As of 10 June 2016

This GOES-R Level 2+ space weather Algorithm Theoretical Basis Document (ATBD) is preliminary and subject to change as the GOES-R Program prepares for a launch in late 2016.

The NOAA National Centers for Environmental Information (NCEI) is currently developing a demonstration version of the Satellite Product Analysis and Distribution Enterprise System (SPADES) which will host the L2+ algorithms. The operational SPADES will be instantiated by the National Weather Service in FY2017 to serve the needs of the Space Weather Prediction Center (SWPC).

Updated versions of the L2+ ATBDs will periodically be made available and posted to the SPADES website.

Bill Denig
NCEI

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NOAA NESDIS CENTER for SATELLITE APPLICATIONS and RESEARCH

GOES-R XRS.09 ALGORITHM THEORETICAL BASIS DOCUMENT
Version 2.0

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TITLE: XRS.09 ALGORITHM THEORETICAL BASIS DOCUMENT VERSION 2.0

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LIST OF ACRONYMS

ATBD	Algorithm Theoretical Basis Document
AWG	Algorithm Working Group
CIRES	Cooperative Institute for Research in Environmental Sciences
LASP	Laboratory for Atmospheric and Space Physics
NGDC	National Geophysical Data Center
SET	Space Environment Technologies
STAR	Center for Satellite Applications and Research
SWPC	Space Weather Prediction Center
XRS	X-ray Sensor

ABSTRACT

This document describes the XRS.09 algorithm that calculates the 0.1-0.8 nm Daily X-ray Background Index, X_{DB}. The logical flow of the algorithm is outlined, including error handling methods, how validation using proxy data sets will be accomplished, and explanations of assumptions.

1.0 INTRODUCTION

1.1 Purpose of This Document

The purpose of this document is to provide product developers, reviewers, and users with a theoretical description (scientific, algorithmic, and mathematical) of the GOES-R XRS.09 Daily X-Ray Background Index algorithm. This document will describe the design and development of the XRS.09 algorithm, which will ingest 1-minute 0.1-0.8 nm X-ray averages, returning a Daily X-Ray Background Index X_{DB}. This document provides the operational requirements for this product and defines how these requirements are met with this algorithm. The algorithm inputs, processing, and outputs are described in enough detail to design, develop, test, and implement the necessary processing software.

1.2 Who Should Use This Document

The members of the Space Weather Forecast Office and the Research and Customer Requirements Section of the SWPC should use this ATBD to verify that their operational requirements are being met by the proposed algorithm. They should also use it to understand the strengths and weaknesses of the algorithm as well as its accuracy and applicability. The STAR AIT group should use this document to integrate the algorithm into their collaborative framework environment. It should also be used by the ground segment contractor to design, develop, test, validate and implement the algorithm into the final operational processing system.

1.3 Inside Each Section

Section 2.0 OBSERVING SYSTEM OVERVIEW:
Describes the GOES-R XRS instrument and the measurements that serve as input to the algorithm.

Section 3.0 ALGORITHM DESCRIPTION:
Describes the development, theory, and mathematics of the XRS.09 algorithm. Describes the logical flow of the algorithm, including input and output flow.

Section 4.0 TEST DATA SETS AND OUTPUTS:
Describes the test data sets used to characterize the performance of the algorithm and the data product quality. Describes the results from the algorithm processing on the input data.

Section 5.0 PRACTICAL CONSIDERATIONS:
Discusses issues involving numerical computation, programming and procedures, quality assessment, diagnostics, and exception handling.

Section 6.0 ASSUMPTIONS AND LIMITATIONS:
Describes assumptions made in the implementation of the calculation of the Daily X-Ray Background Index X_{DB}, and assumptions made in validation, testing, and error handling of the algorithm.

Section 7.0 REFERENCES:
Relevant publications.

1.4 Related Documents

"GOES-R Series Acronym & Glossary Document", DOC/NOAA/NASA (GOES-R Program/Code 417), P417-R-LIST-0142, July 9, 2008.

Nov. 1981 Memorandum from Dave Bouwer to the NOAA Space Environment Laboratory (SEL), describing the derivation of X_{DB}, which was subsequently implemented in operations at NOAA/SEL.

GOES-R XRS.09 Ratio Test Plan and Results, Version 1.0, 2010.

1.5 Revision History

Version 1.0 Jun. 15, 2010. S. Dave Bouwer, First Draft.
Version 2.0 Sep. 24, 2010. S. Dave Bouwer, Delivery

2.0 OBSERVING SYSTEM OVERVIEW

The GOES 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. The integrated 0.1–0.8 nm irradiance is the definitive metric for solar flare classifications, and is a keystone in SWPC operations.

When a daily background X-ray index is calculated, it can be used to provide forecasters an index to characterize coronal evolution from days to years,

including active region evolution, solar rotation, and solar-cycle variations. Additionally, the relative intensity of an X-ray flare above an estimated background can be used as an index to flare intensities and daily active region activity. Figure 1 below illustrates the GOES-14 one-minute X-ray flux for May 5, 2010. The axis on the right are in units of a modified log of the flux, and the color-coded NOAA-R scale used at NOAA/SWPC to issue forecasts and warnings.

This information is useful for forecasters to alert warnings, and for describing solar variability in subsequent scientific studies to understand the solar physics of the corona and active region evolution.

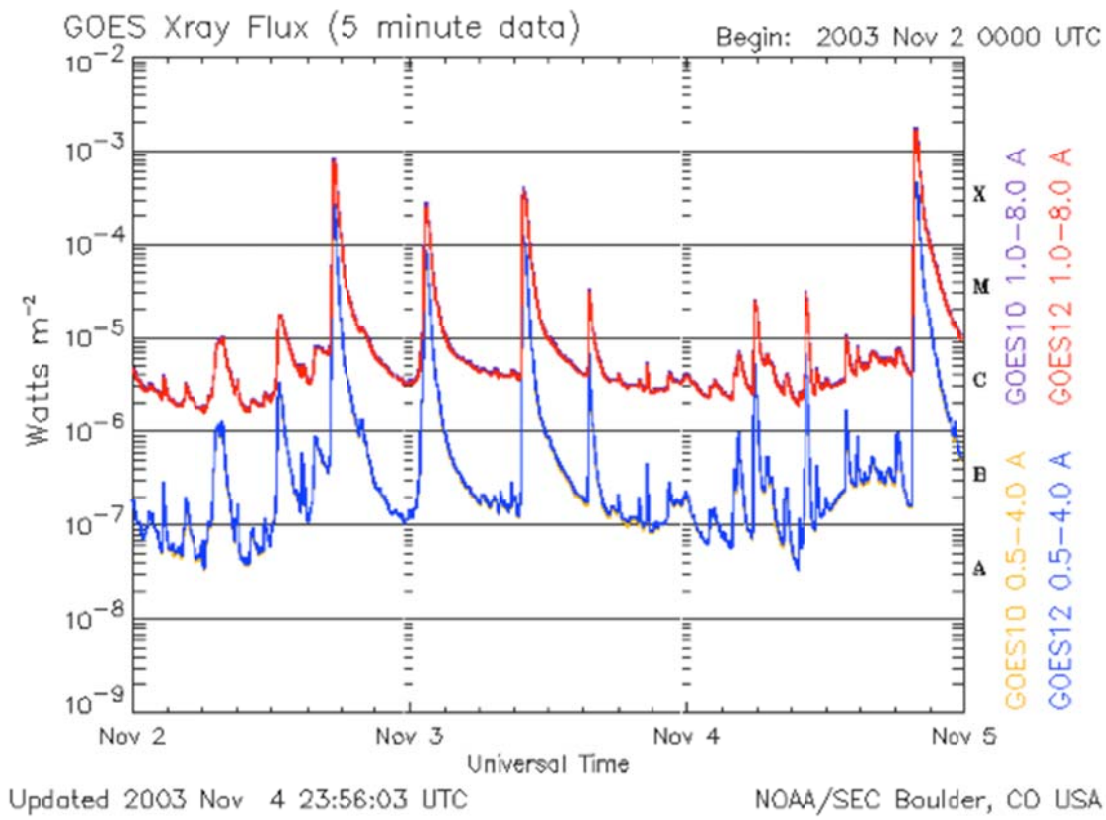

Figure 1. Example the GOES-14 0.1-0.8 1-minute X-ray Flux.

2.1 Product Generated

The XRS.09 algorithm calculates a Daily Background X-ray X_{DB} index from XRS one-minute 0.1 nm to 0.8 nm Flux in units of W/m^2. Because the algorithm has a 35-year legacy, the algorithm is designed to be consistent with the logic from former GOES XRS X_{DB} algorithms originally developed in 1981. Furthermore, information on the verification status for every one-minute X-ray flux value, $X_{1\text{-min}}$, should be included on input to the algorithm to ensure subsequent calculations are correct. However, the X_{DB} algorithm employs a method that ensures a one-minute input average is not used if the one-minute value has a missing value or is out of range, independent of the status flag.

Thus the following data will be included in the XRS.09 Daily X-ray Background product:

Table 1. XRS.09 product data.

Data	Value	Note
X_{DB} status flags	0: missing 1: verified 2: out of range	If X_{DB} cannot be calculated due to missing input data, the status X_{DB} flag is set to 0
X_{DB}	Daily Background X-ray Index, X_{DB}, W/m^2	If X_{DB} cannot be calculated, the missing value flag -99999.0 W/m^2 is used
X_{DB} Time	Julian Day	The corresponding 12:00 UT mid-day X_{DB}

2.2 Instrument Characteristics

Prior to GOES-R, the XRS instrument measured X-ray flux using two bandpass channels from a heritage design employing an ion-chamber. These channels are 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. The ion-chamber design has two limitations: it 'bottom-outs' during low periods of solar activity, and is unable to effectively measure X-ray flux $\Phi < 1.0 \times 10^{-8}$ W/m^2 (approximately), and the instrument becomes saturated during major flares ($\Phi > 1.7 \times 10^{-3}$ W/m^2, approximately).

The primary goal of the re-designed XRS instrument is to continue the XRS measurements in the same spectral channels, while improving on the limitations of the legacy instrument. The new XRS instrument design addresses these limitations, while adding additional capabilities. The changes include using Si photodiodes instead of ionization cells, using multiple channels to allow wider dynamic range, providing quadrant photodiodes for real-time flare location measurements, and improved detailed calibrations using the NIST Synchrotron Ultraviolet Radiation Facility (SURF) in Gaithersburg, Maryland.

The new design will provide irradiance range of more than 6 orders of magnitude by including two photodiode sets covering different portions of the irradiance range for each of the XRS A and B channels, XRS-A1 and XRS-A2, and a similar specification for XRS-B (B1 and B2).

Figure 2 below illustrates the instrument solar diode sensors that measure both the XRS-A and XRS-B channels, in addition to “dark” photodiodes to measure background signal variations, and the configuration of the quadrant photodiodes for flare location determination. The 1-minute averages of the XRS-B channels will be calculated from the Level 1b data product for use in the Daily X-ray Background Index Algorithm.

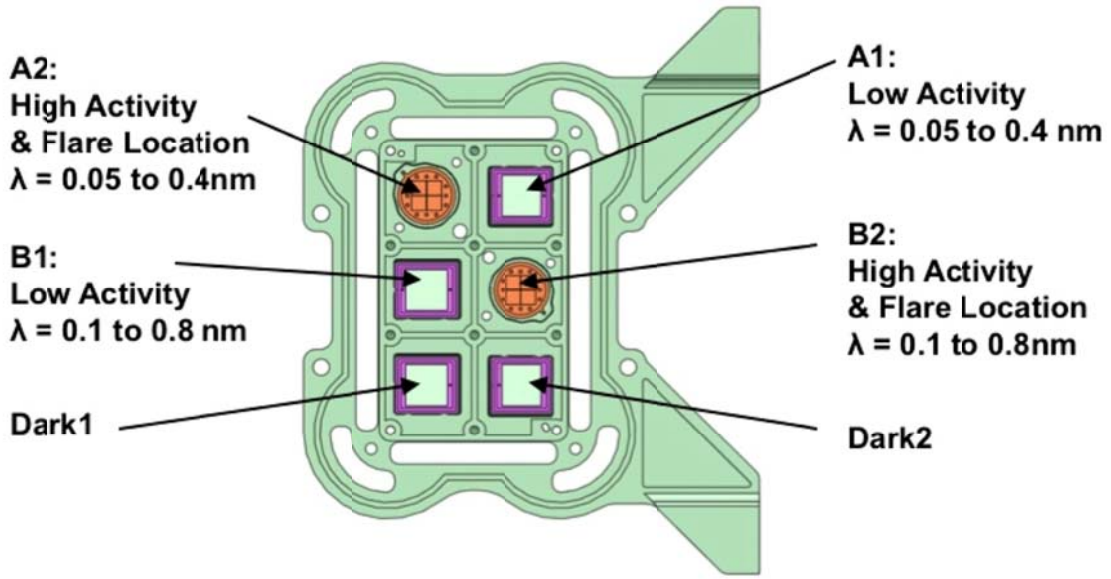

Figure 2. XRS solar diodes configuration.

3.0 ALGORITHM DESCRIPTION

The XRS.09 Daily X-ray Background Index algorithm is, in a sense, a heuristic algorithm based on the minimum of hourly averages of one-minute data. 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., the F10.7 2800-Mhz measurement) could be useful in describing solar active region evolution and the solar cycle.

The XRS.09 Daily X-ray Background Index algorithm will be designed to be robust (i.e., all exception conditions are anticipated and only valid data is passed on), be consistent with the legacy version of the Daily X-Ray Background Index algorithm, and be reasonably computationally efficient.

The algorithm is designed to be a callable routine for increased flexibility and extensibility in final implementation. It is expected it will be run at most once every hour, and will demonstrate no “memory leaks” or other computational exceptions resulting in failure or errors. In other words, the algorithm is designed with a “Trust, but verify” philosophy to ensure maximum fault-tolerance.

The algorithm design is language-independent, easily implemented in Fortran or C/C++. However, the XRS.09 code will be delivered in the Fortran programming language. The XRS.09 algorithm will be compatible with Level 1b software and data.

3.1 Algorithm Overview

The algorithm will be a callable subroutine or object, so it is assumed the caller of the subroutine will provide it input of the historical or near real-time data in data tables or a similar data array structure. Correspondingly, the algorithm will return output data to the caller in a data table or array structure.

The input data are assumed to be in calibrated scientific units of Watts/m^2, which are assumed to come from XRS Level 2 processing algorithms that produce one-minute X-ray flux from the XRS-B (0.1-0.8 nm) channel. The XRS.09 algorithm assumes time values corresponding to the measurement data values are in units of the Julian Day, and that the cadence of data is expected to be monotonically increasing 1,440 one-minute averages, from 00:00 – 23:59 UT.

However, by not binding the algorithm to use only one-minute averages time-tagged with a specific Julian Day or UT hour (e.g., 00:00 - 00:59, 01:00 – 01:59 UT, etc.), using instead the index to each value (0-59, 60-119, etc.), the flexibility of using the algorithm to calculate a “running” background is maintained for possible future use. Consequently, the algorithm that initiates the XRS.09 algorithm has the responsibility to ensure the data array passed to the algorithm is aligned to the desired time range.

3.2 Processing Outline

Figure 3 below presents a flowchart outlining the sequence of operations, consistent with the current algorithm at SWPC. Briefly, the sequence of operations is:

1. Calculate hourly averages from XRS 0.1-0.8 nm one-minute data, (using the data in W/m2 units, calculating an average only if the hour has 1 or more verified non-missing one-minute data),
2. Divide 24 hourly averages into three equal “bins” of 8 hours: e.g., 00-07, 08-15, and 16-23,
3. Calculate the minimum hourly average for each bin,
4. Perform a simple linear interpolation between the minima of the outside bins for an interpolated minimum halfway (in time) between the outside minima (i.e., 00-07, 16-23 UT),
5. Select the lower minimum from either the middle bin (e.g., 08-15) or the interpolated minimum from the outside bins (e.g., 00-07, 16-23), whichever is lower. This selected mid-day minimum is defined as the Daily Background X-ray flux X_{DB},
6. If the middle bin has no data, select the hourly minimum from the interpolated minimum.
7. When either the first or third bin is missing data, select the minimum from one of the two remaining bins hourly minima,
8. If only one bin has sufficient data, use its minimum.

The Daily X-ray Background X_{DB} will have a missing-value flag (a data value equal to -99999.0) substituted for a data value in the event of an exception. This is done to maintain consistency with existing GOES X-ray data products at SWPC. In addition, X_{DB}, and a X_{DB} status flag will be sent back to the caller, and which will have one of three values:

- 0: X_{DB} is missing
- 1: X_{DB} is verified (neither missing or out-of-range)

- 2: X_{DB} exceeds min/max boundaries

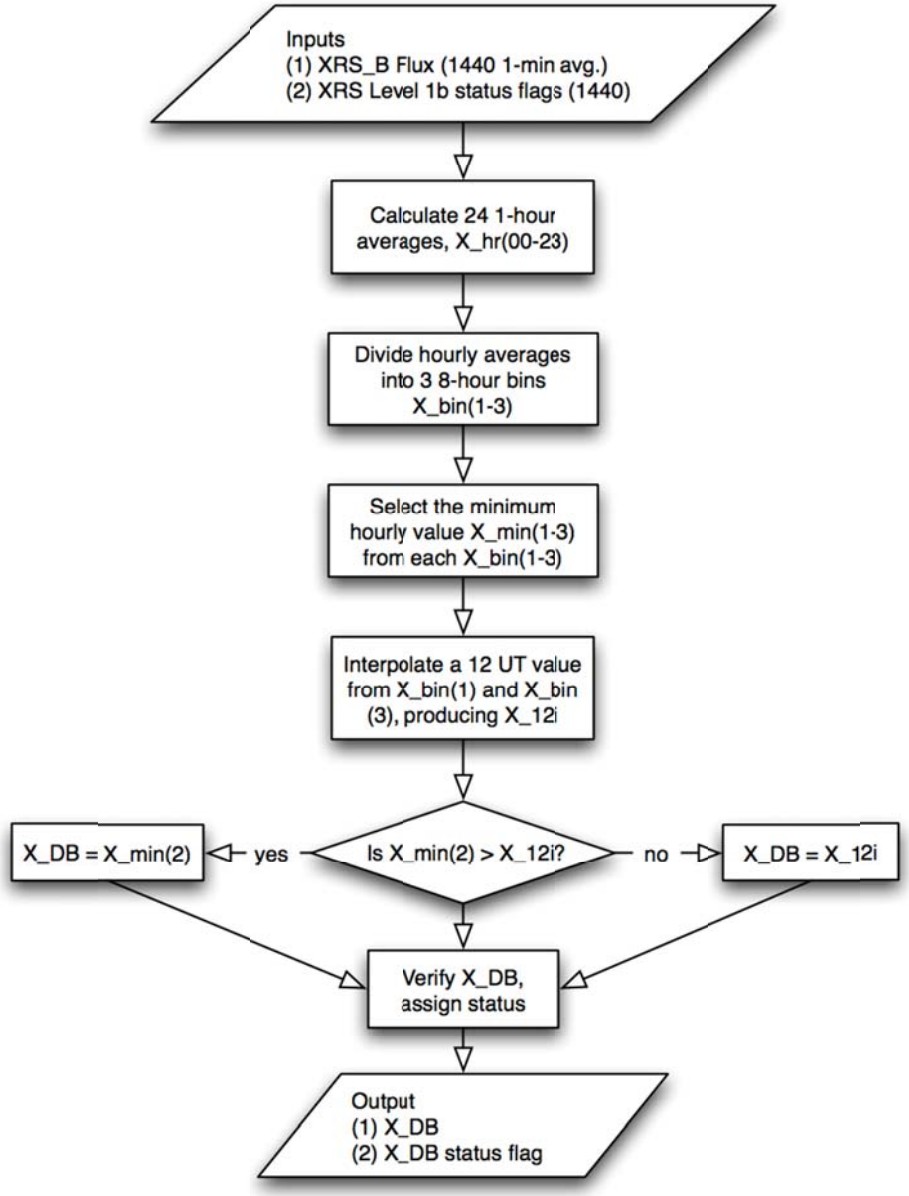

Figure 3. XRS.09 Algorithm Flowchart Overview.

3.3 Algorithm Input

- Data:

- XRS_B_{1min} = 1,140 one-minute averages of the integrated spectrum from 0.1 nm to 0.8 nm, in calibrated science units
- Timestamp of XRS_B_{1min} values, in Julian Days (1,140 values)

- Level 1b Metadata:
  - XRS 0.1-0.8 nm 1-minute average verification status flag (0 missing, 1 verified, 2 out-of-range.)
  - The maximum valid X-ray and minimum a valid X_{DB} value
  - Designated missing-data flag (i.e., -99999.0 W/m^2)

3.3.1 Primary Sensor Data

GOES-R XRS has six channels (Chamberlin et al., 2009): XRS-A1 & XRS-B1 are larger Si diodes to measure low X-ray flux, and XRS-A2 & XRS-B2 are smaller, quadrant Si diodes to measure high X-ray flux, and to also provide approximate flare location on the solar disk. The 'A' channels measure the integrated 0.05-0.4 nm X-ray flux, and the 'B' channels measure the integrated 0.1-0.8 nm flux. Level 1b software will be calculating XRS-B irradiances from the two XRS-B1 and XRS-B2 channels for use by the XRS.09 algorithm.

3.3.2 Ancillary Data

The XRS.09 ratio algorithm is a low-level subroutine that simply calculates a single X-ray daily background index using one-minute X-ray flux averages from Level 1b data sources. There are no relevant ancillary data.

3.4 Theoretical Description

The calculation of the XRS.09 Daily X-ray Background X_{DB} is straightforward: only hourly averages are calculated and selected, and subsequently used to estimate a daily background. The algorithm will be a stand-alone subroutine other software can execute.

The Daily X-ray Background Index is, however, only an approximation because there is no related spatial information of active regions and flares or any other emission properties considered in the calculation. It is a heuristic legacy index developed in 1981 – better methods are now available for determining coronal background irradiances – but nonetheless, it has proven to be useful when applied in long-term correlations with other solar indices and in providing some

approximation needed for describing relative flare emissions above the background. Thus, consistency of the XRS.09 X_{DB} algorithm with the legacy algorithm implemented in 1981 is needed for long-term data comparisons (Bouwer, 1982).

At this time, there is not a well-defined framework software environment to base the algorithm on. In lieu of a framework, a “wrapper” program will be written to simulate a framework. Furthermore, a number of assumptions will necessarily be made due to incomplete performance requirements.

3.4.1 Physics of the Problem

Solar X-rays have two dominant characteristics: A slowly-varying total-disk background component (on the order of days to months) primarily due to active region evolution, and relatively brief rapidly-varying flare component (on the order of seconds to hours), which is often orders of magnitude greater than the background.

To describe the long-term coronal variations on time scales from weeks to years, approximating the daily background X-ray flux provides an index to solar-cycle coronal variations and allows a more meaningful comparison to other daily indices (e.g., F10.7), compared to using the mean daily X-ray flux, which includes the emissions from flares. By estimating coronal variations without the flare component, the relative coronal emissions from dominant active regions can better be described on timescales of weeks to months. Operators and researchers can apply the slowly-varying background X-ray flux and the emissions above the background in understanding ionospheric processes due to D-region ionoization outside of flare events, for example. For time series analysis, weighing the background to a 12 UT value provides a small improvement in accuracy with respect to time.

3.4.2 Mathematical Description

The algorithm will first examine the Level 1b quality flags, included as part of the metadata input to the subroutine, to verify the valid range of 1-minute flux measurements.

The first calculation of X_{DB} is to calculate an hourly average for each hour between 00-23 UT:

$$\Phi_{hourly_avg} = \frac{\sum_{t=0}^{59} \Phi_t \cdot W_t}{\sum_{t=0}^{59} W_t}$$

Equation 1. Hourly X-ray Flux average.

Next, the algorithm creates 3 bins of 8-hours each. It then calculates an average value of the minimums from bins 1 and 3. Finally, the lowest minimum from the middle bin or the average minimum is selected for the Daily X-ray Background Index X_{DB}. In the equations below, X_j represents the hourly average of 1-minute X-ray flux values.

$$X_{\min 1} = \min(X_{j\ =\ 0,7})$$
$$X_{\min 2} = \min(X_{j\ =\ 8,15})$$
$$X_{\min 3} = \min(X_{j\ =\ 16,23})$$
$$X_{\min 1-3_avg} = \left(X_{\min 1} + X_{\min 3}\right) \div 2$$
$$X_{DB} = \min(X_{\min 2}, X_{\min 1-3_avg})$$

Equation 2. Daily X-ray background intermediate calculations.

From Table 1 of Chamberlin (2009), the minimum XRS-A requirement is 10^{-9} W/m^2, and the maximum XRS-B requirement is 10^{-3} W/m^2. We want max/min boundaries that are beyond the bounds of the instrument to ensure all potentially valid data are included, yet sufficiently close to the boundaries to exclude data that can clearly be classified as erroneous. Currently, the algorithm in use at SWPC sets the minimum valid flux at 1.0 x 10^{-7} W/m^2 (B1) and the maximum valid flux approximately at 1.0 x 10^{-2} W/m^2.

However, given the expected improvements to the GOES-R XRS instrument, and pending any post-launch calibrations, the following max/min boundaries to detect out-of-range data are recommended:

- Minimum valid boundary: 1.0×10^{-12} W/m^2
- Maximum valid boundary: 1.0×10^{-1} W/m^2

These values represent "worst-case" scenarios, i.e., they are set to values that are meant to catch exceptions that can result in unambiguously erroneous calculations. For example, negative or near-zero X-ray flux values will clearly not represent realistic data values, and would result in unstable numerical calculations.

In any case, for maximum algorithm flexibility, the status flags (0, 1, or 2) for each 1-minute X-ray value should be included in the ancillary data to the algorithm by the Level 1b software.

3.4.3 Algorithm Output

1. The Daily X-ray Background Index X_{DB}
2. The X_{DB} status flag (0=missing, 1=verified, 2=out-of-range)
3. The mid-day Julian Day timestamp corresponding to X_{DB}

4.0 TEST DATA SETS AND OUTPUTS

Test data sets will be collected from historical GOES-10 XRS measurements, and compared to historical X_{DB} values, re-calculated by SET from 1-minute historical data during 1986-2006. One-minute test data was retrieved from NGDC (http://spidr.ngdc.noaa.gov/spidr/) for re-calculating X_{DB} in long-term test cases, and from SWPC (http://www.swpc.noaa.gov/ftpdir/indices/old_indices/) for verification of selected test cases.

In 2003, it was discovered at SWPC that a software bug in their operations resulted in the X-ray background getting calculated from only the first small subset of data at the beginning of the day, resulting in large errors beginning sometime in mid-1980. In the test cases that follow comparing results between the NGDC-based one-minute values and the SWPC Daily X-ray background, the erroneous data instances will be avoided, although it is unclear at this point when the error was corrected at SWPC, or whether all historical data files have been corrected.

4.1 Simulated/Proxy Input Data Sets

A number of scenarios will be addressed by proxy data sets based on historical GOES XRS data, ranging from solar minimum to maximum. Specifically:

1. Solar minimum: determining behavior of the algorithm when data is at or near the lower instrument cutoff.
2. Solar maximum: determining behavior of the algorithm when there are multiple solar flares during a well-defined period of at least one 28-day solar rotation.
3. Simulated missing value conditions: determining behavior of the algorithm when there are large data gaps resulting in 8 or more hours within one or more of the 8-hour data bins.
4. Comparing X_{DB} from the algorithm to existing published SWPC values, when available.

See Figures 4, 5, 7, and 8 which show the available test data to be used for proxy input data sets.

4.2 Output from Simulated/Proxy Inputs Data Sets

The output will be only the Daily X-ray Background Index, and one status flag:

- X_{DB},
- X_{DB} status flag
- Estimated accuracy of X_{DB}

4.2.1 Precisions and Accuracy Estimates

Because X_{DB} is partly derived from a heuristic algorithm without a “truth” value to compare to, a calculation of precision and accuracy can only estimated. A daily error estimate can be used to determine the relative solar flare activity, which could be used to determine the likelihood a daily X_{DB} is significantly affected by very active solar conditions (e.g., multiple large flares within a day).

However, an error X_{DB} of will necessarily be biased to over-estimating the background, especially when there are multiple flares during the day.

An approximation of accuracy can be derived from the standard deviation of the hourly averages and using the formula

$$\sigma_{DB} = \sqrt{\sum_{i=0}^{23} (\sigma_i^2)}$$

Equation 3. Estimating X_{DB} accuracy from hourly standard deviations.

Where the standard deviation for each hour, using 1-minute values, employs the equation:

$$\sigma_i = \sqrt{\frac{\sum_{j=0}^{n-1} (x_j - \overline{x})^2}{n}}$$

Equation 4. Estimating hourly standard deviations.

4.2.2 Error Budget

Because the Daily X-ray Background is partially based on a heuristic algorithm (i.e., a minimum of an ensemble of hourly values represent the background just prior to a flare), an estimation of the error can only be approximated.

However, SET has developed a decile-based X-ray background index X_{B10} it employs this index in flare evolution predictions for operations (Bouwer, 2006). Briefly, X_{B10} is also calculated from 24 hourly averages, but it uses the 10th decile value of the 24 hourly values within a 24-hour time period, instead of using minimums of 8-hour bins. The X_{B10} value approximates the most likely lowest-limit background, and almost always falls below X_{DB}. The atypical exceptions are during solar minimum when there are very low flux levels, when there are large blocks of missing data, or when a large long-duration flare occurs. X_{DB} will always fall below X_{daily_mean}. The error budget can be estimated from comparisons between the X_{B10} and X_{DB} daily values.

$$X_{B10} \leq X_{DB} \leq X_{daily_mean}$$

Equation 5. X_{DB} relationship to X_{B10} and X_{daily_mean}.

An example is provided below in Figure 4, showing how X_{DB} (solid line) compares to X_{B10} (dot-dash line) and the X_{daily_mean} (dashed line). Showing X_{daily_mean} aids in visualizing how the backgrounds significantly reduce the effects of solar flares, but X_{daily_mean} is not used in error estimates.

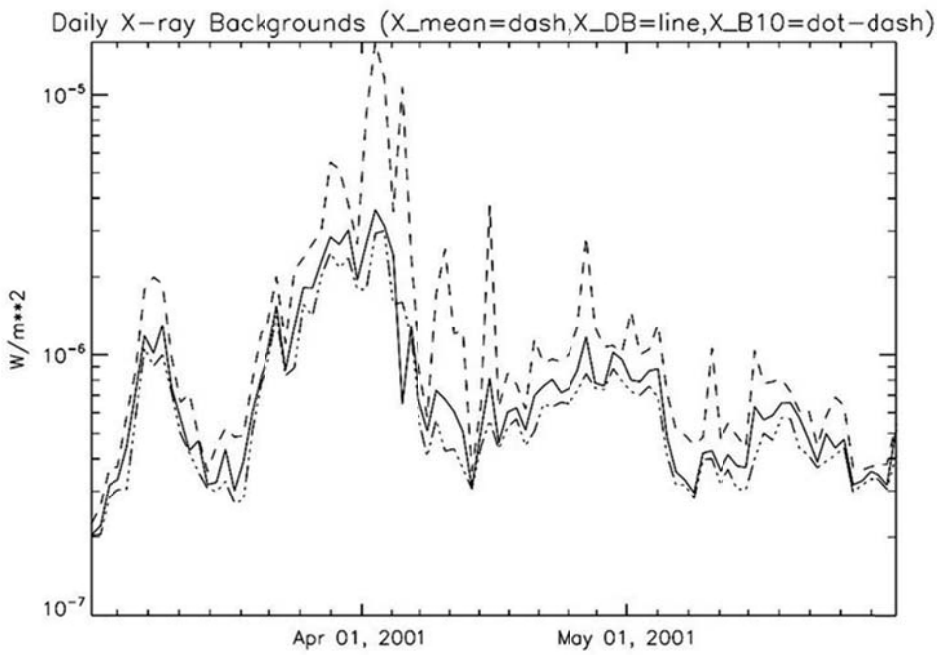

Figure 4. Daily backgrounds example at solar maximum.

The X_{daily_mean} is calculated from:

$$X_{daily_mean} = \frac{\sum_{t=1}^{1440} \Phi_{t,j} \cdot W_j}{\sum_{j=0}^{1440} W_j}$$

Equation 6. Calculation of X_{daily_mean}.

Long time series of X_{DB} and X_{B10} allows us to estimate the bias of X_{DB} with respect to the minimum expected background values. The weights, W_j are equal to one except when the daily background values are flagged as missing or out-of-range, in which case it is zero.

The relative error of the X_{DB} bias, using daily X_{DB} and X_{B10} values, employs the equation:

$$X_{DB}RE = \frac{\sum_{i=0}^{n-1}\left(X_{DB,i} - X_{B10,i}\right)}{X_{B10,i}}$$

Equation 7. Estimating X_{DB} bias relative error.

In Figure 5 below, the X_{B10} (panel a), X_{DB} (panel b), the absolute bias of X_{DB} - X_{B10} (panel c), and the relative error of the bias from 1986 to 2006 (panel d) is shown. The relative differences appear to be uncorrelated with the solar cycle, but increase during lower solar activity due to lower count rates and greater uncertainty. This is shown in Figure 6, which shows the scatter diagram of these estimates. The relative error of the bias has a correlation coefficient of -0.13%, suggesting the bias is uncorrelated with the solar cycle.

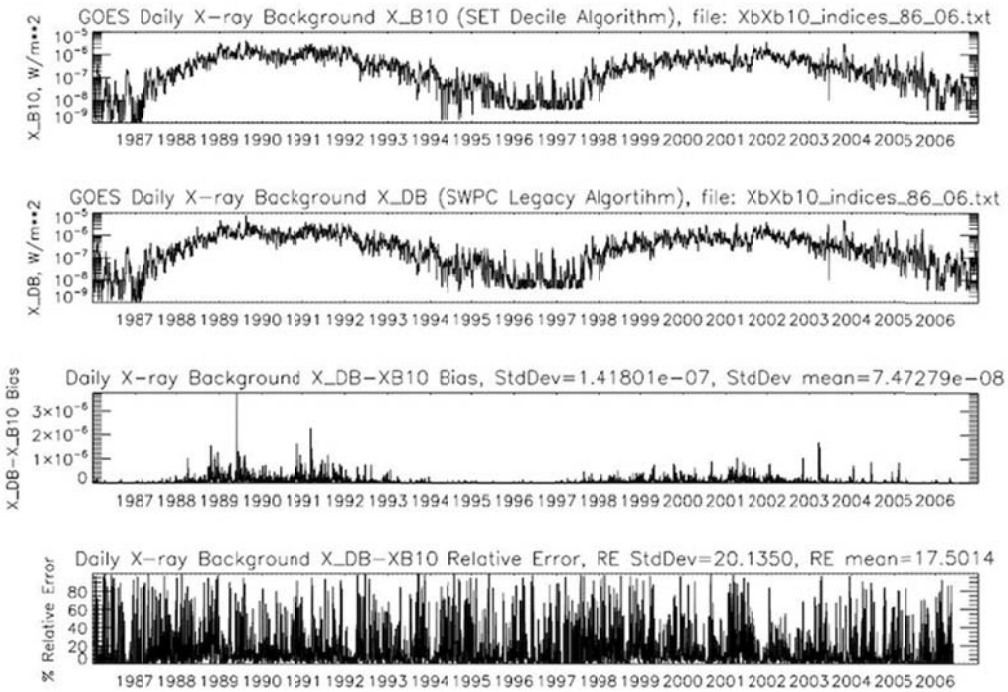

Figure 5. Daily backgrounds X_{DB}, XB_{10}, the $X_{DB} – X_{B10}$ bias, and relative errors for 1986-2006.

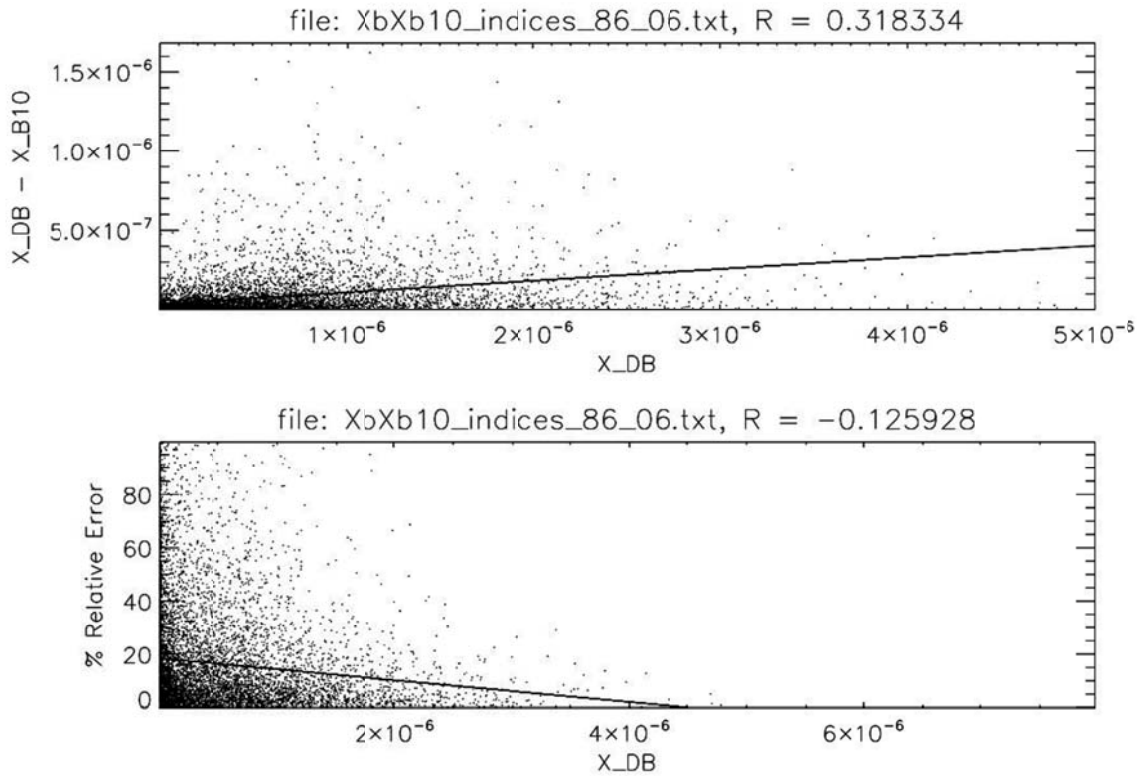

Figure 6. Scatter of Daily backgrounds X_{DB}, X_{B10}, and the relative error of the bias, 1986-2006.

However, the reason for the lack of correlation is partly because that during the solar minimums, the X-ray flux reaches the lower cutoff limit of the XRS instrument and result in low count rates and greater uncertainty. An improved correlation between X_{DB} and X_{B10} can be demonstrated by comparing an ensemble of daily background indices only during moderate-to-high solar cycle time periods; Figure 7 and 8 show this, where an increased correlation coefficient R = 0.75 is attained. Figure 7 shows the background indices during 1988-1993, and Figure 8 shows the background indices during 1999-2004, Figures 9 and 10 show the associated scatter diagrams.

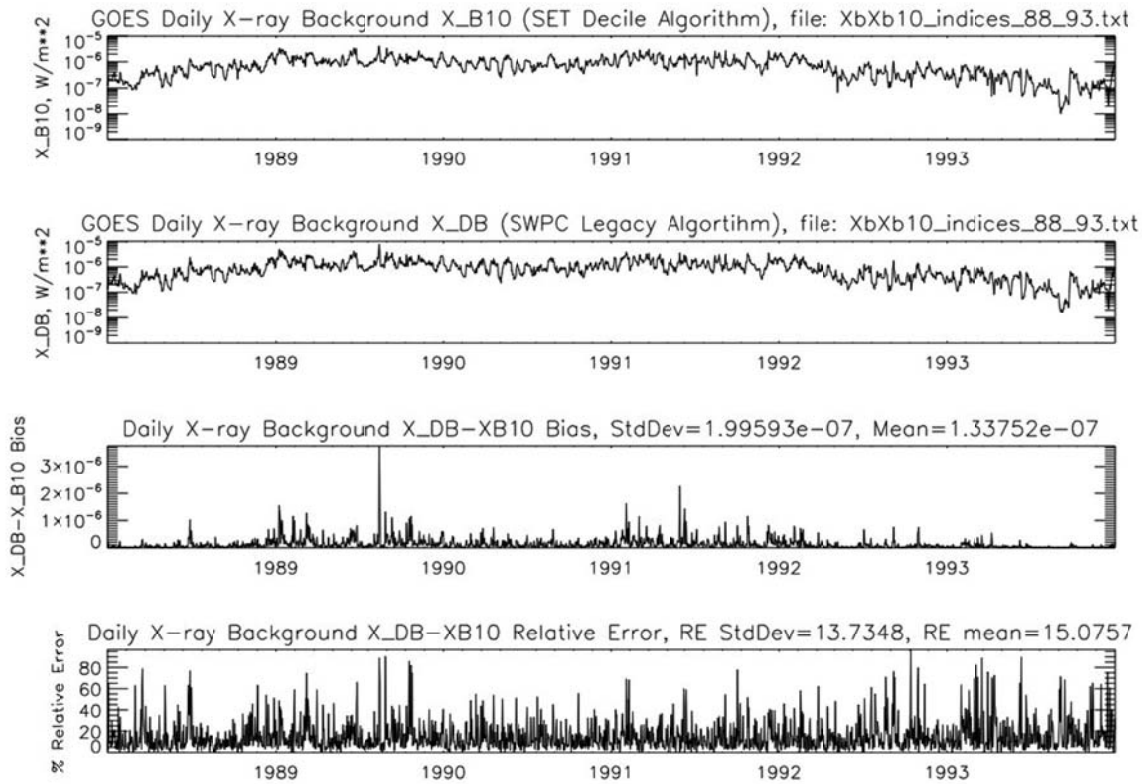

Figure 7. Daily backgrounds X_{DB}, X_{B10}, the X_{DB} – XB_{10} bias, and relative errors for 1988-1993.

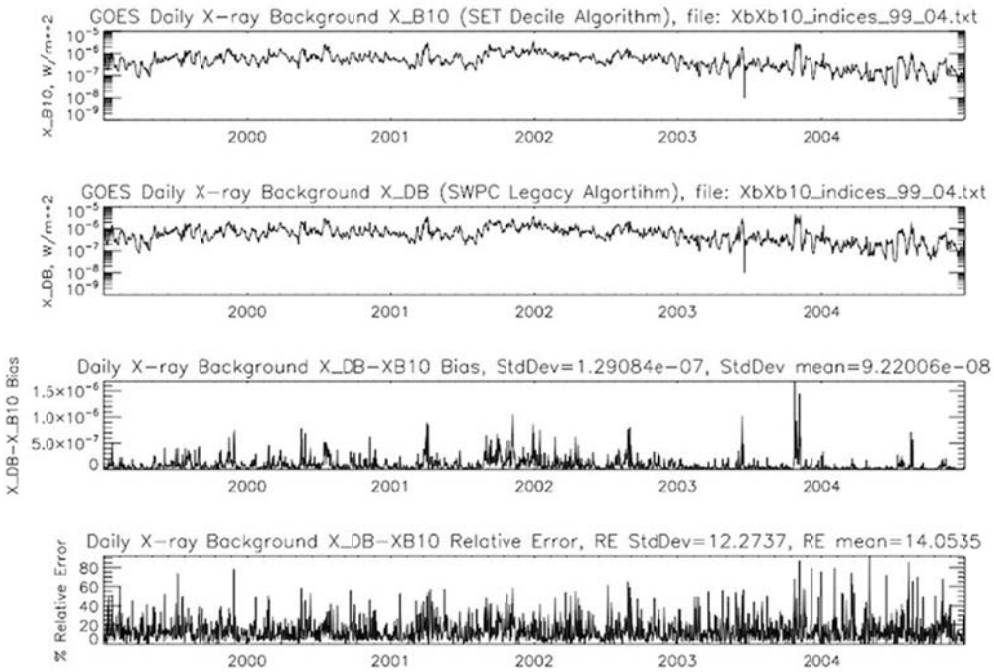

Figure 8. Daily backgrounds X_{DB}, X_{B10}, the $X_{DB} – X_{B10}$ bias, and relative errors for 1999-2004.

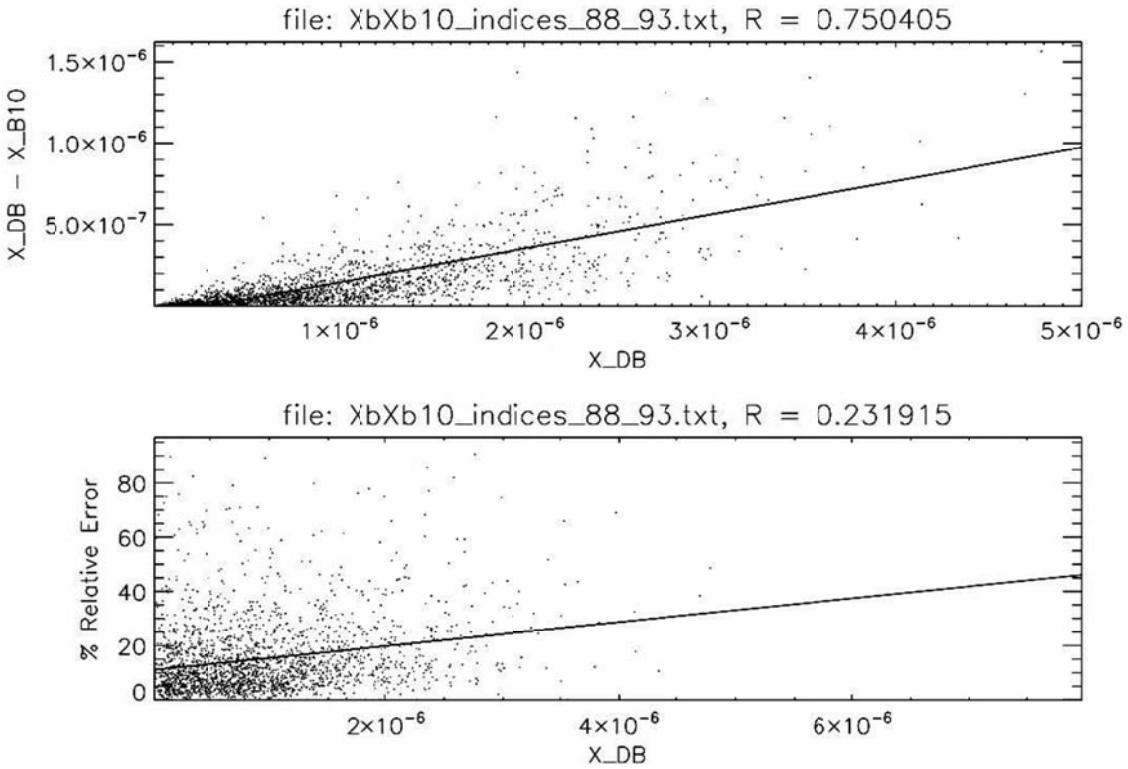

Figure 9. Scatter of Daily backgrounds X_{DB}, X_{B10}, and the relative error of the bias, 1988-1993.

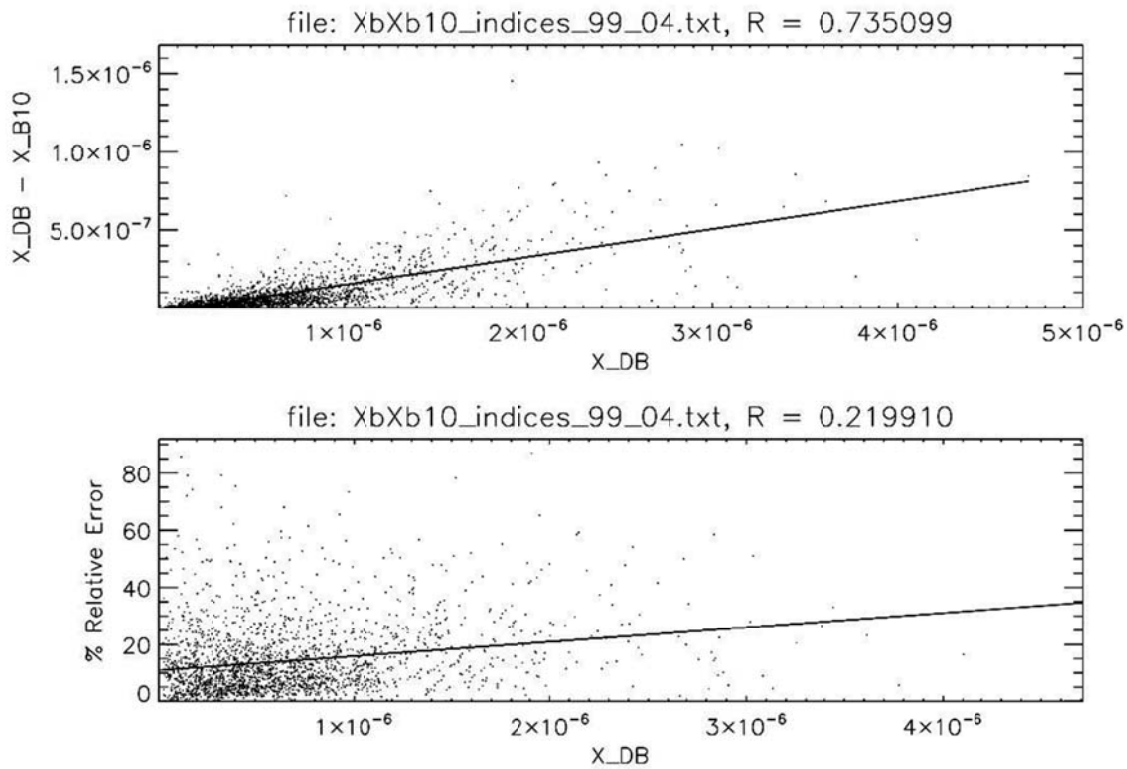

Figure 10. Scatter of Daily backgrounds X_{DB}, X_{B10}, and the relative error of the bias, 1999-2004.

Figures 7-10 clarify the absolute and relative bias errors of the X_{DB} and X_{B10} indices. The standard deviation of the bias ranges from 1.3 x 10^{-7} to 2.0 x 10^{-7}, and this reflects the accuracy of X_{DB}. The correlation coefficient of the absolute bias with respect to X_{DB} is 0.74-0.75 for both cases, and the relative error of both cases averages 14.1%-15.1%. It can be shown that if the time series are de-trended to remove the solar cycle, the results are the same.

Another way to visualize the solar-cycle dependence is to calculate the ratio X_{DB}/X_{B10} and smoothing the data with an 81-day boxcar window. Figure 11 shows the results of this with the 1998-2005 time period. In Figure 11, X_{B10} (top panel a), X_{DB} (panel b), the 81-day smoothed X_{B10} (panel c), the 81-day smoothed X_{DB} (panel d), the X_{DB}/X_{B10} ratio (panel e), and the 81-day smoothed X_{DB}/X_{B10} ratio (bottom panel f) are shown. There does seem to be a solar-cycle dependence in panel f, but it is exceedingly small: on the order of 10 x 10^{-12}, and thus statistically insignificant. Using Equation 7, the mean relative error is 14.3%.

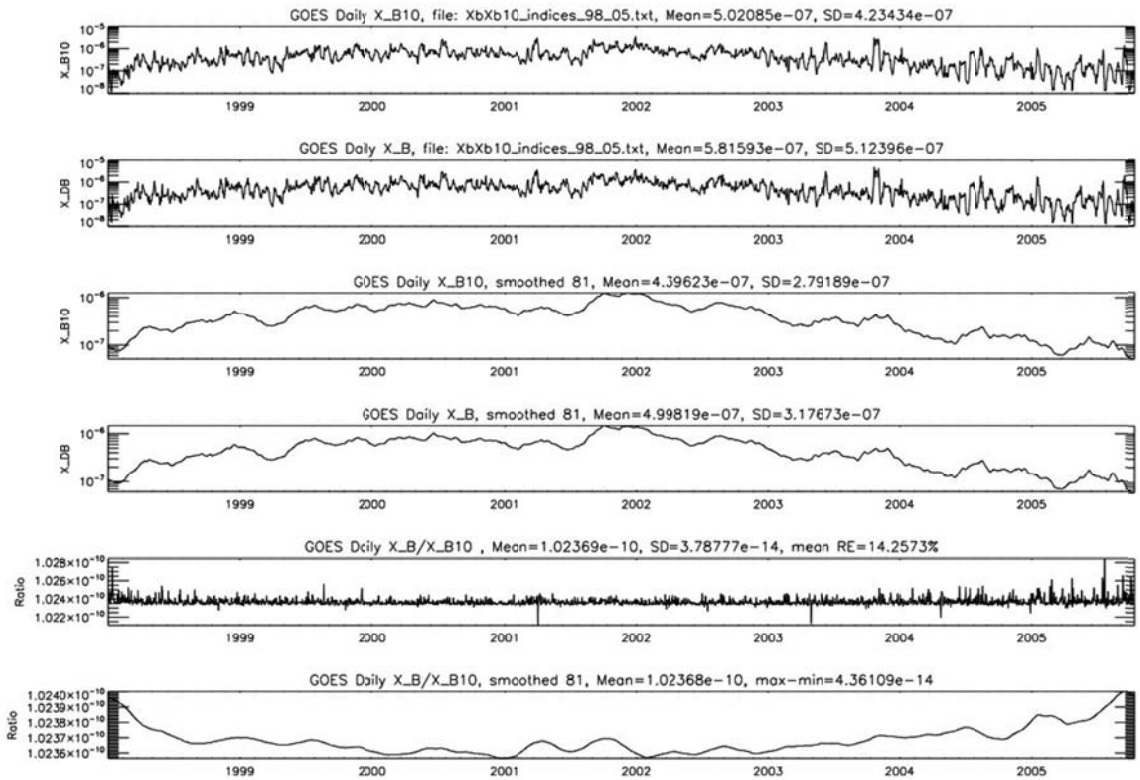

Figure 6. Smoothed daily backgrounds X_{DB}, X_{B10}, and the X_{DB} / X_{B10} ratio, 1998-2005.

The error becomes larger when the X-ray flux reaches the lowest limit of the XRS instrument, but the GOES-R XRS instrument is expected to significantly increase the dynamic range at low flux levels. As a result of this analysis, the best estimate of the relative error of the bias is 15%, based on the mean relative errors ranging from 14.1 to 15.1% (see Figures 7,8,11).

Table 2. Error budget estimates.

Components	**Error Estimate**
XRS-B (0.1-0.8 nm) accuracy	Maximum of 10% (1-sigma standard deviation, per Chamberlin, 2006)
X_{DB} accuracy	2.0 x 10^{-7} W/m^2 mean bias
X_{DB} relative error	15% mean relative error bias

5.0 PRACTICAL CONSIDERATIONS

The only potential change to the XRS.09 algorithm that may be required is if the Level 1b software redefines inputs from what are described in this document.

5.1 Numerical Computation Considerations

The lifecycle of algorithm must be no more than 60 seconds. This is easily achieved. The input data is expected to be at a 1-minute cadence.

5.2 Programming and Procedural Considerations

The XRS.09 algorithm will be written in the Fortran computer language. The algorithm is simple enough that the program logic can easily be re-written in another language such as C/C++.

5.3 Quality Assessment and Diagnostics

The key goals for testing the algorithm are:

- Ensure the algorithm handles any potential exceptions (e.g., missing data)
- Ensure the algorithm performs all calculations within 60 seconds
- The algorithm does not result in a “hung” condition or it does not result in any “memory leaks”
- Ensure the algorithm is consistent with results from the legacy Daily X-ray Background Index algorithm currently implemented at NOAA/SWPC.

These goals can be met by developing a test-bed program that encapsulates the algorithm, reading from data files the simulated input data, then piping the data to the algorithm, and finally retrieving the simulated output data. Test data is from historical archives of GOES XRS one-minute data and compared to historical Daily X-ray Background Indices.

These tests will be performed on a typical Unix computer, with a processor speed of approximately 2 GHz.

5.4 Exception Handling

The algorithm shall trap all exceptions, and in the event much data is missing or out of range and there are insufficient data to calculate a Daily X-ray Background Index X_{DB}.

5.5 Algorithm Validation

The XRS.09 algorithm will be tested with 3 data sets from GOES-10 data archives:

- 30-days of 1-minute data during solar maximum, when there are multiple large flares (e.g., April, 2002).
- 30-days 1-minute data near solar minimum, when the data reaches the lowest cut-off of the instrument (e.g., 1997).
- 30-days of 1-minute data, edited to contain sections where there are large data gaps missing (e.g., 8 hours or more), to verify the algorithm performance when there are missing data.

See Figures 4, 5, 7, and 8 which show the available test data to be used for proxy input data sets

6.0 ASSUMPTIONS AND LIMITATIONS

1. It is assumed that the XRS.09 algorithm inputs will be:
    a. 1,440 XRS-B 1-minute averages, monotonically increasing in time, with missing data flagged with a missing-value flag, i.e., -99999.0.
    b. 1, 440 status flags corresponding to 1,440 XRS-B 1-minute averages (i.e., 0=missing data, 1=verified data, 2=data out-of-range).
    c. The missing-data flag used to flag missing data, i.e., -99999.0,
2. Sufficient data are available to calculate at least 1 hourly average within 1 or more 8-hour “bins”. If not, the following rules are assumed to be sufficient in estimating X_{DB}:
    a. If the middle bin has insufficient data, select the hourly minimum from the interpolated minimum.
    b. When either the first or third bin has insufficient data, select the middle bin minimum.
    c. If only one bin has sufficient data, use its minimum.
3. On days where there is insufficient data available or the majority of flux is below an instrument cut-off (e.g.,1.0×10^{-11} W/m^2), a missing value flag will be substituted for X_{DB} and the X_{DB} status flag will be set to 0.
4. Input data is assumed to be verified prior to input as indicated by the status flag.
    a. For example, during eclipse periods, out-of-range data will be flagged in the status flag as missing or out-of-range on input, and/or the data contains a missing-value flag (e.g., -99999.0).

5. Data at low flux is assumed to have been verified, i.e., Level 1b input data has determined the low instrument cut-off and flagged the data as either missing or out of range.
6. These assumptions need to be verified with a copy of existing SWPC code.

6.1 Performance

The lifecycle of the algorithm (i.e., time to completed calculations from receipt of input to the output of data) shall be less than 60 seconds.

6.2 Assumed Sensor Performance

It is assumed the XRS instrument will operate within design requirements as specified in EXISPORD81 (417-R-EXISPORD-0116, 2008).

6.3 Pre-Planned Product Improvements

The current Daily X-ray background in operations at SWPC does not contain the logic to deal with the instances of large data gaps resulting in 8-hour data bins with all missing values. Per the original Space Environment Center internal memorandum (Bouwer, 1981), the specified algorithm for cases of large data gaps in that document will be included in the algorithm.

7.0 REFERENCES

Chamberlin, P. C., F. G. Eparvier, A. R. Jones, and T. N. Woods, Next Generation X-Ray Sensors (XRS) for the NOAA GOES-R Series Satellites, SPIE Proceedings, in preparation, 2009.

Garcia, H. A., Temperature and emission measure from GOES soft X-ray measurements, Solar Physics, 154, 275, 1994.

Bouwer, S.D, et. al., A Summary of 1-8A Measurements from the SMS and GOES Satellites, 1977-1981, NOAA Tech. Memo. ERL SEL-62, July 1982.

Bouwer, S. Dave, "A Summary of SOLAR 0.1-0.8nm X-ray Measurements From the GOES Satellies,1986-2004", Internal SET report, 2006. http://www.spacewx.com/pdf/SET_TR2006_002.pdf

Woods, T. N., P. C. Chamberlin, W. K. Peterson, R. R. Meier, P. G. Richards, D. J. Strickland, G. Lu, L. Qian, S. C. Solomon, B. A. Iijima, A. J. Mannucci, and B. T. Tsurutani, XUV Photometer System (XPS): Improved irradiance algorithm using CHIANTI spectral models, Solar Physics, 249, doi 10.1007/s11207-008-9196-6, 2008

NASA/GOES-R/Code 417, GOES-R EUVS XRS Irradiance Sensors (EXIS), Performance and Operational Requirements Document (PORD), Document Ref: 417-R-EXISPORD-0116, Vers. 2.3, June 25, 2008.