NOAA NESDIS
Center for Satellite Applications and Research

GOES-R Advanced Baseline Imager (ABI) Algorithm Theoretical Basis Document For Cloud and Moisture Imagery Product (CMIP)

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Version 4.1
March 18, 2024

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ACRONYMS

ABI – Advanced Baseline Imager
AIT – Algorithm Integration Team
ARW – Advanced WRF
ATBD – Algorithm Theoretical Basis Document
AU – Astronomical Unit
AWG – Algorithm Working Group
AWIPS – Advanced Weather Interactive Processing System
BT – Brightness Temperature
BV – Brightness Value
CDR – Critical Design Review
CF – Climate and Forecasts
CFD – Continuous Full Disk
CGMS – Coordination Group for Meteorological Satellites
CIMSS – Cooperative Institute for Meteorological Satellite Studies
CMIP – Cloud and Moisture Imagery Product
CODATA – Committee on Data for Science and Technology
CONUS – Contiguous United States
CRTM – Community Radiative Transfer Model
DC – Digital Count
EDF – Empirical Distribution Function
ENVI – [software package]
EQW – Equivalent Width
FD – Full Disk
FGF – Fixed Grid Format
F&PS – Functional and Performance Specification
GFS – Global Forecast System
GPO – GOES-R Program Office
GRB – GOES ReBroadcast
GS – Ground Segment
GVAR – GOES Variable
HDF – Hierarchical Data Format
IDL – Interactive Data Language
IDV – Integrated Data Viewer
IR – InfraRed
ITT – ITT Industries
I&VT – Imagery and Visualization Team
IV&V – Independent Verification and Validation
KPP – Key Performance Parameter
L1B – Level 1B
McIDAS – Man computer Interactive Data Access System
MRD – Mission Requirements Document
MTF – Modulation Transfer Function
NCSA – National Center for Supercomputing Applications
NetCDF – Network Common Data Format

NIST – National Institute of Standards and Technology
PCI – [data visualization tool]
PORD – Performance Operation Requirement Document
PUG – Product Definition and User's Guide
QC – Quality Control
SOI – Successive Order of Integration
SR – Scaled Radiance
SNR – Signal-to-Noise Ratio
SRF – Spectral Response Function
SSEC – Space Science & Engineering Center
TBD – To Be Determined
TBV – To Be Verified
TOA – Top Of Atmosphere
TRR – Test Readiness Review
UTC – Universal Time Coordinated
UW – University of Wisconsin
VAGL - Vendor-Allocated Ground Latency
WRF – Weather Research and Forecasting

ABSTRACT

This document provides a theoretical description of the algorithms used by the Cloud and Moisture Imagery Product (CMIP) from the Advanced Baseline Imager (ABI) onboard the GOES-R series. The topics covered in this document include requirements for CMIP algorithms and software system, description of CMIP key algorithms, test data sets and outputs, practical considerations, and assumptions and limitations.

The GOES-R ABI observes the Western hemisphere in various time intervals and at 0.5, 1, and 2 km spatial resolutions in visible, near-IR, and IR wavelengths. The ABI has two main scan modes, of which the one used most often allows a full disk image every 10 minutes, along with a Contiguous U.S. (CONUS) image every 5 minutes, and a mesoscale image as often as every 30 seconds (or two locations every minute). CMIP is the ABI tier 1A and Key Performance Parameter (KPP) product, including 16 ABI single-band images for 3 coverage areas plus the multi-band spectral products for each coverage area in NetCDF, which are being used for various applications and other algorithms.

GOES-R ABI CMIP algorithms have been tested on ABI simulated data covering the CONUS and nearly Full Disk areas. The generated image files have been compared with the validation data generated by the research code, and the images are effectively identical.

1 INTRODUCTION

Purpose of This Document

The primary purpose of this Algorithm Theoretical Basis Document (ATBD) is to provide a theoretical description (scientific and mathematical) of the algorithms used by the Cloud and Moisture Imagery Product (CMIP) from the Advanced Baseline Imager (ABI) onboard the GOES-R series of NOAA geostationary meteorological/environmental satellites. CMIP is the ABI tier 1A and KPP product.

Cloud and Moisture Imagery algorithms produce digital maps of clouds, moisture, and atmospheric windows, through which clouds, land and water are observed, from radiances for the visible, near-IR, and IR bands. Information is provided on the conversion from the GRB Counts to reflectance factor (ABI bands 1-6) and Brightness Temperatures (BT), employing the Planck function relationship (ABI bands 7-16). Cloud and Moisture Imagery provides input to other algorithms producing other environmental products.

Who Should Use This Document

The intended users of this document include: algorithm reviewers, who would understand the theoretical basis of CMIP; product users, who would use the product in an operational task; scientific programmers, who would develop new algorithms; and system administrators, who would maintain the software.

Inside Each Section

This document consists of the following main sections:

- **Product Overview**: provides relevant details of the ABI and a brief description of the products generated by the algorithm.

- **Product Requirement Description**: provides the detailed requirements for the CMIP key algorithms and software system.

- **Algorithm Description**: provides the details for CMIP processing outline, input/output parameters and key algorithms.

- **Test Data Sets, and Output**: provides a description of the test data sets used to characterize the performance of the algorithms and quality of the data products. It also describes the results of using test data sets.

- **Practical Considerations**: provides a description of the issues involving CMIP software system programming, quality assessment, diagnostics, and exception handling.

- **Assumptions and Limitations**: provides an overview of the current assumptions and limitations of the approach and a plan for overcoming these limitations with further algorithm development.

Related Documents

GOES-R Ground Segment (GS) Functional and Performance Specification (F&PS).

GOES-R Series Ground Segment Project Notional Transition from GVAR to GRB Operations Plan

GOES-R Mission Requirements Document (MRD)

GOES-R Product Definition and Users' Guide (PUG) Volume 5 (L2+ Products) https://www.goes-r.gov/resources/docs.html#user

Revision History

Version 0.1 was created by Wenhui Wang of NOAA/NESDIS/STAR and I. M. System Groups to accompany the delivery of the version 0.1 algorithm to the GOES-R AWG Algorithm Integration Team (AIT). T. Schmit added several sections.

Version 1.0 of this document was the official adaptation of Version 0.1.

Version 2.0 was developed by Gang Fu of NOAA/NESDIS/STAR and PSGS based on the GOES-R Imagery Critical Design Review (CDR) and Test Readiness Review (TRR) to meet 80% ATBD requirement. This version was reviewed by many, including T. Schmit of NOAA/NESDIS/STAR.

Version 2.0 was completed by T. Schmit (and others), leveraging the many comments from the Independent Verification and Validation (IV&V) reviewers.

Version 2.2 was completed by T. Schmit (and many others), reflecting the change from 14 bits per pixel for most bands and the decision to scale all bands to radiance for the GRB datastream. Don Hillger and Mike Weinreb provided many improvements.

Version 2.3 includes updates related to the down-scaling methodology.

Version 2.4 accommodates the newly defined visible radiance units, along with several clarifications.

Version 4.0 was completed by M. Gunshor to accommodate changes after the launch of GOES-16 (-R) and GOES-17 (-S). This version includes updated information requested by users concerning how to calculate latitude and longitude and how to convert radiance to CMIP units (reflectance factors or brightness temperatures). This version also leverages other documents, such as the Product Users Guides, that didn’t exist earlier.

Version 4.1 was completed by M. Gunshor to accommodate changes associated with GOES-U.

2 PRODUCT OVERVIEW

This section describes the CMIP and the requirements it places on the system.

2.1 Products Generated

The CMIP are produced using all 16 bands in three coverage areas: FD, CONUS, and mesoscale. Bands 1-6 are the visible bands (1 and 2) and near-IR (3-6), while bands 7-16 are IR bands.

The CMIP is responsible for ABI cloud and moisture imagery, and will produce these end-products, including:

- 16 ABI single-band products ([spectral] radiance in bands 1-16) for 3 coverage sectors, each at full spatial resolutions, in NetCDF4 format
- Multi-band spectral products (16 bands at 2 km resolution) for 3 coverage sectors in NetCDF4 format

The three coverage sectors are for full disk, CONUS and mesoscale. The coverage sectors which are available is determined by which scan mode the ABI is in. Additionally, the CMIP end-products will include the information about the methods of converting radiance to reflectance factor for bands 1-6, and converting radiance to brightness temperature (BT). The brightness value (BV) conversion is included, for completeness. By community convention the term “radiance” is used throughout this document and actually refers to a spectral radiance; e.g., technically radiance is only at a single frequency, while spectral radiance is radiance per unit frequency (either wavelength or wavenumber). It should also be noted that the radiance is actually an average value, weighted by the sensor response for that given band.

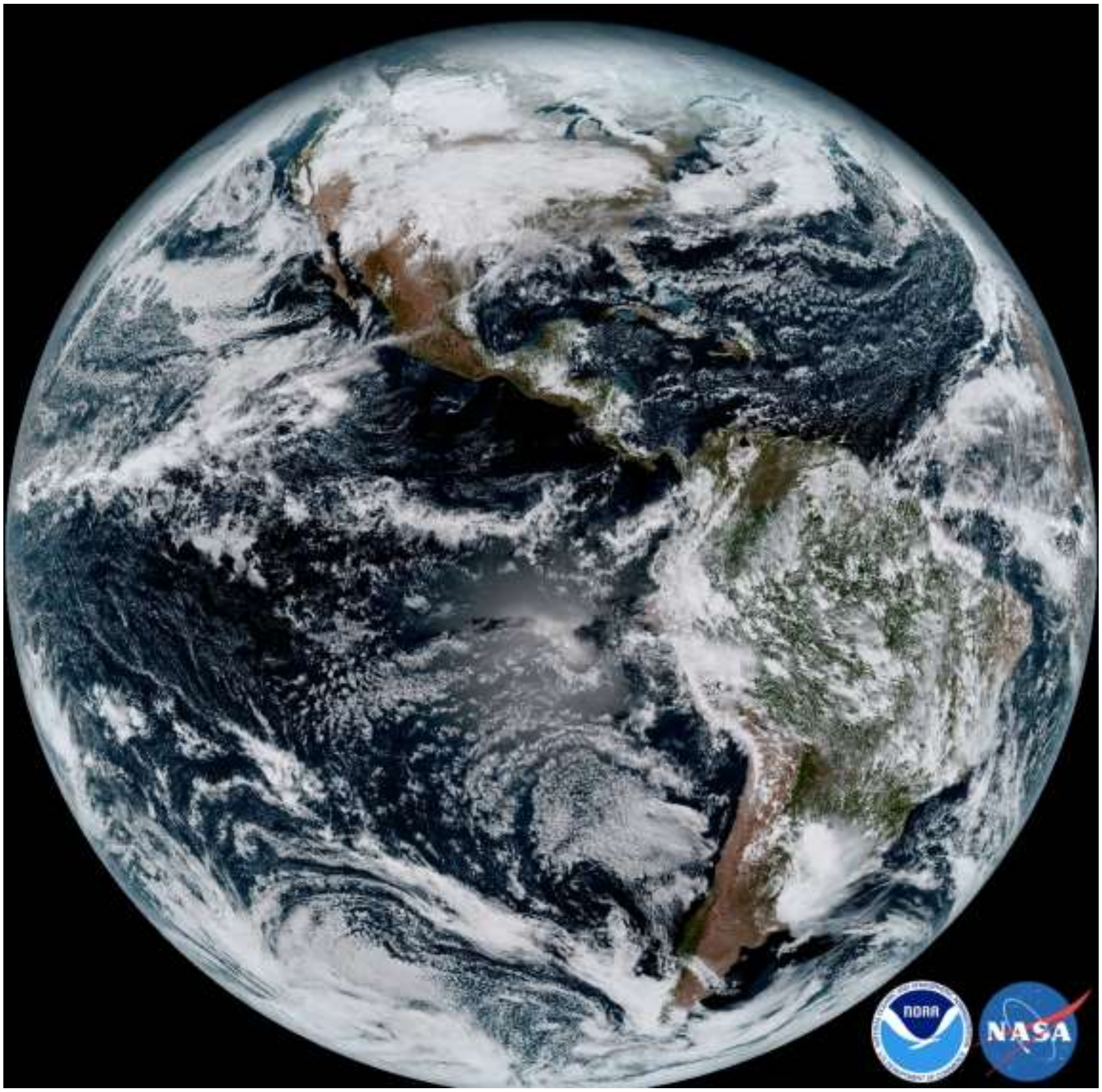

Figure 1. GOES-16 First Light full-disk composite color visible image. Captured at 1:07 PM EST on January 15, 2017 and created using several of the 16 spectral channels available on the ABI. The image shows North and South America and the surrounding oceans. GOES-16 observes Earth from an equatorial view approximately 22,300 miles high, creating full disk images like these from the coast of West Africa, to Guam, and everything in between.

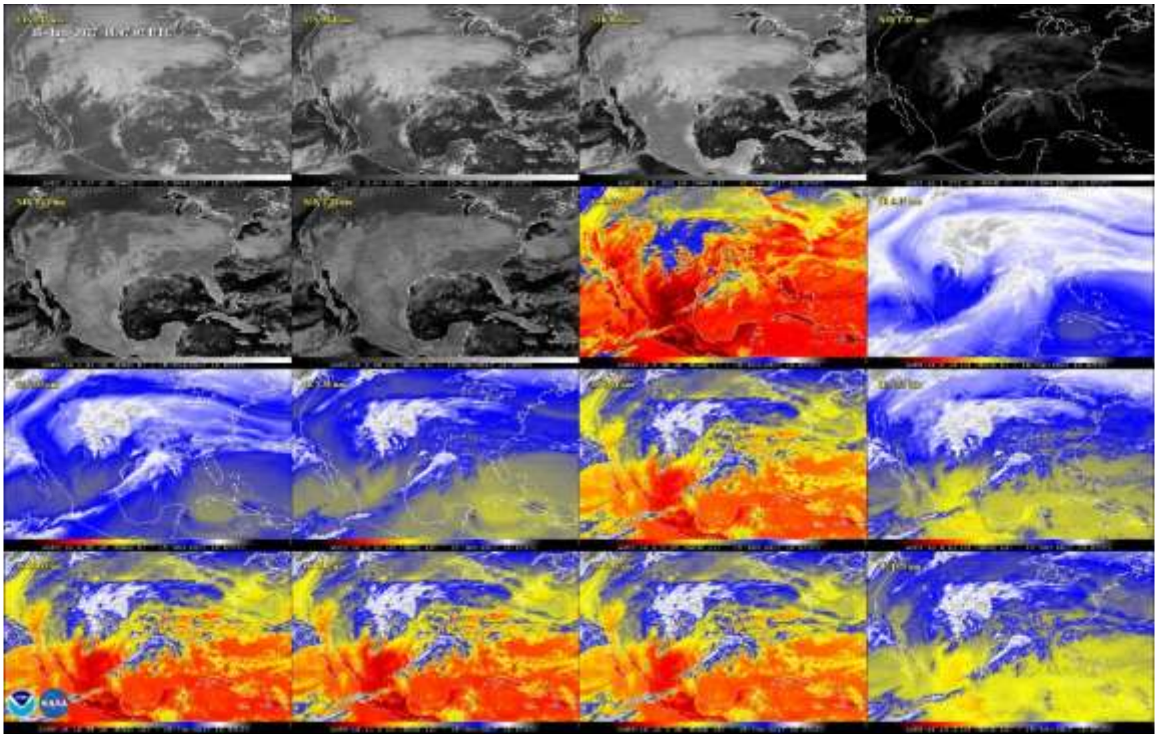

Figure 2. GOES-16 First Light CONUS image. This 16-panel image shows the continental [contiguous] United States in the two visible, four near-infrared and 10 infrared channels on ABI. These channels help forecasters distinguish between differences in the atmosphere like clouds, water vapor, smoke, ice and volcanic ash. GOES-16 has three-times more spectral channels than earlier generations of GOES satellites. The significant storm system that crossed North America on January 15, 2017 and caused freezing and ice that resulted in dangerous conditions across the United States is clearly visible.

2.2 Instrument Characteristics

The ABI on the GOES-R series has 16 spectral bands. The selection of each covers a variety of environmental applications (Schmit et al., 2017; Schmit et al., 2018; Schmit et al., 2019; Gunshor et al, 2020). ABI Infrared (IR) bands have been chosen to coincide either with spectral absorption features (including those of water vapor bands or CO_2 bands) or with regions having little absorption (atmospheric windows) that permit observations of the surface. Visible and near-IR bands have been chosen in order to sense lower tropospheric cloud cover (including fog) and the Earth's surface (NOAA/NESDIS 2007).

Table 1 summarizes the instrument (nominal) central wavelength, spatial resolution (at the sub-point), and bit-depth characteristics of the ABI data in the data stream transmitted to users—the GOES ReBroadcast (GRB). The instrument has three basic modes of operation:

1. Every 15 minutes, ABI will scan the full disk (FD) once, plus the contiguous United States (CONUS) three times (every 5 minutes). A selectable 1000 km × 1000 km mesoscale area will be scanned every 30 seconds. This has been referred to as mode 3 (or 'flex' mode).

2. The ABI can be programmed to scan the FD iteratively. The FD image can be acquired in approximately 5 minutes (Schmit et al. 2005). This mode has been referred to as mode 4 or the Continuous Full Disk (CFD).

3. Every 10 minutes, ABI will scan the full disk (FD) once, plus the contiguous United States (CONUS) two times (every 5 minutes). A selectable 1000 km × 1000 km mesoscale area will be scanned every 30 seconds. This has been referred to as mode 6 (or '10-minute flex' mode). This is the mode used most often.

Band Number	**Nominal Central Wavelength (µm)**	**Spatial Resolution (km)**	**CMIP Bit-Depth**	**Used in Cloud and Moisture Imagery**
1	0.47	1	12	X
2	0.64	0.5	12	X
3	0.86	1	12	X
4	1.37	2	12	X
5	1.61	1	12	X
6	2.24	2	12	X
7	3.90	2	14	X
8	6.19	2	12	X
9	6.93	2	12	X
10	7.34	2	12	X
11	8.44	2	12	X
12	9.61	2	12	X
13	10.33	2	12	X
14	11.2	2	12	X
15	12.3	2	12	X
16	13.3	2	12	X

Table 1. GOES-R ABI instrument characteristics.

The sensor bit-depth and consequently the bit depth of the associated L1b files, is less than the CMIP bit-depth for several of the bands. The bit depth of L1b files for bands 1, 3, 5-6, and 16 is 10; it is 11 for bands 4, 9, and 12; it is 12 for bands 2, 8, 10-11, and 13-15; it is 14 for band 7. Part of the rationale for bit depths of L1b files, which are transmitted via GRB, is to balance the need to ensure that the quantization step of the data does not add noise to the system while minimizing the amount of bandwidth needed to transmit the data. It is expected that the instrument's performance will be better than the specified allowable noise levels.

The central wavelengths listed in Table 1 are nominal for the GOES-R Series flight model spectral response functions. For more accurate calculations of central wavelength calculated from spectral response functions for each band, see Table 7 and Table 8.

2.3 Product Requirement Description

The CMIP performance requirements are derived from the GOES-R Series Ground Segment (GS) Functional and Performance Specification (F&PS) (NOAA/NASA 2010). The software system that generates routine CMIP shall meet the following requirements:

1. The system should be able to convert ABI Scaled Radiance (SR) obtained from the GOES ReBroadcast (GRB) data stream (L1B) into spectral radiance for bands 1-16.

2. The system should define the process for converting radiance to reflectance factor for the visible/reflective bands, and the process for converting radiance to BT for the IR bands.

3. The conversion methods and the associated parameters should be embedded in CMIP end-products. Users can still employ their own enhancements to the data values. For example, the users could employ a 'square root' function on the full bit depth data.

4. The CMIP end-products should be produced in NetCDF (version 4) format and can be produced/served in McIDAS AREA format. The McIDAS convention for GOES-R is 186 for the satellite sensor number and McIDAS Abstract Data Distribution Environment (ADDE) servers can serve the ABI netCDF formatted files directly and write them out as AREA. The NetCDF format will be Climate and Forecasts (CF) conventions compliant. More information can be found at: http://cf-pcmdi.llnl.gov

5. The CMIP should contain the geolocation information with respect to the Fixed Grid Format extracted from the input data stream.

6. The CMIP shall include metadata.

7. The system shall implement an interface to access input data (e.g., GRB) and to store the generated products.

8. The GOES-R system shall produce CMIP in accordance with the requirements listed in Table 2. CMIP Requirements:

	Threshold		
Geographic Coverage/Conditions	CONUS	FD	Mesoscale
Vertical Resolution	N/A	N/A	N/A
Horizontal Resolution	Band dependent, see Table 1		
Mapping Accuracy	1 km	1 km	1 km
Measurement Range	N/A	N/A	N/A
Refresh Rate/ Coverage Time (Mode 3—Flex Mode)	5 min	15 min	30 sec
Refresh Rate/ Coverage Time (Mode 4—Continuous Full Disk mode)		5 min	
Refresh Rate/ Coverage Time (Mode 6—10-Minute Flex Mode)	5 min	10 min	30 sec
VAGL	50 sec	50 sec	23 sec
Product Measurement Precision	N/A	N/A	N/A
Temporal Coverage Qualifier	Day and Night		
Product Extent Qualifier	N/A		
Cloud Cover Conditions Qualifier	N/A	N/A	N/A
Product Statistics Qualifier	N/A		
Primary Instrument	ABI		
Prioritization	1A		

Table 2. CMIP Requirements

3 ALGORITHM DESCRIPTION

This section describes the CMIP software system processing outline, input/output parameters, and key algorithms at their current level of maturity (will be improved with each revision).

3.1 Algorithm Overview

The CMIP algorithms consist of acquiring the radiometrically calibrated and remapped radiances and converting to CMI values (reflectance factor bands 1-6, brightness temperature for bands 7-16). The CMI can be converted to BV and used as indices either to customized color tables or to the red/green/blue color components of a composite image, resulting in enhanced imagery intending to highlight environmental features of interest. The GOES-R ABI CMIP radiometric algorithms are based on GOES 8-15 algorithms (Weinreb et al. 1997; Schmit et al. 1991). Algorithms for mapping TOA reflectance factor and BT to BV are based on examples from the literature (Acharya and Ray 2005; Russ 2002), commercial remote sensing data visualization tools (e.g., ENVI and PCI), and open source tools (e.g. McIDAS-X/V and IDV). Some display systems may be capable of displaying more than 8 bits (or 256 levels). The bit-depth of the end-products for CMIP is 12 bits for all the bands, with the exception of band 7, which is 14 bits. Hence, the enhancements need to be applied on the user display side and not converted to only 8 bits, for example.

CMIP algorithms are responsible for:

1. Re-sampling bands 1, 3, and 5 from 1 km to 2 km for multi-band product. Re-sampling band 2 from 0.5 km to 2 km for multi-band product.

2. Converting to Reflectance Factor (RF) for bands 1-6 and converting the spectral radiance to equivalent BT (bands 7-16).

3. Maintain/generate meta-data.

3.2 Processing Outline

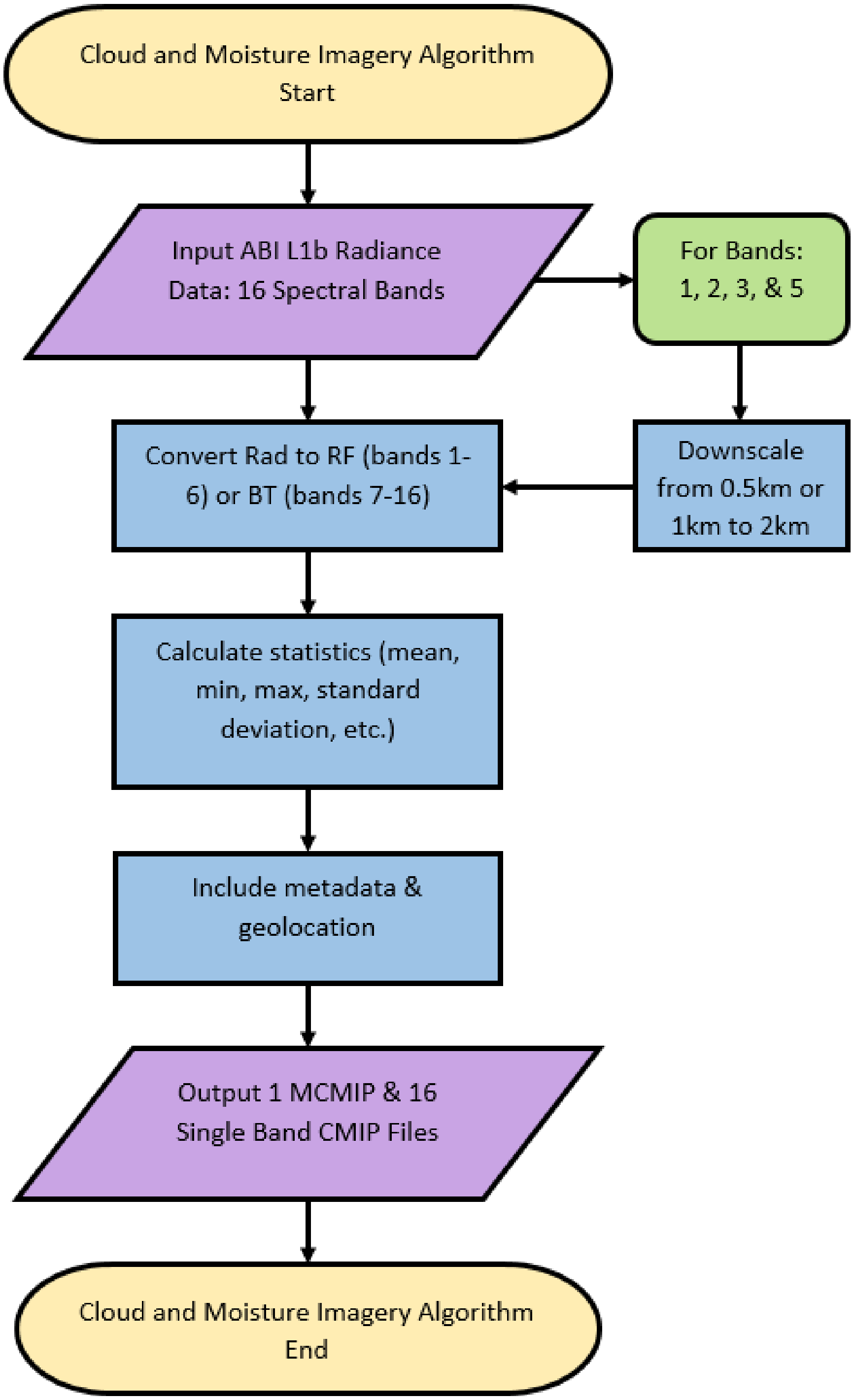

Figure 3. High level flowchart for generating CMIP (for every sector scanned). Note that bands 1,2, 3 & 5 are downscaled to 2km for the multi-band CMIP file, but kept at their 0.5 or 1km resolutions for the individual band files

3.3 Algorithm Input

3.3.1 Primary Sensor Data

The input data to the CMIP algorithm for processing the KPP are the GRB scaled radiance (SR) data (level 1b; provided as digital counts), scaling coefficients and calibration coefficients (also available from the GRB data stream). The scaling coefficients are used to convert GRB SR data to RF for the ABI bands 1 - 6. The Planck calibration coefficients are used to convert to BT for bands 7-16 (e.g., the modified Planck equation values).

The details regarding the actual format and data structures of the GRB are covered in the GOES-R Product User Guide (PUG) documents and hence are not covered in detail in this document.

Tables 3 and 4 show the slope and intercept used in conversion to (and from) SR similar to the work by Hillger and Schmit (2004). The slope and intercept are chosen from a trade-off of two competing interests: 1) accommodate all realistic values of scene radiance for a given band for the lifetime of the satellite series, and 2) use the full dynamic range to maximize the radiometric resolution of the data (Schmit et al. 1991). In CMIP, scale coefficients (slopes and intercepts in Table 4) are also used to convert scaled data to un-scaled quantities. Table 3 shows the values for converting calibrated radiance data to SR for GRB, while Table 4 shows the values for converting the SR into radiances. For Table 3, the slope is the ratio of the number of bits over the radiance range; the intercept is the slope times the negative of the minimum radiance. Note that the radiance units differ between bands 1-6 and 7-16. For Table 4, the slope is calculated as the inverse of the slope from Table 3, while the intercept is negative of the ratio of the intercept to slope from Table 3.

Band Number	Central Wavelength (µm)	Min Value	Max Value	Slope	Intercept
1	0.47	-25.93664701	804.03605737	223.181819	127.968746
2	0.64	-20.28991094	628.98723908	152.709137	127.968748
3	0.86	-12.03764377	373.16695681	141.862818	127.968750
4	1.38	-4.52236858	140.19342584	148.871147	127.968751
5	1.61	-3.05961376	94.84802665	161.462553	127.968749
6	2.26	-0.96095066	29.78947040	263.337115	127.968750
7	3.9	-0.0114	24.962	656.028511	7.478725
8	6.15	-0.1692	28.366	143.505961	24.281209
9	7.0	-0.2472	44.998	90.507438	22.373439
10	7.4	-0.2871	79.831	51.112173	14.674305
11	8.5	-0.3909	134.93	30.261915	11.829383
12	9.7	-0.4617	108.44	37.602788	17.361207

13	10.35	-0.4935	183.62	22.241413	10.976137
14	11.2	-0.5154	198.71	20.554123	10.593595
15	12.3	-0.5262	212.28	19.242580	10.125446
16	13.3	-1.5726	170.19	23.841254	37.492756

Table 3. Slope and intercept to convert from the calibrated radiance data to SR in GRB (the Min/Max Values are given in terms of radiance units (W/ m^2•sr• µm) for bands 1-6 and (mW/(m^2•sr•cm^{-1})) for bands 7-16.

Band Number	Central Wavelength (µm)	Min Value	Max Value	Slope	Intercept
1	0.47	-25.93664701	804.03605737	0.202679537	-25.9366
2	0.64	-20.28991094	628.98723908	0.158553639	-20.2899
3	0.86	-12.03764377	373.16695681	0.094067058	-12.0376
4	1.38	-4.52236858	140.19342584	0.035339632	-4.52237
5	1.61	-3.05961376	94.84802665	0.02390907	-3.05961
6	2.26	-0.96095066	29.78947040	0.00750926	-0.96095
7	3.9	-0.0114	24.962	0.001524	-0.011400
8	6.15	-0.1692	28.366	0.006968	-0.169200
9	7.0	-0.2472	44.998	0.011049	-0.247200
10	7.4	-0.2871	79.831	0.019565	-0.287100
11	8.5	-0.3909	134.93	0.033045	-0.390900
12	9.7	-0.4617	108.44	0.026594	-0.461700
13	10.35	-0.4935	183.62	0.044961	-0.493500
14	11.2	-0.5154	198.71	0.048652	-0.515400
15	12.3	-0.5262	212.28	0.051968	-0.526200
16	13.3	-1.5726	170.19	0.041944	-1.572600

Table 4. Slope and intercept to convert from the GRB SR to radiances (the Min/Max Values are given in radiance units (W/ m^2•sr• µm) for bands 1-6 and (mW/(m^2•sr•cm^{-1})) for bands 7-16.

The values in Table 3 would be used when one is generating GRB (at a central facility). The minimum and maximum values listed in Table 3 and 4 represent the bounds of the spectral radiances. These values are larger than the instrument minimum and maximum values, to limit data being 'clipped' on either end. Coefficients (slopes and intercepts) for converting data to radiance are also input parameters for CMIP. Even though the coefficients are not expected to change during the mission lifetime, they should be obtained from the GRB data stream. The values in Table 4 would be used to un-scale the SR by the many users. Table 5 contains the maximum radiance values used for the generation of the maximum values in Tables 3 and 4. Details about the minimum and maximum values for the solar bands can be found in Padula (2011).

Band Number	Central Wavelength (µm)	Min Rad for Scaling	Max Rad for Scaling	Min Rad - Noise	Max Rad + Noise
1	0.47			-25.93664701	804.03605737

2	0.64			-20.28991094	628.98723908
3	0.86			-12.03764377	373.16695681
4	1.38			-4.52236858	140.19342584
5	1.61			-3.05961376	94.84802665
6	2.26			-0.96095066	29.78947040
7	3.9	0	24.95	-0.0114	24.962
8	6.15	0	28.197	-0.1692	28.366
9	7.0	0	44.751	-0.2472	44.998
10	7.4	0	79.544	-0.2871	79.831
11	8.5	0	134.54	-0.3909	134.93
12	9.7	0	107.98	-0.4617	108.44
13	10.35	0	183.13	-0.4935	183.62
14	11.2	0	198.2	-0.5154	198.71
15	12.3	0	211.76	-0.5262	212.28
16	13.3	0	168.62	-1.5726	170.19

Table 5. Min/Max Values are given in radiance units are (W/ m^2•sr• µm) for bands 1-6 and (mW/(m^2•sr•cm^{-1})) for bands 7-16. A factor of three was used for the IR band spec noise.

3.3.2 Ancillary Data

Many parameters are acquired from the GRB data stream. This includes, but is not limited to: GRB counts of SR, un-scaling coefficients, conversion information to reflectance factor, modified Planck conversion coefficients, day/time stamps, etc.

3.3.3 Derived Data

There is no derived data.

3.4 Theoretical Description

3.4.1 Radiometric Calibration

3.4.1.1 Un-scaling SR to Spectral Radiance (bands 1-16)

The radiance is derived from the SR value. A linear conversion is required:

$$L_\nu = m_\nu * SR_\nu + b_\nu \tag{3-1}$$

where L_ν is spectral radiance ((W/ m^2•sr• µm) for bands 1-6) and (mW/(m^2•sr•cm^{-1}) for bands 7-16) for a band characterized by central wavenumber ν, SR_ν is digital counts of the SR, and m_ν (slope) and b_ν (offset) are scaling coefficients obtained from the GRB data stream and in the L1b file structure are called scale_factor and add_offset. Note that when reading the variable "Rad" from a L1b netCDF file, depending on the netCDF libraries used, the software may automatically unscale the SR to radiance values using the scale_factor and add_offset provided as attributes to the Rad variable.

3.4.1.2 Converting to Reflectance Factor (bands 1-6)

Given the proper amount of ancillary data, the radiance data can be converted into reflectance factor units (nominally 0-1) for bands 1-6. This is generated using what is called the 'kappa (κ) factor' $((\pi \cdot d^2)/E_{sun})$ to convert between reflectance factors and [spectral] radiances (W/ m^2•sr• μm); which are the GOES-R units for bands 1-6. Kappa represents the incident Lambertian-equivalent radiance, where d is the instantaneous Earth-Sun distance (in Astronomical Units) and E_{sun} is the solar irradiance in the respective bandpass (in W/(m2 μm)). The kappa factor is included in the product metadata as the variable "kappa0". The solar irradiance and Earth-Sun distance are also represented as variables "esun" and "earth_sun_distance_anomaly_in_AU", respectively. Equation 3-2 shows how "Kappa" (κ) is used to convert from radiance (L_v) to reflectance factor (pf_v), while the reciprocal of Kappa is used to convert from reflectance factor to radiance.

$$pf_v = \kappa L_v \qquad (3\text{-}2)$$

Inputs needed are the in-band solar irradiance at 1 Astronomical Unit (AU), E_{sun} for each of the first six ABI bands, a correction (e.g., ratio) for the earth-sun distance (*d*) ratio and the value of π. The parameter *d* is the ratio of the actual distance (as acquired via the GRB) to the mean earth-sun distance. The relationship is the reflectance factor (ρf_υ) multiplied by E_{sun}, divided by π and the distance correction squared. Θ is the solar zenith angle. E_{sun} and the distance pare provided as part of L1b and L2 CMIP files. Equation 3-3 is the relationship between the reflectance factor (left-hand side) and the reflectance (ρ_υ).

$$\rho f_\upsilon = \rho_\upsilon \bullet \cos(\Theta) \qquad (3\text{-}3)$$

$$L_\upsilon = \frac{\rho f_\upsilon \bullet Esun_\upsilon}{\pi \bullet d^2} \qquad (3\text{-}4)$$

$$\rho f_\upsilon = \frac{L_\upsilon \bullet \pi \bullet d^2}{Esun_\upsilon} \qquad (3\text{-}5)$$

Equation 3-5 shows how the radiance data will be converted from radiance into reflectance factor. The values for E_{sun} and d are provided via the GRB. The value of π should be consistent between the generation of radiance for the GRB and the conversion in 3-5 to compete the reflectance factor.

Table 6 shows the values of E_{sun} for GOES-16 and GOES-17; these values are derived from spectral response functions and therefore vary between ABI flight models. Note that the solar constant used is 1366.1 W/m^2. At publication these values are on NOAA's GOES calibration website: https://www.star.nesdis.noaa.gov/GOESCal/GOES-R_ABI_Esun_table.php

Band Number	**Central Wavelength (µm)**	**GOES-16 E_{sun} (W/(m^2·µm))**	**GOES-17 E_{sun} (W/(m^2·µm))**	**GOES-18 E_{sun} (W/(m^2·µm))**	**GOES-19 E_{sun} (W/(m^2·µm))**
1	0.47	2017.165	2041.687	2042.551	2043.881
2	0.64	1631.335	1628.08	1624.774	1623.612
3	0.86	957.0699	955.5531	954.0097	954.143
4	1.38	360.9018	361.5188	358.9279	355.3487
5	1.61	242.5404	242.644	239.4179	239.3367
6	2.26	76.8999	77.00672	76.2168	76.08472

Table 6. E_{sun} values for GOES-R Series ABI.

3.4.1.3 Converting Spectral Radiance to BT (bands 7-16)

Planck Function constants are used for the conversion between radiance (mW/(m^2·sr·cm^{-1})) and BT (K) or vice versa. To convert from radiance to temperature (K):

$$T = [\text{fk2} / (\text{alog}((\text{fk1} / L_\lambda) + 1)) - \text{bc1}] / \text{bc2} \qquad (3\text{-}6)$$

To convert from temperature (K) back to radiance (mW/(m^2·sr·cm^{-1})):

$$L_\lambda = \text{fk1} / [\exp (\text{fk2} / (\text{bc1} + (\text{bc2} * T))) - 1] \qquad (3\text{-}7)$$

The SR need to be un-scaled to radiance and then converted according to equation 3-6. The coefficients calculated for GOES-16 ABI are listed in Table 7 and for GOES-17 ABI, Table 8. Note that these will be different for each satellite as they are SRF dependent. Note the units of fk1 are the same as the radiance units for IR bands (mW/(m^2·sr·cm^{-1})), the units of fk2 and bc1 are the units of temperature (K), and bc2 is unitless.

Band Number	**Central Wavelength (µm)**	**Central Wavenumber (cm^{-1})**	**fk1 (mW/(m^2·sr·cm^{-1}))**	**fk2 (K)**	**bc1 (K)**	**bc2 (none)**
7	3.89	2570.37	202263.00	3698.19	0.43361	0.99939
8	6.17	1620.53	50687.10	2331.58	1.55228	0.99667
9	6.93	1443.55	35828.30	2076.95	0.34427	0.99918
10	7.34	1363.23	30174.00	1961.38	0.05651	0.99986
11	8.44	1184.22	19779.90	1703.83	0.18733	0.99948
12	9.61	1040.89	13432.10	1497.61	0.09102	0.99971

13	10.33	968.00	10803.30	1392.74	0.07550	0.99975
14	11.19	894.00	8510.22	1286.27	0.22516	0.99920
15	12.27	815.29	6454.62	1173.03	0.21702	0.99916
16	13.27	753.79	5101.27	1084.53	0.06266	0.99974

Table 7. Planck Coefficients for GOES-16. Note central wavenumber is a weighted average calculated from the SRF and the central wavelength is 10,000 / central wavenumber.

Band Number	**Central Wavelength (µm)**	**Central Wavenumber (cm^{-1})**	**fk1 ($mW/(m^2 \cdot sr \cdot cm^{-1})$)**	**fk2 (K)**	**bc1 (K)**	**bc2 (none)**
7	3.89	2574.06	203135.00	3703.50	0.44554	0.99938
8	6.17	1620.53	50687.10	2331.58	1.54088	0.99669
9	6.93	1442.62	35759.10	2075.61	0.33955	0.99919
10	7.34	1363.02	30160.00	1961.08	0.05653	0.99986
11	8.44	1182.87	19712.50	1701.89	0.19396	0.99946
12	9.61	1040.54	13418.50	1497.10	0.09143	0.99971
13	10.33	968.97	10835.60	1394.12	0.07786	0.99974
14	11.19	893.48	8495.35	1285.52	0.21781	0.99922
15	12.27	814.68	6439.94	1172.14	0.22019	0.99914
16	13.27	751.93	5063.58	1081.86	0.06224	0.99974

Table 8. Planck Coefficients for GOES-17. Note central wavenumber is a weighted average calculated from the SRF and the central wavelength is duplicated from GOES-16 in the file variable "band_wavelength."

Band Number	**Central Wavelength (µm)**	**Central Wavenumber (cm^{-1})**	**fk1 ($mW/(m^2 \cdot sr \cdot cm^{-1})$)**	**fk2 (K)**	**bc1 (K)**	**bc2 (none)**
7	3.89	2562.63	200441.00	3687.05	0.44868	0.99937
8	6.17	1616.86	50343.50	2326.30	1.69185	0.99636
9	6.93	1441.38	35666.70	2073.82	0.30974	0.99926
10	7.34	1362.04	30095.10	1959.67	0.05630	0.99986
11	8.44	1180.61	19599.40	1698.63	0.19307	0.99946
12	9.61	1042.77	13504.80	1500.30	0.09050	0.99972
13	10.33	968.45	10818.40	1393.39	0.07725	0.99974
14	11.19	891.30	8433.26	1282.38	0.22216	0.99921
15	12.27	816.34	6479.45	1174.53	0.21862	0.99915
16	13.27	753.79	5101.35	1084.54	0.06249	0.99974

Table 9 Planck Coefficients for GOES-18. Note central wavenumber is a weighted average calculated from the SRF and the central wavelength is duplicated from GOES-16 in the file variable "band_wavelength."

Band Number	Central Wavelength (µm)	Central Wavenumber (cm^{-1})	fk1 ($mW/(m^2 \cdot sr \cdot cm^{-1})$)	fk2 (K)	bc1 (K)	bc2 (none)
7	3.89	2561.81	200248.00	3685.87	0.48985	0.99931
8	6.17	1618.01	50451.50	2327.96	1.71389	0.99631
9	6.93	1440.76	35620.40	2072.92	0.29884	0.99929
10	7.34	1363.77	30210.00	1962.16	0.05458	0.99986
11	8.44	1177.42	19441.30	1694.05	0.13691	0.99962
12	9.61	1043.15	13519.80	1500.86	0.09101	0.99971
13	10.33	969.71	10860.40	1395.19	0.07481	0.99975
14	11.19	893.66	8500.63	1285.78	0.21051	0.99925
15	12.27	816.76	6489.46	1175.13	0.22448	0.99913
16	13.27	752.97	5084.62	1083.35	0.06004	0.99975

Table 10 Planck Coefficients for GOES-19. Note central wavenumber is a weighted average calculated from the SRF and the central wavelength is duplicated from GOES-16 in the file variable "band_wavelength."

The Planck function is used to convert between radiance and BT. There are equations that can be utilized that take into account the spectral width. The equation that has been in use since the early 1980s for GOES (and several other satellites) is 3-7. Since these equations use the central wavenumber (cwn) these values have been calculated as a weighted average from the individual band SRFs for each IR band on each ABI and presented in the tables. The central wavelengths (cwl) presented in each table were calculated for GOES-16 and then duplicated for subsequent ABIs. This is because cwl is not used in any calculations outlined in this ATBD and users tend to want a consistent value to use as nomenclature and in software packages. These cwl values can be rounded to suit whatever needs users want, but should generally not be used for calculations.

To calculate fk1 and fk2, use Boltzmann's Constant, Planck's Constant, and the velocity of light, along with the central wavenumber.

$$fk1 = 2 \cdot h \cdot c^2 \cdot cwn^3 \tag{3-8}$$

$$fk2 = h \cdot \frac{c}{b} \cdot cwn \tag{3-9}$$

h = Planck Constant (6.62606896 x 10^{-27} erg•s)
b = Boltzmann Constant (1.3806504 x 10^{-16} erg/K)
c = Velocity of light (2.99792458 x 10^{10} cm/s)
cwn = Central Wavenumber (cm^{-1})

Note that these values were considered correct as of 2006 (Mohr et al. 2007) but have been known to change. These are the values used for GOES-16 and GOES-17 and expected to be used for the entire GOES-R series. See Appendix B for further discussion.

For simplification, the first terms in the equations to calculate fk1 and fk2 can be combined as new constants, noted as C1 and C2.

$$C1 = 2 \cdot h \cdot c^2 \quad (3\text{-}10)$$

$$C2 = h \cdot \frac{c}{b} \quad (3\text{-}11)$$

C1 = 1.19104276 x10^{-5} mW/(m^2•sr•cm^{-4})
C2 = 1.43877516 K/cm^{-1}

The coefficients bc1 and bc2, once called ‘band correction’, are the intercept and slope from linear regression fits over equally spaced radiances between a monochromatic Planck conversion and one that integrates over the instrument SRF. The coefficients fk1, fk2, bc1, and bc2 are constants for a given spectral band and should only change if the SRF is changed. In the GRB files these are stored as variables “planck_fk1”, “planck_fk2”, “planck_bc1”, “planck_bc2”. The central wavenumber is not available and instead the central wavelength is provided and called, “central_wavelength.” While one could use this to calculate a central wavenumber (10,000/central_wavelength) this is only good for GOES-16 as the GOES-17 central_wavelength values are just duplicates of the GOES-16 values. The central wavenumber (cwn) used to calculate the fk1, etc values in the equations above is calculated using a weighted average method which takes into account the shape of the SRF.

ABI Flight model SRFs are available online as text files from the GOES-R Calibration Working Group (ncc.nesdis.noaa.gov/GOESR/ABI.php) or from the CIMSS GOES Calibration website (http://cimss.ssec.wisc.edu/goes/calibration/).

3.4.1.4 Converting ABI noise values between temperature and radiance space (bands 7-16)

Instrument specifications for noise are given in temperature (K) for the IR bands. The specification is for an amount of noise at a temperature of 300 K. This is called the Noise Equivalent delta Temperature (NEdT) and the maximum allowable NEdT by pre-launch specifications is 0.1 K for all IR bands except for band 16 (the 13.3 μm band) which is 0.3 K. The Noise Equivalent delta Radiance is referred to as NEdN (mW/(m^2•sr•cm^{-1})). There is a requirement that the quantization step be no larger than 0.5 times the NEdN. Since radiances are distributed and stored as digital counts, there can only be as many values as the bit depth allows (for instance, if data are 12-bits there are 2^{12} = 4096 values that can be used). The difference in radiance units between the values stored in these counts will be uniform across the range of available counts, though it is not uniform in BT. To calculate NEdN from BT, first the radiance at 300 K, where the NEdT is defined, must be calculated. This is done using the modified Planck function which takes into account the instrument’s spectral response, solving for radiance given a BT of 300 K:

$$L_\lambda(300) = \text{fk1} / [\ \exp(\text{fk2} / (\text{bc1} + (\text{bc2} * 300))) - 1\ ] \quad (3\text{-}12)$$

$$\text{NEdN} = L_\lambda(300 + \text{NEdT}) - L_\lambda(300) \quad (3\text{-}13)$$

NEdN is a constant value across the entire temperature range of the instrument. To calculate NEdT at a temperature other than 300 K, the NEdN can be used in conjunction with the modified inverse Planck Function and the modified Planck Function. For example, to calculate NEdT at 240 K, first the radiance at 240 K must be calculated:

$$L_\lambda(240) = \text{fk1} / [\exp(\text{fk2} / (\text{bc1} + (\text{bc2} * 240))) - 1] \quad (3\text{-}14)$$

$$T^+ = [\text{fk2} / (\text{alog}((\text{fk1} / (L_\lambda + \text{NEdN}) + 1)) - \text{bc1}] / \text{bc2} \quad (3\text{-}15)$$

$$\text{NEdT}(240) = T^+ - 240 \quad (3\text{-}16)$$

Equations 3-12 through 3-16 can be used to obtain the NEdT at any BT. Table 9 lists the NEdT values at 300, 240, and 200 K for the IR bands on the GOES-16 ABI.

Band	**Central wavelength (µm)**	**NEdT (@ 300 K) K**	**NEdT (@ 240 K) K**	**NEdT (@ 200 K) K**	**NEdN mW/(m^2•sr•cm^{-1})**
7	3.89	0.1	1.3364	12.3323	0.0037
8	6.17	0.1	0.4384	2.0028	0.0558
9	6.93	0.1	0.3595	1.3719	0.0817
10	7.34	0.1	0.3276	1.1454	0.0955
11	8.44	0.1	0.2653	0.7548	0.1288
12	9.61	0.1	0.2247	0.5418	0.1539
13	10.33	0.1	0.2067	0.4581	0.1642
14	11.19	0.1	0.1901	0.3865	0.1717
15	12.27	0.1	0.1743	0.3238	0.1754
16	13.27	0.3	0.4889	0.8451	0.5245

Table 11. Maximum allowable specified Noise Equivalent delta Temperature (NEdT) and Radiance (NEdN) for the infrared bands on the GOES-16 ABI. NEdT @300 K is given, the other values are derived from it. Note that these values were calculated using the flight model spectral response functions for GOES-16 as a basis for spec noise; these values, except column 3, will change for other ABI flight models and are not representative of actual noise measurements from the ABI.

3.4.2 Calculating BV

This section on BV is provided for information only, given that some users may be interesting in building Brightness Values for displaying the data.

The methods for mapping scaled radiances to integer BV (12/14-bit) are described in this section. Information on 8 bits per pixel is also included here for comparison, which requires mapping TOA reflectance factor and BT calculated from spectral radiance to BV.

For bands 1-6, at 12 bits per pixel, the conversion is simply:

BV12 = GRB_count (SR) (3-16)

The following equations are used to generate the 12-bit (for 9 of the IR bands) and the 14-bit (for ABI band 7) BV:

$$BV12 = abs\ (count- 2^{12} + 1) \quad (3\text{-}17)$$

$$BV14 = abs\ (count- 2^{14} + 1) \quad (3\text{-}18)$$

The square root method is recommended for the visible and near-IR bands as opposed to a linear stretch to BV because this brings out features on the dark end that are difficult to see otherwise. A bi-linear method is recommended for the IR bands when the information has be to ‘compressed’ to only 8 bits, because this will allow the user to better visual the desired range of temperatures for their application. There is a long history in both McIDAS and AWIPS of employing a bi-linear approach for the IR bands and a square root function for the reflective bands. These methods are employed for the 8-bit BV.

3.4.2.1 Bi-Linear Stretch

The Bi-Linear stretch method is recommended to be used for converting BT to BV for IR bands when using a display system that is only 8 bits per pixel (256 possible colors). The advantages and disadvantages of this method are summarized as follows:

- Advantages:
    1. Covers more temperature range than a 1K/1 count stretch.
    2. Heritage
    3. Low risks
    4. Efficient
    5. Algorithm is mature
- Disadvantages:
    1. Not as straight forward as a linear stretch

Assuming 8 bits per pixel in the display system, the bi-linear scaling method provides a linear amplitude transformation of input reflectance or radiance/BTs to output BV which compresses the data from GRB bit depth to 8-bit. The following equations are used in an if/then structure based on brightness temperature.

$$BV08 = 418 - BT \text{ (for “cold” scenes, } BT < 242\text{ K)} \quad (3\text{-}19)$$

$$BV08 = 660 - (2*BT) \text{ (for “warm” scenes, } BT >= 242\text{ K)} \quad (3\text{-}20)$$

where BV08 is the new BV, BT is the original value BT. This allows for two slopes at either side of a break point. For example, if the BT is less then 242 K, then BV08 = 418 – *T*; while for value equal or greater than 242 K, then BV08 = 660 – (2 * *T*). The minimum BV allowed is 0 and the maximum is 255.

Assuming the maximum bit depth (14 for band 7, 12 for other bands) is used for displaying the IR bands, then this 'bi-linear' approach will not be needed, since the information would not need to be similarly 'compressed'. However, it is difficult to maintain heritage color enhancements from an 8-bit bi-linear stretch to a modern display with more bits and a linear stretch.

3.4.2.2 Square Root Stretch

The Square Root stretch method is recommended to be used for converting TOA reflectance to BV for the visible and near-IR bands. Visible imagery includes features of interest that fall on the darker side of the basic 0 to 1 reflectance factor scale. For example, ocean and most land are darker than 0.5. Bright features, such as clouds, need no help via enhancement in being clearly seen in visible imagery. Most users find visible imagery without a square root stretch applied to be "too dark." The advantages and disadvantages of this method are summarized as follows:

- Advantages:
    1. Highlights important features that would have been too dark.
    2. Heritage
    3. Efficient
    4. Algorithm is mature
- Disadvantages:
    1. Not as straight forward as a linear stretch

The example here will be shown for an 8-bit system, but can be applied similarly to any display software. Power law stretch is a nonlinear algorithm that changes image brightness according to:

$$BV08 = y^n \tag{3-21}$$

where BV08 is the new BV for an 8-bit system, y is the original reflectance factor value, and n is the power scaling coefficient. If n > 1, high BV are enhanced disproportionately with respect to low values. If n < 1, low BV are enhanced disproportionately with respect to high values.

The square root enhancement is a special case of the power law stretch (n=1/2). It compresses the upper end of the reflectance factor spectrum and stretches the lower end. This method has been used for decades when displaying GOES visible data (and for many years for AWIPS displays). Reflectance factors darker than 0 would be mapped to a 0 BV, while values greater than 1 will be mapped to 255 (in an 8-bit system).

$$\text{BV08} = \text{NINT}(\text{SQRT}(\text{ReflFactor} * 100.) * 25.5) \tag{3-22}$$

Where NINT (or IDINT) is the "nearest integer" and SQRT is the square root function.

3.4.3 Down-scaling Algorithm

To produce CMIP multi-band end-products, it is necessary to have radiance data at 2 km resolution for all of the bands. This requires down-scaling the radiance data from 0.5 or 1 km to 2 km for ABI visible and near-IR bands (2 or 1, 3 & 5 respectively). Figure 4 shows how there are actually three FGF projections, each based on its spatial resolution (0.5, 1 and 2 km nominally at the satellite sub-point). Note that the reference of 2 km is the nominal resolution at the satellite sub-point. There are two methods for down-scaling: averaging or sub-sampling.

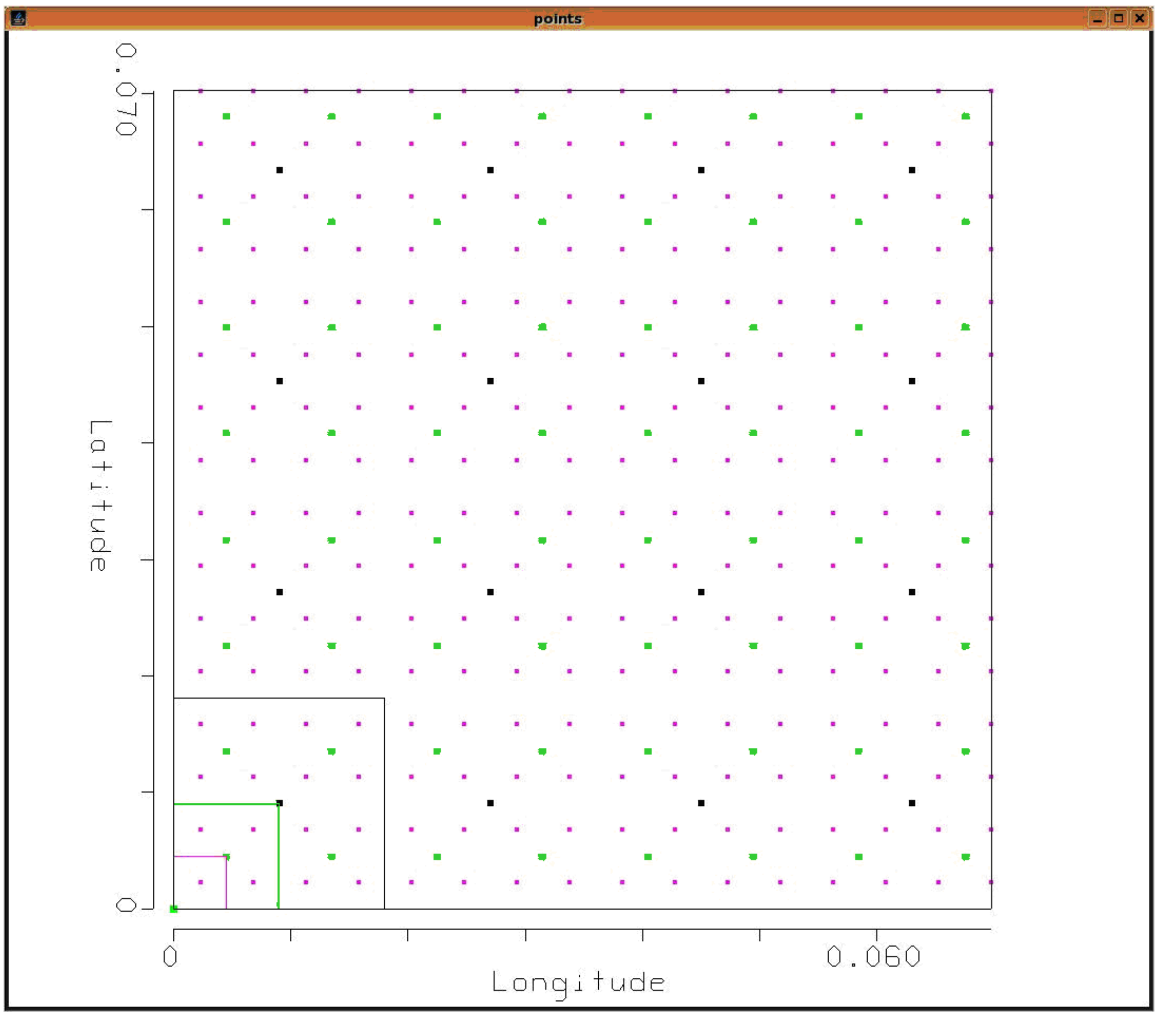

Figure 4. Pixel centers for the ABI FGF for the 0.5, 1 and 2 km. The magenta points represent the center of a 0.5 km pixel, the green points the center of a 1 km pixel and the black points the center of a 2 km pixel. The "lower-left dot" is the satellite sub-point, i.e., there is no pixel centered on the sub-point.

Averaging is the primary method by which the GOES-R ground system down-scales. An advantage of spatial averaging is that it can improve the signal-to-noise ratio and it may more closely match the 2 km IR bands with respect to implicit ‘area averaging.’ It smooths out gradients such that sharp gradient edges, the edge of a cloud for example, will appear smoother. This is especially noticeable when comparing 2 km bands to bands that had been 0.5 or 1 km in resolution prior to down-scaling. Averaging was chosen as the primary method because with sub-sampling it can appear that a feature at a sharp gradient, such as a cloud edge, has moved. This apparent movement is especially disruptive when comparing different bands and the location of a cloud edge, for example, does not match well between bands.

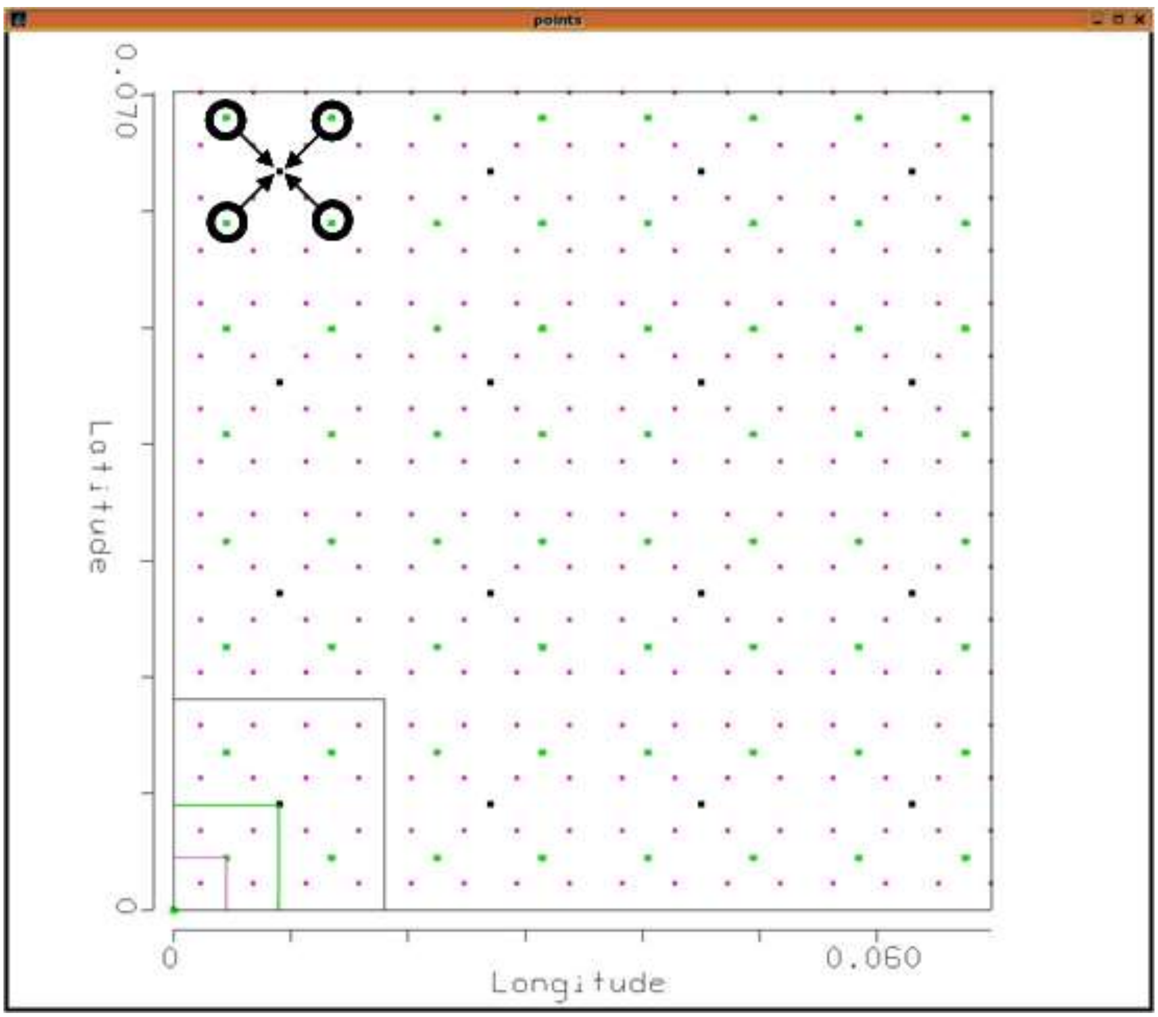

Figure 5. Averaging points for the ABI FGF for the 1 km data. Note the averaging method ‘re-projects’ to the 2 km FGF domain.

The sub-sampling algorithm is the other possible method of down-scaling and is described as follows for the 1 km bands:

$$g(x, y) = f(2x, 2y), \tag{3-23}$$

where $g(.)$ is the sub-sampled data and $f(.)$ is the original data. The g(x,y) array then needs to be re-projected to the 2 km Fixed Grid Format (FGF). For the 1 km data, start with the first pixel, which then gets "shifted" to the "north-east". That assumes the FGF for the coordinate of (0,0) being the most 'southwest' pixel. For example, pixels, (0,0), (0,2), (0,4), etc are selected. This is regardless of the value in any saturation or quality flag. Those corresponding flags will be carried along from the selected pixel.

The ABI band 2 spatial resolution is 0.5 km nominally, therefore more 'down-scaling' (e.g., a factor of 16) is needed for the multi-band files. For the 0.5 km data to 2 km, the pixel just "southwest" of the 2 km pixel will be used. For example, (1,1), (1, 5), (1,9), etc. Assuming (0,0) is in the 'southwest'.

The advantages of using the sub-sampling algorithm include that it is quicker, preserves image gradients, and does not create "artificial" values (values that fall in between scaled radiance values).

In either case, the down-sampling algorithm must account for data quality of the original resolution L1b data and act appropriately to carry data quality flags forward or properly handle missing and bad data pixels.

Users that need the full resolution data could still access the full resolution files (e.g., not the multi-band files). The method used for downscaling to 2km is noted in the multiband netCDF file metadata as an attribute called "downsampling_method" for the CMI variables for bands 1, 2, 3, and 5.

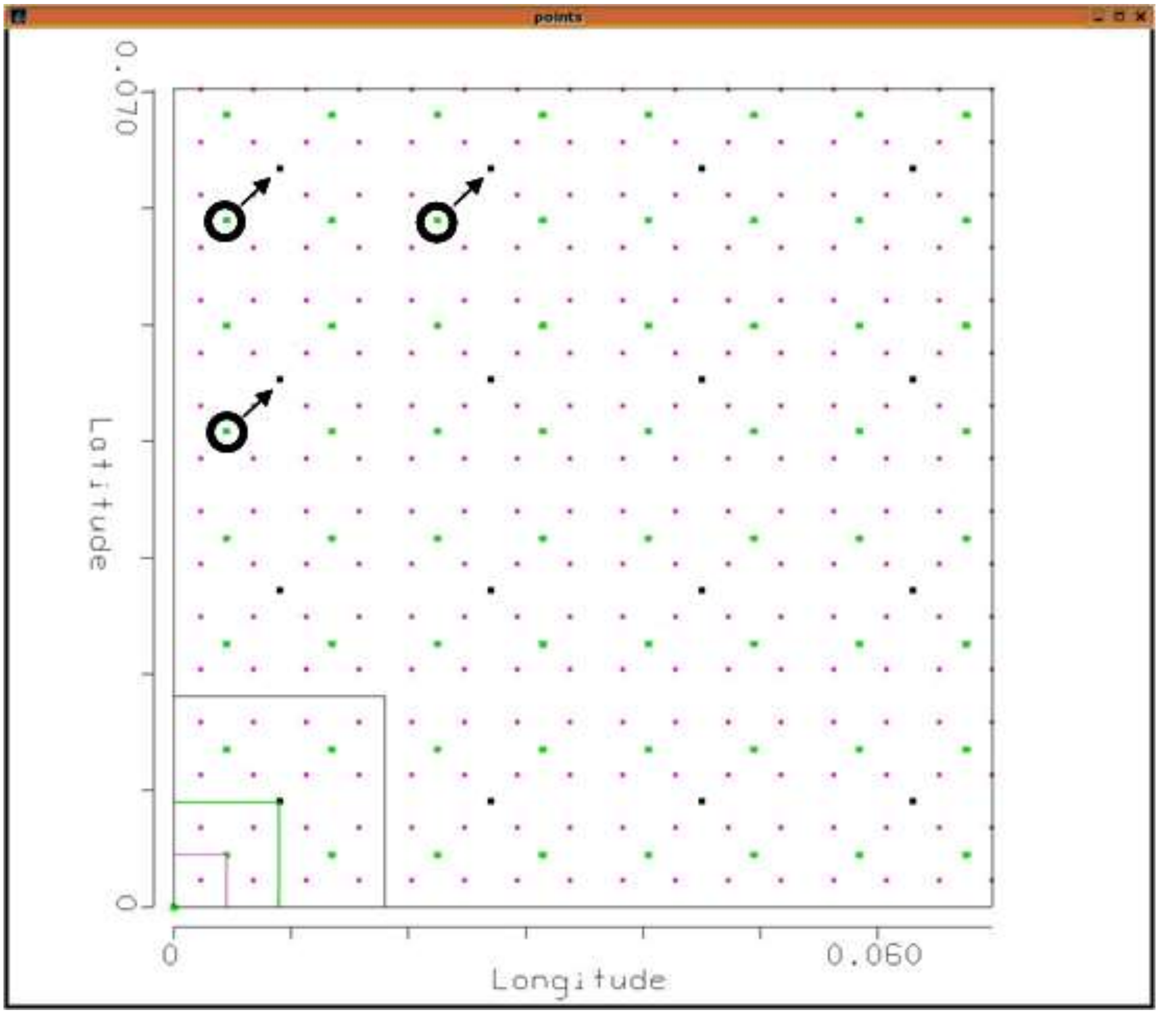

Figure 6. Sub-sampling points for the ABI FGF for the 1 km data. Note the sub-sampling method 're-projects' to the 2 km FGF domain.

3.4.4 Radiance Unit Conversions

The spectral radiance units will be mW/(m^2•sr•cm^{-1}), however, some users may be interested in switching to other units, such as (W/(m^2•sr•µm)). Therefore, the methodology is included here based on Cao and Heidinger (2002).

$$L_\lambda = \frac{L_\nu * EQW_\nu}{1000 * EQW_\lambda}, \qquad (3\text{-}24)$$

where $\mathbf{L_\nu}$ = Radiance in wavenumber (mW/(m^2•sr•cm^{-1}))
$\mathbf{L_\lambda}$ = Radiance in wavelength (W/(m^2•sr•µm))
1000 = convert W to mW
EQW_λ=Equivalent Width in wavelength (µm) space, which is the integral of the SRF in

µm
EQW_ν=Equivalent Width in wavenumber (cm^{-1}) space, which is the integral of the SRF in cm-1

UW SRF	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
Band EQW [cm-1]	1695.3619	2028.3127	464.8830	72.5596	174.3903	91.7739
Band EQW [µm]	0.0376	0.0826	0.0347	0.0137	0.0452	0.0462

Table 12. Equivalent Widths (EQW) for the six visible and near-IR bands on the GOES-16 ABI. Generated using Flight Level SRFs.

UW SRF	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
Band EQW [cm-1]	1682.6986	2078.7224	462.0279	72.5726	174.2840	91.5246
Band EQW [µm]	0.0373	0.0844	0.0345	0.0137	0.0451	0.0460

Table 13 Equivalent Widths (EQW) for the six visible and near-IR bands on the GOES-17 ABI. Generated using Flight Level SRFs.

Table 12 and Table 13 contain the EQW values for the GOES-16 and -17 flight SRFs.

3.5 Algorithm Output

The primary output of this algorithm is the Cloud and Moisture Imagery Product (CMIP) files which contain Reflectance Factor (bands 1-6) or Brightness Temperature (bands 7-16), or both in the case of a multi-band file for each pixel of the fixed grid format. The end-products produced: 16 files, one for each ABI band, for the 3 coverage areas (CONUS, FD, and mesoscale) in NetCDF format at the full spatial resolutions and 1 multi-band file (all 16 bands) at the spatial resolution of the IR bands (2 km) for each of the 3 coverage areas in NetCDF format. The supported format is NetCDF (version 4) format. Output can be converted from NetCDF to McIDAS-X AREA format. Also, the netCDF files can be served in McIDAS-X such that format is fairly transparent to a user, especially for the purposes of generating imagery. Note that McIDAS-X can serve the L1b radiance files, though the radiance units for 1-6 and 7-16 differ, convert to CMI and display CMI converted to BV. Users typically do not serve the actual CMIP files in McIDAS-X, but may choose to view them directly in other viewing software, such as McIDAS-V.

For a full disk 2 km image, the array size of CMIP file will be 5,424 by 5,424 pixels. For a mesoscale image, it will be 1,000 by 1,000. For a CONUS image it will be 2,500 pixels in the East-West direction and 1,500 pixels in the North-South direction. These values are doubled for the 1 km bands and quadrupled for the 0.5 km band 2.

Metadata

The output also includes metadata and geolocation information. Metadata is included in the netCDF file as dimensions, variables, variable attributes, and global attributes. The metadata in individual-band CMI files includes Data Quality Flags (DQF, per pixel), other data quality information, time bounds, projection and navigation information, band wavelengths, statistical information, conversion information to/from CMI values, product version, focal plane module information, and production information. Latitude and longitude information for each pixel is not stored. Instead, information is stored to describe the location of the data on the Fixed Grid. The projection coordinates for the array domain are stored in two 1-D arrays (one each for x and y) whose lengths match those of the data array dimension. Also included are the other data necessary to transform x & y into latitude and longitude, including the nominal sub-satellite point. The equation for conversion to latitude and longitude is in the GOES-R PUG (either volume 3, 4, or 5) along with example calculations.

Data Quality Flags

The data quality flags (DQF)s from L1b files are passed down to the CMIP files. They currently can have values between 0 and 4, where 0 is a "good pixel." The flags are named good_pixel_qf, conditionally_usable_pixel_qf, out_of_range_pixel_qf, no_value_pixel_qf, and focal_plane_temperature_threshold_exceeded_qf. The 5^{th} value (DQF=5) was added to provide some quality information based on GOES-17's compromised loop heat pipe (LHP) system and subsequently that ABI's inability to provide high quality data at all times.

4 TEST DATA SETS AND OUTPUTS

4.1 GOES-R Simulated Input Data Sets

Users now can obtain data from multiple locations, such as NOAA's Comprehensive Large Array-Data Stewardship System (CLASS), where all of the mission CMIP files are archived. NetCDF are also stored as part of the NOAA Big Data Project. Details on data access: http://cimss.ssec.wisc.edu/goes/goesdata.html#data. Prior to launch, simulated GOES-R ABI data had been used to develop, test, and validate the ABI CMIP products. The data were derived from use of a radiative transfer model, where the atmospheric and earth surface representations are provided by a high resolution numerical weather prediction forecast model. The GOES-R Algorithm Working Group Proxy Data Team was responsible for the generation of the proxy and simulated instrument data sets. Within the proxy group, the simulated images used by the imagery team were generated by the Cooperative Institute for Meteorological Satellites Studies (CIMSS). The proxy data system at CIMSS was even used by the National Weather Service (NWS) to test their ingest system and development of AWIPS products for dissemination to Weather Forecast Offices (Greenwald et al., 2016).

Much work was done to generate high-quality simulated ABI images based on output from the high resolution Weather Research and Forecasting (WRF) numerical model. The forward radiative transfer models used to transform from model (environmental parameter) space to measurement (radiances and BTs) space cover from the visible, to the IR spectral regions (Otkin and Greenwald 2008). High quality forward model simulations had been made of each of the ABI 16 bands.

The GOES-R AWG Proxy Data team created several ABI simulations. One of those simulations involved a CONUS simulation which mimicked the scan mode 3segments on the future ABI (Otkin et. al 2007). Though the exact scan scenarios were not yet known, based on Schmit et al. 2005, the team generated data based on Mode 3, full disk (FD) every 15 minutes, 3 CONUS scenes, and a 1000 km x 1000 km selectable area every 30 seconds

The synthetic GOES-R ABI imagery began as a high resolution WRF model simulation. The CONUS simulation was performed at the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign by the GOES-R AWG proxy data team at CIMSS. Simulated atmospheric fields were generated using version 2.2 of the WRF model (Advance Research WRM (ARW) core). The simulation was initialized at 2355 UTC on 04 June 2005 with 1° Global Forecast System (GFS) data and then run for 30 hours using a triple-nested domain configuration. The outermost domain covers the entire GOES-R viewing area with a 6-km horizontal resolution while the inner domains cover the CONUS and mesoscale regions with 2 km and 0.667 km horizontal resolution, respectively.

WRF model output, including the surface skin temperature, atmospheric temperature, water vapor mixing ratio, and the mixing ratio and effective particle diameters for each hydrometeor species, were ingested into the Successive Order of Interaction (SOI) forward radiative transfer model in order to generate simulated top of atmosphere (TOA) radiances. Gas optical depths were calculated for each ABI infrared band using the Community Radiative Transfer Model (CRTM). Ice cloud absorption and scattering properties were obtained from Baum et al. (2005), whereas the liquid cloud properties were based on Lorenz-Mie calculations.

Figure 7, Figure 8, Figure 9, and Figure 10 show examples of simulated ABI imagery images over the CONUS and near Full Disk regions. The simulated data captures the general features and locations well. Some differences can be observed in the cloud structures. Much work was done to help prepare AWIPS for the display of ABI data. This included, but was not limited to: menu structure, band “nicknames”, band data ranges and enhancements (such as the square root for bands 1-6) to leverage the improved ABI bit depth.

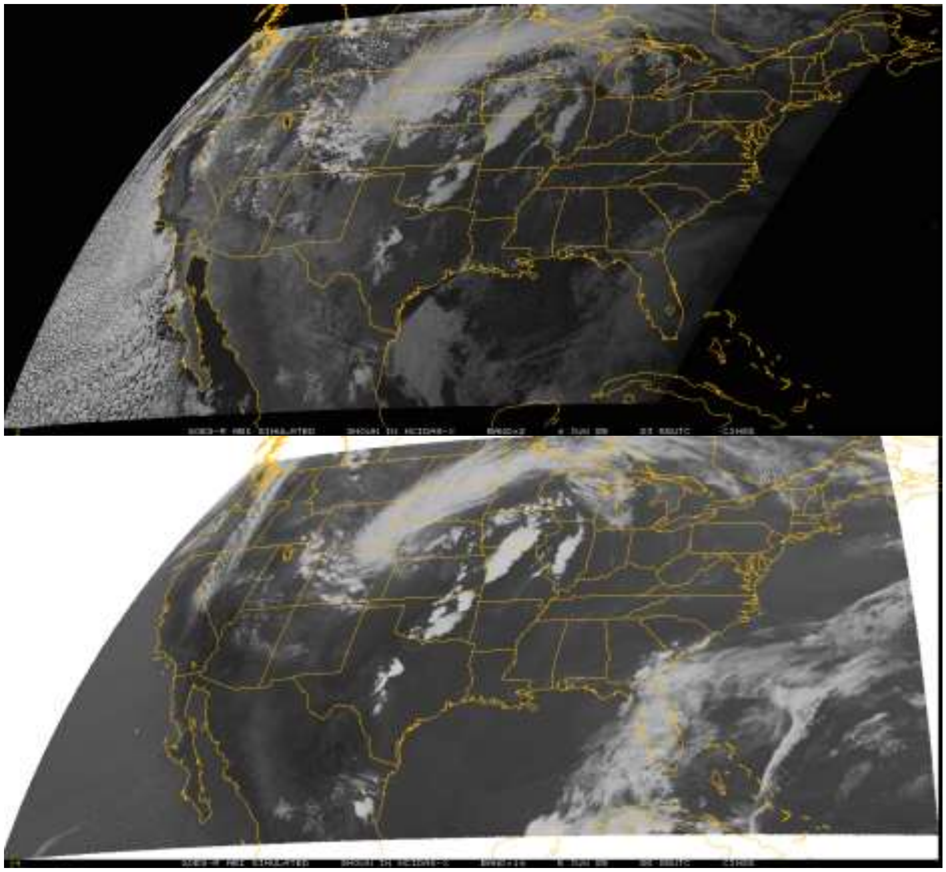

Figure 7. Top panel: ABI Band 2 stored as a McIDAS AREA displayed in McIDAS-X. Bottom panel: ABI Band 14 stored as a McIDAS AREA displayed in McIDAS-X.

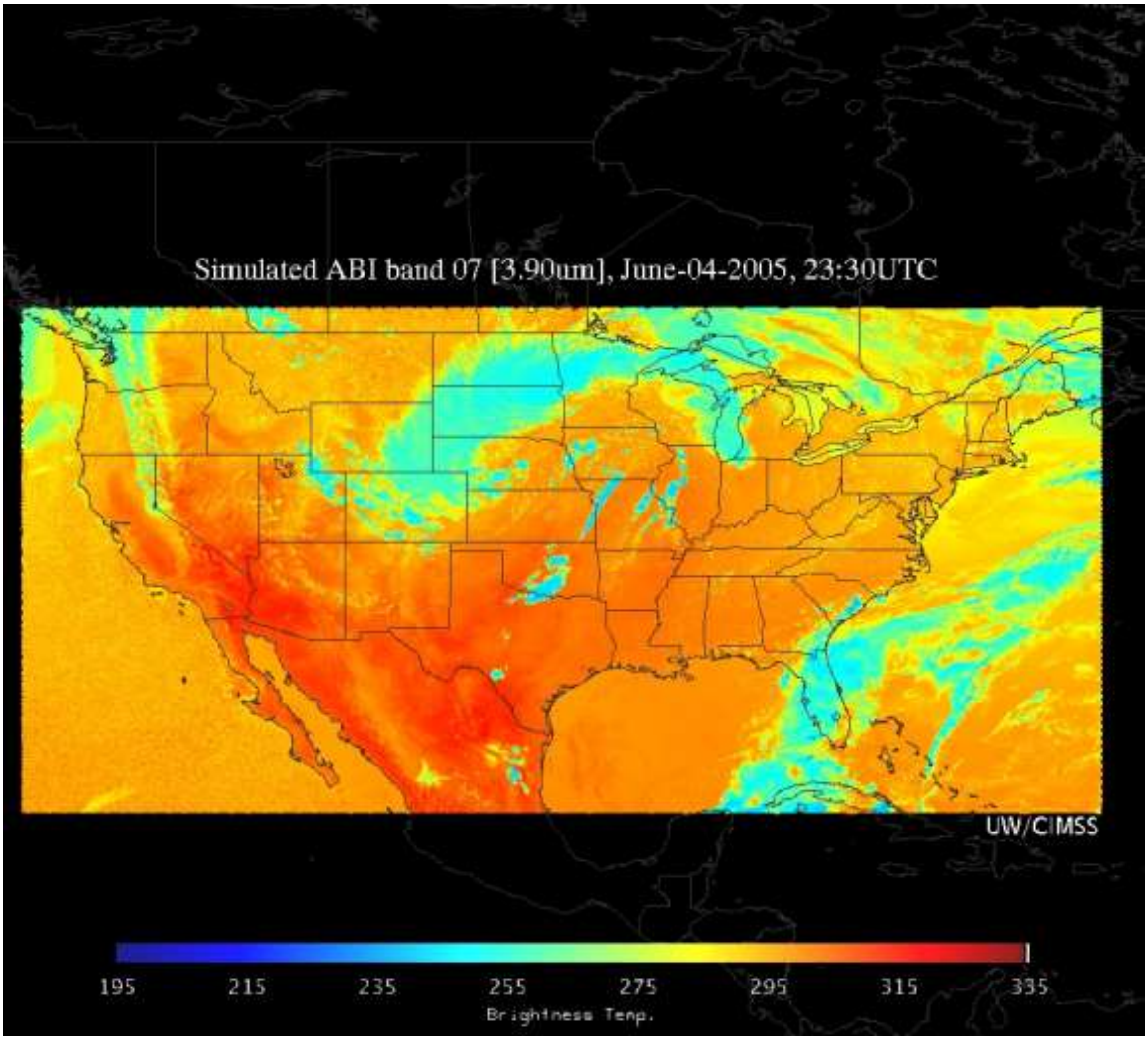

Figure 8. ABI Band 7 stored as a NetCDF displayed in McIDAS-V

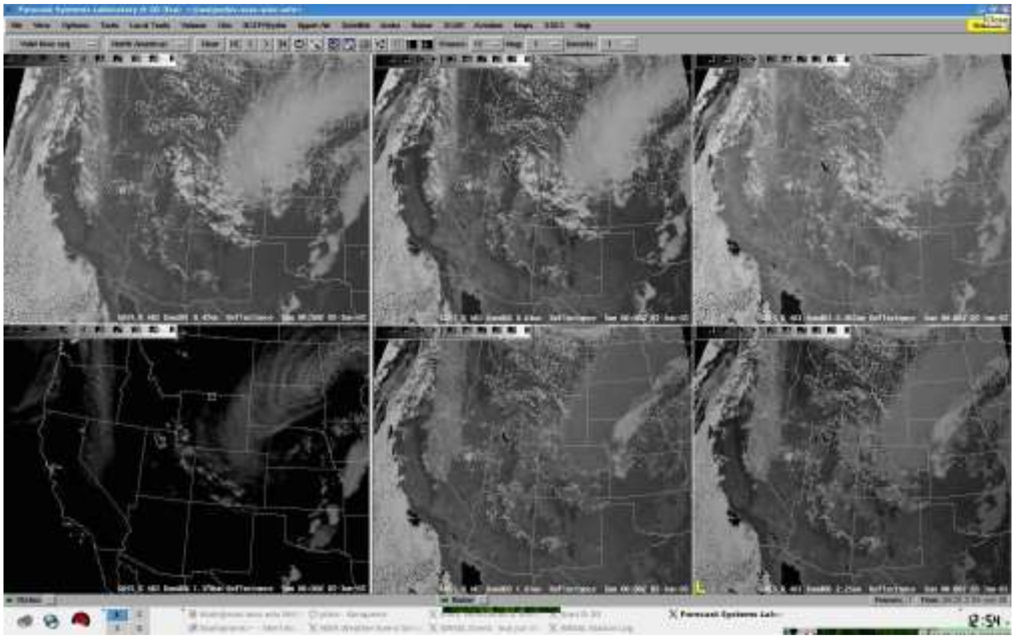

Figure 9. ABI Bands 1-6 converted to an AWIPS-ready NetCDF and displayed in AWIPS

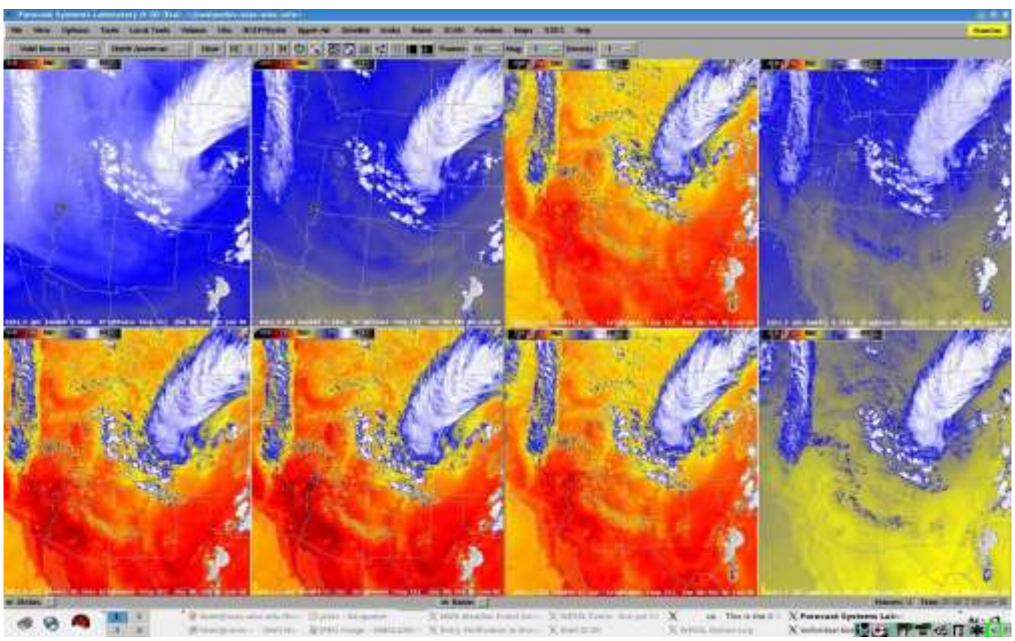

Figure 10. ABI Bands 9-16 converted to an AWIPS-ready NetCDF and displayed in AWIPS

4.2 Imagery from ABI Cloud & Moisture Imagery Product (CMIP)

4.2.1 Imagery Generated from CMIP Data

The GOES-16 ABI First Light images have been provided as examples.
ABI Band 1 CMIP example from November 26, 2020 at ~18:00 UTC:
OR_ABI-L2-CMIPF-M6C01_G16_s20203311800141_e20203311809449_c20203311809554.nc

```
netcdf OR_ABI-L2-CMIPF-M6C01_G16_s20203311800141_e20203311809449_c20203311809554 {
dimensions:
	y = 10848 ;
	x = 10848 ;
	number_of_time_bounds = 2 ;
	band = 1 ;
	number_of_image_bounds = 2 ;
variables:
	short CMI(y, x) ;
		CMI:_FillValue = -1s ;
		CMI:long_name = "ABI L2+ Cloud and Moisture Imagery reflectance factor" ;
		CMI:standard_name =
"toa_lambertian_equivalent_albedo_multiplied_by_cosine_solar_zenith_angle" ;
		CMI:_Unsigned = "true" ;
		CMI:sensor_band_bit_depth = 10b ;
		CMI:valid_range = 0s, 4095s ;
		CMI:scale_factor = 0.00031746f ;
		CMI:add_offset = 0.f ;
		CMI:units = "1" ;
		CMI:resolution = "y: 0.000028 rad x: 0.000028 rad" ;
		CMI:coordinates = "band_id band_wavelength t y x" ;
		CMI:grid_mapping = "goes_imager_projection" ;
		CMI:cell_methods = "t: point area: point" ;
		CMI:ancillary_variables = "DQF" ;
	byte DQF(y, x) ;
		DQF:_FillValue = -1b ;
		DQF:long_name = "ABI L2+ Cloud and Moisture Imagery reflectance factor data quality flags" ;
		DQF:standard_name = "status_flag" ;
		DQF:_Unsigned = "true" ;
		DQF:valid_range = 0b, 4b ;
		DQF:units = "1" ;
		DQF:coordinates = "band_id band_wavelength t y x" ;
		DQF:grid_mapping = "goes_imager_projection" ;
		DQF:flag_values = 0b, 1b, 2b, 3b, 4b ;
		DQF:flag_meanings = "good_pixel_qf conditionally_usable_pixel_qf out_of_range_pixel_qf
no_value_pixel_qf focal_plane_temperature_threshold_exceeded_qf" ;
		DQF:number_of_qf_values = 5b ;
		DQF:percent_good_pixel_qf = 0.9977641f ;
		DQF:percent_conditionally_usable_pixel_qf = 1.1e-06f ;
		DQF:percent_out_of_range_pixel_qf = 0.0022229f ;
		DQF:percent_no_value_pixel_qf = 1.19e-05f ;
		DQF:percent_focal_plane_temperature_threshold_exceeded_qf = 0.f ;
	double t ;
		t:long_name = "J2000 epoch mid-point between the start and end image scan in seconds" ;
		t:standard_name = "time" ;
```

```
		t:units = "seconds since 2000-01-01 12:00:00" ;
		t:axis = "T" ;
		t:bounds = "time_bounds" ;
	short y(y) ;
		y:scale_factor = -2.8e-05f ;
		y:add_offset = 0.151858f ;
		y:units = "rad" ;
		y:axis = "Y" ;
		y:long_name = "GOES fixed grid projection y-coordinate" ;
		y:standard_name = "projection_y_coordinate" ;
	short x(x) ;
		x:scale_factor = 2.8e-05f ;
		x:add_offset = -0.151858f ;
		x:units = "rad" ;
		x:axis = "X" ;
		x:long_name = "GOES fixed grid projection x-coordinate" ;
		x:standard_name = "projection_x_coordinate" ;
	double time_bounds(number_of_time_bounds) ;
		time_bounds:long_name = "Scan start and end times in seconds since epoch (2000-01-01
12:00:00)" ;
	int goes_imager_projection ;
		goes_imager_projection:long_name = "GOES-R ABI fixed grid projection" ;
		goes_imager_projection:grid_mapping_name = "geostationary" ;
		goes_imager_projection:perspective_point_height = 35786023. ;
		goes_imager_projection:semi_major_axis = 6378137. ;
		goes_imager_projection:semi_minor_axis = 6356752.31414 ;
		goes_imager_projection:inverse_flattening = 298.2572221 ;
		goes_imager_projection:latitude_of_projection_origin = 0. ;
		goes_imager_projection:longitude_of_projection_origin = -75. ;
		goes_imager_projection:sweep_angle_axis = "x" ;
	float y_image ;
		y_image:long_name = "GOES-R fixed grid projection y-coordinate center of image" ;
		y_image:standard_name = "projection_y_coordinate" ;
		y_image:units = "rad" ;
		y_image:axis = "Y" ;
	float y_image_bounds(number_of_image_bounds) ;
		y_image_bounds:long_name = "GOES-R fixed grid projection y-coordinate north/south extent of
image" ;
		y_image_bounds:units = "rad" ;
	float x_image ;
		x_image:long_name = "GOES-R fixed grid projection x-coordinate center of image" ;
		x_image:standard_name = "projection_x_coordinate" ;
		x_image:units = "rad" ;
		x_image:axis = "X" ;
	float x_image_bounds(number_of_image_bounds) ;
		x_image_bounds:long_name = "GOES-R fixed grid projection x-coordinate west/east extent of
image" ;
		x_image_bounds:units = "rad" ;
	float nominal_satellite_subpoint_lat ;
		nominal_satellite_subpoint_lat:long_name = "nominal satellite subpoint latitude (platform
latitude)" ;
		nominal_satellite_subpoint_lat:standard_name = "latitude" ;
		nominal_satellite_subpoint_lat:_FillValue = -999.f ;
		nominal_satellite_subpoint_lat:units = "degrees_north" ;
	float nominal_satellite_subpoint_lon ;
```

```
nominal_satellite_subpoint_lon:long_name = "nominal satellite subpoint longitude (platform longitude)" ;
        nominal_satellite_subpoint_lon:standard_name = "longitude" ;
        nominal_satellite_subpoint_lon:_FillValue = -999.f ;
        nominal_satellite_subpoint_lon:units = "degrees_east" ;
    float nominal_satellite_height ;
        nominal_satellite_height:long_name = "nominal satellite height above GRS 80 ellipsoid (platform altitude)" ;
        nominal_satellite_height:standard_name = "height_above_reference_ellipsoid" ;
        nominal_satellite_height:_FillValue = -999.f ;
        nominal_satellite_height:units = "km" ;
    float geospatial_lat_lon_extent ;
        geospatial_lat_lon_extent:long_name = "geospatial latitude and longitude references" ;
        geospatial_lat_lon_extent:geospatial_westbound_longitude = -156.2995f ;
        geospatial_lat_lon_extent:geospatial_northbound_latitude = 81.3282f ;
        geospatial_lat_lon_extent:geospatial_eastbound_longitude = 6.2995f ;
        geospatial_lat_lon_extent:geospatial_southbound_latitude = -81.3282f ;
        geospatial_lat_lon_extent:geospatial_lat_center = 0.f ;
        geospatial_lat_lon_extent:geospatial_lon_center = -75.f ;
        geospatial_lat_lon_extent:geospatial_lat_nadir = 0.f ;
        geospatial_lat_lon_extent:geospatial_lon_nadir = -75.f ;
        geospatial_lat_lon_extent:geospatial_lat_units = "degrees_north" ;
        geospatial_lat_lon_extent:geospatial_lon_units = "degrees_east" ;
    float band_wavelength(band) ;
        band_wavelength:long_name = "ABI band central wavelength" ;
        band_wavelength:standard_name = "sensor_band_central_radiation_wavelength" ;
        band_wavelength:units = "um" ;
    byte band_id(band) ;
        band_id:long_name = "ABI band number" ;
        band_id:standard_name = "sensor_band_identifier" ;
        band_id:units = "1" ;
    int valid_pixel_count ;
        valid_pixel_count:long_name = "number of good and conditionally usable pixels" ;
        valid_pixel_count:_FillValue = -1 ;
        valid_pixel_count:units = "count" ;
        valid_pixel_count:coordinates = "band_id band_wavelength t y_image x_image" ;
        valid_pixel_count:grid_mapping = "goes_imager_projection" ;
        valid_pixel_count:cell_methods = "t: sum area: sum (interval: 0.000028 rad comment: good and conditionally usable quality pixels only)" ;
    int outlier_pixel_count ;
        outlier_pixel_count:long_name = "number of good quality cloud and moisture imagery pixels whose value is outside valid measurement range" ;
        outlier_pixel_count:_FillValue = -1 ;
        outlier_pixel_count:units = "count" ;
        outlier_pixel_count:coordinates = "band_id band_wavelength t y_image x_image" ;
        outlier_pixel_count:grid_mapping = "goes_imager_projection" ;
        outlier_pixel_count:cell_methods = "t: sum area: sum (interval: 0.000028 rad comment: good quality pixels whose values are outside valid measurement range only)" ;
    int total_number_of_points ;
        total_number_of_points:long_name = "number of geolocated/not missing pixels" ;
        total_number_of_points:_FillValue = -1 ;
        total_number_of_points:units = "count" ;
        total_number_of_points:coordinates = "band_id band_wavelength t y_image x_image" ;
        total_number_of_points:grid_mapping = "goes_imager_projection" ;
        total_number_of_points:cell_methods = "t: sum area: sum (interval: 0.000028 rad comment: geolocated/not missing pixels only)" ;
```

float min_reflectance_factor ;
min_reflectance_factor:long_name = "minimum reflectance factor value of pixels" ;
min_reflectance_factor:standard_name = "toa_lambertian_equivalent_albedo_multiplied_by_cosine_solar_zenith_angle" ;
min_reflectance_factor:_FillValue = -999.f ;
min_reflectance_factor:valid_range = 0.f, 1.f ;
min_reflectance_factor:units = "1" ;
min_reflectance_factor:coordinates = "band_id band_wavelength t y_image x_image" ;
min_reflectance_factor:grid_mapping = "goes_imager_projection" ;
min_reflectance_factor:cell_methods = "t: sum area: minimum (interval: 0.000028 rad comment: good and conditionally usable quality pixels only)" ;
float max_reflectance_factor ;
max_reflectance_factor:long_name = "maximum reflectance factor value of pixels" ;
max_reflectance_factor:standard_name = "toa_lambertian_equivalent_albedo_multiplied_by_cosine_solar_zenith_angle" ;
max_reflectance_factor:_FillValue = -999.f ;
max_reflectance_factor:valid_range = 0.f, 1.f ;
max_reflectance_factor:units = "1" ;
max_reflectance_factor:coordinates = "band_id band_wavelength t y_image x_image" ;
max_reflectance_factor:grid_mapping = "goes_imager_projection" ;
max_reflectance_factor:cell_methods = "t: sum area: maximum (interval: 0.000028 rad comment: good and conditionally usable quality pixels only)" ;
float mean_reflectance_factor ;
mean_reflectance_factor:long_name = "mean reflectance factor value of pixels" ;
mean_reflectance_factor:standard_name = "toa_lambertian_equivalent_albedo_multiplied_by_cosine_solar_zenith_angle" ;
mean_reflectance_factor:_FillValue = -999.f ;
mean_reflectance_factor:valid_range = 0.f, 1.f ;
mean_reflectance_factor:units = "1" ;
mean_reflectance_factor:coordinates = "band_id band_wavelength t y_image x_image" ;
mean_reflectance_factor:grid_mapping = "goes_imager_projection" ;
mean_reflectance_factor:cell_methods = "t: sum area: mean (interval: 0.000028 rad comment: good and conditionally usable quality pixels only)" ;
float std_dev_reflectance_factor ;
std_dev_reflectance_factor:long_name = "standard deviation of reflectance factor values of pixels" ;
std_dev_reflectance_factor:standard_name = "toa_lambertian_equivalent_albedo_multiplied_by_cosine_solar_zenith_angle" ;
std_dev_reflectance_factor:_FillValue = -999.f ;
std_dev_reflectance_factor:units = "1" ;
std_dev_reflectance_factor:coordinates = "band_id band_wavelength t y_image x_image" ;
std_dev_reflectance_factor:grid_mapping = "goes_imager_projection" ;
std_dev_reflectance_factor:cell_methods = "t: sum area: standard_deviation (interval: 0.000028 rad comment: good and conditionally usable quality pixels only)" ;
int algorithm_dynamic_input_data_container ;
algorithm_dynamic_input_data_container:long_name = "container for filenames of dynamic algorithm input data" ;
algorithm_dynamic_input_data_container:input_ABI_L2_auxiliary_solar_zenith_angle_data = "I_ABI-L2-AUXF2_G16_*.*" ;
algorithm_dynamic_input_data_container:input_ABI_L1b_radiance_band_data = "OR_ABI-L1b-RADF-M6C01_G16_s20203311800141_e20203311809449_c*.nc" ;
float percent_uncorrectable_GRB_errors ;
percent_uncorrectable_GRB_errors:long_name = "percent data lost due to uncorrectable GRB errors" ;
percent_uncorrectable_GRB_errors:_FillValue = -999.f ;
percent_uncorrectable_GRB_errors:valid_range = 0.f, 1.f ;

percent_uncorrectable_GRB_errors:units = "percent" ;
percent_uncorrectable_GRB_errors:coordinates = "t y_image x_image" ;
percent_uncorrectable_GRB_errors:grid_mapping = "goes_imager_projection" ;
percent_uncorrectable_GRB_errors:cell_methods = "t: sum area: sum (uncorrectable GRB errors only)" ;
float percent_uncorrectable_L0_errors ;
percent_uncorrectable_L0_errors:long_name = "percent data lost due to uncorrectable L0 errors" ;
percent_uncorrectable_L0_errors:_FillValue = -999.f ;
percent_uncorrectable_L0_errors:valid_range = 0.f, 1.f ;
percent_uncorrectable_L0_errors:units = "percent" ;
percent_uncorrectable_L0_errors:coordinates = "t y_image x_image" ;
percent_uncorrectable_L0_errors:grid_mapping = "goes_imager_projection" ;
percent_uncorrectable_L0_errors:cell_methods = "t: sum area: sum (uncorrectable L0 errors only)" ;
float earth_sun_distance_anomaly_in_AU ;
earth_sun_distance_anomaly_in_AU:long_name = "earth sun distance anomaly in astronomical units" ;
earth_sun_distance_anomaly_in_AU:_FillValue = -999.f ;
earth_sun_distance_anomaly_in_AU:units = "ua" ;
earth_sun_distance_anomaly_in_AU:coordinates = "t" ;
earth_sun_distance_anomaly_in_AU:cell_methods = "t: mean" ;
int processing_parm_version_container ;
processing_parm_version_container:long_name = "container for processing parameter filenames" ;
processing_parm_version_container:L2_processing_parm_version = "OR-PARM-CMIP_v01r00.zip, OR-PARM-SEMISTATIC_v01r00.zip, OR-PARM-ANCILLARY_v01r00.zip, OR-PARM-AUXILIARY_v01r00.zip" ;
int algorithm_product_version_container ;
algorithm_product_version_container:long_name = "container for algorithm package filename and product version" ;
algorithm_product_version_container:algorithm_version = "OR_ABI-L2-ALG-CMIP_v01r00.zip" ;
algorithm_product_version_container:product_version = "v01r00" ;
float esun ;
esun:long_name = "bandpass-weighted solar irradiance at the mean Earth-Sun distance" ;
esun:standard_name = "toa_shortwave_irradiance_per_unit_wavelength" ;
esun:_FillValue = -999.f ;
esun:units = "W m-2 um-1" ;
esun:coordinates = "band_id band_wavelength t" ;
esun:cell_methods = "t: mean" ;
float kappa0 ;
kappa0:long_name = "Inverse of the incoming top of atmosphere radiance at current earth-sun distance (PI d2 esun-1)-1, where d is the ratio of instantaneous Earth-Sun distance divided by the mean Earth-Sun distance, esun is the bandpass-weighted solar irradiance and PI is a standard constant used to convert ABI L1b radiance to reflectance" ;
kappa0:_FillValue = -999.f ;
kappa0:units = "(W m-2 um-1)-1" ;
kappa0:coordinates = "band_id band_wavelength t" ;
kappa0:cell_methods = "t: mean" ;
float planck_fk1 ;
planck_fk1:long_name = "wavenumber-dependent coefficient (2 h c2/ nu3) used in the ABI emissive band monochromatic brightness temperature computation, where nu =central wavenumber and h and c are standard constants" ;
planck_fk1:_FillValue = -999.f ;
planck_fk1:units = "W m-1" ;
planck_fk1:coordinates = "band_id band_wavelength" ;

float planck_fk2 ;
planck_fk2:long_name = "wavenumber-dependent coefficient (h c nu/b) used in the ABI emissive band monochromatic brightness temperature computation, where nu = central wavenumber and h, c, and b are standard constants" ;
planck_fk2:_FillValue = -999.f ;
planck_fk2:units = "K" ;
planck_fk2:coordinates = "band_id band_wavelength" ;
float planck_bc1 ;
planck_bc1:long_name = "spectral bandpass correction offset for brightness temperature (B(nu) - bc_1)/bc_2 where B()=planck_function() and nu=wavenumber" ;
planck_bc1:_FillValue = -999.f ;
planck_bc1:units = "K" ;
planck_bc1:coordinates = "band_id band_wavelength" ;
float planck_bc2 ;
planck_bc2:long_name = "spectral bandpass correction scale factor for brightness temperature (B(nu) - bc_1)/bc_2 where B()=planck_function() and nu=wavenumber" ;
planck_bc2:_FillValue = -999.f ;
planck_bc2:units = "1" ;
planck_bc2:coordinates = "band_id band_wavelength" ;
int focal_plane_temperature_threshold_exceeded_count ;
focal_plane_temperature_threshold_exceeded_count:long_name = "number of pixels whose temperatures exceeded the threshold" ;
focal_plane_temperature_threshold_exceeded_count:_FillValue = -1 ;
focal_plane_temperature_threshold_exceeded_count:units = "count" ;
focal_plane_temperature_threshold_exceeded_count:coordinates = "band_id band_wavelength t y_image x_image" ;
focal_plane_temperature_threshold_exceeded_count:grid_mapping = "goes_imager_projection" ;
focal_plane_temperature_threshold_exceeded_count:cell_methods = "t: sum area: sum (interval: 0.000028 rad comment: radiometrically hot geolocated/not missing pixels only)" ;
float maximum_focal_plane_temperature ;
maximum_focal_plane_temperature:long_name = "maximum focal plane temperature value measured for the product" ;
maximum_focal_plane_temperature:_FillValue = -999.f ;
maximum_focal_plane_temperature:units = "K" ;
maximum_focal_plane_temperature:coordinates = "band_id band_wavelength t y_image x_image" ;
maximum_focal_plane_temperature:grid_mapping = "goes_imager_projection" ;
float focal_plane_temperature_threshold_increasing ;
focal_plane_temperature_threshold_increasing:long_name = "focal plane temperature threshold increasing bounds value" ;
focal_plane_temperature_threshold_increasing:_FillValue = -999.f ;
focal_plane_temperature_threshold_increasing:units = "K" ;
focal_plane_temperature_threshold_increasing:coordinates = "band_id band_wavelength t y_image x_image" ;
focal_plane_temperature_threshold_increasing:grid_mapping = "goes_imager_projection" ;
float focal_plane_temperature_threshold_decreasing ;
focal_plane_temperature_threshold_decreasing:long_name = "focal plane temperature threshold decreasing bounds value" ;
focal_plane_temperature_threshold_decreasing:_FillValue = -999.f ;
focal_plane_temperature_threshold_decreasing:units = "K" ;
focal_plane_temperature_threshold_decreasing:coordinates = "band_id band_wavelength t y_image x_image" ;
focal_plane_temperature_threshold_decreasing:grid_mapping = "goes_imager_projection" ;
int channel_integration_time ;
channel_integration_time:long_name = "Channel-dependent Channel Integration Time, as defined in the VNIR or IR Channel Configuration Table Telemetry" ;

```
		channel_integration_time:_FillValue = -1 ;
		channel_integration_time:units = "count" ;
	int channel_gain_field ;
		channel_gain_field:long_name = "Channel-dependent Gain Field, as defined in the VNIR or IR Channel Configuration Table Telemetry" ;
		channel_gain_field:_FillValue = -1 ;
		channel_gain_field:units = "1" ;

// global attributes:
		:naming_authority = "gov.nesdis.noaa" ;
		:Conventions = "CF-1.7" ;
		:Metadata_Conventions = "Unidata Dataset Discovery v1.0" ;
		:standard_name_vocabulary = "CF Standard Name Table (v35, 20 July 2016)" ;
		:institution = "DOC/NOAA/NESDIS > U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Services" ;
		:project = "GOES" ;
		:production_site = "NSOF" ;
		:production_environment = "OE" ;
		:spatial_resolution = "1km at nadir" ;
		:orbital_slot = "GOES-East" ;
		:platform_ID = "G16" ;
		:instrument_type = "GOES R Series Advanced Baseline Imager" ;
		:scene_id = "Full Disk" ;
		:instrument_ID = "FM1" ;
		:dataset_name = "OR_ABI-L2-CMIPF-M6C01_G16_s20203311800141_e20203311809449_c20203311809554.nc" ;
		:iso_series_metadata_id = "8c9e8150-3692-11e3-aa6e-0800200c9a66" ;
		:title = "ABI L2 Cloud and Moisture Imagery" ;
		:summary = "Single reflective band Cloud and Moisture Imagery Products are digital maps of clouds, moisture, and atmospheric windows at visible and near-IR bands." ;
		:keywords = "ATMOSPHERE > ATMOSPHERIC RADIATION > REFLECTANCE, SPECTRAL/ENGINEERING > VISIBLE WAVELENGTHS > REFLECTANCE" ;
		:keywords_vocabulary = "NASA Global Change Master Directory (GCMD) Earth Science Keywords, Version 7.0.0.0.0" ;
		:license = "Unclassified data.  Access is restricted to approved users only." ;
		:processing_level = "National Aeronautics and Space Administration (NASA) L2" ;
		:date_created = "2020-11-26T18:09:55.4Z" ;
		:cdm_data_type = "Image" ;
		:time_coverage_start = "2020-11-26T18:00:14.1Z" ;
		:time_coverage_end = "2020-11-26T18:09:44.9Z" ;
		:timeline_id = "ABI Mode 6" ;
		:production_data_source = "Realtime" ;
		:id = "8bc076bb-f5d9-48bf-840f-b41c96e8fba8" ;
```

The FGF comprises a set of fixed view angles at regular intervals, and their respective intersections with the GRS80 Earth geoid, from an ideal or nominal point in space in the equatorial plane. The geometric transformations from FGF coordinate to Earth location, and vice-versa, are essentially those outlined in the Coordination Group for Meteorological Satellites (CGMS) defined Normalized Geostationary Projection (4.4.3.2) (CGMS, 1999). The description of the FGF is defined in the GOES-R PUG.

4.2.2 Precision and Accuracy Estimation

The performance of the CMIP is sensitive to any imagery artifacts or instrument noise, calibration accuracy, and geolocation accuracy. The CMIP can only be as accurate as the L1b data from which they were derived. Using the Planck Function Coefficients (PFCs) provided in both L1b and CMIP files to convert L1b radiance to CMI values (reflectance factor for bands 1-6, brightness temperature for bands 7-16), the CMI values can produce small differences between user calculated CMI and the CMI generated by the GOES-R ground system as CMIP files, or those files found on archives such as CLASS. These differences are attributed to rounding errors and should never be more than equivalent to one "count." To convert from L1b to CMI, first L1b radiances must be unpacked from scaled integers to real radiances. Then those radiances must be converted to CMI (Reflectance factor or brightness temperature). Then the CMI must be compared to CMI from a CMIP file, which means it must be unpacked from scaled integers into real values. Anecdotally, it is been found that for the vast majority of pixels, this comparison can be done to within 1 "count" such that the difference between a user calculated CMI and a CMIP file CMI value will be less than the scale_factor of the CMI value in the file. Meaning the differences are negligibly small. For most of the CMI files compared this way, the Imagery Team has found no differences. For a rare few files, there have been a small number of pixels that had differences that amounted to 1 "count," the difference between two scaled integers (equivalent to the scale_factor for unpacking scaled integers in a CMI file). For example, in one file ~1,200 out of the 29,419,776 pixels slightly exceeded the 1-count threshold. This is not seen as an inaccuracy as much as a limitation of the way the data are stored and how different software systems on different computers access them.

4.2.3 Error Budget

There is no error budget.

5 PRACTICAL CONSIDERATIONS

5.1 Numerical Computation Considerations

Handling of the large ABI image datasets is one of the major challenges to the CMIP. There is a large data increase for the ABI compared with the previous GOES imager in individual bands. The 0.5 km visible band has a data volume larger than all ten of the IR bands combined. Moreover, for the full disk scans, the temporal resolution is improved to 5, 10, or 15 minutes, depending on mode, compared to 25 minutes for the prior GOES instruments. File sizes become especially large with the ABI band 2 full disk image.

The ‘stepped-edge’ approach of the ABI FD scan certainly improves the efficiency of this operation. At the same time, it complicates the image generation step, given that ‘swaths’ can be varying width. It should be noted that ‘swaths’ exist only in instrument space, before the remap step. The remapping algorithm is designed to smooth swath edges, so the resultant pixels in the vicinity of the swath edge are a combination of the two swaths. For the most part, users should not be able to tell where swath edges are, though under extreme conditions it is possible. For users that acquire either L1b or L2 CMIP netCDF files, the data are stored in square or rectangular arrays, with the outside edges null-filled. On previous GOES, these data contained values scanned in space. With ABI, no off-Earth pixels contain usable/observed space data.

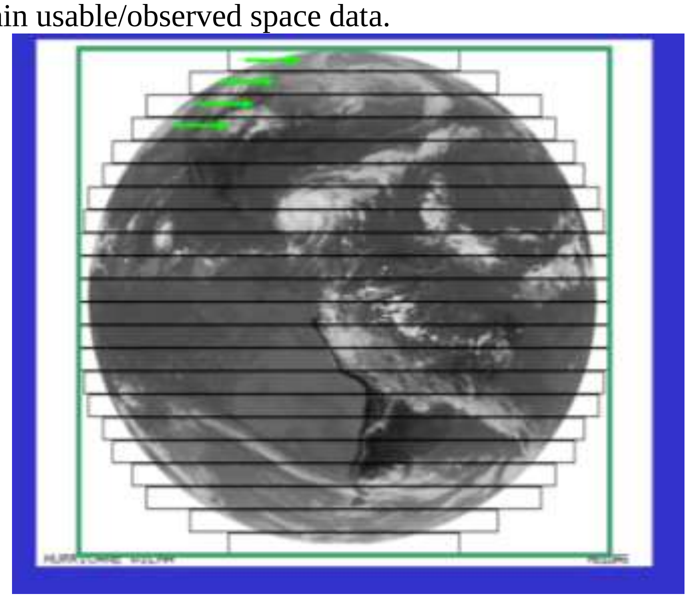

Figure 11. The ‘stepped-edge’ approach of the ABI FD scan.

5.2 Programming and Procedural Considerations

Striping or banding is systematic noise in an image that results from variation in the response of the individual detectors used for a particular band. This usually happens when a detector goes out of adjustment and produces readings that are consistently much higher or lower than the other detectors for the same band. Gunshor et al. (2020) summarized the many imagery artifacts.

Many methods have been developed to correct for striping, such as histogram matching, Empirical Distribution Function (EDF) matching (Weinreb et al. 1989), and moment matching (Gurka and Dittberner 2001). Appropriate methods should be developed or to address the potential striping issue, although this is a calibration group issue and not one addressed by the imagery team.

Due to the irreversible nature of the ABI data being remapped prior to distribution, any needed de-striping will need to be conducted before data distribution. The GOES-R ground system team updates the list of usable detectors when detectors go bad and monitors for striping due to other calibration issues as well.

The pixel time stamp and/or the start time of each swath were not included in the Level 1b or CMI files. A crude estimate of pixel time can be made by linearly interpolating between the start and end times of a file. Users will need to perform calculations if needing more precise times for when a pixel was scanned. The scan mode timeline diagrams from the PUG can help users know approximately how many seconds after the image start time a swath was scanned. Determining more precise scan times at the pixel level is made more complicated at the swath boundaries since pixels are really made from multiple fields of view and there is no way to reverse-engineer the making of a pixel.

5.3 Quality Assessment and Diagnostics

This section describes how the quality of the output products is assessed, documented, and any anomalies diagnosed. In general, any QC information that is included in the GRB will be passed on. This includes information related to the calibration and navigation attributes. For example, the bit-level flags for saturation and quality.

5.4 Exception Handling

The CMIP applies radiometric calibration procedures to convert to the various units. The CMIP also expects the Level 1b processing to flag any pixels appropriately..

Exception handling is required for the development of robust and efficient numerical software. Requirements set forth by the ASSIST also stress the importance of exception handling. While the main modules of the CMIP program are using the AIT-provided subroutine for error messaging, its use is limited. More extensive error checking will be added to future versions of the CMIP.

For the most part, the CMIP assumes that all necessary image and ancillary data are available through the GRB datastream and processing framework.

5.5 Algorithm Validation

Validation of the Imagery products requires comparing to reference ("truth") data for the CONUS and other scan sectors. From these validation data, comparison metrics can be calculated that characterize the agreement between the satellite-derived CMIP and the reference values.

Product validation for CMIP is tied to product validation of the L1b radiances. L1b and CMIP PS-PVR (Peer-Stakeholder Product Validation Review) activities usually go hand-in-hand. The unique aspect of that for CMIP is confirmation that the system is properly converting radiance to CMI values. The product performance guide, combined to cover both radiances and CMI, are posted for GOES-16 (https://www.ncdc.noaa.gov/sites/default/files/attachments/GOES-16_ABI-L1b-CMI_Full-Validation_ProductPerformanceGuide_v2.pdf) and GOES-17 (https://www.star.nesdis.noaa.gov/GOESCal/docs/pdf/SOP/G17_ABI_L1b-CMI_Full_ValidationProductPerformanceGuide_20200731_v1.1.pdf).

6 ASSUMPTIONS AND LIMITATIONS

This section describes the current assumptions and limitations in the current version of the CMIP.

6.1 Assumed Sensor Performance

We assume the sensor will meet its current specifications. However, the CMIP will be dependent on the following instrument characteristics. In addition, it is assumed that the supplied SRF will be the relative response, provided in historically consistent units (cm^{-1}), and unique to each flight model ABI.

- The quality of the CMIP will depend on the amount of striping in the data.
- The quality of the CMIP will depend on the overall quality of the L1b data. This includes (but is not limited to), the cross-talk, the modulation transfer function (MTF), the signal-to-noise ratio (SNR), similarity of detector responses, etc.
- The minimum and maximum radiances for the GRB scaling does not need to change from instrument to instrument.
- GRB will include various version numbers (such as the Planck coefficients, instrument number, etc.)
- Errors in navigation from input GRB data stream will affect the quality of CMIP.
- Unknown spectral shifts in some bands will affect the quality of CMIP.

6.2.2 QC Indicators

The relevant QC flags, obtained from the GRB signal, will be passed along. These will include a flag with respect to pixel-level quality and saturation flag for each band. The CMI does not generate its own set of flags, but is consistent with those from the radiance files.

7 REFERENCES

Acharya, T., and A. K. Ray> 2005: *Image processing: principles and applications*: Wiley-Interscience.

Baum, Bryan A., Ping Yang, Andrew J. Heymsfield, Steven Platnick, Michael D. King, Y-X. Hu, Sarah T. Bedka, 2005: Bulk Scattering Properties for the Remote Sensing of Ice Clouds. Part II: Narrowband Models. J. Appl. Meteor., 44, 1896–1911. doi: 10.1175/JAM2309.1

Cao, C., and A. Heidinger. 2002: Proceedings of SPIE (http://www.star.nesdis.noaa.gov/smcd/spb/calibration/icvs/documents/Cao_2002SPIE.pdf).

CGMS (Coordination Group for Meteorological Satellites) CGMS 03 – LRIT HRIT Global Spec. 2.6. LRIT/HRIT Global Specification, 1999.

Clarke, J., 2010: GOES-R ABI LEVEL 1B SOLAR CHANNEL DATA DISTRIBUTION STUDY: Analysis of alternatives for utilization of Radiance and Reflectance Factor Instrument Data.

Michael D.; Hu, Y.-X., and Bedka, S. T., 2005: Bulk scattering properties for the remote sensing of ice clouds, part II: Narrowband models. *Journal of Applied Meteorology*, Volume **44**, Issue 12, pp.1896-1911.

Greenwald, T. J.; Pierce, R. B.; Schaack, T.; Otkin, J.; Rogal, M.; Bah, K.; Lenzen, A.; Nelson, J.; Li, J. and Huang, H.-L. Real-time simulation of the GOES-R ABI for user readiness and product evaluation. Supplement. Bulletin of the American Meteorological Society, Volume 97, Issue 2, 2016, doi/suppl/10.1175/BAMS-D-14-00007.1.

Gunshor, M. M, T. J. Schmit, D. Pogorzala, S. Lindstrom, J. P. Nelson, III, 2020: GOES-R Series ABI Imagery Artifacts, JARS. https://doi.org/10.1117/1.JRS.14.032411

Gurka, J. J., and G. J. Dittberner. 2001: The next generation GOES instruments: Status and potential impact. Paper read at *Fifth Symp. on Integrated Observing Systems*, Albuquerque, NM.

Hillger, D. W., and T. Schmit. 2004: Quantization noise for GOES-R ABI bands. Paper read at Proceedings of the 13th Conference on Satellite Meteorology and Oceanography, Sep., Norfolk, VA.

NOAA/NASA, 2010: GOES-R Ground Segment (GS) Functional and Performance Specification (F&PS): GOES-R/Code 417.

NOAA/NESDIS, 2007: GOES-R Series Mission Requirements Document (MRD, version 3.1): GOES-R Program/Code 417.

Otkin, J. A., D. J. Posselt, E. R. Olson, H.-L. Huang, J. E. Davies, J. Li, and C. S. Velden, 2007: Mesoscale numerical weather prediction models used in support of infrared hyperspectral measurements simulation and product algorithm development. *J. Atmospheric and Oceanic Tech.*, 24, 585-601.

Otkin, J. A., and T. J. Greenwald, 2008: Comparison of WRF model-simulated and MODIS-derived cloud data. *Mon. Wea. Rev.* 136:1957-1970.

Padula, F. and C. Cao, 2011: CWG (Calibration Working Group) Analysis: ABI Max/Min Radiance Characterization and Validation.

Russ, J. C., 2002: *The Image Processing Handbook, Fourth Edition* CRC Press.

Schmit, T., and M. Gunshor, Book Chapter (2019) on ABI Imagery for the GOES-R Book: The GOES-R Series: A New Generation of Geostationary Environmental Satellites, ISBN: 9780128143278, Elsevier

Schmit, T. J.; Griffith, P.; Gunshor, M. M.; Daniels, J. M.; Goodman, S. J. and Lebair, W. J., 2017: A closer look at the ABI on the GOES-R series: Supplement. Bulletin of the American Meteorological Society, Volume 98.

Schmit, Timothy J.; Lindstrom, Scott S.; Gerth, Jordan J. and Gunshor, Mathew M. Applications of the 16 spectral bands on the Advanced Baseline Imager (ABI). Journal of Operational Meteorology, Volume 6, Issue 4, 2018, pp.33-46.

Schmit, T. J., M. M. Gunshor, W. P. Menzel, J. Li, S. Bachmeier, and J. J. Gurka, 2005: Introducing the next-generation Advanced Baseline Imager (ABI) on GOES-R. *Bull. Amer. Meteor. Soc.* 8:1079-1096.

Schmit, T. J., M. P. Weinreb, and W. P. Menzel, 1991: GVAR IR scale factor coefficients: NOAA.

Weinreb, M. P., M. Jamison, N. Fulton, Y. Chen, J. X. Johnson, J. Bremer, C. Smith, and J. Baucom, 1997. Operational calibration of Geostationary Operational Environmental Satellite-8 and -9 imagers and sounders. *Appl. Opt.* 36:6895-6904.

Weinreb, M. P., J. X. Johnson, J. H. Lienesch, and D. S. Crosby, 1989: Destriping GOES images by matching empirical distribution functions. *Rem. Sens. Environ* 29 (185-195).

ACKNOWLEDGEMENTS

The entire Imagery and Visualization Team (I&VT) is thanked for their input to these critical products. Justin Sieglaff of CIMSS is thanked. Wenhui Wang of NOAA/NESDIS/STAR and I. M. System Groups is thanked for the initial version. The high quality simulated ABI data is from the GOES-R AWG proxy team at CIMSS; for this Jason Oktin is especially thanked. Many members of the GOES-R Calibration Working Group (CWG) also provided much needed information, especially thanked are Fred Wu, Mike Weinreb, and Changyong Cao. Also thanked for review is Steve Miller (CIRA). Don Hillger (NOAA/NESDIS/StAR) is especially thanked for a detailed review of this document. William Straka (CIMSS) is also thanked for a detailed review of this document. ADEB reviewers are also thanked for their time. The authors of the previous version of this ATBD are thanked: Gang Fu (PSGS), Tom Rink (CIMSS), Kaba Bah (CIMSS), Wendy Zhang (Riverside Technology, Inc.), and Walter Wolf (NOAA/NESDIS/STAR). PRO and PRO/PASS are thanked as well.

Appendix A. Converting Spectral Radiance to BT via Historical Method

Historically, spectral radiance has been converted to BT using two steps (Weinreb et al. 1997), the first step is to convert spectral radiance to effective temperature using inverse Planck Function:

$$T_{eff} = \frac{c_2 \upsilon}{\ln\left(\frac{c_1 \upsilon^3}{L_\lambda} + 1\right)} \qquad \text{(A-1)}$$

where T_{eff} is the effective temperature, c_1 and c_2 are two constants (c_1 ; c_2), L_λ is spectral radiance, and□ υ is the central wavenumber of the band.

The second step converts effective temperature to BT (K), accounting for the sensor response function:

$$T = \beta T_{eff} + \alpha \qquad \text{(A-2)}$$

where α and β depend on band.

The relationship between the two approaches is:

$$\text{fk1} = c_1 \upsilon^3 \qquad \text{(A-3)}$$

$$\text{fk2} = c_2 \upsilon \qquad \text{(A-4)}$$

$$\text{bc1} = -\alpha/\beta \qquad \text{(A-5)}$$

$$\text{bc2} = 1/\beta \qquad \text{(A-6)}$$

Finally, the conversion methodology evoked by some has been implemented by using the central wavelength to derive the fk1 and fk2 internally. It should be noted that the central wavenumber needs to be properly computed (significant digits, etc.) to derive the most accurate fk1 and fk2. For example, a nominal value should not be used. The central wavenumber is calculated by the integral of the relative response times the wavenumber divided by the integral of the relative response.

fk1 = C1 * WaveNumber ** 3 (A-7)
fk2 = C2 * WaveNumber (A-8)

$$\text{Var\_Tmp1} = \log(1.0 + \text{fk1} / \text{Radiance}) \quad \text{(A-9)}$$

$$\text{Var\_Tmp} = \text{fk2} / \text{Var\_Tmp1} \quad \text{(A-10)}$$

$$\text{Brt\_Temp} = (\text{Var\_Tmp} - \text{bc1}) / \text{bc2} \quad \text{(A-11)}$$

Appendix B. A note on fundamental constants

The Boltzmann constant is the physical constant relating energy to temperature at the particle level. It is named after the Austrian physicist Ludwig Boltzmann. The Planck Constant is a physical constant that is used to describe the sizes of quanta. It is named after Max Planck, a German physicist and the founder of quantum theory. The speed of light here is actually the speed of light in a vacuum. Without going into a great deal of physics, or quantum physics, as measurement equipment and/or techniques change and improve, these constants can change. These values are maintained at the National Institute of Standards and Technology (NIST) and the Committee on Data for Science and Technology, known as CODATA. CODATA is an international and interdisciplinary committee whose purpose is to periodically provide the international scientific and technological communities with an internationally accepted set of values of the fundamental physical constants and closely related conversion factors for use worldwide. The first such CODATA set was published in 1973, later in 1986, 1998, 2002 and the fifth in 2006. The values presented here are from what is termed the "2006 CODATA recommended values," they are generally recognized worldwide for use in all fields of science and technology.

Great care should be taken before these values are updated. One approach might be to adopt the 2006 values for the life of the GOES-R series. This is consistent with previous NOAA/NESDIS processing.

Reference

Mohr, P. J., B. N. Taylor, and D. B. Newell, 2006: CODATA Recommended Values of the Fundamental Physical Constants. National Institute of Standards and Technology, Gaithersburg, Maryland, USA. Dated: 28 December 2007.

Appendix C: Navigating ABI Pixels

The text and equations in Appendix C are taken in their entirety from the GOES-R ABI Product Definition and User’s Guide (PUG) Volume 3: Level 1b Products, Revision H.1.

C.1 Navigating from N/S Elevation Angle (y) and E/W Scanning Angle (x) to Geodetic Latitude (φ) and Longitude (λ)

Given a point P on the GRS80 ellipsoid with fixed grid coordinates (y,x) find the geodetic coordinates, (φ,λ).

The geodetic latitude (φ) and longitude (λ) are computed by the following equations

$$\begin{pmatrix} \phi \\ \lambda \end{pmatrix} = \begin{pmatrix} \arctan\left(\frac{r_{eq}^2}{r_{pol}^2} \frac{s_z}{\sqrt{(H - s_x)^2 + s_y^2}} \right) \\ \lambda_0 - \arctan\left(\frac{s_y}{H - s_x} \right) \end{pmatrix}$$

For:
x = Fixed Grid E/W scan angle in radians
y = Fixed Grid N/S scan angle in radians

One computes S_x, S_y,S_z as follows:

$$a = \sin^2(x) + \cos^2(x)\left(\cos^2(y) + \frac{r_{eq}^2}{r_{pol}^2} \sin^2(y) \right)$$

$$b = -2H\cos(x)\cos(y)$$

$$c = H^2 - r_{eq}^2$$

$$r_s = \frac{-b - \sqrt{b^2 - 4ac}}{2a} \quad \text{distance from the satellite to point P}$$

$$s_x = r_s \cos(x)\cos(y)$$

$$s_y = -r_s \sin(x)$$

$$s_z = r_s \cos(x)\sin(y)$$

Example

This example is based on the GOES-East satellite for a point, P, in a 2 km CONUS product with fixed grid coordinates given by

y(558) = 0.095340 rad
x(1539) = -0.024052 rad

Note the variables and their subscripts used here are as defined in paragraph 5.1.2.6, Product Data Structures, above.

Values for the parameters used in the equations and their netCDF Product File Attribute Names described in the table immediately above are as follows:

r_{eq} = goes_imagery_projection:semi_major_axis = 6378137 (meters)
1/f= goes_imagery_projection:inverse_flattening = 298.257222096
r_{pol} = goes_imagery_projection:semi_minor_axis = 6356752.31414 (meters)
e = 0.0818191910435
goes_imagery_projection:perspective_point_height = 35786023 (meters)
H = goes_imagery_projection:perspective_point_height +
goes_imagery_projection:semi_major_axis = 42164160 (meters)
x = x(1539) = -0.024052
y = y(558) = 0.095340
λ_0= goes_imagery_projection: longitude_of_projection_origin = -1.308996939

Based on these input values, the intermediate calculations in the above equations yield the following:

a = 1.000061039
b = -83921070.03
c = 1.73714E+15
r_s = 37116295.87
s_x = 36937048.73
s_y = 892635.0779
s_z = 3532287.213

Now using the values specified above and substituting into the equations for φ and λ, we obtain the following for the geodetic latitude and longitude:

φ= 0.590726971 rad = 33.846162 deg
λ= -1.478135612 rad = -84.690932 deg

corresponding to the GOES-East satellite fixed grid coordinates of

y(558) = 0.095340 rad
x(1539) = -0.024052 rad

C.2 Navigating from Geodetic Latitude (φ) and Longitude (λ) to N/S Elevation Angle (y) and E/W Scanning Angle (x)

Given a point P on the GRS80 ellipsoid with geodetic (φ,λ) coordinates find the fixed grid (y, x) coordinates.

Note that if the following inequality is true, then the (φ,λ) location is not visible from the satellite and the elevation and scanning angles should not be computed.

$$H(H - s_x) < s_y^2 + \frac{r_{eq}^2}{r_{pol}^2} s_z^2$$

The N/S Elevation Angle (y) and E/W Scanning Angle (x) are computed by the following equations

$$\begin{pmatrix} y \\ x \end{pmatrix} = \begin{pmatrix} \arctan\left(\frac{s_z}{s_x}\right) \\ \arcsin\left(\frac{-s_y}{\sqrt{s_x^2 + s_y^2 + s_z^2}}\right) \end{pmatrix}$$

Where,

ϕ = GRS80 geodetic latitude in radians

λ = GRS80 longitude in radians

$$\phi_C = \arctan\left(\frac{r_{pol}^2}{r_{eq}^2}\tan(\phi)\right) \quad \text{geocentric latitude}$$

$$r_C = \frac{r_{pol}}{\sqrt{1 - e^2\cos^2(\phi_C)}} \quad \text{geocentric distance to the point on the ellipsoid}$$

$$\begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix} = \begin{pmatrix} H - r_C\cos(\phi_C)\cdot\cos(\lambda - \lambda_0) \\ -r_C\cos(\phi_C)\cdot\sin(\lambda - \lambda_0) \\ r_C\sin(\phi_C) \end{pmatrix}$$

Example

This example verifies that the algorithm defined in paragraph 5.1.2.8.1 has an inverse. This example is based on the GOES-East satellite for a point, P, in a 2 km CONUS product with geodetic latitude and longitude given by

φ= 33.846162 deg = 0.590726966 rad
λ= -84.690932 deg = -1.47813561 rad

Values for the parameters used in the equations and their netCDF Product File Attribute Names described in the table immediately above are as follows:

r_{eq} = goes_imagery_projection:semi_major_axis = 6378137 (meters)
1/f = goes_imagery_projection:inverse_flattening = 298.257222096
r_{pol} = goes_imagery_projection:semi_minor_axis = 6356752.31414 (meters)
e = 0.0818191910435
goes_imagery_projection:perspective_point_height = 35786023 (meters)
H = goes_imagery_projection:perspective_point_height + goes_imagery_projection:semi_major_axis = 42164160 (meters)
φ= 0.590726966
λ= -1.47813561
λ_0= goes_imagery_projection: longitude_of_projection_origin = -1.308996939

Based on these input values, the intermediate calculations in the above equations yield the following:

φ_C = 0.587623849
r_c= 6371541.614
s_x = 36937048.71
s_y = 892635.07
s_z = 3532287.186

Now using the values specified above and substituting into the equations for y and x, we obtain the following for the fixed grid coordinates

y = 0.095340 rad
x = -0.024052 rad

corresponding to the GOES-East satellite geodetic latitude and longitude of

φ= 33.846162 deg
λ= -84.690932 deg

Appendix D: Satellite Specific Band Details

The details in tables for Appendix D are satellite-specific and are calculated from the flight level spectral response functions (SRFs) for the individual ABI instruments on each satellite.