GOES-R Series X-Ray Sensor (XRS): 1. Design and pre-flight calibration

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Abstract

The X-Ray Sensor (XRS) has been making full-disk observations of the solar soft X-ray irradiance onboard National Oceanic and Atmospheric Administration’s (NOAA) Geostationary Operational Environmental Satellites (GOES) since 1975. XRS provides critical information about the solar activity for space weather operations, and the standard X-ray classification of solar flares is based on its measurements. The GOES-R series of XRS sensors, with the first in the series launched in November 2016, has a completely different instrument design compared to its predecessors, GOES-1 through GOES-15. To provide continuity, the two GOES-R XRS spectral bands remain unchanged providing the solar X-ray irradiance in the 0.05-0.4 nm and 0.1-0.8 nm bands. The changes include using Si photodiodes instead of ionization cells to improve performance, using multiple channels to allow for a wider dynamic range, including quadrant photodiodes for real-time flare location measurements, and providing accurate radiometric calibrations using the National Institute of Standards and Technology (NIST) Synchrotron Ultraviolet Radiation Facility (SURF) in Gaithersburg, Maryland. The design and pre-flight calibration results for this next-generation XRS instrument are presented here in this XRS Paper-1, and in-flight solar X-ray measurements from GOES-16, GOES-17, and GOES-18 are provided in the XRS Paper-2.
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\textbf{ABSTRACT}

The X-Ray Sensor (XRS) has been making full-disk observations of the solar soft X-ray irradiance onboard National Oceanic and Atmospheric Administration’s (NOAA) Geostationary Operational Environmental Satellites (GOES) since 1975. XRS provides critical information about the solar activity for space weather operations, and the standard X-ray classification of solar flares is based on its measurements. The GOES-R series of XRS sensors, with the first in the series launched in November 2016, has a completely different instrument design compared to its predecessors, GOES-1 through GOES-15. To provide continuity, the two GOES-R XRS spectral bands remain unchanged providing the solar X-ray irradiance in the 0.05-0.4 nm and 0.1-0.8 nm bands. The changes include using Si photodiodes instead of ionization cells to improve performance, using multiple channels to allow for a wider dynamic range, including quadrant photodiodes for real-time flare location measurements, and providing accurate radiometric calibrations using the National Institute of Standards and Technology (NIST) Synchrotron Ultraviolet Radiation Facility (SURF) in Gaithersburg, Maryland. The design and pre-flight calibration results for this next-generation XRS instrument are presented here in this XRS Paper-1, and in-flight solar X-ray measurements from GOES-16, GOES-17, and GOES-18 are provided in the XRS Paper-2.

\textbf{Keywords:} solar X-Ray irradiance, X-ray photometer, solar flares, space weather instrumentation
1. INTRODUCTION

Since 1975, a series of Geostationary Operational Environmental Satellites (GOES) have been observing the terrestrial weather as well as monitoring many aspects of the space environment. The crucial observations obtained by these satellites have aided the progress of terrestrial weather forecasting and have provided data to study space weather, or how the Sun, both particles and photons, affect Earth’s space environment and our space-based technology. Of particular interest for space weather is the impact of solar storms on our myriad of technology, such as satellites, communication systems, and navigation systems. These observations and monitors are so critical that the organization operating the GOES satellites, the National Oceanic and Atmospheric Administration (NOAA) under the National Weather Service (NWS), requires there to be at all times two operational GOES satellites in geostationary orbit with one over the east coast and one over the west coast for full surface weather coverage of United States and for redundancy of the space weather measurements. NOAA also maintains at least one backup GOES satellite in a ‘parked’ orbit somewhere over the continental US ready to immediately become operational if either of the two operational satellites has anomalies or is decommissioned.

There is a long and continuous record of monitoring for solar X-ray flares from the GOES satellite series, starting with the first GOES satellite in 1975. These data from the X-Ray Sensor (XRS) provide the primary measurements used to classify the magnitude and duration of solar X-ray flares. XRS is designed to measure the full-disk solar X-ray irradiance in two broadband wavelength intervals: 1) $\Delta \lambda = 0.05\text{-}0.4$ nm, called XRS-A (also known as the XRS “short” channel); 2) $\Delta \lambda = 0.1\text{-}0.8$ nm, called XRS-B (XRS “long” channel). Both intervals are in the soft X-ray (SXR) range that extends between 0.1 and 10 nm.

The X-ray flare classification is based on the XRS-B 1-minute-averaged peak intensity for a flare. The X-ray flare classification includes a letter (A, B, C, M, and X) that represents an order of magnitude of XRS-B irradiance and a number (1-9) within the specified order. For example, an X3.2 flare has a peak irradiance of $3.2 \times 10^{-4}$ W m$^{-2}$; whereas, a M3.2 flare has ten times lower irradiance. If the flare is larger than $10^{-3}$ W m$^{-2}$, then the number is extended beyond 9. For example, an X14 flare has a peak irradiance of $14.0 \times 10^{-4}$ W m$^{-2}$. The flare classification is based on the irradiance truncated to one decimal place.
The NOAA Space Weather Prediction Center (SWPC) analysis of the GOES-15 and earlier XRS data indicates that the XRS-B band reported values need to be multiplied by 1.43 (divided by 0.70) to convert from flare levels (e.g., C, M, X) to physical irradiance units of W m$^{-2}$. Similarly, NOAA SWPC recommends that the earlier XRS-A reported values need to be multiplied by 1.18 (divided by 0.85) to convert to physical irradiance units of W m$^{-2}$. As of May 2024, the corrections have been applied for GOES-8 through -15 and will be applied to the early satellites later in 2024. For more information on the previous XRS calibration, see:


There is also a new calibration recommended for the GOES-15 XRS-B using SXR spectra from the Miniature X-ray Solar Spectrometer (MinXSS) CubeSat as described by Woods et al. (2017). This new calibration is consistent with the NOAA recommended multiplication factor of 1.43 for XRS-B intensities larger than C1, but GOES-15 XRS-B reported values are too large for intensities less than B2. It is important to note that for the new GOES-R series XRS “science” products, a multiplication factor to physical irradiance units is not needed, starting with the GOES-16 XRS results. We note that the GOES-R series four satellites are called GOES-R, S, T, and U during development and are renamed after launch as GOES-16, 17, 18, and 19.

The combination of the XRS-A and B data can also provide an estimate of the coronal plasma temperature. One estimation technique is to relate the ratio of the XRS-A 0.05-0.4 nm irradiance to the XRS-B 0.1-0.8 nm irradiance using a spectral model for the solar irradiance (Garcia, 1994; White et al., 2005; Woods et al., 2023). Because the flare temperature typically peaks right before the X-ray irradiance peaks (i.e., maximum of $dE/dt$ in W m$^{-2}$ s$^{-1}$), space weather operators use this XRS channel ratio to forecast the end of the flare impulsive phase (rise of flare profile). These X-ray photons, which travel at the speed of light and arrive at Earth in about 8 minutes, also provide a warning of potential terrestrial-effective particle events that are associated with a flare but travel at slower speeds. These highly energetic particles, called solar energetic particle (SEP) events, pose a serious threat to the safety of our space-based technology and also radiation safety concerns for astronauts, especially during space walks when there is limited shielding for the astronauts. In addition, coronal mass ejection (CME) events are often associated with eruptive flares. Studies of the statistical relationship between CMEs and flare magnitude have revealed a steady increase in the fraction of CME-related events as a function of flare magnitude, ranging from $\sim 20\%$ for C-
class flares to ~50% for M-class flares, and reaching close to 100% for X-class flares (Wang & Zhang, 2007; Hudson, 2011; Woods et al., 2011).

The XRS that was used through the GOES-15 satellite consists of two ionization cells for the two different XRS bands (e.g., Garcia, 1994). These ion-cell XRSs have their limitations though. One of these limitations is that the irradiance measurements ‘bottom-out’ before true solar minimum levels (e.g., Woods et al., 2017), limiting their usefulness to quantify minor solar activity during solar minimum or to compare solar minimum levels from one solar minimum to the next. At the upper end of the magnitude range, the previous XRS sensors saturate at flare levels of about X17; therefore, these previous XRS instruments cannot directly quantify the magnitude and temperature of solar flares larger than X17, such as those that occurred on 28 October 2003 and 4 November 2003. Other limitations with the previous XRS sensors are related to the accuracy of the measurements, based on the limited pre-flight radiometric calibrations and inability to directly monitor for long-term degradation of the XRS channels. The accuracy is most critical for comparing data from different XRSs or over long periods of time with the same instrument. NOAA has fortunately been able to have overlapping XRS measurements since the 1970s to maintain a consistent solar SXR record by being able to adjust new XRS measurements to the other operating XRS instruments. Improved accuracy is desired to more correctly quantify the radiative energy released during flare events, both for solar physics research and for better understanding of the total energy deposited into Earth’s environment. While there hasn’t been any noticeable XRS sensitivity degradation for the earlier missions, the XRS background levels and temperature-dependent gain corrections have changed over time, and those time-dependent corrections have been incorporated into the latest reprocessing of the GOES XRS data.

Many of the aforementioned limitations are resolved with a new design for the XRS sensors as part of the GOES-R Extreme-ultraviolet and X-ray Irradiance Sensors (EXIS) system. This new XRS design, which features multiple channels containing simple passband limiting filters and stable Si photodiodes (Korde & Canfield, 1989), has significant heritage from multiple space-based platforms for observing the solar soft X-ray irradiance over the past two decades. These instruments include the X-Ray Photometer System (XPS) which is part of the Solar EUV Experiment (SEE) (Woods et al., 2005a) onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite, as well as similar XPS sensors that have flown on the Student Nitric Oxide Experiment (SNOE) (Bailey et al., 2000) and the SOlar Radiation and
Climate Experiment (SORCE) (Woods et al., 2005b). Other simple enhancements were made to the design to allow the additional capability of determining the location on the solar disk where flares occur. This paper, XRS Paper-1, presents an overview of the new XRS instrument design for the GOES-R series and the calibration for the XRS aboard GOES-16 (launched 2016 Nov 19), GOES-17 (launched 2018 Mar 1), and GOES-18 (launched 2022 Mar 1). We note that the fourth (and final) satellite in the GOES-R series is expected to be launched in summer 2024. The in-flight performance of these XRS instruments are presented in the XRS Paper-2 by Machol et al. (2024).

2. XRS INSTRUMENT OVERVIEW

The GOES-R series of XRS instruments have the basic goal of continuing the almost five decades of solar soft X-ray measurements from previous XRS instruments. The key XRS requirements, as listed in Table 1, drive many aspects of the engineering and instrument design of the new XRS. These requirements are specified in NOAA’s Performance and Operational Requirements Document (PORD; not publicly available) for the GOES-R EXIS instrument. One of the major design drivers was to span an irradiance range of more than 6 orders of magnitude, while maintaining a signal-to-noise ratio (SNR) greater than one for the lowest irradiance level. These combined requirements drove the XRS design to include two photodiodes per XRS bands. We refer to the four channels in the GOES-R Series XRS as XRS-A1 and XRS-A2 for the A band, and XRS-B1 and XRS-B2 for the B band. The A1 and B1 channels are optimized to make measurements near solar minimum and have a larger limiting aperture of 81.0 mm². This is the maximum aperture area achievable given other optical constraints such as Si photodiode detector size, field-of-view (FOV) requirements, and minimum distance of the aperture to the photodiode. The A2 and B2 channels are the solar flare channels that cover the high portion of the irradiance range. These channels each have a much smaller aperture area of 4.5 mm² that limits the number of photons that are seen at the detector and allows the XRS A2 and B2 channels to exceed their required maximum irradiance levels. The new XRS B2 design is expected to be able to measure up to about X120 flare level before saturation. The A2 and B2 detectors are actually quadrant photodiodes, instead of single element photodiodes as used for A1 and B1. The size and placement of the A2 and B2 apertures also define the capability of A2 and B2 channels to determine the flare location as described in more detail in Section 4. As an end data product, the XRS A and B band
irradiances are reported as single values with the irradiance values selected from the optimum photodiode based on a predefined irradiance level, as discussed more by Machol et al. (2024).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>XRS-A Requirement</th>
<th>XRS-B Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Range</td>
<td>0.05-0.4 nm</td>
<td>0.1-0.8 nm</td>
</tr>
<tr>
<td>Out of Band Rejection</td>
<td>&lt; 10%</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td>Irradiance Range</td>
<td>$10^{-9} - 10^{-3}$ W m$^{-2}$</td>
<td>$10^{-8} - 4 \times 10^{-3}$ W m$^{-2}$</td>
</tr>
<tr>
<td>Irradiance Resolution</td>
<td>$2 \times 10^{-10}$ W m$^{-2}$</td>
<td>$2 \times 10^{-9}$ W m$^{-2}$</td>
</tr>
<tr>
<td>Irradiance Accuracy</td>
<td>&lt; 20%</td>
<td>&lt; 20%</td>
</tr>
<tr>
<td>Spatial Coverage (Sun FOV)</td>
<td>&gt; ±20 arcmin</td>
<td>&gt; ±20 arcmin</td>
</tr>
<tr>
<td>Flare Location Precision</td>
<td>&lt; 5 arcmin for &gt;X1 flares</td>
<td>&lt; 5 arcmin for &gt;X1 flares</td>
</tr>
</tbody>
</table>

The requirements for the spectral bands of XRS-A (0.05-0.4 nm) and XRS-B (0.1-0.8 nm) drive the design to select Si thickness for the photodiodes to define the short wavelength cutoff and to select Be foil filter thickness to define the long wavelength cutoff. Table 2 lists the photodiode and Be filter specifications, and the spectral responsivity for GOES-16 XRS is discussed in more detail in Section 3.

The XRS science FOV requirement is > ±20 arcmin, but the implemented design FOV requirement is ±70 arcmin, or just over 2°. This requirement is derived from combining several other requirements: ±27 arcmin to account for the diameter of the Sun at X-ray wavelengths, ±5 arcmin for accuracy of the spacecraft pointing towards the Sun, and ±25 arcmin for alignment of each channel boresight to the reference optical boresight of the pointing platform that XRS is mounted on, as well as internal alignment of all the optical components (photodiodes and apertures). There is more than ±13 arcmin of margin in the XRS design.
Another significant design driver is the shielding of the optical cavity from the large number of energetic electrons that are present in the space environment at geostationary orbits. These electrons can penetrate thin walls and hit the detectors causing a high background signal. These electrons can also interact with metal walls of the casing producing Bremsstrahlung X-ray radiation in the optical cavity that would then be seen as a “false” signal in the X-ray detectors.

The radiation shielding for XRS has three components: (1) a thick, outer layer of low atomic number (low-Z) material, aluminum (Al), to essentially stop all off-axis energetic electrons; (2) an inner layer of high atomic number (high-Z) material, tungsten (W), to absorb the Bremsstrahlung X-ray radiation that was created in the outer aluminum shield; and (3) a strong magnet assembly in front of the XRS to sweep away electrons from the instrument boresight. Numerical analysis of energetic electrons entering the magnet assembly over the XRS FOV range shows that a field of 800 Gauss (0.08 Telsa) over a length of at least 5 cm will remove on-axis electrons up to an energy of 5 MeV. Detailed radiation analysis, using Geant4 and MULASSIS models (Agostinelli et al., 2003), were performed during the development phase to estimate that the optimal aluminum and tungsten shield thicknesses are 7 mm and 5 mm, respectively. The radiation analysis includes
worst-case radiation environment for a 15-year GOES mission and also includes a safety factor of

An initial 1-D analysis was performed to optimize the shielding thicknesses, and then 3-D analysis was performed to minimize the mass of the shields. This low-Z, high-Z layering can be observed in the cutout view of the XRS instrument shown in Figure 1. We note that the tungsten shield is made using a sintered composite of 90% tungsten (W), 6% nickel (Ni) and 4% copper (Cu), and by using this more malleable composite, instead of pure tungsten, machine time and costs were reduced.

Table 2. GOES-R X-Ray Sensor (XRS) Design Specifications

Model Signal values that are outside the ASIC electrometer range (6fA–6nA) are underlined.

Two channels are used for each passband to cover full range of solar activity.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>XRS-A1</th>
<th>XRS-A2</th>
<th>XRS-B1</th>
<th>XRS-B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>A MIN</td>
<td>A MAX / FLARE</td>
<td>B MIN</td>
<td>B MAX / FLARE</td>
</tr>
<tr>
<td>Spectral Range</td>
<td>0.05-0.4 nm</td>
<td>0.05-0.4 nm</td>
<td>0.1-0.8 nm</td>
<td>0.1-0.8 nm</td>
</tr>
<tr>
<td>Si Diode Type</td>
<td>AXUV100</td>
<td>AXUVPS6 Quad</td>
<td>AXUV100</td>
<td>AXUVPS6 Quad</td>
</tr>
<tr>
<td>and Size</td>
<td>10 mm × 10 mm</td>
<td>7.6 mm Dia.</td>
<td>10 mm × 10 mm</td>
<td>7.6 mm Dia.</td>
</tr>
<tr>
<td>Aperture Size</td>
<td>9 mm × 9 mm</td>
<td>2.1 mm × 2.1 mm</td>
<td>9 mm × 9 mm</td>
<td>2.1 mm × 2.1 mm</td>
</tr>
<tr>
<td>Si Diode Thickness</td>
<td>50 µm</td>
<td>50 µm</td>
<td>50 µm</td>
<td>50 µm</td>
</tr>
<tr>
<td>Be Filter Thickness</td>
<td>600 µm</td>
<td>600 µm</td>
<td>60 µm</td>
<td>60 µm</td>
</tr>
<tr>
<td>Model Signal</td>
<td>32 fA–32 nA</td>
<td>1.6 fA–1.6 nA</td>
<td>110 fA–44 nA</td>
<td>6 fA–2 nA</td>
</tr>
</tbody>
</table>

3. XRS DESIGN OPTIMIZATION

The XRS design requirements, given in Table 1, are specified so that the GOES-R series XRS measurements will continue the past 40+ years of solar X-ray monitoring in a consistent time
series. The XRS signal estimates are calculated by folding reference solar spectra (minimum and maximum solar activity) through the wavelength dependent filter transmission function and detector sensitivities. The detector and electronics design are iterated so that the expected signals, with adequate margins, are detectable. The details of optimizing these instrument elements and how they affect the incoming solar signal to meet the given requirements is the topic of this section.

3.1. Passband Optimization

In designing each of the A and B channels to meet the traditional XRS passband requirements, the spectral sensitivity of the Si photodiodes is first considered. The high-energy X-rays will not be stopped (deposit their energy) in a thin Si detector; therefore, a thicker Si detector is required to detect these shorter wavelength X-rays. The selection of the effective Si thickness determines the short wavelength cutoff for the XRS detectors. The optimal thickness was determined to be 100 µm for XRS-A and 50 µm for XRS-B. However, the 100 µm Si photodiodes from International Radiation Detectors Inc. (IRD) were found to have a lower-than-desired shunt resistance, which causes an undesirable increase in detector noise. IRD 50 µm thick Si photodiodes were selected for XRS-A because they have a much higher shunt resistance and still provide acceptable spectral responsivity.

The other key factor in the passband design is the selection of the thickness of the Be foil filter to set the long wavelength cutoff. Be filters have been used on previous XRS designs and are known to provide excellent stability and extremely good rejection of the visible solar radiation that is orders of magnitude larger than the in-band soft X-ray radiation. The Be filter thickness is adjusted until the filter transmission matches the desired XRS band. This model of the XRS responsivity uses the Henke atomic constants (Henke et al., 1993) to determine the spectral transmission of the Be filter and the Si detector. The ideal Be filter thickness is 600 µm for XRS-A and 60 µm for XRS-B. In order to mitigate the effect of a possible pinhole in these Be foil filters, two filters are used in series. Furthermore, the two-filter approach eliminates the large number of photoelectrons generated in the first filter from reaching the detector. The filters selected for the GOES-R series XRS are two 30 µm filters for XRS-B channel and a 570 µm filter and 30 µm filter for XRS-A channel (with the 30 µm filter in front).

Figure 2 shows the XRS responsivity estimates along with the requirements for the acceptable range of the XRS responsivity. Those responsivity requirements as a function of wavelength were
provided by NOAA based on ionization cell versions of the earlier XRS instruments. The XRS spectral bands are referenced as XRS-A for the 0.05-0.4 nm band and as XRS-B for the 0.1-0.8 nm band. These bands are not obvious from examining the responsivity curves in Figure 2 on a logarithm scale. But the solar irradiance is much larger at the longer wavelengths, so the solar spectrum, convolved with these XRS responsivities, provides the appropriate passband to satisfy the responsivity requirements.

![Figure 2](image.png)

**Figure 2.** The PORD-required minimum and maximum spectral responsivity (grey) for XRS-A (left panel) and XRS-B (right panel) and the GOES-R XRS responsivity (black), showing the required spectral responsivity for each channel is met.

### 3.2. XRS Signal Estimates

With the spectral responsivity specified, solar spectra can be folded in to obtain the expected detector outputs (model signals). A theoretical plasma emission model driven by estimated solar plasma temperatures and densities is used to determine the input solar signal as there are no accurately calibrated measurements covering a full range of solar activity conditions. The NOAA-specified reference solar signal to use for the signal calculations is the Astrophysical Plasma Emission Code (APEC) (Smith et al., 2001). This model uses the Astrophysical Plasma Emission Database (APED) to determine the spectral emissions of very hot plasmas. These reference model spectra, as specified by the XRS PORD, are adjusted in intensity so that the integrated irradiance of the APEC spectra over the XRS bands agree with the solar cycle minimum and maximum
irradiance values provided in the XRS PORD. The APEC minimum (quiet) and maximum (active) solar spectra are shown in Figure 3. This figure shows the increased free-free continuum and bound-bound emission line signals with the higher temperature plasmas that are present during solar maximum. The estimated signal ranges for XRS channels are listed in Table 2.

This signal modeling also permits an examination of the passbands. By accumulating the signal from short wavelength and also from long wavelength and normalizing to the total signal, the ideal passband is estimated for 90% of the model signal as shown in Figure 4. This accumulated signal is the integration of the signal over a limited wavelength range. For example, the accumulated signal at 0.5 nm for each APEC reference spectrum has two values, with one value from integrating the model signal from 0 nm up to 0.5 nm and second value from integrating from long wavelength (1.5 nm for the APEC spectra) down to 0.5 nm. As expected, the ideal passband changes depending on the solar cycle condition, and these ideal passbands are skewed towards the high end of the required passbands (Spectral Range in Table 1) because the solar spectra are several orders of magnitude brighter in the 0.4-0.8 nm range than in the 0.01-0.2 nm range. Using the extremes for the quiet and active solar conditions, the ideal passband for XRS-A is 0.25-0.51 nm, and ideal passband for XRS-B is 0.40-0.92 nm. While these passbands extend to longer wavelengths than the nominal XRS passband requirements in Table 1, the central signal contributions (40-60% of accumulated signal) are primarily within the nominal passbands. As listed in Figure 4, the XRS-A central passband is 0.32-0.42 nm, and XRS-B central passband is 0.59-0.67 nm.
Figure 3. The APEC estimated solar signal at solar cycle maximum (blue) and minimum (red) conditions. The nominal passbands are also shown for XRS-A and XRS-B.

Figure 4. The modeled signals using the APEC reference solar spectra are accumulated from lower wavelength and from upper wavelength and normalized to the total signal to obtain the 5% edges to derive the ideal passband for 90% of the signal. The left panel is for XRS-A, and the right panel is for XRS-B.

3.3. Aperture Size Optimization

To optimize the aperture size, not only does the signal per unit area discussed above need to be known, but also the signal range of the electrometers and noise contributions from the detectors.
The electrometer chosen for XRS is a specialized ASIC electrometer designed for GOES-R EXIS (Aalamia & Jones, 2009). This ASIC has six electrometers per IC and uses an innovative, low-noise, low-power electrometer design from Space Instruments Inc. Additionally, the gain of each electrometer can be calibrated during flight to quantify how much each electrometer channel might be degrading while in space. The charge resolution of the ASIC electrometer is set at 6 fC, so an integration time of 1 sec corresponds to one output data number (DN) corresponding to a 6 fA current from the photodiodes. The ASIC electrometer has a digital 20-bit counter output, so the upper limit is 6 nA for the detector current. The effective lower limit of the electrometer is driven by the internal electronics noise of about 10-20 fA x √Hz.

The dynamic range of a single electrometer cannot meet the XRS requirements for full irradiance range (see Table 1), so two photometers with different aperture sizes are used for both XRS-A and for XRS-B. The XRS-A1 and XRS-B1 channels use a larger aperture and an IRD AUXV100 photodiode (1 cm² active area) to measure the solar X-ray irradiance during low solar activity periods. The XRS-A2 and XRS-B2 channels use a smaller aperture to limit the light coming in during solar maximum or large flare events to measure the highest end of the irradiance range. The minimum channels (A1 and B1) are expected to saturate during the larger X-class flares, and the maximum channels (A2 and B2) are expected to just show noise during solar minimum times. Therefore, the combination of both channels are needed to cover the full range of solar activity.

The apertures for the solar minimum channels are maximized to get the best SNR performance during solar cycle minimum periods. The optimal maximum aperture area is found by simple trigonometry using the maximum possible angle for a FOV of ±θ as discussed in Section 2, the 10 mm width of the A1 and B1 square photodiodes, and the distance of the limiting aperture to the photodiode (y). This will ensure that even at the worst possible FOV angle, all the light that enters the aperture will still fall on the detector. The equation used to find the maximum aperture width, x, is:

$$x = 10\text{mm} - 2 \times y \times \tan(\theta)$$  \hspace{1cm} (1)

The closest distance the aperture could mechanically be to the photodiode, y, which maximizes the aperture width, x, was about 5.0 mm. Given the size of the photodiodes and the ±70 arcmin FOV, the aperture had to be less than 9.2 mm for a given side. A square aperture of 9.0 mm by 9.0
mm was chosen. It can be seen in Table 2 the A1 and B1 channels provide a signal-to-noise ratio (SNR) of 5 and 18, respectively, for the required solar minimum irradiance level, which already has more than a factor of two margin. The XRS PORD specifies a solar minimum level of 1x10^9 W m^-2 and 1x10^8 W m^-2 for XRS-A and XRS-B, respectively. Consequently, the GOES-R XRS was designed to determine the true solar minimum level, unlike earlier versions of GOES XRS that bottom out during solar cycle minimum (e.g., Woods et al., 2017). In reality, there is a stronger than expected response to the on-orbit energetic electrons for both the GOES-R XRS-A1 and XRS-B2 diodes, so the solar minimum levels continue to be a challenge for the X-ray bands. This effect of the on-orbit energetic electrons and in-flight performance of the XRS channels are discussed in more detail by Machol et al. (2024), but we note here that the smaller-aperture XRS-A2 and XRS-B2 are mostly impervious to the on-orbit energetic electrons.

For the solar-maximum (flare) channels, A2 and B2, the apertures are chosen to be smaller so that even the largest flares (at least up to X120) should never saturate the electrometers. The detectors for the maximum channels are IRD AXUVPS6 quadrant photodiodes. As discussed in the next section, these quadrant photodiodes provide flare location information; this is a new capability that the previous GOES XRS sensors did not have. Two other considerations in designing the use of a quadrant photodiode are that the aperture area needs to be slightly larger to account for a 0.1 mm dead gap between the 4 quadrants where signal is lost, and the maximum signal per quadrant is not the total signal divided by four but is the total signal because a flare event (being almost like a point source) at the solar limb could illuminate just a single quadrant. Taking these into account in conjunction with the photometer and electrometer design discussed above, the optimum aperture area is about 0.04 cm^2 for A2 channel and about 0.01 cm^2 for B2. For mechanical simplicity, the A2 and B2 apertures are the same size, each a square with a width of 2.1 mm (area of 0.040 cm^2 when accounting for the 0.1 mm dead-gap). The width and height of the individual apertures are precisely measured, and their areas are provided in Table 3; however, the area values are not critical as long as the same area values are used in the SURF responsivity calculation and the solar irradiance calculation.

The complete current range produced by the required minimum and maximum levels for each channel is summarized in the last row of Table 2. There is plenty of overlap, around three orders of magnitude, between the minimum and maximum channels to ensure that the entire solar X-ray irradiance range will be measured precisely.
3.4. Improved XRS Irradiance Accuracy

The design requirement in the EXIS PORD on XRS irradiance accuracy is to be better than 20%. There are many factors that are included into the XRS irradiance accuracy (total uncertainty) budget, as described in more detail in Section 4.5 but are summarized in this section. Many of the measurement parameters can be very accurately calculated or corrected for, such as the responsivity and linearity of the detectors, the accuracy of the integration time, and the thermal noise on the electrometer. The dominant contributions to the irradiance uncertainties are:

1. Approximately 10% contribution due to imperfect correction of the background signal due to high-energy electrons,
2. About 2% for electrometer gain variations with temperature and electrometer offset variations over the mission,
3. About 2% for radiometric calibration (see Section 4), and
4. Less than 1% for solar measurement precision.

The electron-background contribution to the irradiance uncertainty is dependent on level of the energetic electron storm and also the solar signal level. For example, this contribution is larger (up to 100% during the largest electron flux levels) near solar cycle minimum conditions when the solar signal is small, and this contribution is significantly smaller (<1%) for M and X class flares when the solar signal is large. The new XRS incorporates dark photodiodes (ones shielded within the XRS housing but with no apertures) so that on-orbit measurements of the background signal variations are obtained. In addition, the Space Environment In-Situ Suite (SEISS) aboard the GOES satellites directly measures the electron flux as a function of electron energy. Based on the root-mean-squared (rms) of the uncertainties, the estimated accuracy for XRS irradiance is 10% for C1, 3.2% for M1, and 3.0% for X1 levels.

3.5. Flare Location with Quadrant Photodiodes

It was realized early in the design of the XRS channels that the simple improvement of replacing a single photodiode with a quadrant photodiode (QD) would give the added information of the location of a large flare. This flare location option is possible because the flare, being a compact source on the Sun, has a significantly enhanced signal relative to the other quiescent (non-flare) radiation from the solar disk. This measurement, especially because it can be available near
real-time, is very valuable to the space weather community. The details of the flare location algorithm for the XRS-A2 and B2 quadrant diodes are provided in XRS Paper-2 (Machol et al., 2024), along with in-flight performance of the flare position results and comparisons to flare locations determined by solar extreme ultraviolet imaging.

4. XRS PRE-FLIGHT CALIBRATIONS

There are many XRS tests and calibrations to verify that the XRS performance meets requirements, and the key test results for the responsivity, temperature-dependent background signal, temperature-dependent electrometer gain, field of view (FOV) maps, and sensor linearity are discussed in this paper. The responsivity was determined for the previous GOES XRS instruments by modeling the responsivity of the ionization cell and adjusting the model to agree with calibration tests taken with a calibrated Fe\textsuperscript{55} gamma source with its primary emissions at 5.90 keV (0.21 nm) and 6.49 keV (0.19 nm) (Hill et al., 2005). For the new GOES-R XRS instruments, more detailed calibrations were performed by using the National Institute of Standards and Technology (NIST) Synchrotron Ultraviolet Radiation Facility (SURF) in Gaithersburg, Maryland. In addition, the SURF facility and its calibration capabilities are used to perform FOV mapping of each XRS channel using a two-axis (pitch, yaw) gimbal system inside the SURF Beam Line 2 (BL2) vacuum tank and to provide validation of the XRS linearity by precisely changing the SURF beam intensity (e.g., Woods et al., 2005b).

4.1. Responsivity Calibrations

Calibrations at several wavelengths are challenging for the XRS spectral range from 0.05 to 0.8 nm because of the limited number of X-ray line-sources. For bright gamma sources, only the Fe\textsuperscript{55} has the appropriate emission within the XRS spectral range. Synchrotron radiation is also commonly used to provide X-ray radiation, but as a continuum instead of discrete emission lines. Synchrotron radiation can be used with a grazing incidence monochromator to provide spectral responsivity calibrations, but only down to 5 nm for the NIST SURF facility (Canfield et al., 1989) and only down to 2 nm for the Physikalisch-Technische Bundesanstalt (PTB) synchrotron calibration facility in Germany (Scholze et al., 2001).

Another option with synchrotron radiation is to calibrate with multiple beam energies. This approach was used for the X-ray Photometer System (XPS) calibrations using SURF BL2 (Woods
et al., 2005a; Woods et al., 2005b; Woods et al., 2008). Using this same approach, the XRS directly views the synchrotron radiation (without a monochromator). A model of the spectral response is then refined by adjusting the expected thicknesses of the Be filter so that the expected signals for the various SURF beam energies match the measured signals. The SURF radiometric accuracy is about 1% (Arp et al., 2002), and the resulting uncertainty for the XRS responsivities is about 2%.

The XRS SURF calibration results as listed in Table 3 are the average responsivities from using SURF beam energies of 285, 330, 380, and 408 MeV. These XRS calibration results use known SURF beam irradiances and Henke et al. (1993) atomic X-ray properties of Si, SiO, and Be to find optimal Be foil thickness to fit the measured photodiode signals at different beam energies. The derived Be foil thickness is systematically lower than the physically measured Be foil thickness, and this difference is attributed to systematic uncertainties in the atomic constants for Be. These SURF calibration results in Table 3 include the modeled Be foil filter thickness (T) fitted with the SURF data and the integrated responsivity (R, units A m$^2$ W$^{-1}$) calculated assuming a flat spectrum ($\phi(\lambda)=1$ nm$^{-1}$), aperture area (A, units m$^2$), and modeled spectral responsitivity ($\epsilon(\lambda)$, units A/W) for the nominal passband ($\lambda_1$-\(\lambda_2\)) using Equation 2.

$$R = \frac{A \int_{\lambda_1}^{\lambda_2} \phi(\lambda) \epsilon(\lambda) \, d\lambda}{\int_{\lambda_1}^{\lambda_2} \phi(\lambda) \, d\lambda}$$  \hspace{1cm} (2)

The use of a flat spectrum does not describe a realistic solar X-ray spectrum, but it is the method used for all of the previous XRS responsivity derivations. If one uses instead the APEC minimum (quiet) and maximum (active) reference spectra, then the XRS-A1 responsivities are about 3.1x10$^{-5}$ A m$^2$ W$^{-1}$ and 1.2x10$^{-5}$ A m$^2$ W$^{-1}$, respectively. Similarly, the XRS-B1 responsivities for the APEC reference spectra are about 2.7x10$^{-5}$ A m$^2$ W$^{-1}$ and 1.4x10$^{-5}$ A m$^2$ W$^{-1}$. We note that the responsivities derived with the APEC maximum spectrum is similar in value as the flat-spectrum responsivities, thus the quiet solar irradiance values from the standard XRS data products have significant uncertainties (factor of 2 to 3). The XRS model responsivities as a function of wavelength are plotted in Figure 5 for the GOES-16 XRS and provided on-line for all of the GOES-R series XRS instruments at:

Table 3. GOES-R-series X-Ray Sensor (XRS) Calibration Results

Responsivity (R) is in units of Amps/(W/m²).

Modeled Be foil thickness (T) is in units of μm and has uncertainty of 0.3 μm and 0.1 μm for XRS-A and XRS-B, respectively.

R and T values are the average of results from using four different SURF beam energies.

<table>
<thead>
<tr>
<th>GOES Series</th>
<th>XRS-A1</th>
<th>XRS-A2</th>
<th>XRS-B1</th>
<th>XRS-B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOES-R (16)</td>
<td>R 9.615 x 10⁶</td>
<td>R 5.064 x 10⁻⁷</td>
<td>R 1.469 x 10⁻⁵</td>
<td>R 7.768 x 10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>T 516.6</td>
<td>T 524.0</td>
<td>T 53.4</td>
<td>T 53.2</td>
</tr>
<tr>
<td>GOES-S (17)</td>
<td>R 9.577 x 10⁻⁶</td>
<td>R 5.021 x 10⁻⁷</td>
<td>R 1.479 x 10⁻⁵</td>
<td>R 7.790 x 10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>T 520.1</td>
<td>T 524.0</td>
<td>T 52.6</td>
<td>T 52.5</td>
</tr>
<tr>
<td>GOES-T (18)</td>
<td>R 9.552 x 10⁻⁶</td>
<td>R 5.111 x 10⁻⁷</td>
<td>R 1.464 x 10⁻⁵</td>
<td>R 7.982 x 10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>T 522.0</td>
<td>T 519.3</td>
<td>T 53.8</td>
<td>T 52.7</td>
</tr>
<tr>
<td>GOES-U (19)</td>
<td>R 9.670 x 10⁻⁶</td>
<td>R 4.756 x 10⁻⁷</td>
<td>R 1.432 x 10⁻⁵</td>
<td>R 7.259 x 10⁻⁷</td>
</tr>
<tr>
<td></td>
<td>T 511.1</td>
<td>T 521.6</td>
<td>T 56.7</td>
<td>T 54.3</td>
</tr>
</tbody>
</table>

Figure 5. The GOES-16 XRS modeled responsivities, as based on SURF calibrations, are plotted as a function of wavelength.
4.2. Field of View Maps

To determine the off-axis response of the filter and detector, each XRS channel was illuminated at SURF while off-pointed from its optical center using the SURF pitch-yaw gimbal table. Because the channel apertures are not directly at the gimbal center (the center of rotation), each off-point included compensating changes to X and Y of the instrument relative to SURF beam center to ensure that the channel aperture stayed at the SURF beam center. These FOV maps at SURF were done over a 9x9 grid with 0.2° step size. As expected for photometers, the XRS FOV maps have small gradients with offsets from the optical center, with these relative variations being less than 0.4% within 20 arcmin of the optical center. These pre-flight SURF FOV maps can also be verified in-orbit, as long as the solar X-ray radiation is quiescent during the FOV map experiment.

In-flight FOV maps of the XRS instruments have been obtained, and analysis of those FOV maps are compared to the pre-flight FOV maps. A concern with in-flight FOV maps is that the off-axis response due to pointing across the FOV (inflight pointing range of ±15 arcmin) is quite small and could be completely dwarfed by the variability in solar activity, even during solar-minimum conditions. For more recent times in Solar Cycle 25, the Sun has been much more active, which makes this analysis almost impossible to do. A clever way to remove this solar variability is to use the XRS signal from a different GOES satellite to remove the solar variability before examining the off-axis response due to pointing away from solar center. Shown in Figure 6 are FOV maps of GOES-18 XRS-B1 and -B2 from prelaunch calibration (top panels), and FOV maps of GOES-18 XRS-B1 and XRS-B2 from inflight test data from November 28, 2023. For the inflight data analysis (bottom panels), GOES-16 XRS data were used to remove the effects of an M9.8 solar flare that erupted during this particular FOV test. The SURF FOV map includes convoluting the solar X-ray extended disk (radius 20 arcmin) with the SURF FOV map data (SURF beam is < 2 arcmin radius) and also doing a 90° clockwise rotation to align SURF calibration axes to the GOES satellite axes.
Figure 6. FOV Maps for GOES-18 XRS-B1 and -B2. Top panels are maps from prelaunch calibration, and the bottom panels were from an inflight FOV map obtained on 28-Nov-2023. The bottom FOV maps are over ±15 arcmin (0.25°), and the flight map range of ±15 arcmin is represented as a solid-black box in the top FOV maps that are over ±45 arcmin (0.75°).

As expected for photometers, the XRS FOV maps are relatively flat with uniformity variations being typically less than 1%. Not surprisingly, the Figure 6 right-hand column maps for XRS-B2 show more of a gradient structure across the FOV, where the four diodes in XRS-B2 contribute individually to the aggregate response of XRS-B2. The FOV maps for the A-channel diodes are
similar in structure and are not shown here. For the XRS-B1 map comparison (Figure 6 left-hand column maps), the SURF and flight maps show similar uniformity range of 0.05%, but the SURF map has a slight ramp across the FOV map that is not as obvious in the flight map. For the XRS-B2 map comparison, the SURF and flight maps show similar ramp across the FOV map yaw (alpha) axis, but the flight map has larger uniformity variation (about 1.5%) in the map yaw (alpha) axis than the SURF map variation (about 0.2%). Those large differences in the XRS-B2 map variation might be the result of assuming uniform solar disk illumination for the SURF map analysis, whereas, the flight FOV map can be sensitive to the position of the solar active regions, being four bright active regions on the western part of the solar disk on 28-Nov-2023. Analysis of the flight FOV maps have been challenging due the dynamic variability of the solar X-ray irradiance during the mapping period, so we consider the SURF FOV maps as more accurate maps that could be used in data processing.

4.3. Temperature-dependent Background Signal

The dark-signal component for all XRS diode signals was determined from data acquired during each prelaunch calibration campaign as a function of the ASIC electrometer temperature. The functional form of the model used was a two-parameter exponential, where the two unknown parameters were allowed to vary to minimize $\chi^2$ of the fit:

$$S_D = e^{(a+bT)} \quad (3)$$

Here, $T$ is the ASIC temperature in °C, and $a$ and $b$ are the two unknown parameters. The tests for a given day were done at a predetermined temperature set-point inside a thermally controlled, evacuated tank that housed the EXIS instrument, which was mounted on a movable pitch-yaw gimbal table. Shown in Figure 7, are model-fit results for flight-model 4 (future GOES-19).
Figure 7: Model-fit results for all XRS diodes background signal for the GOES-U (future 19) XRS unit. These results were typical for the other XRS flight units.

4.4. Temperature-dependent Gain

The XRS detector gain (fC/DN) changes slowly with temperature, due to temperature-dependent variations in the electrical properties of the circuitry (primarily the resistance and capacitance of the electrometer and photodiode). Each ASIC electrometer has a self-calibration (Self-Cal) circuit which injects a known current (ramped at 4 levels) into each channel, from which the absolute gain can be determined by comparing the measured signal with the known current input. By running the Self-Cal ramp at various temperatures, the gain temperature dependence can be determined for each channel. The Self-Cal ramps can be performed in any laboratory setting and for in-flight gain checks. The temperature dependence for a channel can also be determined optically, by illuminating the channel with a constant-intensity beam and observing how the relative signal changes with temperature. Both the Self-Cal ramp and optical methods
were performed at SURF, and those results are used to determine the gain as a linear function of temperature as given by Equation 3.

\[ G(T) = G_0 (1 + \Delta g (T - T_0)) \]  

3

An example of the XRS gain calibrations is shown for the GOES-18 XRS instrument in Figure 8. The slope of this temperature dependence (\( \Delta g \)) ranges from \(-1 \times 10^{-3} \ C^{-1}\) to \(1 \times 10^{-3} \ C^{-1}\) for the different XRS channels. Therefore, gain changes over 10 C can be as large as 1%, and so the gain corrections are important to include in data processing. There are slight differences for the gain linear slope with temperature between the two methods. The optical gain results are used for science data processing, and the in-flight Self-Cal gains are executed quarterly to monitor the ASIC electrometer performance.

Figure 8. The GOES-18 XRS gain versus temperature for the EXIS A-side electronics. The blue and red lines are linear fits to the gains for the SURF optical (squares) and self-calibration (circles) measurements, respectively. The dashed and dotted blue lines show the SURF gain fit uncertainty and the PORD-required 2% gain knowledge, respectively.
4.5. Sensor Linearity Validation

Laboratory measurements of the XRS electrometer have shown that its response (output DN per input fA) is extremely linear across its full dynamic range, and laboratory measurements of the IRD Si photodiodes have shown them to be very linear to higher than 1 µA. The linearity of response of the entire detector, photodiode and electrometer, is verified at SURF by illuminating each channel with varying beam intensity and comparing the measured beam current-normalized signal at each beam current. Because the beam intensity is directly proportional to beam current, the beam current-normalized signal should ideally remain completely flat for a linear response. For each channel, the beam current was varied such that measurements were obtained at multiple signal levels from background level to electrometer saturation level. An example of the linearity validation is shown in Figure 9 for the GOES-17 XRS-B2 channel. No non-linear effects were noted in any of the SURF linearity calibrations for the XRS channels, so XRS data processing do not require any non-linearity corrections.

Figure 9. The GOES-17 XRS-B2 linearity calibration at SURF. Left: Beam current-normalized signal (summed over all quadrants) versus SURF beam current (BC) reveals a flat level independent of SURF beam current. Blue diamonds represent individual data points, and red squares show the average values for measurements taken at different beam current levels. The rollover at high BC is due to electrometer saturation. Right: Deviations from the mean normalized signal is also very flat, with ±1% dotted lines and ±2% dashed lines shown for reference.
4.6. Early Validation with Sounding Rocket Flights of Prototype XRS

An engineering model (EM) of the new XRS for the GOES-R series was calibrated at NIST SURF using this multiple beam energy technique and then flown on a NASA sounding rocket flight on 28 October 2006. This XRS rocket unit is identical to the XRS flight design, except that the energetic electron extra shielding and magnetic sweep assembly are not flown on the rocket. From this flight, the rocket XRS-A measured a solar irradiance of \(2.1 \times 10^{-9} \text{ W m}^{-2}\) versus the GOES-12 XRS-A result of \(2.0 \times 10^{-9} \text{ W m}^{-2}\), and the rocket XRS-B result is \(6.8 \times 10^{-8} \text{ W m}^{-2}\). These rocket irradiance values are corrected to the appropriate XRS-A and XRS-B nominal passbands, and the GOES-12 XRS values are scaled up to irradiance values using the standard GOES-12 calibration factors of 1.16 and 1.43 for XRS-A and XRS-B, respectively. This comparison indicates that the new XRS results are in agreement with the original GOES XRS to better than 10%.

4.7. XRS Irradiance Uncertainty Based on the Pre-flight Calibrations

One important assessment for the in-flight XRS measurements and related comparisons is to calculate the statistical uncertainty, \(\sigma_E/E\), for a computed irradiance, \(E\). To begin with, the photodiode current, \(C\), is defined to be:

\[
C = \frac{g(S - S_0)}{\Delta t}
\]  

(4)

Here, \(S\) is the raw in-flight signal in units of DN, \(S_0\) is the model dark signal at a given detector temperature \((T)\) in units of DN, \(g\) is the detector gain and is also temperature dependent, and \(\Delta t\) is the integration time. By propagation of errors, the following relationship for \(\sigma_c\) is:

\[
\sigma_c = C \left[ \left( \frac{\sigma_g}{g} \right)^2 + \left( \frac{\sigma_S}{S - S_0} \right)^2 + \left( \frac{\sigma_{S_0}}{S - S_0} \right)^2 + \left( \frac{\sigma_{\Delta t}}{\Delta t} \right)^2 \right]^{1/2}
\]  

(5)

The uncertainties \(\sigma_g\) and \(\sigma_{S_0}\) are calculated from separate analyses of pre-flight calibration data, and \(\sigma_{\Delta t} = 10 \text{ ms}\). The uncertainty \(\sigma_S\) is constructed dynamically as a function of the in-flight signal size during this analysis. To convert photodiode current into irradiance, the photodiode current (\(C\), units A) is divided by the photodiode responsivity (\(R\)), that is, \(E = C/R\), to yield the irradiance (\(E\), units W m\(^{-2}\)). The uncertainty \(\sigma_E\) is derived by error propagation as:
\[ \sigma_E = E \left[ \left( \frac{\sigma_G}{G} \right)^2 + \left( \frac{\sigma_R}{R^5} \right)^2 \right]^{1/2} \]  \hspace{1cm} (6)

The calculation of \( \sigma_R \) uses pre-flight calibration data, exclusively, where:

\[ R = \frac{G(S-S_0)}{I \Delta t} \]  \hspace{1cm} (7)

Here, \( I \) is the SURF beam current in units of mA. Applying error propagation, we have:

\[ \sigma_R = R \left[ \left( \frac{\sigma_G}{G} \right)^2 + \left( \frac{\sigma_S}{S-S_0} \right)^2 + \left( \frac{\sigma_{S_0}}{S-S_0} \right)^2 + \left( \frac{\sigma_I}{I} \right)^2 + \left( \frac{\sigma_{\Delta t}}{\Delta t} \right)^2 \right]^{1/2} \]  \hspace{1cm} (8)

The relative uncertainty in the beam current is \( \sigma_I/I = 5\% \). Shown in the top panel of Figure 10, is the relative statistical uncertainty, \( \sigma_E/E \), plotted against irradiance for GOES-18 XRS-A1 and -B1 on May 3, 2022, and in the bottom panel, XRS-B1 is shown for GOES-16, -17, and -18.

**Figure 10.** The relative statistical uncertainty, \( \sigma_E/E \), plotted in the top panel as a function of irradiance (in W m\(^{-2}\)) for both XRS-A1 and -B1 aboard GOES-18. Bottom panel shows the statistical uncertainties for XRS-B1 on GOES-16, -17, and -18.
Table 4. Irradiance Statistical Uncertainties for XRS Irradiances

These uncertainties are for XRS-B at three different irradiance flare-class levels:

\[ C1 = 1 \times 10^6 \text{ W m}^{-2}, \quad M1 = 1 \times 10^5 \text{ W m}^{-2}, \quad \text{and } X1 = 1 \times 10^4 \text{ W m}^{-2}. \]

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Flare-Class C1 (%)</th>
<th>Flare-Class M1 (%)</th>
<th>Flare-Class X1 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOES-16</td>
<td>2.61</td>
<td>2.48</td>
<td>2.48</td>
</tr>
<tr>
<td>GOES-17</td>
<td>2.58</td>
<td>2.48</td>
<td>2.47</td>
</tr>
<tr>
<td>GOES-18</td>
<td>2.60</td>
<td>2.48</td>
<td>2.47</td>
</tr>
</tbody>
</table>

It is interesting to note that the three traces shown in the bottom panel of Figure 10 are similar in magnitude and shape for the in-flight XRS-B1 sensors. The similar behavior of these three traces can mostly be attributed to a robust pre-flight calibration campaign for each EXIS flight instrument, as the XRS design and construction were identical. Even though each instrument is a replication of another, deviations in some components (e.g., photodiode noise levels) can drive differences to the level that is observed in the statistical uncertainty traces in the bottom panel of Figure 10. The SURF facility at NIST provided a very stable and reproducible point-source photon beam that was used extensively on each SURF calibration trip to characterize the instrument performance before launch. Because the statistical uncertainty in the irradiance is heavily dependent on the pre-flight calibration of XRS, the likeness in the traces is a testament to the rigorous calibration testing that was performed on each SURF trip. Shown in Table 4 are the irradiance statistical uncertainties (in %) at C-, M-, and X-class flare levels for each flight model.

5. XRS POST-LAUNCH TESTS

The in-flight performance characterization period for each GOES-R Series satellite begins approximately 30 days after launch. For EXIS, the suite of tests for all sensors usually takes about three months to complete. During this post-launch test (PLT) phase, some of these tests are performed to identify any changes that might have occurred during the launch process or from in-
flight conditions. Most calibration parameters are determined during pre-flight calibration, and remain unchanged post launch; however, shifts in pointing, photodiode dark signals, or electrometer gains can be measured and used to update scientific data processing look-up tables, or for monitoring purposes. In addition, comparison of the concurrent solar signals from XRS channels are used to validate pre-flight calibration results and to develop new functions of the background signals that are caused by the energetic electrons in orbit. A couple of those PLT results are presented in this XRS Paper-1, and additional in-flight results are presented in the XRS Paper-2 (Machol et al., 2024).

As one example of PLT validation, the in-flight solar signals are compared to the range of estimated solar signals as listed in Table 2, which are based on XRS responsivities (Figures 2 and 5) and the APEC solar reference spectra (Figure 3). The GOES-16 XRS A2 and B2 signals, after being corrected for background signal, are shown in Figure 11 for day 2017/249 (6-Sep-2017) when there was a X10 flare that saturated the XRS-B1 channel. These in-flight XRS A2 and B2 measurements are within the expected solar signals calculated with the APEC solar minimum and maximum reference spectra (Figure 3); those expected solar signals are shown in this figure as the dashed horizontal lines. With the A2 and B2 channels being the flare channels, it is important that there is significant margin between the measured signal during the X10 flare near 12 UT and the estimated signal for the APEC maximum spectrum (upper lines). For this comparison, the XRS-B2 non-flaring signal is also high quality and well above the estimated signal for the APEC minimum spectrum (lower lines). The XRS-A2 non-flaring signal is more noisy and the discrete data numbers from the XRS electrometer are obvious in the 0-8 UT range. We note that the less noisy data from XRS A1 and B1 channels, with their much larger aperture areas, are used for the XRS data products during non-flaring times.
Figure 11. Example of in-flight XRS signals for GOES-16 XRS A2 and B2 on day 2017/249 (6-Sep-2017) when there was a large X10 flare near 12 UT. These XRS signals are first corrected for the background signal, which is a bigger effect during non-flaring times for A2 than B2. The estimated signals for the APEC solar minimum and maximum reference spectra are the horizontal dashed lines (blue for A2 and red for B2).

While laboratory tests confirmed the performance for the XRS magnet assembly for on-axis electrons, the XRS flight data show a larger background signal for the new XRS units than anticipated. From the in-flight results as provided in the XRS Paper-2 (Machol et al., 2024), this generation of XRS still observes high-energy electrons, and these impact the in-flight background signal and thus the solar X-ray measurements at the lowest irradiance levels (A-class and low B-class flare levels). Further analysis of the XRS mechanical design indicated that the enhanced background was likely due to off-axis electrons interacting with the baffle assembly and producing Bremsstrahlung X-ray radiation in the optical cavity. The aluminum and tungsten shielding also protects XRS from most of the off-axis protons, but the magnet assembly has little effect on the high energy protons. Fortunately, these energetic protons are mostly transmitted through the thin Si photodiodes and thus have only a negligible contribution to the photodiode background signal except during the largest solar energetic particle events.
To test the aforementioned enhanced-background hypothesis, a full, flight-like XRS assembly was brought to the electron-beam (e-beam) facility at Goddard Space Flight Center (GSFC) in spring 2019 to test different baffle assemblies to better understand the potential adverse effects from electrons entering the XRS-A1 and -B1 apertures. Three XRS shielding configurations were tested:

1. Configuration 1: Original flight baffles

2. Configuration 2: Additional tungsten (W) baffles, tucked behind the Al flight baffles to help suppress the in-band characteristic X-ray contribution from W.

3. Configuration 3: Replace the W flight baffles with ones constructed from Al.

Those test results suggested that the new baffle arrangements did not improve the background signal in XRS; therefore, no alterations were made to the XRS flight models in storage (awaiting launch).

To better understand the e-beam results, the full XRS e-beam experiment was modeled using Geant4. This modeling exercise included the preparation of the following inputs for the Geant4 model.

1. A fully rendered computer-automated design (CAD) volume representation of the full XRS instrument was implemented.

2. We performed a 3-D Opera\textsuperscript{1} model computation of the internal magnetic field from the configuration of Sm-Co bar magnets in the magnet assembly.

3. We specified all electron beam characteristics (e.g., beam-spot size and Gaussian energy profile) as input for the Geant4 model.

The Geant4 model also differentiates between photons and electrons that made it to the diode substrate. As shown in Figure 12, the results from an e-beam test with an incident electron beam energy of 300 keV, at a particular orientation of XRS, are compared with the Geant4 simulation results of an identical experimental configuration and electron beam conditions. Both Figure 12 panels show enhanced signal for large incident positive beam angles, while falling off toward negative angles. Furthermore, the model results (bottom panel) shows that electrons are the

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\textsuperscript{1} Dassault Systemes, Simulia Product Line: Opera (www.3ds.com)
dominant particle entering the diode compared to photons produced upstream of the detector. It should be noted that the Geant4 simulation does not have a detailed depiction of the physics of the Si semiconductor response.

The pre-flight tests at GSFC with energetic electron beams do indicate higher detection of the high-energy electrons by the XRS detectors than expected. This Geant4 model was an interesting exercise to study a full simulation of this e-beam experiment, and this type modeling could provide a useful tool for improving future XRS designs at geostationary orbits. In particular, improvements for both the magnetic sweeping assembly and the shielding near the magnetic sweeping assembly could be considered for future XRS instruments.

Figure 12. GSFC e-beam facility results with an incident electron beam energy of 300 keV (top panel) and Geant4 model results (bottom panel) for an identical experimental configuration and conditions show similar incidence-angle dependence for the XRS magnet assembly. The Geant4 model also indicates that electrons dominate the background much more than the electron-excited photons.
6. SUMMARY

The next-generation XRS for the GOES-R series of satellites is extending the long-term time series of the solar X-ray irradiance obtained by previous GOES missions. Furthermore, the GOES-R XRS instrument has improved performance due to using more sensitive Si photodiodes instead of ionization cells, new low-noise ASIC electrometers, multiple photodiodes for both XRS-A and XRS-B channels to enhance the full measurement range, and dark-channel photodiodes for monitoring the high-energy electron background. A new capability for the most recent XRS is providing flare location information by using quadrant photodiodes. Machol et al. (2024) discusses this new flare-location capability for XRS, along with many details about the in-flight performance of the XRS instruments aboard the GOES-16, 17, and 18 satellites. These XRS instruments have all had very steady performance for more than seven years of operations, and we expect them to continue the temporal record of solar X-ray monitoring by NOAA for many years to come.

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DATA AVAILABILITY STATEMENT


REFERENCES


