Post-launch calibration of GOES Imager visible channel using MODIS

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ABSTRACT

Lacking onboard calibration devices, the GOES Imager visible channel must be vicariously calibrated on orbit. Several methods have been explored. In this study, the method using a well-calibrated radiometer (MODIS) as an external reference for calibration was expanded and improved. This method is complementary to other techniques in that, in addition to long term trending, it also provides absolute calibration shortly after launch. Care must be taken, though, to account for the lack of simultaneity of the measurements by the two sensors and the differences in the sensors' spectral response functions.

Keywords: Calibration; Visible channel; GOES Imager; MODIS; Vicarious calibration, Post-launch calibration.

1. INTRODUCTION

The National Environmental Satellite, Data, and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA) has the operational responsibility of the U. S. "weather satellites", which include the operational calibration of the Geostationary Operational Environmental Satellite (GOES). The visible channel of the GOES Imager instrument does not have onboard calibration device. As the sensor responsivity degrades over time, the pre-launch calibration coefficients quickly become obsolete.

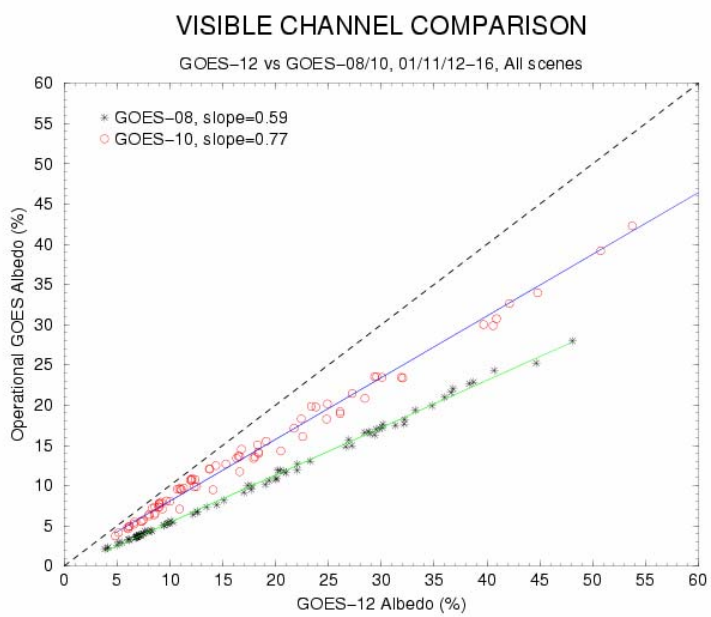

Figure 1: Example of GOES Imager visible channel degradation. See text for more details.

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Figure 1 is an example of GOES Imager visible channel degradation, in which the reflectances measured by GOES-8 and GOES-10 were plotted against those by GOES-12. The satellite measurements have been "co-located", i.e., each pair of satellites were viewing the same targets, at approximately the same time, and with comparable viewing geometry. The reflectance was derived using each sensor's pre-launch calibration coefficients. These measurements were taken in November 2001, during the GOES-12 Post-Launch Test, when the newly launched GOES-12 was stationed between GOES-8 (7.6 years in service) and GOES-10 (3.6 years in service). If all the sensors were perfectly calibrated, they should result in similar values of reflectance such that all symbols would line up close to the diagonal line. In reality, Fig. 1 shows that the GOES-10 reflectance is consistently lower than that of GOES-12, and the GOES-8 reflectance is even lower. When linear regression is performed based on these data, the slopes of the regression lines suggest that, at the time of measurements, the responsivity of GOES-10 and GOES-8 are about 77% and 59% of that of GOES-12.

The GOES Imager visible channels become out of calibration on orbit because these channels, unlike the infrared channels, lack onboard calibration devices and therefore can only be calibrated vicariously once launched. Since the sensor responsivity tends to decrease continuously ("degradation") over time, vicarious calibration must be performed regularly. Several methods have been developed for the vicarious calibration of GOES Imager visible channel, including those based on desert measurements (Rao and Zhang, 2001), star measurements (Bremer et al 1998, Chang et al 2004 & 2005)), and the empirical distribution function of the earth targets (Crosby et al 2005).

This study explores a new method for the vicarious calibration of GOES Imager visible channel, taking advantages of new measurements that were previously unavailable. One way to understand this new method is to view Fig. 1 as a demonstration of using co-located satellite measurements to cross calibrate satellite sensors. In that particular example, unfortunately, GOES-12 Imager visible channel was also uncalibrated; it was only newer on orbit and therefore believed less degraded. But if the uncalibrated GOES-12 data were replaced with measurements by a well calibrated radiometer, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), one could tune the GOES calibration to make the GOES measurements match the MODIS measurements. This is the basic premise of the MODIS-based calibration.

2. METHODOLOGY

2.1 Co-location

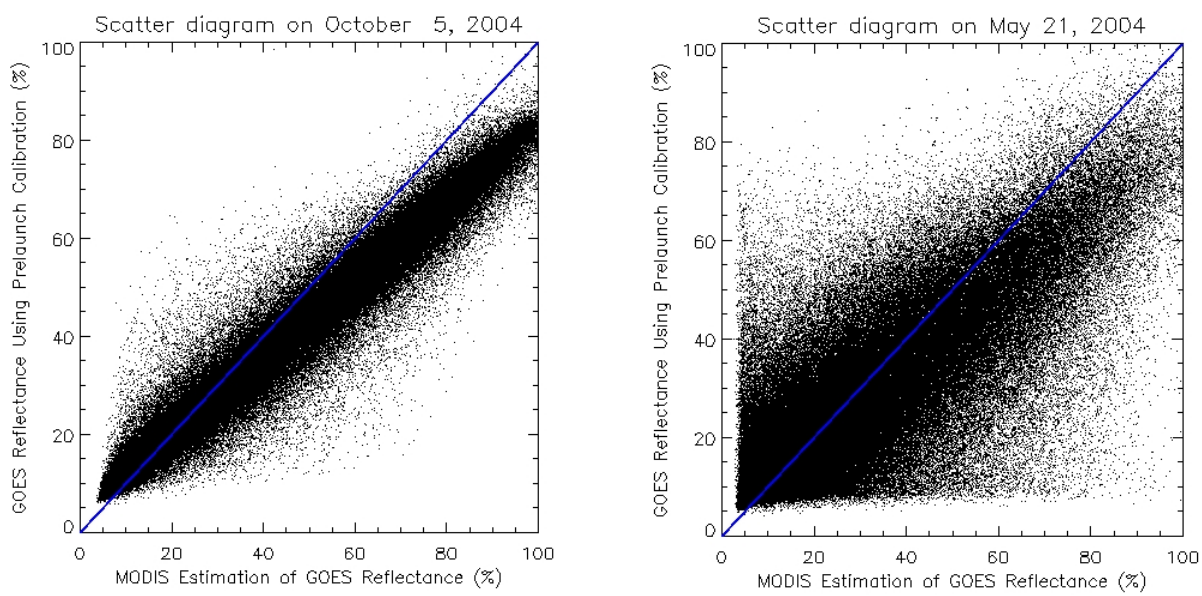


Figure 2: Scatter plots of the co-located MODIS and GOES-12 measurements on 5 October 2004 (left panel), when the two images were separated by 1 minute, and on 21 May 2004 (right panel), when the two images were separated by 6 minutes.

The first step of the MODIS-based post-launch calibration for GOES Imager visible channel is to collect the MODIS and GOES measurements that are co-located in space, concurrent in time, and similar in spatial and spectral coverage. For better match in terms of spectral response function and spatial resolution, the MODIS Channel 1 measurements at 1-km resolution were chosen to calibrate the GOES Imager visible channel. To avoid possible complications due to target bidirectional reflectance characteristics, the view angle by either sensor is limited to about 8.11 degrees from nadir.

The co-located GOES and MODIS measurements are not always well correlated at pixel level, as shown in Fig. 2. This is because the GOES and MODIS rarely observe the same place at exactly the same time. Normally the two images are separated by several minutes (as measured by the time the center of the image was observed by each sensor). At the nominal wind speed of 15-20 m/s, cloud edge can move about 1 km/min, or one pixel per minute for both MODIS and GOES, potentially causing large difference in measurements.

Nevertheless, inspection of MODIS and GOES images (Fig. 3) suggests that, while some features moved in and out of the domain and some may even have changed within the domain between the times when the two images were taken, the majority of the features just moved around. If that is assumed to be true, the two images should have identical distribution of brightness (histogram) even though they do not compare well pixel-to-pixel. For this reason, this work is based on analysis of histograms of GOES and MODIS images that were taken within ten minutes from each other.

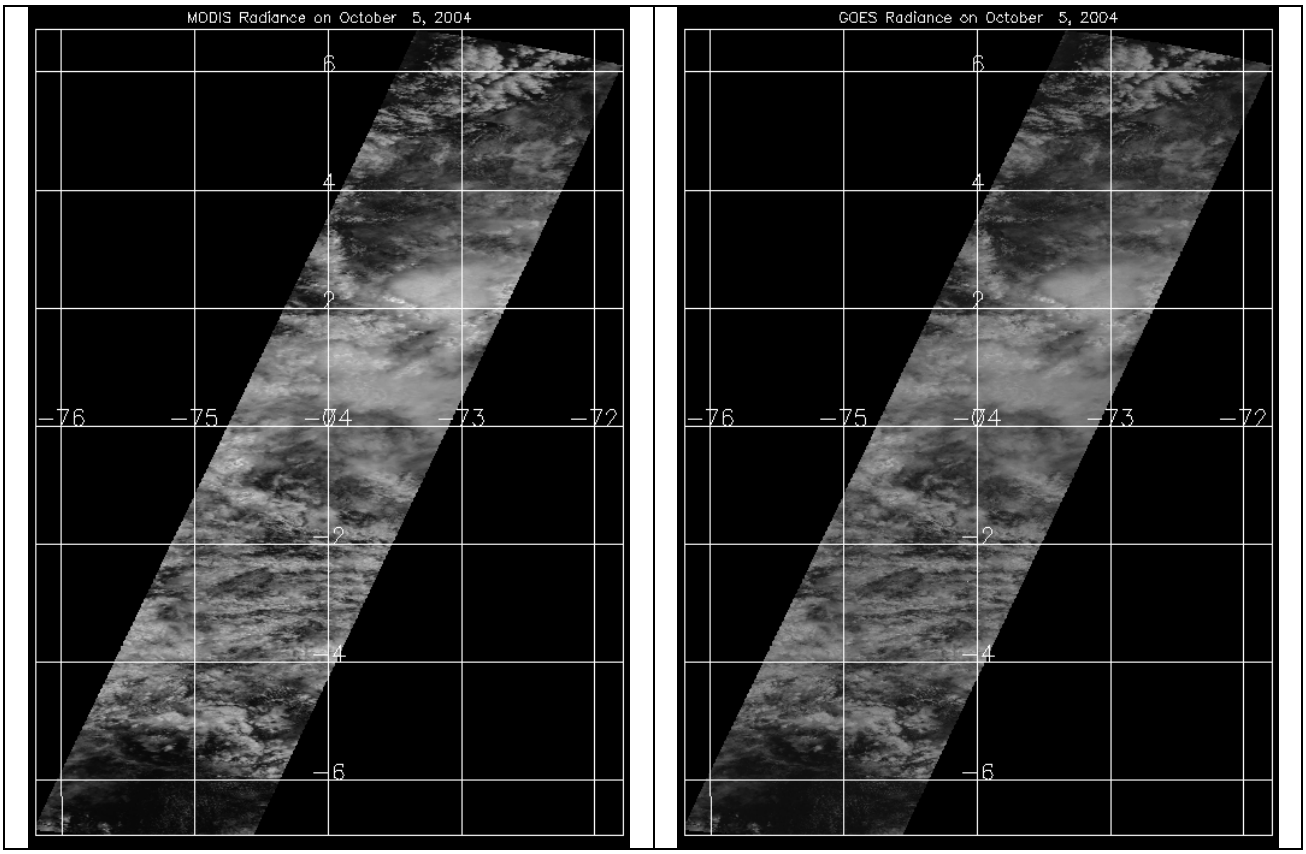


Figure 3: Co-located MODIS (left) and GOES-12 (right) images around 15:24 UTC on 5 October 2004. The GOES measurements were calibrated with pre-launch coefficients. The MODIS measurements, taken about 1 minute later, were projected to the GOES coordinates using operational navigation and spectrally adjusted to the GOES measurements.

2.2 Spectral correction

The spectral response functions of GOES-12 Imager visible channel and MODIS Channel 1 were plotted in Fig. 4. The GOES spectral response function is considerably wider than that of the MODIS on both the shortwave and longwave

sides. The responses of the two sensors to the same target, therefore, may be intrinsically different. It is important to understand this difference before the two measurements can be compared.

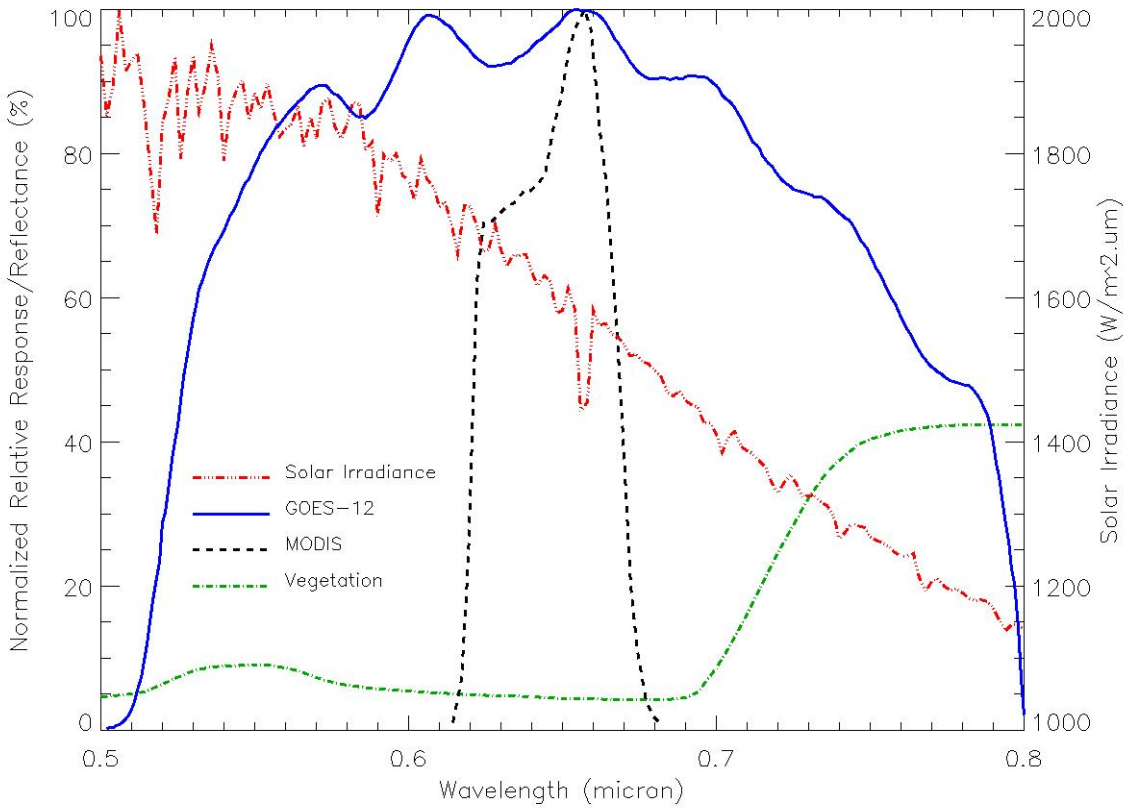


Figure 4: Spectral response functions for GOES-12 Imager visible channel and MODIS Channel 1, superimposed with extraterrestrial solar irradiance and spectral reflectance of typical vegetation.

The Moderate Resolution Transmittance Model Version 4 (MODTRAN4) was used to simulate the sensor responses of GOES and MODIS. For reasons to be detailed in the next section, only cloud targets were considered. Other input parameters for the MODTRAN4 were typical for the tropical locations of interest. The GOES and MODIS in-band radiances were obtained by convoluting the simulated spectral radiance with, respectively, the GOES and MODIS spectral response functions. These in-band radiances were then divided by the respective bandwidth to arrive at the spectral radiances, which were plotted in Fig. 5. The ten values are from simulations with ten different solar zenith angles and otherwise identical conditions. Regression analysis of these data yields the following formulae to estimate GOES measurements from MODIS measurements:

$$GOES10_Radiance = 0.9620 * MODIS_Radiance - 0.2406$$
$$GOES12_Radiance = 0.9618 * MODIS_Radiance - 0.2407$$

These results show that, for cloudy scenes, MODIS should be about 4% brighter than GOES and the difference is very consistent throughout the range of brightness. There is little difference between GOES-10 and GOES-12, which is expected since the spectral response functions of the two sensors are very similar.

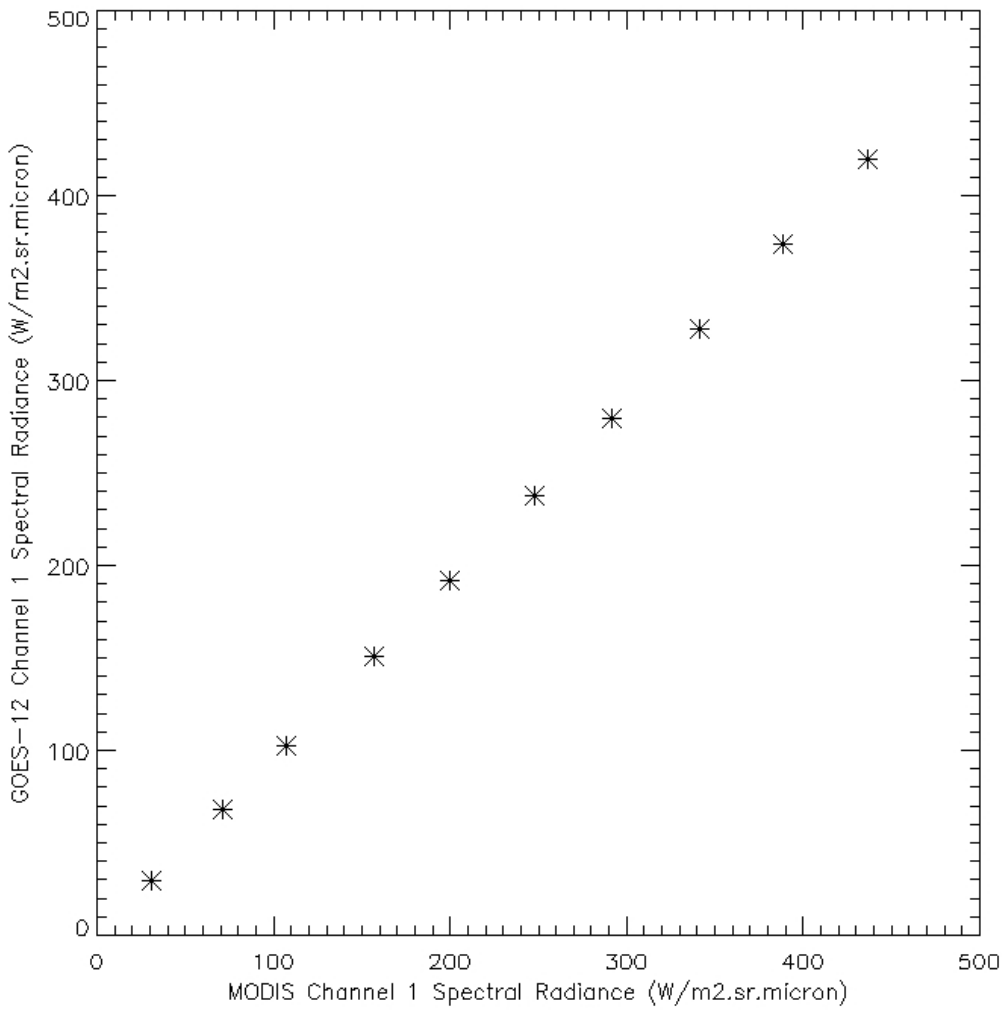


Figure 5: Comparison of the simulated spectral radiances of MODIS Channel 1 and GOES Imager visible channel for a cloudy scene with varying solar zenith angle.

2.3 Target selection

The histograms for the MODIS and GOES-12 images in Fig. 3 were plotted in Fig. 6. The GOES histogram generally appears to the left or the darker side of the MODIS histogram, suggesting that the pre-launch calibration coefficients for GOES Imager visible channel convert sensor measurements (counts) to reflectance lower than the true values. This agrees with the inspection of Fig. 3 that the MODIS image appears brighter than the GOES image, and agrees with the notion that GOES Imager visible channel degrades over time without post-launch calibration.

However, Fig. 6 also shows that, for the darker pixels (reflectance less than 10%), GOES measurements are brighter than MODIS. For example, the GOES-12 histogram has a peak at reflectance of about 10%, and the corresponding feature on the MODIS histogram peaks at reflectance of about 5%. In fact, majority of the scatter plots in Fig. 2 appear above the diagonal for dark pixels and below the diagonal for bright pixels, indicating that MODIS is darker than GOES for dark scenes and brighter than GOES for bright scenes. The difference may be small but is statistically significant.

The reason for this discrepancy is that the spectral response function of the GOES Imager visible channel extends into the near infrared spectrum (wavelength longer than 0.7 μm), where vegetation reflection is strong (Fig. 4). This part of the spectrum was carefully avoided by the MODIS Channel 1. Near the nadir of GOES-12 (0°N, 75°W), the dark pixels

are likely the clear views of vegetated surface. Because of the spectral reflectance of vegetation and the difference in spectral response functions, these pixels can appear brighter for an aging GOES than for a well-calibrated MODIS.

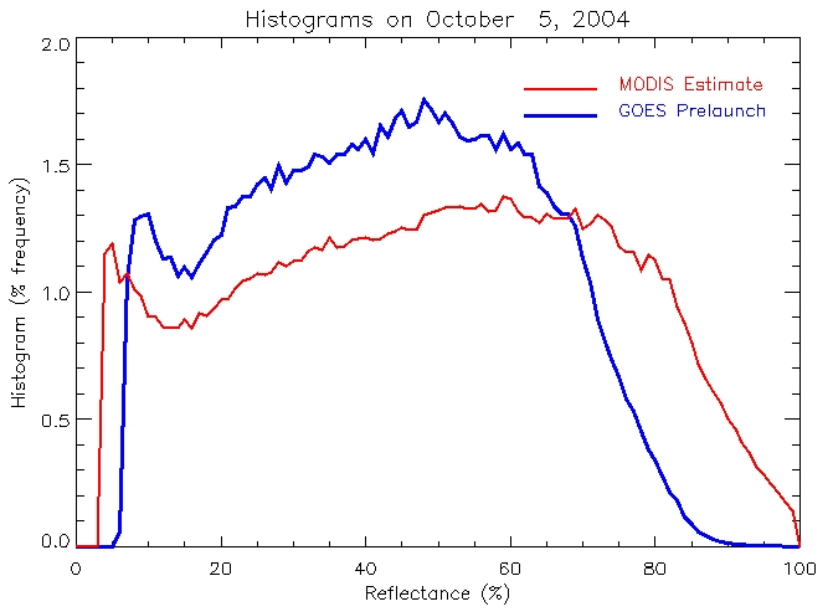


Figure 6: Histograms for the GOES-12 and MODIS images displayed in Fig. 3.

Similar histograms were examined for MODIS and GOES-10 Imager visible channel (Fig. 7), whose spectral response function is similar to that of GOES-12. Stationed at (0°N, 135°W), GOES-10 observes mostly the open ocean when clear. In this particular case, the GOES-10 histogram peaks at reflectance of about 5%, and the MODIS histogram peaks slightly on the brighter side (6-8%). This confirms that the brighter appearance of GOES-12 Imager visible channel measurements (10%) than MODIS (7%) over clear but vegetated surface (Fig. 6) is indeed caused by vegetation reflection. When the surface is changed to ocean (Fig. 7), MODIS measurements become brighter than GOES.

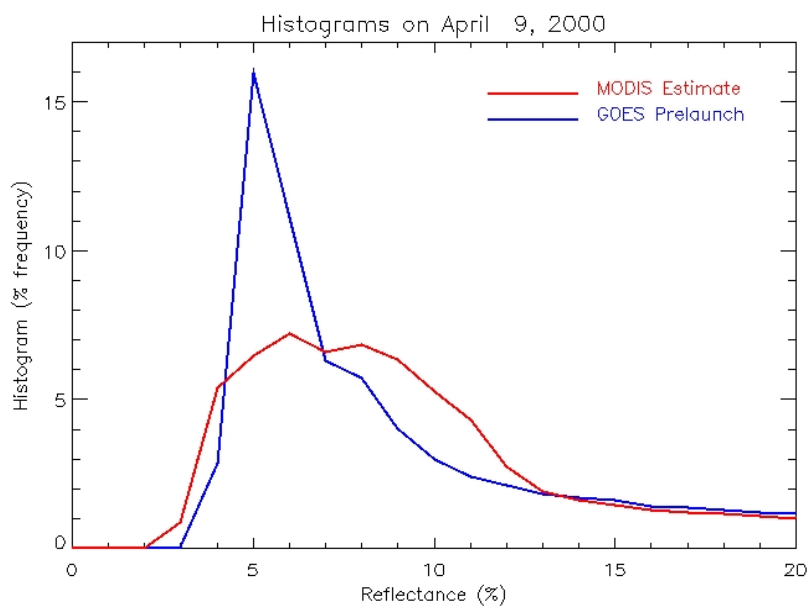


Figure 7: As Fig. 6, but for MODIS and GOES-10 on 9 April 2000.

Nevertheless, for the very dark ocean scenes (reflectance less than 4%), GOES is still brighter than MODIS. The reason is that, compared with MODIS Channel 1, the spectral response function of GOES Imager visible channel also extends into the shortwave side of the spectrum (Fig. 4). This makes the GOES more sensitive than MODIS to Rayleigh scattering by aerosols, which becomes significant for very dark ocean scenes.

Because of enhanced reflection by vegetation over land and Rayleigh scattering by aerosols over ocean, it is necessary to avoid clear pixels when comparing GOES and MODIS measurements in this vicarious calibration. Care must be taken when setting threshold for what should be considered cloudy. A lax criterion compromises the assumption that GOES measurements can be estimated from MODIS measurements by regression, on the other hand an overly stringent criterion reduces the sample size unnecessarily that, in turn, would increase the uncertainty of calibration.

The threshold value should also be chosen with consideration of sensor's predominant views. For GOES Imager visible channel, typical reflectance over vegetated surface is about 10%, whereas typical reflectance over clear ocean is less than 5%. For most time of the year, there are also much less convective activities in the tropical Pacific near the nadir of GOES-10 (0°N, 135°W), compared to the region near the nadir of GOES-12 (0°N, 75°W). For these reasons, the threshold value for GOES-12 should be higher and could be set higher without compromising sample size. In addition, experience indicates that measurements by each sensor should be confirmed of "non-clear" status because the cloud condition may change between the times the two sensors image the scene, and a minimum number of non-clear pixels must be present to warrant the statistical analysis that follows. Table 1 summarizes the selected threshold values.

Table 1: Threshold values in target selection for GOES-10 and GOES-12.

Criterion	Threshold Value	
	GOES-10	GOES-12
Minimum Reflectance for Accepted Pixel	15%	25%
Minimum Number of Accepted Pixels in an Image	10% of max possible	33% of max possible

2.4 Calibration

The GOES Imager visible channel employs silicone detector whose response to signal is linear, therefore only two calibration coefficients are needed, the gain and dark count. Furthermore, since the dark count, or the instrument response to zero signal, is "clamped" in operation, only the instrument gain needs to be determined. GOES calibration is explained in more details by Weinreb et al (1997).

The operational calibration of GOES Imager visible channel takes the form:

Eq. 1 $$R = m(X - X_0)$$

where R is the monochromatic radiance (W/m^2·sr·μm) at the sensor aperture; m is the "slope", or the pre-launch estimate of the reverse of instrument gain; X is the instrument response to a target; and X_0 is the instrument response to a target of zero signal, usually the space. Since most users are more familiar with reflectance, another calibration equation is often used in conjunction with Eq. 1:

Eq. 2 $$\rho = \kappa R$$

where ρ is nominal reflectance, or the fraction of the reflected solar radiation if the sun is at zenith and one astronomical unit away; R is the same as in Eq. 1; and κ is the parameter that convert R to ρ. ρ is sometimes referred to as albedo, although usually albedo is reserved for angular integration of reflectance. For reference, R and κ are defined as:

$$R = \frac{\int_0^\infty R(\lambda)\Phi(\lambda)d\lambda}{\int_0^\infty \Phi(\lambda)d\lambda}, \qquad \kappa = \frac{\pi}{H}, \qquad H = \frac{\int_0^\infty H(\lambda)\Phi(\lambda)d\lambda}{\int_0^\infty \Phi(\lambda)d\lambda}$$

where $R(\lambda)$ is the spectral radiance of the target; $\Phi(\lambda)$ is the sensor's spectral response function; λ is wavelength, $H(\lambda)$ is the spectral extraterrestrial solar irradiance. Values for m and κ are listed in Table 2.

After launch, X_0 is dynamically maintained at a known value and Φ and H are not expected to change. The only parameter that is subject to change is m, the slope. Post-launch calibration is therefore focused on the periodic update of this single parameter. Alternatively, user can use pre-launch calibration (Eq. 1 or Eq. 2) with a post-launch adjustment:

Eq. 3 $$R_{post} = C(t)R_{pre}, \qquad \rho_{post} = C(t)\rho_{pre}$$

where R_{pre} and ρ_{pre} are the radiance and reflectance obtained with pre-launch calibration of Eq. 1 or Eq. 2; C is the post-launch correction that, as expected, is a function of time t; and R_{post} and ρ_{post} are the radiance and reflectance with post-launch calibration.

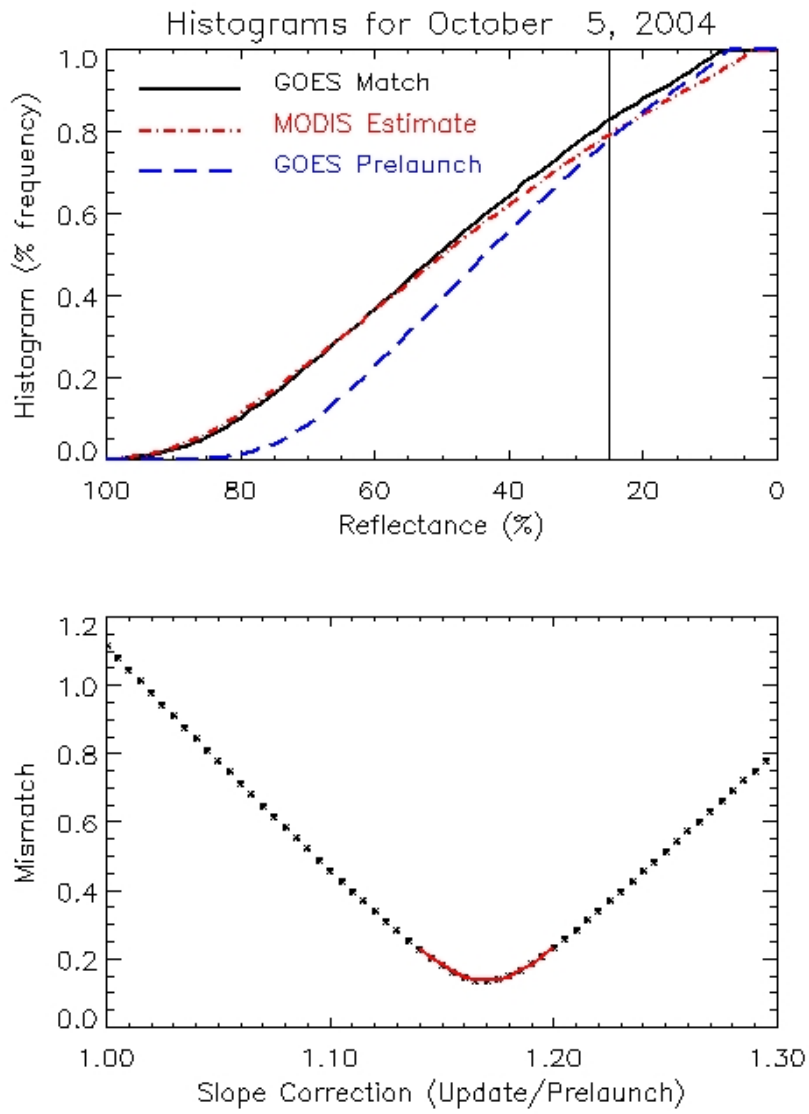


Figure 8: Illustration of post-launch calibration for GOES Imager visible channel using MODIS data.

The GOES Imager visible channel has been calibrated with MODIS data by matching the histogram or frequency distribution in Fig. 4 (Wu 2003). That method has been improved by matching instead the accumulated frequency, which

reduces the noises and stabilizes the post-launch calibration. The process is illustrated in Fig. 7. In the beginning, the accumulated frequency (starting from 100% reflectance) of GOES and MODIS in Fig. 4 are plotted. The difference between these two curves is defined as mismatch *M* that is proportional to the area between the two curves:

Eq. 4 $$M = \int_{100}^{\rho_{cld}} \left[AF_M(\rho) - C \bullet AF_G(\rho) \right]^2 d\rho$$

where AF_G and AF_M are accumulated frequencies that are functions of the nominal reflectance ρ; ρ_{cld} is the minimum reflectance that can be regarded as cloudy (Table 1); and *C* is the correction factor. For the case in the upper panel of Fig. 7, no correction has been applied, so *C*=1. This procedure is then repeated with varying values of *C*, and the corresponding mismatch M is plotted as a function of *C* in the lower panel of Fig. 7. Once the correction factor *C* is found that minimizes the mismatch, the nearby *C* values are approximated by a quadratic fit and the minimum of the quadratic curve is taken as the correction. This is done to further reduce the fluctuation in estimating *C*, which is not apparent in Fig. 7 but could be significant when there are much fewer targets in the co-located images.

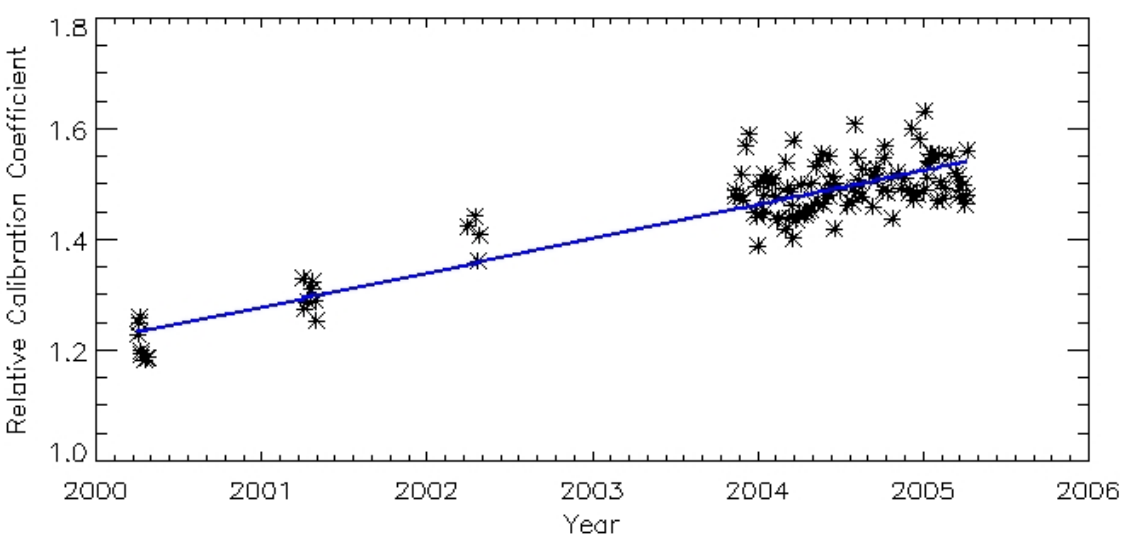
2.5 Time series

The procedure illustrated in Section 2.4 can be repeated for the co-located GOES-MODIS images over time to monitor the instrument degradation. Current results for GOES-10 and GOES-12 are shown in Fig. 9. For GOES-12, all available data since it became operational (1 April 2003) have been analyzed. For GOES-10, the April data from 2000 to 2003 and all data since November 2003 have been analyzed.

Based on these analyses, post-launch calibration correction for GOES Imager visible channel has been estimated by regression:

Eq. 5 $$C(t) = a \exp(bt)$$

where *C* is the correction to be used in Eq. 3; *a* and *b* are regression coefficients; and *t* is the number of years after a starting date. Values of *a, b,* and starting date are listed in Table 2. The coefficient *b* is also called the annual degradation rate, which for GOES-10 is in agreement with other studies (Chang et al 2005, Crosby et al 2005).



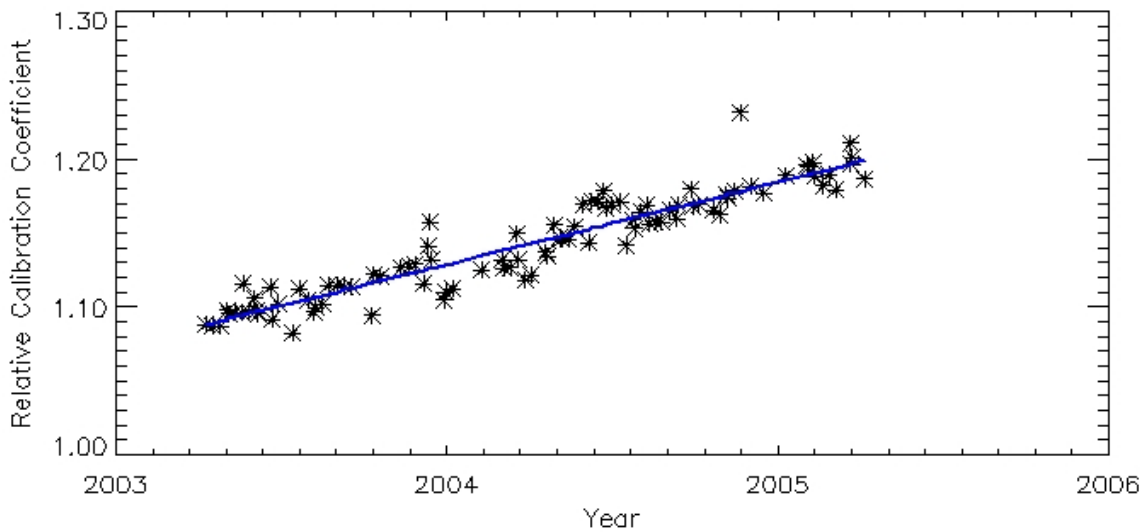


Figure 9: Optimal calibration coefficients plotted as a function of time to show the time trend as a means of monitoring instrument degradation.

Table 2: Pre-launch and post-launch calibration coefficients for GOES-10 and GOES-12.

	GOES-10	GOES-12
m (count-to-radiance)	0.5582154	0.577103
κ (radiance-to-reflectance)	1.98808×10^{-3}	1.97658×10^{-3}
a	1.2248	1.0875
b	0.04389	0.04890
Starting Date	2000/01/01	2003/04/01

3. SUMMARY AND CONCLUSION

Due to the lack of onboard calibration device, the GOES Imager visible channel must be vicariously calibrated on orbit. Several techniques have been explored, including those based on observations of desert (Rao and Zhang, 2001), star measurements (Bremer et al 1998, Chang et al 2004 & 2005), and the empirical distribution function of the earth targets (Crosby et al 2005). This study expanded and improved upon a method (Wu 2003) that uses a well-calibrated radiometer (MODIS) as an external reference for calibration. The major improvement comes from the more extensive analysis of the available data and the use of accumulated frequency (instead of the frequency distribution itself) for minimization.

This study confirms the feasibility of using MODIS data to calibrate the GOES Imager visible channels. This method is complementary to other techniques in that, in addition to long term trending of relative degradation, the MODIS-based post-launch calibration also provides absolute calibration, and the calibration can be made available shortly after launch. Care must be taken to account for the lack of simultaneity of the measurements by the two sensors, and the differences in the sensors' spectral response functions. It was found that GOES-10 has been degrading at the rate of 4.4%/year and current (July 1, 2005) responsivity is about 64% of its pre-launch value. These estimates are in agreement with other studies (Chang et al 2005, Crosby et al 2005). For GOES-12, the degradation rate is 4.9%/year and the current responsivity is about 82% of its pre-launch value. It is interesting to note that, in November 2001, GOES-10 responsivity is about 77% of GOES-12 responsivity, and currently GOES-10 responsivity is 0.64/0.82=78% of GOES-12 responsivity. In other words, the two sensors have degraded by about the same amount over the years.

NOAA/NESDIS will continue to provide operational calibration for its satellite instruments, including the post-launch calibration of GOES Imager visible channels. More data will be collected and analyzed to fill the gaps for GOES-10

before November 2003. Similar analysis will be expanded and continued to include MODIS on Aqua, MERIS on ENVISAT, and VIIRS on NPP/NPOESS.

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