Calibrating a solar x-ray telescope using the Crab Nebula

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Summed observations of a well-studied astronomical x-ray source can provide an inexpensive alternative to data collected with sounding-rocket underflights for calibrating space-based solar telescopes.

The Crab Nebula (see Figure 1) has been used to calibrate x-ray detectors on many satellite-, rocket-, and balloon-borne missions. It provides a bright and stable broadband source with a well-characterized spectrum. For space-based telescopes, in particular, this allows adjusting to changes over time in filters, electronics, optics, and other sensors.¹ We demonstrate here the feasibility of extending this calibration practice to the Solar X-Ray Imager (SXI-N) telescope aboard a Geostationary Operational Environmental Satellites (GOES) mission launched in May 2006.²

The primary mission of the GOES series, which is operated by the National Oceanic and Atmospheric Administration (NOAA), is to monitor weather on Earth. SXI's purpose is to provide real-time images of the sun and solar corona between 6 and 60 Å, which helps space weather forecasters by providing long-term solar climatological observations.

Previous SXI instruments were not calibrated. They suffer from ongoing filter and electronic unit degradation, and a consequent degree of measurement uncertainty. Onboard x-ray calibration of satellite instruments is not generally practical because the required sources would be too large. NOAA's current plan for calibrating SXI-N would use expensive sounding-rocket underflights to make solar observations simultaneously with the GOES.³

In-flight x-ray calibrations using the Crab Nebula may not have been considered in these cases because of the nebula's low flux compared with that of the solar phenomena being measured. To evaluate the feasibility of this approach, we used existing Crab Nebula measurements from the Einstein Observatory, shown in Figure 2,⁴ to see whether SXI-N observations could achieve a signal-to-noise ratio (SNR) of at least 5, which would meet the instrument's 20% photometric requirement. We also modeled likely noise sources that would enter into our signal-to-noise calculations.

Figure 1. The Crab Nebula, shown at visible wavelengths. Courtesy of NASA and ESA (Hubble WFPC2), and Allison Loll and Jeff Hester (Arizona State University).

The conversion of the nebula's photon spectrum $F_{x-ray}(\lambda)$ into signal electrons S_{x-ray} generated by SXI-N's CCD was modeled as the following integral over wavelength λ ,

$$S_{x-ray} = \int_{9\text{\AA}}^{30\text{\AA}} F_{x-ray}(\lambda) \cdot b(\lambda) \cdot ef(\lambda) \cdot A_{eff}(\lambda) \cdot Fil(\lambda) \cdot c(\lambda) \cdot QE_{CCD}(\lambda) d\lambda$$

where:

S_{x-ray}	Signal electrons generated in the CCD by Crab Nebula x-rays.
$F_{x-ray}(\lambda)$	X-ray flux from the astronomical source in photons $\text{s}^{-1}\text{cm}^{-2}\text{keV}^{-1}$.
$b(\lambda)$	Bandwidth conversion, from photons/keV to photons/Å.
$ef(\lambda)$	Entrance filter transmission.
$A_{eff}(\lambda)$	Grazing-incident mirror's effective area.
$Fil(\lambda)$	Filter transmission.
$c(\lambda)$	Electrons generated per x-ray photon at λ .
$QE_{CCD}(\lambda)$	CCD quantum efficiency.

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Figure 2. Measurements of the Crab Nebula x-ray flux spectrum (crosshairs) are shown, along with a model that incorporates interstellar medium absorption by several elements.⁴ Crosshairs give the bandwidth (horizontal bar) and error (vertical bar) of each measurement.

	Thin Polyimide	Be 12
SNR	3.15	2.22
X-Ray Photons Detected	76	11
Images Required for SNR=10	10	21

Table 1. Shown are the estimated SNRs for SXI-N based on 65s Crab Nebula calibration images.

The integration was performed numerically using a Microsoft Excel spreadsheet.

In computing the SNR, the total measurement uncertainty was assumed to be dominated by errors associated with photon counting (Poisson-distributed), CCD thermal noise, digitizer quantization error, and CCD readout noise.

An SNR of 5 ‘just’ meets the photometric requirement, allowing for no performance degradation over time. An improved approach would be to sum several images, which should increase the ratio by the square root of the number of images summed. Using the SXI-N’s longest exposure (65s) with the most (‘Thin Polyimide’) and least (‘Be 12’) transmissive filters, a doubled SNR of 10 would require the sum of 10 and 21 images,

respectively (see Table 1), which represent fairly modest operational demands.

This analysis of calibrating SXI-N using the Crab Nebula shows that effective calibration could be carried out with relatively small operational and analysis costs. Expensive calibration underflights, requiring sounding rockets, would not be needed. If successful, this calibration technique could be used by other space-based instruments that observe the sun at x-ray wavelengths.

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Karl Klett Jr. attended his first SPIE meeting this past August, where he presented a paper that is the basis for this article.

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