Calibration of Geostationary Satellite Imager Data for ARM Using AVHRR

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Introduction

Geostationary satellite imager data are a key part of the Atmospheric Radiation Measurement (ARM) Program. They complement the suite of surface measurements taken at the Southern Great Plains (SGP) and the Tropical Western Pacific (TWP) sites. The data are used to derive cloud properties and the top-of-the-atmosphere radiation budget at several time and space scales. Retrievals of cloud and radiative properties from satellite imager data require accurate calibration of the various channels and satellites used in the retrievals. Generally, most infrared channels have a stable calibration maintained with an on-board blackbody source. The visible channel calibrations, however, are often neglected.

To derive more accurate cloud properties from Geostationary Operational Environmental Satellite (GOES) for the SGP and from the Geostationary Meteorological Satellite (GMS) over the TWP, a technique has been developed to calibrate their visible and infrared channels with National Oceanic and Atmospheric Administration (NOAA) Advanced very high resolution radiometer (AVHRR) data. This approach matches the viewing angles of the geostationary (GEO) satellites with coincident AVHRR data to provide an intercalibration dataset for each month. The AVHRR visible channel calibration is based on the method of Rao and Chen (1996). The GOES-8 calibration is derived directly from NOAA-14, the GOES-9 calibration is determined by intercalibration with GOES-8, and the GMS calibration is determined by intercalibration with GOES-9.

Data

Matched geostationary and NOAA AVHRR data were selected for several days and times for each calibration month from 1995 through 1998 (see Table 1). The data were obtained from a variety of sources including the University of Wisconsin Space Science and Engineering Center, the ARM project external data center at Brookhaven National Laboratory, and the NOAA-National Environmental Satellite data, and Information Service Satellite Active Archive. All of the data were converted for processing in the Man-computer Interactive Data Analysis System (McIDAS; Suomi 1983).

Table 1. Summary of monthly satellite calibration data by year. *NOAA-11 used as reference.

Mon.	N-14	G-8	G-9	GMS	G-7
Jan	98	98	98		
Feb	96,97,98	96,97,98	96,97,98	97	
Mar	98	98	96,98	98	
Apr	95,97	95,97	96,97		94*
May	95,96	95,96			
Jun					
Jul	95,97	95,97	96		
Aug	95,96	95,96	96		
Sep	97	97	96,97		
Oct	95,97	95,97	95,97		95
Nov					
Dec	97	97	97		

AVHRR Data

The initial reference data comprise 4-km resolution Global Area Coverage (GAC) AVHRR channel-1 visible (VIS; ~0.67 µm) and channel-4 infrared (IR; ~10.8 µm) measurements from NOAA-14.

The VIS radiance for the NOAA-14 AVHRR is

$$L_{VA} = (0.000118d + 0.557)(C_{10} - 41) \qquad (1)$$

(Rao and Chen 1996), where C_{10} is the 10-bit visible channel count and *d* is the number of days since launch of the satellite. NOAA-14 was launched into a near sun-synchronous orbit on December 30, 1994.

The AVHRR channel-4 (10.8 µm) equivalent blackbody temperature is

$$T_A = B^{-1}(L_{IR}), \tag{2}$$

where B^{-1} is the inverse Planck Function integrated over the filter function of the channel, L_{IR} is the measured radiance, which is nominally linear with count. Because there is some nonlinearity in the response, a correction using on-board data and the nominal radiance is applied to obtain an accurate radiance (Rao et al. 1993).

GOES-7 Data

GOES-7 was located over the equator at 108.5°W during April 1994 and at 98°W during the summer and fall of 1994. It was moved to 135°W in January 1995 where it remained before being replaced by GOES-9 in January 1996. The GOES-7 visible and infrared spin scan radiometer (VISSR) atmospheric sounder (VAS) VIS channel is centered at 0.65 µm and the radiance is based on a squared relationship to VIS count. The 1-km VIS data were reduced to 8-km resolution by computing the root mean square (rms) averages. The GOES-7 IR data have a nominal resolution of 8-km with a band center near 11.2 µm. The infrared equivalent brightness temperature is a linear function of the infrared (channel-8) count. NOAA-11 AVHRR data were used to calibrate GOES-7 during 1994.

GMS Data

The GMS VISSR has a nominal 1.25-km resolution VIS channel and a 5-km IR channel. Matched data are obtained by computing the 5-km VIS rms average corresponding to a given IR pixel. The VIS calibration is similar to that of GOES-7, while the IR temperature conversion is accomplished with a nonlinear lookup table. The GMS is always located at 140°E. GMS-5 data have been available since June 1995 and will be used for the ARM TWP domain.

GOES-8 and GOES-9 Data

GOES-8 has been located at 75°W since September 1994 and is the prime satellite for monitoring the ARM SGP site. GOES-9 was initially located at 90°W during September 1995 and began regularly monitoring from 135°W in January 1996. The GOES-8 and GOES-9 imagers have 1-km VIS (~0.62 µm) and 4-km IR (10.8 µm) channels (Menzel and Purdom 1994) with data taken at a 10-bit resolution. Simple averaging is used to degrade the VIS resolution to 4 km. Unlike the earlier GOES VISSR VIS channels, the newer GOES imagers are not subject to occasional subjective adjustments so that the calibration should change in an orderly fashion as the instrument optics degrade in the space environment.

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 a single GEO satellite, once calibrated against the reference sensor, is used as a primary reference for the other GEO satellites. Reflectance is the parameter of interest for the visible channel. The VIS reflectance is defined as

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

The solar and viewing zenith and relative azimuth angles are θ_o, θ, and ϕ, respectively, and δ is the Earth-Sun distance correction factor. A value of 526.9 $Wm^{-2}sr^{-1}\mu m^{-1}$ is assumed to be the nominal VIS solar constant E_o. This value is used as a common scaling factor for all of the data. Although the visible channel on each imager has a unique filter function, the spectral bandpass of most of the instruments is between 0.55 µm and 0.75 µm.

The intercalibrations are affected by least squares regression analysis between spatially and temporally matched averages of IR-equivalent blackbody temperatures and between GEO brightness counts and AVHRR radiances L_{VA} for VIS data. The VIS radiance is

$$L_v = L_{VA} = a(C - C_o) \tag{4}$$

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 calibration satellite. The IR temperature is

$$T = T_A = b_1 T_G + b_o, \tag{5}$$

where b_i and b_o are the regression coefficients.

NOAA to GEO Intercalibration

Average radiance L_{VA} and temperature T_A are computed on a 0.5°-grid from NOAA AVHRR data taken near a GEO sub-satellite point. Similarly, mean values of the VIS counts and equivalent blackbody temperatures are computed on the same grid from the GEO data taken at the image time nearest the NOAA overpass. The VIS-count means are computed as simple or rms averages depending on the scaling for the particular sensor. The brightness temperatures are averaged in radiance and then converted to temperature. When data from either satellite are unavailable near the GEO sub-satellite point, the averages are computed on a grid within the available matched areas. The 0.5°-grid used for the GOES-8 intercalibration is shown in Figure 1. The grid is centered at 135°W for the GOES-9/NOAA-14 intercalibrations.

When the near-sub-satellite-point grids are used, only the data in grid boxes having time t and angle differences, $\Delta t <$ 15 minutes, $\Delta\theta_o < 15°$, $\Delta\theta < 15°$, and $\Delta\phi < 15°$, are selected for the calibration. The time difference generally insures that $\Delta\theta_o < 3°$. Data taken in sunlight conditions are excluded.

Sun glint is assumed to be present when the region contains more than 25% water surface and the bidirectional reflectance anisotropic correction factor *c* for clear ocean (Minnis and Harrison 1984) exceeds a threshold value of 1.4, if $\phi <$ 105°, or 1.5, if $\theta_o < 25°$. In all calibrations, the AVHRR VIS radiances are adjusted to the GEO solar zenith angle.

GEO-to-GEO Intercalibration

The same type of regional averages used in the NOAA-GEO calibrations are computed for the GEO intercalibrations except that VIS radiance L_{VG} is computed from the reference GEO satellite. Matching of the data is also different. To minimize angular differences between the two GEO satellites, only data taken at or nearest to local noon along the meridian halfway between the two subsatellite points are used in the regressions. The solar and viewing zenith angles are nearly identical depending on the actual times of the satellite images. The relative azimuth angles immediately on one side of the meridian for one GEO are identical to those on the other side for the other GEO. Therefore, the relative azimuth angle discrepancies should cancel for the regional average. Because of very close temporal matching between the GOES satellites (usually within 2 minutes), 1° regions centered on the bisecting longitude over the continental U.S. are used to develop the regression datasets. For intercalibrations between the GOES and GMS, 2° regions are used to compute averages because the time differences may be as great as 30 minutes. The larger regions yield better correlations when the image times differ significantly.

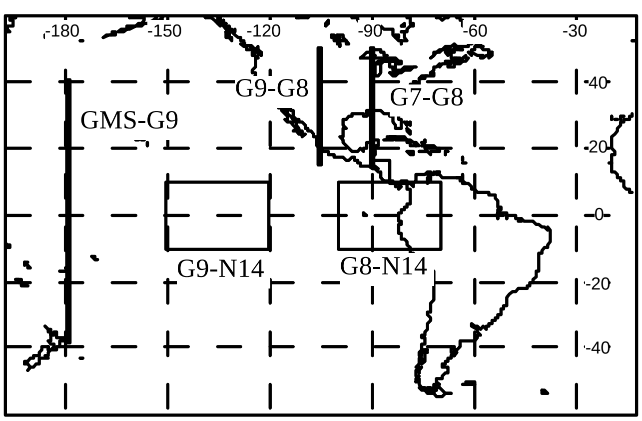

Figure 1. Satellite calibration regions.

Results

The scatterplot for GOES-8 during the ARM/Unmanned Aerospace Vehicle (UAV) Intensive Observation Period (IOP) is shown in Figure 2 with the regression fit forced through the space count, 28.5. The correlation is excellent with the forced fit centered in the data over the full range. Figure 3 shows the IR fit for the same period. The regression fit, close to the line of perfect agreement between GOES-8 and NOAA-14, is typical for the entire period. Figure 4 shows that the visible channel gain for GOES-8 increases linearly with time consistent with steady degradation of the instrument optics. Figure 5 shows the VIS gain for GOES-9, developed from intercomparison with GOES-8, also increases linearly but at a slower rate. No

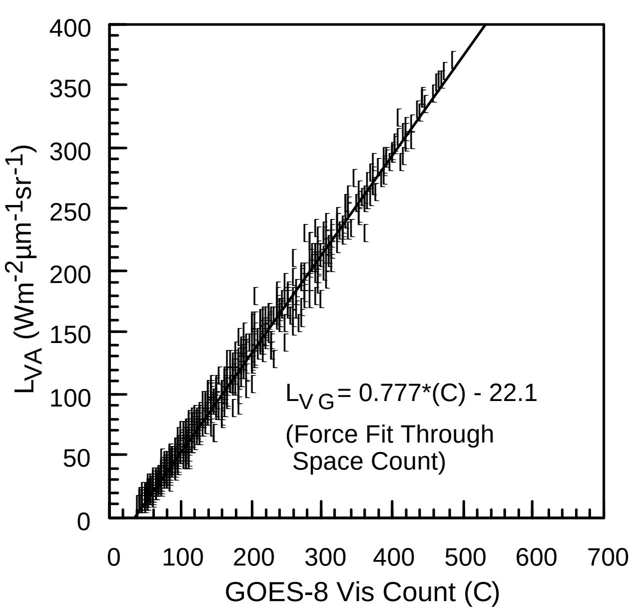

Figure 2. GOES-8 VIS channel calibration, October 1997.

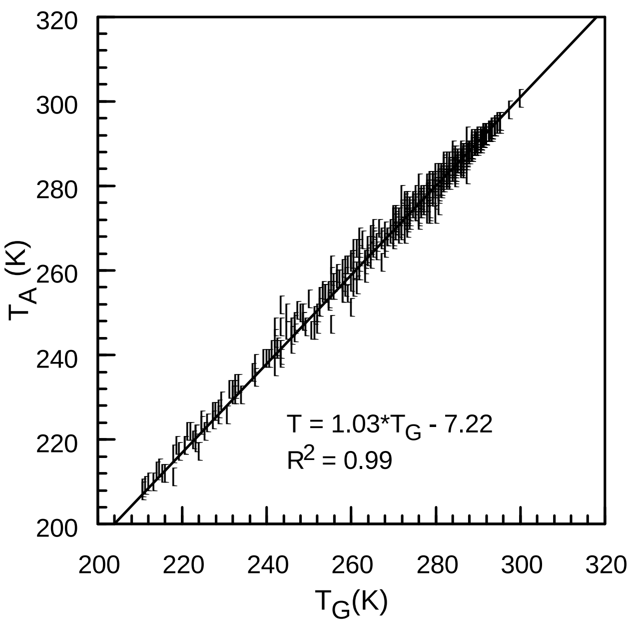

Figure 3. GOES-8 channel 4 calibration, October 1997.

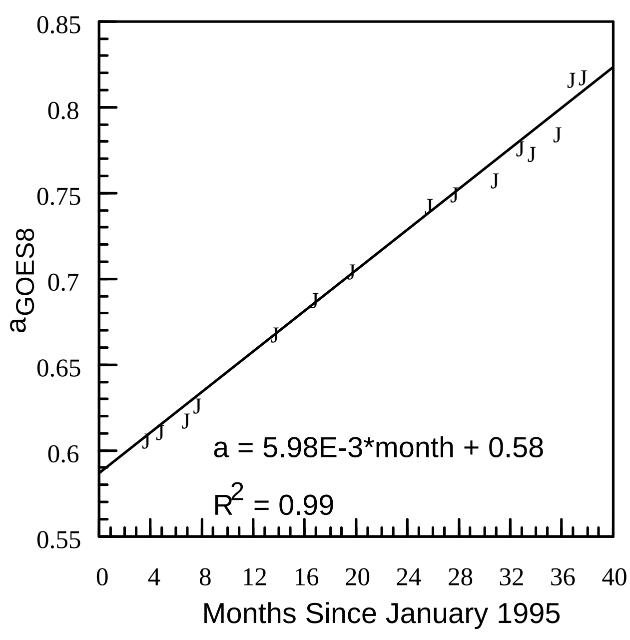

Figure 4. GOES-8 VIS channel gain trend.

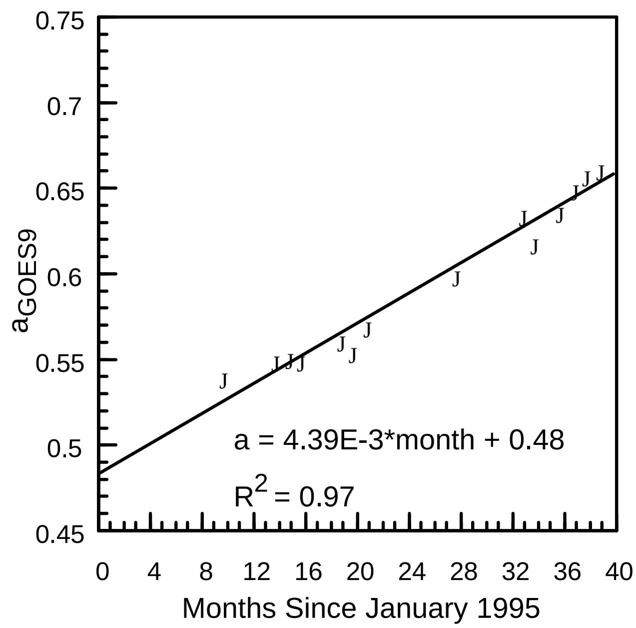

Figure 5. GOES-9 VIS channel gain trend.

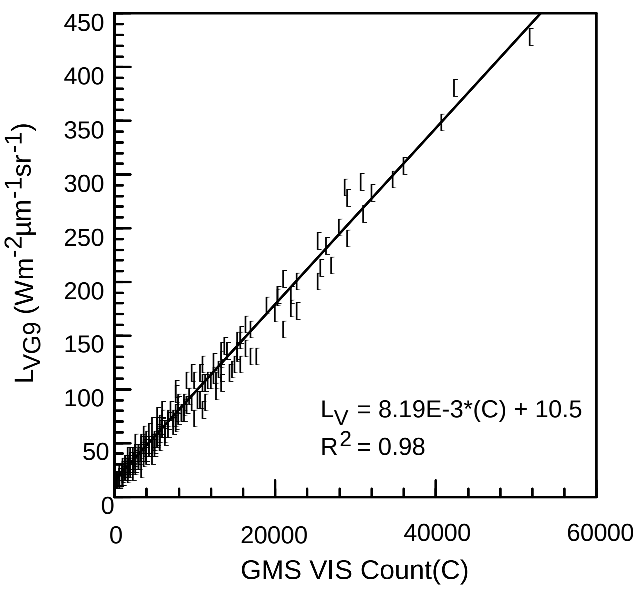

Figure 6. GMS VIS calibration for March 1998.

trends were found in the IR calibrations. The GMS VIS calibration for March 1998 (Figure 6) indicates that a zero radiance cannot occur even when there is no signal. Thus, the GMS data should be used carefully in low sun or shadowed conditions.

Conclusions

Satellite matching yields visible channel calibration coefficients accurate to ±4.8%. A minimum of 50 samples covering most of the dynamic range is required for calibration. The range of time and angular tolerances for matching the data are sufficient for calibration. IR gains vary by only ±0.01 with no trend apparent. The infrared channels on both GOES appear to be stable and show negligible differences with co-aligned AVHRR data. A linear increase in the gain has been found for both the GOES-8 and GOES-9 VIS channels. The method developed here provides accurate calibrations for GEO satellite VIS channels and demonstrates that their on-board IR calibrations are adequate. This approach assumes that the AVHRR sensors are well calibrated. Thus, any errors in the AVHRR calibrations will be transferred to the GEO satellites. Independent validation of these results is an important part of any future research.

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