Chapter 10

Simulations

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10.1 Introduction

Simulations of the HRMA are done by coupling raytraces of the optics with models of the support structure and detectors. The simulations are based as much as possible upon following individual rays from the source, through the HRMA, and to the detectors. In order to minimize the computational burden of these calculations, we model the probabilistic reflection of photons from the mirrors by assigning each photon a unit weight at the entrance aperture and multiplying it by the photon's reflection probability at each surface. Only the weights are used in the analysis of the simulations.

10.2 HRMA Model

The HRMA is composed of several components which are are not entirely separable. We have nonetheless attempted to do so, modelling it according to the following characteristics or systems:

- the geometric properties of the optics (i.e., their figure)
- the surface properties of the optics
- the HRMA baffles and support structure

10.2.1 Optics' Figure

The model of the optics can be thought of as comprising two basic elements: geometric prescriptions for the shape and positions of the optics, and the deviations from those prescriptions. Deviations from the ideal geometry can arise from a host of manufacturing errors (e.g., from current technical limitations in aligning or polishing optical elements) or can be the result of an operational configuration (the XRCF testing environment). Clearly the key to making a high fidelity model of the HRMA lies in accurately modeling the effect of these deviations on X-ray performance. To this end we have identified several classes of deviations:

1. Those which are actually measured and which result in exact geometric distortions of the imaging performance. Examples of such deviations include misalignments measured during the assembly process at EKC and maps of the low spatial frequency manufacturing errors of the optical surfaces from HDOS.

2. Deviations which are measured but which result in probabilistic distortions to the imaging performance. The main example here is the data from HDOS on high spatial frequency manufacturing errors in the form of the power spectral density (PSD) of irregularities on the optical surfaces. For this we use a statistical treatment of scattering from rough surfaces developed by L. Van Speybroeck.

3. Modeled deviations of essentially deterministic effects which result in exact geometric distortions of the imaging performance. Examples include finite element models (FEM) of thermally or gravitationally induced deviations of the optical surfaces.

4. Modeled deviations of non-deterministic effects which result in exact geometric distortions of the imaging performance. Examples include the FEM of manufacturing errors (essentially low frequency) induced on the optical surfaces during assembly of the HRMA in the alignment tower at EKC. These are non-deterministic since they arise from unmeasureable variations of otherwise controlled quantities. It is not clear at the present time how these will be included in the final HRMA model. In general it is expected, based on the error budgets, that these effects result in only modest performance degradations and thus it may be possible to include them, in the ensemble, as a small intrinsic Gaussian broadening of the image core.

Item 2 illustrates that descriptions of the optics' figure contain elements of the surface properties (i.e. roughness), and are thus not quite separable. We discuss the latter more completely in §10.2.3. The components which go into the description of the optics' geometric shape are:

- Geometric prescriptions of the optics, taking into account the actual end-cuts. These are derived from the "EK05lvs" prescription (Van Speybroeck, 1989a).

- HDOS surface deviation maps. These maps are spline fits to the low frequency deviations from the optics' geometric prescriptions, as measured by HDOS.

- Positions and orientations of the optics as determined from measurements in the HRMA Alignment Test System (HATS) during assembly, as well as measurements made at the XRCF (see Chapters 26, 27 and 30).

- Estimates of the second and third order Fourier-Legendre distortions from HATS data.

- Epoxy cure shrinkage effects for two weeks after pump-down.

- Distortions due to the HRMA's horizontal orientation in gravity, including the effects of the off-loading ground support equipment (GSE). These distortions are modelled via a high precision FEM of the optics and the HRMA support structure (HSS), with the optics in their nominal position and orientation. In a consistent treatment, the FEM would include the measured positions and orientations; we have assumed that the deviations from nominal are small enough to be treated as perturbations to the FEM.

- Modifications to the optics' cone-angles to give correct focal positions as determined from XRCF measurements (see Chapter 26).

10.2.2 Baffles and Support Structure

The HRMA support structures include the Central Aperture Plate (CAP) and the Mirror Support Sleeves (MSS), to which the optics are attached via flexures. The CAP, MSS, and flexures impart distortions to the optics, due to assembly strains and gravitational loading. These effects are modelled via the FEM described in §10.2.1. The CAP also serves as an optical obstruction due to its 12 struts. We model this separately, as thick, 100% opaque rectangular struts superimposed upon four open annuli. We do not separately model the CAP scrapers or cut-outs.

There are additional baffles in the system: the forward thermal pre-collimator, the P6 ghost baffle, and the aft thermal post-collimator. We treat these as obstructions; they are not included in the FEM model. These are modeled as a series of 100% opaque plates of zero thickness.

10.2.3 Mirror Surface

We divide our description of the optics' surface characteristics into the two components of reflection and scattering. Again, these are not perfectly separable.

Reflectivity

To confuse matters, this report contains results from simulations with two different models for the surface reflectivity. The simpler model describes the surface as a semi-infinite slab of iridium. The second, more realistic model, treats the surface as a multilayer consisting of layers of iridium and chromium on a semi-infinite base of Zerodur. In both cases we use iridium optical constants derived from the Henke data (Henke et al., 1993) below 2 keV, and from the data released by the MST Synchrotron group on 23 December 1996 for the 065 P6 witness coupon. Optical constants for the chromium and Zerodur are derived from Henke et al. (1993). In both approaches we have assumed a uniform, 100% bulk density of 22.39 $\mathrm{gm} \cdot \mathrm{cm}^{-3}$ for iridium.

The multilayer treatment is similar to the approach layed out by Elsner and O'Dell (1991), but with a few wrinkles.

Surface Scattering

As mentioned above, we use a statistical description for the scattering of rays off of the optics due to surface microroughness. In the formulation we employ (outlined in some detail by Van Speybroeck (1989b)), an in-surface spatial wavelength $1/f$ diffracts (or scatters) light of a given wavelength λ through an angle θ according to the grating equation

$$\theta = f \, \frac{\lambda}{\sin \alpha}, \tag{10.1}$$

with α as the mean grazing angle of the surface. It is possible to relate (Beckmann & Spizzichino 1963) the normalized surface brightness $\psi(\theta)$ at scattering angle θ to the power spectral density (PSD) of surface irregularities $W_1(f)$ through

$$\psi(\theta) = \frac{16\pi W_1(f)}{f} (\frac{\sin \alpha}{\lambda})^4. \tag{10.2}$$

We assume a particular form for the surface PSD and construct a look-up table which relates the amount of incident energy which is scattered to all angles in the focal plane. In general, this table would need to be two-dimensional, i.e., parameterized in terms of both the mean incident graze angle and wavelength of the radiation. However, Eqs. 10.1 and 10.2 reveal that the functional dependence is one-dimensional, i.e., it depends only on the ratio of the sine of the grazing angle to the photon wavelength. We utilize this feature in our implementation of X-ray scatter since it has greatly reduced the complexity associated with building and interpolating the table in the raytrace software. The radii corresponding to 1% increments in the fractional encircled energy distribution are stored for each value of $\sin\alpha/\lambda$ in the table. A power-law extrapolation in the point spread function is used for radii beyond the 99% encircled energy value. During each invocation of a scattering event, a random number between 0 and 1 is selected and used to determine the appropriate radii for the 2 bracketing values of $\sin\alpha/\lambda$ from the table. The final scattering angle is obtained by interpolation between the bracketed values.

Surface micro-roughness scattering derived from high order HDOS surface map data (20 February 1997 distillation). **NOT REALLY! ??**

- a monochromatic point source at the XRCF distance of 527279 mm to the front side of the CAP.

One major deficiency of this model is that the X-ray source is modeled as a point source, rather than as an extended object. Since the source varied in size (up to $\sim 0.2''$), the simulations are uniformly "peakier" in the core than the measurements.

In comparisons to the measurements we make no attempt to model the detectors; instead we rely upon the spectral analysis to determine effective areas free of detector artifacts. All simulation results described in this document are derived from this model, unless otherwise noted.

The MST simulation is composed of the following components (which describe model `xrcf_SAO1G+HDOS_HDOS-scat-970220_03`):

- a monochromatic point source at the XRCF distance of 527279 mm to the front side of the CAP.
- Iridium optical constants derived from the Henke data (Henke et al., 1993) below 2 keV, and from the data released by the MST Synchrotron group on 23 December 1996 for the P6 flat.
- Rigid-body Optic positions and tilts as discussed in Chapters 26, 27 and 30.
- Mirror deformations:
  - Low order surface map data from HDOS.
  - Estimates of the 2nd and 3rd order distortions from HATS data.
  - Epoxy cure shrinkage effects for 2 weeks after pump-down.
  - Distortion due to horizontal orientation in 1g.
  - Modifications to cone-angle to give correct focal positions as determined from XRCF measurements (see Chapter 26).
- Surface micro-roughness scattering derived from high order HDOS surface map data (20 February 1997 distillation)
- Apertures, Collimators, Baffles (Central Aperture Plate (CAP), fore and aft structures, and P6 Ghost baffle) modeled as annuli with rectangular obstructing struts (where appropriate). All plates are 100% opaque, and are of zero thickness, except for the CAP, which is given the as-measured thickness

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