Algorithm Theoretical Basis Document (ATBD) for ray-matching technique of calibrating GEO sensors with Aqua-MODIS for GSICS

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August 19, 2011

Introduction

The ray-matching technique is a vicarious approach of transferring calibration from a well-calibrated satellite sensor to another sensor using coincident, co-angled, and co-located pixels. At NASA Langley Research Center, this technique has been implemented to calibrate the geostationary earth observing (GEO) satellites that do not have on-board calibration for visible channels. The Aqua-MODIS instrument is used as an absolute calibration reference for this purpose.

The ATBD ray-matching technique proposed for GSICS follows the approach outlined in Minnis et al. 2002, and Minnis et al. 2007, with further refinements. The success of this method relies on obtaining ray-matched radiances over the entire dynamic range of the GEO sensor. Having a temporally stable reference sensor in a near-noon sun-synchronous orbit, and having optically thick clouds near the GEO sub-satellite domain during the reference overpass time, can achieve this. This method also provides an independent assessment of the linearity of the GEO sensor response. Sampling errors associated with this method are mitigated by: regressing the matched radiances monthly to improve the prospects of bright clouds thereby increasing the dynamic range, using 50-km spatially averaged radiances to reduce navigation errors and pixel resolution differences, limiting the time difference to 15 minutes and applying a spatial uniformity threshold to reduce advection effects due to the time sampling difference. For each satellite pair, independent matching thresholds are determined to provide the greatest dynamic range with the least radiance pair regression noise. Limiting the domain to ocean regions and encompassing optically thick high clouds reduces the spectral correction between the two sensors. SCIAMACHY footprint pseudo radiances, based on the GEO and reference spectral response functions (SRF), are used to derive the spectral correction factor. Similar SRFs and non-absorbing spectra bands inherently reduce the dependence of the spectral correction factor.

A reference sensor is required for absolute calibration transfer. Stability of the reference sensor is also necessary if ray-matching is applied over the lifetime of the GEO instrument. It has been determined that the Aqua-MODIS instrument is better-characterized and more stable than Terra-MODIS, and, therefore, is the calibration standard for GSICS. The Aqua-MODIS calibration can easily be adjusted if another reference sensor is agreed upon or if stability adjustments are needed.

The Global Space-based Inter-Calibration System (GSICS) aims to inter-calibrate a diverse range of satellite instruments in order to produce corrections that ensure their data are consistent, thereby allowing them to be used to produce globally homogeneous products for environmental monitoring. Although these instruments operate on different technologies for different applications, their inter-calibration can be based on common principles: Observations are collocated, transformed, compared and analyzed to produce calibration correction functions - transforming the observations to common references. To ensure the maximum consistency and traceability, it is desirable to base all the inter-calibration algorithms on common principles, following a hierarchical approach, described here. The algorithm is defined in 5 generic steps:

1. Gridding and subsetting data
2. Collocating GEO and MODIS data
3. Spectral transformation of data
4. Filtering data
5. Monthly regression analysis and temporal gain monitoring

The ATBD also include an uncertainty analysis

1. Gridding and subsetting data

Subsetting of satellite data is required to reduce the data volume necessary for inter-calibration, thereby only including portions of dataset that are likely to produce collocations. For each GEO, a calibration domain is defined over ocean close to the Sub-Satellite Point (SSP) with a threshold of ±20° E, W and ±15° N, S (Figure 1 and Table 1). The GEO raw counts (proportional to radiance) are binned within 0.5° x 0.5° over this region. Using the MODIS orbital information, the Aqua-MODIS overpass over the GEO calibration domain is predicted. The calibrated Aqua-MODIS radiances are also binned within 0.5° x 0.5° over the same domain. Note the larger domains for satellites with more landmass near the GEO sub-satellite point. The subset of GEO raw counts and Aqua-MODIS radiances are archived on a monthly basis. Large areal bins reduce the impact of navigation errors, time matching, and pixel resolution differences. Small areal bins have a greater probability of capturing bright clouds to improve the dynamic range.

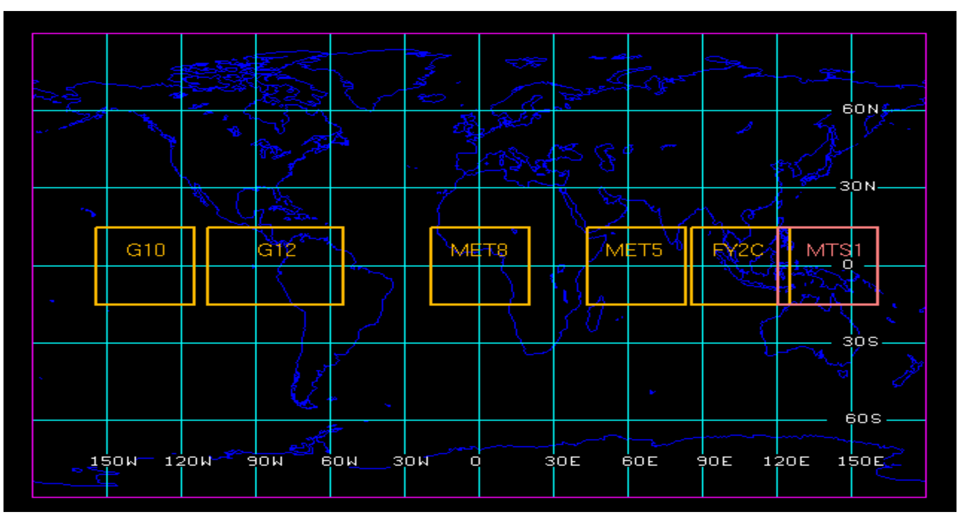

Figure 1: Calibration domains for GEOs.

2. Collocating GEO and MODIS data

This step involves identifying the bins from both instruments that are spatially collocated, temporally concurrent, and geometrically aligned. The bins are collocated in space by comparing their center Lat/Lon coordinates. The threshold for temporal matching is set to 15 minutes. Any Aqua-MODIS collection that differs from GEO acquisition time by more than 15 minutes is excluded.

Each bin identified as being spatially and temporally collocated is then tested to check whether the viewing geometry of the observations from both instruments was sufficiently close. The matching thresholds for solar, viewing, and azimuth angles of the two satellites are set to 5°, 10°, and 15° respectively. Only ocean regions are used. For this stage, a liberal threshold is applied to reduce the matched data volume. Further refinement in Step 4 applies the final matching thresholds. This iterative approach maximizes the number of matched radiance pairs and the dynamic range while minimizing the standard error of the regression.

3. Spectral transformation of data

The purpose of this step is to transform the collocated GEO and Aqua-MODIS data in order to allow for their direct comparison. This includes correction for spectral band differences between the GEO and MODIS channels, and normalization of the cosine of the solar zenith angle difference due the mismatch in time.

The corrections for spectral band differences between geostationary and MODIS bands require the knowledge of the Spectral Response Functions (SRFs) of both of the channels, as well as the spectral signature of the target. Any land pixels over the calibration domain are masked because the spectral signature over land is highly unpredictable. All-sky ocean hyper-spectral data acquired over the calibration domain by the SCIAMACHY sensor onboard ENVISAT are used to derive the spectral footprint of the target. The calibrated hyper-spectral at-sensor radiances from SCIAMACHY are then convolved with the SRFs of both the geostationary and MODIS channels to estimate the Spectral Band Adjustment Factor (SBAF) for individual GEO-MODIS pairs (Eq. 1) and is described in Doelling et al. 2011.

$$SBAF = \frac{\int R_{GEO}(\lambda).\rho_{SCIA}(\lambda)d\lambda / \int R_{GEO}(\lambda)d\lambda}{\int R_{AQUA}(\lambda).\rho_{SCIA}(\lambda)d\lambda / \int R_{AQUA}(\lambda)d\lambda} \quad . \qquad (1)$$

The 2nd-order polynomial regression between GEO and Aqua radiances derived from 5 years of seasonal months from 2003-2007 is used to compute the SBAF. However, over ocean this correction is fairly linear as shown in Figure 2. The current GEO SBAF linear adjustment factors for comparison purposes are given Table 2. For a given reference sensor and monitoring sensor, the radiance measured by the monitoring sensor is related to that of the other by the SBAF if both are perfectly calibrated. The *SBAF* is simply the ratio of the imager pair pseudo-radiances, which are the convolved radiances $L_{Monitoring}$ and $L_{Reference}$ from the SCIAMACHY data and are applied as shown in Eq. 2,

$$L_{Monitoring} = SBAF \text{ x } L_{Reference}. \tag{2}$$

The Metoesat-9 and Aqua-MODIS instruments have very similar SRFs and reveal little scatter about the regression line, whereas FY2E, which is nearly broadband, and Aqua-MODIS, which is very narrow, manifests much more scatter about the regression line. This factor is applied to the ray-matched Aqua-MODIS radiances to derive the equivalent GEO at-sensor radiances.

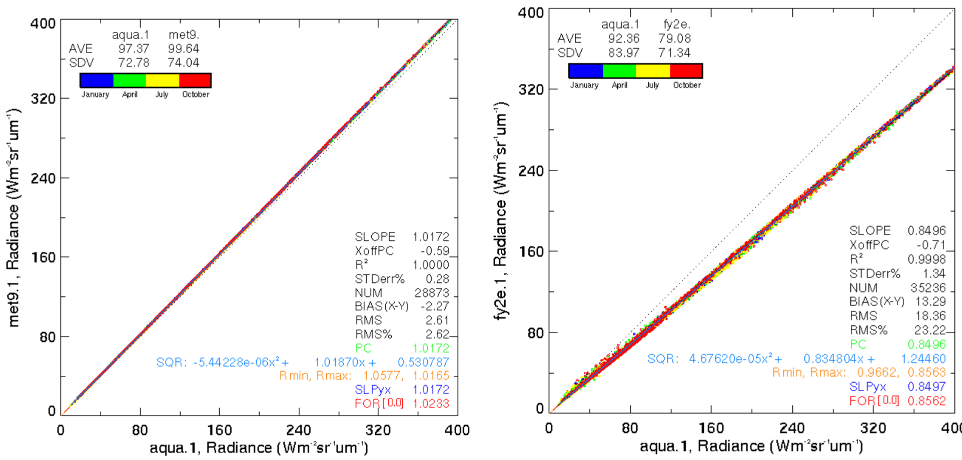

Figure 2: Left panel) Scatter plot of SCIAMACHY-ocean-footprint pseudo Aqua-MODIS and Meteosat-9 0.65-µm radiance pairs over the ray-matching domain. Right panel) Same as left panel except using FY2E.

The binned geostationary raw counts and the adjusted Aqua-MODIS radiances are both normalized to the corresponding solar zenith angles in order to minimize the effect of any temporal difference in the acquisition of data from the two satellites.

4. Filtering data

The collocated and transformed data is further analyzed for scene homogeneity in order to reduce inter-calibration uncertainty. The individual bins are checked for spatial uniformity by calculating the spatial standard deviation of all pixels within each bin. Bins with low spatial standard deviation are indicative of homogeneity, and a small offset in navigation will not have a significant impact on inter-calibration. The threshold for spatial standard deviation is derived empirically for each satellite pair, thereby maximizing the dynamic range of the observations while minimizing the noise. Figure 3 illustrates a 30% reduction in standard error of the monthly regression between Meteosat-9 and Terra-MODIS through restriction of the visible spatial standard deviation to 20% and decreasing the number of matches from 5400 to 1500. This is an effective way to remove outliers and determine the sensor linearity of the instrument.

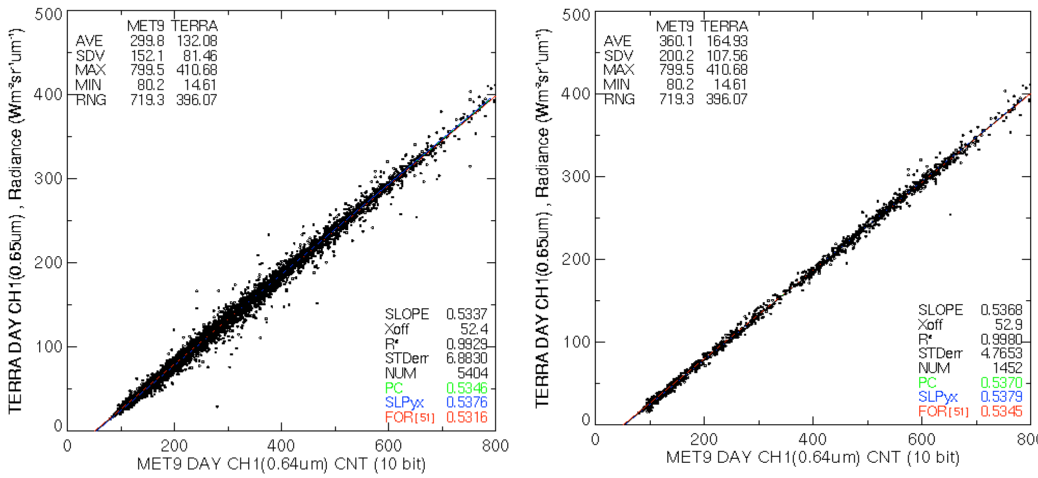

Figure 3: Monthly regression of Meteosat-9 counts and Terra-MODIS 0.5° binned radiances over the Meteosat domain. The left plot has no visible spatial standard deviation threshold applied; the right plot has a 20% threshold applied.

The clear-sky ocean bins that are likely to have sun glint are filtered out using a sun-glint probability routine. Most often, sun-glint probabilities greater than 10% are not used. Any further refinement in the time and angular matching is also applied in this step. It must be noted that at least a full year of monthly regressions need to be analyzed in order to effectively derive the matching thresholds given that clouds vary seasonally over the matching domain. Table 1 summarizes the GEO and Aqua-MODIS ray-matching criteria used in this ATBD.

GEO/MODIS parameter	Ray-Match threshold
Latitude Domain	15°N to 15°S ocean only
Longitude Domain	±20° of GEO sub-satellite
Bin resolution	0.5° by 0.5° lat/lon
Time match difference	< 15 minutes
Solar Zenith Angle difference	< 5°
View Angle difference	<10°
Azimuth Angle difference	<15°
Sun Glint Probability	<10%
Bin spatial homogeneity	20<>80%

Table 1: Summary of GEO/MODIS ray-matching criteria used in this ATBD.

5. Monthly regression analysis and temporal gain monitoring

The collocated, transformed, and filtered GEO raw counts and Aqua-MODIS radiances are systematically compared through a linear regression on a monthly basis using Equation 3.

$$Aqua_{radiance}[\cos(SZA_{GEO})/\cos(SZA_{Aqua})]SBAF_{GEO/Aqua} = Gain_{GEO}(CNT - CNT_{space}) \quad (3)$$

Given that the GEO satellites maintain space as a constant offset, the regression line is forced through the published space count. The slope of the line gives the monthly calibration gain of the GEO sensor. It is not recommended for the linear regression to compute both the space count or offset in addition to the gain.

In order to monitor changes in the GEO sensor gain, the computed monthly gains are plotted as a function of time (Figure 4). Time is measured in days since launch (DSL). The trend line for GEO sensor gain is derived from an appropriate fit to the data. A 95% confidence interval is also drawn in the timeline plot to visualize the adequacy of the fit. The gain taken from the trend line is used to transfer the calibration of Aqua-MODIS to the GEO. Usually the degradation over time is linear for sensors that degrade slowly, and 2nd-order polynomial for those that degrade quickly in the first few years after launch.

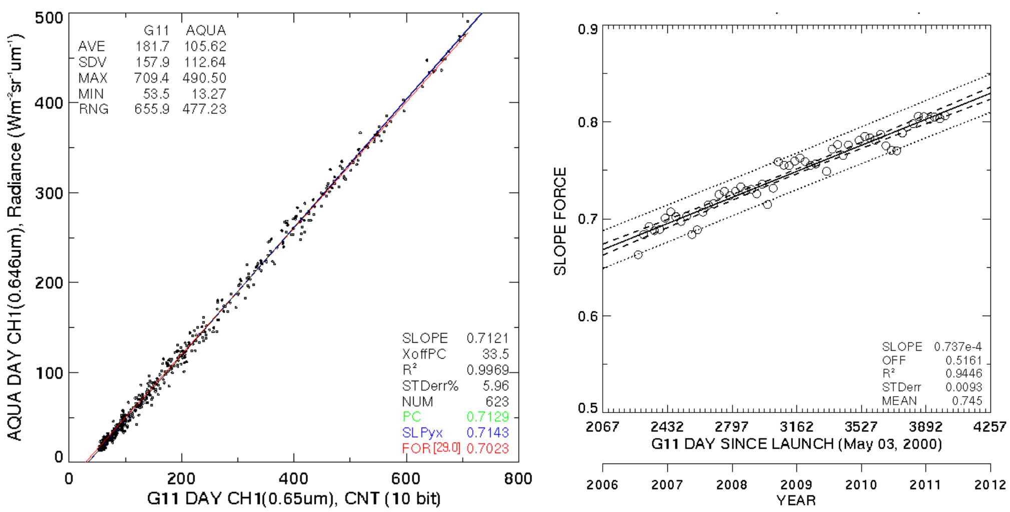

Figure 4: Left plot shows the February 2007 monthly regression of GOES-11 gridded counts and Aqua-MODIS radiances. The fit through the space count is in red. Right plot shows the monthly gains derived using the space count and the 95% confidence levels.

The Terra-MODIS radiances can be adjusted to the Aqua-MODIS reference calibration using nearly simultaneous nadir overpasses. Both Terra and Aqua-MODIS are now available for ray-matching. Figure 5 left panel shows that Terra and Aqua-MODIS and GOES-13 ray-matching monthly gains are nearly parallel over time and within 0.8% in absolute calibration (Morstad et al. 2011). The GOES-13 ray-matched calibration is compared with DCC and desert calibration in figure 5 right panel. The resultant GOES-13 absolute calibrations are within 1.4%, based on the 15-month gain means, indicating the robustness of the ray-matching technique. At least 3-years of monthly means are needed to assess the trend consistency.

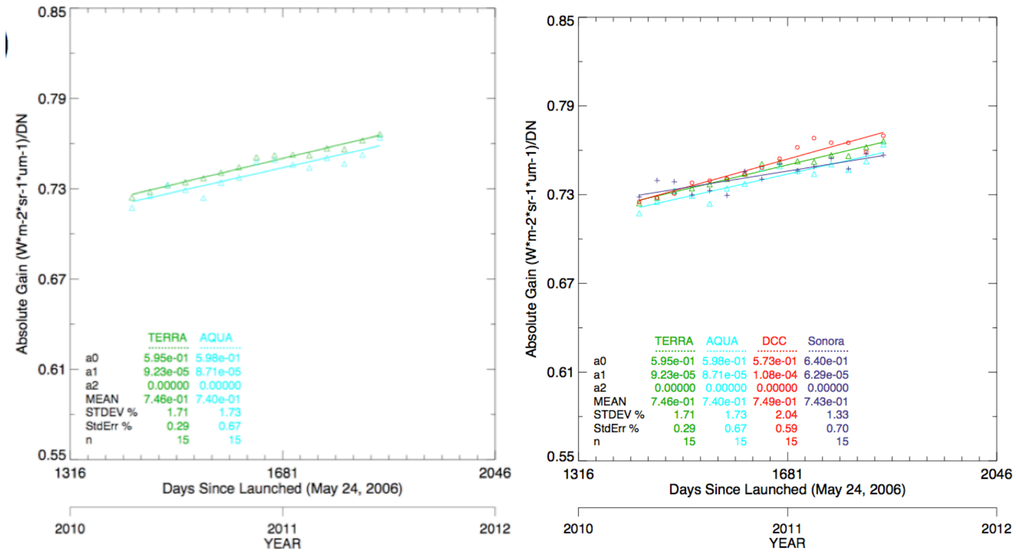

Figure 5: Shows monthly DCC mode gains for GOES-13 as a function of time. Right plot) shows the GOES-13 monthly gains based on ray-matching, desert and DCC approaches.

Uncertainty analysis

The derived GEO gain from ray-match transfer from the Aqua-MODIS absolute calibration can be divided into three components: the Aqua-MODIS calibration, ray-matching, and spectral correction uncertainty.

The Aqua-MODIS absolute calibration band 1 (0.65µm) uncertainty at covers-open after launch is 1.64% (Xiong 2011). The Aqua-MODIS stability is 0.2±0.9%/decade (2 sigma) for the nadir scan position. This ray-matching domain confines the MODIS radiances to be near nadir.

The ray-matching uncertainty has many components: the GEO/MODIS angle, time and space matching errors, and the sampled dynamic range. Although it is impossible to unravel any of these factors completely, the dynamic range is the greatest factor. For any radiance pair, the uncertainty is the monthly standard error as shown in Table 2. Note, however, that if all the radiance pairs are used over the month, the error about the mean radiance describes the uncertainty of the derived monthly gain. Table 2 illustrates the average of the monthly mean regression errors over the lifetime of various GEO satellites. Occasionally there are months when a GEO domain has mainly clear-sky conditions. For these months the signal to noise ratio is small, and the spectral correction becomes more critical. Either tightening the matching criteria for these months or simply removing the clear-sky months along the trend line can reduce the trend uncertainty. The right panel of Figure 4 clearly illustrates a seasonal trend in the monthly gains for GOES-11. The one or two months with gains below the trend line are from times when it is mainly clear over the domain. Usually after three years, these seasonal cycles of monthly gains are predictable. The ray-matching technique uncertainty is the standard error of the temporal regression and is given in Table 2 for various GEOs. Most GEOs are located in domains of continuous active convection, whereas the Meteosat-7 and GOES-11 are over domains of seasonally varying convection. The difference between MTSAT-1 and MTSAT-2 is instrument-related.

GEO satellite	Monthly Standard Error (%) Aqua/Terra	Monthly Mean Error (%) Aqua/Terra	Trend Standard Error (%) Aqua/Terra	Spectral correction slope (radiance/ reflectance)	Spectral Standard Error (%)
FY2E	15/	0.53/	0.9/	0.85/	1.34
GOES-11	8/	0.26/	1.3/	0.97/	1.38
GOES-13	7/	0.22/	0.7/	0.98/	0.85
MTSAT-1	12/	0.44/	3.5/	0.87/	1.23
MTSAT-2	7/5	0.40/0.28	1.0/0.8	0.94/	1.20
MET-7	8/	0.23/	1.6/	0.84/	2.12
MET-9	6/5	0.21/0.14	1.1/0.6	1.02/	0.28

Table 2: Ray-matching and spectral correction uncertainty analysis for several GEO/Aqua-MODIS or Terra-MODIS (adjusted) pairs. The spectral correction uses Aqua-MODIS as the reference.

The spectral correction uncertainty is based on the pseudo SCIAMACHY-derived MODIS and GEO radiances. The GEO instrument SRF uncertainty is not known or the on orbit degradation. Based on MODIS and CERES experience, the blue portion of the spectrum will degrade faster than the longer wavelengths for low earth orbits. It is suspected that contaminants are swept into the optics for low earth orbits. This should not be a problem for GEOs. For this error analysis, the GEO SRF is assumed to be perfect, and there is no change over time. The MODIS SRF is well-monitored and the temporal variations have been small (Xiong et al. 2011). The spectral correction over ocean, based on SCIAMACHY radiances pairs, is quite linear, and the standard error of the regression is a good estimate of the spectral correction uncertainty. The noise in the regression is mainly due to out of band absorption differences over an 85-km^2 region. The SCIAMACHY footprint is slightly larger than the GEO/MODIS grid resolution of 50 km^2, but should have little impact on the overall spectral correction uncertainty.

The SCIAMACHY stability over time is based on the solar diffuser and is assumed to be stable. The absolute calibration of SCIAMACHY is a function of wavelength and is given in Table 3. It is unknown how the various band uncertainties affect the overall spectra, however, the discontinuities in the overlap regions were small. Absolute calibration is unnecessary as long as the band calibration is maintained over time.

Band #	1	2	3	4	5
Band range (μm)	240-314	309-405	394-620	604-805	785-1050
Uncertainty (%)	3	4	3	2	6

Table 3: SCIAMACHY version 7.03 reflectance absolute calibration uncertainty as a function of band, from envisat.esa.int/handbooks/.../disclaimers/SCI_NL__1P_Disclaimers.pdf.

To compute the solar constants from the GEO SRF, the solar incoming spectra is required. This is not a concern if the ray-matching is being performed in reflectance units, but is necessary if radiance is desired. The CEOS community has chosen the

Thuillier solar irradiance spectra. MODIS radiances use Thuillier solar irradiance spectra from 0.4µm to 0.8µm and Neckel and Labs from 0.8µm to 1.1µm (Xiong 2011). For the uncertainty in the solar incoming spectra, the standard deviation of the convolved visible solar constant from six solar incoming spectral datasets was computed. The datasets include Iqbal (1983), Wherli (1985), Kurucz (2001), Thuillier (2003), Neckel & Labs, and a "quiet" (least absorbing) solar spectra from SORCE Spectral Irradiance Monitor (SIM), recommended by Greg Kopp 2011. Thekeakara was not used in the analysis being that it was considered an outlier in the spectra between 0.3 and 1.0 µm. Table 4 illustrates the uncertainty in the solar constant based on the standard deviation between spectra from six different sources. The narrowest bands have the greatest uncertainties.

Satellite band	Aqua 0.65µm	Met-7 visible	Met-9 0.65µm	Met-9 0.86µm	GOES-11 visible	MTSAT-1 visible
Uncertainty (%)	1.04	0.55	0.98	1.06	0.68	0.84

Table 4: Solar constant uncertainties based on the standard deviation of six datasets of solar spectra (see text).

To compute the overall uncertainty of the ray-matching technique for a given GEO/MODIS satellite pair, one would require the combination of the Aqua-MODIS absolute calibration uncertainty, the monthly ray-matching trend standard error, and the SCIAMACHY-based pseudo radiance pair standard error. Table 5 shows the uncertainty calculation for GOES-11.

GEO satellite	Aqua-MODIS (%)	Ray-match (%)	Spectral (%)	Total uncertainty (%)
GOES-11	1.64	1.3	1.38	2.5

Table 5: The uncertainty analysis for GOES-11 following the approach in this ATBD.

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