^2 scales) to 2%. (ACIS-I)

3.3PLANNING

Req 3.3: Other potential observations shall be investigated to the extent necessary to refine observatory level requirements for calibration.

The following are examples of possible AXAF observations:

25. mapping of jets in AGN (ACIS)
26. studies of knots in jets (HRC and ACIS)
27. spectral imaging of galaxy clusters (ACIS)
28. mapping of clusters surrounding quasars (ACIS)
29. determining the size of interstellar grains (ACIS)
30. determining the composition of interstellar grains (ACIS and LETG)
31. spectral imaging of SNRs (ACIS)
32. mapping and spectral imaging of the diffuse x-ray background (HRC and ACIS)
33. measurements of cosmological red shifts (ACIS)
34. determination of abundances, electron densities, and volumes of SNRs (HETG)
35. deep surveys (HRC)
36. studies of interstellar dust using eclipsing sources (ACIS)
37. time-resolved spectra of SNR pulsars (ACIS and HETG and LETG)
38. timing studies of variable sources (HRC)
39. monitoring x-ray binaries in M31 (ACIS)

4OBSERVATORY LEVEL REQUIREMENTS

4.1INTRODUCTION

4.1.1Approach to Deriving Requirements

Req 4.1.1: To the extent possible, derived calibration requirements shall be derived top–down.

4.1.2Required Accuracies

Req 4.1.2: Unless otherwise indicated, required calibration accuracies shall be stated as one sigma or equivalent (67% confidence).

4.2GENERAL REQUIREMENTS

4.2.1Intrinsic Factors

Energy Range

Req : Unless otherwise indicated, calibration accuracies shall apply over the entire energy range of relevance to the response function.

Position in the Focal Plane

Req : Unless otherwise indicated, calibration accuracies shall apply for any position in the focal plane.

Field of View

Req : Unless otherwise indicated, calibration accuracies shall apply over the entire field of view relevant to the response function.

Changes over Time

Req : Unless otherwise indicated, calibration accuracies shall apply over the life of AXAF (nominally five years on-orbit).

4.2.2Environmental Factors

Thermal Range

Req : Unless otherwise indicated, calibration accuracies shall apply over the entire operating temperature range of AXAF.

Contamination Range

Calibration accuracies must be maintained independent of the actual level of particulate or molecular contamination.

Particulate Contamination Range

Req : Unless otherwise indicated, calibration accuracies shall apply independent of the level of particulate contamination or changes thereto.

Molecular Contamination Range

Req : Unless otherwise indicated, calibration accuracies shall apply independent of the level of molecular contamination or changes thereto.

4.2.3Facility Factors

Finite Source Distance

Req : Unless otherwise indicated, calibration accuracies shall apply to sources at infinite distances.

Gravitational Effects

Req : Unless otherwise indicated, calibration accuracies shall refer to on-orbit (zero-g) performance.

4.2.4Corrections to Measurements

It is unrealistic to expect high accuracy after applying large corrections, because of uncertainties in the correction. For example, at the X-Ray Calibration Facility (XRCF), the HRMA will be horizontal and subject to gravitational distortion. Without off-loading the 1-g distortion, accurate prediction of the on-orbit performance is implausible.

Req 4.2.4: Whenever possible, no correction larger than 15% (absolute) shall be applied to a parameter in order to determine its on-orbit value.

4.3ON-ORBIT CHARACTERISTIC CALIBRATION ACCURACIES

The requirements in this section are encompass all measurements which affect the calibration accuracy of the AXAF on-orbit performance. Thus, the scope of the requirements given in this section is ***not*** limited to only those calibration measurements made on-orbit.

4.3.1Focal-Plane Science Instruments (FPSIs)

The requirements in this section apply to each HRMA-FPSI combination --- namely, HRMA–ACIS-I, HRMA–ACIS-S, HRMA–HRC-I, and HRMA–HRC-S.

Spatial Characteristics

Spatial Resolution

Req : Spatial resolution shall be calibrated to an accuracy of better than 3%.

Relative Position Accuracy

Req : The observatory shall be calibrated such that the relative celestial positions of all points within the field of view can be determined to within ±0.1 arcsec.

Absolute Position Accuracy

Req : The observatory shall be calibrated such that the absolute celestial coordinates of any point in the field of view may be determined to within ±1 arcsec.

Spectral Characteristics

Energy Resolution

Req : The ACIS energy resolution shall be calibrated to within 3%.

Relative Energy Scale

Req : The ACIS relative energy scale shall be calibrated to within 5 eV.

Absolute Energy Scale

Req : The ACIS absolute energy scale shall be calibrated to within 10 eV.

Temporal Characteristics

Time Resolution

Req : Time resolution shall be calibrated to within 0.1%.

Time Difference Accuracy

Req : The time difference between HRC events shall be calibrated to within ±16μs.

Barycentric Time Accuracy

Req : Calibrations shall permit the determination of barycentric time within ±100 μs.

Spacecraft Position Accuracy

In order allow phasing of pulse arrival times to within 16 ms, the ground system must be capable of determining accurately the spacecraft position.

Req : Calibrations will be performed to permit determination of the orbital position relative to the geocenter to within 4 km.

Flux Characteristics

Background

Accurate measurements of the background are an important aspect of the ground and flight calibration programs. Planning and implementation of these measurements should account for anticipated rates as low as 10^{-4} counts s^{-1} cm^{-2} of detector area, over the entire energy band and detector area.

Relative Point Response Function (PRF)

Specification of the calibration of the PRF relative to its peak value includes “range” from the peak, size of the bins, and accuracy of calibration on the scale of a bin.

Req : The relative PRFs of each HRMA-FPSI shall be calibrated to accuracies appropriate to a given bin size, over the ranges as specified in Table .

Table : Required accuracy for Point Response Function (PRF)

Range (about peak) (arcsec diameter)	**Bin size** (arcsec^2)	**Accuracy** (1 σ)
peak	0.5x0.5	as required
1–16	1x1	0.1% of peak
16–20	5x5	0.001% of peak
16–60	8x8	0.001% of peak
60–360	30x30	0.001% of peak
360–1080	180x180	0.001% of peak
>1080	300x300	0.001% of peak
For sources 20–60 arcmin off axis:		
at on-axis location	36x36	0.001% of peak
at on-axis location	2000x2000	0.001% of peak

Table also includes a specification addressing wings of the PRF produced by sources outside the field of view. This is required for accounting for x-ray contamination by such sources.

Relative Effective Area

Req : The relative effective area of each focal plane x-ray detector shall be calibrated to within 1%.

Absolute Effective Area

Req a: The HRMA-ACIS absolute effective area (within a 5-arcsec core radius) shall be calibrated to within ±2%.

Req b: The HRMA-HRC absolute effective area HRC (within a 5-arcsec core radius) shall be calibrated to within ±7%.

4.3.2Transmission-Grating Spectrometers (TGSs)

A TGS includes the HRMA, an Objective Transmission Grating (OTG) and a readout Focal Plane Science Instrument The requirements in this section apply to the following TGSs --- HRMA–LETG–HRC-S, HRMA–LETG–HRC-I, HRMA–HETG–ACIS-S, HRMA–HETG–ACIS-I, HRMA–LETG–ACIS-S, HRMA–HETG–HRC-S, HRMA–HETG–HRC-I.

Energy Resolution

Req : The energy resolution of each TGS shall be calibrated to 1/30 of the Full width at Half Maximum (FWHM).

Relative Energy Scale

Req a: The relative energy scale of each LETGS shall be calibrated to 0.002 nm.

Req b: The relative energy scale of each HETGS shall be calibrated to 1/30 of the FWHM.

Absolute Energy Scale

Req a: The absolute energy scale of each LETGS shall be calibrated to 0.002 nm.

Req b: The absolute energy scale of each HETGS shall be calibrated 1/30 of the FWHM.

Relative Line Response Function (LRF)

Specification of the calibration of the line response function (LRF) relative to its peak value includes "range" from the peak, size of the bins (expressed in terms of the energy resolution of the grating), and accuracy of calibration on the scale of a bin.

Req : The relative LRFs shall be calibrated to accuracies appropriate to a given bin size, over the ranges as specified in Table .

Table : Required accuracy for Line Response Function (LRF)

Width (about peak) (arcsec diameter)	**Binwidth** (arcsec)	**Accuracy** (1 σ)
peak	energy resolution	as required
1–6000	energy resolution	1% of peak
For sources 20–60 arcmin off axis:		
at on-axis location	360	0.001% of peak

Relative Effective Area

Req : The relative effective area of each TGS shall be calibrated to ±3%.

Absolute Effective Area

Req : The absolute first-order effective area of each TGS shall be calibrated to ±10%.

5MODELING

5.1OVERVIEW

5.1.1Role of Modeling

Modeling is integral to the calibration process. Prior to ground calibration, models provide performance predictions for calibration planning. Subsequently, analysis of data acquired during ground calibration fixes parameters defining the model and may indicate other needed refinements in the model. Finally, comparison of performance predictions with on-orbit data will permit further refinement of the model and, hence, the calibration. *In essence, the model is the "calibration".*

This section establishes the modeling effort from pre-XRCF to on-orbit operations. Some divisions within this structure are artificial, in that the same model may apply at several levels or program phases. The remainder of this section describes requirements for the AXAF performance models and performance predictions.

5.1.2"Calibrated Model"

Throughout this section we make use of the term "calibrated model". This term is defined as a model based on experimental data as opposed to a purely theoretical construct.

5.1.3Responsibilities

Planning and Coordination of Modeling

The first requirement is for planning and coordination of the modeling activities.

Req : The AXAF Science Center (ASC) shall establish a plan and schedule for accomplishing the modeling necessary for the calibration of AXAF. The ASC shall coordinate the activities of the various contributors.

HRMA Modeling

Req : The Telescope Scientist is responsible for determining and overseeing the modeling and calibration of the HRMA response function.

OTG Modeling

Req : The developer of each Objective Transmission Grating (OTG) is responsible for modeling and calibrating the response function of that OTG and should complete this activity before instrument delivery.

FPSI Modeling

Req : The developer of each Focal-Plane Science Instrument (FPSI) is responsible for modeling and calibrating the response function of that FPSI and should complete this activity before instrument delivery.

5.2GENERAL REQUIREMENTS

The various AXAF models will employ both analytical and numerical formulas derived from theoretical, empirical, or semi-empirical relations. In some cases, Monte-Carlo simulations may play an integral role. A few general requirements apply to all modeling.

Req 5.2a: When Monte-Carlo simulations are used, the number of realizations shall be sufficient to reduce the statistical uncertainty in the simulation to less than 5% of the (statistical and systematic) uncertainty in the data to which it is compared or applied.

Req 5.2b: Predictions of each model shall be capable of being represented as a continuous function of the parameters and variables upon which it depends.

Req 5.2c: The predictions of a model shall include uncertainties attributable to the modeling process, including the parameters and variables upon which it depends.

Req 5.2d: All models shall be cross-checked against data or independent models.

5.3ON-ORBIT OBSERVATORY RESPONSE FUNCTIONS

Req 5.3: The entire results of the calibration program — ground and orbital — shall be contained in a complete set of response functions.

5.3.1Input

Req 5.3.1: The on-orbit response functions shall be based upon on-orbit performance prediction models (§5.4) and on-orbit calibration measurements and analyses.

5.3.2Accuracy

Req 5.3.2: On-orbit response functions shall generate values for all observatory characteristics to the accuracy required in §4, for each observatory configuration.

5.3.3Refinements

Req 5.3.3: On-orbit response functions shall be refined through comparison of on-orbit performance predictions with on-orbit measurements, in order to obtain higher fidelity representation of performance within constraints set by the ground calibrations.

5.4ON-ORBIT PERFORMANCE PREDICTIONS

Req 5.4: The entire results of the on-ground calibration program shall be contained in a complete set of on-orbit performance prediction models.

5.4.1Input

Req 5.4.1: On-orbit performance-prediction models shall be based upon ground-to-orbit transformation models (§5.5), XRCF-based HRMA–SI response functions (§5.6), spacecraft component and subsystem models (§5.7), and other calibrated models as required.

5.4.2Accuracy

Req 5.4.2: On-orbit performance prediction models shall generate values for all observatory characteristics to the accuracy defined in §4.

5.5 GROUND-TO-ON-ORBIT TRANSFORMATIONS

Much of the calibration data taken prior to launch are necessarily obtained under conditions quite different from orbital operations. Obvious examples are gravitational distortion and finite-distance effects at the XRCF.

> **Req 5.5:** Calibrated models shall provide transformations from ground-based to on-orbit performance predictions.

5.5.1 Input

> **Req 5.5.1:** The ground-to-orbit transformation models shall be based on calibrated models for the effects of gravity and the HRMA off-loaders, of finite distance, of particulate and molecular contamination, and of any other factor requiring adjustment of a ground-based measurement to an on-orbit value.

5.5.2 Accuracy

> **Req 5.5.2:** The ground-to-orbit transformation models shall produce corrections to ground-based data to an accuracy which, when convolved with other necessary models (§5.6 and §5.7), meets the requirements of §5.4.2.

5.6 XRCF RESPONSE FUNCTIONS

Testing, calibration, and verification of the HRMA-XGSE and HRMA–SI combinations at the XRCF requires performance predictions (§5.8) to evaluate progress and to recognize anomalies. After XRCF activities, the data will be used to construct a fully calibrated set of response functions for the Observatory in the XRCF configuration, which, when convolved with the ground-to-orbit transformations (§5.5), lead to on-orbit predictions.

> **Req 5.6a:** Calibrated models (§5.1.2) shall summarize the HRMA–XGSE response functions after testing at the XRCF.
>
> **Req 5.6b:** Calibrated models (§5.1.2) shall summarize the HRMA–SI response functions after testing at the XRCF.

5.6.1 Input

> **Req 5.6.1:** The post-XRCF response functions shall be based upon XRCF HRMA–SI (§5.8) and HRMA-XGSE (§5.9) performance-prediction models, calibration data, and calibrated models for other inputs as required.

5.6.2 Accuracy

> **Req 5.6.2:** The XRCF response functions shall be determined to an accuracy which, when convolved with other necessary models (§5.5 and §5.7), meets the accuracy requirements of §5.4.2.

5.6.3 Refinements

> **Req 5.6.3:** The XRCF HRMA–SI response functions shall be refined through comparison of XRCF performance predictions with XRCF HRMA-XGSE and HRMA–SI data. Should statistically significant discrepancies arise, these functions and their uncertainties shall be adjusted to agree with XRCF measurements within constraints provided by applicable off-site (non-XRCF) pre-launch calibration measurements.

5.7SPACECRAFT SUBSYSTEM AND COMPONENT MODELS

Numerous spacecraft components and subsystems affect the on-orbit response functions. Scientifically critical items must be carefully modeled and calibrated in order to generate accurate on-orbit response functions.

Req 5.7: Calibrated models of *all* spacecraft subsystems and components needed to establish on-orbit scientific response functions are required. These include the following:

- Aspect camera
- Gyroscopes
- Fiducial light system
- Optical bench
- Location, dimension, and material composition of all components (for radiation-background calculations)
- Spacecraft clock
- Other subsystems and components, as needed to meet the requirements of §5.4

5.7.1Accuracy

Req 5.7.1: The accuracy of spacecraft subsystem and component models shall be such that, when convolved with the XRCF response functions and ground-to-orbit transformations, the accuracy requirements of §5.4.2 are satisfied.

5.8XRCF PERFORMANCE PREDICTIONS

Req 5.8: In order to plan and evaluate testing at the XRCF, performance predictions of the HRMA-XGSE and HRMA–SI configurations shall be required.

5.8.1Input

Req 5.8.1: The XRCF performance prediction models shall be based upon:

- HRMA model based on metrology and reflectance data
- Calibrated models of XRCF GSE (§5.9), especially XGSE
- Calibrated models of SI performance (§5.10)
- Calibrated models of reflectance based on the AXAF synchrotron program (§)
- Data and models of particulate and molecular contamination of the optics prior to delivery to the XRCF (§)
- Other data or models, as required

5.8.2Accuracy

Req 5.8.2: The XRCF models shall predict performance to an accuracy that, when confronted with measurements leads to XRCF response functions consistent with the accuracy requirements of §5.6.2.

5.9XRCF GSE MODELS

The performance of XRCF equipment directly impacts the calibration effort.

Req 5.9: Calibrated models of the performance of all XRCF GSE that impacts the interpretation of x-ray data shall be obtained.

5.9.1Input

Req 5.9.1: Models shall include the results of the measurements required in §6.4.

The following emphasizes key inputs to assure that they are considered.

X-Ray Calibration Facility

Req : Details of the as-built XRCF (especially distances from the HRMA entrance aperture to the x-ray sources and the locations of baffles) are required.

X-ray Sources and Monochromators

Req : Calibrated models that, at a minimum, account of all x-ray monochromators and x-ray sources — including target geometry and operating parameters (voltage and current), and filter composition, thickness, and uniformity.

XGSE

The Smithsonian Astrophysical Observatory (SAO) HRMA X-ray Detector System (HXDS) comprises various detectors (in the focal plane and near the HRMA aperture), precision translation stages, and arrays of apertures (pinholes, slits, and annuli). Each component needs to be well characterized.

Req : Calibrated models shall be obtained that, at a minimum, account for the following:

- Quantum efficiency, energy resolution, linearity, gain, dead time, background, pulse-pileup and saturation characteristics, temperature sensitivity, etc., of detectors
- Spatial variation of quantum efficiency and energy resolution for imaging detectors
- Maps of x-ray-transmitting detector windows
- Wire diameter and mesh period and its variations for mesh-supported windows
- Accuracy and repeatability of precision translation stages
- Size, shape, and orientation of apertures

Motion Detection System (MDS)

The TRW built MDS will provide data on high-frequency random vibration and lower frequency positional shifts over time scales of seconds to hours.

Req : A calibrated model (§5.1.2) of the performance of the MDS is required.

5.10SI MODELS

5.10.1Input

Req 5.10.1: SI models shall be based on the results of off-line (not XRCF) SI calibration programs and shall include the results of measurements required in §.

The following emphasizes key inputs to assure that they are considered.

High-Resolution Camera (HRC)

The spatial and spectral characteristics of the HRC depend upon those of the individual detectors and characteristics of the detector assembly. Thus, HRC models must encompass descriptions of these elements as a function of the environments to be encountered during both on-ground and on-orbit operation. The spectral and spatial responses depend upon the UV/ion shield, the Micro-Channel Plate (MCP), and the event-triggered read-out device, each to be characterized during subassembly calibration.

Req 5.10.1a: At a minimum, the model of the HRC should include the following as functions of position, incident angle, and energy:

- Transmission at x-ray, ultraviolet (UV), and visible wavelengths of UV/ion shield
- Quantum efficiency
- Count-rate linearity
- Dead time
- Gain/energy scale
- Energy resolution
- Stability
- Spatial linearity
- Internal background
- Response to out-of-band photons and charged particles (for induced background)

The HRC comprises two detectors: HRC-I is primarily for imaging; HRC-S, primarily for spectroscopic read-out. HRC-I has 1 square MCP with its surface nominally at right angles to the optical axis; HRC-S has 3 MCPs arranged in a strip conforming approximately to the Rowland circle of the transmission gratings. On-orbit orientations may differ from those on the ground, owing to differing thermal and gravitational stresses or launch shifts.

Req b: The HRC model shall accommodate differences between on-ground and on-orbit alignments.

AXAF CCD Imaging Spectrometer (ACIS)

The spatial and spectral characteristics of the ACIS depend upon those of the individual detectors and characteristics of the detector assembly. Thus, the ACIS model must encompass descriptions of these elements as a function of the environments to be encountered both on-ground and on-orbit. The spectral and spatial responses depend upon the optical blocking filter, the Charge-Coupled Devices (CCD), and the read-out mode, each to be characterized during subassembly calibration.

Req a: At a minimum, the ACIS model shall include the following as functions of position, energy, and operating mode:

- Transmission at x-ray, UV, and visible wavelengths of optical blocking filter
- Quantum efficiency
- Energy resolution
- Bias
- Gain/energy scale
- Count-rate linearity
- Charge-transfer inefficiency (CTI)
- Effective read noise
- Dark current
- Internal background
- Response to out-of-band photons and charged particles (for induced background)

Proton-induced displacement damage increases the CTI of CCDs, thus degrading spectral resolution.

Req b: The ACIS model shall include the effects of proton-induced displacement damage and that of any mitigating on-orbit treatment.

The ACIS comprises two detectors: ACIS-I is primarily for imaging; ACIS-S, primarily for spectroscopic read-out. ACIS-I has 4 CCDs arranged in a square conforming roughly to the focal surface; ACIS-S has 6 CCDs arranged in a strip conforming approximately to the Rowland circle of the transmission gratings. On-orbit orientations may differ from those on the ground, owing to differing thermal and gravitational stresses or launch shifts.

Req c: The ACIS model shall accommodate differences between on-ground and on-orbit alignments.

Low-Energy Transmission Grating (LETG)

LETG models must describe the individual characteristics of each grating facet. Depending upon the results of the subassembly calibration, mean values may suffice:

Req a: At a minimum, the model of the LETG shall account for the following:

- Grating efficiency as a function of energy and diffraction order
- LRF as a function of energy and diffraction order
- Grating period as a function of temperature
- Grating-period variations within elements
- Facet spatial dimensions

Grating elements are mounted to the Grating Element Supporting Structure (GESS), a plate with a (non-planar) Rowland-toroid figure.

Req b: The LETG model shall account for deviations from the theoretical figure and changes in figure due to gravitational and thermal stresses.

Req c: The model of the assembled LETG grating array shall account for the following:

- Positional errors in individual facet mounts
- Grating-element alignment
- Obscuration due to grating mounts and support assembly

High-Energy Transmission Grating (HETG)

HETG models must describe the individual characteristics of each grating facet. Depending upon the results of the subassembly calibration, mean values may suffice:

Req a: At a minimum, the model of the HETG shall account for the following:

- Grating efficiency as a function of energy and diffraction order
- LRF as a function of energy and diffraction order
- Grating period as a function of temperature
- Grating-period variations within elements
- Facet spatial dimensions

Grating elements are mounted to the HETG Element Supporting Structure (HESS), a plate with a (non-planar) Rowland-toroid figure.

Req b: The HETG model shall include deviations from the theoretical figure and changes in figure due to gravitational and thermal stresses.

Req c: The model of the assembled HETG grating array shall account for the following:

- Positional errors in individual facet mounts
- Grating-element alignment
- Obscuration due to grating mounts and support assembly

5.10.2Accuracy

Req 5.10.2: The SI models shall predict performance to an accuracy that, when compared with measurements, leads to XRCF response functions consistent with the accuracy requirements of §5.6.2.

6CALIBRATION MEASUREMENTS

6.1GENERAL

6.1.1Accuracy

Req 6.1.1: Unless specifically stated, the accuracy of the required measurements shall be consistent with the requirements of §4.

6.1.2Treatment of Uncertainties

There are two types of contributions to the uncertainty for any given measurement — namely, statistical and systematic.

Photon Counting Statistics

Req : The number of photons for a given measurement shall be maximized, consistent with time, flux, count-rate, and instrumental lifetime constraints, until the statistical contribution is less than half the required accuracy.

Systematic Errors

Req : Systematic errors shall be identified and budgeted so that their overall contribution to uncertainty is less than the required overall accuracy.

6.1.3Finite Source Distance

It is important to remember that the accuracy of measurements taken at finite-source distance shall be such that the source-at-infinity () requirement is met.

6.2PRE-XRCF MEASUREMENTS

6.2.1HRMA

HRMA Element Metrology

Overview

Metrology of the AXAF optical surfaces comprises azimuthal, axial, and surface (microroughness) measurements.

40. The Circularity and Inner Diameter Station (CIDS) provides azimuthal (circularity) measurements near the ends of each optic.
41. The Precision Metrology Station (PMS) provides axial measurements, which “connect” the circularity measurements.
42. The Micro-Phase Measurement Interferometer (MPMI) provides measurements of the high-spatial-frequency surface properties of each optic.

During CIDS and PMS measurements, the optic sits vertically in as force-free and reproducible an environment as possible. Fixturing for CIDS and PMS metrology is as structurally determinate as possible, given the geometry and material properties of the optics. During and MPMI measurements, the optic lies horizontally in a statically over-determined and rigid fixture.

Planning

Req : A plan for obtaining HRMA metrology measurements shall be developed to include the following:

- Plans for making appropriate measurements
- Plans for archiving data
- Plans for transferring data to the Telescope Scientist and the ASC

Measurement Accuracy

Inner Diameter

Req : The inner diameter of each HRMA element shall be measured to an absolute accuracy of ±1.83 μm.

Data Products: Data files of raw and processed CIDS data, and any ancillary data (spindle calibration tables, reference-bar calibration data, etc.) used to establish the capability of meeting this requirement.

Circularity

Req : The roundness of the inside of each HRMA element shall be measured to an absolute accuracy of ±0.074 μm.

Data Products: Data files of raw and processed CIDS data, and any ancillary data (spindle calibration tables, reference bar calibration data, etc.) used to establish the capability of meeting this requirement.

Sag

Req : The sag associated with each element of the HRMA shall be measured to an absolute accuracy of 16.0 nm.

Axial Power Spectral Density

Req : The power spectral density (PSD) of the HRMA optical surfaces shall be measured to the accuracy shown in Figure over the PMS spatial-frequency band (1×10^{-3} mm^{-1} to 1 mm^{-1}), at no fewer than 144 axial locations equally spaced around the circumference and spanning the entire length.

Data Products: Data files of raw and processed PMS data, and any ancillary data (toroid calibrations, three-flat test results, etc.) used to establish the capability of meeting the accuracy requirement.

Calibration of the PMS itself is complicated: A toroid is piecewise calibrated against reference flats in 190-mm subaperture scans which are “stitched” together. The flats must also be calibrated, using a “three-flat test” wherein 3 flats are measured against each other in a configuration minimizing gravity distortion. The toroid is “pitched” to different angles appropriate to the cone angles of the optical elements in 2 orientations (wide-end-down and narrow-end-down). Gravity distortions are significant and must be taken into account. After conversion of the measured fringe intensities into a shape using an elegant numerical method (Hilbert transform), corrections for gravity distortion of the toroid and the optic are applied to determine the axial figure.

Surface Roughness

The MPMI provides surface-roughness measurements with 3 different objectives (1.5X, 20X, 40X), to sample the power spectrum over the spatial-frequency band 0.25 to 1500 mm^{-1}.

Req : The power spectral density (PSD) of the HRMA optical surfaces shall be measured to the accuracy shown in Figure over the MPMI spatial-frequency band (0.25 mm^{-1} to 1500 mm^{-1}), at several locations.

Data Products: Data files of MPMI measurements and any ancillary data used to establish the capability of meeting this requirement.

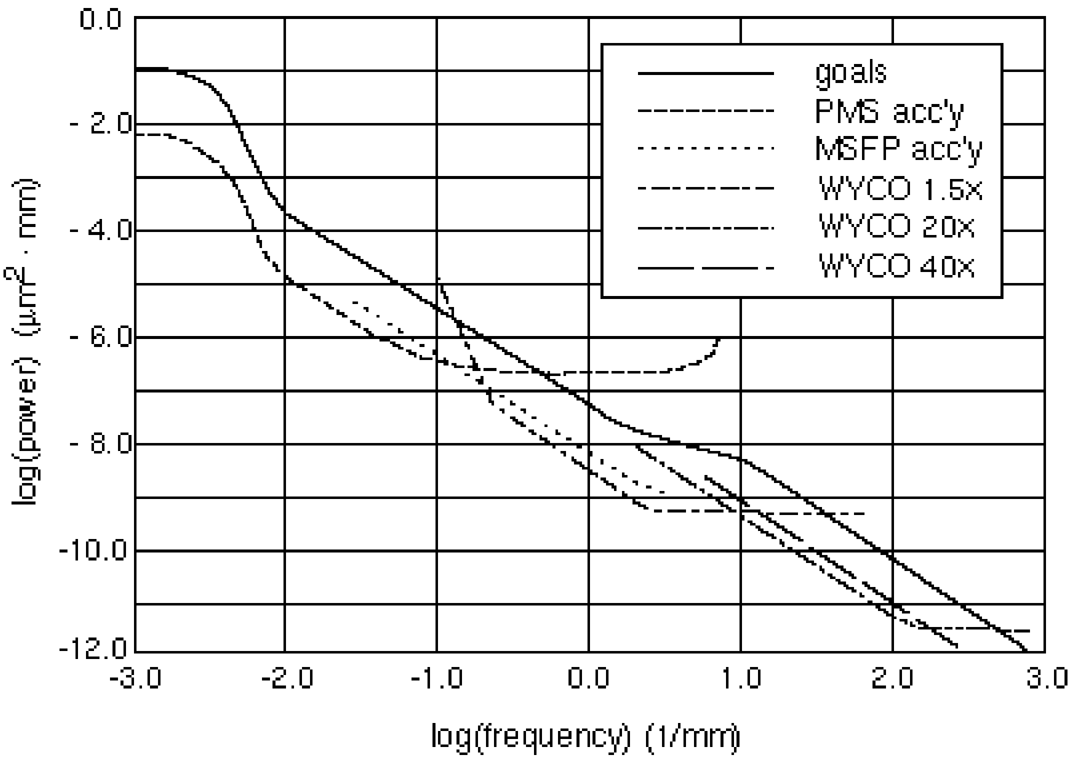

Figure — Accuracy requirements of metrology of Power Spectral Density of HRMA optics.

Precision Metrology Mount (PMM) Measurements

The PMM supports the optics in the most stress-free configuration possible, using 3 "hard points" for a kinematic mount and 6 to 15 "off-loaders". Prior to metrology, the optic is carefully leveled to eliminate tangential forces. Steel "buttons" glued to the ends provide a mechanical interface to distribute vertical forces at the end surface of the optic. Because symmetry breaking complicates structural models used to account for gravity induced deformations, the buttons should be located in an azimuthally symmetric pattern.

Req : Measurements of parameters needed to account for gravity distortions while the optic is in the PMM to an accuracy consistent with meeting the requirements of § through .

HRMA Structure and Alignment

Measurements

Req : Measurements shall be obtained that will determine the following:

- Placement and alignment of each HRMA optical element, including any rotations introduced for performance optimization
- Alignment and spacing of collimators, baffles, etc. in the telescope's field of view (FOV)
- Locations and forces applied by gravitational off-loaders during x-ray testing

Planning

Plans for obtaining the HRMA structure and alignment measurements shall be developed to include the following:

- Req **a**: Plans and schedules for deriving appropriate accuracies and for making needed measurements
- Req **b**: Plans for archiving the data
- Req **c**: Plans and schedules for transferring the data to the ASC

HRMA Reflectance

Measurements

It has not been feasible to equip the XRCF with a well calibrated continuum x-ray source or a well calibrated high resolution spectrometer. Thus, we require supplementary data for determining the HRMA effective area as a continuous function of energy:

Req a: A “coating-witness-sample” program shall be established, to coat Zerodur optical flats with iridium, during qualification runs and during coating of the flight optics. At a minimum, this program shall address the following:

- Repeatability of the coating process
- Axial dependence of the coating process
- Azimuthal dependence of the coating process

Req b: A “synchrotron” program shall be established, to obtain absolute and relative measurements of the x-ray reflectance as a continuous function of energy over the AXAF spectral band. At a minimum, this program shall include measurements of the following:

- X-ray reflectance as a function of energy and grazing angle
- Surface roughness
- Level of particulate contamination as a function of particulate size and composition
- Level of molecular contamination as a function of thickness and composition

Planning

Req : A plan for obtaining the x-ray reflectance measurements of the coating witness samples shall be developed, to include the following:

- Plans and schedules for deriving the accuracy of and taking the measurements
- A basis for selection of the angles of incidence
- Plans for archiving all data and associated equipment calibrations
- Plans and schedules for transferring data to the ASC

HRMA Contamination

Measurements

The AXAF optics are quite sensitive to particulate and molecular contamination; thus a major contamination-control program has been implemented. Nevertheless, knowledge of any contamination of the optics is essential to preserve the calibration accuracy.

Measurements of molecular and particulate contamination of the HRMA optics shall be performed at specific times from coating *through launch*.

To accomplish this, we require a contamination-monitoring program.

Req a: A program that utilizes witness samples placed at or near the HRMA shall be established to measure the following:

- Fractional areal coverage
- Molecular-layer thickness
- Under exceptional circumstances it may be necessary to measure particle composition and molecular-layer composition

Req b: Witness samples shall be replaced and measured at the following times, at a minimum:

- Immediately before and after HRMA assembly
- Immediately after HRMA installation into the XRCF
- Immediately before and after each XRCF evacuation/repressurization cycle
- As close to launch as practical

Verifying that contamination has not compromised the calibration has also resulted in the inclusion of a ground-to-orbit transfer of the flux scale. This is accomplished by employing radioactive calibration sources mounted on the HRMA forward contamination cover which shall be used to measure the degree of contamination change between the ground and on-orbit.

Req c: Precise measurements of the flux from the radioactive sources that passes through the HRMA and arrives in the focal plane shall be made on the ground at the XRCF and on-orbit prior to opening the forward contamination cover.

Planning

Plans for determining the level of contamination from non-x-ray measurements shall be developed:

- **Req a:** Plans for deriving accuracy requirements and making measurements
- **Req b:** Plans for archiving data
- **Req c:** Plans for transferring data to the ASC

Plans for determining the level of contamination from x-ray measurements shall be developed:

- **Req d:** Plans for deriving accuracy requirements and making measurements
- **Req e:** Plans for archiving data
- **Req f:** Plans for transferring data to the ASC

6.2.2Science Instruments (SIs)

General

Measurements

Pre-delivery calibration of the Science Instruments (HRC, ACIS, LETG, and HETG) is essential to the success of the calibration program.

Req a: A complete calibration of each SI shall be performed prior to delivery to the XRCF. This calibration may include post-XRCF calibrations on suitable transfer standards.

Because each FPSI contains millions of pixels, full pixel-by-pixel calibration is neither feasible nor required. The minimum spatial scale has been established by the "dither" amplitude of the spacecraft — 15 arcseconds.

Req b: Each FPSI shall be calibrated, averaged over a spatial scale no larger than 15 arcsec $\times$ 15 arcsec.

Planning

Plans shall be formulated for off-line calibrations of each SI:
- **Req a:** Plans for deriving accuracy requirements and making measurements
- **Req b:** Plans for archiving data
- **Req c:** Plans for transferring data to the ASC

HRC

Req : The flight microchannel plates, flight UV/ion shields, and HRC-I and HRC-S flight instruments shall be independently calibrated.

UV/Ion Shield

Req : At a minimum, the following UV/ion-shield measurements shall be performed:
- X-ray transmission as a function of energy and position
- UV transmission as a function of energy and position
- Visible light transmission
- Operating potential
- Electron photoemissivity yield

Microchannel Plates (MCPs)

Req : At a minimum, the following MCP measurements shall be performed:
- Quantum efficiency as a function of energy, position, and incident angle.
- Energy resolution as a function of energy, position, and incident angle .
- Photocathode stability (for non-flight MCPs) as a function of charge accumulation.

HRC-I & HRC -S

Req : At a minimum, the following HRC measurements shall be performed:
- Room background as a function of energy and position.
- Quantum efficiency as a function of energy, position, and incident angle.
- Spatial resolution as a function of energy, position, and incident angle.
- Spatial linearity as a function of energy, position, and incident angle.
- Count-rate linearity as a function of energy.
- Quantum efficiency in the ultraviolet as a function of energy and position
- Preamplifier gains
- Preamplifier noise levels
- Energy scale as a function of position
- Linearity of all analog-to-digital converters
- Linearity of all pulse height analyzers
- Position and orientation of all HRC-I and HRC-S detector reference points and axes with respect to the HRC fiducial lights

ACIS

Req : The flight CCDs, flight filters, and flight ACIS-S and ACIS-I detector assemblies shall be independently calibrated.

Filters

Req : At a minimum, the following filter measurements shall be performed:

- X-ray transmission as a function of energy and position.
- UV transmission as a function of energy and position
- Visible-light transmission

CCDs

Req : At a minimum, the following CCD measurements shall be performed:

- Quantum efficiency as a function of position, energy, and temperature

ACIS-I and ACIS-S

Req : At a minimum, the following ACIS measurements shall be performed:

- Room background as a function of energy and position
- Quantum efficiency as a function of energy, read-out mode, position, and temperature
- Spatial resolution as a function of energy, read-out mode, position, and temperature
- Spatial linearity as a function of energy, position, and incident angle.
- Dark current and system noise as a function of position and temperature
- Energy resolution as a function of energy, read-out mode and position
- Charge-transfer and charge-collection efficiency, as functions of position, energy, and temperature
- Gain as a function of energy, position, and temperature
- Energy scale as a function of energy
- UV and optical response as a function of energy and position
- Position and orientation of all ACIS-I and ACIS-S detector reference points and axes with respect to the ACIS fiducial lights

LETG

Req : The grating facets, the Grating Element Support Structure (GESS), and the complete LETG assembly shall be independently calibrated.

Grating facets

Req : At a minimum, the following measurements shall be performed on a statistically meaningful sample of grating facets:

- Line period and line period variability as a function of temperature
- Slit-to-period ratio
- Efficiency as a function of energy and order number
- Line Response Function (LRF) as a function of energy and temperature

GESS

Req : At a minimum, the following GESS measurements shall be performed:

- Detailed spatial mapping of the as-built structure

LETG Assembly

Req : At a minimum, the following LETG measurements shall be performed:
- Alignment of individual facets with respect to the LETG reference axis

HETG

Req : The polyimide substrates, the grating facets, the HETG Element Support Structure (HESS), and the complete HETG assembly shall be calibrated independently.

Polyimide Substrates

Req : At a minimum, the following substrate measurements shall be performed on representative samples of non-flight material:
- X-ray transmission as a function of energy

Grating facets

Req : At a minimum, the following measurements shall be performed on a statistically meaningful sample of grating facets:
- Line period and line period variability (as a function of temperature if appropriate)
- Efficiency as a function of energy and order number

HESS

Req : At a minimum, the following HESS measurements shall be performed:
- Detailed mapping of the as-built HESS structure.

HETG Assembly

Req : At a minimum, the following HETG measurements shall be performed:
- Alignment of individual facets with respect to the HETG reference axis

6.3SPACECRAFT SYSTEMS AND SUBSYSTEMS MEASUREMENTS

All spacecraft systems and subsystems may impact the scientific performance of AXAF. We have specifically identified measurements necessary for calibration of the aspect system and the Inertial Reference Units (IRUs), both of which impact the aspect solutions. In addition, there are numerous alignments which require careful measurement.

6.3.1Planning

Req 6.3.1a: Plans shall be formulated for calibrating relevant spacecraft systems and subsystems — including calibration of the aspect system, Inertial Reference Units (IRUs), and spacecraft clock, and measurements of relative alignments of Focal-Plane Science Instruments (FPSIs), Objective Transmission Gratings (OTGs), Aspect Camera Assembly (ACA), Fiducial Light System (FLS), and telescope assembly:
- **Req 6.3.1b:** Plans and schedules for deriving accuracy requirements and making measurements
- **Req 6.3.1c:** Plans for archiving data
- **Req 6.3.1d:** Plans and schedules for transferring data to the ASC

6.3.2 Aspect System

Req 6.3.2: Aspect-camera CCDs, FLS, and ACA shall be calibrated independently.

CCDs

Req : At a minimum, the following CCD measurements shall be performed:
- Pixel-by-pixel maps as a function of wavelength, temperature, and intensity
- Pixel-by-pixel maps of dark current as a function of temperature
- Read-out noise
- Charge-transfer efficiency

Fiducial Light System (FLS)

Req : At a minimum, the following FLS measurements shall be performed:
- Emission spectra
- Absolute intensity

Aspect Camera Assembly

Req : At a minimum, the following ACA measurements shall be performed:
- Distortion maps
- Spatial resolution as a function of energy, intensity, and temperature
- Spectral resolution as a function of energy, intensity, and temperature
- Alignment to aspect camera subassembly reference points

We recommend that the distortion maps be constructed from at least 81 4×4 pixel maps from a 9×9 array of point sources. This array should be moved over the entire CCD field in steps small compared to a pixel.

6.3.3 Inertial Reference Units (IRUs)

Req 6.3.3: At a minimum, the following IRU measurements shall be performed:
- Bias
- Read-out noise
- Torque noise
- Drift rate ramp
- Scale factors
- Alignment parameters

6.4 XRCF AND XRCF X-RAY EQUIPMENT

6.4.1 Planning

Req 6.4.1a: Plans shall be developed for performing measurements characterizing the XRCF and its x-ray test equipment:
- **Req 6.4.1b:** Plans for deriving accuracy requirements and making measurements
- **Req 6.4.1c:** Plans for archiving data
- **Req 6.4.1d:** Plans for transferring data to the ASC

6.4.2X-Ray Source System (XSS)

Capabilities

Sources and Monochromators

X-ray calibration requires x-ray sources and monochromators and/or filters (for spectral purity). The X-ray Source System (XSS), derived to perform the measurements listed in §6.5 comprises the following:

43. A stationary-anode Electron-Impact Point Source (EIPS);
44. 2 high-intensity electron-impact Rotating Anode Sources (RASs);
45. A Penning Gas Discharge Source (PGDS)
46. 2 monochromators — a Reflection-Grating Monochromator (RGM, for <0.1 keV to 1.5 keV) and a Double-Crystal Monochromator (DCM, for 1 keV to 12 keV); and
47. A double filter-wheel assembly (for up to 2 thin filters in the x-ray path).

X-ray Line Energies

Table gives the x-ray line energies of electron-impact sources for probable target materials.

Table : Energies of lines from electron-impact targets

Target Material	Line	Energy (keV)	Wavelength (Angstroms)
Be	Kα	0.108	114.77
B	Kα	0.183	67.73
C	Kα	0.277	44.75
N	Kα	0.392	31.62
O	Kα	0.525	23.61
Na	Kα	1.041	11.91
	Kβ	1.071	11.57
Mg	Kα	1.253	9.89
	Kβ	1.302	9.52
Al	Kα	1.49	8.32
	Kβ	1.56	7.95
Si	Kα	1.74	7.12
	Kβ	1.84	6.74
Ti	Kα	4.51	2.75
	Kβ	4.93	2.51
	Lα	0.452	27.42
	Lβ	0.458	27.06
Cr	Kα	5.4	2.30
	Kβ	5.94	2.09
Fe	Kα	6.39	1.94
	Kβ	7.06	1.76
	Lα	0.705	17.58
	Lβ	0.718	17.26
Co	Lα	0.776	15.97

	Lβ	0.791	15.67
Ni	Kα	7.46	1.66
	Kβ	8.26	1.50
	Lα	0.851	14.57
	Lβ	0.868	14.28
Cu	Kα	8.03	1.54
	Kβ	8.9	1.39
	Lα	0.93	13.33
	Lβ	0.95	13.05
Zn	Lα	1.011	12.26
	Lβ	1.034	11.99
Ga	Lα	1.097	11.30
	Lβ	1.124	11.03
Ge	Lα	1.188	10.43
	Lβ	1.218	10.18
Zr	Lα	2.042	6.07
	Lβ	2.124	5.84
Mo	Lα	2.29	5.41
	Lβ	2.39	5.19
Ag	Lα	2.98	4.16
	Lβ	3.15	3.93
Sn	Lα	3.44	3.60
	Lβ	3.66	3.39
Au	Lα	9.71	1.28
	Lβ	11.44	1.08

Images of Sources and Source–Monochromators

Req : To determine spatial uniformity, high-resolution (0.1-mm) images of each x-ray source and x-ray source–monochromator shall be obtained. The peak of the distribution shall be measured to an accuracy of 10^{-4}.

Spectra and Line Shapes

Req : At a minimum, measurements shall be made to characterize the XSS line fluxes.

Filters

Req : At a minimum, the following filter measurements shall be performed:

- X-ray transmission as a function of energy and position
- Uniformity

Monochromators

Req : At a minimum, the following measurements shall be performed:
- Energy scale
- Relative throughput

6.4.3 HRMA X-ray Detector System (HXDS)

The XRCF will have the HRMA X-ray Detector System (HXDS), comprising the following detectors:

48. Flow Proportional Counters (FPCs);
49. Solid-State Detectors (SSDs); and
50. A MCP High-Speed Imager (HSI).

Some of these detectors — referred to as Beam Normalization Detectors (BNDs) —will monitor the x-ray beam to provide data for determining the relative and absolute efficiency of HRMA–FPSI combinations. In the following (§, §, and §), we discuss measurements required to characterize adequately the HXDS.

Flow Proportional Counters (FPCs)

Req : At a minimum, the following FPC measurements shall be performed:
- Background (at the XRCF) as a function of energy
- X-ray transmission as a function of energy and position, of the FPC's thin windows
- Relative efficiency as a function of energy, position, and gas composition.
- Absolute efficiency as a function of energy, position, and gas composition to an accuracy of 1%.
- Energy resolution as a function of energy, position, and gas composition
- Efficiency relative to other HXDS proportional counters, to an accuracy of 0.17%.
- Energy scale — i.e., conversion of pulse amplitude to energy

Solid-State Detectors (SSDs)

Req : At a minimum, the following SSD measurements shall be performed:
- Background (at the XRCF) as a function of energy
- Relative efficiency as a function of energy and position
- Absolute efficiency as a function of energy and position, to an accuracy of 1%
- Energy resolution as a function of energy and position
- Efficiency relative to other HXDS solid state detectors, to an accuracy of 0.17%
- Energy scale — i.e., conversion of pulse amplitude to energy
- Dark-current and system noise

High-Speed Imager (HSI)

Req : At a minimum, the following measurements shall be performed:

- Background (at the XRCF) as a function of energy and position
- Quantum efficiency as a function of energy, position, and incident angle
- Spatial resolution as a function of energy, position, and incident angle
- Spatial linearity as a function of energy, position, and incident angle
- Count-rate linearity as a function of energy
- Preamplifier gains
- Preamplifier noise levels
- Energy scale — i.e., conversion of pulse amplitude to energy — as a function of amplitude and position
- Linearity of all analog-to-digital converters (ADCs)
- Linearity of all pulse height analyzers

6.4.4X-ray Scattering

Req 6.4.4: The flux, if any, reaching the HRMA via an indirect path from each x-ray source (or x-ray source–monochromator or x-ray source–filter assembly) shall be characterized to a level of 10^{-5} of the clear beam.

6.4.5Position and Alignment Measurements

Precise knowledge of the relative position and alignment of the equipment at the XRCF can be important in modeling of performance and in determining the ultimate accuracy of the response functions.

Req 6.4.5: The relative positions of the XSS, HRMA, OTG, FPSI, and HXDS reference points and reference axes shall be accurately measured. The HRMA–FPSI separation shall be measured to an accuracy of 0.05 mm.

6.5HRMA AND SI CALIBRATIONS AT THE XRCF

6.5.1Introduction

In §6.5.2 we discuss the process to be used to arrive at the list of measurements to be performed at the XRCF. In §6.5.3 we provide a preliminary list: These should be regarded as definitive but not as requirements. However,

Req 6.5.1: The equipment necessary to accomplish the measurements listed in 6.5.3 is required.

We describe each measurement in terms of an objective and an accuracy. We also list the appropriate configuration and the required instrumentation, including analysis software. Specifically, each measurement description specifies the following:

51. Objective
52. Required accuracy
53. Test configuration
54. Appropriate aperture in which data is to be taken and/or analyzed
55. Appropriate energy bandwidth over which data is to be taken and/or analyzed
56. Accuracy of an individual data point.
57. Orientation of the HRMA relative to the focal plane detector.
58. Orientation of the HRMA relative to the x-ray source.
59. Environmental condition under which the measurements are to be performed.
60. Positioning equipment that needs to be used for the particular measurement
61. Photon energy or energies as appropriate
62. Particular x-ray source to be utilized
63. Data acquisition system
64. Brief description of the analysis that must be performed to interpret the data
65. Other information required to accomplish analysis of the data

We emphasize that *specific accuracies are preliminary*. In most cases, stated accuracies follow from analyses provided in references 16, 17 and 18 (§2); in some, stated accuracies follow from comments raised during preliminary review of drafts of this document. In general stated accuracies do not yet comply with requirements of §4. In §6.5.2 we specify the approach for dealing with this inconsistency.

6.5.2General Requirements

Calibration Implementation Team (CIT)

The spacecraft contractor (TRW) has overall responsibility for receiving inputs and for coordinating and documenting plans and procedures for accomplishing measurements at the XRCF. Success of this process relies on the active participation of appropriate parties.

> **Req :** A Calibration Implementation Team (CIT) — with participants from the SI teams, Project Science, ASC, SAO Mission Support, and other relevant organizations — shall be established to facilitate the accomplishment of the requirements in this document applicable to activities at the XRCF.

Planning

The spacecraft contractor (TRW) will describe in document XC01, overall plans and schedules for AXAF calibration activities at the XRCF.

> **Req :** At a minimum, XC01 shall include the following:
> - Plans for the development of procedures, and for procedure generation.
> - Plans for integrating systems
> - Plans for test rehearsal(s)
> - Plans for thermal testing
> - Plans for performing measurements — including x-ray measurements during rehearsal (§), and thermal testing and follow-up investigations resulting from analysis of planned measurements
> - Plans for disassembly and egress

Required Activities

Req : The test schedule and program shall include sufficient time for needed activities:

- Rehearsal(s) prior to the delivery of the HRMA to the XRCF. At least one in-depth rehearsal shall be performed. Rehearsals shall simulate as closely as possible the actual HRMA and HRMA–SI calibration activity and shall utilize all XSS and HXDS equipment.
- Planned measurements while the HRMA is at the XRCF
- Follow-up investigations while the HRMA is at the XRCF

Time Allocation

The HRMA and SIs will spend a limited time at the XRCF; thus careful planning is essential.

Req a: A carefully planned process shall be established for determining which measurements will be made. The Calibration Task Team (CTT) shall solicit and coordinate inputs (preliminary results listed in §6.5.3):

- Predictions to establish the importance of a measurement for determining the particular parameter (or parameters) of the relevant response function
- Evaluation of the possibility of accomplishing the measurement prior to XRCF
- Consideration of trade-off between on-ground and on-orbit measurements
- Simulations/calculations to evaluate which alternatives would contribute to optimizing the calibration

The results of this time-allocation process, equivalent to a revised version of §6.5.3, will serve as input to the CIT and be documented in XC03. It is quite possible that accomplishing all of the measurements requested exceeds the amount of time available while the HRMA is at the XRCF.

Req b: If there is insufficient time for all calibration measurements, the Project Scientist — in consultation with the CTT and subject to review by the Science Working Group — shall decide which measurements are to be performed.

X-ray Beam Monitoring and Characterization

Req : All focal-plane x-ray measurements (§6.5.3) at the XRCF shall be supplemented with measurements with appropriate non-focal-plane HXDS detectors — i.e., BNDs.

Data Archiving and Transfer

Req : All acquired data shall be stored, using predetermined formatting standards, in a secure and orderly manner and shall be available to the ASC.

6.5.3X-ray Measurements

This section summarizes representative configurations and x-ray measurements for calibrating AXAF. This preliminary list of measurements provides the basis for defining the scientific requirements for equipment to support the calibration of AXAF.

Alignment

HRMA Alignment

1. *Objective:* Measure the tilt angle between parabolic and hyperbolic elements of each mirror pair and the relative angles between the optical axes of different mirror pairs.
2. *Approach:* Compare out-of-focus images from single quadrants of each mirror pair.
3. *Accuracy:* ±0.1 arcsec.

Configuration	HRMA: Each quadrant of each mirror pair for all 16 combinations of quadrants and mirror pairs Detector: HSI
Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy the measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Detector center aligned with HRMA optical axis, out-of-focus.
HRMA–Source Relative Orientation	On-Axis
Environment	Nominal
Incident Energy	Al-K
Source Configuration	EIPS, filtered to maximize the line to continuum ratio
Positioning equipment	HRMA shutter and grating positioners; HSI positioner
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze HSI images, obtain relative focus positions, and determine alignment and tilt
Additional Input	HSI plate scale, HSI flat field, XRCF positioning and alignment parameters

4. *Special equipment requirements:* Shutters; X-positioning range of HXDS.

HRMA–HETG Alignment

5. *Objective:* Measure effects due to any transverse (Y&Z) misalignment of the HETG and determine focus-direction (X) repeatability of the insertion mechanism.
6. *Approach:* Examine the uniformity of out-of-focus zeroth- and first-order images; compare images after several insertion cycles.
7. *Accuracy:* ±0.5 mm in Y and Z and ±0.3 mm in X (focus direction).

Configuration	HRMA: Full aperture Grating: HETG Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy the measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Zeroth and first order images centered on detector, out of focus
HRMA–Source Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; HETG insertion mechanism; HSI positioner
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze HETG–HSI images and to determine relative alignment parameters
Additional input	HSI plate scale, HSI flat field, XRCF positioning and alignment parameters

HRMA–LETG Alignment

8. *Objective:* Measure effects due to any transverse (Y&Z) misalignment of the LETG and determine focus-direction (X) repeatability of the insertion mechanism.
9. *Approach:* Examine the uniformity of out-of-focus zeroth- and first-order images; compare images after several insertion cycles.
10. *Accuracy:* ±0.5 mm in Y and Z and ±0.3 mm in X (focus direction).

Configuration	HRMA: Full aperture Grating: LETG Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy the measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Zeroth and first order images centered on detector, out of focus
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; LETG insertion mechanism; HSI positioner
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze LETG–HSI images and to determine relative alignment parameters
Additional input	HSI plate scale, HSI flat field, XRCF positioning and alignment parameters

Focus

HRMA Focus — “Flapper Test”

11. *Objective:* Determine best focus location for each mirror pair.
12. *Approach:* Compare out-of-focus single-quadrant images for each mirror pair, as a function of detector position along focus (X) direction.
13. *Accuracy :* ±0.050 mm (each mirror pair).

Configuration	HRMA: Each quadrant of each mirror pair for all 16 combinations of quadrants and mirror pairs Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Detector center aligned with HRMA optical axis, vary focus
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; HSI positioner
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze HSI images and determine relative focus positions
Additional Input	HSI plate scale, HSI flat field, XRCF positioning and alignment parameters

HRMA Focus — Pinhole Test

14. *Objective:* Verify that the flapper test (§) has determined best-focus location for each mirror pair.
15. *Approach:* Examine pinhole scans of image at best focus, as determined with the flapper test.
16. *Accuracy :* ±0.050 mm (each mirror pair).

Configuration	HRMA: Each quadrant of each mirror pair for all 16 combinations of quadrants and mirror pairs Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Detector center aligned with HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; HSI positioner
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze HSI images and determine PRF
Additional Input	HSI plate scale, HSI flat field, XRCF positioning and alignment parameters

HRMA–HETG Focus

17. *Objective:* Determine location of best focus.
18. *Approach:* Compare centroids of single-quadrant images at zeroth order, as a function of detector position along focus direction.
19. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Grating: HETG Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	>2500 zeroth-order events / image
HRMA–Detector Relative Location and Orientation	Detector center aligned with HRMA optical axis, vary focus
Source–HRMA Relative Orientation	On-Axis
Environment	nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; HSI positioner, HETG insertion mechanism
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze HETG–HSI images and determine relative focus
Additional Input	HSI plate scale, HSI flat field, XRCF positioning and alignment parameters

HRMA–LETG Focus

20. *Objective:* Determine location of best focus.
21. *Approach:* Compare centroids of single-quadrant images at zeroth order, as a function of detector position along focus direction.
22. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Grating: LETG Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	>2500 zeroth-order events / image
HRMA–Detector Relative Location and Orientation	Detector center aligned with HRMA optical axis, vary focus
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; HSI positioner, LETG insertion mechanism
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze LETG–HSI images and determine relative focus
Additional Input	HSI plate scale, HSI flat field, XRCF positioning and alignment parameters

HRMA–ACIS-I Focus

23. *Objective:* Determine location of best focus.
24. *Approach:* Compare centroids of single-quadrant images, as a function of position along focus direction.
25. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Detector: ACIS-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS-I images and determine relative focus
Additional Input	ACIS-I plate scale, ACIS-I flat field, XRCF positioning and alignment parameters

26. *Special equipment requirements:* SIMSS X-position range

HRMA–ACIS-S Focus

27. *Objective:* Determine location of best focus.
28. *Approach:* Compare centroids of single-quadrant images, as a function of position along focus direction.
29. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Detector: ACIS-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus
Source–HRMA Relative Orientation	On-Axis
N	nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS-S images and determine relative focus
Additional Input	ACIS-S plate scale, ACIS-S flat field, XRCF positioning and alignment parameters

- *Special equipment requirements:* SIMSS X-position range.

HRMA–HRC-I Focus

1. *Objective:* Determine location of best focus.
2. *Approach:* Compare centroids of single-quadrant images, as a function of position along focus direction.
3. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant; full Detector: HRC-I
Detector Aperture	Full; shuttered
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus, dithered
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-I images and determine relative focus
Additional Input	HRC-I plate scale, HRC-I flat field, XRCF positioning and alignment parameters

4. *Special equipment requirements:* SIMSS X-position range.

HRMA–HRC-S Focus

5. *Objective:* Determine location of best focus.
6. *Approach:* Compare centroids of single-quadrant images, as a function of position along focus direction.
7. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	>1000 counts / image
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus, dithered
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze dithered HRC-S images and determine relative focus
Additional Input	HRC-S plate scale, HRC-S flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–HETG–ACIS-I Focus

8. *Objective:* Determine location of best focus.
9. *Approach:* Compare centroids of single-quadrant images at zeroth order, as a function of position along focus axis.
10. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Grating: HETG Detector: ACIS-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus, dithered
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze dithered HETG–ACIS-I images and determine relative focus
Additional Input	ACIS-I plate scale, ACIS-I flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–HETG–ACIS-S Focus

11. *Objective:* Determine location of best focus.
12. *Approach:* Compare centroids of single-quadrant images at zeroth order, as a function of position along focus axis.
13. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Grating: HETG Detector: ACIS-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	>1000 counts / image
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus, dithered
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze dithered HETG–ACIS-S images and determine relative focus
Additional Input	ACIS-S plate scale, ACIS-S flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–HETG–HRC-I Focus

14. *Objective:* Determine location of best focus.
15. *Approach:* Compare centroids of single-quadrant images at zeroth order, as a function of position along focus axis.
16. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Grating: HETG Detector: HRC-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus, dithered
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze dithered HETG–HRC-I images and determine relative focus
Additional Input	HRC-I plate scale, HRC-I flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–HETG–HRC-S Focus

17. *Objective:* Determine location of best focus.
18. *Approach:* Compare centroids of single-quadrant images at zeroth order, as a function of position along focus axis.
19. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Grating: HETG Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus, dithered
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze dithered HETG–HRC-S images and determine relative focus
Additional Input	HRC-S plate scale, HRC-S flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–LETG–ACIS-S Focus

20. *Objective:* Determine location of best focus.
21. *Approach:* Compare centroids of single-quadrant images at zeroth order, as a function of position along focus axis.
22. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Grating: LETG Detector: ACIS -S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	>1000 zeroth-order counts / image
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus, dithered
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze dithered HETG–ACIS-S images and determine relative focus
Additional Input	ACIS-S plate scale, ACIS-S flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–LETG–HRC-I Focus

23. *Objective:* Determine location of best focus.
24. *Approach:* Compare centroids of single-quadrant images at zeroth order, as a function of position along focus axis.
25. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Grating: LETG Detector: HRC-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus, dithered
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze dithered LETG–HRC-I images and determine relative focus
Additional Input	HRC-I plate scale, HRC-I flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–LETG–HRC-S Focus

26. *Objective:* Determine location of best focus.
27. *Approach:* Compare centroids of single-quadrant images at zeroth order, as a function of position along focus axis.
28. *Accuracy:* ±0.050 mm in focus (X) direction, ±0.002 mm in transverse plane.

Configuration	HRMA: Each quadrant Grating: LETG Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	>1000 counts / image
HRMA–Detector Relative Location and Orientation	Near nominal observing position with respect to HRMA optical axis, vary focus, dithered
Source–HRMA Relative Orientation	On-Axis
Environment	Nominal
Incident Flux	Al-K
Source Configuration	EIPS, Al filter
Positioning equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze dithered LETG–HRC-S images and determine relative focus
Additional Input	HRC-S plate scale, HRC-S flat field, XRCF positioning and alignment parameters, output from dither control

PRF/LRF: Inner Core

HRMA PRF: 0–3 arcsec

29. *Objective:* Determine PRF out to 3-arcsec radius as a function of energy, off-axis angle, and temperature.
30. *Approach:* Scan central portion of the image of a point source with a small pinhole in front of the appropriate HXDS focal-plane detector (FPC for low energies, SSD for high energies).
31. Accuracy: TBD.

Configuration	HRMA: Full aperture Detector: FPC, SSD
Detector Aperture	0.010 mm diameter pinhole
Detector Energy Bandwidth	Full
Data Point Accuracy	>50000 counts / point
HRMA–Detector Relative Location and Orientation	15x15 x-y scan in 0.2 arcsec steps, centered on HRMA optical axis, in-focus
Source–HRMA Relative Orientation	TBD directions ranging from 0-8 arcmin off-axis
Environment	TBD temperatures in range ± 5 C about nominal
Incident Flux	TBD energies from selection given in Table
Source Configuration	With FPC: EIPS, filtered With SSD: RAS, filtered
Positioning Equipment	HRMA shutter and grating positioners; image-plane FPC positioner, image-plane SSD positioner; FPC aperture select, SSD aperture select
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze pinhole data, to determine PRF, and to compare with predictions
Additional Input	Relative FPC efficiency, relative SSD efficiency, XRCF positioning and alignment parameters, x-ray source size and shape

• *Special equipment requirements:* Size and shape of x-ray source.

HRMA: 0–20 arcsec

32. *Objective:* Measure PRF out to 20-arcsec radius as a function of energy, off-axis angle, temperature.
33. *Approach:* Image a point source.
34. *Accuracy:* TBD.

Configuration	HRMA: Full aperture Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	TBD
HRMA–Detector Relative Location and Orientation	Centered on optical axis, in focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-8 arcmin off-axis
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	TBD energies from selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; HSI positioner
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze dithered HSI images, to determine PRF, and to compare with predictions
Additional Input	HSI plate scale, HSI flat field, XRCF positioning and alignment parameters, output from dither control

35. *Special equipment requirements:* Source size and shape; HSI spatial resolution, flat field and plate scale.

HRMA–ACIS-I PRF: 0–20 arcsec

36. *Objective:* Measure PRF out to 20-arcsec radius as a function of energy, off-axis angle, temperature, and ACIS read-out mode.
37. *Approach:* Image a point source. Obtain standard (dithered) images with a fixed central position for the detector and non-dithered images taken by moving the detector in sub-pixel steps (a 3×3 array) about the central position.
38. *Accuracy:* 2% in 0.5-arcsec bins at 0–16 arcsec; 5% in 5-arcsec bins at 16–20 arcsec.

DITHERED

Configuration	HRMA: Full aperture Detector: ACIS-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	>5000 counts / pixel (<16 arcsec radius), >1 count / pixel 16-20 arcsec radius
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis but offset from center sufficiently to obtain entire image on one chip, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-8 arcmin off-axis
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	TBD energies from selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze dithered ACIS-I images, to determine PRF, and to compare with predictions
Additional Input	ACIS-I plate scale, ACIS-I flat field, XRCF positioning and alignment parameters, output from dither control

NON-DITHERED

Configuration	HRMA: Full aperture Detector: ACIS-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	>5000 counts / pixel (<16 arcsec radius), >1 count / pixel 16-20 arcsec radius
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis but offset from center sufficiently to obtain entire image on one chip, in-focus, stepped
Source–HRMA Relative Orientation	TBD directions ranging from 0-8 arcmin off-axis
Environment	TBD temperatures in range ± 5 C about nominal
Incident Flux	TBD energies from selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS-I images, to determine PRF, and to compare with predictions
Additional Input	ACIS-I plate scale, ACIS-I flat field, ACIS-I pixel by pixel efficiency map of central region, XRCF positioning and alignment parameters

HRMA–ACIS-S PRF: 0–20 arcsec

39. *Objective:* Measure PRF out to 20-arcsec radius as a function of energy, off-axis angle, temperature, and ACIS read-out mode.
40. *Approach:* Image a point source.
41. *Accuracy:* 2% in 0.5-arcsec bins at 0–16 arcsec; 5% in 5-arcsec bins at 16–20 arcsec.

Configuration	HRMA: Full aperture Detector: ACIS-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	>5000 counts / pixel (<16 arcsec radius), >1 count / pixel 16-20 arcsec radius
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis but offset from center sufficiently to obtain entire image on one chip, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-8 arcmin off-axis
Environment	TBD temperatures in range ± 5 C about nominal
Incident Flux	TBD energies from selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS-S images, to determine PRF, and to compare with predictions
Additional Input	ACIS-S plate scale, ACIS-S flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–HRC-I PRF: 0–20 arcsec

42. *Objective:* Measure PRF out to 20-arcsec radius as a function of energy, off-axis angle and temperature.
43. *Approach:* Image a point source.
44. *Accuracy:* 1% of peak in 1-arcsec bins at 0–16 arcsec; 0.001% of peak in 5-arcsec bins at 16–20 arcsec.

Configuration	HRMA: Full aperture Detector: HRC-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–HRC-I FOV
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	TBD energies from selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-I images, to determine PRF, and to compare with predictions
Additional Input	HRC-I plate scale, HRC-I flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–HRC-S PRF: 0–20 arcsec

45. *Objective:* Measure PRF out to 20-arcsec radius as a function of energy, off-axis angle and temperature.
46. *Approach:* Image a point source.
47. *Accuracy:* 1% of peak in 1-arcsec bins at 0–16 arcsec; 0.001% of peak in 5-arcsec bins at 16–20 arcsec.

Configuration	HRMA: Full aperture Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–HRC-S FOV
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	TBD energies from selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-S images, to determine PRF, and to compare with predictions
Additional Input	HRC-S plate scale, HRC-S flat field, XRCF positioning and alignment parameters, output from dither control

HRMA–HETG–ACIS-I LRF: ±16 arcsec

48. *Objective:* Measure Line Response Function (LRF) within 16 arcsec of peak, as a function of focal length, energy, off-axis angle, and grating order.
49. *Approach:* Image x-ray lines dispersed by the grating. Integrate over cross-dispersion direction to obtain 1-arcsec bins along dispersion direction.
50. *Accuracy:* Determine each data point to better than 0.1% of peak response.

Configuration	HRMA: Full aperture Grating: HETG Detector: ACIS-I
Detector Aperture	Appropriate size CCD frame
Detector Energy Bandwidth	Sufficient to perform order separation
Data Point Accuracy	0.1% of peak response
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–ACIS-I FOV
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±2 angstroms of the line energy, TBD energies from the selection given in Table , at least one line in the energy range from 0.35 to 0.55 keV
Source Configuration	PGDS or RAS with RGM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze HETG–ACIS-I images, to determine LRF, and to compare with predictions
Additional Input	ACIS-I plate scale, ACIS-I flat field, XRCF positioning and alignment parameters, output from dither control, source spectra

51. *Special equipment requirements:* Narrow line between 0.35 keV and 0.55 keV.

HRMA–HETG–ACIS-S LRF: ±16 arcsec

52. *Objective:* Measure LRF within 16 arcsec of peak, as a function of focal length, energy, off-axis angle, and grating order.
53. *Approach:* Image x-ray lines dispersed by the grating. Integrate over cross-dispersion direction to obtain 1-arcsec bins along dispersion direction.

Accuracy: Determine each data point to better than 0.1% of peak response.

Configuration	HRMA: Full aperture Grating: HETG Detector: ACIS-S
Detector Aperture	Appropriate size CCD frame
Detector Energy Bandwidth	Sufficient to perform order separation
Data Point Accuracy	0.1% of peak response
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–ACIS-S FOV in dispersion direction
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±2 angstroms of the line energy, TBD energies from the selection given in Table , at least one line in the energy range from 0.35 to 0.55 keV
Source Configuration	PGDS or RAS with RGM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze HETG–ACIS-S images, to determine LRF, and to compare with predictions
Additional Input	ACIS-S plate scale, ACIS-S flat field, XRCF positioning and alignment parameters, output from dither control, source spectra

- *Special equipment requirements:* Narrow line between 0.35 keV and 0.55 keV.

HRMA–HETG–HRC-I LRF: ±16 arcsec

1. *Objective:* Measure LRF within 16 arcsec of peak, as a function of focal length, energy, off-axis angle, and grating order.
2. *Approach:* Image x-ray lines dispersed by the grating. Integrate over cross-dispersion direction to obtain 1-arcsec bins along dispersion direction.
3. *Accuracy:* Determine each data point to better than 0.1% of peak response.

Configuration	HRMA: Full aperture Grating: HETG Detector: HRC-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	0.1% of peak response
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–HRC-I FOV
Environment	TBD temperatures in range ± 5 C about nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ± 2 angstroms of the line energy, TBD energies from the selection given in Table , at least one line in the energy range from 0.35 to 0.55 keV
Source Configuration	PGDS or RAS with RGM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze dithered HETG–HRC-I images, to determine LRF, and to compare with predictions
Additional Input	HRC-I plate scale, HRC-I flat field, XRCF positioning and alignment parameters, output from dither control, source spectra

4. *Special equipment requirements:* Narrow line between 0.35 keV and 0.55 keV.

HRMA–HETG–HRC-S LRF: ±16 arcsec

5. *Objective:* Measure LRF within 16 arcsec of peak, as a function of focal length, energy, off-axis angle, and grating order.
6. *Approach:* Image x-ray lines dispersed by the grating. Integrate over cross-dispersion direction to obtain 1-arcsec bins along dispersion direction.
7. *Accuracy:* Determine each data point to better than 0.1% of peak response.

Configuration	HRMA: Full aperture Grating: HETG Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	0.1% of peak response
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–HRC-S FOV in the dispersion direction
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±2 angstroms of the line energy, TBD energies from the selection given in Table , at least one line in the energy range from 0.35 to 0.55 keV
Source Configuration	PGDS or RAS with RGM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze dithered HETG–HRC-S images, to determine LRF, and to compare with predictions
Additional Input	HRC-S plate scale, HRC-S flat field, XRCF positioning and alignment parameters, output from dither control, source spectra

8. *Special equipment requirements:* Narrow line between 0.35 keV and 0.55 keV.

HRMA–LETG–ACIS-I LRF: ±16 arcsec

9. *Objective:* Measure LRF within 16 arcsec of peak, as a function of focal length, energy, off-axis angle, and grating order.
10. *Approach:* Image x-ray lines dispersed by the grating. Integrate over cross-dispersion direction to obtain 1-arcsec bins along dispersion direction.
11. *Accuracy:* Determine each data point to better than 0.1% of peak response.

Configuration	HRMA: Full aperture Grating: LETG Detector: ACIS-I
Detector Aperture	Appropriate size ACIS frame
Detector Energy Bandwidth	Sufficient to perform order separation
Data Point Accuracy	0.1% of peak response
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–ACIS-I FOV
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±2 angstroms of the line energy, TBD energies from the selection given in Table , at least one line in the energy range from 0.085 to 0.110 keV
Source Configuration	PGDS or RAS with RGM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze dithered LETG–ACIS-I images, to determine LRF, and to compare with predictions
Additional Input	ACIS-I plate scale, ACIS-I flat field, XRCF positioning and alignment parameters, output from dither control, source spectra

12. *Special equipment requirements:* Narrow line between 0.085 keV and 0.110 keV.

HRMA–LETG–ACIS-S LRF: ±16 arcsec

13. *Objective:* Measure LRF within 16 arcsec of peak, as a function of focal length, energy, off-axis angle, and grating order.
14. *Approach:* Image x-ray lines dispersed by the grating. Integrate over cross-dispersion direction to obtain 1-arcsec bins along dispersion direction.
15. *Accuracy:* Determine each data point to better than 0.1% of peak response.

Configuration	HRMA: Full aperture Grating: LETG Detector: ACIS-S
Detector Aperture	Appropriate size ACIS frame
Detector Energy Bandwidth	Sufficient to perform order separation
Data Point Accuracy	0.1% of peak response
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–ACIS-S FOV in the dispersion direction
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±2 angstroms of the line energy, TBD energies from the selection given in Table , at least one line in the energy range from 0.085 to 0.110 keV
Source Configuration	PGDS or RAS with RGM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze dithered LETG–ACIS-S images, to determine LRF, and to compare with predictions
Additional Input	ACIS-S plate scale, ACIS-S flat field, XRCF positioning and alignment parameters, output from dither control, source spectra

16. *Special equipment requirements:* Narrow line between 0.085 keV and 0.110 keV.

HRMA–LETG–HRC-I LRF: ±16 arcsec

17. *Objective:* Measure LRF within 16 arcsec of peak, as a function of focal length, energy, off-axis angle, and grating order.
18. *Approach:* Image x-ray lines dispersed by the grating. Integrate over cross-dispersion direction to obtain 1-arcsec bins along dispersion direction.
19. *Accuracy:* Determine each data point to better than 0.1% of peak response.

Configuration	HRMA: Full aperture Grating: LETG Detector: HRC-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	0.1% of peak response
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–HRC-I FOV
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±2 angstroms of the line energy, TBD energies from the selection given in Table , at least one line in the energy range from 0.085 to 0.110 keV
Source Configuration	PGDS or RAS with RGM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze dithered LETG–HRC-I images, to determine LRF, and to compare with predictions
Additional Input	HRC-I plate scale, HRC-I flat field, XRCF positioning and alignment parameters, output from dither control, source spectra

20. *Special equipment requirements:* Narrow line between 0.085 keV and 0.110 keV.

HRMA–LETG–HRC-S LRF: ±16 arcsec

21. *Objective:* Measure LRF within 16 arcsec of peak, as a function of focal length, energy, off-axis angle, and grating order.
22. *Approach:* Image x-ray lines dispersed by the grating. Integrate over cross-dispersion direction to obtain 1-arcsec bins along dispersion direction.
23. *Accuracy:* Determine each data point to better than 0.1% of peak response.

Configuration	HRMA: Full aperture Grating: LETG Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	0.1% of peak response
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–HRC-S FOV in the dispersion direction
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±2 angstroms of the line energy, TBD energies from the selection given in Table , at least one line in the energy range from 0.085 to 0.110 keV
Source Configuration	PGDS or RAS with RGM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze dithered LETG–HRC-S images, to determine LRF, and to compare with predictions
Additional Input	HRC-S plate scale, HRC-S flat field, XRCF positioning and alignment parameters, output from dither control, source spectra

24. *Special equipment requirements:* Narrow line between 0.085 keV and 0.110 keV.

PRF: 16–360 arcsec

HRMA

25. *Objective:* Measure PRF at radii from 16 arcsec to 360 arcsec, as a function of energy, off-axis angle, and temperature.
26. *Approach:* Image a point source, but occult the central core (out to 16-arcsec radius).
27. *Accuracy:* At least 50 counts per 8-arcsec × 8-arcsec bin (radii 16–60 arcsec); at least 50 counts per 30-arcsec × 30-arcsec bin (radii 60–360 arcsec).

Configuration	HRMA: Full aperture Detector: HSI
Detector Aperture	Full aperture with central core occulted
Detector Energy Bandwidth	Full
Data Point Accuracy	>50 counts / 8 $arcsec^2$ (16-60 arcsec) >50 counts / 30 $arcsec^2$ (60-360 arcsec)
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	TBD directions ranging from on-axis to FWHM of the combined HRMA–HSI FOV
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	TBD energies from selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; HSI positioner, image occulter
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze HSI images, to determine PRF, and to compare with predictions
Additional Input	HSI plate scale, HSI flat field, HSI PRF, XRCF positioning and alignment parameters, source spectra

28. *Special equipment requirements:* Positioning accuracy of HSI.

LRF: ±100 arcsec

HRMA–MEG

29. *Objective:* Measure LRF within 100 arcsec of peak in zeroth, ±1st, and ±3rd order.
30. *Approach:* Scan across dispersed images with various sized pinholes.
31. *Accuracy:* 2%.
32. *Note:* Investigate use of the HSI as an alternate detector for this measurement.

Configuration	HRMA: HEG occulted Grating: HETG Detector: FPC
Detector Aperture	0.1, 0.22, 0.6, 1.1, 2.8, 13 arcsec diam. pinholes
Detector Energy Bandwidth	Full
Data Point Accuracy	>10000 counts
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±1 angstrom of the line energy, two energies - Mg-K and one line near 0.4 keV
Source Configuration	PGDS RAS with RGM
Positioning Equipment	HRMA shutter and grating positioners; HRMA shutter control, image plane FPC positioner, FPC aperture select
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display FPC pulse height spectra, counts in focal plane and beam normalization detectors, and calculate and display LRF.
Additional Input	Relative FPC efficiencies, XRCF positioning and alignment parameters, source size/shape, source spectra

33. *Special equipment requirements:* High-resolution monochromator.

HRMA–HEG

34. *Objective:* Measure LRF within 100 arcsec of peak in zeroth, ±1st, and ±3rd order.
35. *Approach:* Scan across dispersed images with various sized pinholes.
36. *Accuracy:* 2%.
37. *Note:* Investigate use of the HSI as an alternate detector for this measurement.

Configuration	HRMA: MEG occulted Grating: HETG Detector: FPC
Detector Aperture	0.1, 0.22, 0.6, 1.1, 2.8, 13 arcsec diam. pinholes
Detector Energy Bandwidth	Full
Data Point Accuracy	>10000 counts
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±1 angstrom of the line energy, TBD energies from the selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; HRMA shutter control, image plane FPC positioner, FPC aperture select
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display FPC pulse height spectra, counts in focal plane and beam normalization detectors, and calculate and display LRF.
Additional Input	Relative FPC efficiencies, XRCF positioning and alignment parameters, source size/shape, source spectra

HRMA–LETG

38. *Objective:* Measure LRF within 100 arcsec of peak in zeroth and ±1st order.
39. *Approach:* Scan across dispersed images with various sized pinholes..
40. *Accuracy:* 2%.

Configuration	HRMA: Full aperture Grating: LETG Detector: FPC
Detector Aperture	0.1, 0.22, 0.6, 1.1, 2.8, 13 arcsec diam. pinholes
Detector Energy Bandwidth	Full
Data Point Accuracy	>10000 counts
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Narrow line emission with E/dE>1000, the line to satellite line plus continuum ratio must be greater than 100 within ±5 angstrom of the line energy, TBD energies from the selection given in Table
Source Configuration	PGDS RAS with RGM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; image plane FPC positioner, FPC aperture select
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display FPC pulse height spectra, counts in focal plane and beam normalization detectors, to calculate and display LRF.
Additional Input	Relative FPC efficiencies, XRCF positioning and alignment parameters, source size/shape, source spectra

41. *Special equipment requirements:* A penning gas discharge source and a low energy monochromators.

PRF: Wings

HRMA–HRC-I PRF: 6–32 arcmin

42. *Objective:* Measure PRF from 6-arcmin to 32-arcmin radii, as a function of energy.
43. *Approach:* Image a point source. Bin data in 3-arcmin × 3-arcmin cells at 6–18 arcmin from peak and in 5-arcmin × 5-arcmin cells at 18–32 arcmin from peak.
44. *Accuracy:* 0.001% of peak as determined from inner core measurements (§).

Configuration	HRMA: Full aperture Detector: HRC-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	0.001% of peak surface brightness (§).
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Line emission with a minimum of continuum, TBD energies from the selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-I images and to determine PRF.
Additional Input	HRC-I parameters, XRCF positioning and alignment parameters, source size/shape, source spectra

45. *Special equipment requirements:* Positioning range of SIMSS.

HRMA–ACIS-I PRF: 6–32 arcmin

46. *Objective:* Measure PRF from 6-arcmin to 32-arcmin radii, as a function of energy.
47. *Approach:* Image a point source. Bin data in 3-arcmin × 3-arcmin cells at 6–18 arcmin from peak and in 5-arcmin × 5-arcmin cells at 18–32 arcmin from peak.
48. *Accuracy:* 0.001% of peak as determined from inner core measurements (§).

Configuration	HRMA: Full aperture Detector: ACIS-I
Detector Aperture	Full
Detector Energy Bandwidth	ACIS-I FWHM centered on line
Data Point Accuracy	0.001% of peak surface brightness ().
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Line emission, TBD energies from the selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS-I images and to determine PRF.
Additional Input	ACIS-I parameters, XRCF positioning and alignment parameters, source size/shape, source spectra

49. *Special equipment requirements:* Positioning range of SIMSS.

Encircled Energy

HRMA

50. *Objective:* Determine absolute and relative effective area of the HRMA, as a function of off-axis angle, energy, and temperature, for radii from 0.1 arcsec to the greater of 400 arcsec or the 99%-encircled-energy radius.
51. *Approach:* Center pinholes of various radii on image of a point source.
52. *Accuracy:* Absolute: TBD. Relative: 1% of peak for values exceeding 10% of peak and 10% for smaller values.

Configuration	HRMA: Full aperture Detector: FPC or SSD (depending on energy)
Detector Aperture	approx. 0.05, 0.08, 0.11, 0.16, 0.21, 0.31, 0.42, 0.52, 0.73, 1.04, 1.56, 2.08, 3.1, 5.2, 10.4, 20.8, 41.7, 52, 104, 208, 396 arcsec radius
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>100000 counts within BND energy resolution >100000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	TBD directions ranging from 0-30 arcmin off-axis
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	FPC: Line emission, TBD energies from the selection given in Table SSD: continuum
Source Configuration	EIPS, filtered RAS, filtered
Positioning Equipment	HRMA shutter and grating positioners; FPC aperture select, image plane FPC positioner, SSD aperture select, image plane SSD positioner, filter selector
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to calculate absolute effective area for each pinhole size, combine results to obtain encircled energy curve, cross-check with PRF measurements, and compare with predictions.
Additional Input	Relative and absolute FPC efficiencies, relative and absolute SSD efficiencies, XRCF positioning and alignment parameters, source size/shape, source spectra, filter transmission, beam uniformity

53. *Special equipment requirements:* Pinhole positioning and area accuracies; relative and absolute FPC and SSD efficiency accuracies (including live-time accuracy, electronic gain stability, etc.); source size, shape, and intensity stability; and spatial resolution of beam maps.

Effective Area

HRMA–ACIS-I Effective Area

54. *Objective:* Determine absolute effective area of the HRMA–ACIS-I, as a function of off-axis angle, energy, temperature and ACIS read-out mode over several TBD-sized focal-plane areas.
55. *Approach:* Compare x-ray-line flux in images with that obtained by an absolutely calibrated SSD BND.
56. *Accuracy:* 1%.
57. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Detector: ACIS-I
Detector Aperture	TBD
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>100000 counts within BND energy resolution >100000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-30 arcmin off-axis
Environment	TBD temperatures in range ± 5 C about nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS-I images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	ACIS-I parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, filter transmission, beam uniformity

58. *Special equipment requirements:* SSD-BND absolute efficiency, gain stability, spectral resolution, etc.; spatial scale of beam maps; x-ray source stability and filter uniformity.

HRMA–ACIS-S Effective Area

59. *Objective:* Determine absolute effective area of the HRMA–ACIS-S, as a function of off-axis angle, energy, temperature and ACIS read-out mode over several TBD-sized focal-plane areas.
60. *Approach:* Compare x-ray-line flux in images with that obtained by an absolutely calibrated SSD BND.
61. *Accuracy:* 1%.
62. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Detector: ACIS-S
Detector Aperture	TBD
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>100000 counts within BND energy resolution >100000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-30 arcmin off-axis
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS-S images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	ACIS-S parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, filter transmission, beam uniformity

HRMA–HRC-I Effective Area

63. *Objective:* Determine absolute effective area of the HRMA–HRC-I, as a function of off-axis angle, energy, and temperature over several TBD-sized focal-plane areas.
64. *Approach:* Compare x-ray-line flux in images with that obtained by an absolutely calibrated FPC BND.
65. *Accuracy:* 5%.
66. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Detector: HRC-I
Detector Aperture	TBD
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>70000 counts within BND energy resolution >70000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-21 arcmin off-axis
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	RAS with RGM RAS with DCM EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-I images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	HRC-I parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

67. *Special equipment requirements:* FPC-BND absolute efficiency, gain stability, spectral resolution, etc.; spatial resolution of beam maps; x-ray source stability and filter uniformity.

HRMA–HRC-S Effective Area

68. *Objective:* Determine absolute effective area of the HRMA–HRC-S, as a function of off-axis angle, energy, and temperature over several TBD-sized focal-plane areas.
69. *Approach:* Compare x-ray-line flux in images with that obtained by an absolutely calibrated FPC BND.
70. *Accuracy:* 5%.
71. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Detector: HRC-S
Detector Aperture	TBD
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>70000 counts within BND energy resolution >70000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-21 arcmin off-axis
Environment	TBD temperatures in range ±5 C about nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-S images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	HRC-S parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

HRMA–HETG–ACIS-I Effective Area

72. *Objective:* Determine on-axis absolute and relative effective area of the HRMA–HETG–ACIS-I, as a *continuous* function of energy, off-axis angle, and grating order, for a TBD number of arcsec-wide regions centered on the LRF peak.
73. *Approach:* Compare x-ray-line flux in images with that obtained by absolutely calibrated BNDs. Use a high-intensity source–monochromator to fill in region between bright lines. Scan spectrum with resolving power of E/30; repeat selected regions (those with features) with E/100.
74. *Accuracy:* 10% absolute; 2% relative.
75. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Grating: HETG Detector: ACIS-I
Detector Aperture	Appropriate sized ACIS frame centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>70000 counts within BND energy resolution >70000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-11 arcmin off-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.4 to 4.0 keV
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze HETG–ACIS-I images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	ACIS-I parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

HRMA–HETG–ACIS-S Effective Area

76. *Objective:* Determine on-axis absolute and relative effective area of the HRMA–HETG–ACIS-S as a *continuous* function of energy, off-axis angle, and grating order, for a TBD number of arcsec-wide regions centered on the LRF peak.
77. *Approach:* Compare x-ray-line flux in images with that obtained by absolutely calibrated BNDs. Use a high-intensity source–monochromator to fill in region between bright lines. Scan spectrum with resolving power of E/30; repeat selected regions (those with features) with E/100.
78. *Accuracy:* 10% absolute; 2% relative.
79. *Note:* It may be advantageous to defocus, rather than dither, the focal plane detector.

Configuration	HRMA: Full aperture Grating: HETG Detector: ACIS-S
Detector Aperture	Appropriate sized ACIS frame centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>70000 counts within BND energy resolution >70000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-11 arcmin off-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.4 to 4.0 keV
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze HETG–ACIS-S images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	ACIS-S parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

HRMA–HETG–HRC-I Effective Area

80. *Objective:* Determine on-axis absolute and relative effective area of the HRMA–HETG–HRC-I, as a *continuous* function of energy, off-axis angle, and grating order, for a TBD number of arcsec-wide regions centered on the LRF peak.
81. *Approach:* Compare x-ray-line flux in images with that obtained by absolutely calibrated BNDs. Use a high-intensity source/monochromator to fill in region between bright lines. Scan spectrum with resolving power of E/30; repeat selected regions (those with features) with E/100.
82. *Accuracy:* 10% absolute; 2% relative.
83. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Grating: HETG Detector: HRC-I
Detector Aperture	Appropriate sized HRC region centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>70000 counts within BND energy resolution >70000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-21 arcmin off-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.4 to 4.0 keV
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HETG–HRC-I images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	HRC-I parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

HRMA–HETG–HRC-S Effective Area

84. *Objective:* Determine on-axis absolute and relative effective area of the HRMA–HETG–HRC-S, as a *continuous* function of energy, off-axis angle, and grating order, for a TBD number of arcsec-wide regions centered on the LRF peak.
85. *Approach:* Compare x-ray-line flux in images with that obtained by absolutely calibrated BNDs. Use a high-intensity source–monochromator to fill in region between bright lines. Scan spectrum with resolving power of E/30; repeat selected regions (those with features) with E/100.
86. *Accuracy:* 10% absolute; 2% relative.
87. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Grating: HETG Detector: HRC-S
Detector Aperture	Appropriate sized HRC region centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>70000 counts within BND energy resolution >70000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-21 arcmin off-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.4 to 4.0 keV
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HETG–HRC-S images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	HRC-S parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

HRMA–LETG–ACIS-S Effective Area

88. *Objective:* Determine on-axis absolute and relative effective area of the HRMA–LETG–ACIS-S, as a *continuous* function of energy, off-axis angle, and grating order, for a TBD number of arcsec-wide regions centered on the LRF peak.
89. *Approach:* Compare x-ray-line flux in images with that obtained by absolutely calibrated BNDs. Use a high-intensity source–monochromator to fill in region between bright lines. Scan spectrum with resolving power of E/30; repeat selected regions (those with features) with E/100.
90. *Accuracy:* 10% absolute; 2% relative.
91. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Grating: LETG Detector: ACIS-S
Detector Aperture	Appropriate sized ACIS frame centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>70000 counts within BND energy resolution >70000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-24 arcmin off-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.09 to 4.0 keV
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze LETG–ACIS- S images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	ACIS-S parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

HRMA–LETG–HRC-I Effective Area

92. *Objective:* Determine on-axis absolute and relative effective area of the HRMA–LETG–HRC-I, as a *continuous* function of energy, off-axis angle, and grating order, for a TBD number of arcsec-wide regions centered on the LRF peak.
93. *Approach:* Compare x-ray-line flux in images with that obtained by absolutely calibrated BNDs. Use a high-intensity source–monochromator to fill in region between bright lines. Scan spectrum with resolving power of E/30; repeat selected regions (those with features) with E/100.
94. *Accuracy:* 10% absolute; 2% relative.
95. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Grating: LETG Detector: HRC-I
Detector Aperture	Appropriate sized HRC region centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>70000 counts within BND energy resolution >70000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-21 arcmin off-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.09 to 4.0 keV
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze LETG–HRC-I images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	HRC-I parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

HRMA–LETG–HRC-S Effective Area

96. *Objective:* Determine on-axis absolute and relative effective area of the HRMA–LETG–HRC-S, as a *continuous* function of energy, off-axis angle, and grating order, for a TBD number of arcsec-wide regions centered on the LRF peak.
97. *Approach:* Compare x-ray-line flux in images with that obtained by absolutely calibrated BNDs. Use a high-intensity source–monochromator to fill in region between bright lines. Scan spectrum with resolving power of E/30; repeat selected regions (those with features) with E/100.
98. *Accuracy:* 10% absolute; 2% relative.
99. *Note:* It may be advantageous to defocus, rather than dither, the focal-plane detector.

Configuration	HRMA: Full aperture Grating: LETG Detector: HRC-S
Detector Aperture	Appropriate sized HRC region centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	>70000 counts within BND energy resolution >70000 counts within focal plane detector energy resolution
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	TBD directions ranging from 0-21 arcmin off-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.09 to 4.0 keV
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze LETG–HRC-S images, apply dithering correction (if necessary), calculate effective area within selected regions, and compare with predictions.
Additional Input	HRC-S parameters, BND absolute and relative efficiency, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

Wavelength Scale

HRMA–LETG–ACIS-S Wavelength Scale

100. *Objective:* Determine on-axis absolute wavelength scale for the HRMA–LETG–ACIS-S.
101. *Approach:* Utilize data from measurements of LRF (§) and effective area (§). Measure spacing between zeroth- and first-order peaks of LRF as a function of energy.
102. *Accuracy:* 0.01 Angstrom.
103. *Note:* Effective-area measurements may not be usable for this purpose if data are obtained out-of-focus.

Configuration	HRMA: Full aperture Grating: LETG Detector: ACIS-S
Detector Aperture	Appropriate sized ACIS region centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.09 to 4.0 keV
Source Configuration	PGDS and/or RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze LETG–ACIS-S images, apply dithering correction (if necessary), calculate peak of LRF, calculate differences, and compare with predictions.
Additional Input	ACIS-S parameters, line energies, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

HRMA–LETG–HRC-I Wavelength Scale

104. *Objective:* Determine on-axis absolute wavelength scale for the HRMA–LETG–HRC-I combination.
105. *Approach:* Utilize data from measurements of LRF (§) and effective area (§). Measure spacing between zeroth- and first-order peaks of LRF as a function of energy.
106. *Accuracy:* 0.01 Angstrom.
107. *Note:* Effective-area measurements may not be usable for this purpose if data are obtained out-of-focus.

Configuration	HRMA: Full aperture Grating: LETG Detector: HRC-I
Detector Aperture	Appropriate sized HRC region centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.09 to 4.0 keV
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze LETG–HRC-I images, apply dithering correction (if necessary), calculate peak of LRF, calculate differences, and compare with predictions.
Additional Input	HRC-I parameters, line energies, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

HRMA–LETG–HRC-S Wavelength Scale

108. *Objective:* Determine on-axis absolute wavelength scale for the HRMA–LETG–HRC-S combination.
109. *Approach:* Utilize data from measurements of LRF (§) and effective area (§). Measure spacing between zeroth- and first-order peaks of LRF as a function of energy.
110. *Accuracy:* 0.01 Angstrom.
111. *Note:* Effective-area measurements may not be usable for this purpose if data are obtained out-of-focus.

Configuration	HRMA: Full aperture Grating: LETG Detector: HRC-S
Detector Aperture	Appropriate sized HRC region centered on line image
Detector Energy Bandwidth	FWHM centered on line
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table , other energies in bandwidth from 0.09 to 4.0 keV
Source Configuration	RAS with RGM RAS with DCM EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM instrument positioner, dithering control (if necessary), filter selector
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze LETG–HRC-S images, apply dithering correction (if necessary), calculate peak of LRF, calculate differences, and compare with predictions.
Additional Input	HRC-S parameters, line energies, XRCF positioning and alignment parameters, source spectra, monochromator transmission, filter transmission, beam uniformity

Off-Axis Effects: Spatial Distribution

HRMA

112. *Objective:* Determine spatial distribution of secondary effects (ghost images — non-reflected and singly-reflected x rays; fluorescence; scattering) in the image plane.

113. *Approach:* Obtain data with the x-ray source (20–60 arcmin) off-axis but with the detector centered on HRMA optical axis. Examine detected flux over entire detector aperture, in 5-arcmin × 5-arcmin bins.

114. *Accuracy:* 0.001% of peak (on-axis) intensity (estimated from the BNDs).

Configuration	HRMA: Full aperture Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	TBD directions ranging from 20-60 arcmin
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV) or Be-K and Fe-K
Source Configuration	RAS or EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; HSI positioner
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze HSI images, and to correlate intensity with BND.
Additional Input	HSI parameters, XRCF positioning and alignment parameters

115. *Special equipment requirements:* Tilt range of the HRMA with respect to the source-detector axis; position range of the HXDS.

HRMA–HETG–HRC-S

116. *Objective:* Determine spatial distribution of secondary effects (ghost images — non-reflected and singly-reflected x rays; fluorescence; scattering) in the image plane.
117. *Approach:* Obtain data with the x-ray source (20–60 arcmin) off-axis but with the detector centered on HRMA optical axis. Examine detected flux over entire detector aperture, in 5-arcmin × 5-arcmin bins.
118. *Accuracy:* 0.001% of peak (on-axis) intensity (estimated from the BNDs).

Configuration	HRMA: Full aperture Grating: HETG Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	TBD directions ranging from 20-60 arcmin
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV) or Be-K and Fe-K
Source Configuration	RAS or EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; HETG insertion mechanism, SIMSS positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-S images, and to correlate intensity with BND.
Additional Input	HRC-S parameters, XRCF positioning and alignment parameters

119. *Special equipment requirements:* Tilt range of the HRMA with respect to the source-detector axis; position range of the SIMSS.

HRMA–LETG–HRC-S

120. *Objective:* Determine spatial distribution of secondary effects (ghost images — non-reflected and singly-reflected x rays; fluorescence; scattering) in the image plane.

121. *Approach:* Obtain data with the x-ray source (20–60 arcmin) off-axis but with the detector centered on HRMA optical axis. Examine detected flux over entire detector aperture, in 5-arcmin × 5-arcmin bins.

122. *Accuracy:* 0.001% of peak (on-axis) intensity (estimated from the BNDs).

Configuration	HRMA: Full aperture Grating: LETG Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	TBD directions ranging from 20-60 arcmin
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV) or Be-K and Fe-K
Source Configuration	RAS or EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; HETG insertion mechanism, SIMSS positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-S images, and to correlate intensity with BND.
Additional Input	HRC-S parameters, XRCF positioning and alignment parameters

123. *Special equipment requirements:* Tilt range of the HRMA with respect to the source-detector axis; position range of the SIMSS.

HRMA–HRC-I

124. *Objective:* Determine spatial distribution of secondary effects (ghost images — non-reflected and singly-reflected x rays; fluorescence; scattering) in the image plane.
125. *Approach:* Obtain data with the x-ray source (20–60 arcmin) off-axis but with the detector centered on HRMA optical axis. Examine detected flux over entire detector aperture, in 5-arcmin $\times$ 5-arcmin bins.
126. *Accuracy:* 0.001% of peak (on-axis) intensity (estimated from the BNDs).

Configuration	HRMA: Full aperture Detector: HRC-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	TBD directions ranging from 20-60 arcmin
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV) or Be-K and Fe-K
Source Configuration	RAS or EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-I images, and to correlate intensity with BND.
Additional Input	HRC-I parameters, XRCF positioning and alignment parameters

127. *Special equipment requirements:* Tilt range of the HRMA with respect to the source-detector axis; position range of the SIMSS.

Off-Axis Effects: Spectral Composition

HRMA

128. *Objective:* Determine spatial distribution of secondary effects (ghost images — non-reflected and singly-reflected x rays; fluorescence; scattering) in the image plane.
129. *Approach:* Obtain data with the x-ray source (20–60 arcmin) off-axis but with the detector centered on HRMA optical axis.
130. *Accuracy:* TBD.
131. *Note:* This measurement is needed only if those in § give positive results.

Configuration	HRMA: Full aperture Detector: SSD
Detector Aperture	200 arcsec
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to satisfy measurement accuracy requirement
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	TBD directions ranging from 20-60 arcmin
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV)
Source Configuration	RAS
Positioning Equipment	HRMA shutter and grating positioners; focal plane SSD positioner, SSD aperture select
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze SSD spectra, and to correlate intensity with BND.
Additional Input	SSD parameters, XRCF positioning and alignment parameters

Molecular Contamination

HRMA–HETG

132. *Objective:* Search for effects of molecular contamination of the HRMA–HETG–HSI.
133. *Approach:* Obtain a spectrum over the entire operating range of the HETG; search for unanticipated spectral features.
134. *Accuracy:* 2% relative.

Configuration	HRMA: Full aperture Grating: HETG Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	10000 counts / energy bin
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV)
Source Configuration	RAS or EIPS
Positioning Equipment	HRMA shutter and grating positioners; HSI positioner
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze HETG–HSI spectra
Additional Input	HSI parameters, HETG parameters, XRCF positioning and alignment parameters

135. *Special equipment requirements:* Accuracy of HSI efficiency as a function of energy.

HRMA–LETG-HSI

136. *Objective:* Search for effects of molecular contamination of the HRMA–LETG–HSI.

137. *Approach:* Obtain a spectrum over the entire operating range of the LETG; search for unanticipated spectral features.

138. *Accuracy:* 2% relative.

Configuration	HRMA: Full aperture Grating: LETG Detector: HSI
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	10000 counts / energy bin
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV)
Source Configuration	RAS or EIPS
Positioning Equipment	HRMA shutter and grating positioners; HSI positioner
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze LETG–HSI spectra
Additional Input	HSI parameters, LETG parameters, XRCF positioning and alignment parameters

139. *Special equipment requirements:* Accuracy of HSI efficiency as a function of energy.

HRMA–ACIS-I

140. *Objective:* Search for effects of molecular contamination of the HRMA–ACIS-I.

141. *Approach:* Obtain a spectrum over the entire operating range of the ACIS-I; search for unanticipated spectral features.

142. *Accuracy:* 2% relative.

Configuration	HRMA: Full aperture Detector: ACIS-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	10000 counts / energy bin
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV)
Source Configuration	RAS or EIPS
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS spectra
Additional Input	ACIS-I parameters, XRCF positioning and alignment parameters

HRMA–HETG–ACIS-S

143. *Objective:* Search for effects of molecular contamination of the HRMA–HETG–ACIS-S.

144. *Approach:* Obtain a spectrum over the entire operating range of the HETG-ACIS-S; search for unanticipated spectral features.

145. *Accuracy:* 2% relative.

Configuration	HRMA: Full aperture Grating: HETG Detector: ACIS-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	10000 counts / energy bin
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV)
Source Configuration	RAS or EIPS
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze HETG–ACIS-S spectra
Additional Input	ACIS-S parameters, HETG parameters, XRCF positioning and alignment parameters

HRMA–LETG–HRC-S

146. *Objective:* Search for effects of molecular contamination of the HRMA–LETG–HRC-S.
147. *Approach:* Obtain a spectrum over the entire operating range of the LETG-HRC-S; search for unanticipated spectral features.
148. *Accuracy:* 2% relative.

Configuration	HRMA: Full aperture Grating: LETG Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	10000 counts / energy bin
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	Continuum (0.09-12 keV)
Source Configuration	RAS or EIPS
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze LETG–HRC-S spectra
Additional Input	HRC-S parameters, LETG parameters, XRCF positioning and alignment parameters

Spatial Conversions

HRMA–ACIS-I

149. *Objective:* Determine conversion from detector coordinates to distance and — through knowledge of focal length — angle, as a function of energy and temperature.
150. *Approach:* With the detector in focus and the source on-axis, vary transverse position of the detector to change position of image relative to the detector.
151. *Accuracy:* Relative position of centroid locations to within 4 micrometers.

Configuration	HRMA: Full aperture Detector: ACIS-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to measure separation between centroids to <4 microns
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner, dither control
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS images, apply dithering correction, and to determine relative displacement between images.
Additional Input	ACIS-I parameters, XRCF positioning and alignment parameters

152. *Special equipment requirements:* SIMSS alignment and positioning accuracy (<2 micrometers).

HRMA–ACIS-S

153. *Objective:* Determine conversion from detector coordinates to distance and — through knowledge of focal length — angle, as a function of energy and temperature.

154. *Approach:* With the detector in focus and the source on-axis, vary transverse position of the detector to change position of image relative to the detector.

155. *Accuracy:* Relative position of centroid locations to within 4 micrometers.

Configuration	HRMA: Full aperture Detector: ACIS-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to measure separation between centroids to <4 microns
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner, dither control
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to display/analyze ACIS images, apply dithering correction, and to determine relative displacement between images.
Additional Input	ACIS-S parameters, XRCF positioning and alignment parameters

156. *Special equipment requirements:* SIMSS alignment and positioning accuracy (<2 micrometers).

HRMA–HRC-I

157. *Objective:* Determine conversion from detector coordinates to distance and — through knowledge of focal length — angle, as a function of energy and temperature.

158. *Approach:* With the detector in focus and the source on-axis, vary transverse position of the detector to change position of image relative to the detector.

159. *Accuracy:* Relative position of centroid locations to within 4 micrometers.

Configuration	HRMA: Full aperture Detector: HRC-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to measure separation between centroids to <4 microns
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner, dither control
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-I images, apply dithering correction, and to determine relative displacement between images.
Additional Input	HRC-I parameters, XRCF positioning and alignment parameters

160. *Special equipment requirements:* SIMSS alignment and positioning accuracy (<2 micrometers).

HRMA–HRC-S

161. *Objective:* Determine conversion from detector coordinates to distance and — through knowledge of focal length — angle, as a function of energy and temperature.
162. *Approach:* With the detector in focus and the source on-axis, vary transverse position of the detector to change position of image relative to the detector.
163. *Accuracy:* Relative position of centroid locations to within 4 micrometers.

Configuration	HRMA: Full aperture Detector: HRC-S
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	Sufficient to measure separation between centroids to <4 microns
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner, dither control
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to display/analyze HRC-S images, apply dithering correction, and to determine relative displacement between images.
Additional Input	HRC-S parameters, XRCF positioning and alignment parameters

164. *Special equipment requirements:* SIMSS alignment and positioning accuracy (<2 micrometers).

Count-Rate Linearity

HRMA–ACIS-I

165. *Objective:* Determine linearity and accuracy of the measured counting rate in the ACIS-I detector, as a function of energy, incident flux, and read-out mode
166. *Approach:* Vary incident flux from a maximum of a few counts/100-pixels/frame read-out time down to 1% of this value. Compare with BND values.
167. *Accuracy:* 1% for full field and 5% for single pixel.

Configuration	HRMA: Full aperture Detector: ACIS-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	15000 counts in BND and ACIS frame, 600 counts in brightest pixel.
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner, dither control
Data Acquisition Hardware and Software	ACIS system
Data Reduction	Software to determine ACIS-I count rate and compare with BND.
Additional Input	ACIS-I parameters, XRCF positioning and alignment parameters

- *Special equipment requirements*: BND dynamic range for count rates.

HRMA–HRC-I

1. *Objective:* Determine linearity and accuracy of the measured counting rate in the HRC-I detector, as a function of energy, incident flux rate.
2. *Approach:* Vary incident flux from the HRC maximum down to 1% of this value. Compare with BND values.
3. *Accuracy:* 1% for full field and 5% for single pixel.

Configuration	HRMA: Full aperture Detector: HRC-I
Detector Aperture	Full
Detector Energy Bandwidth	Full
Data Point Accuracy	15000 counts in BND and HRC-I, 600 counts in brightest pixel.
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus, dithered
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from the selection given in Table
Source Configuration	EIPS with filters
Positioning Equipment	HRMA shutter and grating positioners; SIMSS positioner, SIM positioner, dither control
Data Acquisition Hardware and Software	HRC system
Data Reduction	Software to determine HRC-I count rate and compare with BND.
Additional Input	HRC-I parameters, XRCF positioning and alignment parameters

- *Special equipment requirements*: BND dynamic range for count rates.

Background

Measurements of the background (x-ray-like events in the detectors with the x-ray source off) are an integral part of the measurement process.

Req : Background measurements shall be performed as necessary to ensure that the uncertainty in the background contributes less than 0.05% to the uncertainty in any x-ray measurement taken at the XRCF.

Particulate Contamination

HRMA

1. *Objective:* Measure amount of particulate contamination that has accumulated on the HRMA.
2. *Approach:* The amount of particulate contamination may be estimated through analysis of data obtained during examination of the PRF wings (§). If the fractional areal coverage by dust exceeds 10^{-5}, repeat measurements, illuminating only individual HRMA quadrants, to measure azimuthal dependence.
3. *Accuracy:* Fractional areal coverage to better than 10^{-5}.

Configuration	HRMA: Single quadrants Detector: HSI
Detector Aperture	Full aperture with central core occulted
Detector Energy Bandwidth	Full
Data Point Accuracy	>50 counts / 8 arcsec^2 (16-60 arcsec) >50 counts / 30 arcsec^2 (60-360 arcsec)
HRMA–Detector Relative Location and Orientation	Aligned with and normal to HRMA optical axis, in-focus
Source–HRMA Relative Orientation	On-axis
Environment	Nominal
Incident Flux	TBD energies from selection given in Table
Source Configuration	EIPS, filtered
Positioning Equipment	HRMA shutter and grating positioners; HSI positioner, image occulter
Data Acquisition Hardware and Software	HXDS system
Data Reduction	Software to display/analyze HSI images, to determine PRF, and to compare with predictions
Additional Input	HSI plate scale, HSI flat field, HSI PRF, XRCF positioning and alignment parameters, source spectra

6.6POST-XRCF MEASUREMENTS

6.6.1HRC

Req 6.6.1: At a minimum, and subsequent to integration with the spacecraft, the following measurements shall be performed:

- Preamp gain, system noise, ADC and PHA linearity (using GSE precision pulsers)
- Preamp gain, system noise, ADC and PHA linearity (using on-board pulsers)
- Quantum efficiency and gain stability using an x-ray calibration source
- Background

6.6.2ACIS

Req 6.6.2: At a minimum, and subsequent to integration with the spacecraft, the following measurements shall be performed:

- TBD

6.6.3Spacecraft Subsystems

Req 6.6.3: At a minimum, and subsequent to integration of the instruments and HRMA with the spacecraft, the following measurements shall be performed:

- Alignment of the HRMA reference points with respect to the HRC and ACIS fiducial lights
- Alignment of the aspect camera system (including the periscope assembly) with respect to the HRC and ACIS fiducial lights
- Stray-light analyses and/or measurements

6.7ON-ORBIT MEASUREMENTS

Crucial to the calibration program are on-orbit calibration data — either from planned calibration measurements or from science observations. A clear understanding of on-orbit calibration, especially with regard to capabilities, can and should play an important role in establishing the on-ground program. When meaningful, on-orbit measurements are far more relevant than on-ground measurements because they reflect the actual on-orbit performance. For example, calibration of the plate scale and PRF and LRF cores seem amenable to on-orbit calibration. On the other hand, spectral response functions would seem to be uncalibratable on-orbit, given the absence of any spectral standards. Ultimately, the ASC is responsible for conducting the on-orbit calibration program.

Req 6.7: A program of on-orbit measurements shall be developed to support the requirements of §4.

6.7.1HRC

Req 6.7.1: At a minimum, on-orbit calibrations with the HRMA–HRC combinations shall include the following measurements:

- Relative PRF as a function of energy, off-axis angle, focal plane position, and time
- Energy resolution as a function of time.
- Alignment with respect to the aspect camera as a function of time
- UV sensitivity as a function of time
- Plate scale as a function of time
- Quantum efficiency (using radioactive sources) as a function of time.
- Best focus position as a function of time

6.7.2ACIS

Req 6.7.2: At a minimum, on-orbit calibrations with the HRMA–ACIS combinations shall include the following measurements:

- Relative PRF as a function of energy, off-axis angle, focal plane position, and time
- Energy resolution as a function of time
- Alignment with respect to the aspect camera as a function of time
- UV sensitivity as a function of time
- Dark current as a function of time
- Bias voltages as a function of time
- Plate scale as a function of time
- Quantum efficiency (using radioactive sources) as a function of time
- Best focus position as a function of time
- Level of molecular contamination added to the HRMA between the time the HRMA was at the XRCF and launch.

6.7.3Low-Energy Transmission-Grating Spectrometer (LETGS)

Req 6.7.3: At a minimum, on-orbit calibrations with the HRMA–LETG–FPSI combinations shall include the following measurements:

- Relative LRF as a function of energy, off-axis angle, focal plane position, and time
- Best focus position as a function of time.
- Absolute energy scale (using absorption edges in system response) as a function of time.

6.7.4High-Energy Transmission-Grating Spectrometer (HETGS)

Req 6.7.4: At a minimum, on-orbit calibrations with the HRMA–HETG–FPSI combinations shall include the following measurements:

- Relative LRF as a function of energy, off-axis angle, focal plane position, and time.
- Best focus position as a function of time.
- Absolute energy scale (using absorption edges in the system response) as a function of time.

6.7.5 Aspect Determination System

Req 6.7.5: At a minimum, on-orbit calibrations of the Aspect Determination System shall include the following measurements:

- Focus as a function of time.
- PRF as a function of stellar category, position in the FOV, and time.
- Plate scale as a function of time.
- Flat field as a function of time using the bright earth as a source.
- Read-out noise as a function of time.