README FOR SCIENCE-QUALITY GOES 8–15 XRS DATA

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Contents

1 Summary

The NOAA Geostationary Operational Environmental Satellites (GOES) carry instruments for space weather and terrestrial weather. On each GOES satellite there are two X-ray Sensors (XRS) which provide solar X-ray irradiances for the wavelength bands of 0.5 to 4 Å (short channel) and 1 to 8 Å (long channel). Measurements in these X-ray bands have been made by NOAA satellites since 1974 and the design has changed little during that time period [Garcia, 1994]. The operational (real time) data comes came from from the NOAA Space Weather Prediction Center (SWPC). Both operational and science-quality data are provided by the NOAA National Centers for Environmental Information (NCEI).

This ReadMe discusses reprocessed, science-quality GOES-8 through -15 XRS data. It focuses on the highest-cadence data products at the measurement cadences of 2 seconds for GOES-13 through -15 and 3 seconds for GOES-8 through 12. A User's Guide for the higher order (Level 2) products is at `https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes/goes16/l2/docs/GOES-R_XRS_L2_Data_Users_Guide.pdf` GOES-1 through -7 XRS data will be reprocessed to be science-quality in the coming year.

Users of the GOES XRS science-quality data are responsible for inspecting the data and understanding the known caveats prior to use. Questions about the GOES-8 through -15 XRS data can be sent to james.mothersbaugh@noaa.gov and janet.machol@noaa.gov, while questions about data access should be sent to kim.baugh@noaa.gov. If you wish to be notified of updates to GOES XRS (and/or Extreme Ultraviolet Sensor (EUVS)) data sets, please send an email to janet.machol@noaa.gov.

2 GOES X-Ray Sensor (XRS)

XRS consists of two gas-filled ion chambers, one for each band. Sweeper magnets deflect incoming electrons away from the assemblies so that only X-rays are measured. GOES-8 through -12 (GOES I–M series) and GOES-13 through -15 (GOES NOP series) have ion cell detectors and the detector/filter combinations that make the spectral bandpasses nearly identical between both satellite series (and to earlier XRS detectors). A description of the GOES-8 instrument is given by Hanser and Sellers [1996]. For each sensor, the short wavelength cutoff is defined by the ion cell, while the long wavelength cutoff is defined by the thickness of the beryllium (Be) filter. Figure 1 shows the normalized detector responses for the short and long wavelength bands. Response functions are provided with the irradiance data. The terms irradiance and flux are used interchangeably in this document.

Data cadence varied for the different satellites. The GOES-8 through -12 measurements were at a 3-s cadence, and the GOES-13 through -15 measurements were at a 2-s cadence. There is no high-resolution (i.e., 3-s cadence) data available for GOES-9, although 1-minute averaged data will be available.

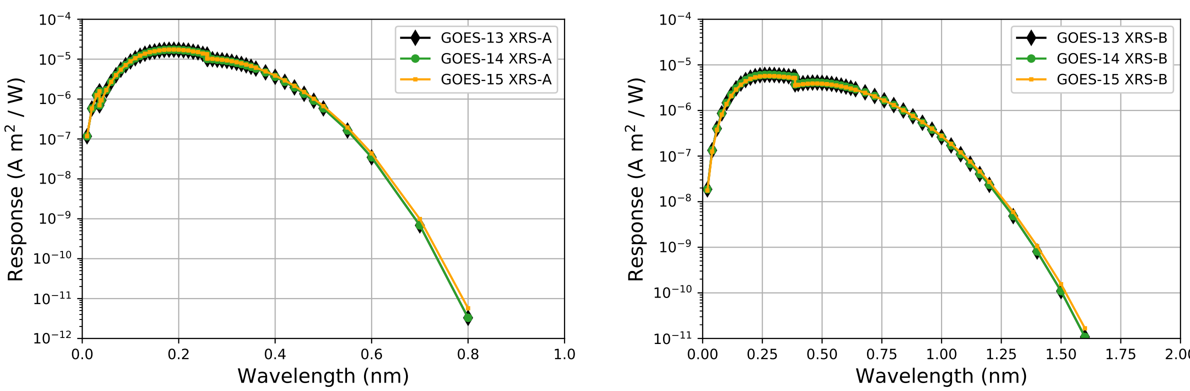

Figure 1: Response functions for XRS-A (left) and XRS-B (right). There are only minor differences between the three satellites.

GOES satellites are in geostationary orbits near the equator at an altitude of approximately 36,800 km. Near the equinoxes, each satellite's line of sight to the Sun is eclipsed by Earth each day for up to approximately 70 minutes. In order to have continuous operational data coverage, NOAA maintains two operational GOES satellites; these are at geostationary locations that are 60 degrees apart. One satellite is designated by NOAA as primary, and the other satellite is designated as secondary (i.e., back-up). Figure 2 shows the primary and secondary GOES satellites for the XRS data. Table 1 lists the launch dates of the GOES satellites, along with the date ranges for the science-quality data. The primary and secondary GOES satellites for XRS since 1986 are listed in Table 6 in Appendix A.

Table 1: Dates of Satellite Launch and Science-Quality Data

Satellite	Launch	Data Start	Data End
GOES-8	1994/04	1995/01	2003/06
GOES-9	1995/05	1996/04	1998/07
GOES-10	1997/04	1998/07	2009/12
GOES-11	2000/01	2001/05	2008/02
GOES-12	2001/07	2003/01	2007/04
GOES-13	2006/05	2013/06	2017/12
GOES-14	2009/06	2009/09	2020/03
GOES-15	2010/03	2010/03	2020/03

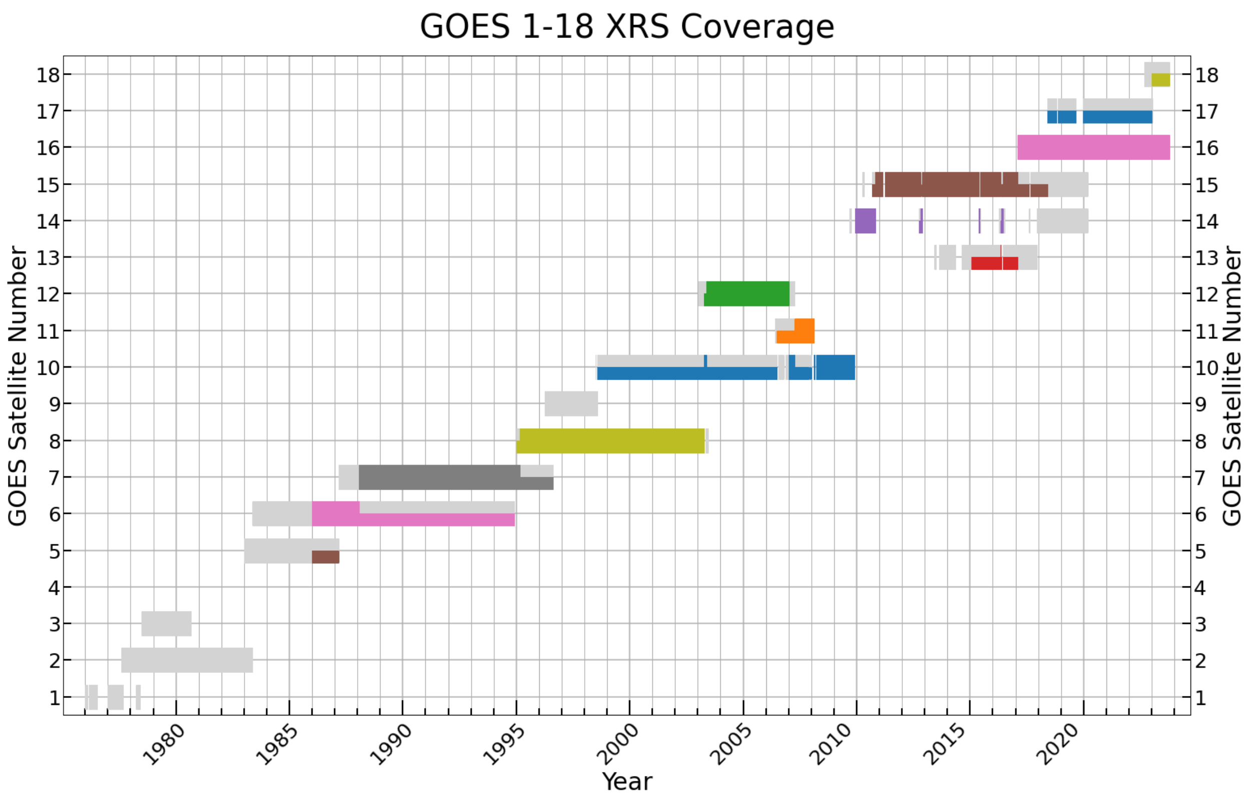

Figure 2: Primary (thick lines) and secondary (thin lines) GOES satellites for XRS data between 1975 and 2023. GOES-13 XRS measurements were unstable for many years, but were stable after late 2014. XRS data goes back to 1974, but the original designation of primary and secondary satellites prior to 1986 is not known.

While GOES-13 took data for years before the start date of the science-quality data, it was unstable until June 2013. The GOES 13 XRS had an electronics problem early in the mission; it is suspected that a capacitor failed. This resulted in a changing calibration and periods of data inversion (where flares appear as dips). We refer to these periods as "anomalous mode." While this mode is obvious during flares, when the signal is low, the anomalous and normal modes are indistinguishable. The science-quality data for GOES-13 begins in June 2013 when GOES-13 XRS ceased to go into anomalous mode.

3 Science-Quality Irradiances

The retrospective XRS science-quality data has been reprocessed with many corrections. The science-quality data differs from the operational data in several ways.

First, in the science data, the calibration coefficients are smoothly varying values, while sporadic calibration updates in the operational data resulted in step functions in the irradiances. The X-ray irradiance in each channel is calculated as

$$\text{Irradiance [W/m}^2\text{]} = (\text{Counts} - B) \times G/C \tag{1}$$

where B is the background, G is the gain, and C is the units conversion factor. The background values are really electronic offsets, and are measured when the satellite is pointed away from the Sun. The gain is also examined on orbit, but does not change much from its pre-launch values. For GOES-8 through GOES-12 data, only irradiances instead of counts data was available for the reprocessing, and so background adjustments could not be made on this data.

Second, as described in Section 3.1, the science-quality data was corrected so that it does not contain the SWPC scaling factors. Figure 3 shows an example of the differences between the rescaled and smoother science-quality data and the original operational data.

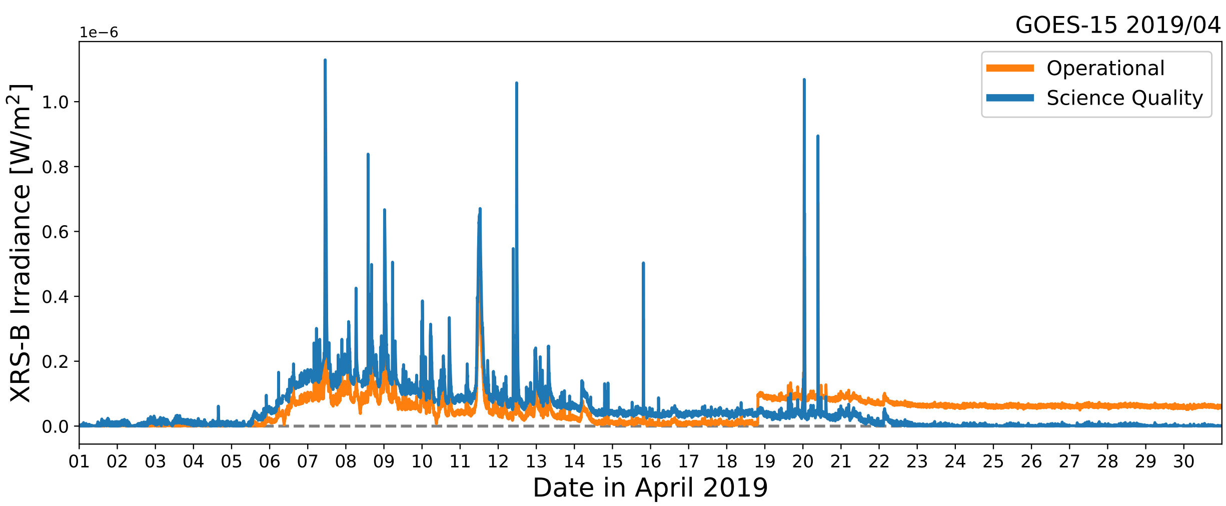

Figure 3: Comparison of operational (orange) and science-quality (blue) 1-minute averaged GOES-15 XRS-B data for the month of April 2019. Both the revised scaling and a discontinuity in the operational data due to a background adjustment on 18 April are apparent.

A third major adjustments were bandpass corrections. In the operational data, for GOES-1 and -2, a solar spectrum was presumed, while for all later satellites, a flat spectrum is presumed. After GOES-2, the units conversion factor of Eq. 1 includes a factor in the denominator for the width of the bandpass. After GOES-2, in the operational data, the assumed XRS-B bandpass is the same for all of the satellites (1 to 8 Å), however the XRS-A bandpass was 0.5 to 3 Å for GOES-3 through GOES-12 and 0.5 to 4 Å for the later satellites. For the science-quality data for GOES-3 through GOES-12, the data has been rescaled for a 0.5 to 4 Å bandpass. (When the science-quality datasets for GOES-1 and -2 data are created in the coming year, they will also use these same bandpasses.)

A fourth major correction for the science-quality data was the revision or creation of data quality flags. For some of the satellites, the science-quality flags are similar to those in the SWPC operational data, but with corrections as to where the data is flagged. For other satellites, there were no operational data quality flags, and so the flags in the science-quality data are new.

3.1 Flare Magnitudes

The magnitude of a flare (i.e., the flare index) is defined by SWPC based on the 1-minute average of the GOES operational irradiance in the XRS-B channel at the peak of the flare. Flare indices, denoted by a letter and a number based on the $\log_{10}$ peak irradiance of the flare, are 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 5×10^{-5} W/m^2 peak irradiance, and an X2.4 index is defined as an irradiance level of 2.4×10^{-4} W/m^2 peak irradiance. The flare index is defined by the truncated (not rounded) irradiance; e.g., a flare with peak irradiance of 4.19×10^{-5} W/m^2 is an M4.1 flare, not an M4.2 flare. An XRS Level 2 (L2) product useful for flare detection is the flare summary product which provides flare peak irradiances, flare indices, and peak times.

A notable change between the GOES 13-15 science-quality data and the operational data is that the science XRS irradiances are provided in true physical units of W/m^2, and the flare indices are based on these true irradiances. The operational data prior to GOES-16 had scaling factors applied by SWPC which adjusted the GOES 8–15 irradiances to match those from GOES-7. To go from the scaled operational irradiances to the true irradiances, it was necessary to divide out the SWPC scaling factors of 0.85 (for XRS-A) and 0.7 (for XRS-B). The scaling factors have been removed from the science-quality GOES-8 through -15 data and are not used in any data for the new GOES-R series (GOES 16-through -19).

Because of the SWPC scaling factors in the operational data, flare indices for the operational data were reported as 42% (1.0/0.7) smaller than for the science GOES 13-15 and GOES-R data (e.g., an X2.5 class flare reported operationally for GOES-15 is an X3.6 class flare for the GOES-15 science-quality data and for GOES-16).

3.2 Time

The time variable, $time[secs] = Time[UTC] - base\_time[UTC]$, is an elapsed time in units of "secs since *base_time*" where $base\_time[UTC]$ and was calculated without including leap seconds that occurred since *base_time*. Time stamps can be calculated by the user in Coordinated Universal Time (UTC) as

$$Time[UTC] = base\_time[UTC] + time[secs] + n[secs] \tag{2}$$

where $n = 0$ for a time conversion function which ignores leap seconds (e.g., Python cftime.num2date or netCDF4.num2date) and $n = \textit{number of leap seconds since base\_time}$ 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`.

4 XRS Data Products

The highest resolution (2 or 3-s) irradiance measurements and the other Level 2 (L2) products for XRS are listed in Table 2. The GOES 8-12 data availability is given in Tables 7 and 8. Details of these products can be found in the User's Guide for GOES-R XRS L2 Products at `https://www.ngdc.noaa.gov/stp/satellite/goes-r.html`.

Available plots include high-cadence and one-minute data at monthly, yearly and mission-long durations. The monthly and mission plots show the XRS-A and XRS-B irradiance for each satellite. The yearly plots show the XRS-A and XRS-B irradiance for every satellite that has data in that year. As an example, Figure 4 below shows the 1-minute XRS-B irradiance for the entire mission of each of the GOES 8-12 satellites. The flare class levels are shown on the right y-axis.

Table 2: Summary of XRS Products

Product	Name	Description
high cadence fluxes	irrad	XRS irradiances at a 2-s or 3-s cadence
1-min fluxes	avg1m	XRS irradiances at a 1-min cadence
flare summary[1]	flsum	flare detection flags such as start and peak
flare detection[1,2]	fldet	flare detection status for every minute
daily background[1]	bkd1d	daily X-ray irradiance background
plots	–	monthly and mission-duration plots

[1] Product not yet available for GOES 8-12.
[2] Most users should use the the flare summary instead of the flare detection product. See warning in GOES-R XRS L2 Readme.

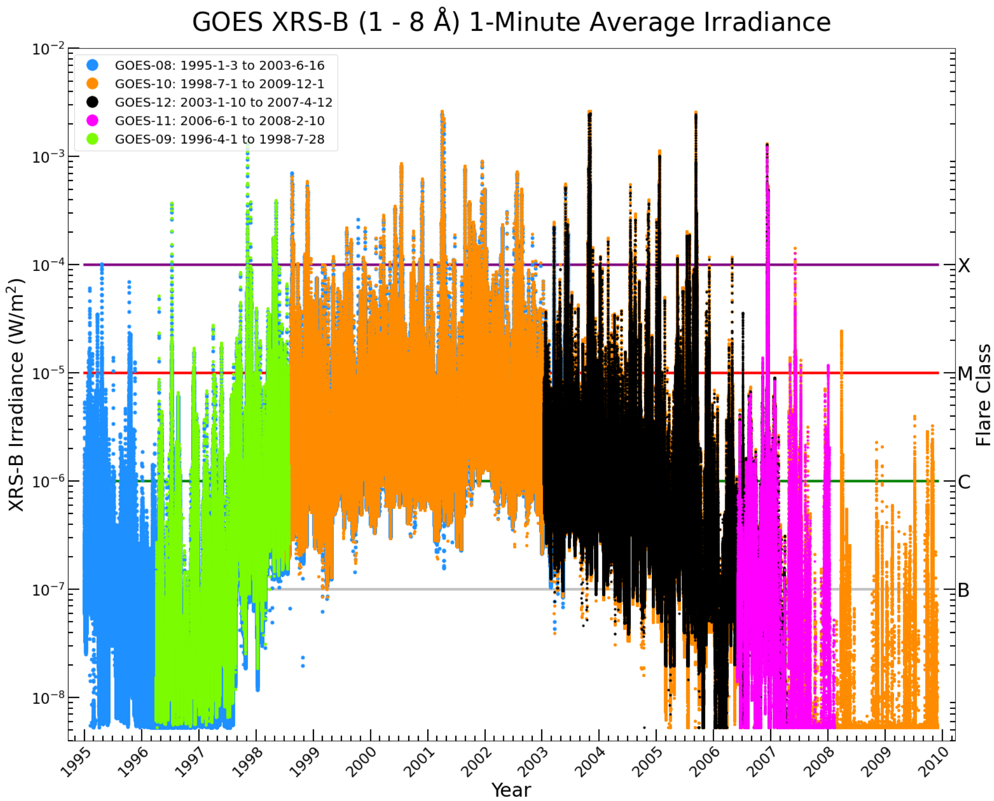

Figure 4: GOES 8-12 XRS-B irradiance.

We note that there are several major differences between the GOES-8 through -15 data and the GOES-R data that will be apparent in the L2 Users Guide.

1. The GOES-R L2 User's Guide lists two products, 1-second irradiances and flare location, that are not available for GOES-8 through -15 data.

2. Flagging for the GOES-8 through -15 L2 data is necessarily slightly different than for GOES-R. Flagging is defined in the netcdf file metadata and discussed in Section 5.

3. The L2 User's Guide mentions additional XRS detectors. GOES-R has two sets of detectors for each channel resulting in XRS-A1, XRS-A2, XRS-B1 and XRS-B2, while earlier satellites have just one detector for each channel, called XRS-A and XRS-B. For GOES-R, the L2 primary detectors for the two channels are identified at each time, and they are named as XRS-A and XRS-B, just as for the earlier satellites.

5 Data Flags

The quality flags are listed for high-cadence irradiances in Table 3 and for 1-minute averaged irradiances in Table 4. Flags that are specific to the science-quality data are described in the following subsections.

Relative to the original SWPC data quality flags, the science-quality GOES 8-15 flags have more complete coverage for eclipses, outages and other events and a reduced number of flags. The SWPC eclipse flag contained just the umbra, but the eclipsed_by_earth flags in the science-quality data include both the penumbra and the umbra. The high cadence data files also include the original SWPC flags for comparison.

It is recommended that software to decode data flags uses the flag mnemonics instead of the bit numbers to examine the data. Python code examples to read flags and netcdf data are given on the NCEI GOES-R webpage at `https://www.ngdc.noaa.gov/stp/satellite/goes-r.html`.

Table 3: Quality Flags for High Cadence Data

Bit #	GOES 8-12	GOES 13-15
0	eclipsed_by_earth	calibration
1	saturation	off_pointed
2	bad_missing_data	eclipsed_by_earth
3	–	eclipsed_by_moon
4	–	eclipsed_by_unknown*
5	–	temperature_recovery
6	–	spike
7	–	unknown_bad_data
8	–	saturated*
9	–	gain_state_change*

* Flag is never set.

Table 4: Quality Flags for 1-Min Averaged Data

Bit #	GOES 8-12	GOES 13-15
0	eclipsed_by_earth	bad_data
1	saturation	eclipsed_by_earth
2	bad_missing_data	temperature_recovery
4	temperature_recovery*	–

* Flag is never set.

5.1 Temperature Recovery Flag

XRS cools during eclipses, resulting in decreasing background counts over the course of the eclipse. After the eclipse ends, the instrument slowly warms back up to its pre-eclipse temperature. Depending on the level of solar activity, this post-eclipse warming may have a major impact on the count rate in which case the temperature recovery flag is set. This flag is never set for GOES 8-12. This is further discussed in Appendix C.

5.2 Spike Flag

Single-point spikes, significantly above the local noise level, are likely due to galactic cosmic rays. The rate of these spikes increases dramatically during solar energetic particle (SEP) events. Spikes in the data are marked with the 'Bad or missing data' flag for GOES-8 through -12 and with the 'Spike' flag for the later data. For GOES-13 through -15 we identify these spikes via a lightly-modified Hampel filter, a type of median filter particularly suited for removing single-point outliers from time-series data with large signal variance such as the XRS data.

5.3 Eclipse Flag

The eclipse flag is set for both full eclipse and penumbra-only eclipse events. The eclipse flag is primarily set during the equinoxes, when the Earth eclipses the satellite's view of the sun. The method for setting the eclipse flag is descrbed in Appendix D.

5.4 Saturation

During the most extreme flare events, the GOES XRS channels can saturate. During the 2003 Halloween storms, on GOES-12, the XRS long channel saturated at 2.46 x 10^{-3} W/m^2 (X17 class flare) and the short channel saturated at 7.95 x 10^{-4} W/m^2. Saturation levels for the GOES 8-12 satellites were similar. The science-quality data has no saturation events for GOES-11 and GOES-13 through -15. Saturation events for GOES-8 through -15 are given in Table 5.

Table 5: Saturation Events for GOES-8 through -15

Start Date	Time	XRS-A	XRS-B
2001-04-02	21:51	GOES-8, -10	GOES-8, -10
2001-04-15	13:48	GOES-8*, -10	
2003-10-28	11:05	GOES-10, -12	GOES-10, -12*
2003-11-04	19:50	GOES-10, -12	GOES-10, -12
2005-09-07	17:37	GOES-10, -12	GOES-10, -12*

* Saturation duration is <2 minutes.

5.5 Bad Data

The bad data flag is set during periods when the counts are zero or near-zero. Such low counts cannot be physical because the counts have a large electronic offset. This flag is also set when there are other unexplained or uncorrectable problems in the data, such as gain changes or instrument calibrations.

6 Data Caveats

The following are known issues with the data.

1. GOES-13 XRS-B scaling: Presumably due to the anomalous mode issues, GOES-13 XRS-B irradiances are 26% lower than GOES-15 when the pre-launch conversion factor, C, is used. Due to the size of this discrepancy, we revised C so that it scales GOES-13 XRS-B to GOES-15 XRS-B for all measurements which overlap in time. For XRS-A it was not necessary to change C from the pre-launch value. Due to the anomalous mode and the XRS-B scaling, we recommend using GOES-13 only as necessary for gap-filling.

2. Electron contamination: XRS is sensitive to background contamination due to energetic electrons. In the future, a correction may be applied to remove this electron contamination.

3. Lunar eclipse flags: The timing of the lunar eclipse flag is sometimes misaligned by up to approximately 15 minutes.

4. XRS-A calibration: There remains a discrepancy in the XRS-A fluxes between the earlier satellites and the GOES-R satellites; the ratio of XRS-A for GOES-16/GOES-15 = 1.34; this at least partly due to slight differences in the detector response functions, but the source of this discrepancy remains under investigation.

5. Digitized data: As described by Simões et al. [Simoes et al., 2015], the digitization of the GOES XRS data is larger than the Poisson noise from photon counting statistics. This can be problematic when differencing or taking derivatives of the flux data. GOES-8 through -12 had three different gain ranges and the digitization is apparent at the edges of these ranges. For GOES-10, the contractor changed the

electronics to reduce the noise level of the XRS which had the unintended consequence of enhancing the digital steps or quantization at low levels for the 1-minute averaged data.

6. Low signal: There are periods of very low signal in the GOES 8-12 3-second data when the irradiance is indistinguishable from the background level except during flares. This is thought to be caused by background levels that were set too high; when the background is subtracted from the measured irradiance, the signal is mostly noise. Because the counts data was not used for reprocessing, this could not be corrected in the science data. The periods affected are:
   GOES-10: XRS-A in June-December 2008 and January-November 2009; XRS-B in April-December 2008 and January-November 2009
   GOES-11: XRSB in March-April 2007, September-December 2007 and January 2008
   GOES-12: XRSB in February-April 2007

7. Missing data for GOES-15 March 2011: This full month of data is missing. For now, if you need data for this month, you will need to use the operational data from `https://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html` and correct it to remove the SWPC scaling factors. To do that, divide the short channel (XRSA) fluxes by 0.85 and divide the long channel (XRSB) fluxes by 0.7. Additionally, the quality flags will not be optimized for this data, and for the high time resolution data, the timing will be a bit off as well, as described in `https://ngdc.noaa.gov/stp/satellite/goes/doc/GOES_XRS_readme.pdf`.

7 Data Access

The reprocessed science-quality GOES-8 through -15 XRS data, responsivity functions, plots, and associated documentation can be accessed from the 'GOES 1–15' tab at `https://www.ngdc.noaa.gov/stp/satellite/goes-r.html`. Daily files are available for all data products, with the exception of daily backgrounds. Mission-length aggregations are available for all data products (except 2- and 3-s fluxes). These mission-length files are located in the main directories for each product. Monthly aggregations of the high-time-resolution fluxes are available for GOES-13 through -15.

The operational data for GOES-1 through -15 is available at `https://www.ngdc.noaa.gov/stp/satellite/goes/` with an associated ReadMe with caveats at `https://www.ngdc.noaa.gov/stp/satellite/goes/doc/GOES_XRS_readme.pdf`

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Frederick A. Hanser and Francis Bach Sellers. Design and calibration of the GOES-8 solar x-ray sensor: the XRS. In Edward R. Washwell, editor, *GOES-8 and Beyond*, volume 2812, pages 344 – 352. International Society for Optics and Photonics, SPIE, 1996. doi: 10.1117/12.254082. URL `https://doi.org/10.1117/12.254082`.

P.J. Simoes, H.S. Hudson, and L. Fletcher. Soft X-ray pulsations in solar flares. *SoPh*, 691, 2015. doi: 10.1007/s11207-015-0691-2.

Appendix A Primary and Secondary GOES Satellites

In general, there have been two operational GOES satellites for each instrument, a primary and a secondary. Primary satellite data should be used over secondary satellite data whenever it is available. There will be gaps in good data for the primary satellites due to eclipses and in-flight calibrations. The satellites for XRS are listed in Table 6. Where the transition time is unknown, the time is marked as '00:00'. Satellites are listed in the table only when there are changes; blanks imply no change in the primary or secondary satellite from the previous line. For the GOES-R (GOES-16 through -19) satellites, the dates in the table refer to when the science-quality data is good, not when the operational data became good.

Table 6: Primary and Secondary GOES Satellites for XRS from 1986 through January 2023

Date and Time	Primary	Secondary
2023-01-04 00:00		18
2018-01-06 00:00		17
2017-02-07 00:00	16	15
2016-06-09 17:30	15	13
2016-05-16 17:00		15
2016-05-12 17:30	14	13
2016-05-03 13:00	13	14
2015-06-09 16:25	15	
2015-05-21 18:00	14	
2015-01-26 16:01		13
2012-11-19 16:31	15	14
2012-10-23 16:00	14	15
2011-09-01 00:00		14
2010-10-28 00:00	15	none
2010-09-01 00:00		15
2009-12-01 00:00	14	
2008-02-10 16:30	10	none
2007-04-12 00:00	11	10
2007-01-01 00:00	10	
2006-06-28 00:00		11
2003-05-15 15:00	12	10
2003-04-08 15:00	10	12
1998-07-27 00:00		10
1995-03-01 00:00	8	7
1994-12-11 00:00		8
1988-01-26 00:00	7	6
1986-01-01 00:00	6	5

Appendix B GOES 8-12 Data Availability

For the GOES 8-12 series, 3-second (high-cadence) and 1-minute (averaged) data is available for each of the satellites. The dates of available data are indicated in the Tables 7 and 8.

Table 7: GOES 8-12* 3-second Data Availability

Year	GOES-8	GOES-10	GOES-11	GOES-12
1995	None	None	None	None
1996	None	None	None	None
1997	None	None	None	None
1998	None	None	None	None
1999	None	None	None	None
2000	None	None	None	None
2001	Mar-Dec	Mar-Dec	None	None
2002	Jan-July	All	None	None
2003	None	Jan-Apr, Aug-Dec	None	Jul-Dec
2004	None	All	None	All
2005	None	All	None	All
2006	None	Jan-Jun	Jul-Dec	All
2007	None	None	Jan-Jun, Aug-Dec	Jan-Apr
2008	None	Mar-Dec	Jan	None
2009	None	Jan-Nov	None	None

* *There is no 3-second data for GOES-9.

Table 8: GOES 8-12 1-Minute Data Availability

Year	GOES-8	GOES-9	GOES-10	GOES-11	GOES-12
1995	All	None	None	None	None
1996	All	Apr-Dec	None	None	None
1997	All	All	None	None	None
1998	All	Jan-Jul	Jul-Dec	None	None
1999	All	None	All	None	None
2000	All	None	All	None	None
2001	All	None	All	None	None
2002	All	None	All	None	None
2003	Jan-Jun	None	All	None	All
2004	None	None	All	None	All
2005	None	None	All	None	All
2006	None	None	All	Jun-Dec	All
2007	None	None	All	All	Jan-Apr
2008	None	None	All	Jan-Feb	None
2009	None	None	All	None	None

Appendix C Temperature Recovery Flag

The temperature recovery flag, used for GOES-13 through -15, is set to indicate where the time period where the XRS counts are decreased after an eclipse period. The relative importance of temperature on counts is determined by comparing the effect of the cooling on the background counts during the eclipse to the counts above the background after XRS has warmed for 70 minutes. This algorithm to set the temperature flag is demonstrated in Figure 5. It should be noted that while these short-term temperature effects caused by eclipses are flagged and left uncorrected, long-term temperature effects are corrected in the background measurements.

An additional minor temperature effect that appears on the ends of many eclipses occurs when an on-board heater tries to partially compensate for the eclipse cooling. The heater often starts too early or stops too late, causing a small increase in the counts on either or both ends of the eclipse. The eclipse flags are set to include these bumps. Figure 6 shows examples of these bumps.

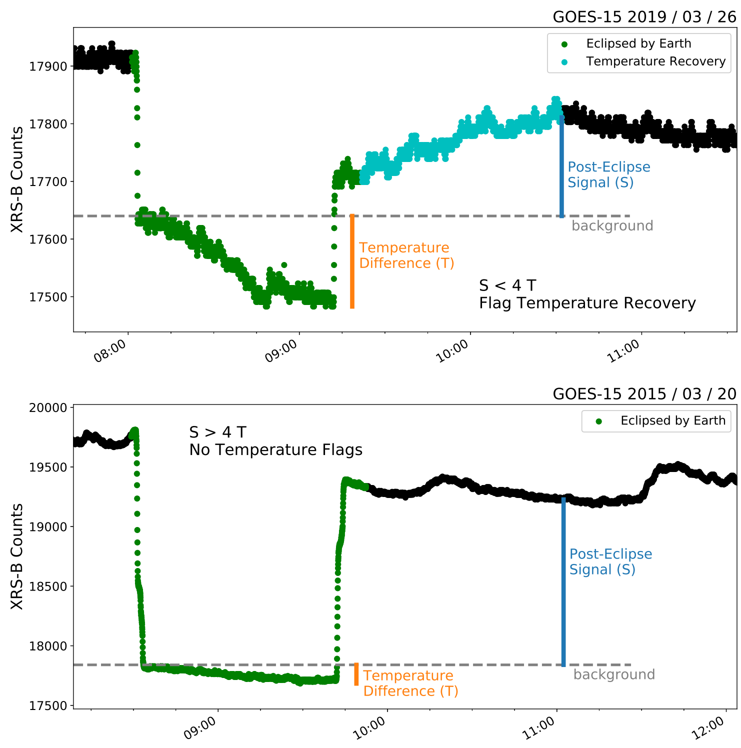

Figure 5: The need to set the temperature recovery flag is determined by comparing the post-eclipse signal to the signal difference due to cooling during the eclipse. If the post-eclipse signal (at 70-mins after the eclipse) is less than four times the counts change during the eclipse, the temperature effects are considered significant, and the recovery period is flagged. The upper plot demonstrates an instance were the temperature effects were significant, and the lower plot demonstrates an instance of when they were unimportant.

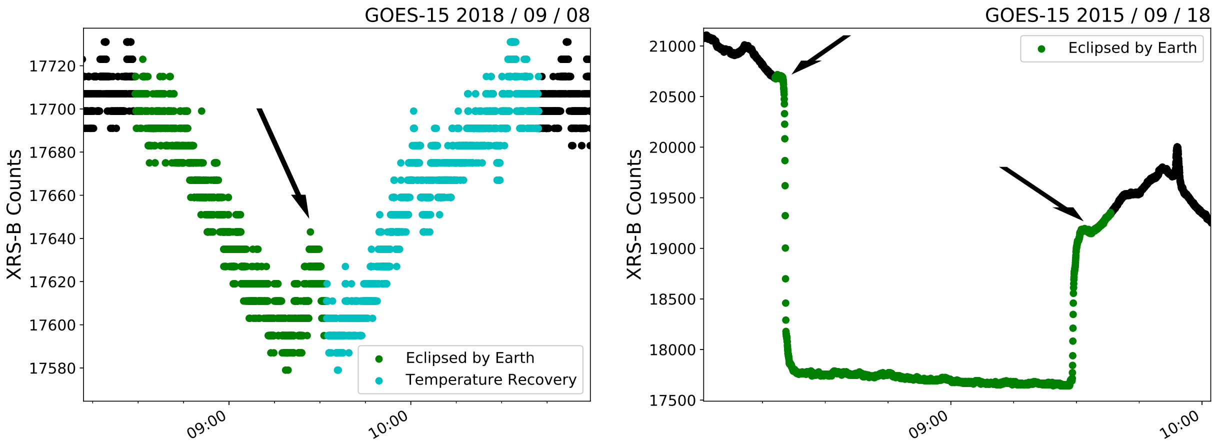

Figure 6: Two examples of bumps (indicated by arrows) in the counts on one or both ends of an eclipse due to overcompensation by the on-board heaters. The left plot shows one of these bumps as an eclipse ends while the Sun is quiet. The right plot shows an eclipse during greater solar activity, with bumps both at the start and end.

Appendix D GOES-8 through -12 3-Second Eclipse Flags

Eclipse flags are set in the science-quality data both when the GOES satellite is in full eclipse (the umbra) where the Sun is entirely blocked by the Earth, and in partial eclipse (the penumbra) before and after the eclipse when the data shows small dips as the spacecraft enters Earth's shadow. Figure 6 shows an example of the flags set in the umbra, and Figure 7 shows an example of the flags set in the penumbra. After 2004, eclipse flags in the science-quality data are based on the SWPC operational eclipse flag, although they were expanded in duration each day to ensure penumbra coverage.

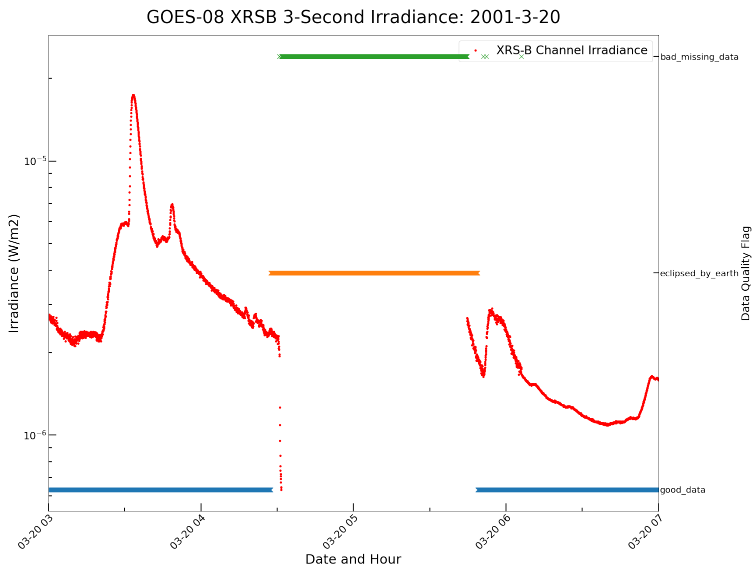

Figure 7: GOES-8 XRS-B irradiance (red dots) on March 20, 2001. Other colors indicate the data quality flag settings as indicated on the right y-axis. The obvious data gap is an eclipse during which the 'Eclipsed by Earth' flag is set.

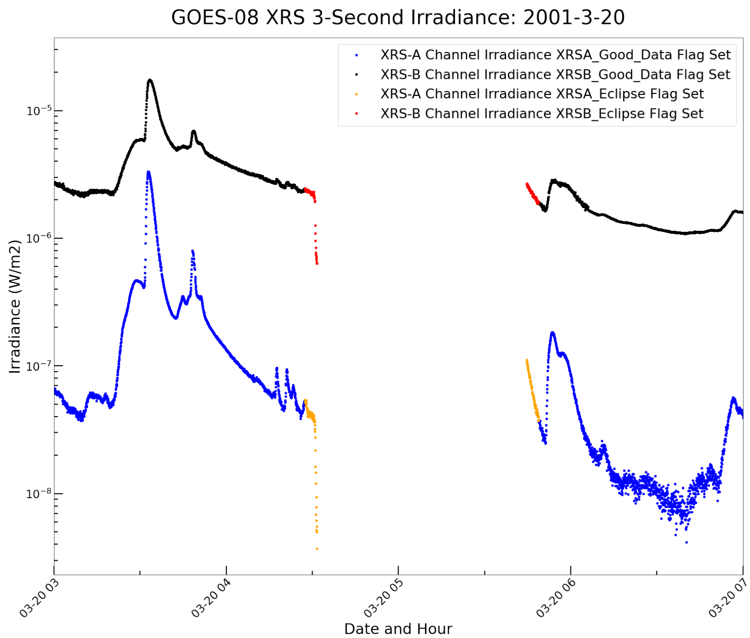

Figure 8: GOES-8 XRS-A and -B irradiances on March 20, 2001. Points when the 'Eclipsed by Earth' flag is set in the penumbra for XRS-A are gold and for XRS-B are red.

The day before the first eclipse and the day after the last eclipse of each eclipse season are "penumbra-only" eclipse days, in which the satellite passes through an eclipse penumbra while the Sun is still visible. For days when this feature is visible in the irradiance as a sharp, isolated dip in signal, the 'Eclipsed by Earth' flag is set in the penumbra. An example of this flagging is shown in Figure 8. No flag is set when the penumbra-only eclipse is not apparent.

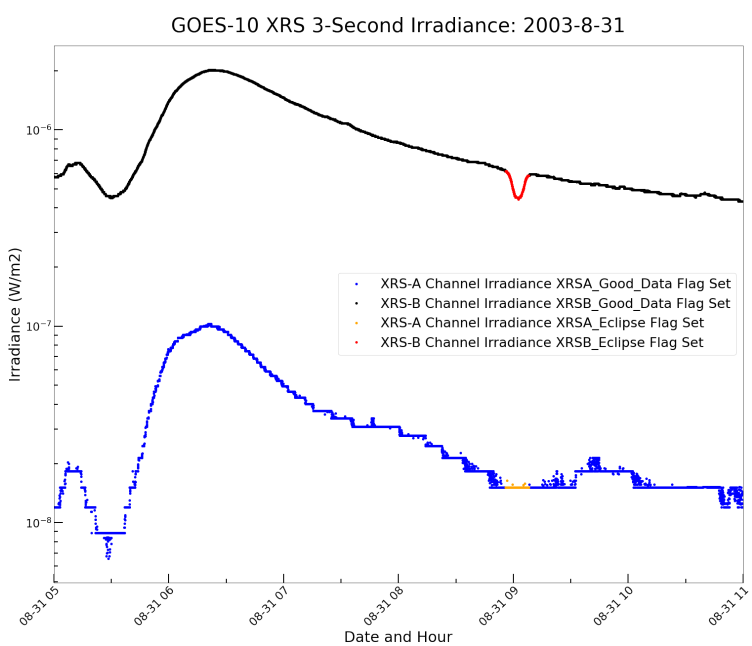

Figure 9: GOES-10 XRS-A and XRS-B data on August 31, 2003. The penumbra-only dip is visible in XRS-B but not XRS-A. Eclipse flags are set at 08:56-09:08 in both channels. This time range is empirically determined. The color-coded points in this plot are the same as in Figure 7.

Prior to the middle of 2004, no SWPC operational eclipse flags were set, so the eclipse flags before this date for GOES-8 through -12 were determined using the method described below.

'Eclipsed by Earth' flags are set in the umbra with the following method:

1. Find the data file timestamp corresponding to GSE local midnight.
2. Set the 'Eclipsed by Earth' and 'Bad or Missing Data' flags where there is reduced or no signal around the local midnight timestamp. There is no valid irradiance data in this time period because the Sun is blocked by the Earth.

On days where there is an eclipse, the data gap is easily identifiable. The length of the gap, and thus the duration of the eclipse umbra, varies during the eclipse season, and is at maximum length on or within a few days of the equinox.

The 3-second data shows consistent, noticeable dips in the irradiance as the spacecraft moves through the eclipse penumbra before and after entering the umbra. The irradiance data in the penumbra is still valid, and must be flagged to indicate it was taken in the penumbra.

'Eclipsed by Earth' flags are set in the penumbra with the following method:

1. Angular size of the Sun on the sky as seen by GOES:
   θ_{Sun} = arctan($Diameter_{Sun}$ / (EarthSunDistance + GOESOrbitDistance))
   = arctan(1,391,000 km / (1.49×10^8 km + 35,786 km))
   = arctan(0.009333)
   = 0.009333 radians (small-angle approximation)
   where GOESOrbitDistance = geosynchronous orbit altitude.
2. Angular size of the Earth on the sky as seen by GOES:
   θ_{Earth} = arctan($Diameter_{Earth}$ / GOESOrbitDistance)
   = arctan(12,732 km / 35,786 km)
   = arctan(0.35578)
   = 0.3418 radians

   In both Steps (1) and (2), the angular size assumes the Earth and Sun are both solid bodies. The solar chromosphere and corona and Earth's atmosphere increase the angular size slightly.
3. As expected, $\theta_{Earth} > \theta_{Sun}$. As GOES orbits Earth in the eclipse seasons, Earth will block the Sun. The penumbra duration is the same as the time it takes for GOES to move the angular size of the Sun on the sky, when the Earth is in front of the Sun.
4. Angular speed of GOES in geosynchronous orbit:
   ω_{GOES} = (2π radians/day) × (1 day / 86,400 s)
   = 0.0000727 rad/s
5. Time for Earth to eclipse the Sun:
   $\Delta_{Penumbra} = \theta_{Sun} / \omega_{GOES}$
   = 0.009333 rad / 0.0000727 rad/s
   = 128.38 s
   This is the duration of the penumbra.
6. Total time in eclipse umbra:
   $\Delta_{Umbra} = \theta_{Earth} / \omega_{GOES}$ = 0.3418 rad / 0.0000727 rad/s
   = 4,702 s / 60 s/minute = 78.3 minutes
   This is within 1-2 minutes of the maximum eclipse duration of the GOES 16-19 satellites, so we can

be confident the method is accurate.

This equation is technically correct only when GOES is in the ecliptic. As the GOES orbit precesses relative to the ecliptic, the umbra and penumbra times will vary. This method also assumes the longest eclipse occurs when GOES is in the ecliptic.

7. The umbra time is accurately calculated at any point in the eclipse season with the umbra method described above. To correctly scale the penumbra duration based on the umbra duration, we assume the time in the penumbra is proportional to the time in the umbra. Then:

   PenumbraDuration = (PenumbraTimeEcliptic / UmbraTime) × PenumbraScaling
   = (128.38 s / UmbraTime) × PenumbraScaling

   UmbraTime is the duration of the of the data gap while the satellite is in the eclipse umbra. PenumbraScaling is a multiplier to ensure the calculated penumbra duration actually includes all data points in the penumbra. This extra scaling is determined by empirical analysis of data on the eclipse days. This adjustment also accounts for at least part of the thickness of the Earth and solar atmospheres. XRS wavelengths are absorbed in Earth's atmosphere, which contributes to the penumbra irradiance dip. The duration of the flagged penumbra may be slightly too large in one or both channels due to the approximations inherent with this method.