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1. INTRODUCTION

Global retrievals of surface, cloud and radiative properties from geostationary (GEO) and low-Earth-orbit (LEO) meteorological satellites require accurate calibration of their imagers. An accurate and consistent calibration increases the reliability and effectiveness of long-term monitoring of climate changes. More emphasis has been placed on calibrating the thermal infrared (IR) channel. The lack of on-board calibration in the visible (VIS) channel has prompted efforts to characterize the degradation of the VIS sensor using vicarious post-launch calibration techniques that measure bright stable desert targets from space and aircraft (e.g., Rao and Chen, 1996) or using satellite-to-to-satellite normalizations (e.g., Desmoreaux et al. 1993). 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 examines the use of research satellite imagers to provide stable calibration references for the visible (VIS, ~0.65 µm) channels and develops a method for rapid intercalibration of existing satellites. Calibration coefficients are determined for the Geostationary Operational Environmental Satellites (GOES-8 - GOES-10), Geostationary Meteorological Satellite (GMS-5), Meteosat-7, and the NOAA-14 Advanced Very High Resolution Radiometer (AVHRR). As a reference calibration source, this technique uses the self-calibrating sensors on the Tropical Rainfall Measuring Mission (TRMM) Visible Infrared Radiometers (VIRS) or the ERS-2 Along Track Scanning Radiometer (ATSR-2). GOES-8 is calibrated with VIRS and then its calibration is transferred to other GEO or LEO satellites. The absolute accuracy of this technique relies on the assumption that the on-board calibration is stable and well maintained. Minnis et al (2001) assessed the VIRS calibration using comparisons with other self-calibrated satellite sensors including the broadband Clouds and Earth's Radiant Energy System (CERES) scanners, the ERS-2 Along Track Scanning Radiometer (ATSR-2), and the Terra Moderate-resolution Imaging Spectroradiometer (MODIS). Thus, the VIRS data can be confidently used as the initial reference source.

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3. METHODOLOGY

The general approach taken here is similar to the Desormeaux et al. (1993) method except that the data-matching constraints are less stringent and GOES-8, once calibrated against the VIRS, is used as a primary reference for calibration other satellites. GOES-8 is used because the degradation of the VIS channel is linear and well characterized, it has more 6 years of operational service, and its archived data are readily available.

The intercalibrations are performed between spatially and temporally matched averages of the data from the corresponding channels of two satellites. Additionally, the data are only selected if they have nearly the same values of viewing zenith θ and relative azimuth ϕ angle. For the GOES-8 calibration, VIRS is used as the reference calibration source. The GOES-8 data are matched with VIRS data taken within 15 minutes and have corresponding values of θ and ϕ that differ by less than 10°. Data taken in possible sunglint conditions are filtered out of the datasets. The reference radiance is normalized to the GOES-8 solar zenith angle θ_0 and to a solar constant E_0 of 526.9 $Wm^{-2}sr^{-1}\mu m^{-1}$. To account for the time and navigation differences, the radiances are averaged on a 0.5° grid to yield a pair of data points for each grid box.

Similarly, GEO satellites are also inter-calibrated with each other (GEO-to-GEO). For example, GOES-8 is used to calibrate GOES-10. Very close matches in time and space are possible because of the fixed views and regular imaging schedules. The GEO data are taken at local noon or midnight at the bisecting longitude between the two satellites. Local noon insures that all of the angles are nearly identical. The GEO data are matched to within 2 minutes. Because reflectance anisotropy may not be entirely symmetrical, average radiances at each 1° of latitude are computed for two 1° boxes that straddle the bisecting longitude. The regions used to cross-calibrate many of the various satellites are shown in Fig. 1.

In addition to the GEO-to-GEO matches, the GEO satellites are used to cross-calibrate with imagers like MODIS and AVHRR on Sun-synchronous satellites. Because TRMM is in a 35°-inclined orbit, the VIRS has few close matches with polar orbiters. However, it can frequently be collocated and bore-sighted with GEO data to within a few minutes. Thus, GEOs can serve as calibration sources for other satellites. Calibrations between Sun-synchronous satellites follow the approach of Loeb (1997) who used the frequent polar overpasses of such orbiters to obtain well-matched data. Data are averaged on a 0.5° grid for GEO-to-GEO and GEO-to-LEO intercalibrations.

While the calibrations are performed for all channels that are spectrally similar, only IR (~11μm) and VIS channels are used here. The VIS brightness counts are regressed against the reference VIRS radiances L_V is

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

where a is the gain, C is the observed brightness count or squared count, and C_o is the space count. The VIS regression forces the lines through the space count for the particular satellite. Although the VIS channel on each imager has a unique filter function, the bandwidth for most of the instruments is between 0.55 and 0.75 μm. The IR temperature is

$$T = b_1 T_o + b_o, \qquad (2)$$

where b_i and b_o are the regression coefficients. The mean IR temperatures T_o for each data point are computed in radiance and converted to T with the appropriate Planck function. Despite the spectral differences between the various IR channels, it is assumed that the equivalent blackbody temperatures should be the same for all of the sensors.

3. DATA

Matching GEO & LEO data are collected for a month at a time. A regression is then performed for each month of data. Data taken between 1994 and 2001 are used here. Table 1 shows an example of the monthly sampling used for each satellite calibration. GEO data were acquired from University of Wisconsin-Madison, AVHRR from the NOAA Satellite Active Archive, VIRS from NASA Langley DAAC, and ATSR-2 from the Rutherford Appleton Laboratory in Chilton, UK.

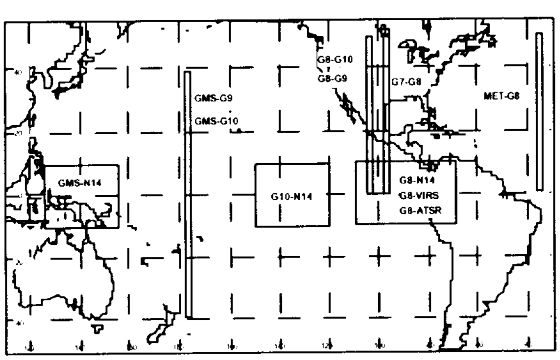

Fig. 1. Satellite intercalibration regions.

Satellites	Years	Total Mo.
VIRS - GOES8	1998-2001	23
GOES8 - ATSR2	1995-1999	12
GOES8 - N14	1995-2001	48
GOES8 - GOES9	1996-1998	14
GOES8 - GOES10	1998-2001	31
GOES8 - MET7	2000-2001	8
VIRS - GMS5	2000-2001	13

Table 1. Monthly calibration data by year.

3.1 VIRS

VIRS was launched on TRMM satellite at a 35° inclination and has been operating since late December 1997. The TRMM precessing orbit observes all local hours and viewing angle within a 45-day period. Channel 1 VIS (0.63μm) and 4 (IR) have a 2-km nominal resolution. The VIRS calibration is based on pre-launch and on-board procedures as reported by Barnes et al. (2000). As a reference source, the on-board system uses a solar diffuser plate that views the sun. The VIRS channel-1 radiances L_v are obtained the from Version-5 data, and the solar constant E_v is 531.7 $Wm^{-2}sr^{-1}\mu m^{-1}$. For comparisons with GOES, GMS, Meteosat-7, and ATSR-2, the L_v are normalized to equivalent GOES radiances by multiplying by the ratio of the GOES and VIRS solar constants (E_o / E_v = 0.9923). The VIRS channel-1 reflectance is

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

where δ is the Earth-Sun distance correction factor.

3.2 AVHRR

NOAA-14 was launched into a near Sun-synchronous orbit on December 30, 194. The afternoon polar orbiter has an equatorial crossing time of 14:30 local time (LT). The orbit has since drifted to approximately 16:36 LT in early 2001. The AVHRR channel-1 VIS (0.67μm) and channel 4 IR (10.8μm) 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 are used and matched with GOES-8 in the tropics.

3.2 Meteosat-7

The EUMETSAT Meteosat-7 was launched in September 1997 and is located at 0° where it 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. Meteosat-7 and GOES-8 radiances are matched in ocean regions where the effect of the wide Meteosat-7 spectral response function is minimized.

3.3 GMS-5

The GMS-5 VISSR has a nominal 1.25-km resolution VIS channel and a 5-km IR channel. Matched data are obtained by averaging 0.5° grids over ocean regions. The IR temperature conversion uses a nonlinear lookup table. GMS-5, at 140°E, has provided data since June 1995. GMS-5 is calibrated directly with VIRS (Minnis et al., 2001) from March 2000 to March 2001. Farther examination of the GMS-5 calibration will be assessed with the GEO-to-GEO method from 1995 to 1999.

3.4 GOES-8, 9, 10

GOES-8 has been the primary GOES-East satellite since September 1994. GOES-9 operated as GOES-West at 135°W from January 1996 to July 1998. GOES-10, launched in April 1997, replaced GOES-9 in July 1998. The GOES imager has 1-km VIS and 4-km IR (10.7μm) channels (Menzel et al., 1994) with data taken at a 10-bit resolution. Simple averaging is used to degrade the VIS resolution to 4 km. GOES-9 and 10 are calibrated using GOES-8.

4. RESULTS

A scatterplot for the GOES-8 VIS calibration during July 2000 is shown in Fig. 2a with the regression fit forced through the space count, 31. The squared correlation coefficient is 0.993 and the data cover a large dynamic range. The standard error of the estimates using these fits is less than 10%. The IR scatterplot (Fig. 2b) shows a near perfect agreement between GOES-8 and VIRS with a gain of 1.001 and R^2=0.995. The IR gains from 1998 to 2001 are typical with a mean RMS error of 0.5% and a 0.4 K bias. Figure 3 shows that the GOES-8 VIS gain trends calibrated with VIRS (Os) and ATSR-2 (Xs) increase linearly with time consistent with a steady degradation of the instrument optics. The ATSR-2 trend line is consistent with VIRS to within 1%. Either calibration could be used as reference but VIRS was chosen as an absolute calibration for GOES-8 and other satellites because its VIS-channel filter is more like the operational satellites' than the ATSR-2 filter. For a given satellite, the post-launch calibration formula is

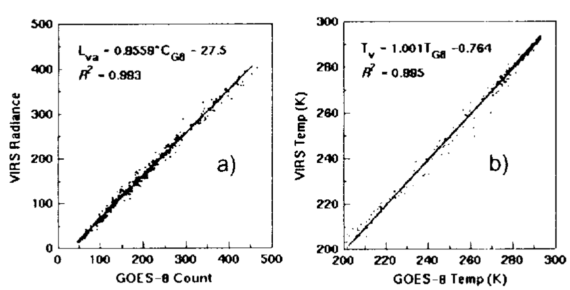

Fig 2. GOES-8 VIS & IR for July 2000. Radiance in $Wm^{-2}sr^{-1}\mu m^{-1}$.

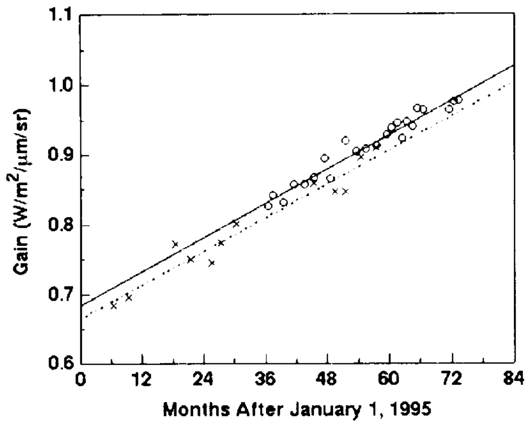

Fig 3. Monthly GOES-8 VIS gain trend from VIRS (O) and ATSR-2 (X). The solid (VIRS) and dotted (ATSR-2) lines are linear regression fit.

$$L_v = (\Delta g\, d + g_o)(C - C_o), \qquad (4)$$

where L_v is the normalized radiance, g_o is the initial gain, Δg is the 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. For GMS-5, C is expressed as 8-bit squared counts. The calibration coefficients for several satellites are given in Table 2. The VIS reflectance can be calculated using (3).

The GOES gain trends in raw count are shown in figure 4. GOES-8 VIS count is 16.7% lower than GOES-9 in February 1996 and 28% lower than GOES-10 in March 1998. The VIS channel sensor on the GOES-8, 9 &10 degrade linearly at an annual rate of 7.5%, 5.8%, and 11.1% respectfully the first year after launch as calculated from Table 2. These rates are consistent with the 7.6% (GOES-8) and 4.9% (GOES-9) reported by Bermer et al. (1998) who uses star measurements for estimating the sensor degradation. The GMS-5 VIS sensor has an annual degradation rate of 1.4% (Minnis et al.). The NOAA-14 AVHRR VIS channel has a non-linear degradation (fig. 5) and the calibration equation is

$$L_{va} = (-3.139E\text{-}8d^2 + 9.318E\text{-}5d + 0.6074)(C - 41) \qquad (5)$$

where L_{va} is the radiance, C is 10-bit count, and d is the day after launch, 30 December 1994. The reflectance can be calculated using (3) and the NOAA-14 solar constant of 510.6 $Wm^{-2}sr^{-1}\mu m^{-1}$ instead of E_o. The calibration equation is not recommended for data after December 2001 since the trend is non-linear and the orbit is drifting into a terminator orbit. The calibration equation (5) for the period from 1995 to 1999 is ~7% greater than reported by Rao et al. (1996,1999), however, it is in good agreement with Vermote and El Saleous study as reported by Doelling et al.(2001). The Meteosat-7 calibration coefficients in Table 2 may not be as reliable for data from 1998 to 2000.

Satellite	g_o	Δg	C_o	Ref Date
GOES10	0.5234	1.5983E-4	34	04/25/97
GOES-9	0.5819	9.1929E-5	34	05/23/95
GOES-8	0.6497	1.3415E-4	31	04/13/94
GMS-5	0.00798	3.0301E-7	-30[2]	03/19/95
MET-7	1.6846	6.1048E-4	6	09/02/97

Table 2. Calibration coefficients for equation (4). g_o and Δg in $Wm^{-2}sr^{-1}\mu m^{-1}$.

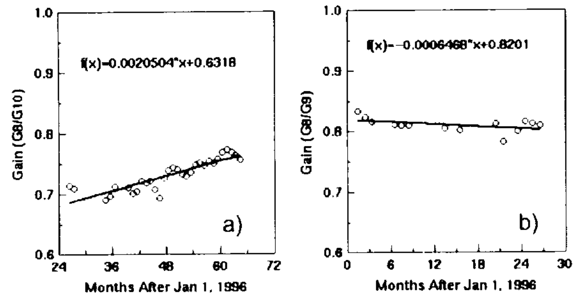

Fig 4. GOES-10 and GOES-9 VIS channel gain trends in count.

Presently, only data from 2001 were analyzed. The degradation rate is ~9% per year in 2001.

The IR channel comparisons from several satellites show that most sensors are relatively stable. The GOES-8/GOES-10 gains show no apparent trend and are stable from 1998 to 2001. The mean bias is –0.5 K with an RMS error of 0.6%. The GOES-8/GOES-9 gains are similar with RMS error of 0.4% and bias of 0.4 K. The GOES-8/NOAA-14 IR gains show a small trend in the NOAA-14 IR channel. In 1995, the IR channels were in excellent agreement. However, in 2001, the NOAA-14 cold temperatures (~210K) are 3 K lower than their GOES-8 counterparts.

To validate the cross calibration, a three-way calibration was performed. VIRS-to-GOES-8-to-NOAA-14 and VIRS-to-NOAA-14 calibration (Doelling et al., 2001) were performed. The two calibration slopes are within 1% showing that the method of using GOES-8 as a transfer medium is accurate and reliable.

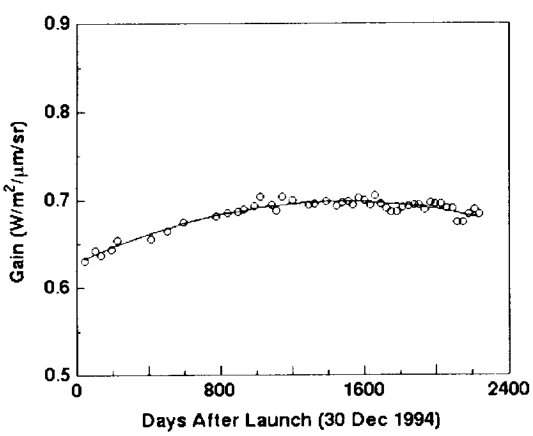

Fig 5. NOAA-14 AVHRR VIS channel gain trend in $Wm^{-2}sr^{-1}\mu m^{-1}$.

5. CONCLUSIONS

The method presented here provides a means for accurately calibrating satellite VIS channels in a timely fashion. This approach assumes that the VIRS sensors are well calibrated. Thus, 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. Other new satellites and sensors will be examined and the validation of the VIS channels will continue. These calibrations provide the basis for consistent retrievals 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, thus paving the way for a near-real time analysis of radiative properties from these satellites.

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