GOES/SXI Team Adopts CREOL X-ray Telescope Design

The Geostationary Operational Environmental Satellite (GOES) system is a geosynchronous dual weather satellite system that continuously senses climatic changes in the western hemisphere of the earth's atmosphere as well as measuring other environmentally crucial factors. The GOES system is operated by the National Oceanic and Atmospheric Administration (NOAA) with headquarters in Boulder, Colorado. NOAA's mission is to create and disseminate reliable assessments and predictions of weather, climate, space environment, ocean and living marine resources, and nautical and geodetic phenomena. Future GOES systems will therefore continuously gather data on *space weather* occurring both locally and at the Sun.

The Solar X-ray Imager (SXI) is a complimentary, add-on instrument designed primarily for use on the GOES next generation satellites; however, its modular design is suitable for installation on many other spacecraft platforms. Its primary mission is to continuously observe the full solar disc at X-ray wavelengths; including coronal holes, active regions, flares, and coronal mass ejections. A solar flare erupts when stored magnetic energy in the sun's convection zone is suddenly released into the corona. The corona is almost entirely composed of plasma. This plasma is dominated by the physics of magneto-hydrodynamics and by bremsstrahlung effects. Electrons are the main carrier of the plasma energy and are easily guided by the prevailing magnetic fields. When oppositely directed magnetic fields reconnect into a cusp, non-thermal electrons release hard X-rays that can be distinguished from the spectrum of soft X-rays produced by thermal electrons. Sunspots are the visible manifestations of flare footprints and represent the redistribution of ambient energy from the Sun's blackbody spectrum into the X-ray spectrum.

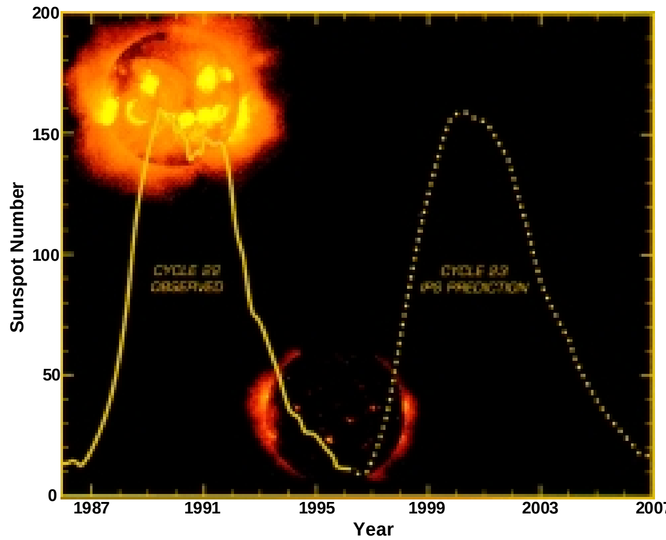

Figure 1. Recent sunspot activity versus time.

For reasons not fully understood, solar flare and sunspot activity varies dramatically on an eleven-year cycle as shown in Figure 1. Solar flare induced space weather and its detrimental effects include: geomagnetic storms (malfunction of compass and GPS systems); electromagnetic interference (communication systems failure); ionospheric expansion (satellite deorbit); power grid overloads (blackouts); radiation overdose (astronaut health hazard); and single event upsets (satellite electronics malfunction).

UCF/CREOL Professor James E. Harvey and graduate student Patrick Thompson are providing technical support to the Lockheed Martin Solar and Astrophysics Laboratory (LMSAL), prime contractor for the design and fabrication of the SXI telescope for the GOES N and O satellites. Raytheon Optical Systems, Inc. of Danbury, CT is the X-ray mirror manufacturer. NASA's Goddard Space Flight Center in Greenbelt, MD is serving as the contract monitor for the Lockheed Martin contract. The NASA baseline design for the SXI telescope is a classical grazing incidence Wolter Type I design consisting of a paraboloidal primary mirror and a hyperboloidal secondary mirror. Designs of this type have been successfully used on NASA's recently launched Chandra (AXAF) Observatory,[1] the European Space Agency's ROSAT X-ray telescope launched in 1990,[2] and the U.S. Einstein Observatory launched in 1978 which marked the beginning of the burgeoning field of X-ray astronomy.[3] The Lockheed Martin SXI modular design and some of its specific optical features and associated support systems are illustrated in Figure 2. The entire telescope is only about 100 centimeters long and 20 centimeters in diameter.

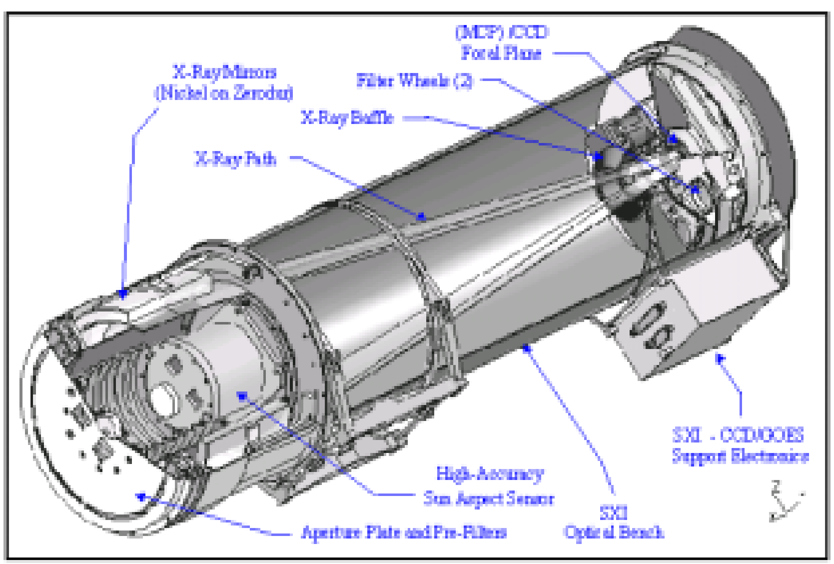

Figure 2. SXI modular design illustrating specific optical features and support systems.

CREOL's role in the SXI program was originally to perform detailed image quality predictions, including the detrimental effects of surface scatter at the very short X-ray wavelengths of 6-60 angstroms. Harvey and Thompson have developed a systems engineering approach to image analysis where they calculate the aperture diffraction point spread function (PSF), the geometrical PSF, the surface scatter PSF, and the miscellaneous residual error PSF independently. These four functions are then convolved numerically to yield the system PSF, or aerial image, produced by the X-ray telescope (see Figure 3). Once the system PSF is known, most of the commonly used image quality criteria are readily calculated.

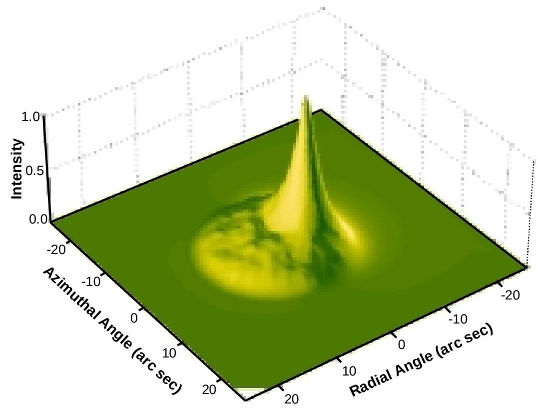

Figure 3. SXI aerial image for 6 arc min field angle.

The primary top level image quality requirement placed upon the SXI prime contractor was expressed in terms of on-axis fractional encircled energy, with the off-axis performance being dictated by the imaging characteristics of the telescope optical design. A similar requirement had been (appropriately) imposed by NASA upon both the Einstein and the Chandra Observatories. However, they were both small-field *stellar* X-ray telescopes that are precisely pointed at the object of interest. SXI is intended to operate as a staring telescope, pointed at the center of the sun, providing wide-field images of the full solar disc. Since the features of interest (solar flares or sunspots) can appear virtually anywhere on the solar disc, there is no merit in optimizing the on-axis image quality at the expense of the off-axis performance. A field-weighted-average measure of resolution is therefore more appropriate for the SXI application. Harvey suggested that minimizing the area-weighted-average half power radius (HPR_{awa}) over a particular field-of-view (FOV)

$$HPR_{awa} = \frac{1}{A_T} \int_{\theta=0}^{\theta_{max}} HPR(\theta)\, 2\pi\theta\, d\theta, \quad \text{where } A_T = \pi\,\theta_{max}^2$$

would maximize the number of average spatial resolution elements in that FOV

$$N = \#\text{ of spatial resolution elements} = \frac{A_T}{\pi\,(HPR_{awa})^2},$$

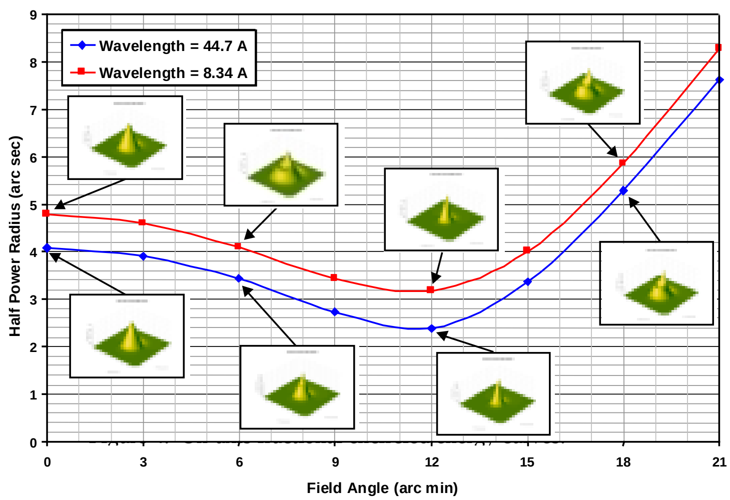

Figure 4. HPR versus field angle for H-T#17.

and thus maximize the total information content of the image. This new image quality requirement led Harvey and Thompson to develop a whole new family of optimal grazing incidence X-ray telescope designs, where each member of the family is optimized for a different FOV. This new family of X-ray telescope designs differs from the classical Wolter Type I design in that they consist of a hyperboloidal primary mirror and a hyperboloidal secondary mirror. This is reminiscent of the well-known aplanatic Cassegrain (Ritchey-Chretien) normal incidence telescope design that is corrected for spherical aberration and coma. However, since scattering effects dominate geometrical aberrations at small field angles, and field curvature and astigmatism dominate coma at large field angles, there is little merit in using precious design variables for eliminating either coma or spherical aberration.[4] Instead the five free parameters of the hyperboloid-hyperboloid design can be used to balance all aberrations (defocus against field curvature, spherical aberration and astigmatism against oblique spherical aberration) to obtain an optimum design for a given FOV. One member of this new family of generalized Wolter Type I X-ray telescope designs, designated as H-T#17, yields a predicted **80% increase** (over the baseline design) in the number of spatial resolution elements in an 18 arc min radius FOV. The HPR versus field angle is illustrated in Figure 4 for the H-T#17 X-ray telescope design.

After an intensive effort during which NASA and ROSI corroborated the predictions of Harvey and Thompson, and after the necessary cost and schedule impact on the mirror fabrication program, the GOES/SXI team formally adopted the H-T#17 optical design for the SXI telescopes for the GOES N and O satellites at the Lockheed Martin SXI Critical Design Review (CDR) briefing on July 15-16, 1999.

1. M. V. Zombeck, "Advanced X-ray Astrophysics Facility (AXAF)-Performance Requirements and Design Considerations", Proc. SPIE **184** (1979).
2. B. Aschenbach, "Design, Construction, and Performance of the ROSAT High Resolution Mirror Assembly", Appl. Opt. **27**, 1404-1413 (1988).
3. R. Giacconi et al., "The Einstein (HEAO 2) X-ray Observatory, Astrophys. J. **230**, 540 (1979).
4. P. L. Thompson and J. E. Harvey, "A Systems Engineering Analysis of Aplanatic Wolter Type I X-ray Telescopes", submitted for publication in Opt. Eng. (May 1999).