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.

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NCEI

http://www.ngdc.noaa.gov/stp/space-weather/online-publications/stp_sii/spades/

NOAA NESDIS CENTER for SATELLITE APPLICATIONS and RESEARCH

SUVI CORONAL HOLE IMAGE ALGORITHM THEORETICAL BASIS DOCUMENT

Version 1.0

TITLE: SUVI CORONAL HOLE IMAGE ALGORITHM THEORETICAL BASIS DOCUMENT VERSION 1.0

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SUVI CORONAL HOLE IMAGE ALGORITHM THEORETICAL BASIS DOCUMENT VERSION HISTORY SUMMARY

Version	**Description**	**Revised Sections**	**Date**
1.0	Created by Dr. E. Joshua Rigler CIRES/SWPC	New Document	Jul. 21, 2011

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LIST OF ACRONYMS

AIA	Atmospheric Imaging Array
AIT	Algorithm Integration Team
AT	Application Team
ATBD	Algorithm Theoretical Basis Document
AU	Astronomical Unit (~150,000,000 km)
AWG	Algorithm Working Group
CCD	Charge Coupled Device
CDR	Critical Design Review
CIRES	Cooperative Institute for Research in Environmental Sciences
CME	Coronal Mass Ejection
EIT	EUV Imaging Telescope
EUV	Extreme UltraViolet
GOES-R	Geostationary Orbiting Environmental Satellite – R series
HDR	High Dynamic Range
ICM	Iterated Conditional Modes
L1B	Level 1B (data)
L2	Level 2 (data)
MAP	Maximum *A priori* Probability
ML	Maximum Likelihood
MRD	Mission Requirements Document
NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
POV	Point Of View
SDO	Solar Dynamics Observatory
SEP	Solar Energetic Particle
SOHO	Solar and Heliospheric Observatory
STAR	Center for Satellite Apps and Research
SUVI	Solar Ultra-Violet Imager
SWPC	Space Weather Prediction Center
SWx	Space Weather
SXI	Solar X-ray Imager
TBD	To Be Determined
TBR	To Be Reviewed
XRS	X-ray Sensor

ABSTRACT

The Solar Ultraviolet Imager (SUVI) will provide high cadence images of the solar corona to support Space Weather forecast activities at the Space Weather Prediction Center (NOAA/NWS/NCEP/SWPC). This document provides a comprehensive description of the SUVI Coronal Hole Image algorithm. Coronal Hole images are little more than composites of high dynamic range (HDR) SUVI Composite Images (another L2 SUVI data product) assembled over temporal windows appropriate for studying coronal holes.

HDR Composite Images optimally combine multiple and nearly simultaneous images taken with different exposure times. Ideally, these exposures would be taken near enough in time that corrections for pointing and solar rotation would be unnecessary. However, since this cannot be guaranteed in general, the HDR Composite Image algorithm included a variety of supplemental algorithms to translate, rotate, and rescale images to a common field of view (FOV), as well as apply transformations that correct for the point of view (POV) of the observer in both time and space. The latter even included a simple model of the sun's latitudinal differential rotation.

The only significant difference between the HDR Composite Images and the Coronal Hole Image product is that the latter are expected to include many more images, taken over a significantly longer baseline. The primary objective in doing this is to reduce pixel noise inside coronal holes, and increase contrast at coronal hole boundaries, thus enhancing their operational value, and their value as an input to downstream products like the SUVI Coronal Hole Boundary generator.

This document provides information to developers and reviewers necessary to verify the algorithm meets operational requirements. In particular, it addresses issues of image registration and navigation, signal-to-noise discontinuities, and integration into observing sequence planning. It also provides, where applicable, traceability to heritage, as well as the design details necessary for development and implementation of the algorithm into operational use. Test and validation procedures are provided along with assumptions and known limitations of the algorithm.

1 INTRODUCTION

The GOES-R Algorithm Working Group (AWG) Space Weather (SWx) Application Team (AT) is responsible for producing the algorithms to generate products using the space environment data from the GOES-R series satellites. These algorithms shall meet operational needs of the NOAA/NWS Space Weather Prediction Center (SWPC) to observe and forecast space weather conditions impacting near-earth systems such as satellites, communications, electrical power grids, manned space missions and many others. They shall also meet the requirements of outside operational and research agencies as agreed. This ATBD provides details on the Solar Ultraviolet Imager (SUVI) Coronal Hole Image algorithm that will inform users of the proposed methods and processes to transform Level-2 GOES-R SUVI Composite Images into low-noise, high-contrast EUV images of the solar corona that are suited for space weather forecasting.

1.1 Purpose of This Document

This ATBD provides details of the GOES-R SUVI Coronal Hole Image algorithm design and processing. Since Coronal Hole Images are little more than long baseline composites, this document is essentially a slightly modified version of the ATBD used to describe the SUVI algorithm that produces composite images of the sun in the extreme ultra-violet spectral range from observed GOES-R satellite data. It provides operational requirements for this product and defines how these requirements will be 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 and storage mechanisms.

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 shall use this ATBD to verify 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 applicability, accuracy, and robustness. The STAR AIT group shall use this document to integrate the algorithm into their collaborative framework environment. It shall also be used by the prime development and implementation 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:

- provides objectives of the SUVI Composite algorithm including the output composite solar images and how they should be used operationally;
- discusses SUVI instrument characteristics and the algorithm approach;

Section 3.0 ALGORITHM DESCRIPTION:

- contains the complete SUVI Composite algorithm description including an outline of the processing, input data and a theoretical description;
- provides estimates of the algorithm performance and output quality;
- reviews the numerical computation, programming and procedural issues and a description of how the algorithm has been validated;

Section 4.0 TEST DATA SETS AND OUTPUTS:

- describes the test data sets used to characterize the performance of the algorithm and output quality, including the breadth of the domain (typical versus stressing states) used in the analysis and assessment;
- discusses the results from algorithm processing on simulated input data;

Section 5.0 PRACTICAL CONSIDERATIONS:

- discusses issues involving numerical computation, programming and procedures, quality assessment and diagnostics and exception handling at a level of detail appropriate for the current algorithm maturity;

Section 6.0 ASSUMPTIONS AND LIMITATIONS:

- describes all assumptions concerning the SUVI Composite algorithm theoretical basis and performance;
- discusses planned product improvements for future enhancements;

Section 7.0 REFERENCES:

- Provides references to all sources cited in the ATBD.

1.4 Related Documents

- GOESR SUVI Coronal Hole Image Test Plan and Results
- GOESR SUVI Coronal Hole Image Implementation and User’s Guide

1.5 Revision History

Revision Number	Date	Author	Revision Description	Reason for Revision

2 OBSERVING SYSTEM OVERVIEW

SUVI Coronal Hole images allow regions of space weather interest on the sun to be studied in great detail, and will be used by the SWPC Forecast Office to identify and forecast effects of solar activity, especially those related to solar coronal holes. SUVI Coronal Hole Images are simply SUVI Composite Images that include more than a single long-short exposure pair of images. The SUVI Composite Image algorithm was recursive by design, and can easily add multiple L1b images together into a single composite image, or even combine L2 HDR composites if appropriate metadata is provided. The remainder of this section is simply taken *ver batim* for the ATBD for the SUVI Composite Image algorithm.

2.1 Product Generated

The SUVI Composite Image Algorithm will combine multiple nearly simultaneous exposures from each SUVI spectral channel in a manner that generates a much higher dynamic range image of the sun than any single exposure, while also minimizing image noise due to low photon counts and/or pixel saturation. Figure 1 provides an example of a composite image derived from a GOES-13 Solar X-ray Imager (SXI) long/short exposure set.

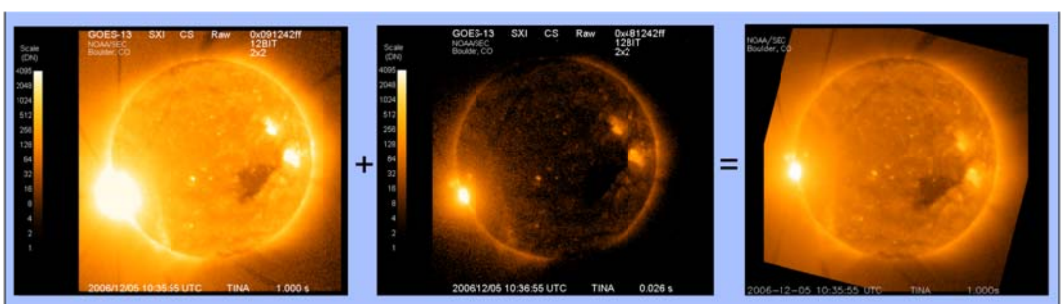


Figure 1 GOES-13 SXI Composite Image
In this example, the final image is generated by combining long (1.0s) and short (0.026s) exposure GOES-13 SXI images during a flare event, thereby reducing the number of saturated pixels, as well reducing noise in regions with low raw data counts.

2.2 Instrument Characteristics

The SUVI instrument operational requirements are detailed in section 3.4.2.4 of the GOES-R Series Mission Requirements Document (MRD) Version 3.0 dated February 2007. The algorithm relies on spectral, spatial and temporal data and tests. The performance of the Composite Image algorithm is therefore sensitive to any imagery artifacts, instrument noise, pointing errors or timing errors. Well-calibrated observations are critical because the SUVI Composite Image algorithm scales observed values from two (or more) dramatically different integration times to counts per second. Inaccuracies in calibration or CCD response function linearity will result in substantial errors in the Composite Image product.

Individual SUVI channel specifications are given in the MRD section 3.4.2.4.0-4 and repeated below for ease of reference, along with the expected nominal sampling interval, and an example of the type of EUV feature that will be studied using each channel. The SWx Algorithm Team assumes the instrument meets the performance outlined in this section of the ATBD during development efforts.

Table 1 SUVI L1b image spectral channels

Channel	**Sampling**	**Wavelength**	**Sample Use**
SUVI (Fe XVIII)	every 4 min	9.39 nm	Flares (~6x106 °K)
SUVI (Fe XX / Fe XXIII)	every 4 min	13.1 nm	Flares (~10x106 °K) and Hot flares (~15x106 °K)
SUVI (Fe IX)	every 4 min	17.1 nm	Active regions (~6x105 °K)
SUVI (Fe XII / Fe XXIV)	every 4 min	19.5 nm	Active regions (~1x106 °K) and Hot Flares (~20x106 °K)
SUVI (Fe XV)	every 4 min	28.4 nm	Coronal holes (~2x106 °K)
SUVI (He II)	every 4 min	30.4 nm	Filaments (~6x104 °K)

3 ALGORITHM DESCRIPTION

As noted previously, the SUVI Coronal Hole image algorithm is not really a new algorithm at all, but simply a variation of the SUVI Composite Image algorithm that combines many L1b or L2 images into a longer baseline composite image that is better suited for coronal hole analysis. This section is mostly lifted from the SUVI Composite Image ATBD, with one or two slight modifications.

3.1 Algorithm Overview

The SUVI composite image algorithm combines multiple, nearly simultaneous, Level 1B images of the solar disk into a single high dynamic range (HDR) image using a weighted averaging scheme that deemphasizes pixels whose counts either fall below a specified ‘noise floor’, or are saturated in regions of extreme brightness. Each composite image will be derived from at least one ‘short’ and one ‘long’ exposure, although additional exposures may be processed to further increase dynamic range and/or reduce noise that arises from both instrumental and non-instrumental sources.

3.2 Processing Outline

The steps required for the proper construction of a composite image are:

1. Process input parameters:
    a. desired ‘wavelength’, or unique identifier to match channel;
    b. minimum observation date to include in a composite image;
    c. maximum observation date to include in a composite image;
2. Read metadata from the most recent L1b or L2 input image:
    a. retrieve observation date;
    b. retrieve unique identifier for SUVI channel;
3. Proceed if the observation date of the image file is between the minimum and maximum desired observation dates passed to the algorithm; else write current composite image and exit;
4. Proceed if the unique channel identifier in the L1b file matches the desired ‘wavelength’ passed to the algorithm; else return to step 2;
5. Read whole image array;
6. Assign weights as function of calibrated counts (i.e., the product of the pixel value and exposure time):
7. Align image’s 2D field of view (FOV) with the FOV of the latest exposure yet included in the current composite image;
8. Align image’s 3D point of view (POV) with the POV of the latest exposure yet included in the current composite image;
9. Merge L1b or L2 image with current composite image using a weighted average of their pixel values;
10. Return to step 2

The process flow is depicted graphically in Figure 2.

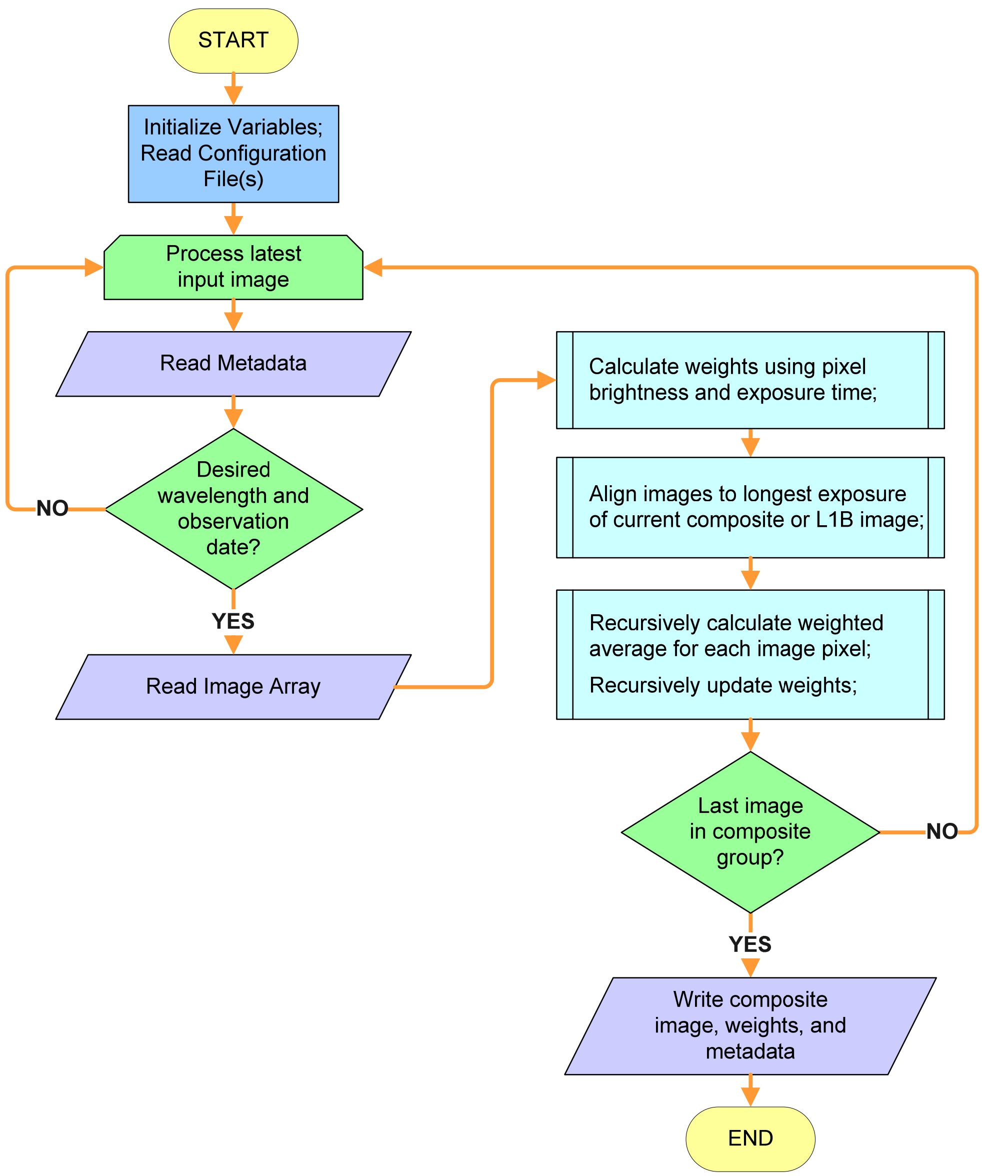


Figure 2 High-level Process Flow of SUVI Composite Image Algorithm
This flow diagram details the accumulation of individual SUVI images (left side), then pixel weight assignment, alignment, and compositing (right side).

3.3 Algorithm Input

3.3.1 Primary Sensor Data

The SUVI Coronal Hole Image algorithm assumes that each SUVI L1B or L2 image file contains an 'image' of floating point numbers that describe either photon flux, energy flux, or some other form of calibrated counts normalized by exposure time and pixel area. In addition to the array of pixel values, other information is required to group similar input images, calculate weights, and properly align the image's 2D FOV and 3D POV. The minimum set of these data are listed in Table 2. If inputs are L2 SUVI Composite Images instead, the minimum set of data and metadata are described in Table 3.

Table 2. SUVI L1b inputs to Composite Image algorithm

Name	Description	TYPE (Dimension)
Date/Time	Image date and time tags (e.g. YYYY,MM,DD,hh,mm,ss.sss)	CHAR(1) or Integer(7)
Channel/Filter	Identifier for channel/filter combo	CHAR (1)
Exposure Time	Total exposure duration	REAL (1)
Pixels	L1B Image pixel value	REAL (n_x, n_y)
Pixel Flags	L1B Pixel flags	INTEGER (n_x, n_y)
DC_{pix}	X & Y pixel coordinates of solar disk center	REAL (2)
Δ_{pix}	Pseudo-angle describing a pixel's plate scale in the X & Y directions	REAL (2)
P_0	Position angle between solar north and image Y-axis	REAL (1)
L_0	Carrington longitude of Earth	REAL (1)
ϕ_0	Stonyhurst longitude of SUVI (0 if SUVI and Earth are co-located)	REAL (1)
B_0	Heliographic latitude of SUVI	REAL (1)
D_S	Distance from sun center to SUVI	REAL (1)

3.3.2 Ancillary Data

Ancillary data are assumed to be data that are not generated on-orbit by SUVI or the spacecraft. The only ancillary data required by the SUVI Composite Image algorithm consists of count nodes that define the inflection points of a “hat” function that describes pixel weights as a function of calibrated counts. This is necessary for the weighted average portion of the algorithm. A default set of node values may be hard-coded into the algorithm, but more than likely these count nodes would not be appropriate for all SUVI channels, or all the time. This approach, including the classification of weighting function count nodes as ancillary data, may change as the ground system design matures.

3.4 Theoretical Description

If multiple similar solar disk images are well aligned with one another in both time and space, they can be combined with one another to produce an average image whose pixel value uncertainty is less than any single image pixel value. If the only difference in the component images is their respective exposure times, it is also possible to apply a weighting function that deemphasizes pixels corrupted by either low-count statistics, or saturation, both inherent limitations to charge-coupled detector (CCD) technology.

3.4.1 Physics of the Problem

The dynamic range of a scene is the ratio of highest to lowest photon flux, or some other measure of intensity. Given a fixed cross section, fixed instrument optics, geometries, and filters, and finally, the fact that a CCD’s fidelity, or ability to differentiate between different intensity levels, is essentially fixed upon its manufacture, there are limits to how much of a scene’s dynamic range can be recorded in a single image.

An imaging device like SUVI must rely almost entirely on its ability to adjust the duration of exposures in order to maximize the number of pixels that contain useful information (i.e., pixels that are neither saturated, nor do the number of incident photons fall below the inherent noise floor of the CCD). However, while a longer exposure ensures that low-intensity regions in a scene are sampled enough for the signal to rise above the inherent noise floor, it may lead to pixel saturation in parts of the scene that are already very bright. On the other hand, while a shorter exposure reduces the number of pixels that saturate, it may leave dimmer regions in a scene corrupted by instrument noise. In other words, the dynamic range of the scene can exceed the dynamic range of the instrument. This is often the case when viewing the sun in EUV wavelengths.

One solution is to combine multiple images, adjusted to a common FOV and POV, with the same set of filters in place, but with different exposure times. Combining raw counts from differently exposed pixels serves little purpose by itself, since this would be like averaging apples and oranges. However, if the number of counts per pixel is divided by the image's exposure time, a rate of photon deposition on the CCD is generated. For exposure times measured in seconds, this provides an effective count per pixel as if all of the images' exposure times were exactly one second. Now, with apples to compare to apples, it is perfectly reasonable to combine different images.

3.4.2 Mathematical Description

The simplest form of composite image involves replacing "bad" pixels from one image with good pixels from the same coordinates in another image. For example, replacing pixels flagged as saturated in a long exposure, with non-saturated pixels from a shorter exposure. This tends to result in image artifacts near the boundaries between good and bad pixels.

Another approach is to simply average two images. This reduces the artifacts, or noise, but does not take into account the fact that some pixel values are simply more reliable than others, and should influence the final composite image more. A measure of confidence, or weight, can be associated with each pixel in an image though, and a weighted average of pixel values can be constructed that deemphasizes noisier pixels when constructing the composite.

Weighted Average Pixel Values:

Because 1) it is not guaranteed that all L1b images destined to be merged into a single composite will be made available at once, and 2) there are other SUVI L2+ products that benefit from the ability to generate composites of composites, this weighted average is implemented somewhat generally, and recursively. This requires that each composite image store the total number of images that have been merged into it thus far. Assigning this value a label k for the first composite, a label l for the second composite, and defining pixel values as X_i and pixel weights as w_i, where the pixel index is i, allows composites of composites to be formed using (3.1).

$$\overline{X}_i = \frac{k \times w_{k,i} \times X_{k,i} + l \times w_{l,i} \times X_{l,i}}{k \times w_{k,i} + l \times w_{l,i}}$$
$$\overline{w}_i = \frac{k \times w_{k,i} + l \times w_{l,i}}{k + l} \qquad (3.1)$$

If $\overline{X}_i$ and $\overline{w}_i$ are saved as each L1b image is processed in sequence, and each L1b image is treated as a composite of 1 (i.e., l =1), composite images can be built up recursively.

Pixel Weighting Function:

A binary weighting function (i.e., 0 or 1) is too course, and would likely generate image artifacts in those regions of the composite image surrounding bad pixels from one of the component images. A simple 'hat' function might be used, and is indeed the suggested default when channel-specific, or even time-dependent, weighting function parameters are not provided. The weighting function as implemented is the flexible, generalized 'hat' function presented in (3.2).

$$w_i = \begin{cases} \max\left(w(C_i, C_{\min}, C_{\text{mid1}}, C_{\text{mid2}}, C_{\max}), w_{\min}\right) & \text{for } \mathrm{C_i} \neq \text{"bad"} \\ 0 & \text{for } \mathrm{C_i} = \text{"bad"} \end{cases} \quad (3.2)$$

C_i is the calibrated count of each pixel in the image. $C_{\min}$ represents the noise floor in calibrated counts. C_{mid1} marks the beginning of a sweet spot in the instrument response, while C_{mid2} marks the end. Finally, $C_{\max}$ represents the number of counts associated with pixel saturation. This function maximizes at the largest floating point number possible less than 1 between C_{mid1} and C_{mid2}, and assigns any calibrated count below $C_{\min}$ or above $C_{\max}$ a minimum weight equal to one minus the maximum weight. If C_i falls between these extremes (i.e., $C_{\min} \rightarrow C_{\text{mid1}}$ or $C_{\text{mid2}} \rightarrow C_{\max}$), the weighting function interpolates between the minimum weight and maximum weight appropriately. Any actual 'bad' pixels receive a weight of zero.

Field of View Image Alignment:

Pointing knowledge of instruments is typically much more reliable than the ability to actually control exactly where the instrument is pointed. This is particularly true for SUVI, since it is mounted on an observation platform whose primary function is not solar viewing, but rather Earth viewing. This pointing knowledge is encoded into each SUVI image, and should be used to align images before they are merged into composites. There are essentially two kinds of alignment we are concerned with: 1) field of view (FOV), which relates to the orientation between the target and the imager's focal plane; and 2) the point of view (POV), which relates to the location of the imager in a target-centered coordinate system. Techniques for dealing with the first are described in this subsection, while the second is addressed in the following subsection.

To start, the center of each pixel must be assigned a floating point Cartesian coordinate. The actual coordinate system is not important, but we choose one in which the image center is the coordinate system origin, or {0,0}, in order to simplify things. Image rotation, translation, and scaling are most efficiently performed using matrix operations. This requires that the coordinates of each pixel be stored as a column vector in the following format:

$$\mathbf{P} \equiv \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{3.3}$$

The reason for this special format becomes clear when one considers the forms potential 2D transformation matrices will take:

$$\mathbf{R} \equiv \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \mathbf{T} \equiv \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \quad \mathbf{S} \equiv \begin{bmatrix} s_x & 0 & 0 \\ 0 & s_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.4}$$

A position vector must be pre-multiplied by the associated transformation matrix. The matrix **R** rotates a point θ radians about the origin in the counter-clockwise direction. The matrix **T** translates, or shifts, the position of a point by t_x in the x direction, and by t_y in the y direction. Finally, the matrix **S** multiplies a point's position by s_x in the x direction, and s_y in the y direction, effectively rescaling the entire image.

If more than one operation needs to be performed on each pixel location (e.g., the image must be rotated by the angle θ, followed by a translation { t_x, t_y }), the associative property of matrix multiplication makes it possible to multiply transformation matrices together to produce a single transformation that can be applied to the pixel location vectors just once.

Matrix multiplication is not, however, commutative, so individual transformations must be multiplied by one another in the same order they would be performed separately (i.e., $\mathbf{P}' = \mathbf{T} \times \mathbf{P}$, $\mathbf{P}'' = \mathbf{R} \times \mathbf{P}'$, is the same as $\mathbf{P}''=(\mathbf{T} \times \mathbf{R}) \times \mathbf{P}$). For example, to rotate the image by the angle θ, followed by the translation { t_x, t_y }, we generate a new transformation matrix **A**:

$$\mathbf{A} \equiv \mathbf{T} \times \mathbf{R} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & t_x \\ \sin\theta & \cos\theta & t_y \\ 0 & 0 & 1 \end{bmatrix} \quad (3.5)$$

At this point, it is important to note that we have been discussing the rotation, translation, and rescaling of pixel coordinates themselves, but in reality it is the pixel coordinate frame that must be transformed before 2D interpolation can be used to resample the original image and create the required transformed image for subsequent operations. This means we must apply the inverse of our coordinate transform. To understand this better, consider Figure 3, where the inverse of individual transforms is shown graphically. To rotate an image counter-clockwise, pixel coordinates must be rotated clockwise. To shift an image down and left, pixel coordinates must be shifted up and right. And to expand an image, pixel coordinates must be scaled down. 2D interpolation is then used to generate new pixel values for these coordinates based on the known values at the center of every pixel in the original image.

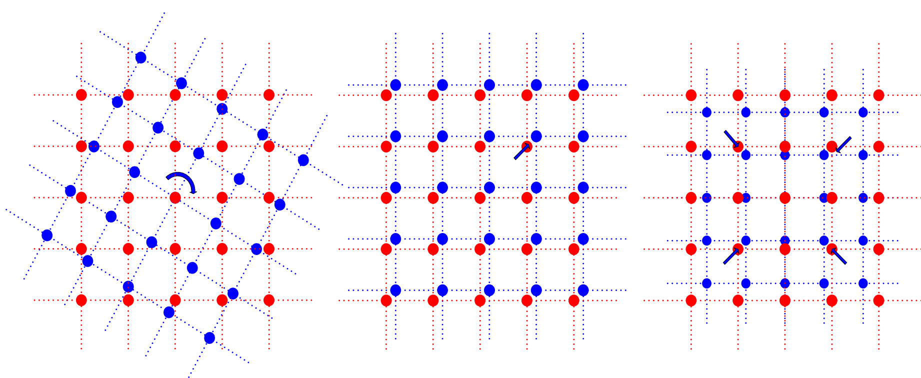
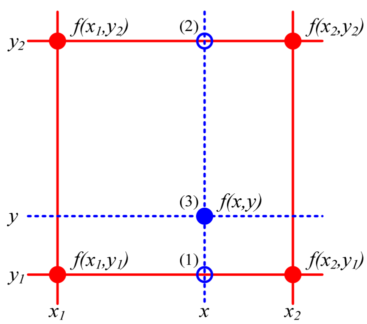


Figure 3 Transforming coordinate systems
The coordinate system of an image array (blue) is rotated by angle $-\theta$ in lieu of an actual image rotation of $+\theta$ (left); the coordinate system translates $\{+t_x,+t_y\}$ to achieve image translation of $\{-t_x,-t_y\}$ (middle); the coordinate system is scaled by $\{1/s_x,1/s_y\}$ to scale the image by $\{s_x,s_y\}$ (right). In all cases, the original image pixels remain on a fixed, rectangular grid to facilitate interpolation.

Bilinear interpolation is conceptually simple: 1) interpolate linearly to a desired x coordinate that falls between two known values with the same y coordinate; 2) interpolate linearly to the same desired x coordinate between two values with a different y coordinate; 3) interpolate linearly to a desired y coordinate that falls between the two y coordinates used in steps 1 and 2, along the vertical line passing through the desired x coordinate. Given four known pixel values f that fall at the lower-left (x_1,y_1), lower-right (x_2,y_1), upper-left (x_1,y_2), and upper-right (x_2,y_2) corners of a rectangular region of interest, interpolation to a desired point within this region is defined mathematically as:



$$f(x,y) \approx \frac{f(x_1,y_1)}{(x_2-x_1)(y_2-y_1)}(x_2-x)(y_2-y) + \frac{f(x_2,y_1)}{(x_2-x_1)(y_2-y_1)}(x-x_1)(y_2-y) + \frac{f(x_1,y_2)}{(x_2-x_1)(y_2-y_1)}(x_2-x)(y-y_1) + \frac{f(x_2,y_2)}{(x_2-x_1)(y_2-y_1)}(x-x_1)(y-y_1) \quad (3.6)$$

This equation is generally applicable. However, if the coordinate system in which the four points are known can be scaled such that x_1=y_1=0 and x_2=y_2=1, a more compact and efficient bilinear interpolation scheme based on matrix operations may be used:

$$f(x,y) \approx \begin{bmatrix}(1-x) & x\end{bmatrix} \times \begin{bmatrix} f(0,0) & f(0,1) \\ f(1,0) & f(1,1) \end{bmatrix} \times \begin{bmatrix}(1-y) \\ y\end{bmatrix} \quad (3.7)$$

The SUVI images are expected to each possess metadata that will define the translation necessary to center the solar disk on the image array, and the rotation angle necessary to align solar spin axis with the image y-axis. Furthermore, each SUVI image should possess metadata that define the pixel plate scale. The ratio of this plate scale and that of GOES 13 SXI can be used to derive a scaling factor that guarantees SUVI images will be directly comparable to GOES 13 SXI.

Point of View Image Alignment:

The point of view (POV) of an image relates to the location in 3D space of the imager, and should be adjusted to align pixels in images that have not been obtained from identical locations.

We first correct for the distance from the Sun, rescaling the image so that the Sun's apparent radius is always equal to the apparent radius seen from 1AU. There is currently no correction for perspective change, since variations in the imager's distance from the sun would lead to changes in actual visible solar surface area that are not detectable using 32-bit floating point pixel coordinates. If the algorithm were ever applied to non-SUVI images, this shortcoming may need to be remedied.

We also correct for changes in heliographic latitude and longitude. While latitude does not vary appreciably between L1b images, heliographic longitude varies at a rate of ~14 degrees per day. We might neglect this correction for images taken just a few seconds to minutes apart, but as the time between images approaches an hour or more, features will shift by whole pixels and more at the center of the solar disk. Normal composite images whose time stamps differ by only seconds to minutes will not suffer much, but difference images and composites of composites used in other SUVI L2+ products will be severely impacted if these POV corrections are not made.

The first step is to convert 2D pixel coordinates to 3D heliocentric Cartesian. The X and Y coordinates simply become the pixel coordinate multiplied by the pixel plate scale. The Z coordinate is determined by assuming a spherical sun with known radius, and applying (3.8).

$$p_z = \sqrt{R_S^2 - p_x^2 - p_y^2} \qquad (3.8)$$

Once 3D Cartesian coordinates are available, changes in perspective not related to distance from the Sun are applied using three rotations: 1) rotate from the heliographic latitude of the observer to the solar equator; 2) rotate through the change in heliographic longitude ($\Delta\phi = \phi_{targ} - \phi_0$); and 3) rotate to the target heliographic latitude. The transformation matrices for these rotations are presented in (3.9).

$$
\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(-B_0) & \sin(-B_0) \\ 0 & -\sin(-B_0) & \cos(-B_0) \end{bmatrix} \times \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}
$$

$$
\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} \cos(\Delta\phi) & 0 & -\sin(\Delta\phi) \\ 0 & 1 & 0 \\ \sin(\Delta\phi) & 0 & \cos(\Delta\phi) \end{bmatrix} \times \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \qquad (3.9)
$$

$$
\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(B_{targ}) & \sin(B_{targ}) \\ 0 & -\sin(B_{targ}) & \cos(B_{targ}) \end{bmatrix} \times \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}
$$

If no further POV alignment were necessary, the X and Y components of the resulting pixel coordinates would be divided by the plate scale to return to image pixel coordinates, and all pixels with negative Z coordinates would be filtered out, since these are not visible the observer. Pixels that were not visible before these rotations will be assigned “bad” values, or NaNs.

However, the Sun exhibits differential rotation in that its apparent surface spins faster at the equator and slower toward the poles. A variety of models of this differential rotation exist in the literature, and nearly all of them define the time derivative of longitude as a function of latitude, so it is necessary to convert the 3D Cartesian coordinates to latitude and longitude in order to correct for the Sun’s differential rotation. This can be done using equations in (3.10) (see Thompson (2006), *Astronomy & Astrophysics*).

$$
\begin{aligned}
r_i &= \sqrt{p_x^2 + p_y^2 + p_z^2} \\
\theta_i &= \sin^{-1}\left(\left(p_y \times \cos B_{targ} + p_z \times \sin B_{targ}\right)/r\right) \\
\phi_i &= \phi_{targ} + \mathrm{atan2}\left(p_x, p_z \times \cos B_{targ} - p_y \times \sin B_{targ}\right)
\end{aligned} \qquad (3.10)
$$

Once Cartesian pixel coordinates have been converted to radius (r_i), latitude (θ_i), and longitude (ϕ_i), the transformation in (3.11) can be applied to each pixel’s coordinates to simulate differential rotation (see Snodgrass and Ulrich (1990), *Astrophysical Journal*).

$$
\begin{aligned}
\frac{d\phi_i}{dt} &= 14.713 - \left(2.396 \times \sin^2 \theta_i\right) - \left(1.787 \times \sin^4 \theta_i\right) \\
\theta_i &= \theta_i + \frac{d\phi_i}{dt} \times \Delta t
\end{aligned}
\tag{3.11}
$$

In order to convert from heliographic coordinates back to Cartesian, use the relations in (3.12) (see Thompson (2006), *Astronomy & Astrophysics*).

$$
\begin{aligned}
p_x &= \cos\theta_i \times \sin\left(\phi_i - \phi_{targ}\right) \times r \\
p_y &= \left(\sin\theta_i \times \cos\theta_{targ} - \cos\theta_i \times \cos\left(\phi_i - \phi_{targ}\right) \times \sin\theta_{targ}\right) \times r \\
p_z &= \left(\sin\theta_i \times \sin\theta_{targ} - \cos\theta_i \times \cos\left(\phi_i - \phi_{targ}\right) \times \cos\theta_{targ}\right) \times r
\end{aligned}
\tag{3.12}
$$

3.4.3 Algorithm Output

The SUVI Composite Image algorithm generates output images that are very similar in structure to its inputs. This is because the algorithm as implemented in code is general enough to be used to merge either L1b images, L2 composite images and L1b images, or L2 composite images only. These outputs are listed in Table 3. The only significant differences between an L1b input image and the composite output is that composite images should have metadata that indicates the number of images that have been combined, and they will always contain an extra array of pixel weights that shadow the pixel values.

Table 3. Level 2 Outputs of SUVI Composite Image algorithm.

Name	Description	TYPE (Dimension)
Date/Time	Image date and time tags (e.g. YYYY,MM,DD,hh,mm,ss.sss)	CHAR(1) or Integer(7)
Channel/Filter	Identifier for channel/filter combo	CHAR (1)
Exposure Time	Accumulated exposure duration	REAL (1)
N_{comp}	Number of images in composite	INTEGER (1)
Pixels	Composite image pixel value	REAL (n_x, n_y)
Pixel Weights	Composite image pixel weights	REAL (n_x, n_y)
Pixel Flags	Composite image pixel flags	INTEGER (n_x, n_y)
DC_{pix}	X & Y pixel coordinates of solar disk center	REAL (2)
Δ_{pix}	Pseudo-angle describing a pixel's plate scale in the X & Y directions	REAL (2)
P_0	Position angle between solar north and image Y-axis	REAL (1)
L_0	Carrington longitude of Earth	REAL (1)
ϕ_S	Stonyhurst longitude of SUVI (0 if SUVI and Earth are co-located)	REAL (1)
B_0	Heliographic latitude of SUVI	REAL (1)
D_S	Distance from sun center to SUVI	REAL (1)

4 TEST DATA SETS AND OUTPUTS

4.1 Simulated/Proxy Input Data Sets

GOES 12 images are used to test the algorithm's ability to handle GOES operations quality images. Archived SXI images already exist in nearly simultaneous short-long exposure pairs that are corrupted by real pixel-value uncertainties due to both random instrument noise and accuracy of pointing knowledge (both are inherently less certain for shorter exposures).

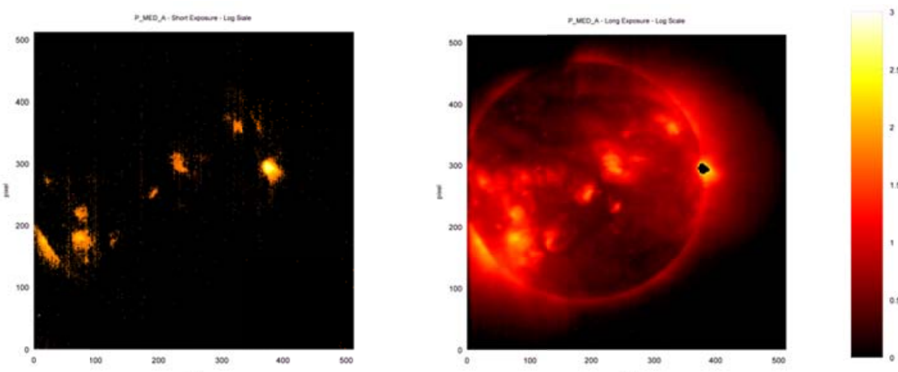


Figure 4 GOES-12 SXI Short and Long Exposures
In this example, the first image is a 0.03 second exposure taken ~10:45am on December 1st, 2001. The second image is a 3 second exposure taken within a minute of the first. Only the very brightest regions show up in the first, while the second has at least one major saturated region, designated here by black pixels just above the equator on the western limb (right).

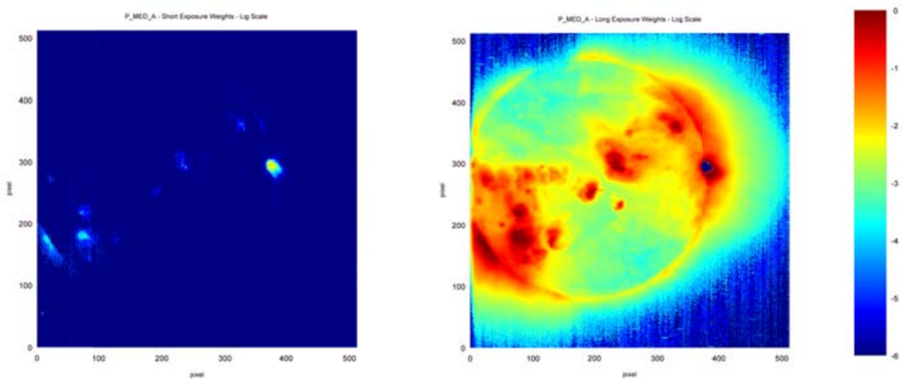


Figure 5 GOES-12 SXI Short and Long Exposure Weights
In this example, the first image shows count-dependent weights calculated from the short exposure irradiance pixel values and exposure time. The second image corresponds to a long exposure. Even though the long exposure dominates most of the image, the short exposure fills in saturated regions in the long exposure that are assigned zero weight.

The GOES 12 instrument design and spectral bands differ considerably from GOES-R SUVI. However, the Extreme-ultraviolet Imaging Telescope (EIT) on board the Solar and Heliospheric Observatory (SoHO) satellite uses similar technology to SUVI to generate images at four of the six wavelengths measured by SUVI. The EIT does not typically generate short-long exposure image pairs, so photon counting noise based on an assumed calibration constant and long and short exposure times was added to the EUV images. Furthermore, an artificial saturation threshold based on the calibrated counts was imposed.

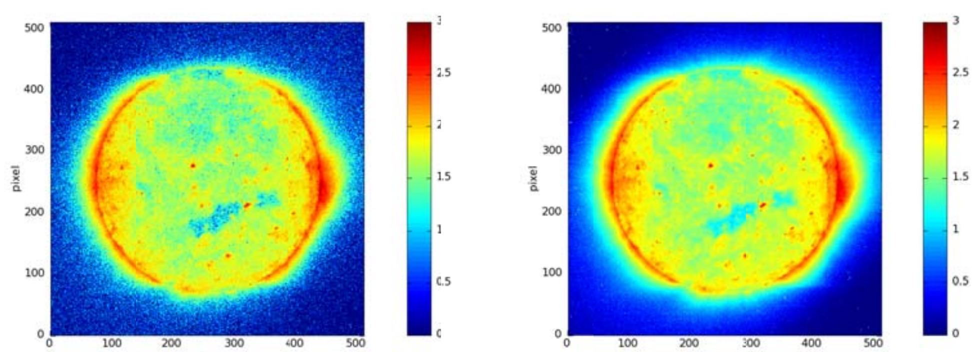


Figure 6 Simulated short/long exposures using EIT 19.5 nm images

4.2 Output from Simulated/Proxy Inputs Data Sets

The SUVI Composite Image algorithm will generate image and metadata as described in subsection 3.4.3.

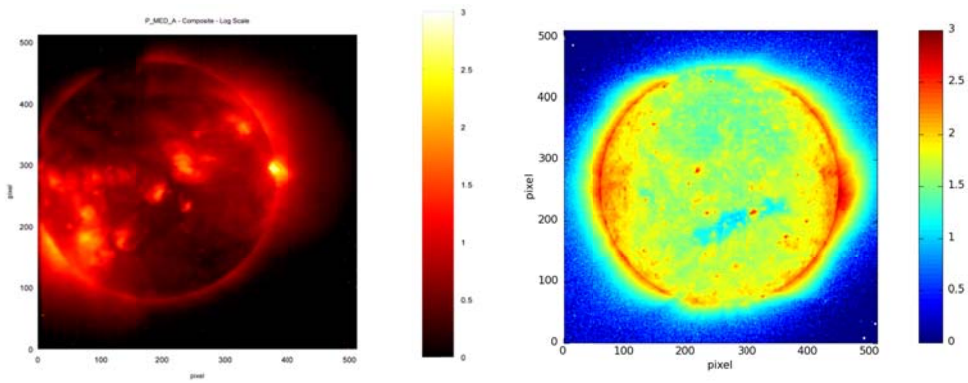


Figure 7 Example Composite Images
A composite image generated from one SXI short and one SXI long exposure taken within one minute of each other is shown on the left. A Composite image generated from one simulated short and one simulated long exposure is shown on the right.

4.2.1 Precisions and Accuracy Estimates

Assuming the SUVI instrument performs as designed, and is properly calibrated, the uncertainty associated with each pixel-value may be reasonably described as the standard deviation of a white-noise process. If a composite pixel-value is no more than an average of the *n* pixel-values taken from nearly contemporaneous exposures, the relative change in uncertainty is just $1/\sqrt{n}$ if all pixel-values exhibit the same uncertainty. Of course if the weighted averaging scheme described in subsection 3.4.2 is used, it is implied that different pixel-values do not exhibit the same uncertainty, so the $1/\sqrt{n}$ scaling factor is modified to be:

$$\sqrt{\sum_{j=1}^{n} w_j^{\,2} \bigg/ \left(\sum_{j=1}^{n} w_j\right)^2} \qquad (4.1)$$

The assumption so far is that all uncertainty can be described as random (white) instrument noise, and exhibits no bias that cannot be corrected with appropriate calibration procedures. If the operational dynamic range is exceeded however, such as when the CCD saturates or measured pixel-values fall below an inherent noise floor, pixel-value bias is unavoidable. The weighting function is therefore designed to remove such “bad” pixels from the composite entirely by assigning zero weight to them. If there remains at least one valid pixel-value from amongst the different exposures used to generate the composite, the accuracy of the composite pixel-value will be improved with respect to saturated or under-exposed pixels.

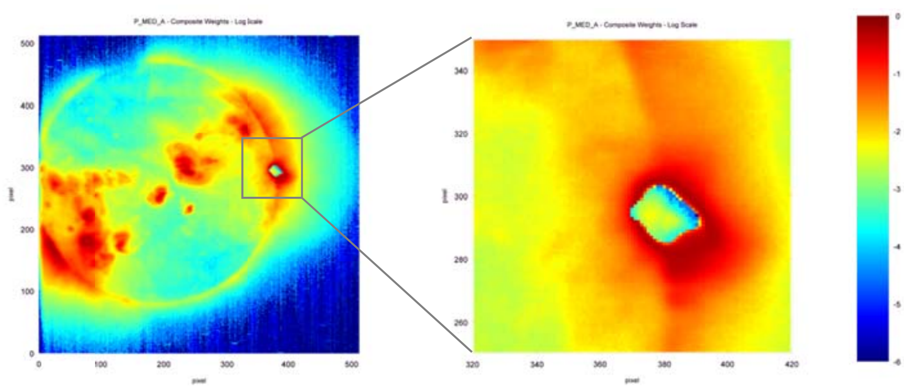


Figure 8 GOES-12 SXI Composite Weights
In this example, the first image is the average of weights from all exposures used to generate the composite image. Note how the weights inside the bright region are quite small, due to the fact that this region only used pixels from low-count, highly uncertain pixels taken from the short exposure.

4.2.2 Error Budget

TBD

5 PRACTICAL CONSIDERATIONS

5.1 Numerical Computation Considerations

There are no significant numerical computation considerations in the current implementation of the Composite Image algorithm.

5.2 Programming and Procedural Considerations

The count nodes necessary to customize weighting functions to each spectral channel need to be determined externally, and passed to the Composite Image algorithm via a space weather product software framework. This framework does not exist as of the delivery date of the SUVI Composite Image algorithm.

5.3 Quality Assessment and Diagnostics

Composite images will be periodically retrieved, examined, and compared with contemporaneous data from other solar imaging instruments (operational and scientific) operating at similar wavelengths in order to assess the quality of the output.

Since SUVI Composite Images are the fundamental building block for nearly all other SUVI L2+ data products, these too will be examined closely to see if they accentuate possible flaws that may not have been visible in the composite image alone (difference products will be especially useful in this regard).

Space weather forecasters are trained to recognize deviations from normal conditions, and so will be consulted regularly to determine if, and to what degree, the composite image product quality degrades with time. Such changes will almost certainly be due to degradation in the L1B data, but it may be possible to implement changes to the SCA that can alleviate some of these issues.

The weighting function described in subsection 3.4.2 is a reasonable start, but the low/high count thresholds, as well as the peak, will be adjustable parameters in the final algorithm. Over time, required changes in these parameters will be inevitable, but tracking such changes will help the developer ascertain the robustness of the SCA, and implement possible improvements.

5.4 Exception Handling

Possible exceptions, and the required actions, include:

- bad or incomplete metadata in single L1b input data file;
    - action: do NOT merge L1b image with composite;
    - action: fill L1b image shadow array with zeros;
    - action: proceed to next L1b image in composite group;
- all L1B files for a composite image have bad or incomplete metadata;
    - action: fill composite image pixel array with "bad" values, and the composite shadow array with zeros;
- bad pixel in single L1B data file (missing or otherwise flagged data);
    - action: do NOT merge L1b pixel with composite pixel;
    - action: assign zero to shadow array pixel;
- all L1B pixels to be combined into SCA pixel are bad;
    - action: assign NaN to composite pixel (the shadow array pixel will already be zero in a recursive averaging scheme);

5.5 Algorithm Validation

The SUVI Coronal Hole Image algorithm will be validated by ascertaining its operational value to the SWPC forecast office, both as an independent data product, and as input to other more derived data products. Ideally this will be done as part of a GOES Program Proving Ground demonstration project.

6 ASSUMPTIONS AND LIMITATIONS

6.1 Performance

The SUVI Coronal Hole Image algorithm is nothing more than the SUVI Composite Image algorithm configured to include many more input images than are required for the high cadence, high dynamic range (HDR) images. The HDR composites require properly chosen exposure times so that the dynamic range of short, long, and possibly medium length exposures for each spectral channel overlap. If they don't, there will be image artifacts near the boundaries between good and bad pixels.

6.2 Assumed Sensor Performance

The SUVI instrument is expected to perform to its operational requirements described in the GOES-R Mission Requirements Document (MRD), and related documentation. As of the time of this writing, the SUVI vendor has informally agreed to provide metadata with each image that informs the user or algorithm if/when these level 1b performance requirements may not be getting met. This includes, for example, channel-specific noise floors and saturation thresholds in units comparable to the pixel values.

6.3 Pre-Planned Product Improvements

6.3.1 Improvement 1

If the FOV and POV related metadata provided along with the L1b images is not accurate enough to guarantee image alignment between components of a L2 composite image, an alternative form of the SUVI Composite Image algorithm will include an option to perform optimized pixel alignment. This process will involve making sub-pixel adjustments to FOV and POV metadata in one of the images until a maximum in the correlation coefficient between two images is achieved. This is expected to substantially more computationally expensive than the current algorithm, so additional optimization of the current algorithm for speed and memory usage will be required.

7 REFERENCES

Debevec, P. E. and M. Jitendra (1997), Recovering high dynamic range radiance maps from photographs, SIGGRAPH Proceedings

Hapgood, M.A. (1992), Space physics coordinate transformations: a user guide, *Planet. Space Sci.*

Lucke, R. L. and R. A. Kessel (2006), Signal-to-noise ratio, contrast-to-noise ratio, and exposure time for imaging systems with photon-limited noise, *Opt. Eng.*

Rigler, E. J., S. Hill, GOES R SUVI Coronal Hole Image Implementation and User’s Guide, Version 1.0, July 21, 2011.

Rigler, E. J., S. Hill, GOES R SUVI Coronal Hole Image Algorithm Test Plan and Results, Version 1.0, July 21, 2011.

Snodgrass and Ulrich (1990), "Rotation of Doppler features in the solar photosphere, *Astrophysical Journal*

Thompson, W. T. (2006), Coordinate systems for solar image data, *Astronomy & Astrophysics*