FOXSI: Properties of optics and detectors for hard X-rays

Abstract

The Focusing Optics X-ray Solar Imager (FOXSI) is a state-of-the-art direct focusing X-ray telescope designed to observe the Sun from 4 to 15 keV. This experiment completed its second flight onboard a sounding rocket last December 11, 2014 from the White Sands Missile Range in New Mexico. FOXSI optics have a Wolter-I geometry and consist of iridium-coated nickel/cobalt mirrors. Those mirrors were made using a replication technique based on an almost "perfect" polished surface. This allows a very good angular resolution. The FOXSI focal plane consists of seven double-sided strip detectors that were donated by the Astro-H group at ISAS/JAXA. These detectors underwent a thorough calibration using radioactive isotopes with known X- ray emission lines, including Am-241, Ba-133, and Fe-55, with peaks in their spectra within FOXSI's energy range.

We present on various properties of Wolter-I optics that are applicable to solar hard X-rays (HXR) observation, including angular resolution measurements of the FOXSI optics. Of particular interest for our scientific needs are the effective area vs photon energy, single-bounce ("ghost ray") patterns from sources outside the field of view, and the variation in point spread function for different source angles. We also present detector calibration results, paying attention to energy resolution.

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FOXSI - Focusing Optics X-ray Solar Imager

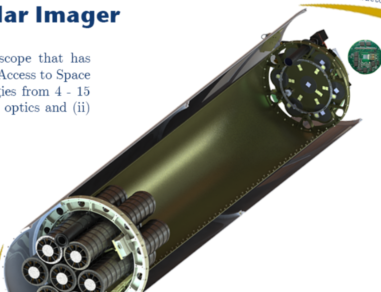
FOXSI is a state-of-the-art direct focusing hard X-rays telescope that has flown twice on a sounding rocket funded by NASA's Low Cost Access to Space program. FOXSI observed several targets on the Sun at energies from 4 - 15 keV. FOXSI is composed of two major parts: (i) The focusing optics and (ii) A set of semiconductor strip detectors.

FOXSI has seven focusing X-ray optics modules built at the Marshall Space Flight Center (MSFC), see figure 1. Each module consists of seven (or ten) nested nickel mirrors produced by an electroformed nickel replication process that follows a Wolter I geometry.

The table below summarizes FOXSI optics parameters obtained from laboratory calibrations.

Parameter	Measured Value
Focal length	2 m
Optics type	Wolter I
Number of optics modules	7
Number of mirror shells	7 or 10 per module, 55 total
Detector type	Double-sided Si strip
Strip pitch	75 μm
Detector dimensions	9.6×9.6 mm^2 (128×128 strips)
Angular resolution	
Detector strip pitch	7.7 arcsec (75 μm)
Optics PSF, FWHM	4.3 ± 0.6 arcsec (on-axis)
	5.1 ± 0.4 arcsec (7 arcmin off-axis, long axis)
	3.7 ± 0.4 arcsec (7 arcmin off-axis, short axis)
Combined optics + detectors	8.8 ± 0.3 arcsec (on-axis)
	9.2 ± 0.2 arcsec (7 arcmin off-axis, long axis)
	8.5 ± 0.2 arcsec (7 arcmin off-axis, short axis)
Half power diameter	27.1 ± 1.7 arcsec (on-axis)
Field of view	16.5×16.5 arcmin^2 (detector area)
	~20 arcmin diameter (optics FWHM)
Energy range	~4 to 15 keV
Energy resolution	509 ± 74 eV
Nominal effective area	~100 cm^2 at 10 keV
	~10 cm^2 at 15 keV

Semiconductor detectors



Optics Focusing X-rays

Figure 1. FOXSI mechanical model.

Focusing hard X-rays

Focusing X-rays is more difficult than focusing visible light. X-ray reflection requires total external reflection and very small angles of incidence. However, there is a well known geometry, called Wolter-I, that uses double bounces over first a parabolic and then a hyporbolic mirror to focus X-rays.

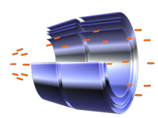


Figure 2. Nested mirrors following a Wolter-I geometry to focus X-rays. Image credit: NASA, Chandra, and Smithsonian Astrophysical Observatory.

Mirrors could be nested with different radii, as shown in figure 1, to increase the collecting area of the optics. X-ray focusing optics have been used in astronomy-aimed spacecraft (i.e. Chandra, XMM-Newton and NuSTAR), however, there is no exclusively solar dedicated spacecraft that uses focusing hard X-ray optics.

Detector selection

The detector material determines which photon energies it can recognize.

Semiconductors (like silicon and germanium) make excellent detectors because of their closely-spaced valence and conduction bands. Silicon has good efficiency for photons with energies up to 15 keV.

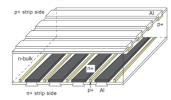


Figure 3: Double sided strip detector

5 of the 7 detectors flown in FOXSI-2 were silicon with a 75 micron pitch. 2 were new Cadmium-Telluride with a 60 micron pitch.

Calibration procedure

The following isotopes with known emission lines were used to calibrate the detectors:

Isotope	Energy peaks (in keV)
Am-241	13.76, 13.95, 17.75, 17.99, 20.78, 59.54
Ba-133	30.62, 30.97, 34.92, 34.98
Fe-55	5.89

A raw photon count from the readout ASICs needs a "translation" into energy units. Calibration software was used to recognize peaks in the raw spectrum and match their centers to known energies. Figure 4 shows an Am-241 calibrated spectrum for 64 (individually calibrated) channels.

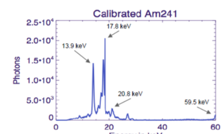


Figure 4: Fully calibrated Am-241 spectrum, w ith the 13.9 keV line at a width of ~0.5 keV

We also analyzed how much of the photons that reach one detector hit only one strip over those photons that hit two or three strips. Almost all events are 1-strip events on the P-side, 7% are 2-strip events on the N-side. See figure 5.

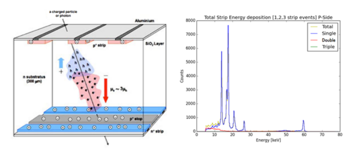


Figure 5. Left: Conceptual representation of a charged particle or a photon hitting a strip detector. Right: Single and double strip events for an Am-241 spectrum.

Calibrating the FOXSI optics

Angular resolution measurements

Solar microflare hard X-ray structures are discernible at angular resolution of less than 9.5 arcsec [Christe, et.al. 2011]. FOXSI has that resolution. The FOXSI optics were calibrated via measurements of their point spread function (PSF). That calibration was done at the 100-meter evacuated beamline of the Stray Light Facility at the NASA/MSFC in Huntsville, AL.

The FOXSI PSF was measured placing a Trufocus X-ray generator at one end of the bell chamber and one optics module at the end of the beamline with a CCD camera for direct imaging on the focal plane.

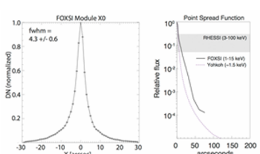


Figure 6. Left: FOXSI-PSF for a source on-axis. Right: Comparison of the FOXSI angular resolution with other two solar X-ray instruments.

The FOXSI angular resolution is the full width at half maximum (FWHM) of the core gaussian of the PSF (figure 6). That is FWHM = 4.3+/-0.6 arcsec for an on-axis source. At the right side of figure 6 we also show a comparison between the FWHM of FOXSI with that two other solar dedicated space-borne X-ray instruments.

The PSF for an off-axis X-ray source is squeezed in one direction and broadened in the other. For sources very far off-axis some single bounce photons also reach the detectors. We measured the PSF for several off-axis positions of the source (figure 7).

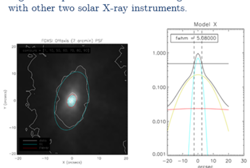


Figure 7. Measurement of the PSF for a source 7 arcmin off-axis. Left: Direct image on a CCD detector with a gaussian fit in cyan. Right: Transverse cut of the PSF and measurements of the FWHM via three gaussian fits.

Effective area

The FOXSI effective area (EA) strongly depends on the energy of those photons that hit the mirrors. We used a 3.0mm pinhole over a monolithic CdZnTe detector to measure long exposures with and without every optical module, see figure 8.

$$A = A_{pin} \cdot \frac{F_1}{F_2} \cdot \frac{t_2}{t_1} \qquad (1)$$

If F_1 photons are counted with the optic present over time t_1 and F_2 photons are counted without the optic over time t_2, using a pinhole of area A_{pin}, then the effective area A is given equation (1).

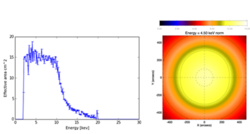
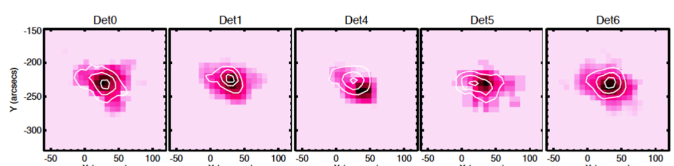


Figure 8. Left: Measurement of the effective area for a seven shell FOXSI optical module as a function of the energy of an incident beam of X-rays. Right: Effective area for X-rays of 4.5 keV.

Recent FOXSI observational results



FOXSI-2 was able to image at least two active regions, including two microflares, on the Sun during its 6.5-minute observation, as seen in the figure 9. The images are integrated over 25 seconds on a specific target. The composite image (all Si added) shows a solar microflare in active region 12230.

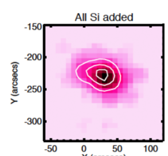


Figure 9: Active solar region imaged by FOXSI-2. The background image and contours show 4-5 keV and 6-9 keV emission, respectively.

Conclusion

We presented the FOXSI optics properties including angular resolution measurements. Among the characteristics important to us are the effective area for each optical module, single-bounce patterns generated by off-axis sources, and the point spread function dependence with the source location.

There is still plenty of analysis to be done, but the silicon detectors instantly showed the active regions on the Sun (Figure 9). The addition of the two CdTe detectors extended FOXSI's efficient energy range to around 20 keV, deeper into the hard x-ray range. Improvements to the calibration would include more isotopes to gather a wider range of peaks in the energy spectrum.

NASA Black Brant sounding rocket - FOXSI-2, December 11, 2014

References

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