AXAF VETA-I Mirror Ring Focus Measurements

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ABSTRACT

The AXAF VETA-I mirror ring focus measurements were made with a HRI (microchannel plate) X-ray detector. The ring focus is a sharply focused ring formed by X-rays before they reach the VETA-I focal plane. It is caused by spherical aberrations due to the finite source distance and the despace in the VETA-I test. The ring focus test reveals some aspects of the test system distortions and the mirror surface figure which are difficult or impossible to detect at the focal plane. The test results show periodical modulations of the ring radius and width which could be caused by gravity, thermal, and/or epoxy shrinkage distortions. The strongest component of the modulation has a 12-fold symmetry, because these distortions were exerted on the mirror through the 12 flexures of VETA mount. Ring focus models were developed to simulate the ring image. The models were compared with the data to understand the test system distortions and the mirror glass imperfection. Further studies will be done to complete this work. The ring focus measurement is a very powerful test. We expect that a ring focus test for the finally assembled mirror of AXAF-I – HRMA – will be highly valuable.

1. INTRODUCTION

The Advanced X-ray Astrophysical Facility (AXAF), a satellite X-ray telescope, is the third of NASA's four Great Space Observatories [1]. Due to the budget constraint, AXAF went through redesign in 1992, which restructured AXAF into two missions: AXAF-I (for imaging) and AXAF-S (for spectroscopy), both scheduled to be launched by the end of the Century. AXAF missions assemble state of the art technology: from scientific instruments to computer software; from X-ray detectors to X-ray mirrors. The heart of the AXAF-I is the largest X-ray mirror assembly ever built – the High Resolution Mirror Assembly (HRMA). HRMA consists of four pairs of nested Wolter Type I grazing incidence mirrors. These nearly cylindrical paraboloid-hyperboloid mirror pairs are made of Zerodur and all coated with iridium. Mirror diameters range from 0.64 m to 1.22 m with a length of 838.2 mm for each cylinder. The mean grazing angles range from 27.1 arcmin for the inner pair to 51.2 arcmin for the outer pair. The focal length of HRMA is 10 meters.

The Verification Engineering Test Article I (VETA-I) is the uncoated and uncut outmost pair of HRMA. The two VETA-I mirrors are called P1 (paraboloid) and H1 (hyperboloid). A test of the mirror glass surface quality was successfully performed on VETA-I at the Marshall Space Flight Center from September 1 to October 18, 1991. The test system used X-ray sources 528 meters from the VETA and X-ray detectors that measured the focused X-rays. The mirror is designed to focus parallel incident X-rays from infinitely distant sources. Because the P1 and H1 were not cut to the design length, they had to be spaced 109.03 mm farther apart than the design spacing during the test (this fact is called despace). For the ground test with a finite distant source and despace, there are two interesting focal planes where our measurements were made (see Figure 1). One is called the overall focal plane or the finite-distant focal plane (for the rest of the paper we just simply call it the focal plane), which is located farther away from the mirror than the designed focal length. This is the location for the waist of focused X-rays by the entire mirror. Another is called the ring-focus plane, which is located in between the on-orbit focal plane and the finite-distant focal plane. In the ring-focus plane, X-rays form a sharply focused ring before reaching the focal plane . The ring focus is caused by spherical aberration in the VETA-I test. In the focal plane, we measured FWHM (this is the main goal of the VETA test), encircled energy and effective area. The results of these measurements were discussed in 16 papers published in the SPIE '92 proceeding [2]. There is also a paper discussing the result

Figure 1: VETA-I ring focus measurement.

of the ring focus test with a proportional counter by D.E. Zissa [3]. The present paper discusses the ring focus measurements with a microchannel plate – HRI, presents the results, and compares the results with models.

2. RING FOCUS

The ring focus test for the AXAF mirrors was originally proposed by D. Korsch and D.E. Zissa [4, 5]. This test is applicable to an optical system that has a narrow annular aperture and also has spherical aberration, which is suitable for VETA-I. In the VETA-I test the spherical aberration was caused by the finite source distance and the despace. The ring focus test is a complementary test to the focal plane tests. It reveals some aspects of the test system distortion and the mirror surface figure which are difficult or impossible to detect at the focal plane. Our motivations to perform the ring focus test can be summarized as follows:

- The image at the focal plane is large due to the spherical aberration.
- Low frequency errors are collapsed together in the focal plane.
- The separation of mirror surface errors and the test system effects is easier at the ring focus plane.

For a perfect optical system, the ring is sharply focused but its width is not infinitesimal. The width of the ring is a function of the spherical aberration of the system. It can be calculated accurately for a perfect optical system. If VETA-I was a perfect mirror and the test system was also perfect, the ring width solely due to the system spherical aberration, the finite source distance and the despace, should be 0.15 μm.

However, in the real VETA-I system, the mirror surface errors and the test system properties caused the ring image to be distorted and blurred, and the ring width to be broadened. Factors that could cause the ring width broadening are:

1. Theoretical test geometry (small).
2. Source size ($\sim$ 0.12 arcsec, 6 μm).
3. Detector resolution ($\sim$ 0.5 arcsec, 25 μm).
4. Mounting system induced distortions: Gravity, Thermal, epoxy shrinkage.
5. Mirror glass surface imperfections.

The ring width broadening due to the first three factors can be calculated accurately based on the experimental data we obtained before the VETA test. The effects of the fourth factor were not well known at the time of the test. They have to be extrapolated by comparing the test data with the ring focus models which we will discuss in section 5. The fifth factor – Mirror surface imperfections – is the one we want to measure. So our goal is to separate the system errors (the first 4 factors) from the mirror surface error (fifth factor) from the test data.

3. MEASUREMENTS

The ring focus measurements were carried out after the VETA focal plane measurements. There was no precise measurement (to submillimeter level) of the distance between VETA-I mirrors and the focal planes. So the axial coordinate difference between the ring and finite-distant foci was used for the data taken and analysis. Defining the optical axis as the X-axis (pointing from mirrors to the focus) and the on-orbit focus is at X = 0, the X offsets of the ring focus plane and the focal planes are, based on a ray-trace calculation for a perfect VETA-I system, 39.70 mm and 218.42 mm, respectively. Thus the distance between the two focal planes is 178.72 mm for a perfect system.

The C-K line was the only X-ray source used for the ring focus measurements. The measurements were made with two kinds of detectors: 1) a gas proportional counter with vertical and horizontal slits (9.5 μm $\times$ 290 μm); 2) a microchannel plate called HRI (High Resolution Imager) with a resolution of 25 μm (FWHM). Because of mirror and test system distortions, the actual ring focus plane (i.e. the plane contains the narrowest ring width) is not located 178.72 mm from the focal plane. To search for the actual ring focus plane, the proportional counter was placed on six locations on the X-axis to measure the ring width. The measurements were made as the counter and its horizontal (vertical) slit aperture scanned across the top and bottom (left and right) portions of the ring [3]. The results show that the actual radial profiles of the ring had triple peaked structures varying with the azimuthal angle. The ring width RMS for top and bottom (left and right) portions of the ring had different X coordinates. Therefore, there is no single plane that could be referred to as the actual ring focus plane. A plane was chosen with a compromised X position – 215.1 mm from the focal plane – where the ring widthes for both top and bottom were relatively narrow. HRI images were then taken in this plane. Because the ring size (25.5 mm diameter) is larger than the HRI, four images were taken for top, bottom, left and right quadrants of the ring. Each image had exposure time of 30 minutes. While the proportional counter with slits could only measure (with slightly higher resolution) the radial profiles at four locations, the HRI measurements can reveal the radial profile of any azimuthal angle around the ring.

However, the X position of the ring images – 215.1 mm – is rather far from the ideal ring focus plane. Based on lessons learned from our data analysis, we should do the measurements at the ideal ring focus plane in the future. If time allows, we can do it in both ideal and actual ring focus planes. The reasons are: 1) Because the depth of focus of the ring is relatively large, it is difficult to find the actual ring focus plane accurately and efficiently, and there may not be a single plane due to the system tilt; 2) Detections of test system effects are easier for images from the ideal ring focus plane.

4. DATA ANALYSIS

The four images taken with HRI were digitized to readout pixels of 6.45 μm $\times$ 6.45 μm. Each image collected about 0.3 million photons. Before the data analysis, the HRI scale was carefully measured and evaluated. One of the processes is called degap. In order to prevent loosing data near readout ports, 16 vertical and 16 horizontal gaps were deliberately left in the raw images. The degap process is to restore the image so that each pixel appears at its actual location. Figures 2 and 3 show a ring image before and after the degap process. This image was taken at a position in between the ring focus plane and the focal plane, where the ring is smaller, in order to capture the entire ring with HRI. It is seen that the image is nicely restored after the degap. Four large gaps at $\pm$ 45° and 135° on the ring are due to the VETA supporting struts. All the VETA HRI images were restored by this degap process. Figure 4 shows the four images of the ring focus measurements after degap.

Based on these four images and the HRI motor position log, a common ring center was located on each one of the quadrant images. The ring images were then divided into annuli and pie sectors with respect to this common center, using the IRAF/PROS software. In the vicinity of the ring, each annulus was chosen to be one pixel (6.45 μm) wide. The sectors were 2° each, which gives adequate statistical errors and enough azimuthal resolution. Photon counts in each cell of the annulus-sector grid were tabulated. Radial profiles near the ring for each azimuthal angle were then plotted, as shown in Figure 5 and 6. For some parts of the ring, the width and the radius stay the same for different azimuthal angles (Figure 5). While for other parts, they change drastically (Figure 6).

The ring width RMS and FWHM, and mean radius were calculated for each radial profile. There are large amounts of scattered photons in each image. Because a photon far away from the ring can carry large statistical weight, the above calculations are meaningless without clipping. Therefore, a window of 250 μm was set around the ring in order to perform the calculations. Inside this window, focused photons were strongly dominant over the scattered photons. All the photons outside this window, where scattered photons were dominant, were ignored. Thus the photon scattering does not affect the ring focus data analysis and therefore it is also not considered in the ring focus models discussed later. Of course, we did not intend to use the ring focus data to measure the scattering from the mirror surface, which was done by using the focal plane data.

In Figure 7, the top part is a plot of the ring width RMS vs. the azimuthal angle. (We chose RMS to represent the ring width because it has a better statistical value than FWHM.) When looking towards the +X direction, 0° is on the bottom of the ring; 90° is on the left; 180° is on the top; and -90° is on the right. A modulation with a 30° period is clearly shown in this plot. The bottom part of Figure 7 is the Fourier transform of the top plot, plotted as the modulation power vs. the frequency in one circumference. The modulation has dominant frequencies of 2 (180° period), 12 (30° period) and its higher harmonics. Figure 8 shows the ring mean radius plot and its Fourier transform. It also has a 12-fold symmetry, i.e. a modulation frequency of 12.

5. MODELS

The ring focus models are computer generated images of the ray-trace which simulates the X-rays passing through the VETA-I mirror and the test system. The VETA models used in the ray-trace were built, as a joint effort of SAO and Kodak, according to our best knowledge of the VETA test system.

As mentioned earlier, we understood the test geometry (such as the source distance, mirror position and tilt, detector positions, etc.) very well. The VETA mounting system is the major concern in building the VETA model. Each one of the VETA mirrors (P1 and H1) was held by 12 flexures in the middle of the cylinder (see Figure 9). The flexures were made of titanium and located aa the same as the positions of 12 hours on a clock. Attached to the middle of each flexure was an invar pad, which was epoxied to the outside of the mirror. The 12 flexures were attached to an aluminum ring of the VETA mount. There are three mounting system induced distortions:

1. **Gravity & compensation:** In the beginning of the VETA test, it was found, from measurements in

the focal plane, that the mirror was ovalized under the earth's gravitation, i.e. the mirror diameter in the horizontal direction is slightly larger than that in the vertical direction. This distortion was promptly corrected by applying squeezing force on the two sides of the mirror. This was the gravity compensation for the global effect. But the gravity also had local effect which was not compensated. As illustrated in Figure 10, because the mirror was hung at 12 rather small areas (1 inch $\times$ 1 inch), the gravity caused local distortions at those 12 locations. The distortions along the sides of the mirror were more severe than at the top or bottom. These local distortions would cause a shifted 12-fold symmetry (i.e. near 11 or 13 fold) and possibly a 2-fold symmetry due to the fact that the side distortions were different than the top and bottom. Although an over or under squeezed mirror would also have a 2-fold symmetry.

2. **Thermal effects:** The 12 flexures were attached to an aluminum ring which has a high thermal expansion coefficient. Meanwhile, the Zerodur mirror is well known for its extremely low thermal expansion coefficient. If the test temperature was different from the temperature when the mirror was mounted, the aluminum ring would pull or push the mirror through the flexures and invar pads at the 12 mounting points (see Figure 11). A uniform thermal effect should cause a symmetric distortion on the mirror and therefore a 12-fold symmetry in the ring focus image. A non-uniform thermal effect could cause an asymmetric distortion on the mirror.

3. **Epoxy shrinkage:** The shrinkage of epoxy in between invar pads and the mirror could cause local distortions in the mirror plane and in the direction normal to the plane. Assume the amount of the epoxy is about the same under each pad, this distortion is also symmetric and hence produces a 12-fold symmetry in the ring focus image.

Table 1 lists all the distortions for a complete VETA ring focus model. Our current model has included all of them except the mirror surface errors which is what we aim to obtain by comparing the model with the actual data. Parameters used for source distance, source size, despace and detector resolution were accurately measured. Errors due to alignment between P1, H1 and optical axis were estimated according to the focal plane data. All the mount induced distortions were provided by Kodak. The gravity & compensation distortion was calculated based on actual squeezing force applied. The thermal effect was calculated based on the test temperature record measured around the mirror during the test. The temperatures at different point of the mirror varied between 70.0 °F (the nominal temperature) and 70.2 °F. The distortion due to such a small temperature variation is actually negligible. So there is no thermal effect induced 12-fold symmetry. Compared to the ring focus data, the epoxy shrinkage distortion appears to be larger than the original prediction. Our current model contains $\times$ the predicted epoxy shrinkage distortion. The ring focus model was then made with 20 million rays tracing through the VETA model. Figure 13 and 14 show the ring width RMS and ring radius and their Fourier transforms based on our current VETA ring focus model.

Table 1. VETA Ring Focus Model

Table 2. Comparisons of VETA Ring Focus Data With Model

Symmetry	Data	Model	Comparison & Discussion
Ring Radius			
4 fold	Yes	Yes	Supporting strut & 4 HRI pictures.
12 fold	Strong	None	Data show symmetric distortions.
11,13 fold	Weak	Strong	local 1-g effect dominates the model.
Ring Width			
1 fold	Weak	Strong	Model has wider ring width at the bottom than the top.
2 fold	Strong	Weak	Data show strong local 1-g effect on both sides of mirror.
4 fold	Weak	Strong	Model has stronger 4 fold symmetry than data.
12 fold	Strong	Strong	Data and model both show symmetric distortions.
11,13 fold	Yes	Yes	Data and model both show local 1-g effect.
Base width	20μm	12μm	Mirror glass imperfection caused broadening $= \sqrt{20^2 - 12^2} = 16\mu$m.

Complete Model	Current Model	Parameters for Models
Test geometry:		
Source distance	Yes	Measured
Source size	Yes	Measured
Despace	Yes	Measured
Detector resolution	Yes	Measured
Alignment errors	Yes	Estimated
Mount induced distortions:		
Gravity & compensation	Yes	Calculated
Thermal effects	Yes	Calculated
Epoxy shrinkage	Yes	Estimated
Mirror surface errors (To be measured)	No	From optical test

6. COMPARING DATA WITH MODEL

Having reduced the data and established a model, comparing the two brings us to the central part of this work. Table 3 is a list of the comparisons. We now discuss them one by one:

Ring Radius:

- **4-fold symmetry:** The 4-fold symmetry is due to the VETA supporting struts and the HRI images taken for each quadrant of the ring.
- **12-fold symmetry:** The data show strong 12-fold symmetry with large variations on the ring radius (± 30 μm), which is likely due to the temperature change, epoxy shrinking in the normal direction of the surface and/or other mechanical effects causing

the 12 invar pads to exert force normal to the mirror surface. This symmetric distortion is absent in the model.

- **11,13-fold symmetries:** The data show 11 and 13-fold symmetries weaker than the 12-fold. Meanwhile these symmetries are dominate in the model. The 11 and 13-fold symmetries are due to the local gravity effect acting on those 12 supporting points outside the mirror. In other words, it is caused by the beating between $cos(\theta)$ (gravity) and $cos(12\theta)$ (flexures):
$$cos(\theta)[cos(12\theta)+cos(24\theta)+\cdots] = \frac{1}{2}[cos(11\theta)+cos(13\theta)+cos(23\theta)+cos(25\theta)+\cdots]$$
However, the amplitude of the modulation ($\pm$ 2.5 μm) in the model is much smaller than the 12-fold modulation in the data. This is an indication that the model underestimated the 12-fold symmetry and meanwhile overestimated the local gravity effect which caused available 12-fold modulation to completely shift to 11 and 13 fold.

Ring Width

- **2-fold symmetry** For ring width RMS, the 2-fold symmetry shown in its Fourier transform is strong in the data and relatively weak in the model. This effect is clearly seen in the top plot in Figure 7, where the ring width modulation amplitude along the sides ($\pm$ 90°) of the mirror are more than twice as much as that near the top or the bottom (0° or 180°). While in the model, there is no obvious change in the modulation amplitude. This indicates that the data show exactly the local gravity effect described in section 5. Even though the current model also shows the local gravity effect (see 11 and 13-fold symmetries in radius and width), it does not give an accurate account of the modulation amplitude.

- **3-fold symmetry** The model shows a strong 3-fold symmetry. This can be seen clearly in Figure 12 which is a 3-D surface plot of the P1 mirror according to the Kodak 1-g model. This indicates that the current model may over estimated the global 1-g effect.

- **5-fold symmetry** The 5-fold symmetry in the model is due to the shifted 3-fold symmetry, i.e. the modulation is not exactly separated by 120° and one of the separations is near 108°, as shown in the top plot in Figure 13.

- **12-fold symmetry** The data and model both show strong 12-fold symmetries, which could be caused by thermal and/or epoxy shrinkage distortions, however, there is a big difference (see Figures 7 and 12). The modulation in the data has sharper and higher peaks ($20-43$ μm); the modulation in the model has broader and lower peaks ($12-16$ μm). This means that the data show distortions localized near the invar pads and distortions normal to the mirror surface, which agrees with the discussion given in the ring radius 12-fold symmetry – the 12 invar pads did exert force normal to the mirror surface. Meanwhile the model has distortions extended to larger areas and distortions in the plane of the mirror surface, which are mainly caused by the epoxy shrinkage effect.

- **11,13-fold symmetry** The data and the model both show 11 and 13 fold symmetries weaker than the 12-fold. Thus they both have the local gravity effects, which agree with what we observed in the ring radius.

- **Base Width** The base (i.e. the narrowest part) of the ring width RMS is 20 μm for the data and 12 μm for the current model. This leaves us a $\sqrt{20^2 - 12^2} = 16$ μm ring width broadening due to the mirror glass surface imperfection. But our current model is not complete. We expect that the base line will be higher after we improve the model. So the ring width broadening due to the mirror surface error is expected to be less than 16 μm.

Our current model agree with the data only to certain degree. There are many aspects that the model does not give a accurate description of the actual VETA. We understand some of the aspects and process needed for improving the model. But there are aspects in the current model still yet to be understood. For example, why is the ring radius modulation has larger amplitude at the sides of the mirror than that at the top or bottom, and while the amplitude stay the same for the ring width?

We plan to further study the VETA ring focus results and theory to complete the model so it can match the data. We will then derive the mirror surface error by removing all the distortions described by the model from the data, and compare this error with the metrology error obtained from the optical test prior to the VETA-I test.

7. SUMMARY

- High quality Ring-focus test data allows diagnosis of features not evident in focal plane.
- We successfully accomplished this test.
- Our further studies will include thermal distortion (Uniform and Nonuniform) and epoxy shrinkage models.
- Ring-focus measurement is a very powerful test. By application of a high fidelity thermal model, we expect to investigate intrinsic details of the mirror figure.
- We expect that a ring focus test of the HRMA will be highly valuable.

8. HRMA RING FOCUS MESUREMENTS

9. ACKNOWLEDGMENT

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