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

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

NOAA NESDIS CENTER for SATELLITE APPLICATIONS and RESEARCH

GOES-R SUVI FLARE LOCATION ALGORITHM THEORETICAL BASIS DOCUMENT

Version 0.1

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TITLE: SUVI FLARE LOCATION ALGORITHM THEORETICAL BASIS DOCUMENT VERSION 0.1

AUTHORS:
Jonathan Darnel
Steven Hill
William Denig

APPROVAL SIGNATURES:

_____<Actual Signature Date>
<Name of Technical Approver> Date
Technical Approver

_____<Actual Signature Date>
<Name of Agency Approver> Date
Agency

SUVI FLARE LOCATION ALGORITHM THEORETICAL BASIS DOCUMENT
VERSION HISTORY SUMMARY

Version	**Description**	**Revised Sections**	**Date**
0.0	Created Jonathan Darnel CIRES/NGDC	New Document	8/12/2013
0.1	Incorporating comments and feedback	All	12/11/2013

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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 GOES-R Solar Ultraviolet Imager (SUVI) will provide high-cadence full-disk images of the solar atmosphere in six narrow-band extreme ultraviolet (EUV) spectral channels that will support Space Weather forecast activities at NOAA's Space Weather Prediction Center (SWPC).

This document provides a comprehensive description of the SUVI Flare Location algorithm. A solar flare occurs when magnetic reconnection within the solar corona rapidly heats the solar plasma. This coronal heating results in an intense brightening of the heated plasma, which can increase the emission of the Sun in the X-ray and Extreme Ultraviolet portions of the electromagnetic spectrum by several orders of magnitude. The SUVI Flare Location reads in the SUVI Thematic Map and, for each distinct flaring region, will determine the intensity-weighted centroid that indicates the location of each flare. The SUVI Flare Location is called when the XRS.07 Event Detection product indicates that a solar flare is in progress by way of the SUVI.13 Bright Region.

The algorithm chosen to fulfill the requirements for the SUVI Flare Location is triggered by a positive Event Detection report from the XRS.07 product. The Flare Location algorithm then ingests the SUVI Thematic Map and determines if there are EUV flare pixels that have been identified. If so, the algorithm then ingests the SUVI Bright Region product and the SUVI Composite Image products. The algorithm then determines the intensity-weighted centroids and the association with known bright regions for all the SUVI channels for each flare event that is identified.

Information necessary for developers and reviewers to verify that the algorithm meets operational requirements is presented. Also presented, when applicable, is traceability to heritage, and the design details necessary for development and implementation of the algorithm into operational use. Test and validation procedures are also provided along with assumptions and known limitations of the algorithm.

1 INTRODUCTION

The GOES-R Space Weather Team (SWxT) at the National Geophysical Data Center (NOAA/NESDIS/NGDC) is responsible for producing algorithms that generate products using space environment data from the GOES-R series satellites. These algorithms shall address the operational needs of the NOAA/NWS/NCEP 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 address the requirements of outside operational and research agencies as agreed.

1.1 Purpose of This Document

This Algorithm Theoretical Basis Document (ATBD) details the GOES-R Solar Ultraviolet Imager (SUVI) Flare Location algorithm design and processing methodology. The ATBD lists operational requirements for this product and defines how these requirements will be met using 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

This document 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. The members of the NWS Space Weather Forecast Office (NWS SWFO) shall also use this ATBD to verify their operational requirements are being met by the proposed algorithm. Finally, NWS SWFO should also use it to understand the strengths and weaknesses of the algorithm as well as its applicability, accuracy, and robustness.

1.3 Inside Each Section

Section 2.0 OBSERVING SYSTEM OVERVIEW:

- provides objectives of the SUVI Flare Location algorithm including the output and how they may be used operationally;
- discusses SUVI instrument characteristics and the fundamental algorithm approach;

Section 3.0 ALGORITHM DESCRIPTION:

- contains a complete SUVI Flare Location 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 quality of the data product(s);
- 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 Flare Location algorithm theoretical basis and performance;
- discusses planned product improvements for future enhancements;

Appendix A ONE METHOD FOR CLUSTERING/LABELING

- describes a basic method for determining distinct clusters of contiguous values amongst a 2d data array

Appendix B CONVERSION TO HELIOGRAPHIC COORDINATES

- describes the method to convert from on-disk pixel coordinates to heliographic latitude/longitude coordinates

Section 7.0 REFERENCES:

- Provides references to all sources cited in the ATBD.

1.4 Related Documents

GOESR SUVI Flare Location Test Plan and Results
GOESR SUVI Flare Location Implementation and User's Guide

1.5 Algorithm Requirements and Traceability

Table 1: SUVI.14 Requirements

Product: SUVI.14 Flare Location		
Reference: GOES-R_Level 2+ SWx Algorithm Requirements Phase 3 07262012.xlsx		
Revision: Revised to reflect changes recommended during and following the SUVI Flare Location CDR, 06/19/13.		
1. General		
SUVI.14.01.01	The algorithm shall Identify flaring regions in the solar EUV imagery and provide statistics for the region including total output, peak output, and location.	
SUVI.14.01.02	The algorithm shall identify from the thematic map (SUVI.19) distinct flaring regions based upon pixel classification.	
SUVI.14.01.03	The algorithm shall meet a cadence of 1 minute.	
SUVI.14.01.04	The algorithm shall perform all operations in less than 1 minute after a new thematic map (SUVI.19) has been generated.	
SUVI.14.01.05	The algorithm shall meet an accuracy for all reported locations of no more than 5 heliographic degrees from the true location.	
2. Algorithm Inputs		
SUVI.14.02.01	The algorithm shall ingest all necessary inputs to detect and locate solar flare events from the designated SUVI.19 Thematic Map.	
SUVI.14.02.02	The algorithm shall ingest all necessary inputs from the SUVI.13 Bright Regions algorithm.	
SUVI.14.02.03	The algorithms shall ingest all necessary inputs from the SUVI.07 Composite Images algorithm.	
3. Processing		
SUVI.14.03.01	The algorithm shall perform all processing as a callable method or object.	
SUVI.14.03.02	The algorithm shall determine cluster membership for each solar flare	

	event from the thematic map.	
SUVI.14.03.03	The algorithm shall determine the location of each flare by calculating the intensity-weighted centroid on each flare cluster in each bandpass.	
SUVI.14.03.04	The algorithm shall convert from pixel coordinates to heliographic latitude/longitude for all flares on the solar disk.	
SUVI.14.03.05	The algorithm shall convert from pixel coordinates to off-disk coordinates ($R_{\odot}$, θ) for all flares off the solar disk.	
SUVI.14.03.06	The algorithm shall convert the pixel coordinates of each bright region centroid location to heliographic coordinates for all bright regions located on the solar disk.	
SUVI.14.03.07	The algorithm shall determine the association of each flare with Bright Regions by calculating the Great Circle Distance between each flare and each Bright Region in the SUVI.13 product.	
4. Algorithm Outputs		
SUVI.14.04.01	The algorithm shall report the location of each solar flare event in either heliographic or off-disk coordinates.	
SUVI.14.04.02	The algorithm shall report for each solar flare event associated with a bright region the bright region area in heliographic square degrees.	
SUVI.14.04.03	The algorithm shall report for each solar flare event associated with a bright region the total flux in each bandpass.	
SUVI.14.04.04	The algorithm shall report for each solar flare event associated with a bright region the peak flux in each bandpass.	
SUVI.14.04.05	The algorithm shall report for each solar flare event associated with a bright region the bright region's SRS association.	
SUVI.14.04.06	The algorithm shall report the latest XRS.07 Event Detection Status (1 or 0).	
5. Error Handling		
SUVI.14.05.01	The algorithm shall wait for the next SUVI.19 thematic map value if the current thematic map value is missing.	
SUVI.14.05.02	The algorithm shall provide a quality flag to indicate if any SUVI.07 products are older than 4 minutes	
SUVI.14.05.03	The algorithm shall provide a quality flag to indicate if any SUVI.13 product is older than 4 minutes	
6. Ancillary Data		
SUVI.14.06.01	The algorithm shall, if necessary, ingest the *Astronomical Almanac* data to perform the conversion from pixel to heliographic coordinate from an external data file.	
SUVI.14.06.02	The algorithm shall, if necessary, ingest configurable quantities such as	

	the Great Circle Distance threshold from an external data file.	

1.6 Revision History

Revision Number	Date	Author	Revision Description	Reason for Revision
Draft 0.1	12/11/2013	J. Darnel	Blonde, blue-eyed	Comments, feedback

2 OBSERVING SYSTEM OVERVIEW

2.1 Product Generated

The product for the SUVI.14 Flare Location algorithm will generate tables of coordinates for the flare centroids along with all the data from the SUVI.13 Bright Region report for any bright region association.

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 3.9, dated November 2009. The SUVI thematic map algorithm assumes inputs that meet these minimum requirements, although in all likelihood, the delivered instrument performance will exceed these requirements. To start, individual SUVI spectral channel specifications are repeated in Table 2 for ease of reference, along with the type of EUV solar feature that motivated each spectral channel choice.

Table 2: SUVI image spectral channels

Channel	Wavelength	Sample Use
SUVI (Fe XVIII)	9.39 nm	Flares (~$6x10^6$ °K)
SUVI (Fe VIII)	13.1 nm	Flares (~$10x10^6$ °K) and Hot flares (~$15x10^6$ °K)
SUVI (Fe IX)	17.1 nm	Active regions (~$6x10^5$ °K)
SUVI (Fe XII)	19.5 nm	Active regions (~$1x10^6$ °K) and Hot Flares (~$20x10^6$ °K)

SUVI (Fe XV)	28.4 nm	Coronal holes (~$2x10^6$ °K)
SUVI (He II)	30.4 nm	Filaments (~$6x10^4$ °K)

The minimum spatial resolution of a SUVI image is 2.5 arcseconds, which when combined with a field-of-view requirement of 1.3 solar radii, translates to an image array of approximately 1000x1000 pixels. A measurement range of 0.3-10^6 photons/s/cm^2/$arcsec^2$ is also specified in the MRD, a dynamic range that is not achievable with a single exposure given SUVI's hardware limitations. Multi-exposure, high dynamic range composite images, a separate level 2 SUVI data product, will serve as the primary input to the SUVI thematic map algorithm.

SUVI's minimum refresh rate is one full dynamic range image every 2 minutes. Note that this does not call for all spectral channels to refresh every 2 minutes. If higher level data products (e.g., solar flare location report) require a thematic map input at a relatively high cadence, it is likely, that a single full dynamic range composite image will serve as input to more than one thematic map. The SUVI Thematic Map algorithm assumes all necessary input images are assembled and presented to it by a space weather data processing framework.

Finally, while SUVI has not yet flown aboard any NOAA satellite, the Solar Dynamics Observatory (SDO) was launched in the spring of 2010. One of the payload onboard SDO is the Atmospheric Imaging Array (AIA), a scientific instrument that has mostly compatible spectral channels to SUVI, and a very similar optical design and hardware selection. Details about the SUVI proxy data generated from SDO/AIA images will be presented later, but Figure 1 offers a preview of the kind of solar image data that will be returned by GOES-R SUVI, which serves as input for the SUVI Thematic Map algorithm.

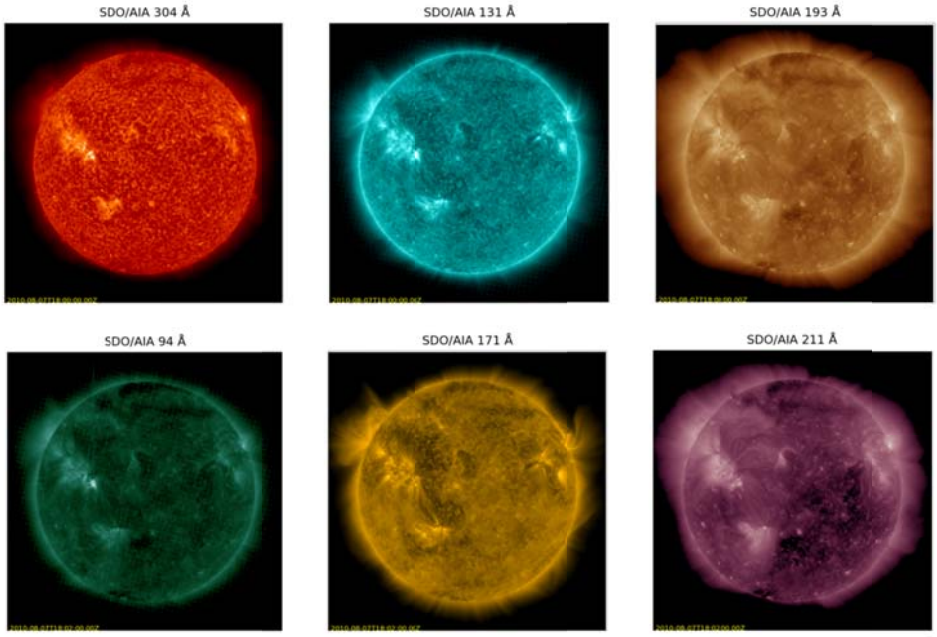

Figure 1 SUVI proxy data
Six select EUV channels from the Solar Dynamics Observatory (SDO) Atmospheric Imaging Array (AIA) are spatially and temporally binned/re-sampled to closely match SUVI's expected characteristics. The spectral band passes also nearly match those expected on SUVI, with the exception of SUVI's 28.4 nm channel, which we have chosen to replace with AIA's 21.1 nm channel for development and testing purposes.

3 ALGORITHM DESCRIPTION

3.1 Algorithm Overview

3.2 Processing Outline

Steps required to construct a SUVI Flare Location product are:

1. Pre-process the SUVI.19 Thematic Map product:
    a. read in the Thematic Map data
    b. read in the Thematic Map metadata
    c. test Thematic Map data for flare pixels
        i. if there are no flare pixels, go to 4a
        ii. determine distinct regions of flare pixels and continue to 2a
2. Ingest other inputs:
    a. Read in SUVI.07 Composite Image products
        i. Each channel: 094, 131, 171, 195, 284, 304
    b. Read in SUVI.13 Bright Region product
3. Process Flare Data:
    a. Calculate intensity-weighted centroid for each channel
    b. If on-disk, calculate the locations in Stonyhurst and Carrington heliographic coordinates
    c. If off-disk, calculate the locations in (r,θ) coordinates – r is the radius from solar center and θ is the angle from solar north
    d. Test for proximity to SUVI Bright Region locations
    e. Repeat 3a-3d until all flare regions have been processed
4. Write out flare report with associated metadata
    a. If the thematic map contains no flare pixels, then the report will state clearly "No Flares Detected"
    b. For detected flares events, the report shall state the locations, association with Bright Region, and associated data

The process flow is depicted graphically in Figure 2.

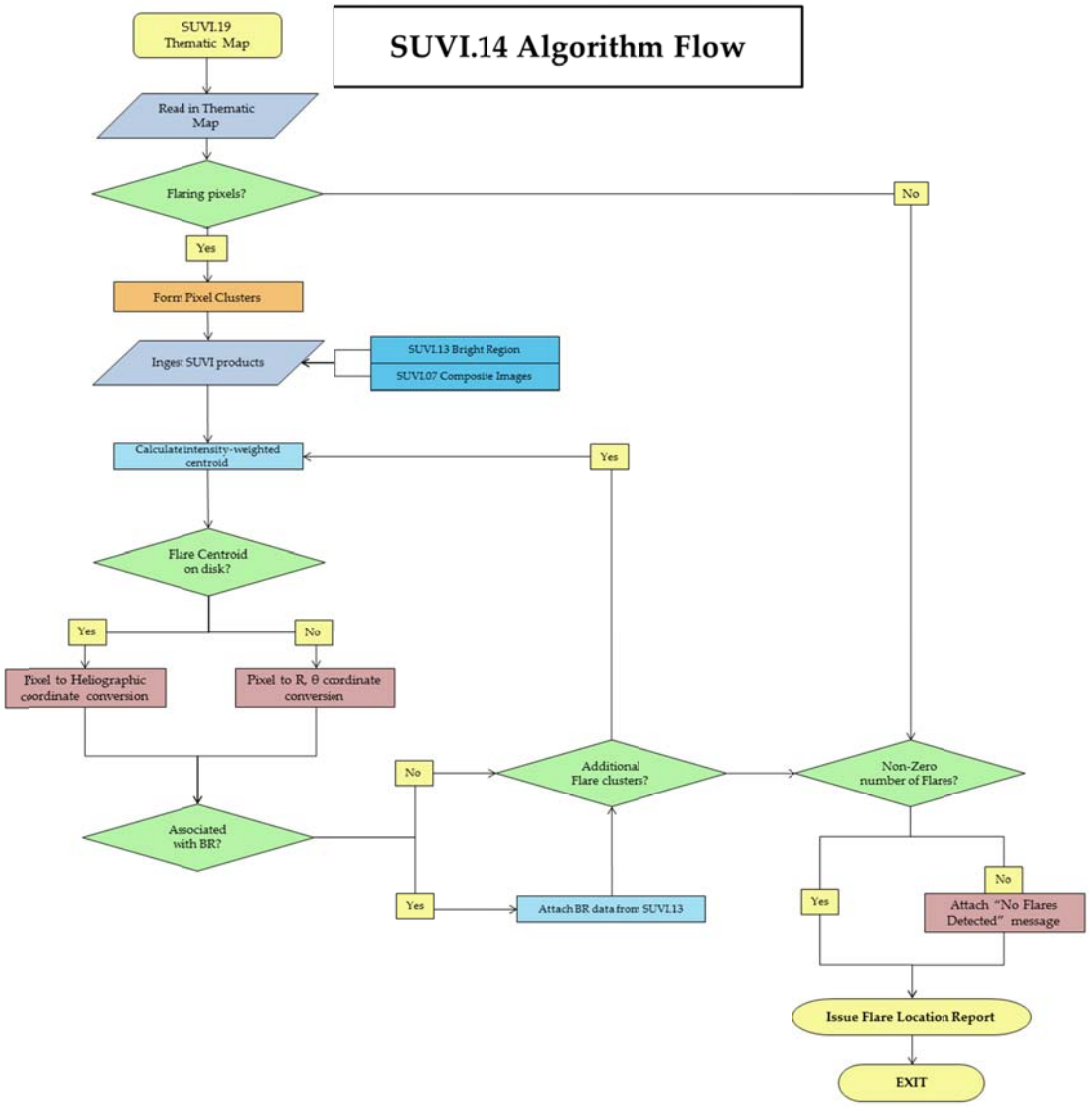

Figure 2: Flow diagram of SUVI Flare Location algorithm
This flow diagram depicts at a high level steps required to generate a SUVI Flare Location product from the SUVI Thematic Map and Composite Images.

3.3 Algorithm Input

3.3.1 Primary Sensor Data

The primary inputs required by the SUVI Flare Location algorithm requires are the SUVI Thematic Map, the high dynamic range SUVI Composite Images, and the SUVI Bright Region product. All these are separate level 2 SUVI data products. It is assumed that a Space Weather L2 data processing framework will make all necessary images available. The information required from each of the primary input products is listed below in Table 3-4.

Table 3: Inputs from SUVI.07 Composite Images

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)
Pixels	Composite image pixel value	REAL (n_x, n_y)

Table 4: Inputs from SUVI.13 Bright Region

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)
$N_{regions}$	Number of bright regions in the report	Integer(1)
Peak Fluxes	Peak fluxes for regions	REAL ($N_{regions}$, 6)
Total Fluxes	Total fluxes for regions	REAL ($N_{regions}$, 6)
Locations	Location of region centroid (on disk)	REAL ($N_{regions}$, 2)
Locations	Location of region centroid (off disk)	REAL ($N_{regions}$, 2)
SRS	NOAA designation from SRS report	Integer ($N_{regions}$)
Areas	Area of regions, -1 if not applicable	REAL ($N_{regions}$)

Table 5: Inputs from the SUVI.19 Thematic Map

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)
Pixels	Composite image pixel value	REAL (n_x, n_y)
$\mathbf{DC_{pix}}$	X & Y pixel coordinates of solar disk center	REAL (2)
$\mathbf{\Delta_{pix}}$	Pseudo-angle describing a pixel's plate scale in the X & Y directions	REAL (2)
$\mathbf{P_0}$	Position angle between solar north and image Y-axis	REAL (1)
$\mathbf{L_0}$	Carrington longitude of Earth	REAL (1)
$\boldsymbol{\phi_S}$	Stonyhurst longitude of SUVI (0 if SUVI and Earth are co-located)	REAL (1)
$\mathbf{B_0}$	Heliographic latitude of SUVI	REAL (1)
$\mathbf{D_S}$	Distance from sun center to SUVI	REAL (1)

3.3.2 Ancillary Data

Ancillary data are assumed to be data not generated by SUVI or the GOES-R spacecraft. Included here are configurable quantities and the information from the *Astronomical Almanac* if it is not provided within one of the SUVI L2+ products listed as input. These are all listed in 5.

Table 6. Ancillary inputs to SUVI thematic map algorithm

Name	Description	TYPE (Dimension)
$\mathbf{P_0}$	Position angle between solar north terrestrial north from the *Astronomical Almanac*	REAL (1)
$\mathbf{B_0}$	Heliographic latitude of SUVI from the *Astronomical Almanac*	REAL (1)
GCD	Great Circle Distance - optional user configuration	REAL (1)

3.4 Theoretical Description

The SUVI Flare Location algorithm interprets the SUVI.19 (Thematic Map) product to identify the portions of the solar environment known as "flares". Information relevant to forecasters, such as flare centroid locations, can be derived from the SUVI.07 and the SUVI.13 products. The SUVI.19 product provides an interpretation of the multispectral solar imagery that is the SUVI L1b product into a finite number of solar features, and is taken as truth for the SUVI Flare Location algorithm. The SUVI.19 product classifies the solar environment into features represented by a 2-D array of integer values. One of these integer values will correspond with flares, and the SUVI Flare Location algorithm will use this to identify all flare events within the SUVI.19 product. The SUVI Flare Location algorithm will then perform analysis upon each distinct flare event to obtain the necessary information for the Flare Location product.

3.4.1 Physics of the Problem

The SUVI Flare Location algorithm must be able to define individual flare events from the Thematic Map. Then, the algorithm will retrieve fluxes from each Composite Image co-located with the Thematic Map pixel. From these, the algorithm will calculate the heliographic location of each unique flare centroid. Very little of these tasks are physics based, and image analysis and simple trigonometric techniques are more applicable.

3.4.2 Mathematical Description

The SUVI Flare Location algorithm takes advantage of the definitiveness of the SUVI Thematic Map to identify the flare events on the solar disk. Since the Thematic Map uses a finite set of integers to represent the classification of individual pixels into solar features, it is a fairly straightforward procedure to 1) find the flare pixels and 2) differentiate the unique flaring events. Table 4 contains the possible values of the Thematic Map elements.

Feature Name	Thematic Map value
Outer Space	0
Coronal Hole (on disk)	1
Coronal Hole (off disk)	2
Quiet Corona	3
Prominence of Filament	4
Active Region	5
Flare	6

Table 7: Thematic Map features and corresponding values

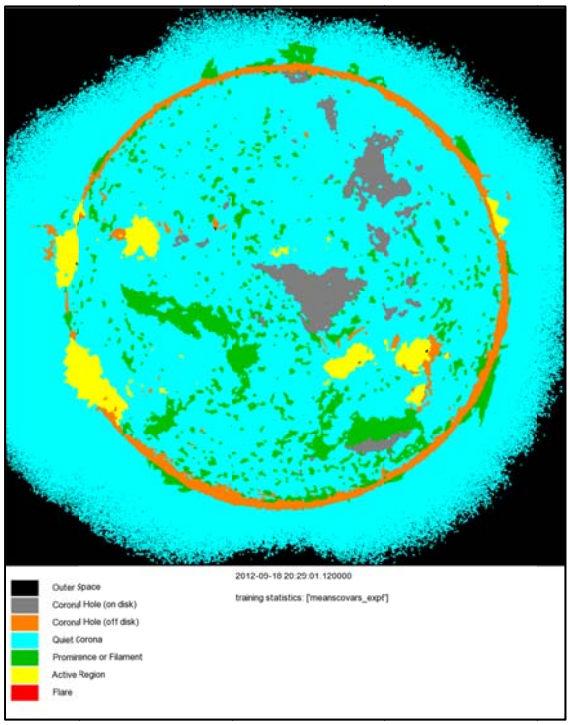

Figure 3: Sample Thematic Map

Currently included within the Thematic Map product created by the Space Weather Prediction Center's Proving Ground is a table of the features whose order coincides with the feature pixel value. Thus, if the values happen to change or the order shifts, algorithms such as SUVI Flare Location will be able to adapt to those changes. It needs to be stressed that any and all operations detailed in the procedures below should not change the Thematic Map product data. The quantity called A_{TM} below represents a copy of the Thematic Map data. If, as seen in Table 4, the flare pixels all have a value of "6" we can then isolate all the flaring pixels by setting all others to "0".

$$A_{TM}[A_{TM} \neq 6\,] = 0$$

The results of this operation can be seen in Figure 4.

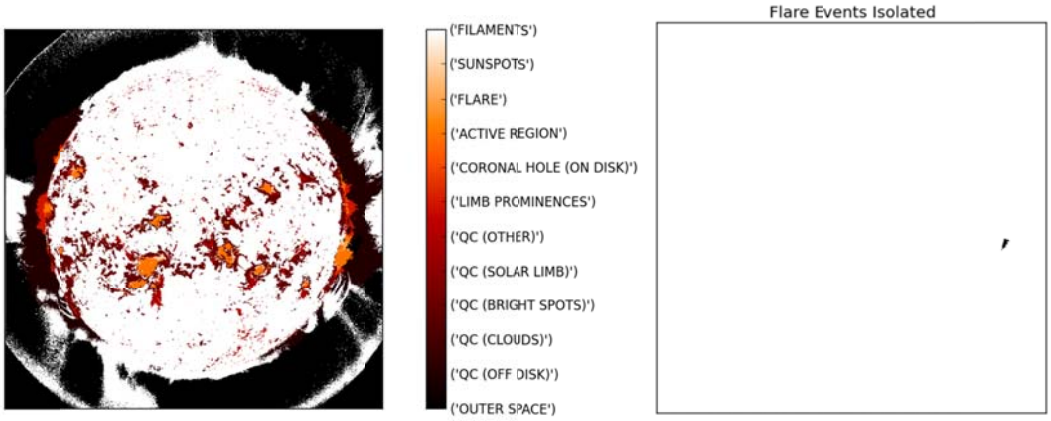

Figure 4: Example Feature Demonstration
(*left*) SWPC PG Thematic Map before isolating flare pixels. (*right*) After isolating flare pixels, all flaring region pixels stand out and are easily identifiable.

After setting all non-flare pixels to the value "0", the task of isolating individual flaring regions features is much simplified. The non-flare pixels can be effectively ignored and focus can be given to differentiating the individual flaring regions. In Figures 3 and 4, flare regions are identified for the purposes of visual demonstration of the algorithm.

In order to efficiently isolate the flaring features, an image processing routine called "labeling" is currently utilized by the development code. An example of the output of a labeling routine can be seen in Figure 5. Similar routines can and have been written from scratch. It should be noted, however, that built-in routines tend to be more highly optimized and efficient than those written from scratch. We describe one strategy to label individual clusters in **Appendix A**.

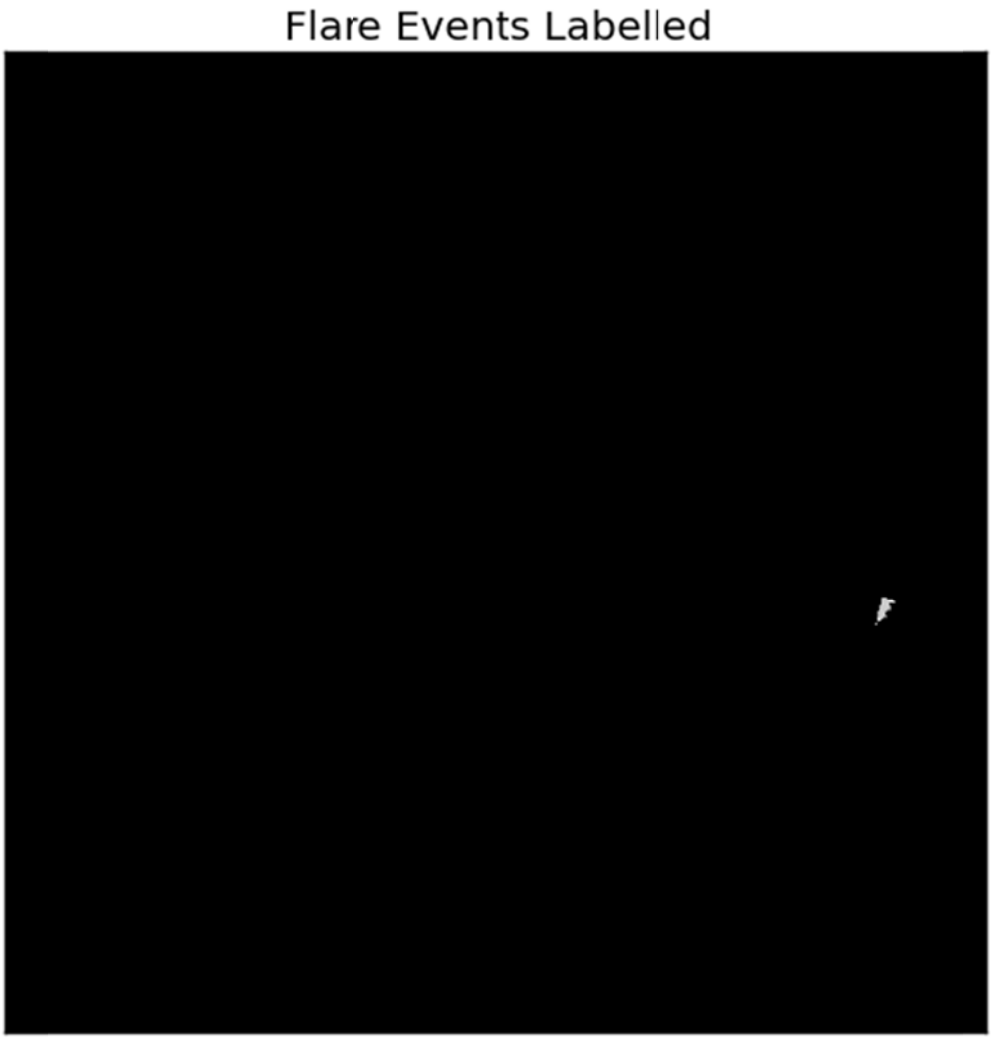

Figure 5: Example Feature Labeling
Flare events features in the thematic map are labeled. Each unique bright region feature is indicated by a different color.

Each distinct flaring event should now have a unique label, and each flare event can undergo the necessary analysis. First, the intensity-weighted centroid needs to be calculated for each channel. The total flux of the flare is calculated for each channel (i):

$$\Phi_{i,total} = \sum \Phi_{i,x,y}$$

Then the centroid can be calculated for each channel i:

$$X_{i,centroid} = \frac{1}{\Phi_{i,total}} \sum \Phi_{i,x,y} x$$
$$Y_{i,centroid} = \frac{1}{\Phi_{i,total}} \sum \Phi_{i,x,y} y$$

In order to report the proper coordinates of the centroids, we need to discriminate those which are within the solar limb (on the solar disk) and those which are off the solar limb. For those centroids which are not on the solar disk, we will provide coordinates in radius and angle from solar north. Those which are on the solar disk will have provided the centroid coordinates in both Stonyhurst and Carrington heliographic coordinates:

$$coordinates = \begin{cases} (\varphi, \lambda) \; if \; r < R_{\odot} \\ (r, \theta) \; if \; r \geq R_{\odot} \end{cases}$$

The conversion from pixel to heliographic coordinates is dependent upon many quantities: the solar P and β angles, the distance from the Sun, and the rotation of the instrument relative to the ecliptic. The solar P and β angles are retrieved by using the observation date to reference against a Look-Up Table (LUT) of Astronomical Almanac values or a forward model. All these quantities, the distance to the Sun, instrument rotation and the solar P and β angles, are preferably included in the SUVI.19 product metadata. A detailed description of the conversion from pixel to both the heliographic coordinate system and (r, θ) coordinates can be found in **Appendix B**.

One way to determine if a flare event is associated with a bright region is to compare the location of the bright region centroids with those of the flare event. There a high probability that the flare centroid lies close to the bright region centroid due to the emission of even weak flares being orders of magnitude greater than the bright region. To perform this comparison, the great circle distance is used:

$$\Delta\sigma = \left(\frac{\sqrt{(\cos(\varphi_{FL})\sin(\lambda_{BR} - \lambda_{FL}))^2 + (\cos(\varphi_{BR})\sin(\varphi_{FL}) - \sin(\varphi_{BR})\cos(\varphi_{FL})\cos(\lambda_{BR} - \lambda_{FL}))^2}}{(\sin(\varphi_{BR})\sin(\varphi_{FL}) + \cos(\varphi_{BR})\cos(\varphi_{FL})\cos(\lambda_{BR} - \lambda_{FL}))} \right)$$

The Δσ term is the angular separation of the bright region and the flare centroids, also known as the central angle. This angular separation is sufficient for the purpose of testing for proximity. The flare event should be associated with the bright region if Δσ is smaller than some limit (2 heliographic degrees, for example):

$$\Delta\sigma \leq 2.0\ degrees \begin{cases} if\ True\text{:}\ \ Include\ BR\ information \\ if\ False\text{:}\ Fill\ Value\ or\ No\ Action \end{cases}$$

If a flare event is associated with a bright region, then the information for that region in the Bright Region product will be included in the Flare Location product as well.

3.4.3 Algorithm Output

The SUVI Flare Location algorithm will necessarily report each flare event that was classified by the SUVI Thematic Map along with the locations of the intensity-weighted centroids in each channel. In addition, quality flags for each of the inputs should be included to indicate the status of the inputs the algorithm has to work with. These quality flags should indicate the availability of data from each of the Composite Images, the Thematic Map, and the SUVI.13 Bright Region products.

There remains a question as to how flexible the output structure should be in the case of bright region association or lack thereof. All the fields can be provided with each product and, in the case of no bright region association, merely have a fill value (-1, NaN, "N/A", etc.). Alternatively, the fields for the bright region data can only be used in the case of bright region association. In this case, there would need to be some indication linking the flare event to the relevant bright region data (see the $\Delta\sigma$ calculation above). Additionally, some sort of data structure can be used to group the relevant data together; the user would need to know how to navigate this structure.

All outputs are listed in Table 8.

Table 8. Level 2 outputs of SUVI Flare Location algorithm.

Name	Description	TYPE (Dimension)
Date/Time	Date and time tags of latest composite image	CHAR(1) or Integer(7)
SUVI.19 product	Filename of the Thematic Map used in the SUVI.13 algorithm	CHAR (1)
Composite Image	Filenames of the Composite Image files used in the SUVI.13 algorithm	CHAR(6)
N_{Flare}	Sum of flare events found in Thematic Map	Integer(1)
FL Centroid	Flare Locations	FLOAT(N_{Flare}*(6,2))
Φ_{peak}	Bright Region Peak Fluxes	FLOAT(N_{Flare}*(6,1))
Φ_{total}	Bright Region Total Fluxes	FLOAT(N_{Flare}*(6,1))
BR Centroid	Bright Region Centroid Locations	FLOAT(N_{Flare}*(6,2))
Area	Area of the Bright Region	FLOAT(N_{Flare})
XRS.07	XRS Flare Status	BOOL(1)
EUV Flare	Thematic Map classified flares	BOOL(N_{Flare})
SRS	SRS Association	CHAR($N_{features}$)
CI Quality	Composite Image Quality Flags	BOOL(6)
TM Quality	Thematic Map Quality Flag	BOOL(1)
BR Quality	SUVI.13 Quality Flag	BOOL(1)

4 TEST DATA SETS AND OUTPUTS

4.1 Simulated/Proxy Input Data Sets

The SUVI.14 Flare Location algorithm utilizes other SUVI Level 2 products: the SUVI.19 Thematic Map and the SUVI.07 Composite Image products (one for each SUVI channel). Thus, proxy data for the SUVI.14 algorithm will require thematic maps and EUV solar imagery at the same resolution and roughly similar

wavelengths. An ideal source for thematic map proxy data are those generated by the NWS/SWPC Proving Ground using an implementation of the SUVI.19 product to produce thematic maps using the synoptic data from the SDO/AIA EUV instruments.

The Solar Dynamics Observatory (SDO) Atmospheric Imaging Array (AIA) was launched in the spring of 2010, and has a very similar design, both optical and electronic, to SUVI. The important differences are:

- SDO/AIA is comprised of four separate telescopes, compared to SUVI's single telescope, quadrupling the rate at which images can be acquired;
- each SDO/AIA primary mirror has ~4x the photon collecting area of the SUVI primary mirror for each spectral channel;
- the SDO/AIA CCD is 4096x4096 pixels, compared to the SUVI CCD's ~1000x1000 pixels;

The SDO/AIA synoptic images, however, have been rebinned to 1024x1024 pixels and are in physical units instead of digital number (DN). The resolution of the SDO/AIA synoptic images is therefore very similar to the SUVI resolution and thus the synoptic images are useful in creating thematic map without further processing.

For the purpose of developing, testing, and demonstrating a prototype of the SUVI Flare Location algorithm, the algorithm should be run against a collection of thematic maps and the synoptic images that were used to generate those thematic maps along with the appropriate SUVI.13 product. The algorithm will need to demonstrate the ability to read in the appropriate data and utilize it correctly. The purpose of testing the SUVI Flare Location algorithm against a collection of proxy data is to demonstrate that the algorithm functions as intended regardless of solar activity.

4.2 Output from Simulated/Proxy Inputs Data Sets

To be added.

4.2.1 Precisions and Accuracy Estimates

The SUVI Flare Location algorithm has a requirement that states that the accuracy of the reported flare locations to within ±5 arcseconds. The accuracy of the Flare Location product will depend greatly upon the accuracy of the SUVI Thematic Map; mis-classification of flaring features will impact which pixels are used in the centroid calculations. During the GOES-R Proving Grounds effort at NWS/SWPC it was discovered that the stronger flares, M-class and higher, confidence in the ability of the Thematic Map to correctly classify the flare pixels is high. For the weaker flares, C-class and lower, there is a greater chance that pixels will be mis-classified into bright region or other feature. In the SUVI.19 Thematic Map ATBD, confidence is given in terms of a confusion matrix coefficient κ. Values for κ provided within the Thematic Map ATBD are > 95%. There is a possibility that these values are overstated due to the limited data set used to validate the algorithm.

4.2.2 Error Budget

TBD

5 PRACTICAL CONSIDERATIONS

5.1 Numerical Computation Considerations

- Because of the similarity of the Flare Location algorithm processes to that of the SUVI.13 algorithm, it is suggested that the implementer give serious consideration to combining the SUVI.13 and SUVI.14 algorithms.
- The development version of the SUVI Flare Location algorithm utilizes several specialized image processing tools available in open source libraries. These are typically already optimized for speed, so consideration should be given to taking advantage of these instead of "reinventing the wheel".

- After the initial classification of the thematic map into individual features, the algorithm can then take advantage of multi-CPU processing of each flare feature, if applicable.

5.2 Programming and Procedural Considerations

- Consideration should be given to the case where the SUVI.19 Thematic Map has failed to update. If an older thematic map has been used in the SUVI.13 Bright Region algorithm, then there should be some qualifier (based on the age of the thematic map) that prohibits the Flare Location algorithm from being called.
- Conversion to heliographic coordinates requires an input from the Astronomical Almanac for the Solar P and β angles. It is an assumption that, somewhere in the product chain, all the inputs required for the conversion will be supplied to the Flare Location algorithm within the Thematic Map metadata. Currently, these inputs are supplied in an external LUT by the developer. If, these quantities are not to be supplied by the Thematic Map, then provisions should be made for a forward model or a rolling LUT maintained to supply these quantities.

5.3 Quality Assessment and Diagnostics

Before the SUVI.14 Flare Location algorithm moves into operations, the algorithm should undergo an extensive demonstration and testing phase. Using reliable thematic maps as inputs, several cases of solar flares of varying strengths should be processed through the algorithm. The results of these test cases should be compared with other, more established flare location products. The SDO Feature Finding Team Flare Location algorithms and the H-alpha flare reports are plausible candidates for cross-comparison.

5.4 Exception Handling

The following is a list of exceptions and possible actions for the SUVI Flare Location algorithm:

- No Thematic Map

   a. "Evolve" older Thematic Map
   b. Exit with Error Report detailing exceptions
   c. Exit with Null Report
- Thematic Map with no data
   a. "Evolve" older Thematic Map
   b. Exit with Error Report detailing exceptions
   c. Exit with Null Report
- Thematic Map with mis-matching codes/values
   a. "Evolve" older Thematic Map
   b. Exit with Error Report detailing exceptions
   c. Exit with Null Report
- Heliographic Conversion ancillary data not available
  TBD

5.5 Algorithm Validation

It is recommended that the SUVI Flare Location algorithm be validated by being implemented in a testing and demonstration status, comparing the results with similar products from NOAA, NASA, USAF , etc. The results of the automated Flare Location product can also be compared with those performed by subject matter experts. The product will be considered successful if it is found to have met its requirements. If successful, the algorithm will be considered to have ascertained 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 activity can be done as part of a GOES Program Proving Ground or similar demonstration project.

6 ASSUMPTIONS AND LIMITATIONS

6.1 Performance

The SUVI Flare Location algorithm utilizes a collection of image processing routines/procedures that operate upon the SUVI Thematic Map product. It is only after these processes are completed that the retrieval of values from the SUVI Composite Image products is performed. As such, the accuracy of the SUVI Bright Region product is highly dependent upon the accuracy of the SUVI.19 and SUVI.07 products.

6.2 Assumed Sensor Performance

The SUVI instrument is expected to meet the operational requirements as 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 the level 1b performance requirements are not being met. Scenarios when this might occur include channel-specific noise floors and saturation thresholds in units comparable to the pixel values.

6.3 Possible Product Improvements

6.3.1 Improvement #1

Serious consideration needs to be given towards performing the processing of the SUVI.14 Flare Location algorithm within the scope of the SUVI.13 Bright Region algorithm. This would cut down on the latency of the SUVI.14 product and negate the need to read in the SUVI.13 product into the SUVI.14 algorithm. It would be feasible to spawn a new process to produce the Flare Location report (the SUVI.14 product) if the SUVI.13 determine the criteria for flare conditions have been met.

Appendix A: One Method for Clustering/Labeling

For any Thematic Map, it is simple to focus on one type of thematic map feature by setting all values not equivalent to the feature value to one value. In this instance where the thematic map values are integers, and the features that need to be analyzed in the SUVI Phase 3 products are non-zero, then it is convenient to set all values from features not of interest to zero. I.e.:

$$A_{TM}[A_{TM} \neq < feature\ value >] = 0$$

It is also advantageous to set the pixels that comprise the features of interest to "1":

$$A_{TM}[A_{TM} = < feature\ value >] = 1$$

One way to identify what we call "clusters" is to iterate either through the rows or columns of the Thematic Map's 2-D array. For this example, we will use rows. For each row, we take the entire row as a slice across the array (Figure 6):

Figure 6: Representation of an array slice.
The blue cells represent where the array values equal one.

We then perform an element-by-element difference across the array slice (Figure 7):

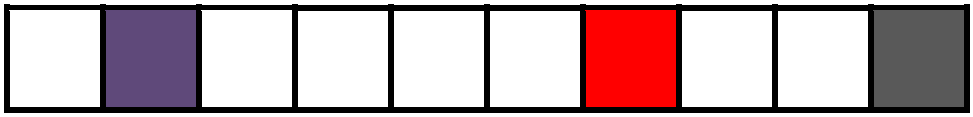

Figure 7: A representation of the differenced array slice.

Notice the different colored blocks: the gray denotes where we need to pad the array with a fill value (the difference operation leaves the result one element shorter), the purple denotes a negative value, and the red denotes a positive value. These results allow us to scan across the slice to determine the portions that belong to the feature's clusters: negative values are the start of a cluster, the positive values indicate the end (in that slice). It is important to record the index values so that it is possible to compare across adjacent slices (Figure 8):

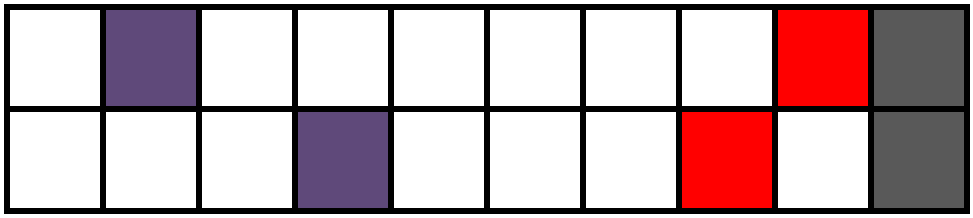

Figure 8: A representation of two difference slices with a demonstrated intersection of feature fragments.

By comparing the indexes across adjacent slices, one can determine which cluster fragments belong to the same cluster. If there is an intersection in the indexes, then the fragments belong in the same cluster. In the case where a positive value precedes a negative value in the difference slice, then it can be assumed that the

cluster fragment starts at the beginning of the slice. Similarly, if the last non-zero value in the difference slice is a negative value, then the cluster fragment ends at the end of the slice.

The SUVI detector rows contain 1280 pixels, so it is completely feasible that any individual row will contain fragments from several different feature clusters. Each successive row is compared to the previous row, and where there is intersection of the indices of the cluster fragments then the fragments are added to the clusters with which they overlap. It is also possible that a cluster fragment will have overlap with more than one cluster. In this case the clusters that overlap will be merged into one cluster and will be treated thereafter as a single cluster.

Appendix B: Conversion to Heliographic Coordinates

To convert points in pixel coordinates to heliographic coordinates (Stonyhurst and Carrington), several pieces of information are needed. These are listed in the table below:

Name	Description
x	Column number of pixel
y	Row number of pixel
x_{center}	Column number of solar center
y_{center}	Row number of solar center
Δ_x	Instrument platescale – x direction
Δ_y	Instrument platescale – y direction
r_{sun}	Solar radius in pixels
P	Solar P angle at time of observation (radians)
β	Solar β angle at time of observation (radians)
D_Θ	Solar Diameter (meters)
S_{rot}	Rotation of satellite relative to ecliptic
I_{rot}	Rotation of instrument relative to satellite axis

First, we convert the radius of the Sun to arcseconds:

$$R_{Sun} = r_{sun} * \Delta_{(x,y)}$$

Second, the 2-D pixel array coordinates need to be converted to 3-D angular coordinates:

$$x_{\odot} = R_{Sun} * \cos\left(sin^{-1}\left(\frac{(x - x_{center})}{R_{Sun}}\right)\right)$$
$$y_{\odot} = R_{Sun} * \sin\left(sin^{-1}\left(\frac{x - x_{center})}{R_{Sun}}\right)\right)$$
$$z_{\odot} = R_{Sun} * \sin\left(sin^{-1}\left(\frac{(y - y_{center})}{R_{Sun}}\right)\right)$$

Next, the rotation of the image relative to solar north needs to be accounted for:

$$x_{derotated} = x_{\odot} * cos(\beta) + z_{\odot} * sin(\beta)$$
$$y_{derotated} = -1 * x_{\odot} * sin(P) * sin(\beta) + y_{\odot} * cos(\beta) + z_{\odot} * sin(P) * cos(P)$$
$$z_{derotated} = -1 * x_{\odot} * cos(P) * sin(\beta) - y_{\odot} * sin(P) + z_{\odot} * cos(P) * cos(\beta)$$

Finally, the conversion to Stonyhurst heliographic latitude/longitude can be performed:

$$\varphi_{Stonyhurst} = \left(\frac{360°}{2\pi}\right) * tan^{-1}\left(\frac{z_{derotated}}{\sqrt[2]{(x_{derotated}^2 + y_{derotated}^2)}}\right)$$
$$\lambda_{Stonyhurst} = \left(\frac{360°}{2\pi}\right) * tan^{-1}\left(\frac{y_{derotated}}{x_{derotated}}\right)$$

Heliographic latitude is equivalent between Stonyhurst and Carrington coordinates:

$$\varphi_{Carrington} = \varphi_{Stonyhurst}$$

For the Carrington longitude, the Stonyhurst longitude is added to an offset to account for the Carrington rotation:

$$\lambda_{Carrington} = modulus((\lambda_{Stonyhurst} + L_0), 360)$$

$$L_0 = 360 * \left(1 - \frac{t_{rot}\ (days)}{27.2753\ days}\right)$$

7 REFERENCES

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