CWG Analysis: ABI Max/Min Radiance Characterization and Validation

Contact:
Frank Padula
Integrity Application Incorporated
Email: Frank.Padula@noaa.gov

Dr. Changyong Cao
NOAA/NESDIS/STAR
Email: Changyong.Cao@noaa.gov

Date:
25 February 2015

Prepared for:
Imagery Team

Additional Participants:

NOAA – Fred Wu, Mike Weinreb, Bob Iacovazzi
NASA – Jack Xiong
NESDIS: University of Wisconsin – Tim Schmit
MIT-LL – Monica Coakley

Purpose: Summarize and document the GOES-R Calibration Working Group (CWG) analysis and characterization of the recommended ABI solar band (Ch. 1-6) max/min radiance values for GOES-R GOES Re-Broadcast (GRB).

Table 1: a) Recommended ABI solar band max/min radiance values [mW/m^2 sr cm^{-1}].

ABI Band #	Band Minimum	Band Maximum
1	-0.57338338	17.77488538
2	-0.83799012	25.97769412
3	-0.90205983	27.96385483
4	-0.85959404	26.64741504
5	-0.79255993	24.56935793
6	-0.48595030	15.06445930

b) Recommended ABI solar band max/min radiance values [W/m^2 sr µm].

ABI Band #	Band Minimum	Band Maximum
1	-25.93664701	804.03605737
2	-20.28991094	628.98723908
3	-12.03764377	373.16695681
4	-4.52236858	140.19342584
5	-3.05961376	94.84802665
6	-0.96095066	29.78947040

1 Context

The GOES-R Calibration Working Group was tasked to determine the ABI solar band (Ch. 1-6) max/min radiance values to be observed on orbit. These values are used to appropriately scale the dynamic range of the ABI's imagery in GOES-R GRB. The goal is to determine the set of values that will ensure the data-stream does not saturate pixels under typical operational conditions on the high end, as well as ensure that information is not lost as a result of the previous on the low end.

To first order, the subsequent methodology can be followed to calculate the desired values: 1) ABI solar channel spectral response functions (SRFs) are convolved with the solar exoatmospheric irradiance, to obtain the in-band solar irradiance for each channel; 2) in the absence of the atmosphere, the in-band solar irradiance can be propagated to the earth's surface, reflected, and then propagated to the sensor, by assuming the earth is a pure 100% Lambertian reflector. Combining steps one and two yields the approximate maximum radiance for each band.

Due to earth objects exhibiting highly specular reflectance in the field of view of the instrument (i.e. clouds, water glint, etc.), referred to as a given material type's Bi-Reflection Distribution Function (BRDF), the first order calculation is invalid, as it tends to under estimate the maximum observed radiance. In addition, the atmosphere will also contribute to the observed signal; however this effect is considerably less than the previous. To address these shortcomings, it is recommended to "pad" the maximum 1st order approximate values to account for operationally applicable BRDF effects.

Section 2 discusses the analysis preformed: 1) investigates the sensitivity of minor SRF changes to the observed solar exoatmospheric irradiance; 2) determination of theoretical max/min radiance values; 3) determination of the recommended max/min radiance values; 4) quantization limitations analysis and document summary. Note Appendix A provides a description of relevant radiance unit conversions.

2 Analysis Preformed

2.1.1 Spectral Response Function Sensitivity to the MODTRAN v4 Solar Model

The MODTRAN 4V1R1 solar model was used for this study. Three unique sets of ABI pre-launch SRFs were used: 1) NOAA/NESDIS at University of Wisconsin (UW); 2) GOES-R Calibration Working Group (CWG); 3) Proto-Type Model (PTM). The UW developed a purely simulated set of Gaussian like or commonly referred to as "Gaussian Boxcar Hybrid" functions uniquely centered at each of the central wavelength locations specified for the ABI [ftp://ftp.ssec.wisc.edu/ABI/SRF/readme_02Mar2005.txt]. Like the UW SRF data the GOES-R CWG SRF data are also "simulated", although this data used vendor supplied ABI witness sample measurements as a basis set of functions, then modified each band to comply with ABI band specifications. The PTM data represents the closest set of SRFs to the final set of ABI SRF data of all three types (as of June 2010).

The effective spectral irradiance observed by the sensor is found by convolving each ABI solar band SRF (ch. 1-6) with the spectral exoatmospheric solar irradiance:

$$E_{sun(\lambda)} = \frac{\int_{\lambda_1}^{\lambda_2} E_{ex} R_{\lambda}^{'} d\lambda}{\int_{\lambda_1}^{\lambda_2} R_{\lambda}^{'} d\lambda} \qquad \left[\frac{W}{cm^2 cm^{-1}}\right] \qquad (1)$$

where E_{ex} is the MODTRAN 4V1R1 derived exoatmospheric solar irradiance [W/cm^2 cm^{-1}], $R_{\lambda}^{'}$ is the peak normalized spectral response function for each ABI band. Equation 1 was used to derive ABI band effective exoatmospheric solar irradiance values for all sets of ABI SRFs.

Analysis showed that the in-band ABI SRFs sensitivity (i.e. slight differences in SRF due to each of the three unique sets used), regarding the exoatmospheric solar irradiance was small, all below 1% different [Figure 1].

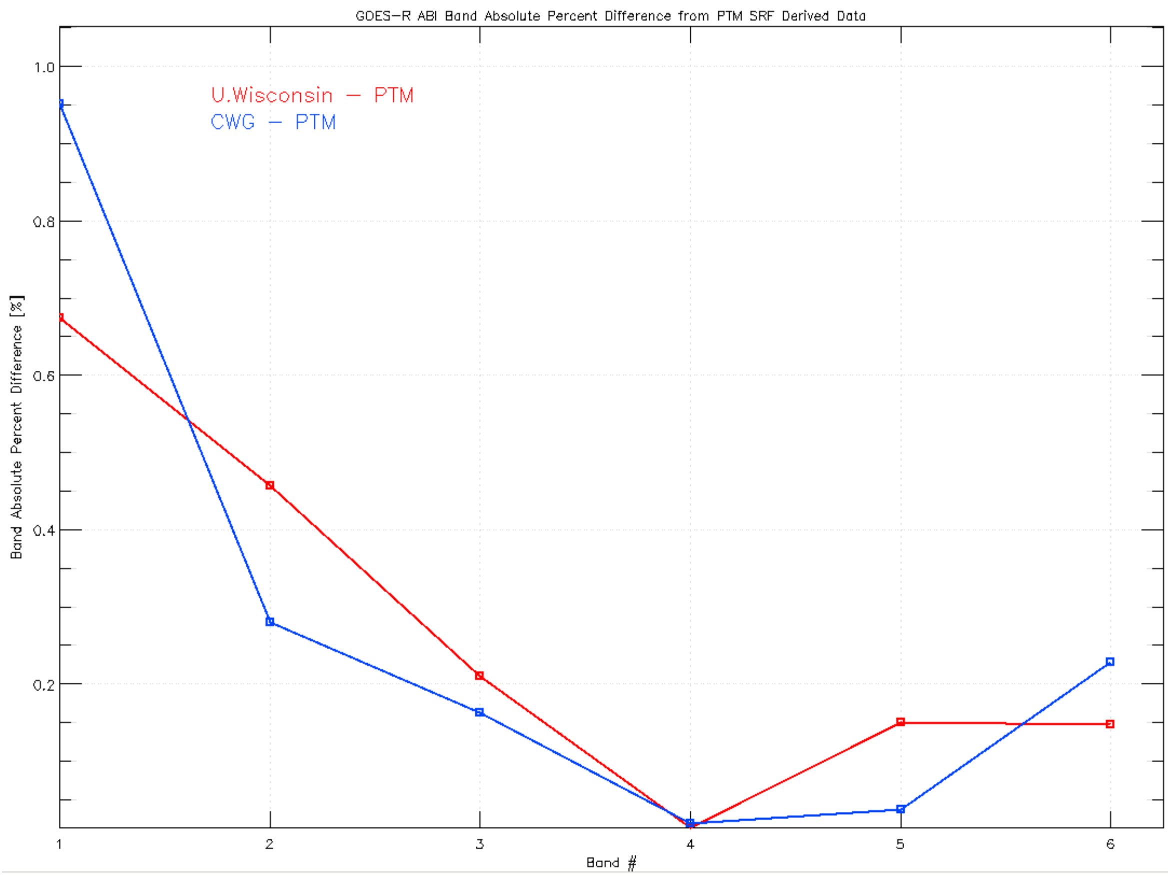

Figure 1: Illustrates the observed percent difference between each of the SRFs investigated compared to the PTM set of data.

Table 2: Provides the calculated band effective ABI irradiance values for each set of SRFs [mW/m^2 cm^{-1}].

ABI Band #	University of Wisconsin	Proto-Type Model	Calibration Working Group
1	45.127903	45.434075	45.001586
2	66.401132	66.099227	65.913797
3	71.477924	71.328299	71.212233
4	68.109387	68.100063	68.112996
5	62.706545	62.801310	62.777551
6	38.449359	38.506003	38.417868

Note that Table 2 highlights the maximum in-band radiance values calculated for each ABI band.

2.2 Theoretical Determination of ABI Max/Min Radiance Values (Lambertian Assumption)

This section illustrates the calculation of theoretical ABI max/min radiance values. Discussion begins with deriving the maximum ABI radiance values for a 100% Lambertian reflector, and follows with the methodology to compute the minimum ABI radiance values.

2.2.1 Maximum Radiance Calculation

2.2.1.1 Determination of K_o Factor:

$$K_o = \frac{\Pi}{E_{sun(\lambda)}}\left(\frac{R_{sun-obs}}{R_o}\right)^2 \qquad \left[\frac{W}{cm^2 cm^{-1}}\right]^{-1} \tag{4}$$

where $E_{sun(\lambda)}$ is the band effective exoatmospheric solar irradiance [W/cm^2 cm^{-1}] (Eq.1), $R_{sun-obs}$ is the earth sun distance at the time of image acquisition [AU] and R_o is the annual average earth sun distance [AU]. Assuming the distance between the earth and sun is at perihelion (i.e. the minimum distance), the ratio $R_{sun-obs}/R_o$ becomes 0.98329 [AU]. Using the irradiance values listed in Table 2, K factors were found for each band of the three SRFs using Eq.4 [Table 3].

Table 3: ABI Band minimum K factor values for each set of SRFs [W/cm2 cm-1]-1.

ABI Band #	University of Wisconsin	Proto-Type Model	Calibration Working Group
1	0.067308207	0.066854629	0.067497136
2	0.045744374	0.045953309	0.046082586
3	0.042495333	0.042584476	0.042653882
4	0.044597057	0.044603163	0.044594694
5	0.048439572	0.048366479	0.048384784
6	0.078999451	0.078883239	0.079064206

2.2.1.2 Determination of Radiance (*L*):

$$L = \frac{\rho_f}{K_o} \qquad \left[\frac{W}{cm^2 cm^{-1}}\right] \tag{5}$$

where ρ_f is the reflectance factor of a Lambertian object on the earth's surface and K_o is the K factor [W/cm^2 cm^{-1}]$^{-1}$. To compute the maximum ABI radiance for each band, the reflectance factor (ρ_f) is assumed to be a 1.0 (or 100%) Lambertian reflector. Using the values listed in Table 3 as input to Eq. 5 the maximum radiance values were derived [Table 4].

Table 4: ABI theoretical maximum radiance values (100% Lambertian reflector) [mW/m^2 sr cm^{-1}].

ABI Band #	University of Wisconsin	Proto-Type Model	Calibration Working Group	Band Maximum	Source
1	14.857029	14.957827	14.815443	14.957827	PTM
2	21.860612	21.761218	21.700171	21.860612	UW
3	23.531996	23.482736	23.444525	23.531996	UW
4	22.423004	22.419935	22.424192	22.424192	CWG
5	20.644278	20.675477	20.667655	20.675477	PTM
6	12.658316	12.676964	12.647948	12.676964	PTM

2.2.2 Minimum Radiance Calculation

The SNR values for all GOES-R solar bands are 300:1 at 100% albedo [GOES-R PORD]. By dividing the maximum band values listed in Table 2, by 300 a baseline estimate for the minimum ABI radiance can be determined [Table 5].

Table 5: ABI noise specification in radiance (100% Lambertian reflector) [mW/m^2 sr cm^{-1}].

ABI Band #	Noise
1	0.049859425
2	0.072868706
3	0.078439985
4	0.074747308
5	0.068918255
6	0.042256547

2.3 "Padding" the Theoretical ABI Max/Min Radiance Values

To attempt to account for the inadequacies of the Lambertian assumption, the reflectance factor (ρ_f) in Eq. 5 is assumed to be a 1.15 (or 115%) Lambertian reflector. The additional 15% adjustment was established based on consensus of experienced calibration experts. The updated max/min radiance values are shown in Table 6.

Table 6: ABI theoretical max/min radiance values (115% Lambertian reflector) [mW/m^2 sr cm^{-1}].

ABI Band #	University of Wisconsin	Proto-Type Model	Calibration Working Group	Band Maximum	Adjusted Noise
1	17.085584	17.201502	17.037760	17.201502	0.057338338
2	25.139704	25.025401	24.955197	25.139704	0.083799012
3	27.061795	27.005147	26.961203	27.061795	0.090205983
4	25.786455	25.782925	25.787821	25.787821	0.085959404
5	23.740920	23.776798	23.767803	23.776798	0.079255993
6	14.557063	14.578509	14.545141	14.578509	0.048595030

To determine the final radiance values it is recommended to multiply the minimum radiance values [Table 6] by a factor of 10 (i.e. 10 standard deviations) to provide the appropriate padding to guarantee that the system can characterize radiance values up to 115%, in reference to a Lambertian reflector. The padded minimum values are then added to the maximum values to adjust for uncertainty on the high end; on the low end the padded minimum values are multiplied by negative one to yield the final max/min ABI radiance values [Table 7].

Table 7: Recommended ABI solar band max/min radiance values [mW/m^2 sr cm^{-1}].

ABI Band #	Band Minimum	Band Maximum
1	-0.57338338	17.77488538
2	-0.83799012	25.97769412
3	-0.90205983	27.96385483
4	-0.85959404	26.64741504
5	-0.79255993	24.56935793
6	-0.48595030	15.06445930

b) Recommended ABI solar band max/min radiance values [W/m^2 sr µm].

ABI Band #	Band Minimum	Band Maximum
1	-25.93664701	804.03605737
2	-20.28991094	628.98723908
3	-12.03764377	373.16695681
4	-4.52236858	140.19342584
5	-3.05961376	94.84802665
6	-0.96095066	29.78947040

2.3.1 Analysis of Quantization Limitations

GOES-R GRB is intended to have a bit depth of 12 bit resolution for all solar reflective bands (ch. 1-6). For verification purposes, a simple calculation was preformed to determine the number of bits needed to completely characterize each ABI band by using the following expression:

$$Bits\ \ Needed = \frac{Bit\ \ resolution}{Noise} \tag{6}$$

The equivalent band radiance relative to one digital count can be determined by the following:

$$Equivalent\ \ Radiance\ \ to\ \ 1\ \ count = \frac{Maximum\ \ band\ \ radiance}{Bit\ \ resolution} \tag{7}$$

Equations 6 & 7 were used to populate Table 8 and Table 9, respectively. The values in Table 8 should ideally be greater than three to provide adequate sampling. Through visual inspection [Table 8], a bit depth of 10 demonstrates adequate bit depth to avoid quantization limitations at the noise specification requirement, however, if SNR levels exceed specification then more bits may be required in the GOES-R GRB.

Table 8: Quantization evaluation [Eq. 6].

ABI GRB Bit Depth	Quantization Noise (Noise in Counts) SNR 300:1	Quantization Noise (Noise in Counts) Exceeding Specification SNR 600:1	Quantization Noise (Noise in Counts) Exceeding Specification SNR 1200:1
10	3.413333333	1.706666667	0.853333333
11	6.826666667	3.413333333	1.706666667
12	13.65333333	6.826666667	3.413333333
13	27.30666667	13.65333333	6.826666667
14	54.61333333	27.30666667	13.65333333

From Table 9, it is clear that at all specified bit depths the band equivalent radiance to one digital count is less than the estimated noise specification, which states that the noise can be adequately resolved by the system.

Table 9: Band equivalent radiance to one digital count [mW/m^2 sr cm^{-1}]. Note these values were derived using the 115% Lambertian reflector values [Table 6], not the noise padded estimates.

Band Maximum	Calc. Band Noise	Equivalent Band Radiance to 1 Count Bit Depth: 10	11	12	13	14
17.77488538	0.05733834	0.01736	0.00868	0.00434	0.00217	0.00108
25.97769412	0.08379901	0.02537	0.01268	0.00634	0.00317	0.00159
27.96385483	0.09020598	0.02731	0.01365	0.00683	0.00341	0.00171
26.64741504	0.0859594	0.02602	0.01301	0.00651	0.00325	0.00163
24.56935793	0.07925599	0.02399	0.01200	0.00600	0.00300	0.00150
15.0644593	0.04859503	0.01471	0.00736	0.00368	0.00184	0.00092

3 Summary

ABI solar band max/min radiance values were derived, guaranteeing ABI the capability to characterize the radiance from a 115% Lambertian surface. The radiance values were padded with a factor of ten, to account for the any uncertainties at both the high and low end of the systems dynamic range to yield the recommended GOES-R ABI GRB max/min radiance values [Table 7]. Note these scaling coefficients are not expected to change for GOES-S.

4 References

[1] Specific final location: "ABI_solarBand_Study.ppt".

[2] Schlapfer and Schaepman, "Modeling the noise equivalent radiance requirements of imaging spectrometers based on scientific applications".

[3] Cao, C., and A. Heidinger, 2002, Inter-Comparison of the Longwave Infrared Channels of MODIS and AVHRR/NOAA-16 using Simultaneous Nadir Observations at Orbit Intersections, Earth Observing Systems, VII, Edited by W. Barnes, Proceedings of SPIE Vol. 4814, pp.306-316. Seattle, WA.

Appendix A

Unit Conversion: ABI band integrated radiance [mW/m² sr cm⁻¹] to [mW/m² sr µm]

This method was document in Cao et al. 2002:

At sensor radiance (L_s) is defined as:

$$L_s = \int_{\lambda_1}^{\lambda_2} L \; R_\lambda^{'} \; d\lambda \qquad \left[\frac{mW}{m^2 sr} \right] \tag{2}$$

where L is the sensor reaching radiance, $R_\lambda^{'}$ is the peak normalized spectral response function for a give band. To obtain the desired effective spectral radiance reaching the sensor, Eq. 2 must be divided by the unique band equivalent width:

$$L_{eff} = \frac{\int_{\lambda_1}^{\lambda_2} L \; R_\lambda^{'} \; d\lambda}{\int_{\lambda_1}^{\lambda_2} R_\lambda^{'} \; d\lambda} \qquad \left[\frac{mW}{m^2 sr \; cm^{-1}} \right]$$

$$L_{eff} = \frac{\int_{\lambda_1}^{\lambda_2} L \; R_\lambda^{'} \; d\lambda}{\boxed{\int_{\lambda_1}^{\lambda_2} R_\lambda^{'} \; d\lambda}} \longrightarrow Band \;\; Equivalent \;\; Width = Eqw = \int_{\lambda_1}^{\lambda_2} R_\lambda^{'} \; d\lambda \tag{3}$$

where L_{eff} is the effective spectral radiance reaching the sensor, $R_\lambda^{'}$ is the peak normalized spectral response function for a given band. Note that the band Eqw has units which are dependent upon the units provided in the spectral response file either [wave-number or wavelength]. By convention $R_{\lambda \, wn}^{'}$ illustrates an Eqw [wave-number], where $R_{\lambda \, wvl}^{'}$ illustrates an Eqw [wavelength].

To convert band integrated values from wave-number space to wavelength space and vice versa, the band equivalent width (Eqw) is used. Below describes the processing steps that should be followed. The conversion from wave-number to wavelength is shown; note that the same process can be applied to perform the opposite conversion. The equivalent width values for the both the CWG and UW SRFs are provided in Table 10 & Table 11.

Wave-number to Wavelength:

1. Multiple the L_{eff} (Eq.3) [mW/m^2 sr cm^{-1}] by the band Eqw [wave-number], which yields L_s (Eq.2):

$$L_{eff} = \frac{\int_{\lambda_1}^{\lambda_2} L\ R_{\lambda}^{'}\ d\lambda}{\int_{\lambda_1}^{\lambda_2} R_{\lambda\,wn}^{'} d\lambda} \cdot \frac{\int_{\lambda_1}^{\lambda_2} R_{\lambda\,wn}^{'} d\lambda}{1} = \int_{\lambda_1}^{\lambda_2} L\ R_{\lambda}^{'}\ d\lambda = L_s \qquad \left[\frac{mW}{m^2 sr}\right]$$

2. Divide L_s by the band Eqw [wavelength] to obtain units of [mW/m^2 sr µm]:

$$L_{eff} = \frac{L_s}{\int_{\lambda_1}^{\lambda_2} R_{\lambda\,wvl}^{'} d\lambda} \qquad \left[\frac{mW}{m^2 sr\ \mu m}\right]$$

Table 10: Calibration Working Group (CWG) SRF band Eqw's.

CWG	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
Band Eqw [cm-1]	1534.5160	2252.5984	455.3989	77.5797	180.9592	87.8661
Band Eqw [µm]	0.0337	0.0906	0.0337	0.0147	0.0468	0.0445

Table 11: University of Wisconsin simulated SRF band Eqw's.

UW	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
Band Eqw [cm-1]	1872.4315	2535.0581	537.7881	81.5463	238.4452	101.1587
Band Eqw [µm]	0.0415	0.1047	0.0403	0.0155	0.0618	0.0512