Section 1

Introduction

This document details the ground calibration of the HETG, including the basic models, subassembly ("laboratory") data, XRCF measurements, and the resulting calibration products. This section provides an overview of the HETG and its calibration.

Part I of this document presents the basic operating principles and models of the HETG (Sections 2 and 3) and the laboratory measurements made on the component facets of the flight HETG (section 4.)

Part II consists of an introduction to the XRCF calibration activities (Section 5) followed by XRCF analyses broken down into a set of projects (Sections 6.2 through 7.9). The status of these analysis efforts is given in Table 5.10.

Lastly, in Part III the complete set of ground calibration results are sythesized to produce "Calibration Products" for use in flight analysis software. Methods of accessing the calibration data are described in Section 8. The current best estimates of the parameters describing the HETG and HETGS are available in Section 9.

1.1 The HETG on AXAF

The High Energy Transmission Grating (HETG) is one of four Scientific Instruments (SIs) that will operate with the High Resolution Mirror Assembly (HRMA) in NASA's Advanced X-ray Astrophysics Facility (AXAF). Two of the AXAF SIs are imaging detectors at the HRMA focal plane: the AXAF CCD Imaging Spectrometer (ACIS) and the High Resolution Camera (HRC). These detectors each consist of two sub-imagers: an "-I" imager (ACIS-I, HRC-I) of large area and square aspect ratio for imaging applications and an "-S" imager (ACIS-S, HRC-S) with a more rectangular aspect ratio designed for grating readout.

Either of the two grating SIs, HETG or LETG[12, 63], can be inserted into the optical path just behind the HRMA and, through diffraction, deflect the converging rays by angles roughly proportional to their wavelength, Figure 1.1. By combining the HRMA's high angular resolution (of order 1 arc second) and the grating's large diffraction angles (as high as 100 arc seconds/Å), the HRMA-grating-detector systems are capable of spectral resolving powers up to $E/dE \approx 1000$

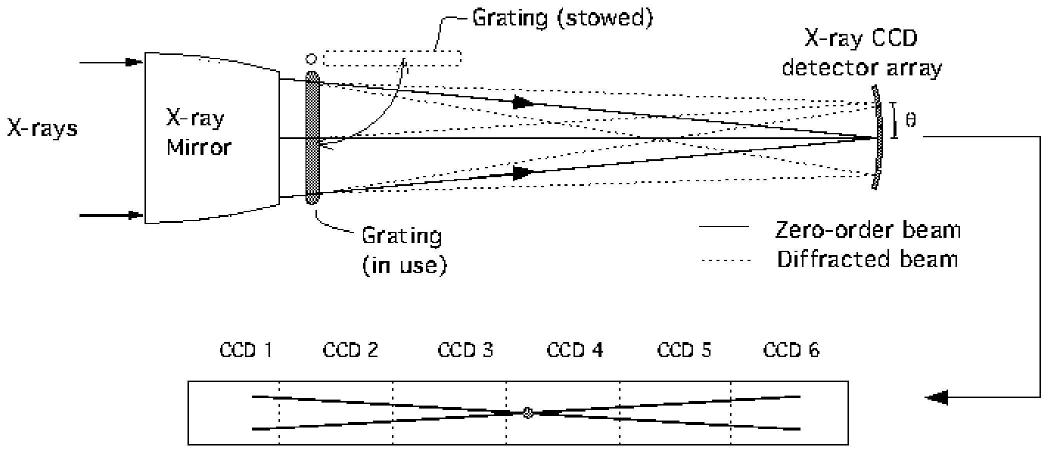

Figure 1.1: Schematic of the HETGS Configuration. The HETG can be inserted into the optical path behind the AXAF mirror (HRMA) to intercept and diffract the converging X-rays. The X-rays are diffracted by an angle β given in Equation 1.1 and are detected by the six chips of the ACIS-S CCD array. The HEG and MEG gratings have their dispersion axes oriented ±5 degrees to the ACIS-S long axis.

in the AXAF energy band.

The prefered detector for use with the HETG is the ACIS-S array consisting of 6 imaging CCDs in a 1x6 array. An illustration of the ACIS-S focal plane layout and an HETG-diffracted spectra is shown in figure 1.2.

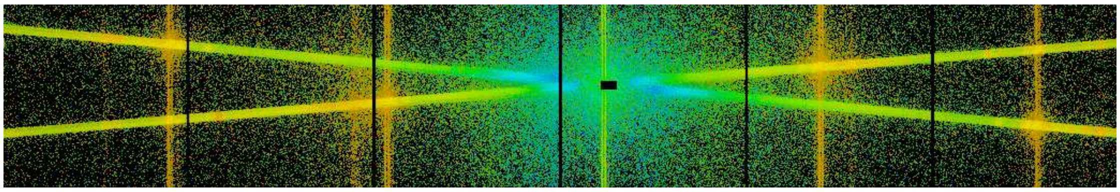

Figure 1.2: Image from the HETGS at XRCF. A unfiltered Cu-anode source produces a broadband X-ray continuum that is spread out along the HEG and MEG dispersion axes. The illustration shows the set-up of the six CCD devices, designated S0 to S5 from left to right, with the gaps between the devices. The MEG disperses into the upper right (and lower left corner), the HEG into the lower right (upper left corner). The vertical traces that appear at the 0th order image as well as at Cu-L (0.93 keV) diffracted orders are CCD-frame transfer read-out effects.

1.2 The HETG Itself

Details of the HETG have been presented previously in SPIE conferences[13, 46]. The HETG is a faceted Rowland torus design[6] that has been engineered to place each facet at its prescribed location and orientation on a Rowland torus with Rowland Diameter of 8634 mm. Specifically, in Figure 1.4 the precision, lightweight HETG Element Support Structure[61] (HESS) is populated with 336 individual grating facets. This design combined with the period and period variation properties of the facets allows high resolving powers.

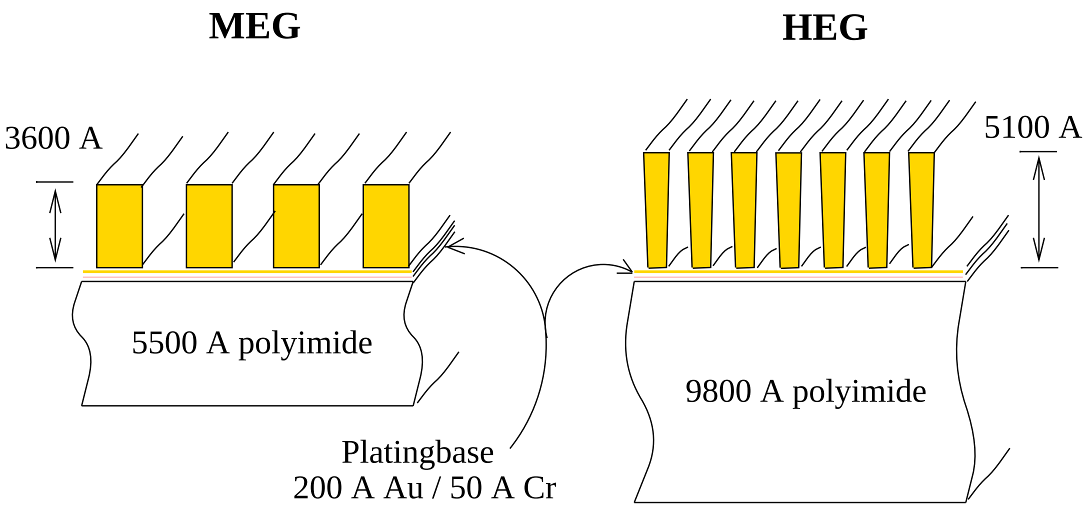

Figure 1.3: Cross-section schematic of the HETG gratings. The fine-period gold grating bars are supported on a polyimide membrane. A uniform "platingbase" layer provides adhesion of the bars to the polyimide.

The 336 grating facets of the flight HETG were fabricated in-house at M.I.T. in the Space Microstructures Laboratory (SML) using state-of-the-art holographic lithography techniques[67] to create a fine period, high aspect ratio grating structures supported on a thin polyimide membranes, Figure 1.3. Each facet was then tested in-house for period and diffraction efficiency characteristics[17].

The four rings of facets on the HETG are designed to intercept and diffract X-rays from the corresponding four HRMA mirror shells. Because most of the high energy area of the HRMA is due to the inner two shells, very fine period (2000 Å) "High Energy Grating" (HEG) facets are used here. The outer two shells have "Medium Energy Grating" facets ("MEG", 4000 Å period) that are efficiency-optimized below 2 keV. These two grating sets have their dispersion axes offset by 10 degrees from each other so that their spectra are spatially separated on the detector. In this way the HETG enables high-resolution spectroscopy ($E/dE > 100$) in the 0.4 keV to 9 keV band.

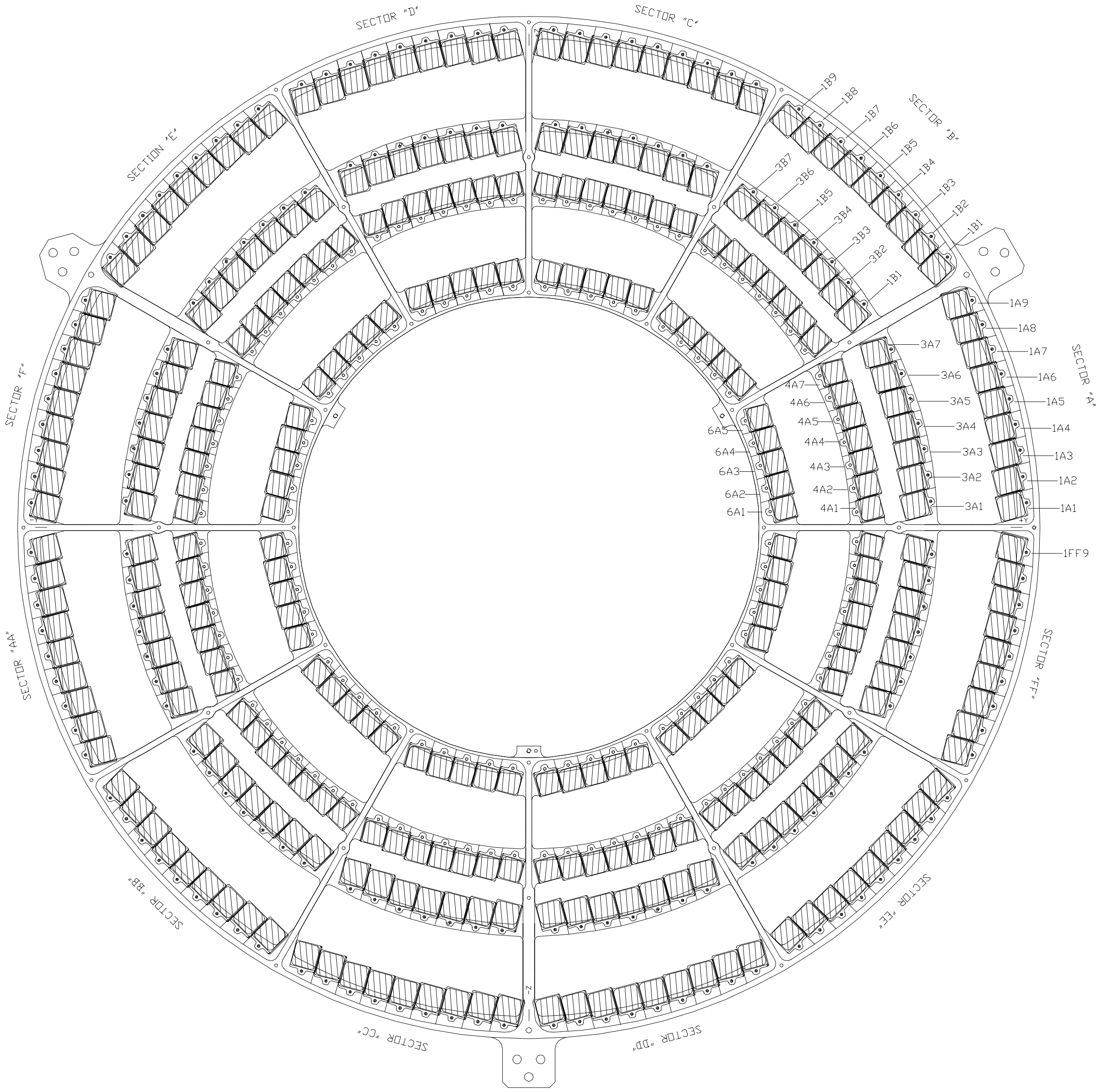

Figure 1.4: The HETG. A lightweight ($\approx$ 10 kg) aluminum structure supports 336 individual grating facets in a Rowland geometry. This view of the HETG is from the HRMA side and the facet-location identification scheme is indicated. Positive Z-axis is towards the top of the page and positive Y-axis is to the right. The HETG, as installed for ground calibration at XRCF, was rotated 180 degrees about the optical axis from this view.

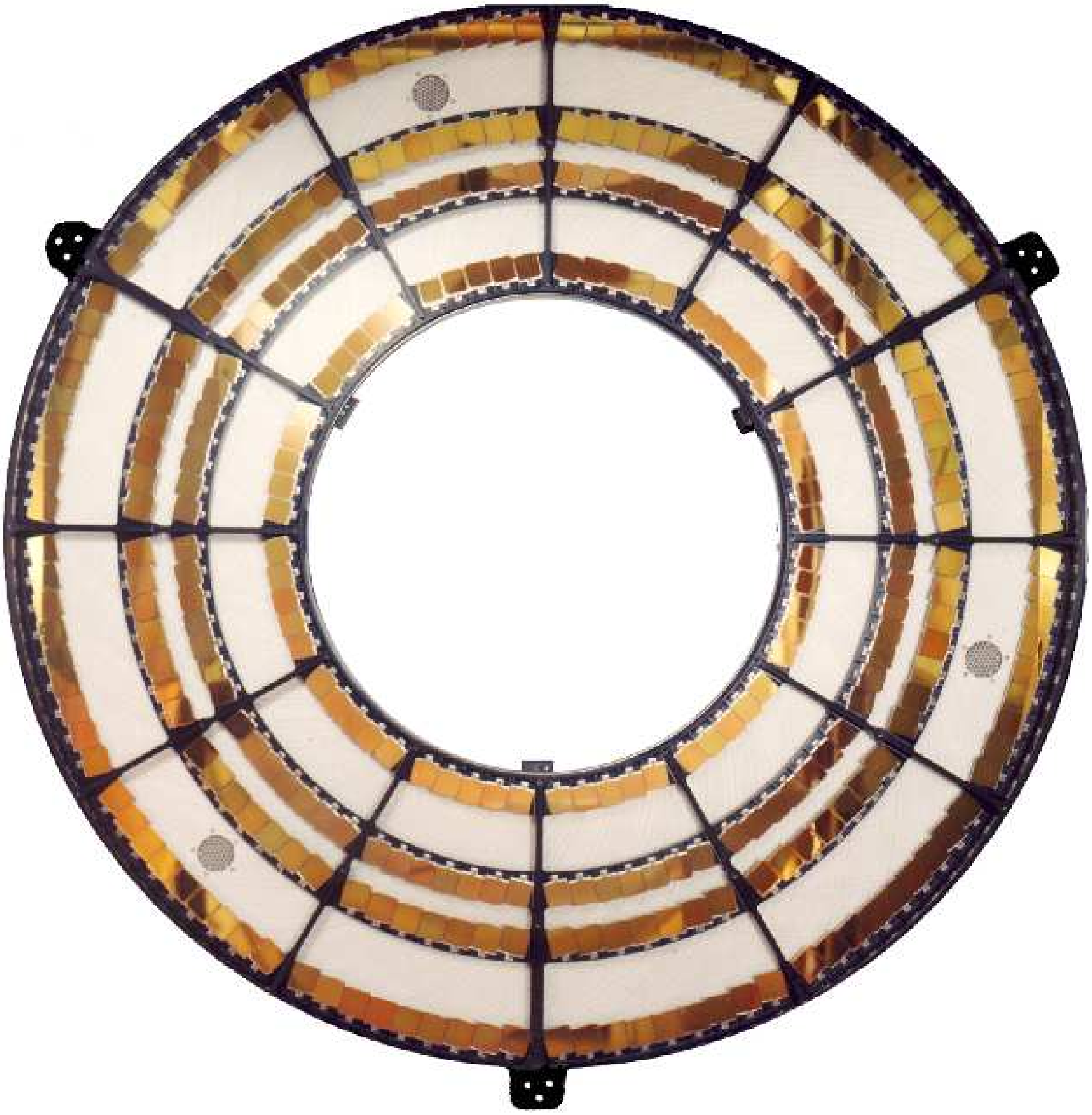

Figure 1.5: Photograph of the HETG assembly. It is made of 336 grating facets attached to a light-weight aluminum structure. The two outer rings are tiled with MEG facets, the two inner rings have HEG facets.

1.3 HETGS Calibration Definition and Goals

The complete flight instrument that will be utilized and must be calibrated is the combination of the HRMA, HETG, and the ACIS-S—the *HETG Spectrometer (HETGS)*. The HETGS calibration requirements generally fall into two categories: calibration of the *Effective Area* and calibration of the *Line Response Function (LRF)*. Scientific goals set calibration requirements on the HETGS in these areas which are then flowed-down to requirements on the individual HEG and MEG elements themselves.

1.3.1 Effective Area and Efficiency Definitions

The HETGS response to an on-axis monochromatic point source consists of images in the various *diffracted orders* produced at locations given by the grating equation[9]:

$$sin(\beta) = \frac{m\lambda}{p} \tag{1.1}$$

where m is the order of diffraction (an integer 0, $\pm1, \pm2$, ...), p is the grating period and β is the dispersion angle. Knowledge of the dispersion axis and the grating-to-detector distance (the Rowland spacing) allows a conversion of the angle β to a physical location on the detector.

These diffracted images are, for the most part, spatially localized and so it is possible and convenient to express the system response to a monochromatic source with incident flux of 1 photon/cm^{2}s as the sum of weighted spatial functions:

$$\text{HETGS response}(E,\dots) = \sum_m SEA(E,m,\dots) \times PSF(E,m,\dots) \tag{1.2}$$

where $SEA(E,m,\dots)$ is the *system effective area*, described further below, and $PSF(E,m,\dots)$ is a unit-normalized 2-dimensional point spread function which describes the spatial distribution of the m-th order detected events, see Section 1.3.3 below. The dots $(\dots)$ in the arguments indicate that there are other dependancies, *e.g.*, off-axis angles, defocus, detector modes, etc.

The system effective area for the HETGS, in cm^{2}counts/photon, can be calculated from the following terms:

$$SEA(E,m,\dots) = \sum_{s=1,3,4,6} A_s(E,\dots)\; G_s(E,m)\; QE(E,\dots) \tag{1.3}$$

Here the sum is over the HRMA mirror shells, A_s is the *optic effective area* for HRMA shell s in cm^2, and $QE(E,\dots)$ is the detector quantum efficiency including effects of detector spatial uniformity (*e.g.*, BI/FI chips, gaps) and detection mode (*e.g.*, event grading) in counts per photon.

$G_s(E,m)$ is the average diffraction efficiency for the gratings on shell s and is calculated from the individual facet efficiencies $g_f(E,m)$:

$$G_s(E,m) = \nu_s \frac{1}{N_s} \sum_{f\in\{s\}} g_f(E,m) \tag{1.4}$$

where N_s is the number of facets on shell s and ν_s is a unitless shell-by-shell vignetting factor to account for the inter-grating gaps. Thus, the physics of $g_f(E,m)$ governs the HETG contribution to the HETGS effective area.

Finally, it is useful to define the grating "effective efficiency" for combinations of more than a single HRMA shell:

$$G_{\text{config}}(E,m) = \frac{\sum_{s\in\{\text{config}\}} A_s(E)\; G_s(E,m)}{\sum_{s\in\{\text{config}\}} A_s(E)} \tag{1.5}$$

where "config" may usefully be the HEG (shells 4,6), MEG (shells 1,3), or HETG (shells 1,3,4,6). In practice, it is the effective efficiencies of these configurations that are measured and used.

1.3.2 Effective Area Calibration Goals

Calibration of the effective area of the HETGS is driven by the desire to extract information about the physical parameters of an emitting region (e.g., temperature, ionization age, elemental abundances) from the observed intensity of spectral lines through plasma diagnostics[15]. Analysis of the sensitivity of scientific conclusions on the calibration accuracy has led to the requirements that the HETGS effective area be known with an absolute accuracy of order 10% (1σ) at all energies, and that the relative effective area at two different energies be known to of order 3% (1σ). Note that the effective area needs to be known at least on an energy grid comparable to the coarser of the astrophysical spectrum feature scale and the instrumental response variation scale.

These requirements for HETGS calibration have implications for the calibration of the HRMA and focal plane detectors as well as the HEG/MEG elements. Ideally the effective area and/or efficiency of all components would be know accurately enough so that the composite system would be calibrated to the 3% (1σ) level on an energy scale of $\Delta E \approx E/1000$, especially around instrumental edges.

For our laboratory calibration of the HEG/MEG elements we have set a goal of 1% (1σ). This allocates most of the error to the HRMA and focal plane detector calibrations where the calibration process is inherently more difficult (i.e., measuring an effective area or an absolute detection efficiency as opposed to a transmission efficiency.)

Though not as central as the (first-order) diffraction efficiency measurements, it is important that the zero-order and higher orders be calibrated as well.

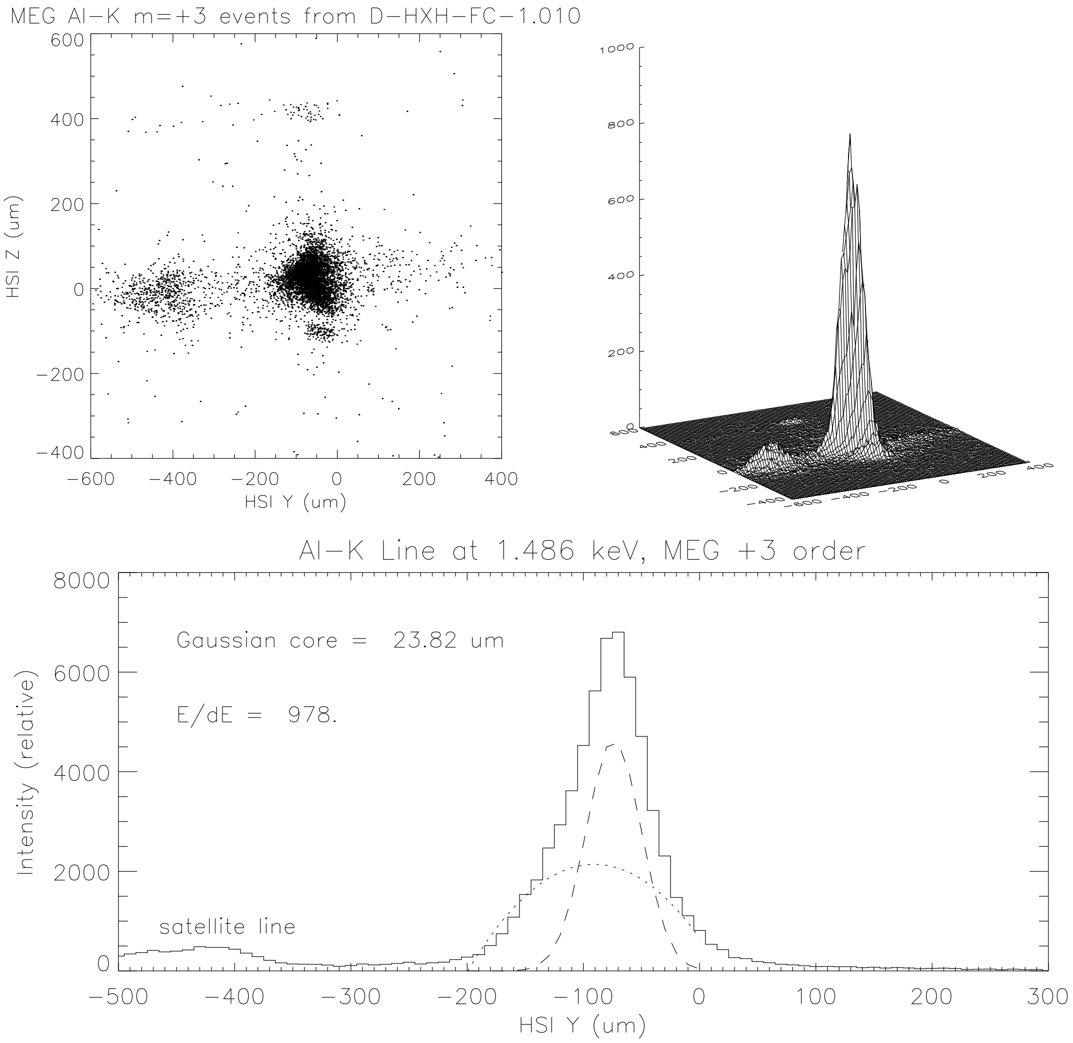

Figure 1.6: PSF and LFR example. The event distribution (top left) may be described by a 2-D point spread function PSF, $\rho(y, z)$ (top right). The resulting 1-D line response function $l(y')$ (lower plot) is shown with a Gaussian plus quadratic fit to its core.

The events are from an XRCF HSI image of the 3rd-order MEG Al-K line; the HSI is centered at HSI_Y = 54.76 mm, HSI_Z = 4.496 mm. Visible in addition to the main peak is the "satellite line" at HSI_Y = -400. PSF outliers at HSI_Z = +400 and -100 represent mis-aligned grating facets.

1.3.3 LRF Definition

As described above the focal plane image that results from a monochromatic near-axis point source can be considered as a set of images, one for each grating-order. The distribution of each of these images can be described by a *2-dimensional Point Spread Function (PSF)* which gives the normalized density of detected photons in the detector plane:

$$\rho(y, z) \Leftarrow PSF(E, m, \dots) \tag{1.6}$$

where y, z are the detector coordinates, E, m are the energy and grating-order, and "…" is again a placeholder for other dependancies, *e.g.*, the telescope defocus, location of the source with respect to the optical axis, etc. As an example, an X-ray event plot and the corresponding $\rho(y, z)$ PSF is shown in the upper plots of Figure 1.6 (these are data from XRCF and are used here for illustration purposes; they are discussed in Section 6.3.)

Because the spectroscopic information of a grating dispersive instrument is along the dispersion direction, it is useful to define the *one-dimensional Line Response Function (LRF)* to be the PSF integrated over the cross-dispersion direction:

$$l(y') = \int dz' \rho(y', z') \tag{1.7}$$

where the y', z' indicate axes aligned with the dispersion and cross-dispersion directions in the detector plane. The lower plot in Figure 1.6 gives the LRF corresponding to the example PSF. Because of the image properties of the mirror, it is generally useful to (conceptually) break the LRF into at least two regions: a core or inner LRF and the wings or outer portion of the LRF.

The *Resolving Power* of the spectrometer at energy E is defined as

$$R(E, m) \;=\; E/dE \;=\; y'_{\mathrm{centroid}}/dy'_{\mathrm{FWHM}} \tag{1.8}$$

where dE is the full-width at half-maximum (FWHM) of the LRF. Typically the LRF core can be well fit by a Gaussian profile and in this case $dE \approx 2.35\sigma$ approximates the FWHM.

1.3.4 LRF Calibration Goals

The goal of HETGS LRF calibration is to produce LRF models which are accurate (have low χ^2) when fitting a line containing of order 1000 counts. Additionaly, it is important that any "wings" or "ghosts" in the dispersed spectrum be identified and quantified. Specifically, the contribution of wings at all scales should be known or limited to 1% of the peak line flux in a resolution element.

1.4 Ground Calibration Overview

The HETG ground calibration program consists of 4 main activities:

- Creating and validating models for the HETGS LRF performance, Section 2.
- Synchrotron testing of sample and reference gratings to understand and validate the diffraction model $g_f(E, m)$, Section 3.
- Laboratory testing and assembly of all flight gratings, Section 4.
- XRCF tests of the flight hardware, Part II, Sections 5-7.

1.5 HETG Documentation

It is assumed that the reader is familiar with AXAF, the HETG, and XRCF calibration and has access to the documents below.

Table 1.1: HETG Documentation

Printed documents:		
AXAF Observatory Guide	ASC/User Support	October 1997
AXAF Proposers Guide	ASC/User Support	October 1997
MARX Manual	ASC/SDS	October 1997
HETG Ground Calibration Report	HETG and ASC	October 1997
HETGS Flight Performance and Calibration Report	ASC/Cal	TBD
Electronic documents:		
`http://asc.harvard.edu`	ASC	dynamic
`http://space.mit.edu/HETG/xrcf.html`	HETG	dynamic