# ASTRO-H Soft X-ray Telescope (SXT)

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## Abstract

ASTRO-H is an astrophysics satellite dedicated for X-ray spectroscopic study non-dispersively and to carry out survey complementally, which will be borne out of US-Japanese collaborative effort. Among the onboard instruments there are four conically approximated Wolter-I X-ray mirrors, among which two of them are soft X-ray mirrors[1], of which the energy range is from a few hundred eV to 15 keV, currently being fabricated in the X-ray Optics Lab at Goddard Space Flight Center. The focal point instruments will be a calorimeter (SXS) and a CCD camera (SXI), respectively. The reflectors of the mirror are made of heat-formed aluminum substrate of the thickness gauged of 152 μm, 229 μm, and 305 μm of the alloy 5052 H-19, followed by epoxy replication on gold-sputtered smooth Pyrex cylindrical mandrels to acquire the X-ray reflective surface. The epoxy layer is 10 μm nominal and surface gold layer of 0.2 μm. Improvements on angular response over the Astro-E1/Suzaku mirrors come from error reduction on the figure, the roundness, and the grazing angle/radius mismatching of the reflecting surface, and tighter specs and mechanical strength on supporting structure to reduce the reflector positioning and the assembly errors. In this paper, we report the results of calibration of the engineering model of SXT (EM), and project the quality of the flight mirrors.

**Keywords**: X-ray Optics, X-ray Telescope, X-ray Astrophysical Instrument

## 1. Introduction

Conical approximation of the Wolter-I type X-ray imagers has been a major tool for spectroscopic study in the last quarter of century since the launch of a sounding rocket experiment to study SN1987A. The high throughput, essential for the spectroscopic study, of the telescope is provided by using thin-foil reflectors, and the continuous improvement of angular response on X-ray imaging is accomplished by switching the substrate surface smoothing scheme from earlier lacquer-dipping to recent epoxy replication that reduced the mid-frequency waviness[2]. The low micro-roughness of the surface produces specular reflection of X-rays, with high Z material such as Au, Pt, or Ir as the reflecting surface. The energy range coverage can be up to 15 keV by lowering the grazing angle. Despite the continuous improvement over the last two decades from 4 to 1.7 arc-minutes, the demand of even better angular resolution of such thin-foil mirrors is high. The current image quality is still far from achieving the conical approximation limit, which is about 0.2 arc-minute. The difficulty comes from the relatively weak mechanical integrity of the reflectors and the imprecision in the assembly/alignment scheme. The improvement of HPD from the Suzaku mirror of 2 arc-minutes to the recent test of engineering model of ASTRO-H of 1 arc-minute will be the main subject of this paper.

Table 1 Design parameters of ASTRO-H and Suzaku

|  | ASTRO-H | Suzaku |
|---|---|---|
| Effective aperture diameter (cm) | 11.6-45.0 | 11.6-40.0 |
| Focal length (m) | 5.6 | 4.75/4.50 |
| Reflector height (cm) | 10.16 | 10.16 |
| # of reflectors | 203 | 175/168 |
| Mass (kg) | 45 | 20 |
| # of mirrors (0.4-12 keV) | 2 | 4/1 |
| Substrate thickness (μm) | 152, 229, 305 | 152 |
| Epoxy thickness (μm) | 10 | 25 |

| | | |
|---|---|---|
| Au thickness (Å) | 2000 | 2000 |
| Grazing angle (°) | 0.15-0.59 | 0.18-0.62/0.19-0.65 |
| FOV (arc-minute) | 17 | 19 |
| Expected effective area (cm$^2$) | 562/426 @ 1/6 keV | 450/320 @ 1.5/8.0 keV (measured) |

## 2. The Scheme

Error terms of image at the quadrant level can be categorized with quality of reflectors and assembly. For those coming from reflectors are axial figure, roundness, radius/grazing angle matching, surface roughness, and micro-roughness of the reflecting surface. Assembly errors come from precision of the holding structure, alignment, thermal, and under the gravity influence/image stability. We shall list the status of the error reduction.

Table 2 Error terms at quadrant level. The dominant term of error is the reflector positioning (alignment)

| | ASTRO-H | Suzaku |
|---|---|---|
| Radius/grazing angle mismatching | 1.2-2.5% | 2.3-9.2% |
| Axial figure (arc-minute) | 0.4 | 1 |
| Mid-frequency, μm-mm (Å) | 4-6 | 4-6 |
| Micro-roughness (Å) | 5 | 5 |
| | | |
| Alignment groove position drift (μm) | < 5 | < 40 |
| Alignment groove random (μm) | 5 | 12 |
| Alignment (μm) | 5 | 10 |
| Focal length uncertainty (cm) | 0.5 | < 5 |
| | | |
| Image quality HPD (arc-minute) | 1.1 | 1.7-2.2 |

### 2.1 Reflectors

Forming mandrels were conically shaped with sequentially increasing radius so that to provide the complete set of substrate at all design radii. There are 71 pairs of aluminum mandrels for ASTRO-H vs. 20 pairs of quartz mandrels for Suzaku. CTE matching with the substrate during forming at 200°C are much improved ($23\times10^{-6}$/°C vs. $0.59\times10^{-6}$/°C).

Radius/grazing angle matching: related to substrate forming scheme. For all substrate thickness, we stack 11 pieces in one forming batch. Only the innermost foil in the batch will have the right radius/grazing angle match, the rest of the batch will have the matching error, from inner to outer foils, of 9.2%/2.3% for Suzaku and 2.5%/1.2% for ASTRO-H.

Axial figure: generally is improved from 4 μm to 1-2 μm (surface figure error of the substrate forming mandrels was reduced). RMS error of the figure slope is about 0.4 arc-minute[3].
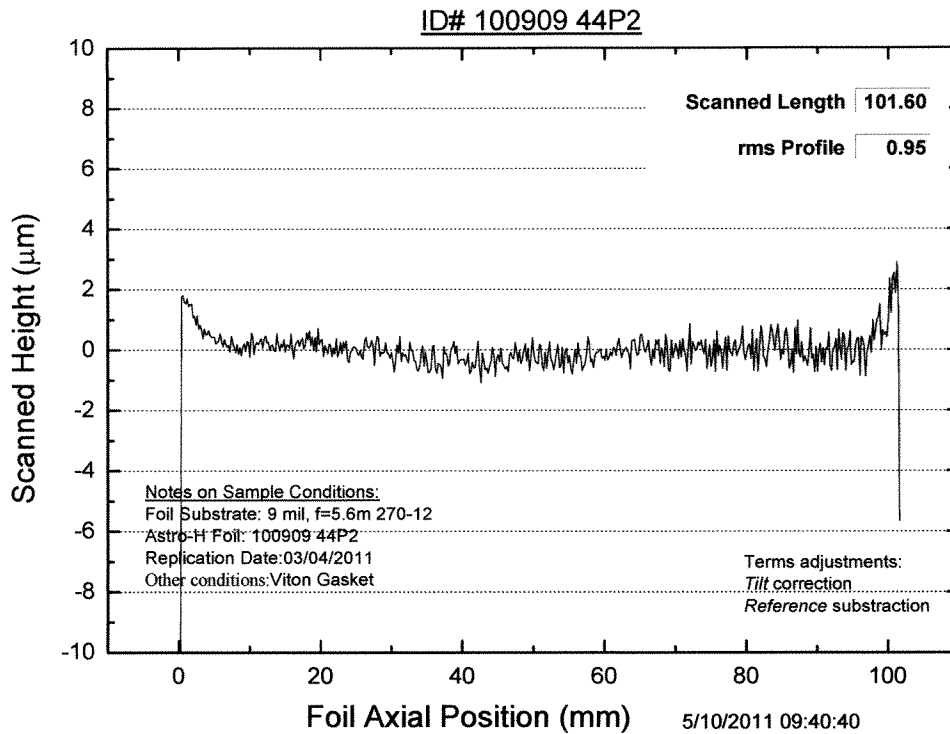
ID# 100909 44P2

Scanned Length 101.60

rms Profile 0.95

Scanned Height (μm)

Notes on Sample Conditions:
Foil Substrate: 9 mil, f=5.6m 270-12
Astro-H Foil: 100909 44P2
Replication Date:03/04/2011
Other conditions:Viton Gasket

Terms adjustments:
*Tilt correction*
*Reference* substraction

Foil Axial Position (mm)    5/10/2011 09:40:40

Fig.1 Axial figure of a typical reflector. Scan resolution is 200 μm

Roundness: error of 1/3 arc-minute (substrate size difference ~ +/- 1), which translates to 10 μm in reflector edge positioning error in the alignment bar grooves. RMS of this term is on an order of 1 arc-minute, which largely a limiting factor for reaching a sub-arc-minute image quality.

Mid-frequency roughness: 4-5 Å at spatial wavelength $10^{-3}$ - 1 mm. Result of Zygo surface profilometer is provided below.
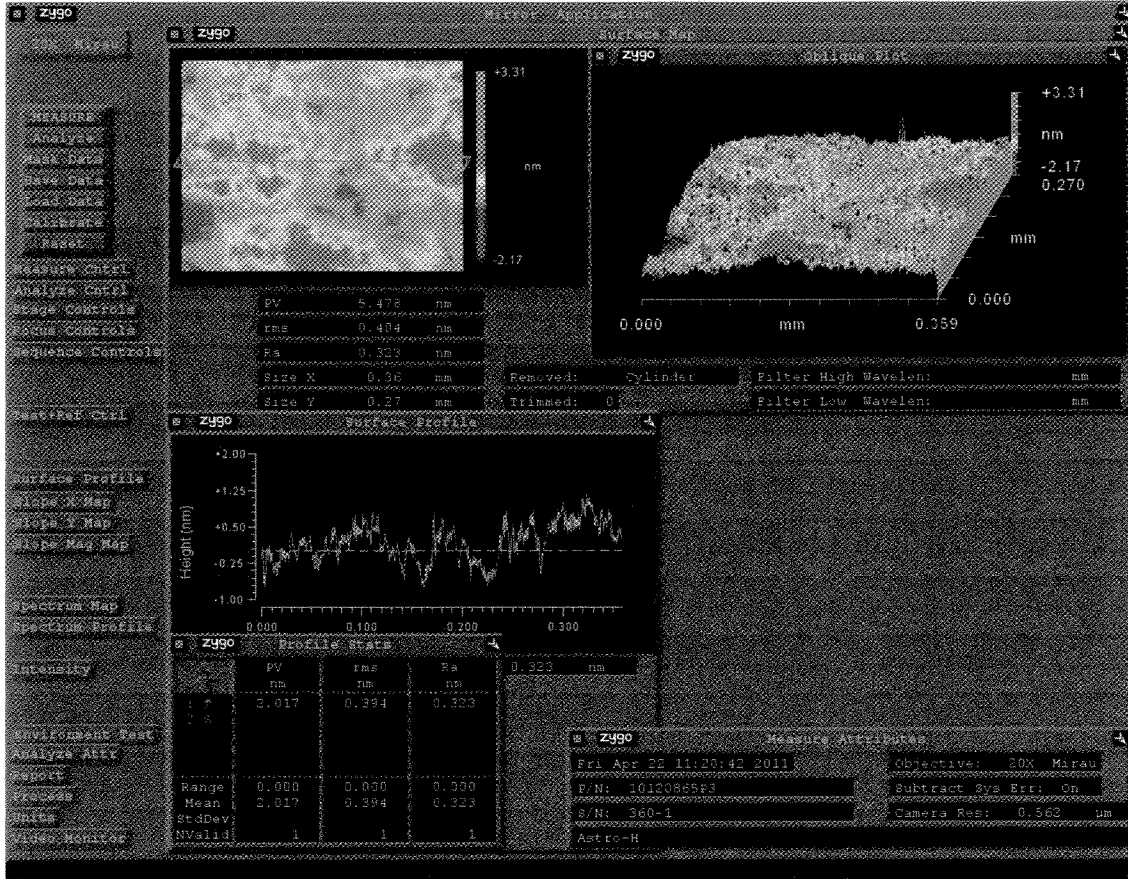
Fig. 2 Surface profile of a typical reflector

Micro-roughness: no obvious problem was implied by X-ray scattering.

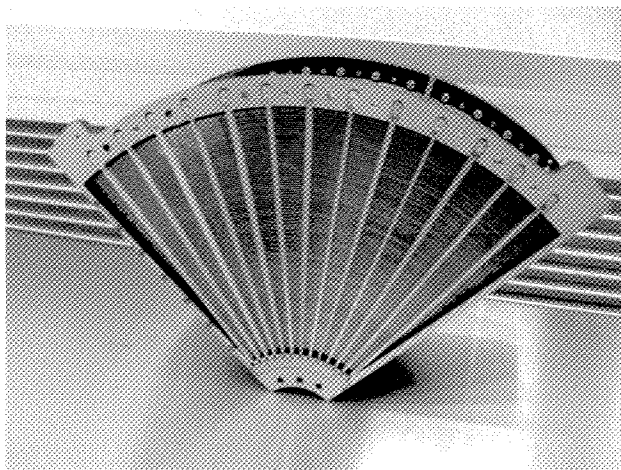## 2.2 Assembly at quadrant level



Fig. 3 ASTRO-H EM fully-populated primary housing of 203 shells. There are 13 alignment bars, on each phase, each with 203 grooves that hold the 203 shells by the edges

Holding structure:

- alignment bars, < 5 μm systematic walk of groove position from end to end; random error of the groove position: +/- 5 μm.
- mechanically strengthen the housing structure to resist distortion in the assembly;
distortion was minimized with 3-point mount scheme at two plane interface. The rest of the connecting screw positions will be dabbed with epoxy as liquid shims. These set of screws will be tightened after the epoxy is fully cured.

Alignment: any one of the two systems below will do the alignment. The EM alignment was done with the machine in the upper panel. It consists of a rotation table that carries the quadrant housings (see fig. 4) and a linear translation stage that carries a 500x magnification microscope which monitor the radial position of the alignment bars in the housing. After center of rotation is set within +/- 1 μm, each alignment bar can be adjusted to its design radial position. Focal length determination shall be within +/- 5 mm. The focal length is determined by the angle extending between primary and secondary housings, which can be achieved by adjusting thickness of the shims on three points in between the two housings to the accuracy of 2 μm.
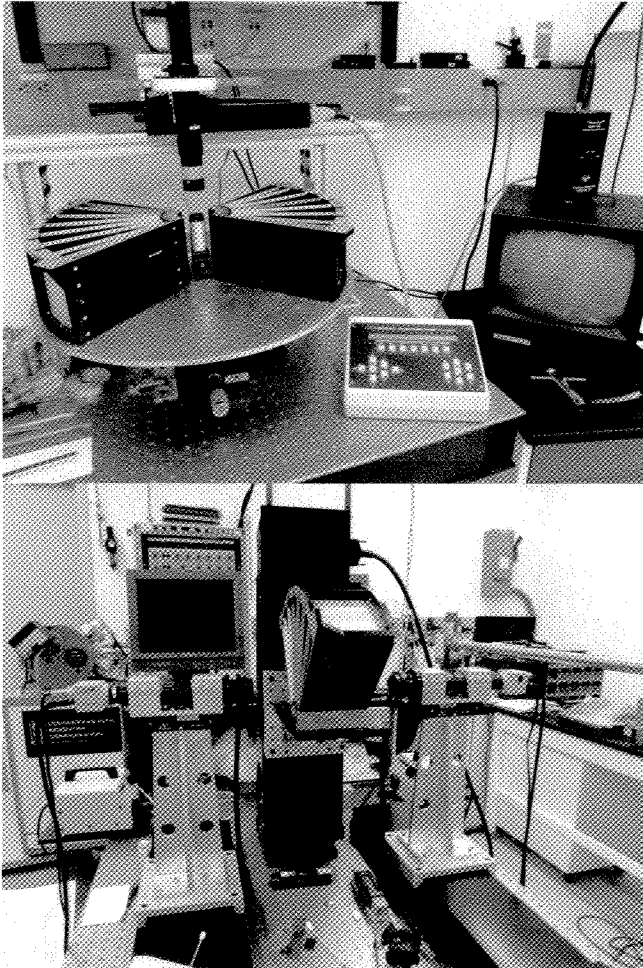


Fig. 4 Two alignment setups in polar/Cartesian coordinate, respectively. Precision and repeatability of the translation stages are at 1 μm, and wobble of the rotation stage is at 1 μrad

Stabilize the image by staking reflectors to the alignment bars: once tuning is final, apply Arathane (Uralane) 5753A/B in line along the bars. Staking reflectors onto alignment bars while the quadrant is in the upright orientation. This is to eliminate free-play of the reflectors in the grooves, and thus gravity-oriented instability, so that the ground calibration of the mirror can be preserved in the space operation. The image of the quadrant has been checked in the horizontal and vertical optical beams, and no difference in the two orientation was observed.

Thermal: EM mirror quadrant was tested for thermal dependence of HPD. At 22°C +/- 10°C the HPD changed within 1.1 +/- 0.05 arc-minute.

## 2.3 Assembly at telescope level

Features so designed to ensure the confocality of the four quadrants and optical axes alignment are kept in the assembly and environmental tests

- Rings at the inner radii at top/bottom of the mirror and a ring at the outer radius to connect the four quadrants at secondary bottom phase
- Stainless tabs on 8 locations at outer flange of the quadrant boundaries to keep the relative positions between the quadrants
- Stycast FT2850/24LV was used as liquid pins in between the quadrants in 8 places
- All elements were held with 3-point mounts and liquid shims, to achieve minimal stress in the assembled system
- Mounting pre-collimator (PC) onto top of the primary stage
- Placing thermal shield (TS), 0.2-micron polyimide supported by stainless wire mesh (94% transmission), onto the PC
- Match-drilled, in four groups of interface foot (I/F as seen in the above picture at outer flange of the housings), of 2 points a group, of 90° apart at the outer rim at interface of the primary and secondary housings, to be anchoring onto the top plate of the spacecraft
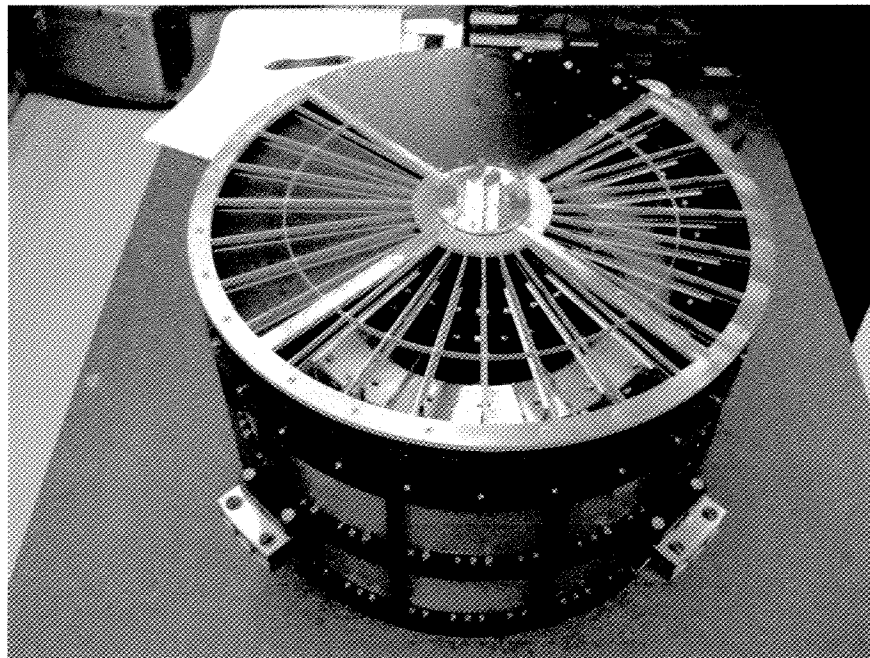


Fig. 5 ASTRO-H EM integrated mirror of one optical quadrant, three quadrants with mass simulators (provided by JAXA/ISAS), one pre-collimator (PC, from ISAS) on the optical quadrant, and one thermal shield (TS, from Nagoya University) on one of the quadrant with mass simulator

## 2.4 X-ray Test Results

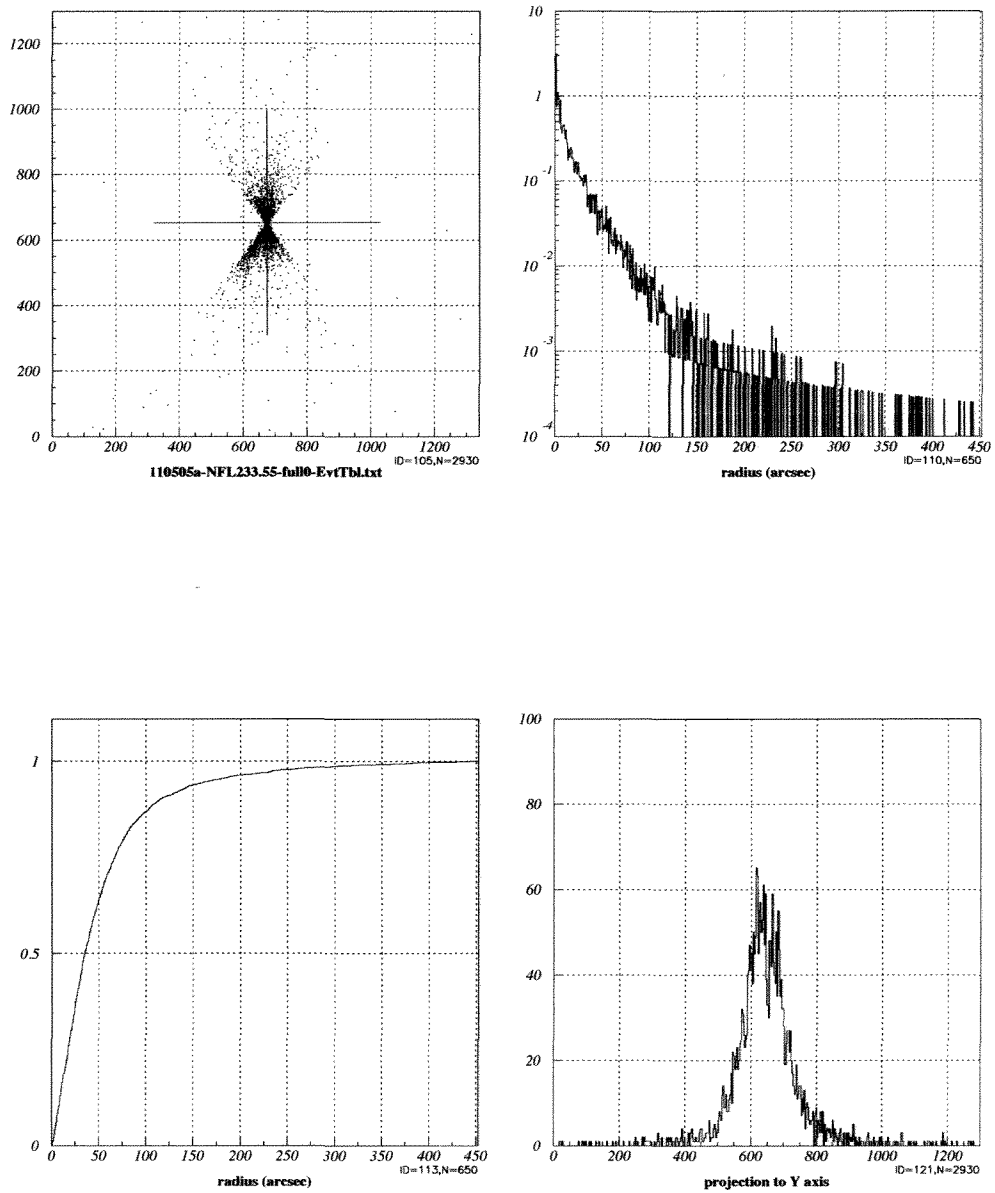EM quadrant results: a fully loaded EM quadrant

Fig.6 ASTRO-H EM quadrant X-ray test result, clockwise from top left: X-ray image on CCD, Point Spread Function (PSF) of the image, Profile of the image projected to the abscissa, and Encircled Energy Function (EEF). HPD of the EM image is 1.1 arc-minute

Sector image and the sector centroid distribution. Sector image is ~ 50-60 arc-seconds. The centroid of the sector image spread ~ 0.6 mm on the focal plane, and the RMS of the error is ~ 0.2 arc-minute.
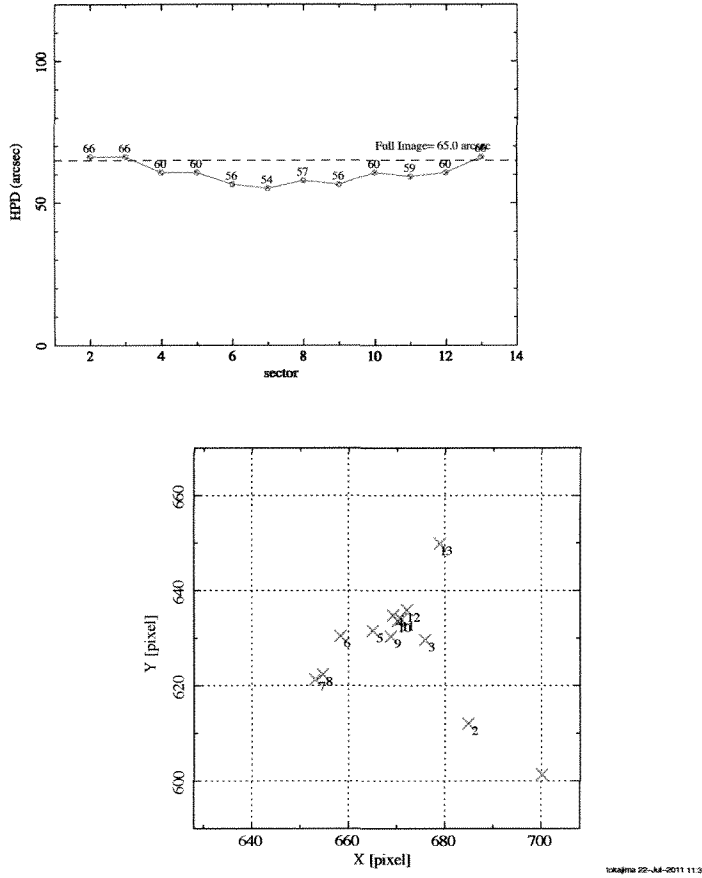
Fig. 7 The upper panel, sector image HPD. 13 alignment bars divided the quadrant aperture into 12 sector in between and 2 half-sectors at quadrant ends; lower panel, sector centroid location on the focal plane, pixel size 20 μm x 20 μm.

## 3 Discussion

Quality of the flight mirror will be similar to that of the EM quadrant.

Vibration test: the EM went through the vibration test at the qualification level. The execution was nearly complete but for the last axis due to a design flaw for the mass simulator. The image quality of the EM optical quadrant was verified after the vibration. The change was insignificant and there were no observable damages of the reflectors and the supporting structure.

As we demonstrated in the study, roundness error of the reflectors, which in turn contribute to the image ~ 1 arc-minute RMS, is the dominant one. The axial figure and surface roughness can be temporarily ignored until the dominant one being sufficiently reduced. Beyond the quadrant level, assembly focuses on the confocality of the quadrants and the parallelism of the four quadrants optical axes, which have little impact on the image quality at current level.

## 4 Conclusion

- High throughput X-ray mirrors with image quality at 1 arc-minute provide an excellent tool to study spectroscopy of the celestial X-ray sources
- Thin-foil X-ray mirror technology made a 2-fold improvement on angular resolution over the Suzaku mirrors
- The integrated mirror with four optical quadrants has not been assembled and tested yet, but the error in the integration is expected to be minimal

- As the reflector design/fabrication and assembly scheme keep on improving, the future of this low cost imagers may achieve HPD at 10-20 arc-seconds level

## Acknowledgement

## References

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[2] Peter J. Serlemitsos, Yang Soong, "Foil X-ray Mirrors", Astrophysics and Space Science, 239, 177, 1996
[3] Gubarev, Mikhail V., MSFC group for SXT-I, private communication, 2010