User’s Guide for GOES-R XRS L2 Products
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1 Summary

The GOES X-Ray Sensor (XRS) measurements have been a crucial component of space weather operations since 1975, providing an accurate measurement of geo-effective X-ray irradiance from second-to-second real-time conditions to solar-cycle time scales (Garcia, 1994). XRS measurements are in two bandpass channels commonly referred to as the XRS-A (0.05-0.4 nm) and XRS-B (0.1-0.8 nm), both of which are in the soft X-ray portion of the electromagnetic spectrum. This User’s Guide discusses the algorithms used to generate the GOES-R XRS L2 data products.

The GOES-R XRS instrument provides irradiance ranges of more than 6 orders of magnitude by using two photodiode sets to cover overlapping portions of the irradiance range for the XRS-A channel and also for the XRS-B channel. XRS-A1 and XRS-B1 are larger Si diodes used to measure low X-ray fluxes, and XRS-A2 and XRS-B2 are smaller, quadrant Si diodes used to measure high X-ray fluxes, and to also provide approximate flare location on the solar disk. For each 1-s measurement, one of the A channels and one of the B channels are designated as the primary channels depending on the measured irradiance and channel switching threshold. Use of the primary channel avoids issues at low fluxes were the XRS-A2 and -B2 channels are not sensitive, and at very high fluxes, where the XRS-A1 and -B1 diodes saturate. The XRS instrument is described in detail by Chamberlin et al. (2009). On the GOES-R series satellites, XRS is part of the Extreme Ultraviolet and X-Ray Irradiance Sensors (EXIS). EXIS was designed and built by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado Boulder.

For XRS, the Level 2 (L2) data consists of cleaned 1-s data and higher order products such as irradiance averages, flare event summaries, and flare location. The 1-minute integrated XRS-B irradiance is used for solar flare classifications, and is key to NOAA Space Weather Prediction Center (SWPC) operations, allowing early warnings of major flares to be issued. Due to the Neupert effect (Neupert, 1968), during a solar flare, the harder X-rays measured by XRS-A reach their maximum value in advance of the softer XRS-B X-rays. The ratio of the XRS-A to -B irradiance has a variety of uses including the issuance of alerts by the SWPC forecasters, calculations of the flare temperature (e.g., Woods et al., 2008), and the derivation of the mean solar coronal temperature during non-flare conditions (Thomas et al., 1985; Garcia, 1994; White et al., 2005). The flare summary files can have a number of practical and scientific applications, such as determining the total energy input to the ionosphere’s D-region.

Science-quality XRS L1b and L2 netCDF datasets are produced by NOAA’s National Center for Environmental Information (NCEI), and differ from the operational products used at SWPC in that the data have been reprocessed from the start of the mission to the present date and incorporate retrospective fixes for issues and outages in the operational product (see Section 2.1). Users are advised to use the science quality data XRS L2 data instead of the operational data. The science quality data directories have names which end in "science" and the file names have prefixes of "sci".

This User’s Guide gives details of the GOES-R XRS L2 algorithms. Users of the GOES-R XRS data are responsible for inspecting the data and understanding the known caveats prior to use. Data caveats are given in the GOES-R Science Quality L2 Readme. Links to the science-quality XRS data, Readme’s, a User’s Guide, plots, responsivity data, and associated documentation can be found at https://www.ngdc.noaa.gov/stp/satellite/goes-r.html. Technical questions about this data can be sent to janet.machol@noaa.gov or courtney.peck@noaa.gov, while questions about data access should be sent to pamela.wyatt@noaa.gov.

2 XRS L2 Products Overview

XRS measures soft X-ray fluxes at 1-second cadence in the historical bandpasses of 0.05 to 0.4 nm and 0.1 to 0.8 nm, corresponding to Channels XRS-A and -B, respectively. Each channel has two irradiance sensors to capture the full dynamic range of the solar X-ray irradiance, where "1" denotes the low-irradiance sensor and "2" is for the high-irradiance sensor. This numbering is utilized in the variable naming where, for example, “xrsa2_flux” corresponds to the irradiance in Channel A on the high irradiance sensor. The flag “xrsa_primary_chan” indicates whether XRS-A1 or XRS-A2 provides the primary irradiance values and for each channel, the value from the selected primary sensor is available in the "xrsa_flux" or "xrsb_flux" variable. The current thresholds for switching the primary channels are 10^{-5} W m^{-2} for Channel A and 10^{-4} W m^{-2} for Channel B. The terms irradiance and flux are used interchangeably in this document.
The six L2 products for XRS are listed in Table 1.

<table>
<thead>
<tr>
<th>Product</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1s fluxes</td>
<td>fluxs</td>
<td>XRS irradiances at 1-s cadence</td>
</tr>
<tr>
<td>1-min fluxes</td>
<td>avg1m</td>
<td>XRS irradiances at 1-min cadence</td>
</tr>
<tr>
<td>flare summary</td>
<td>flsum</td>
<td>flare detection flags such as start and peak</td>
</tr>
<tr>
<td>flare detection*</td>
<td>fldet</td>
<td>flare detection status for every minute</td>
</tr>
<tr>
<td>flare location</td>
<td>flloc</td>
<td>flare location</td>
</tr>
<tr>
<td>daily background</td>
<td>bkd1d</td>
<td>daily background and daily averages</td>
</tr>
</tbody>
</table>

* Most users should use the flare summary instead of the flare detection product. See warning in Section 5.

2.1 Science Quality versus Operational XRS Data

The science quality L2 data products differ from the operational L2 products used in operations at SWPC in that they incorporate retrospective fixes that are not in the operational data as well as some recovered data that was missing in the real-time operational products. Also, this dataset uses the most recent calibrations. The science-quality L2 data products are created from the science quality L1b data. The operational L1b and L2 data, especially from the earlier dates, contain significant issues that are not retroactively corrected, and therefore should be used with great caution and not for scientific analysis.

2.2 Flare Magnitudes

A notable change between the GOES-R and previous GOES data is that the GOES-R XRS irradiances are provided in true physical units of W m$^{-2}$. The operational data prior to GOES-16 had scaling factors applied by SWPC to adjust the GOES 8-15 irradiances to match fluxes from GOES-7. The flare index was based on the operational irradiances, but to get true irradiances from the operational data, the scaling factors of 0.85 (for the XRS-A channel) and 0.7 (for the XRS-B channel) applied to GOES 8-15 had to be removed. There are no such scaling factors in the GOES-R XRS data; the provided irradiances are in true physical units.

The magnitude of a flare is defined by SWPC with a flare index that is based on the 1-minute average of the GOES operational irradiance in the XRS-B channel at the peak of the flare. Flare indices are denoted by a letter and a number based on the log 10 peak irradiance of the flare (X: $10^{-4}$ W m$^{-2}$, M: $10^{-5}$ W m$^{-2}$, C: $10^{-6}$ W m$^{-2}$, B: $10^{-7}$ W m$^{-2}$, and A: $10^{-8}$ W m$^{-2}$). For instance, an M5 index is defined for a 5x$10^{-5}$ W m$^{-2}$ peak irradiance, and an X2.5 index is defined as an irradiance level of 2.5x$10^{-4}$ W m$^{-2}$ peak irradiance. Because of the SWPC scaling factors in the pre-GOES-R data, flare indices for the earlier satellites were based on irradiances that were reported as 42% (1.0/0.7) smaller than for GOES-R (e.g., an X2.5 class flare reported operationally for GOES-15 will be an X3.6 class flare for GOES-R). Two XRS Level 2 (L2) products useful for flare detection are the event detection and event summary which provide flare peak irradiances, indices, and times.

A related note is that science-quality GOES 13-15 XRS reprocessed L1b and L2 data are now available. In the reprocessed GOES 13-15 data, the irradiances are provided in physical units (i.e., without the SWPC scaling factors) to match the GOES-R data. This earlier data is available from the GOES 8-15 tab at https://www.ngdc.noaa.gov/stp/satellite/goes-r.html

2.3 XRS Response Functions

The responsivity for the GOES-16 XRS channels is shown in Figure 1. The response functions for all satellites, plots, a Readme, and an IDL code to read the data are available from the Documents link at https://www.ngdc.noaa.gov/stp/satellite/goes-r.html
2.4 Time

The time variable, \( \text{time[secs]} = \text{Time[UTC]} - \text{base\_time[UTC]} \), is an elapsed time in units of “secs since \text{base\_time}” where \( \text{base\_time} = 2000-01-01\ 12:00:00[UTC] \) and was calculated without including leap seconds that occurred since 1 Jan 2000. Time stamps can be calculated by the user in Coordinated Universal Time (UTC) as

\[
\text{Time[UTC]} = \text{base\_time[UTC]} + \text{time[secs]} + n[secs]
\]

where \( n = 0 \) for a time conversion function which ignores leap seconds (e.g., Python cftime.num2date or netCDF4.num2date) and \( n = \text{number of leap seconds since base\_time} \) if the function includes leap seconds. It should be noted that the reference epoch of “2000-01-01 12:00:00 UTC” is not the same as the J2000 epoch, because the latter is given in terrestrial time (TT) units which differ by more than a minute from UTC. For a table of leap seconds, see [https://www.nist.gov/pml/time-and-frequency-division/time-realization/leap-seconds](https://www.nist.gov/pml/time-and-frequency-division/time-realization/leap-seconds).

3 1-second Irradiances Product

This product provides the XRS irradiances for the -A and -B channels along with a condensed set of quality flags. Values are provided for each detector (e.g., XRS-B1) and for the selected primary detectors (e.g., XRS-B). Additional variables include corrected currents for XRS-A2 and -B2, the roll angle, a factor to convert fluxes to 1 AU, and a yaw flip flag. Particle spikes, probably due to galactic cosmic rays, are flagged in the data.

Status flags are listed in Table 2.
Table 2: Status Flags for 1-sec data

<table>
<thead>
<tr>
<th>Flag</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>good_data</td>
<td>no other flags set</td>
</tr>
<tr>
<td>eclipse</td>
<td>Earth eclipse or lunar transit</td>
</tr>
<tr>
<td>particle_spike</td>
<td>particle spike</td>
</tr>
<tr>
<td>calibration</td>
<td>in flight calibration</td>
</tr>
<tr>
<td>off_point</td>
<td>satellite off-pointed</td>
</tr>
<tr>
<td>temperature_error</td>
<td>XRS temperature out of range</td>
</tr>
<tr>
<td>data_quality_error</td>
<td>signal too low/high or non-nominal condition</td>
</tr>
<tr>
<td>pointing_error</td>
<td>pointing uncalibrated or pointing error &gt; 0.4°; yaw flip in progress</td>
</tr>
<tr>
<td>invalid_mode</td>
<td>invalid L1b flags</td>
</tr>
<tr>
<td>missing_data</td>
<td>missing data</td>
</tr>
<tr>
<td>L0_error</td>
<td>L0 checksum error</td>
</tr>
</tbody>
</table>

Spikes are flagged with a simple equation with two terms which compare the signal to the current median irradiance and the noise level for the past hour. For an irradiance, $I$, a spike is defined as when

$$I_{\text{flat}} > 0.01 \cdot I + 1.05 \cdot \text{noise}$$  \hspace{1cm} (2)

where the flattened irradiance, $I_{\text{flat}} = I - \text{median}_5\text{-point}(I)$ and $\text{noise} = \min(\text{noise}_{\text{hour}}, \text{noise}_{\text{thresh}})$. Here $\text{noise}_{\text{hour}}$ is the lowest value ($< 0$) in $I_{\text{flat}}$ during the previous hour, and $\text{noise}_{\text{thresh}}$ is the static quiet time minimum determined over a long term. The flux term has an impact at high fluxes and ensures that spikes are significant at high fluxes. The noise term has an impact at low fluxes and during SEP events. This technique accounts for the fact that the signal has a relatively flat noise component which increases only when there is an SEP event.

4 1-minute Averages Product

This product contains the 1-minute averages of the 1-s cadence data. Data is flagged as good when it is not in an eclipse, does not have degraded pointing, is not a particle spike, and does not have the bad data flag set. Status flags are listed in Table 3. The number of 1-s data points included in the average as well as the union of flags for the 1-s data that were excluded from the averages are also provided with the data.

Table 3: Status Flags for 1-min averages

<table>
<thead>
<tr>
<th>Flag</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>good_data</td>
<td>neither eclipse flag nor bad data flag is set</td>
</tr>
<tr>
<td>eclipse</td>
<td>Earth eclipse or lunar transit</td>
</tr>
<tr>
<td>bad_data</td>
<td>large pointing error (&gt; 0.4°), missing data, or otherwise bad data</td>
</tr>
<tr>
<td>e_contam_significant</td>
<td>electrons contribute significantly to the observed X-ray flux.</td>
</tr>
<tr>
<td>e_correction_valid</td>
<td>valid electron correction</td>
</tr>
<tr>
<td>e_correction_invalid</td>
<td>invalid electron correction</td>
</tr>
<tr>
<td>e_correction_interp</td>
<td>electron correction is interpolated over a small gap in electron data</td>
</tr>
<tr>
<td>electron_correction_decay</td>
<td>electron correction is a decaying function</td>
</tr>
</tbody>
</table>

Electron contamination is removed in the 1-min-averaged data with a model based on a non-negative least squares fit of the GOES-R SEISS MPS-HI measurements of electron flux as a function of angle and energy (Boudouridis et al., 2020). Three X-ray averaged irradiance values are reported for each channel: the irradiance observed by the instrument (e.g., xrsb_flux_observed), the estimated electron contamination (e.g., xrsb_flux_electrons), and irradiance corrected for the electron contamination (e.g., xrsb_flux). For most purposes, the corrected flux should be used. The averaged irradiances are constrained to be above a minimum threshold of $10^{-9}$ W m$^{-2}$. 

5
As shown in Table 3, there are five flags regarding the electron contamination correction. The valid and invalid flags are mutually exclusive. The correction method for doing the electron contamination removal is imperfect and sometimes when the amount of contamination is large, noticeable artifacts of the electron contamination remain in the corrected data. The e_contamin significant flag indicates when the estimated contamination is more than about 50% of the observed signal and thus may be significantly impacted by the imperfect correction; the exact threshold for this flag is given in the file metadata. Figure 2 shows the X-ray data for August 2020 for the XRS-B1 channel.

The electron correction interpolation and decay flags provide extra context. When there are missing SEISS electron measurements in the retrospective data, the correction factor is interpolated for gaps less than one hour and the electron_correction_interp flag is set in addition to electron_correction_valid. For missing data in real time or gaps longer than one hour in retrospective data, the correction is a decaying function as shown in Figure 3. The electron_correction_decay flag will be set, along with electron_correction_valid for the first 60 minutes of decay. After 60 minutes of decay, the electron_correction_invalid flag is set instead, even as the decay continues.

The electron correction interpolation and decay flags provide extra context. When there are missing SEISS electron measurements in the retrospective data, the correction factor is interpolated for gaps less than one hour and the electron_correction_interp flag is set in addition to electron_correction_valid. For missing data in real time or gaps longer than one hour in retrospective data, the correction is a decaying function as shown in Figure 3. The electron_correction_decay flag will be set, along with electron_correction_valid for the first 60 minutes of decay. After 60 minutes of decay, the electron_correction_invalid flag is set instead, even as the decay continues.

Figure 2: GOES-16 XRS-B1 observed signal (blue), estimated signal from electrons (black), and corrected XRS signal (dark and light orange) for the month of August 2020. Values in light orange indicate points where the e_contamin significant flag is set.

Figure 3: Decaying function applied to the electron contamination for gaps of greater than 1 hour. The decay function is $1.005/(1 + 0.005 \cdot e^{0.07 \cdot t})$ which is a logistic decay for time, $t$, in minutes.
5 Flare Summary and Flare Detection Products

The flare summary and detection products provide information on flares, including flare class, start and end times, integrated flux, and background flux based on 1-minute cadence XRS-B irradiances. The flare detection algorithm provides output every minute while the flare summary provides records only for the four most important states. Table 4 shows the available status flags for the two products.

<table>
<thead>
<tr>
<th>Flag</th>
<th>Description</th>
<th>Summary</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>MONITORING</td>
<td>There is no event in progress.</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>EVENT_START</td>
<td>A flare has just started.</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>EVENT_RISE</td>
<td>Flare has started but not reached its maximum.</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>EVENT_PEAK</td>
<td>Flare maximum.</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>EVENT_DECLINE</td>
<td>Flare has begun to decay.</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>EVENT_END</td>
<td>Flare has declined to 1/2 of flare maximum.</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>POST_EVENT</td>
<td>Flare declined to background.</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IMPAIRED</td>
<td>Algorithm has insufficient data to determine status.</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

For most users, the flare summary product should be used and the flare detection product should not be used. The flare summary provides true time stamps for events. The flare detection algorithm must detect X-ray flares in real-time operations. The flare detection time stamps represent the time when the algorithm detected an event, such as the flare peak, rather than when the actual peak occurred. For two event types, flare start and flare peak, this results in flare detection time stamps that are delayed by several minutes. The flare detection product is used in real-time forecast operations, where minute-to-minute status information is the priority and also provides the input triggers to three other GOES-R L2 algorithms: XRS Flare Location, SUVI Bright Regions and SUVI Flare Location. The flare detection product is provided retrospectively for users who wish to examine the algorithm behavior.

Figure 4 illustrates how the status flags are applied and the differences between the flare summary and flare detection time stamps. Details of the flare detection algorithm are provided in Appendix A.
Figure 4: X-ray irradiance from GOES-16 on 28 February 2017. The dots color coded for the flare detection status at each minute. The vertical lines, with the same color codes, are at the actual event times as provided in the flare summary product. The EVENT\_START and EVENT\_PEAK true times (green and red vertical bars) occur prior to the detection of those event (green and red circles).

6 Flare Location Product

Flare location on the solar disk is determined based on the measurements from the high flux XRS-B2 quad diode detector (Chamberlin et al., 2009). Flare location is provided at EVENT\_PEAK in four coordinate systems: Stonyhurst/heliographic (lon, lat), Carrington (lon, lat), heliocentric-radial (R, θ) and heliocentric Cartesian (x,y) coordinates. The solar P-angle and apparent solar angular radius are also provided. More details about the Flare Location Product calculation can be found in Appendix B.

This product was empirically scaled and validated with comparisons to flare locations from the Helio- physics Event Registry (HER; https://www.lmsal.com/sungate/). The HER data is included in the Helio- physics Events Knowledgebase (HEK; https://www.lmsal.com/hek/index.html). As shown in Table 5, the median errors are < 1 arcmin for C class and above flares.

For the current algorithm, due to the limitations of a 4-pixel sensor (i.e., the quad photodiode), the flare location algorithm works best for flares that do not overlap in time because it assumes that the background brightness of the Sun does not change between EVENT\_START and EVENT\_PEAK. If the background brightness of the Sun does change significantly, for example, due to a decaying flare in a different active region, this will introduce error in the flare location product.

<table>
<thead>
<tr>
<th>Class</th>
<th>GOES-16</th>
<th>GOES-17</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of Flares</td>
<td>Median Error [arcmin]</td>
</tr>
<tr>
<td>X</td>
<td>5</td>
<td>0.87</td>
</tr>
<tr>
<td>M</td>
<td>39</td>
<td>0.43</td>
</tr>
<tr>
<td>C</td>
<td>226</td>
<td>0.67</td>
</tr>
<tr>
<td>B</td>
<td>644</td>
<td>3.28</td>
</tr>
<tr>
<td>All</td>
<td>954</td>
<td>1.83</td>
</tr>
</tbody>
</table>

* For flares between 2017-02-09 to 2020-08-20 for GOES-16 and 2018-06-18 to 2020-08-20 for GOES-17 and excluding flares that overlap in time.
This product provides daily average irradiances and daily backgrounds for XRS-A and -B. The algorithm uses hourly and 8-hour minima of the 1-minute averages to determine the daily background values. The algorithm is designed to be consistent with the logic from the former GOES XRS daily background algorithm originally developed by Dave Bouwer in 1981. Using the observation that most major X-ray flares last at most about 8 hours, and that the algorithm is most applicable in describing mid-to-long-term coronal variations on time scales of weeks to years, an approximation of coronal background variations for statistical time series comparisons to other solar indices (e.g., F10.7 cm radio emissions) could be useful in describing solar active region evolution and the solar cycle. An example of the daily background product is shown in Figure 5. The details of the daily background algorithm are given in Appendix C.

Figure 5: Daily background (green) and 1 minute XRS averages (blue) over 5 days.

Monthly summary plots are provide for both the science-quality and operational 1-minute averaged data. The files contain plots for each of the four detectors (A1, B1, A2, and B2). Traces are shown for the observed and electron-corrected irradiances as well as the estimated electron contamination. An example of the summary plots is shown in Figure 6 for September 2017, a period with X-class flares.
Figure 6: Example monthly summary plot showing X-class flares in GOES-16 XRS science-quality data for September 2017.
9 Acknowledgements

We thank the following people for their work on the development of the L2 algorithms:

Flare Location: L. Rachmeler, A. Reinard

1 Space Environment Technologies (SET)
2 Laboratory for Atmospheric and Space Physics (LASP), University of Colorado Boulder
3 Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder
4 NOAA National Centers for Environmental Information (NCEI), Boulder
5 NOAA Space Weather Prediction Center (SWPC), Boulder

We thank Laurel Rachmeler for validation of the flare location algorithm. We thank Tom Woods and Don Woodraska for the responsivity values, plots, and code. We thank Tom Eden and Rodney Viereck for algorithm discussions.

10 References


Appendix A  Flare Detection Algorithm

A.1  Flare Detection Algorithm

One of the challenges in developing the event detection algorithm was mitigating the effects of signal noise which can result in false-positives or inaccurate identification of the flare peak or end. Because the block of data examined each moment ("data-frame") is small (generally less than ten points of 1-minute data so as not to include multiple flares), accurate statistics are difficult to achieve. In most cases, the algorithm uses a variety of criteria including an exponential fit to determine that a flare has begun. Figure 7 shows the irradiance during a flare in the first figure and the second derivative in the second figure. The start of the flare is before the inflection point as the irradiance rises. On the rising edge, the inflection point is at the maximum of the first derivative and a zero of the second derivative. For an increasing slope, the second derivative peaks just prior to the inflection point.

![Exponential fit for flare detection algorithm.](image1)

The recent background flux level is used both for the exponential fit for the flare rise and for determining the flare end. The best choice for the background can be difficult to select; for example, an hourly average or a shorter time interval could be used to estimate a background. Also, significant signal noise or rapidly repeating flares can result in a too high background estimate, significantly hindering the ability of an algorithm to detect or characterize a flare. By fitting an exponential model to the initial rise of a flare, and using its minimum value, a more accurate background can be estimated that is less susceptible to rapid flaring or signal noise. However, this background can still be in error by up to about ±20% in cases where the pre-flare data has significant signal noise or the flare rises to its peak in several minutes.

Figure 8 presents a flow chart outlining the sequence of operations for the algorithm. Fill values are used whenever a calculation cannot be performed due to missing data. Section A.2 presents the algorithm steps.
A.2 Algorithm Steps

The following sections describe the steps in the algorithm. The algorithm inputs and processing variables are defined in Section A.3.
A.2.1 (Steps 1-6) Prepare data and do simple comparisons

1. **Read** next 1-minute data point with *flux* and *curr_time*. **Initialize** variables as needed.

2. Set *prev_status* = IMPAIRED and all fluxes to *bad_flux*.

3. **Read** in recent data and current parameters.

4. Create the real time "raw data frame" of raw fluxes, $X_i$, numbered from 0 to $N-1$, where $N = frame_mins$. Put most recent flux in the final element of frame. Transfer fluxes from the previous frame into the current frame, leaving the last element available for the new data point. Any gaps in time or differences in array length will result in those elements in the current frame filled with *bad_flux*.

5. If there is any *bad_flux* in the frame, then set *status* = IMPAIRED and proceed to "Final steps".

6. For raw fluxes $X_i$ where $i$ is in the first $N-2$ values, **calculate the standard_dev** as

\[ \sigma = \sqrt{\frac{\sum_i (X - X_i)^2}{X}} \]

where $\bar{X}$ is the mean. Also, **smooth** the full data frame with a small, simple boxcar filter over $n_smooth$ points to mitigate noise and reduce false positives. This produces a new data frame of $x_0$ to $x_{n-1}$, where the number of elements is $n = N - (n_smooth - 1)$. Typically a 3-minute window is adequate. To simplify timing, the filter width should be an odd number.

7. If $x_{n-1} < min_flux_good$ then set *status* = IMPAIRED and proceed to "Final steps".

A.2.2 (Steps 8a-f) Check for start of flare

At this point, there is a full frame of good data. If the status is not currently in a flare, then the following steps are followed to check if there is a start of a flare. The status is already in a flare event if *prev_status* = not(MONITORING, IMPAIRED, EVENT_END or POST_EVENT).

8. If *prev_status* did not indicate a flare event, then proceed through Steps a-j.

   a. If $x_{n-1} < background$ then set *status* = POST_EVENT, set background = -999.0, and proceed to "Final steps". The background value is set low to ensure that POST_EVENT is only set once.

   b. If **flux is high** and previously points were low, i.e., $(X_{n-1} > high_flux)$ AND $\max([X_0,...X_{n-2}]) < (R2 - min_num_std \cdot \sigma)$, then set *status* = EVENT_START, set the pre-flare background to the minimum smoothed flux in frame and proceed to "Final steps".

   c. Set *status* = MONITORING.

   d. If the flux is inadequate for an inflection point, $x_{n-1} < min_inflection_flux$, then proceed to "Final steps".

   e. If an **inflection point** has not been reached in the slope of the data frame using the second derivative of the data frame, then proceed to "Final steps". The inflection point is at $\max(d^2x/dt^2)$. To know that this is the inflection point, and not just part of an increasing slope, requires that this point not be the final point within the frame; so, this routines checks the penultimate second derivative. With $n$ time steps of 1 minute (i.e., $dt = 1$), there are $n - 1$ first derivatives in the data frame and $n - 2$ second derivatives which we calculate as $dx_i = x_{i+1} - x_i$, for $i = 0$ to $n - 1$ and $d^2x_j = dx_j - dx_{j-1}$, for $j = 0$ to $n - 2$.

   f. If flux data has not risen by at least a minimum number of **standard deviations**, then proceed to "Final steps". Calculate the difference in the mean of the first 3 data points versus the mean of the last 3 data values in the frame. There is a potential flare if

\[ x_{n-1} - x_0 > min_num_std \cdot \sigma. \] (3)
g. Fit to an exponential function. The fit for the impulsive rise of the flare is to the function:

$$\Phi_{\text{imp}}(t) = a \cdot e^{b \cdot t} + c \quad (4)$$

where \( t > 0 \). Determine the correlation_coef and set temp_background to minimum of the fitted exponential function (value at \( i = 0 \)).

Proceed to "Final steps" in any of the following cases:

i. The rise is inadequate if \( x_{n-1}/\text{temp}\_\text{background} < \text{min\_ratio}\_\text{to}\_\text{bkd} \) or \( a < 0 \) or \( b < 0 \).

ii. The exponential fit is bad if \( \text{correlation\_coef} < \text{min\_corr\_coef} \).

iii. The exponential function is not increasingly concave as it should be. The exponential fit determines that the flux is increasing (i.e., \( a > 0 \) and \( b > 0 \) in Equation 4), and so in this step it is only necessary to verify that the function is concave. A function is concave if the second derivative is > 0. The second derivative of Equation 4 is

$$d^2\Phi_{\text{imp}}(t)/dt^2 = a \cdot b^2 \cdot e^{b \cdot t} \quad (5)$$

The fit function is concave when \( d^2\Phi_{\text{imp}}(t)/dt^2 > 0 \); i.e., when \( a > 0 \). (Redundant with Step i.)

iv. The SNR is not adequate if the mean of the last 3 points of the exponential function estimate lies a factor less than \( \text{min\_exp\_rise\_factor} \) above the mean of the first 3 data points of the exponential fit.

h. Set status = EVENT\_START, set the pre-flare background to temp_background, and set mins\_since\_event to the number of minutes (> 0) between the time of the minimum flux and the end of the frame. Proceed to "Final steps".

A.2.3 (Steps 9a-c) Rising flare

9. If flare is rising (prev_status = EVENT\_START or EVENT\_RISE) then proceed through Steps a-c to look for a peak:

a. There was a flare maximum if the maximum flux in the last peak\_frame\_mins of the frame is the first point in this peak frame.

b. If there was no flare max then, set status = EVENT\_RISE and proceed to "Final steps".

c. In this case, a flare max has occurred. Set status = EVENT\_PEAK, peak\_flux = maximum flux, mins\_since\_peak = peak\_frame\_mins − 1, and peak\_time = curr\_time − mins\_since\_peak. Proceed to "Final steps".

A.2.4 (Steps 10a-b) Declining flare

10. If flare is declining (prev_status = EVENT\_PEAK or EVENT\_DECLINE) then proceed through Steps a-e to check for a flare end or a new flare start:

a. If end of flare, then set status = EVENT\_END and proceed to "Final steps". The event end is defined as when

$$\{\text{median}(X_{n-3}, X_{n-2}, X_{n-1}) − \text{background}\} \leq (\text{peak\_flux} − \text{background})/2 \quad (6)$$

Set mins\_since\_event = curr\_time − time_i for first i where \( (X_i − \text{background}) \leq (\text{peak\_flux} − \text{background})/2 \).

Note: the POST\_EVENT flag is set in Step 8a if flux < background.

b. Set status = EVENT\_DECLINE

c. If the elapsed time since the peak is too short to start looking for another flare (curr\_time − peak\_time < min\_time\_after\_peak), then proceed to "Final steps".
d. If a new flare has begun, then set \( status = \text{EVENT\_START} \), set the pre-flare \( \text{background} \) to the minimum non-smoothed flux since the peak, and set \( \text{mins\_since\_event} = \text{curr\_time} - \) (time of this minimum flux).

A new flare is indicated if either (1) the \text{flux is high} \( (X_{n-1} > \text{high\_flux}) \) and \( \text{peak\_flux} < \text{high\_flux} \), or (2) the smoothed flux has risen by at least a minimum number of standard deviations.

In the second case, in the subset of the current frame where the time is at least \( \text{mins\_since\_peak} \) minutes have elapsed since the peak, the index \( j \) of the minimum flux is found. There is a flare start if:

\[
x_{n-1} - x_j > \text{min\_num\_std} \times \sigma.
\]

(7)

c. Proceed to "Final steps".

A.2.5 (Steps 11a-e) Final steps to exit

11. Final steps to exit.

a. If \( status = \text{IMPAIRED} \) or \( \text{POST\_EVENT} \), then set \( \text{background} = \text{background\_reset} \) so that a subsequent \( \text{POST\_EVENT} \) will not be declared.

b. If \( status = \text{EVENT\_START} \), then

\[
\text{integrated\_flux}[J/m^2] = \frac{60 \text{ s}}{1\text{-min average}} \cdot \sum_{n-1-\text{mins\_since\_start}}^{n-1} x_i[W/m^2].
\]

(8)

c. If \( status = \text{EVENT\_RISE}, \text{EVENT\_PEAK}, \text{EVENT\_DECLINE}, \) or \( \text{EVENT\_END} \), then add to the integrated flux:

\[
\text{integrated\_flux}[J/m^2] += \frac{60 \text{ s}}{1\text{-min average}} \cdot x_{n-1}[W/m^2]
\]

(9)

d. Write a real time flare detection record with \( \text{curr\_time}, status, \) and \( x_{n-1} \). Also write out the integrated flux if \( status = \text{EVENT\_START}, \text{EVENT\_RISE}, \text{EVENT\_PEAK}, \text{EVENT\_DECLINE}, \) or \( \text{EVENT\_END} \).

e. Write a flare summary record if \( status = \text{EVENT\_START}, \text{EVENT\_PEAK}, \text{EVENT\_END}, \) or \( \text{POST\_EVENT} \).

A.3 Algorithm Inputs

For the flare detection algorithm the input data is the XRS-B fluxes from the L2 1-minute average files (xrsf-l2-avg1m). Some of the configurable inputs for the algorithm are given in Table 6. Some of the variables used within the algorithm are given in Table 7.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Example</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>frame_mins</td>
<td>data frame size</td>
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<td>mins</td>
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<td>high_flux</td>
<td>threshold for expedited flare declaration</td>
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<td>W/m^2</td>
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<td>minimum correlation coefficient</td>
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<td>minimum ratio of end of fit to start of fit</td>
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</tr>
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<td>minimum flux threshold below which status is IMPAIRED</td>
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<td>W/m^2</td>
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<td>minimum ratio to background for event start</td>
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<td>mins</td>
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<tr>
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<td>-</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
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<td></td>
</tr>
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<td>---------------------</td>
<td>------------------------------------------------------------------</td>
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<td></td>
</tr>
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<tr>
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<td>current status</td>
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</tr>
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<td>value &lt; 0 to reset background</td>
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</tr>
<tr>
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</tr>
<tr>
<td>integrated_flux</td>
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<td>standard deviation of n-2 smoothed frame elements</td>
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<td></td>
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<td>peak_time</td>
<td>time of last peak</td>
<td></td>
<td></td>
</tr>
<tr>
<td>event_time</td>
<td>time of last event</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix B  Flare Location Algorithm

We describe the mathematical formulation of the Flare Location Algorithm in this appendix.

As input, this algorithm uses the 1-minute XRS data product and the Flare Summary product. The Flare Location Algorithm is triggered when a flare EVENT_PEAK is flagged in the Flare Summary product, and calculates a location using the quad diode intensities in the 1-minute product.

The four quad diodes in the XRS-B2 detector are ordered clockwise (Figure 9).

![Figure 9: Cartoon of the XRS-B2 quad diode on the right with the quadrants labeled and a flaring Sun on the left. The background light from the Sun is represented in yellow and the light from the flare in red. The algorithm calculates the location of the flare as the center-of-mass of light from the flare.](image)

The first step of the calculation is to isolate the flaring light by subtracting a background solar brightness from each quadrant so that

\[ Q_i = q_i - b_i \]

where \( q_i \) is the corrected current and \( b_i \) is the background corrected current for quadrant \( i \). The independent background in each quadrant is the average intensity over 7 minutes prior to EVENT_START, only considering intensities below the EVENT_START value. If no values meet this criteria, then the corrected current at EVENT_START is used as the background.

The measured center-of-mass of the background-subtracted flare intensity is then calculated in detector coordinates:

\[
\begin{align*}
x_{det}' &= (Q_1 + Q_2) - (Q_3 + Q_4) \\
y_{det}' &= (Q_1 + Q_4) - (Q_2 + Q_3)
\end{align*}
\]

where the detector coordinates are in the range of \(-1 < x < 1\) and \(-1 < y < 1\).

The location is then converted from detector coordinates \((x_{det}, y_{det})\) to Heliocentric Cartesian coordinates \((x_{XRS}, y_{XRS})\) in arcmin. This involves a rotation correction by an angle \( \alpha' \) to align solar north with \( x_{det} \), and has several parameters associated with both static and dynamic offsets in pointing, roll, and field-of-view.

\[
\begin{align*}
x' &= x_{det} + x_{offset} \\
y' &= y_{det} + y_{offset}
\end{align*}
\]

\[
\begin{align*}
x_{XRS} &= -(x' \cos \alpha' - y' \sin \alpha')F \\
y_{XRS} &= (x' \sin \alpha' - y' \cos \alpha')F
\end{align*}
\]

\[
\alpha' = (P_{ang} + \alpha_{roll} - 180 + \alpha_{offset}) \frac{\pi}{180}
\]

The parameters in the above equations are defined as follows: \( x_{offset} \) and \( y_{offset} \) are free parameters representing static offsets applied in the detector coordinates. Physically they can be interpreted as a small offset between the satellite pointing and the center of the field-of-view of the detector. The overall correction angle, \( \alpha' \) (measured counterclockwise) is a combination of the measured roll-angle of the satellite relative to the celestial pole \( \alpha_{roll} \), the solar P-angle \( P_{ang} \), which is the position angle between the celestial north pole and the solar rotational north pole, 180° to account for the satellite-to-instrument orientation, and a small static angular offset of the detector \( \alpha_{offset} \) which is a free parameter. The \( F \) free parameter is defined as the half-field-of-view of XRS, the full field-of-view goes from \(-F\) to \(+F\) in both \( x \) and \( y \). The \( P_{ang} \) is
a known parameter that can be calculated from solar ephemeris data; it is included as a parameter in the Flare Location algorithm. The spacecraft roll, $\alpha_{\text{roll}}$, is a parameter in the 1-minute average product.

The free parameters in the coordinate transformation are thus: $x_{\text{offset}}$, $y_{\text{offset}}$, $\alpha_{\text{offset}}$, and $F$. We use a Monte Carlo method to optimize these four parameters simultaneously for each satellite. A set of known flare locations, as reported in the Heliophysics Event Registry (HER), was used as the “true” location of the flare, and the Monte Carlo method was used to determine the set of parameter values that minimized the difference between the flare location as reported in the HER and in XRS. Overlapping flares were excluded from these calculations. The best-fit parameters are listed in Table 8; these parameters were used to calculate the statistics provided in Section [6]. These parameters may be updated in the future, especially for GOES-17, because only a limited number of flares were available at the time.

Table 8: Best-fit parameters* for the XRS Flare Location algorithm, excluding overlapping flares

<table>
<thead>
<tr>
<th>Free Parameter</th>
<th>GOES-16</th>
<th>GOES-17</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{\text{offset}}$ [detector units]</td>
<td>0.000278</td>
<td>-0.0333</td>
</tr>
<tr>
<td>$y_{\text{offset}}$ [detector units]</td>
<td>-0.0144</td>
<td>0.0207</td>
</tr>
<tr>
<td>$\alpha_{\text{offset}}$ [degree]</td>
<td>-1.28</td>
<td>-0.232</td>
</tr>
<tr>
<td>$F$ [arcmin]</td>
<td>87.39</td>
<td>85.24</td>
</tr>
</tbody>
</table>

* As of August 2020.
Appendix C  Daily Background Algorithm

This algorithm creates a daily X-ray background irradiance from the XRS-B 1-minute irradiances. If there is no data to be averaged, then a fill value is output for the irradiances and the flag is set to bad data. Figure [10] presents a flow chart outlining the sequence of operations for the algorithm. Fill values are used whenever a calculation cannot be performed due to missing data.

Figure 10: Flowchart of daily background algorithm.

The sequence of operations is:

1. Calculate hourly averages from XRS-B (0.1-0.8 nm) one-minute fluxes if there is at least 1 valid data point for the hour.
2. Divide 24 hourly averages into three equal blocks of 8 hours, x_8hr: e.g., 00-07, 08-15, and 16-23.
3. Calculate the minimum hourly average for each of the 3 blocks.
4. Perform a simple average of the minima of the 2 outer blocks for an interpolated minimum at noon.
5. Set the X-ray daily background (xdb) as the mid-day minimum if at least one of the three bins has 
good data. Set the xdb_flag=0.
   a. If all three 8-h blocks have good data, select the lower minimum from either the middle bin or 
      the interpolated noon bin.
   b. If the middle block has no data, select the interpolated minimum.
   c. When either the first or third block does not have data, select the lower of the two remaining 
      blocks.
   d. If only one block has data, use its value.

6. If no blocks have good data, set xdb to the fill value and set the xdb_flag=1 for missing data.