3.10 FIRST FORECAST PRODUCTS FROM THE GOES-12 SOLAR X-RAY IMAGER

Christopher C. Balch*, Steven M. Hill, V. J. Pizzo
U.S. Department of Commerce, NOAA/SEC, Boulder, Colorado
Daniel C. Wilkinson
U.S. Department of Commerce, NOAA/NGDC, Boulder Colorado

Abstract. The Solar X-ray Imager (SXI) was launched 23 July 2001 on NOAA's GOES-12 satellite. When the spacecraft enters operation, this instrument wiill provide routine, nearly uninterrupted, full-disk, soft X-ray movies of the Sun's outer atmosphere called the corona. This is the first instrument of its kind flown by NOAA and the first of its kind flown by any organization for routine space weather monitoring and forecasting operations. The instrument's 0.6-6.0 nm bandpass makes it sensitive to the coronal temperature range of 10^6-10^7 K. The corona is the source of most space weather disturbances. The imaging nature of the SXI will add two-spatial dimensions to the already routine observations of disk-integrated solar X-ray intensity. The NOAA Space Environment Center (SEC) will use the images in its Space Weather Operations. At the time of this conference, the SXI will have completed initial on-orbit testing and calibration. This paper presents results of that test period and describes future operational forecast products. System performance will be assessed along with its impact on the forecast products.

1. Introduction

The first Solar X-ray Imager (SXI) has been added to the complement of GOES instruments that monitor space environment conditions. The significant advantages of an X-ray imager for monitoring and understanding the Sun's hot and constantly changing corona have been realized by the scientific community for over twenty years. Major advances in understanding this aspect of solar activity were achieved in particular by the Skylab soft X-ray telescope S-054 (Moore et al., 1980) and by the Yohkoh soft X-ray telescope (Watanabe et al. 1998). The realization that observing the corona was key to monitoring and predicting solar-geophysical activity prompted NOAA, in partnership with the USAF and NASA, to propose, fund, develop, build, and fly an operational solar X-ray telescope to support the operational space weather missions of NOAA and the USAF.

The instrument uses grazing incidence optics to focus solar X-rays onto a microchannel plate (MCP). The incident X-rays produce electrons, which are accelerated and amplified through the MCP and impinge on a plane of phosphor grains. The phosphor generates optical photons in response to the electrons, and these photons are funneled down optical tapers, and impinge on an optical CCD. A 12-position analysis filter wheel is positioned in front of the MCP and enables operational control over the wavelength response of the instrument. The filter positions include a fully open setting, a set of relatively thin polyimide filters, a set of relatively thick beryllium filters, and a closed (radiation shield) position (Bornmann et al. 1996).

Throughout the initial check-out period, the instrument has performed as expected and should have no difficulty achieving its operational goals. In this paper we discuss briefly how the SXI will improve space weather operations and we will illustrate various ways in which this new, exciting, voluminous data source will be utilized.

2. Space weather and SXI

A critical element of the mission of the NOAA Space Environment Center (SEC) is to monitor and predict space weather phenomena to help minimize their impacts on human activities. Space weather phenomena consist of many components including solar flares, coronal mass ejections, geomagnetic storms, near-earth solar radiation storms, variability of solar background flux levels, and the production of high energy electrons at geosynchronous orbit. These phenomena interact with a number of human and technical systems including spacecraft operations, manned spacecraft missions, high-flying or polar-route airline flights, electrical power grids, pipelines, and various radio communication systems that use or pass through the Earth's ionosphere (Tascione, 1988, Song et al., 2001). The NOAA/SEC space weather operations center monitors space weather conditions continuously, and provides various nowcast and forecast products to these users. The Solar X-ray Imager will be a useful tool to enhance many aspects of these services. In particular, the

* *Corresponding author address:* Christopher Balch, U.S. Department of Commerce, NOAA/SEC, 325 Broadway, Boulder, CO, 80305-3328, email: Christopher.Balch@NOAA.GOV

main goals of the SXI instrument are to help NOAA/SEC:

- Improve the ability to predict solar flares
- Detect coronal changes that are indicative of a coronal mass ejection
- Observe solar coronal holes
- Support prediction of solar radiation storms by pinpointing the location of major solar flares
- Monitor the distribution of coronal emissions

In the following section a brief explaination is given on how SXI will support these objectives.

3. Specific applications for the SXI

3.1. Solar flare prediction

The SXI will observe the morphology of magnetic field loops associated with sunspot regions in the corona. These magnetic fields store energy which may subsequently be released in a solar flare. By monitoring the appearance and evolution of these loop systems, space weather forecasters will be able to qualitatively assess the level of magnetic shearing and the emergence (or decay) of magnetic flux in active regions. This will enhance the ability of forecasters to make predictions for solar flares.

3.2. Observation of coronal mass ejections

The last 20-25 years has seen a substantial increase in the observations and understanding of the origin of transient flows which originate from the Sun and propagate through interplanetary space (Crooker, Joselyn & Feynman, 1997). It is now appreciated that these coronal mass ejections, and their interaction with the ambient solar wind are the drivers for non-recurrent geomagnetic disturbances here at Earth. Observations of the Sun's corona during coronal mass ejections has shown that there are often indicators visible in solar X-ray emission that are indicative of a coronal mass ejection. Apparently the processes leading to coronal mass ejections leave partially open magnetic field lines which subsequently release magnetic energy on closed loops as they reconnect. This energy release is manifested in long duration thermal X-ray emission from these loops, and by the successive formation of loops of greater height and width as a function of time (Webb et al, 1976).

3.3. Observation of coronal holes

Another key discovery of the Skylab era was that the source of recurrent geomagnetic activity could be traced to regions of open coronal magnetic fields (Zirker, 1977). These regions appear relatively dark in solar coronal X-ray emission and permit solar wind to be rapidly accelerated into interplanetary space. The continuous monitoring of these coronal holes will be of great value in predicting the occurrence of geomagnetic activity originating from solar coronal holes.

3.4. Solar radiation storms

The location of a major solar flare has a significant influence on the nature of any associated solar radiation storm (Balch, 1999). The importance of this measurement has long been recognized, and NASA, USAF and other agencies have undertaken efforts to support worldwide, ground-based flare patrol for this purpose. However, with the realization that solar X-ray emission is really the dominant component of flare emissions, and the practical issue that ground-based observatories are subject to the limitations of adverse weather, the value of having continuous, minute-by-minute observations of X-ray emission on a geosynchronous spacecraft has become evident.

3.5. Distribution of coronal emission

Solar variability has a strong influence on the Earth's ionosphere and the upper regions of the neutral atmosphere. In order to support users who are affected by this variability, NOAA space weather operations provides forecasts and reports of solar flux values. The variability of this flux is strongly linked with the location and evolution of solar active regions and with the location of solar coronal holes. Solar active regions are clearly distinguished in solar X-ray images by the presence of hot, closed magnetic loop structures. Not only are the regions on the disk clearly indicated, but the three dimensional nature of these loops allows forecasters a glimpse of solar active regions before they rotate onto the solar disk, thereby enhancing NOAA's ability to predict this important parameter.

4. First products from SXI

A number of products will be derived from SXI to assist users of the data in extracting this key information from a vast volume of data. The list of products includes:

- Real-time image and movie displays

- Automatic flare location detection
- Image and movie analysis tools
- Composite Images
- Derivation of coronal hole parameters
- Region of interest analysis

We now briefly describe each of these products and their anticipated application in space weather operations.

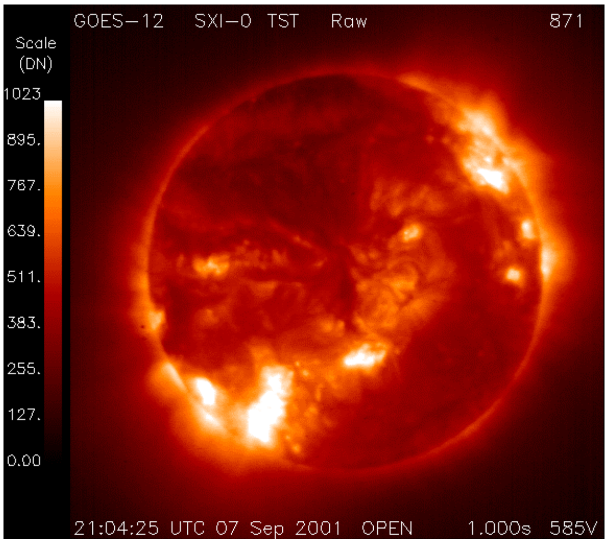

Figure 1. Real-time display of the first official SXI image using the open filter position (shows the coolest plasma).

4.1. Real-time image and movie displays

Up-to-the-minute images and series of images will be displayed in the operational forecast center, enabling space weather forecasters to directly observe the phenomena we have just described (see figure 1). This continuous watch and review by the forecast center will support many existing space weather products including flare alerts and proton event warnings.

4.2. Automatic flare location detection

NOAA/SEC has developed an automated algorithm to pinpoint the location of flares using SXI data. The algorithm will run continuously in real-time and will notify the space weather operations centers of the locations of flares. This information will be reviewed by the operations staff in real-time and will then be made available to the public through the space weather operations event list, using the world-wide web. The rapid identification of flare locations, as mentioned previously, is a key step in assessing the need to issue warnings for solar radiation storms. An example of output from the algorithm is shown in figure 2.

4.3. Image and movie analysis tools

As was mentioned previously, changes observed in the Sun's corona with the SXI are useful for analyzing and predicting solar flares, coronal mass ejections, coronal holes, and solar variability. To support this analysis effort, SEC has designed and developed tools to allow forecasters to examine SXI images in detail, and to examine time-lapsed series of images in sequence. A high level of control of the movie sequences is possible, so that forecasters can look carefully for changes over subsets of the series. These controls include the ability to pause and manually step back and forth through any images of interest and to dynamically adjust the color scaling of the images. In addition, the forecaster may request to view the images as running differences, a calculation which is done on-the-fly within seconds of the request (see figure 3).

4.4. Composite images

It is possible to expand the dynamic range sampled by the SXI by combining information from multiple images taken in the same filter at nearly the same time. The process of forming a composite image begins with a relatively long-exposure image. The long exposure image will typically do a good job of showing relatively faint features, but often has the limitation that the details of brighter regions are not discernable because they are overexposed. However, this problem is overcome by replacing those saturated pixels by their time-normalized values as measured by a relatively short-exposure image. Finally, information about the instrument point spread function (PSF) enables us to deconvolve the signal from PSF, leading to a sharper image. The resultant composite image is a very good summary of the state of the solar corona (see figures 4 and 5).

```
BRTREG_20010928_192540495_BA_12         T    100.00     Q     0  C     8  R     2
     Rank  Intensity   Coord1    Coord2  Npix OnDisk     MaxVal  NMaxPix
        1   32080.86  -26.136     5.169   208      1  160.6816        1
        2   19605.60   24.830    53.029   137      1  168.4302        1
```

Figure 2. Example bright region report at 2001-09-28 19:25 UT.

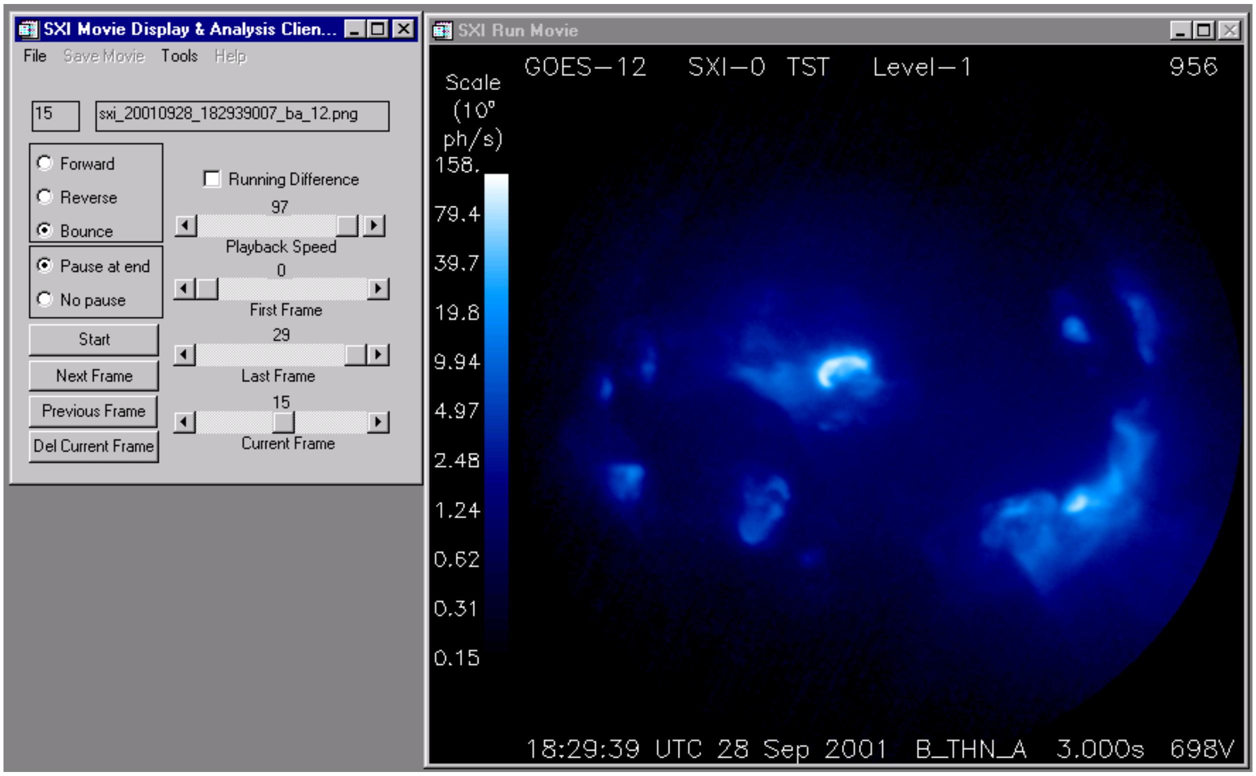

Figure 3. The SXI movie analysis client showing a single frame and controls. The filter wheel is positioned to the beryllium filter (shows the hottest plasma).

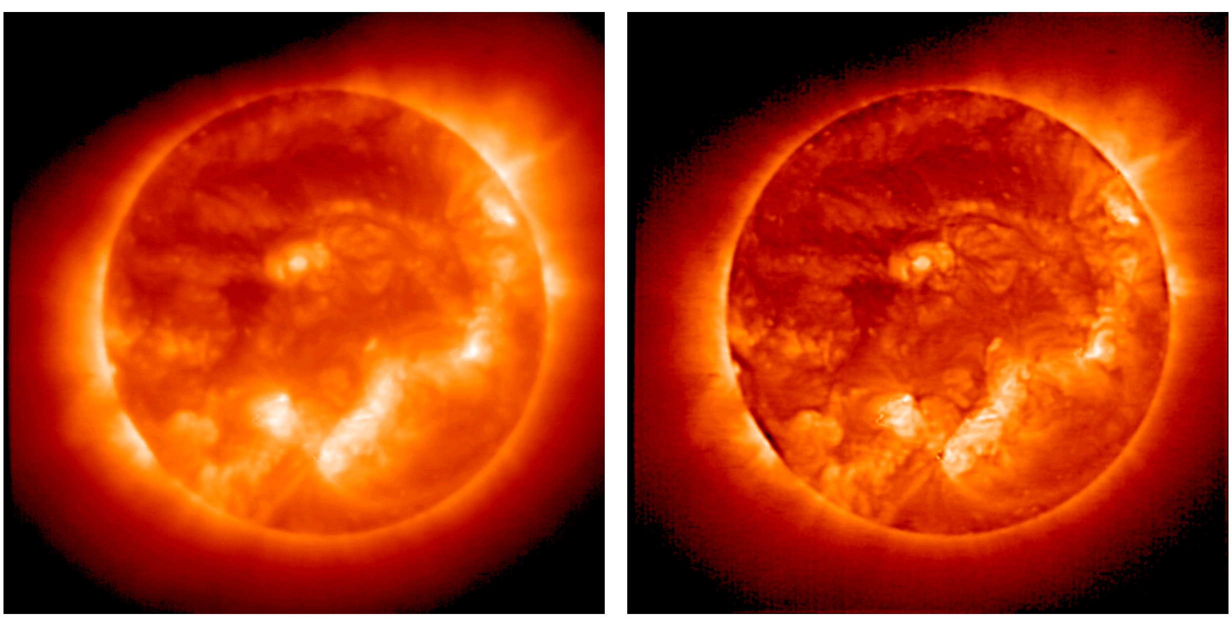

Figure 4. SXI composite image (left) using the open filter wheel position. Shown to the right is the same image corrected for the instrument point spread function.

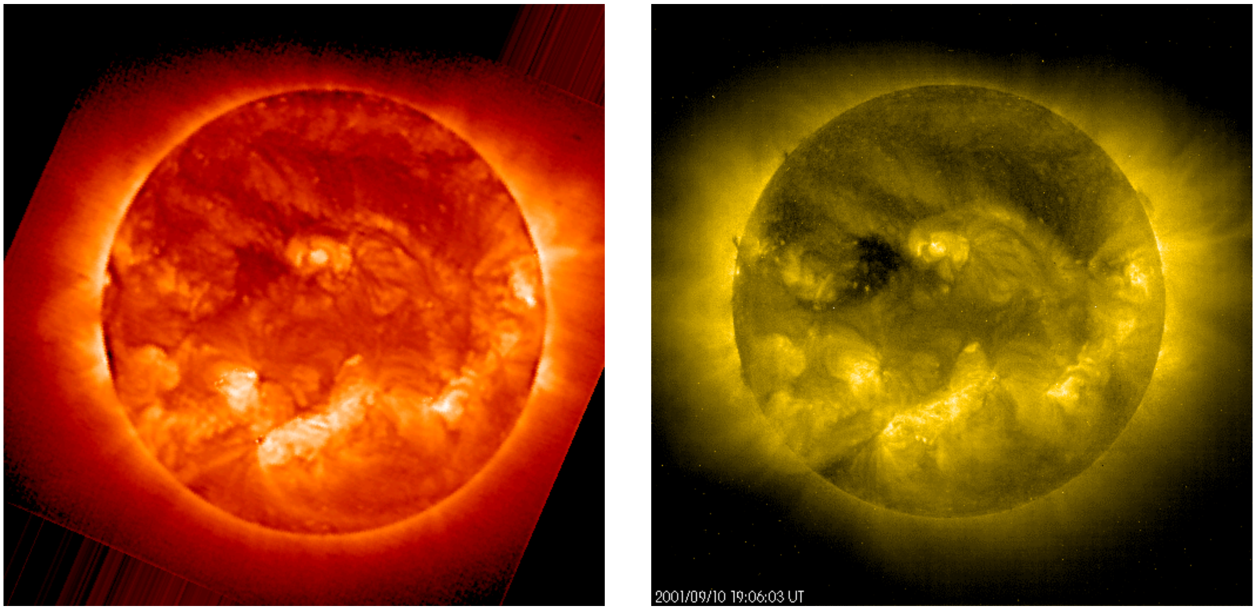

Figure 5. Point-spread corrected SXI image (left) compared to a contemporaneous EIT image (right, scaled to 512x512 pixels). The SXI image uses our 'coolest' filter (open position) and the EIT image is its 'hottest' filter (28.4 nm).

4.5. Coronal hole parameters

Software tools have been designed to enable forecasters to indicate the location and characteristics of solar coronal holes using a point-and-click interface with SXI data. The parameters derived from this software tool will be issued in a coronal hole product and will be made available on the NOAA/SEC website.

4.6. Region of interest analysis

Software has been designed to allow forecasters to track particular regions of interest on the Sun using SXI data. A point-and-click interface enables the forecaster to specify the region of interest. Automatic software programs will keep track of region parameters as a function of time, including total X-ray emission, maximum brightness, and the occurrence of events. These tools will help forecasters to assess objectively the evolution of solar active regions and should support forecasts for flares and solar flux variability. An example of time-series emission from an active region is illustrated in figure 6.

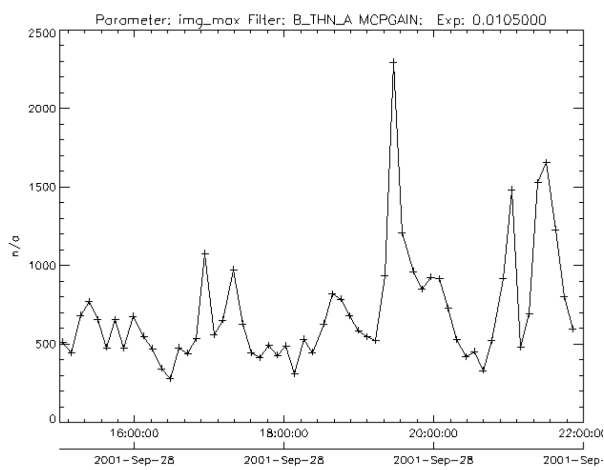

Figure 6. Sample pseudo-light curve for the Beryllium filter. Values represented are those of the instantaneously brightest pixel for a given image.

5. Future products

We have identified some additional products which may provide further useful information from the SXI dataset. We plan to investigate these for practicality and usability in space weather operations. In particular we will evaluate the utility of ratios of images, which should serve as a coronal plasma temperature diagnostic. We also plan to select a representative composite image each day, so that a long time-series of X-ray images may be combined and compared. These daily synoptic images should support analysis for long-term trends in solar activity, and may also eventually be used as key inputs for large scale solar wind models. A final product we have identified is the calculation of flux as a function of heliographic longitude from SXI images. By quantifying the distribution of flux with longitude, the forecaster should be able to produce a better, more objective forecast for variability of solar flux.

6. Conclusion

In this discussion, we have briefly covered aspects of space weather and their impacts on human activities. We have discussed in particular the realization by the scientific community of the key role played by the solar corona in staging and, to a certain extent, initiating the types of solar activity that are fundamental to space weather processes. The new solar X-ray imager, launched on GOES-12, provides NOAA an opportunity for the first time to observe directly the dynamics and morphology of the solar corona on a continuous, minute-by-minute basis with a dedicated, operational instrument. This improved monitoring of solar activity will enhance the value of existing NOAA/SEC products, particularly in the areas of solar flare prediction, energetic particle event prediction, geomagnetic forecasts, and solar variability forecasts. In addition, we have discussed some new products that will help reduce and assimilate the data in useful ways.

7. For further information

Additional information on SXI is available at the following websites:
http://sec.noaa.gov/sxi/
http://sxi.ngdc.noaa.gov/

8. References

Balch, C. C., SEC proton prediction model: verification and analysis, *Radiation Measurements*, 30, 231-250, 1999.

Bornmann, P. L., D. Speich, J. Hirman, V. Pizzo, R. N. Grubb, C. Balch, and G. Heckman, The GOES Solar X-ray Imager: Overview and Operational Goals, in *GOES-8* and Beyond, *Proc. SPIE Vol. 2812*, pp. 309-319, 1996.

Crooker, N., J. Joselyn, J. Feynman (eds), *Coronal Mass Ejections*, Geophysical Monograph Series, 99, AGU, 1997.

Moore, R. L., *et al.*, The thermal x-ray flare plasma, p. 341, in *Solar Flares*, ed. P.A. Sturrock, Colorado Assoc. Univ. Press, Boulder, Colorado,1980.

Song, P, H. J. Singer, G. L. Siscoe (eds), *Space Weather*, Geophysical Monograph Series, 125, AGU, 2001.

Tascione, T. F., *Introduction to the Space Environment*, Orbit Book Company, Malabar, Florida, 1988.

Watanabe, T., T. Kosugi, A. C. Sterling, *Observational Plasma Astrophysics: Five Years of Yohkoh and Beyond*, Dordrecht-Kluwer Academic, Boston, 1998.

Webb, D. F., A. S. Krieger, D. M. Rust, Coronal x-ray enhancements associated with H-alpha filament disappearances, *Solar Physics*, 48, 159, 1976.

Zirker, J. B. (ed), *Coronal Holes and High Speed Wind Streams*, Colorado Assoc. Univ. Press, Boulder, 1977.