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An On-Orbit Determination of the On-axis Point Spread Function of the *Hinode* X-Ray Telescope

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Abstract

The Hinode X-Ray Telescope provides unprecedented observations of the solar corona in x-rays, due in part to its fine resolution. The x-ray point spread function (PSF) was measured before launch at the NASA X-Ray Calibration Facility to have a FWHM of 0.8 arc-seconds. This paper describes the work to verify the PSF measurements using on-orbit observations of planetary transits and solar eclipses. Analysis of a Mercury transit gives a PSF FWHM = 1.0 ± 0.12 arcseconds. Hinode is an international project supported by JAXA, NASA, PPARC, and ESA. We are grateful to the Hinode team for all their efforts in the design, development, and operation of the mission.

Key words: Sun: X-rays, gamma rays — instrumentation: high angular resolution — techniques: high angular resolution

1. Introduction

The X-Ray Telescope (XRT; Golub et al. 2007) on-board the *Hinode* spacecraft (Kosugi et al. 2007) is the highest resolution solar x-ray imager ever flown. The instrument relies on a Wolter Type-III, grazing-incidence design which uses two reflections on a paraboloid-hyperboliod mirror in order to meet the Abbé sine condition that the magnification be constant over the full aperture of the telescope. The XRT has good image performance over a wide field-of-view ($\gtrsim 34\times34$ arcminutes), and has a spectral response from 6Å to more than 60Å.

The telescope's on-axis PSF was measured before launch at NASA's X-Ray Calibration Facility (XRCF), and was found to have FWHM = 0.92 arcseconds. However, these measurements were subject to two effects that the XRT does not see on-orbit: a finite source distance, and mirror deformation due to gravity. Models were used to correct the XRCF measurements for these effects, which gave a prediction of an on-orbit FWHM = 0.8 arcseconds.

Fortunately, it is possible to make measurements on-orbit at high spatial frequencies with the sharp-edged shadows of Sun-transiting celestial bodies, such as the inner planets and the Moon. Since launch, *Hinode* has been able to view a Mercury transit and multiple solar eclipses by the Moon. In this Paper, we use data from these events to measure the on-orbit, on-axis PSF of the XRT.

In § 2, we discuss the general method of analysis. In § 3, the analysis of the Mercury transit is presented, and the attempt to analyze a solar eclipse is touched upon in § 4. A conclusion is given in § 5.

2. Method of Analysis

For the pre-launch XRCF analysis, the XRT PSF was modeled with a Gaussian core and a Lorentzian tail representing the scattering of x-rays by surface roughnesses. The goal of the on-orbit investigation was to estimate the width of the PSF core using a Gaussian sigma parameter that best fit the signal drop-off below the shadow's limb. The Lorentzian tail has a maximum value only about 1% of that of the Gaussian core, and so was ignored for studying the signal right at the shadow edges near the illuminated areas. Of course, this component would be significant for studying the XRT signal seen farther within the shadow.

For each event, an image was selected such that (a) the edge of the shadow was sharp and well-illuminated according to the image exposure time; (b) the edge was near the center of XRT's field-of-view; and (c) the coronal features immediately behind the limb were bright and nearly uniform. It was also important that the image was taken with no on-chip binning of pixels (i.e., selected for one-arcsecond pixels). Due to these constraints, there were only a few images during the entire Mercury transit that were suitable for the analysis, one image in particular. Furthermore, the *Hinode* spacecraft repointed regularly during the transit, so Mercury's shadow was always near the XRT FOV center and optical axis. For these reasons, the XRT PSF function could be analyzed for the best focus position for the optical axis, but it was not possible to sample the PSF across the entire FOV or at different focus positions.

To ensure the sharpest possible edge, rows of pixels were analyzed where the limb was aligned with the direction of

Fig. 1. Illustration of model. *Solid*: The sharp limb of a planetary shadow. *Dotted*: A Gaussian PSF with $\sigma = 1$ arcsecond. *Dashed*: The convolution of the Gaussian with the edge.

the shadow's motion. This minimized edge blurring due to the motion of the shadow during the exposure duration of the image. (The shadow motion is discussed more in § 3.) The spacecraft jitter is on the order of 0.1–0.2 arcseconds over 10 seconds, which is a smaller displacement, for a 16-second exposure, than the size of the XRT platescale (∼1.03 arcsec per CCD pixel). The orbital (thermal) variation of the XRT is approximately 2 arcseconds (p-p) over a 97-minute orbit, and thus has negligible effect during a 16-second exposure. Shimizu et al. 2007 derive the instrument roll-angles using the same Mercury transit event analyzed in this paper. They determine that the XRT roll-angle is 0.73 ± 0.03 degrees over a period of 36 minutes, which indicates that roll effects are insignificant for a 16-second exposure.

At these locations aligned with the shadow tangent, a few lines of pixels were selected that cut across the shadow limb. The light-curve for these rows show characteristic features: a region of steep descent, with moderated turn overs on either side. This structure was modeled as the convolution of a Gaussian core PSF with a step-function shadow limb.

Figure 1 illustrates this model. The cross-section of a shadow limb is shown by the dotted line as a step-function. The solid line shows the cross-section of a 2D Gaussian kernel with $\sigma = 1$. The dashed line shows the convolution of the Gaussian kernel with the sharp edge. The region of transition from zero shadow to full shadow has a length scale wider than 1σ. The central area of steepest, nearly linear drop-off has a slope and roll-over sensitive to the value of σ. Although this figure is shown as a 1D slice, it was computed for two cases with 2D arrays for the shadow and kernel. For the two cases, the shadow's edge was (a) a straight-line; and (b) a circle with a diameter of 10 arcseconds. These two cases match the two events described in the following sections (the shadows of the Moon and Mercury, at XRT resolution, are straight and curved, respectively). It was discovered that for these length-scales, the convolved model does not substantively differ between the two cases; however, each event was fitted with the appropriately shaped 2D shadow model. (The PSF model is implicitly cylindrically symmetric to keep the number of free parameters manageable.)

Fig. 2. Mercury in transit across the Sun at 23:50:31 UTC. The relative motion was horizontal from left to right in this image. The field-of-view is 512×512 arcseconds.

For the analysis of the Mercury and lunar transits, a 2D Gaussian model of a point-like PSF was convolved with a 2D shadow. The model shadow was given the size and shape of the predicted celestial shadow, and was given a step-function like horizon. The convolved, blurred shadow of the model was then fit to the observations. The position and sigma of the Gaussian PSF model were varied to produce the best fit with specific rows of pixels cutting across the least motion-blurred edge of the shadow. Using this iterative, forward-fitting process, the best-fit PSF FWHM was determined.

3. Mercury Transit

A Mercury transit was observed by *Hinode*, beginning at 2006 Nov 8 19:12, and lasting until Nov 9 00:10 UTC. Mercury cast a shadow with an angular diameter of 10.1 arcseconds, and moved across the Sun at an apparent velocity of 0.077 arcseconds per second. For a 16.4 sec exposure, the shadow moved about 1.25 arcseconds. Therefore, a sharp edge was observed parallel to the direction of motion. The observations were made with the instrument focussed for the best on-axis focus, as determined by on-orbit measurements made during the spacecraft commissioning process.

An XRT image at 23:50:31 UTC (Fig. 2) was selected according to the criteria listed in the Sec. 2. According to the orbit of Mercury and *Hinode*, and to the orientation of the XRT, the shadow appeared to move effectively horizontally across the telescope's FOV, so the three vertical columns of pixels cutting across the North side of the shadow were expected to provide the sharpest limb (Fig. 3).

Fig. 3. Three light-curves across Mercury's shadow.

Fig. 4. Model fit to Mercury's limb. *Dashed and diamonds*: Mean normalized intensity of three light-curves from Fig. 3, across the Northern (right-hand) limb, with error bars representing the variation of the data. *Solid*: Best model fit to limb, Gaussian $\sigma = 0.6$ arcseconds.

The mean and variation of these three light-curves for the pixels of steepest gradient were identified. The convolved model described in Sec. 2 was forward-fitted to this part of the light-curve. The best-fit model (Fig. 4) had a PSF Gaussian core with $\sigma = 0.6 \pm 0.07$ arcseconds. This corresponds to a FWHM $= 1.0 \pm 0.12$ arcseconds. This is 2σ larger than the laboratory measurement of 0.8 arcseconds.

4. Solar Eclipse

Three consecutive solar eclipses were observed by *Hinode*, on 2007 March 19 UTC. The Moon cast a shadow with an angular diameter of approximately 896 arcseconds, and moved across the Sun at an apparent velocity of 0.5 arcseconds per second. For a 16.4 sec exposure, the shadow moved about 10 arcseconds. Therefore, only a small part of the limb appeared to have a sharp edge. The analysis was attempted, but gave inconclusive results, and so is not described in detail here. The relative motion of the Moon was much larger than that of Mercury's transit, and so caused difficulties with blurring of the shadow edge. Furthermore, the lunar surface has mountains and valleys which can vary by as much as 4–5 arcseconds as seen from low earth orbit. This would cause a broad, diffuse shadow edge where some pixels were only exposed to the Sun for less than the full exposure duration because of occultation by the lunar topology. This would tend to flatten the apparent gradient of the slope.

5. Conclusion

In principle, one of the best ways to measure a telescope PSF is to observe a Sun-transiting celestial body that has a sharp horizon. An alternate method would be to utilize observations of bright features smaller than the instrument platescale, such as microflares. To date, XRT has not performed any directed observations to look for sub-arcsecond features, nor has the mission data been searched for these features, to the best knowledge of the authors. All microflares which have been noted in the data have been resolved at sizes greater than two arcseconds.

The analysis of the XRT on-axis PSF using Mercury transit data gave a result of a FWHM $= 1.0 \pm 0.12$ arcseconds, which is consistent with measurements pre-launch (FWHM ~ 0.8 arcseconds). For comparison with a similar instrument, the *Yohkoh* Soft X-ray Telescope (SXT; Tsuneta et al. 1991) had a PSF best fitted by a Moffat function, with a FWHM of 3–5 arcseconds (Sakurai and Shin 2000). Similar analysis of a solar eclipse did not give robust results, due to the relative speed and limb shape of the lunar topography. The Mercury data-set was optimized for analyzing the on-axis PSF, but due to selection criteria and observation constraints, the data-set is not suitable for a broader study of how the PSF varies across the FOV. However, this PSF variance was measured pre-launch and is reported in Golub et al. (2007). An on-orbit confirmation can be performed in the future.

The observations were made with the instrument focussed for the best on-axis focus, as determined by on-orbit measurements made during the spacecraft commissioning process. Because of the focus mechanism control, and because of varying solar conditions along Mercury's transit path, it would not have been practical to study how the PSF varies with focus position. The high-cadence observations were made in a single thin filter, in order to obtain good illumination of Mercury's shadow, but this does not facilitate an analysis of the wavelength dependence. The wavelength dependence of the XRT PSF was investigated for specific x-ray lines during pre-launch calibrations, and will be verified with future on-orbit tests using multiple filters.

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References

Kosugi, T., et al. 2007, Sol. Phys., in press
Golub, L., et al. 2007, Sol. Phys., in press
Sakurai, T., Shin, J. 2007, Adv. Sp. Res., 25, 1761
Shimizu, T., et al. 2007, PASJ., submitted
Tsuneta, S., et al. 1991, Sol. Phys., 136, 37