Rapid technique to cross calibrate satellite imager visible channels

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ABSTRACT

Rapid and accurate calibrations of satellite imager sensors are critical for remote sensing of surface, cloud and radiative properties. A post-launch technique has been developed to routinely cross calibrate and normalize the imager visible (VIS) channel on-board operational geostationary (GEO) and low-Earth-orbit (LEO) satellites. As a reference calibration source, this simple approach uses the self-calibrating sensor from the Tropical Rainfall Measuring Mission (TRMM) Visible Infrared Scanner (VIRS) to calibrate other GEO and LEO satellites. The VIRS sensors have been found to be a stable and reliable reference source. This technique uses VIRS to calibrate the eighth Geostationary Operational Environmental Satellite (GOES-8) VIS sensor using collocated data with similar viewing zenith, solar zenith, and relative azimuth angles. GOES-8 is then used as a transfer medium to cross calibrate other GEO and LEO satellites. Post-launch VIS (~0.65 µm) calibration coefficients for GOES-8, -9, -10, -12, Meteosat-7, -8, and NOAA-14 AVHRR satellites are presented. GOES-8 had a non-linear degradation rate of 11% the first year of operational service and 4% in last year before it was decommissioned. GOES-9 degraded linearly at 7.9% per year during 1995-1998. GOES-10 degraded 12% the first year and 1.6% less each year after that. GOES-12 degraded 6% per year. The VIRS visible channel calibration is in good agreement with the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on-board the *Terra* and *Aqua* satellites supporting its use as a reference.

Keywords: Calibration, GOES-8, GOES-10, GOES-12, AVHRR, Meteosat-7, Meteosat-8, MODIS, Visible, Imager

1. INTRODUCTION

The retrievals of surface, cloud and radiative properties from meteorological and research satellites require accurate and consistent calibration of the imager channels. A rapid, accurate and consistent calibration increases the reliability and effectiveness of long-term monitoring of climate changes and will help improve retrievals of cloud products from remote sensing algorithms. The lack of on-board calibration in the VIS channels on most GEO and LEO satellites have made it difficult to retrieve consistent products. Several post-launch calibration techniques have been developed, including vicarious techniques that measure bright stable desert targets[1,2] and ice sheets over Greenland and Antarctica[3], satellite-to-to-satellite normalizations[4], and statistical analysis of star measurements[5]. While such inter-calibrations are valuable and widely used, the lack of a well-characterized calibration reference source and the lengthy time delay between updates have minimized their effectiveness in climate monitoring.

To address these shortcomings, this paper discusses a rapid technique to cross calibrate operational and historical meteorological satellite VIS (~0.65 µm) sensors. This technique uses the VIRS self-calibrating instrument[6] as a reference calibration source to directly calibrate sensors such as GOES-8. The VIRS calibration can then be transferred indirectly to other GEO and LEO satellites using GOES-8 as a transfer medium. Monthly VIS calibrations are performed for each instrument. The degradation rates and calibration coefficients can then be determined from the slope time series equations. The absolute accuracy of this technique relies on the assumption that the VIRS on-board calibration is stable and well maintained. The VIRS calibration has been evaluated by using comparisons with other self-calibrated satellite sensors[7], including the broadband Clouds and Earth's Radiant Energy System (CERES) scanners, the second Earth Resources Satellite (ERS-2) second Along Track Scanning Radiometer (ATSR-2), and *Terra* MODIS, and using lunar models and MODIS data[8]. These comparisons have validated the calibration and shown the stability of the instrument. Thus, the VIRS calibration can be confidently used as the reference source.

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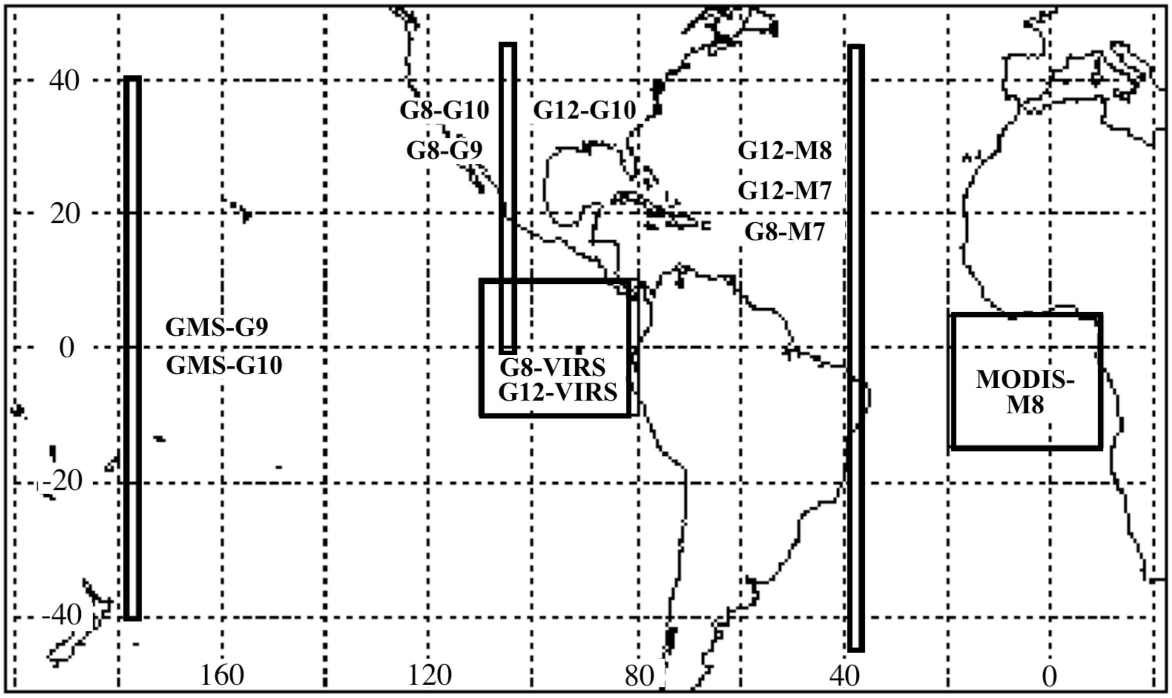

Figure 1. Inter-calibration regions for each satellite pair.

2. DATA

Satellite data are taken from nine different sensors during the ten-year span from 1994-2004. Each satellite is paired with a neighboring satellite and inter-calibrated over the various regions as shown in Figure 1. GEO datasets are collected using the University of Wisconsin-Madison's Space Science Engineering Center (SSEC) Man computer Interactive Data Access System (McIDAS) software. AVHRR data are ordered from the NOAA Satellite Active Archive (SAA). VIRS and MODIS data were retrieved from NASA Langley Atmospheric Science Data Center. The collocated data are collected daily for each satellite pair and processed into monthly time series.

2.1 VIRS

The VIRS instrument is carried on the TRMM satellite that was launched on November 27, 1997. TRMM orbits the Earth at a 35° inclination. Its unique precessing orbit observes all local hours and viewing angles up to 45° within a 45-day period. The VIRS data are taken at 2-km nominal resolution. The VIRS calibrated radiances, based on pre-launch and on-board procedures[6], were obtained the from level 1B01 Version-5a data. The VIRS channel-1 radiance is obtained from the following equation

$$L_v = a(C - C_o) \qquad (1)$$

where a is the gain, C is the observed brightness count, and C_o is the space count. The VIRS solar constant E_v is 531.7 $Wm^{-2}sr^{-1}\mu m^{-1}$. For comparisons with GOES, *Meteosat*, MODIS, and AVHRR, the VIRS radiances are normalized to equivalent GOES radiances by multiplying them by the ratio of the GOES and VIRS solar constants (E_o/E_v = 0.991) where the GOES solar constant E_o is 526.9 $Wm^{-2}sr^{-1}\mu m^{-1}$. VIRS data were averaged on a 0.5° equal angle grid for matching with other satellites.

2.2 GOES-8, -9, -10, -12

The GOES satellites provide coverage for much of the Western Hemisphere. GOES-8[9] served operationally as the GOES-East satellite for about eight years (1 June 1995 - 2 April 2003) at 75°W. The reliability and longevity of the instrument makes GOES-8 a primary candidate to use as a transfer medium for the VIRS calibration. The nominal VIS channel resolution is 1 km with continental United States (CONUS) and Northern Hemisphere (NH) coverage every 15 and 30 minutes, respectively. GOES-9 served briefly as GOES-West, at 135°W, from 1996 through 1998 before it developed instrument problems. It was placed on standby and replaced by GOES-10. GOES-11, launched on 3 May 2000, has never served operationally and is currently in standby mode. GOES-12 became the operational GOES-East satellite in April 2003. In 2003, GOES-9 was revived from over 4 years of storage and moved to 155°E to replace the Japan Meteorological Agency (JMA) GMS-5 satellite. Data from all GOES were taken at a 4-km resolution and averaged on a 0.5° equal angle grid for matching with LEO satellites or on a 1.0° grid for matching with other GEO satellites.

2.3 *Meteosat-7*, *-8*

The EUMETSAT *Meteosat-7*, located at 0°, was launched in September 1997 and became operational during June 1998. The *Meteosat-7* Visible and Infrared Spin Scan Radiometer (VISSR) is a 3-channel 8-bit imager with a nominal resolution of 5 km (2.5-km VIS). The center wavelength of the VIS channel is 0.75 µm and the radiance varies linearly with the VIS count. Although the VIS channels on other imagers have unique filter functions, the bandwidth for most of the instruments is between 0.55 and 0.75 µm (Figure 2). The *Meteosat-7* bandwidth is much larger than those from GOES-8 and VIRS. Thus, the *Meteosat-7* radiances are matched in ocean regions where the effect of the spectral response function is minimized. *Meteosat-7* data were taken at a 5-km resolution and matched with GOES-8 and GOES-12 data on a 1.0° grid. *Meteosat-7* was replaced by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) on the Meteosat Second Generation satellite (MSG, *Meteosat-8*), in late 2002. SEVIRI data were taken at a 3-km resolution and matched with GOES-12 on a 1.0° grid.

2.4 NOAA-14 AVHRR

NOAA-14 was launched into a near Sun-synchronous orbit on 30 December 1994. This afternoon polar orbiter has a nominal equatorial crossing time of 1430 local time (LT). The orbit had drifted to approximately 1636 LT by early 2001. The AVHRR channel-1 VIS (0.67 µm) has a nominal spatial resolution of 1.1-km (High Resolution Picture Transmission, HRPT) and 4-km (Global Area Coverage, GAC). In this study, the GAC datasets were used and matched with GOES-8 data in the Tropics on a 0.5° grid.

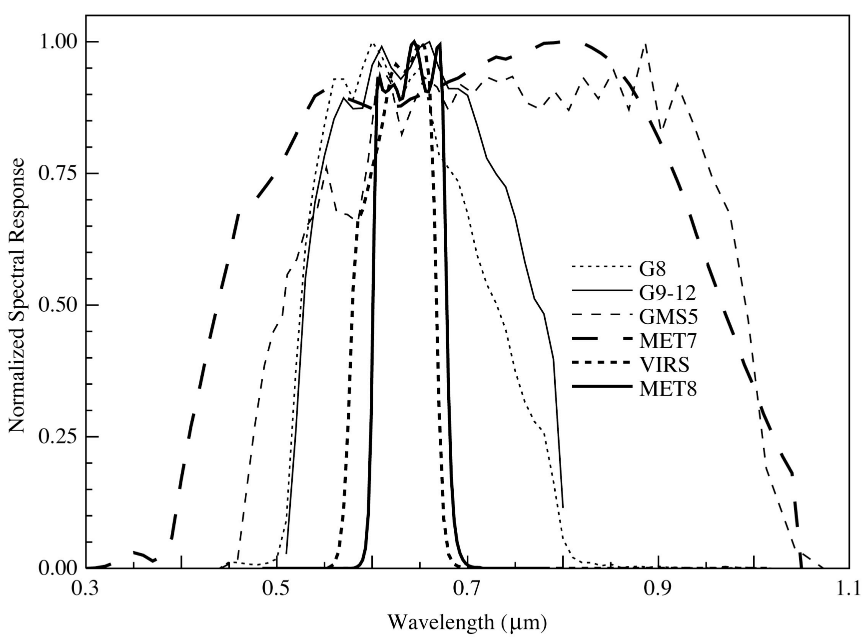

Fig. 2. Spectral response functions for the visible channels on various GEO and LEO satellites.

3. METHODOLOGY

The inter-calibration technique used in this study is similar to an earlier satellite normalization approach[4], except that the data-matching constraints are less stringent and GOES-8 and GOES-12, once calibrated directly against VIRS, are used as a primary reference for the calibration of other satellite imagers. The direct and indirect transfer of the VIRS calibration can be applied using GEO-to-GEO or LEO-to-GEO techniques. The inter-calibrations are performed on collocated scenes between spatially and temporally matched data for each satellite pair as shown in Figure 1. Additionally, the data are only selected if they have nearly the same values of viewing zenith θ and relative azimuth ϕ angle. In the LEO-to-GEO method, GEO data are matched with LEO data taken within 15 minutes, have corresponding values of θ and ϕ that differ by less than 15°, 10° <= ϕ => 170°, and cosine of θ_o greater than 0.1. Data taken in possible sun glint conditions are removed from the dataset. L_v is normalized to the ratio of the GEO and VIRS cosine of solar zenith angle, θ_o. To account for time and navigation differences, the radiances are averaged over a 0.5° grid box, yielding a pair of data points for each grid box in the appropriate calibration region (Figure 1). The VIS regression is forced through the space count for the particular satellite. The monthly trend time series were then computed for each satellite pair.

Similarly, GEO satellites are also inter-calibrated with each other using the GEO-to-GEO method. For example, GOES-12 at 75°W is used to calibrate GOES-10 at 135°W. Very close matches in time and space are possible because of the fixed views and regular imaging schedules from GOES. The GEO data are taken at local noon at the bisecting longitude between the two satellites (i.e. 105°W in the previous example). Local noon insures that all of the angles are nearly identical. Typically, the GEO data are matched to within 2 minutes, although for some satellite pairs, matches are allowed for observations up to 15 minutes apart. Because reflectance anisotropy may not be entirely symmetrical, the data are averaged on a 1° grid box with two 1° boxes straddling the bisecting longitude between the two GEO satellite pairs as shown in Figure 1.

Once the GEO satellites are calibrated with the VIRS, they can serve as a calibration source for other satellites. In this study, the GEO is used to compare the VIRS calibration by matching the GEO with imagers like MODIS on *Terra* and *Aqua* and the AVHRR on the LEO NOAA satellites. Because TRMM is in a 35°-inclined orbit, the VIRS has few close matches with polar orbiters. While a polar matching technique[10] that uses collocated data in polar regions is effective, it is limited because only a couple months of data can be used each year due to the high solar zenith angle θ_o, generally over 70°, and the time required to retrieve matched datasets from the NOAA SAA. Thus, the use of GEO satellites to cross calibrate the AVHRR and other sensors on LEO satellites is more feasible because of the increased frequency of collocated scenes with bore-sighted views.

4. RESULTS

The LEO-to-GEO technique is used to directly calibrate the GOES-8 and GOES-12 VIS channels. Figures 3a and 3b show scatter plots and linear regression fits between VIRS and GOES-8 and GOES-12 for October 2002 and February 2004, respectively. The fits are forced through the space count of 31 and 34 for GOES-8 and GOES-12, respectively. The space counts were determined based on the mean offset of the *non-forced* fit from all the months that were processed. The slope on the aging GOES-8 instrument is higher than the GOES-12 slope. The 10-bit digital counts on the newer GOES-12 cover a much larger dynamic range. Both fits have excellent squared correlation coefficients of 0.99. The standard error of the estimate is less then 8.7 W/m^2/µm/sr. Similar results and correlations are seen for the other months in the time series. The gain trend lines for GOES-8 (Figure 4a) and GOES-12 (Figure 4b) show the slopes increasing with time. This is consistent with a steady degradation of the instrument optics. The non-linear instrument degradation is more apparent in GOES-8 than for GOES-10 after 4 to 5 years of operational service.

The GEO-to-GEO technique is used to indirectly calibrate GOES-9, GOES-10, *Meteosat-7* and *Meteosat-8*. GOES-9 (from 1996 to 1998) and GOES-10 were paired with the GOES-East satellite (GOES-8 or GOES-12). Data were matched along the bisecting longitude of 105°W using local solar noon CONUS images taken at 1900 UTC. The trend

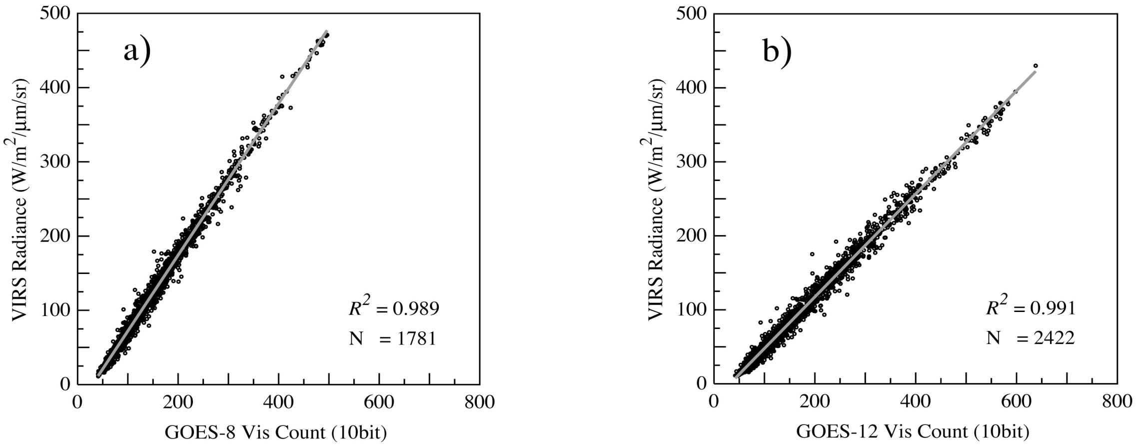

Fig. 3. Correlation of VIRS radiance with GOES-8 and GOES-12 VIS count for (a) Oct 2002 and (b) Feb 2004.

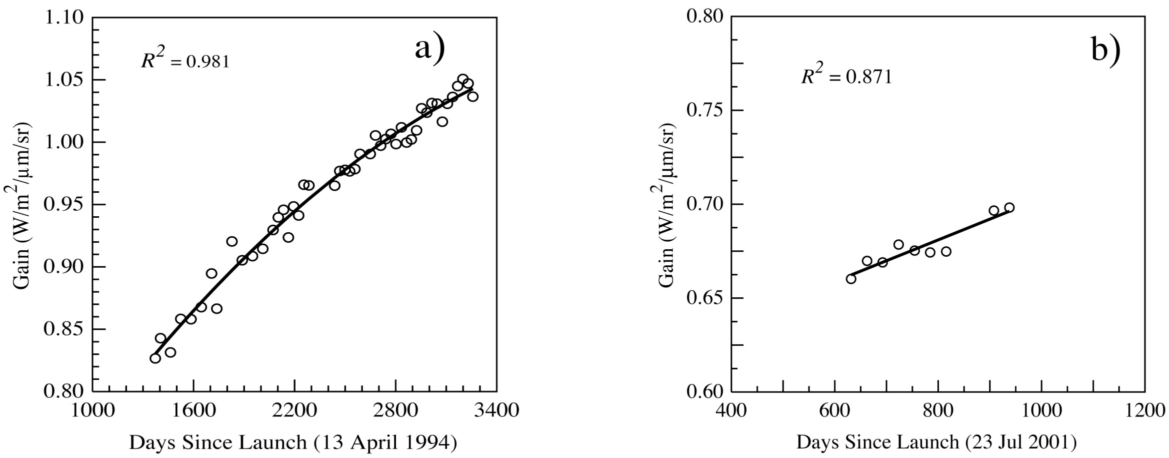

Figure 4. Time series of GOES-8 (a) and GOES-12 (b) VIS channel regression slopes determined using VIRS data.

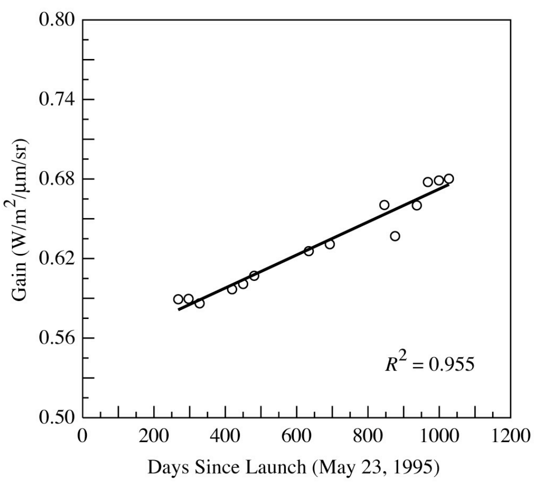

Figure 5. Time series of GOES-9 VIS slopes using calibrated GOES-8 data.

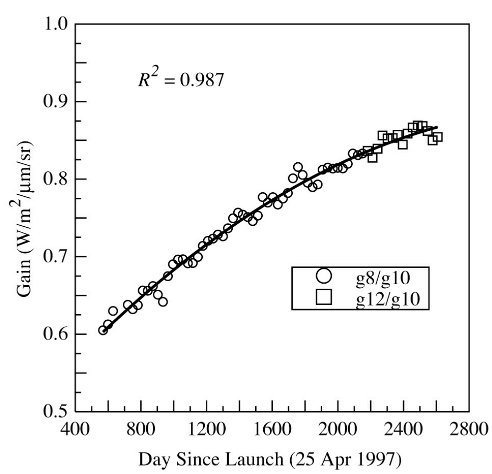

Figure 6. Time series of GOES-10 VIS slopes using GOES-8 (circles) and GOES-12 (boxes) data.

line for GOES-9 (Figure 5) shows a steady linear degradation during 1996 to 1998 before the satellite was put in storage. In 2003, the GOES-9 was moved to replace GMS-5 and became the operational satellite for JMA. The GOES-9 slopes from 2003 through 2004 (not shown) have similar trends. GOES-8 from 1998 to 2003 and GOES-12 from 2003 to 2004 were used to calibrate GOES-10. Figure 6 shows the GOES-10 slope trend line with no discontinuity using slopes derived from GOES-8 or GOES-12. Similarly, *Meteosat-7* was paired with GOES-8 from 2001 through 2003 and then with GOES-12 from 2003 through 2004. Data were matched along the bisecting longitude of 37.5°W using local solar noon full disk images taken at 1445 and 1430 UTC for GOES and *Meteosat-7*, respectively. The standard error of the *Meteosat-7* gain trend (Figure 7a) is 0.083 and is slightly higher than the GOES counterpart and may be attributed to the spectral response function and the 15-minute time differences. The real-time broadcast of the *Meteosat-8* signal was not available to the until April 2004, and therefore, the *Meteosat-8* trend (Figure 7b) contains only 5 months of data and will likely change when more months are processed and added to the time series. The NOAA-14 AVHRR slopes from 1995-2001 (not shown) have a similar degradation trend as GOES-8. The NOAA-14 calibration equation listed in Table 1 is not recommended for data after December 2001.

For a given satellite, the post-launch calibration formula is

$$L_v = (\Delta g_2 d^2 + \Delta g_1 d + g_o)(C - C_o), \qquad (2)$$

where L_v is the normalized VIRS radiance in $Wm^{-2}\mu m^{-1}sr^{-1}$, g_o is the initial gain, Δg_1 and Δg_2 is first and second order polynomial term of the gain trend, d is the days since the reference date (or launch date), C_o is the offset count, and C is the raw 8 or 10-bit count. The calibration coefficients for various satellites are given in Table 1. The VIS reflectance can be calculated using

$$\rho = \frac{L_v(\theta_o, \theta, \phi)}{E_o \cos\theta_o \delta(day)}, \qquad (3)$$

where δ is the Earth-Sun distance correction factor for the day of the year.

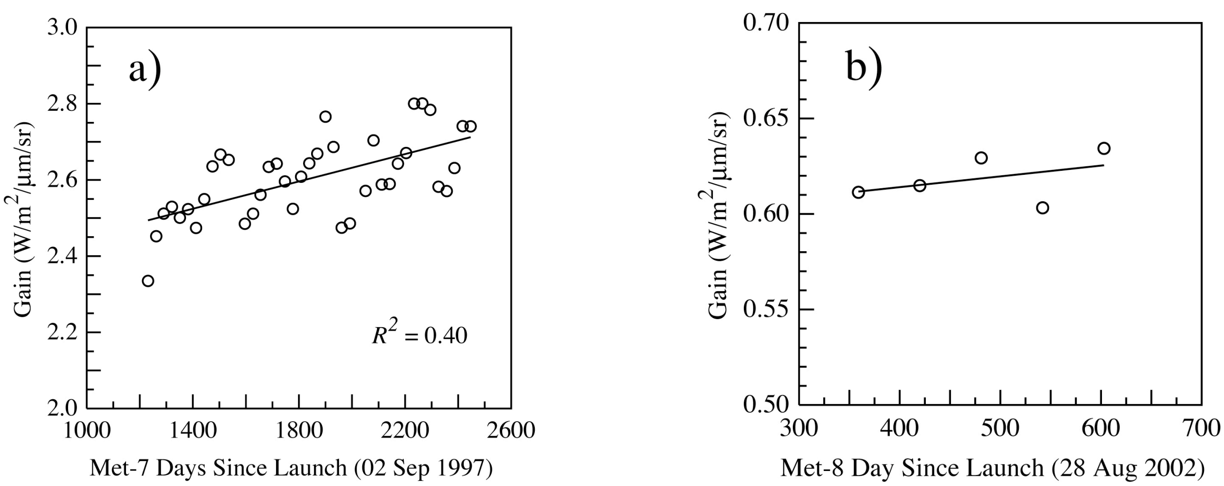

Figure 7. Time series of (a) *Meteosat-7* and (b) *Meteosat-8* VIS slopes using calibrated GOES data.

Satellite	g_o	Δg_1	Δg_2	C_o	Reference Date	Operation Date
GOES-12	0.5924	1.108E-4	0	32	Jul 23, 2001	Apr 01, 2003
GOES10	0.4773	2.4055E-4	-3.4923E-8	34	Apr 25, 1997	Aug 27, 1998
GOES-9 *	0.5480	1.2449E-4	0	34	May 23, 1995	Jan 11, 1996
GOES-9 **	0.03985	2.2538E-4	0	34	May 23, 1995	May 22, 2003
GOES-8	0.5671	2.2473E-4	-2.4156E-8	31	Apr 13, 1994	Jun 01, 1996
Meteosat-7	2.2731	1.794E-4	0	6	Sep 02, 1997	Jun 03, 1998
Meteosat-8	0.5914	5.6394E-5	0	46	Aug 28, 2002	Dec 12, 2002
N14 AVHRR	0.5779	1.5307E-4	-4.9407E-8	41	Dec 30, 1994	Apr 10, 1995

Table 1. Post-launch calibration coefficients for various satellite VIS channels in $Wm^{-2}\mu m^{-1}sr^{-1}$. The symbols * and ** indicate GOES-9 calibration coefficients for data during taken during 1995-1998 and 2003-2004 respectfully.

5. DISCUSSION

The GOES-8, GOES-10, and NOAA-14 AVHRR VIS sensors are degrading at a non-linear rate. Although the calibrations from GOES-12, GOES-9, & *Meteosat* (Figures 4b, 5, and 7) show a linear trend, the instrument optics when exposed for more than 4 to 5 years may exhibit non-linear decay. The post-launch calibration coefficients (shown in Table 1) can be used to predict future gains and offsets. However, the uncertainty in the gain prediction increases as one moves forward in time from the last month used in the time series. A trend with a linear fit generally predicts higher future gains whereas a trend with a quadratic fit tends to estimate lower gains. The confidence limits of the trend lines and the uncertainty of the predictions need additional analysis.

The annual degradation rate (ADR) is the single most used metric to compare various post-launch calibration methods. Often these rates are misleading because different reference dates are used when calculating the ADR. Typically, calibration coefficients are published with a reference date, usually measured as the number of days since launch (DSL) and then compared with g_o to obtain the ADR. For example, the GOES-12 calibration equation in Table 1 has a linear trend and an ADR of 7%. However, GOES-10, with a quadratic trend, shows an ADR of 17% for the first year. This misleading and high ADR from GOES-10 can be explained. The published GOES-10 pre-launch g_o is 0.558 (averaged from the 8 detectors)[11] whereas g_o from Table 1 is 0.4773. This low g_o is the result of GOES-10 being put in storage for 489 days before it became operational on 27 August 1998. If referenced to day since operational (DSO), the new g_o would have a reasonable value of 0.586. Assuming the VIS sensor did not degrade while in storage, a good degradation trend should have a value of g_o near the pre-launch values if referenced to DSO. However, the VIS sensor will degrade slightly from pre-launch values from the time it was calibrated in the lab to the time it reaches space due to launch contamination and exposure to the harsh space environment[12]. These factors will increase g_o slightly from the pre-launch value. Also, the GOES-10 instrument was open and exposed during science testing as early as the beginning of July 1998 (approximately 60 days). Therefore, to account for this additional 60 days, the equation should reference day since exposure (DSE). If DSE of 429 is used, the resulting g_o is 0.574. DSE can sometimes be difficult to determine, therefore, it is recommended that the calibration equation reference date be set to DSO for ADR calculations.

The ADR for the various satellite VIS sensors are calculated using DSO as the reference date. GOES-8, with 8 years of operational service, had a non linear ADR of 11% the first year and 4% the last year; degrading 1% less each year. GOES-9 degraded linearly at 7.9% per year during 1995-1998. The GOES-10 degraded 12% the first year and 1.6% less each year after that. By the 7^{th} year, it degraded a mere 2.5%. The GOES-12 ADR is 6% per year. *Meteosat-7* degraded 2.8% and *Meteosat-8* degraded 3.5% annually.

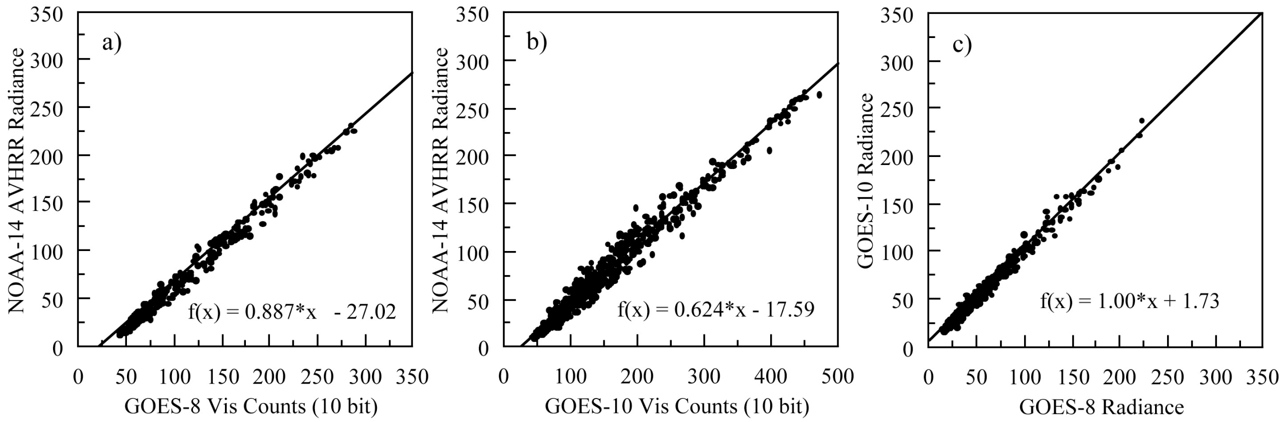

Fig 8. Three-way calibration comparison showing GOES-8 (a) and GOES-10 (b) directly calibrated against the reference source. Plot (c) shows indirect calibration using the same references source in perfect agreement.

To assess the accuracy of using GEO satellites as a transfer medium to cross-calibrate other satellites, a three-way calibration was performed. In one study[10], VIRS was used to calibrate GOES-8, then GOES-8 was used to calibrate NOAA-14 (VIRS-to-GOES-8-to-NOAA-14), and finally, VIRS was used to directly calibrate NOAA-14 (VIRS-to-NOAA-14). The two slopes of the regression fits are within 1%. In another study, two GEO and one LEO satellites were used. Here, a NOAA-14-to-GOES-8-to-GOES-10 calibration was performed and then NOAA-14-to-GOES-10 (Figure 8). The two slopes of the regression fits are nearly identical (less then 0.1% difference). In the earlier study[10], the LEO satellites were collocated in the Tropics and, therefore, difficult to match. This study has demonstrated the value of using a GEO satellite as a calibration transfer medium not only for the ease of matching data but also for increasing the accuracy and reliability of the calibration source.

5. CONCLUSIONS

This method provides a means for accurately calibrating satellite VIS channels in a timely fashion. This approach assumes that the VIRS sensors are well calibrated. Although the transfer of the calibration source is very accurate, any errors in the VIRS calibrations will be transferred to the other satellites. Independent validation of these results is an important part of this effort. The VIRS has been compared to MODIS on *Terra* and *Aqua*[13] and has found to be in good agreement. These calibrations provide the basis for consistent retrieval of cloud and surface properties and radiative fluxes from all of the different satellites used for climate monitoring. These techniques also permit rapid evaluation of the geostationary satellite data, and are currently being used in near-real time analysis of radiative properties from these satellites.

ACKNOWLEDGMENTS

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