Calibration of the Geostationary Operational Environmental Satellite Using Satellite and ARM Enhanced Shortwave Experiment Aircraft Data

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Introduction

The Geostationary Operational Environmental Satellite (GOES) data are a key component of the Atmospheric Radiation Measurement Program (ARM). They complement the suite of surface measurements taken at the ARM sites in Oklahoma. The data are used to derive cloud properties and the top-of-the atmosphere radiation budget at several time and space scales. Calibration of the GOES narrowband visible (0.65 µm) and infrared (11 µm) radiances is essential for accurate determination of quantities such as cloud optical depth, height, and emittance. Conversion of these radiances to broadband shortwave albedo and longwave flux is performed using empirical functions based on coincident Earth Radiation Budget Satellite (ERBS) measurements taken prior to the ARM program. These calibrations and conversions are based on historical matched satellite-to-satellite datasets. It is important to have an independent verification of these calibrations. A contemporaneous calibration using a reliable source is even better. The ARM/Unmanned Aerospace Vehicle (UAV) Program includes well-calibrated airborne radiance and flux measurements that can be used to verify and improve the calibration coefficients for operational meteorological satellites. This paper uses satellite and aircraft measurements taken during the 1995 ARM Enhanced Shortwave Experiment (ARESE) to perform calibrations of the GOES-8 visible and infrared sensors.

Satellite Data

The ARESE was conducted over the ARM Southern Great Plains site in northern Oklahoma from September 25 - November 1, 1995. Visible (VIS) and infrared (IR) radiances were observed every 15 min by the GOES-8 (G8) and GOES-9 (G9) satellites. G8 was located over the equator at 75°W, while G9 was centered at 90°W. The nominal resolutions of the VIS and IR sensors are 1 and 4-km, respectively. The prelaunch gain for the G8 VIS calibration was adjusted shortly after launch to yield

$$L_8 = 0.606 \ D_8 - 14.33 \tag{1}$$

where D is the 10-bit digital count and L_8 is the G8 radiance in $Wm^{-2}sr^{-1} \ \mu m^{-1}$. The G9 VIS radiance L_9 was determined by correlating average values of G9 VIS counts D_9 with collocated values of D_8 at local noon along the longitude (82.5°W) bisecting the two satellites (Figure 1). The resulting calibration is

$$L_9 = 0.556 \ D_9 - 15.37 \tag{2}$$

The GOES 11-µm channel is calibrated in terms of equivalent blackbody temperature.

Aircraft Data

The correlative measurements are provided by the NASA ER-2 which serves as a surrogate for the ARM/UAV in this study. Two flights of the ER-2 were dedicated to satellite calibration. During the first flight on September 27, 1995, the ER-2 flew from Austin, TX to southern Alabama, southwestward into the Gulf of Mexico and then returned to Austin. The second flight took the ER-2 at 20 km over hurricane Roxanne in the Gulf of Mexico on October 12, 1995. The flight track of the ER-2 is shown in Figure 2 with notations indicating the UTC time at certain points and the satellite for which the observations were intended. The ER-2 MODIS Airborne Simulator (MAS) is a 50-channel cross-track

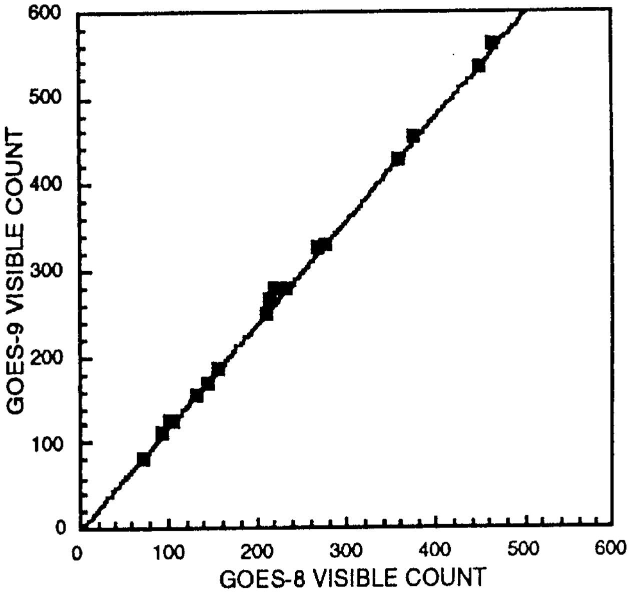

Figure 1. Correlation of matched GOES-8 and GOES-9 visible counts taken at 82.5°W, 1730 UTC, September 12, 1995.

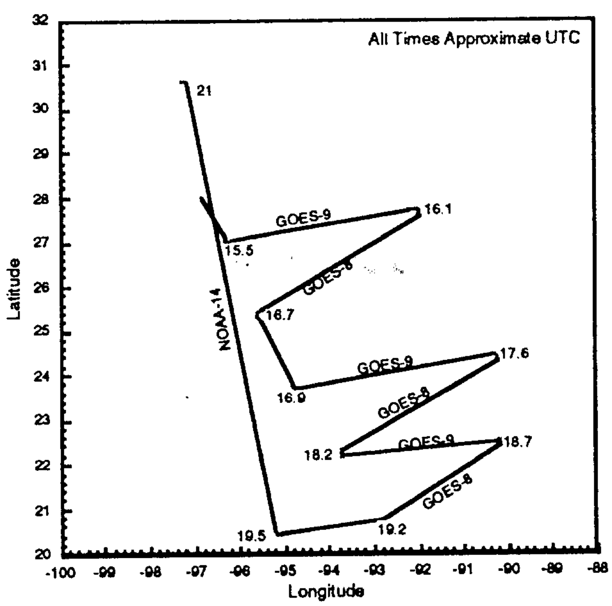

Figure 2. Flight path of ER-2 during second ARESE calibration flight. Legs corresponding to constant satellite viewing angle are indicated by the name of the satellite.

scanner that has a nominal pixel resolution of 50 m and a maximum viewing zenith angle θ of 46° at 20 km. The ground tracks of the ER-2 were selected to coincide with constant values of θ from GOES or to be parallel to the NOAA-14 ground track. Channel 2 of the MAS has a central wavelength of 0.653 μm. The radiance measured by channel 2 is

$$L_e = a_e D_e \tag{3}$$

where a_θ is the sensor gain and D_e is the 16-bit digital count. The solar constant for the MAS bandpass is 1502 $Wm^{-2}\mu m^{-1}$. The MAS IR channel is calibrated in terms of equivalent blackbody temperature.

Data Analysis

The MAS and GOES data are paired at coincident times in the following manner. Because of the height differences, the GOES pixels are much larger than the MAS pixels. The MAS pixels from a given flight leg are navigated and assigned to the nearest GOES pixel. All of the MAS radiances, solar (θ_O) and viewing zenith angles, and relative azimuth (ϕ) angles are then averaged for each corresponding GOES pixel. Roughly, 400 - 500 MAS pixels are averaged to equal a single 1-km GOES VIS pixel. Approximately 7200 MAS pixels are used for one G8 4-km IR pixel. The GOES radiances and the mean MAS pixel radiances are then correlated using a range of shift values to obtain optimal spatial matching of the two datasets. This optimum is defined as the pixel-line shift yielding the highest correlation coefficient. The MAS radiances are then corrected to the GOES viewing angles by applying the anisotropic correction models of Minnis and Harrison (1984). A subset of the matched, shifted GOES and mean MAS pixels are then selected for intercalibration using those pixels meeting the following criteria. The differences in θ_O, θ, and ϕ must be less than 2.5°, 2°, and 20°, respectively. Thus, the MAS pixels span 5° of θ, while the corresponding GOES pixels cover only a fractional change in θ.

Ideally, the aircraft heading should be aligned perpendicular to the line between the aircraft, GOES, and a point along a fixed VZA. In this case, the azimuth to the viewed point will be the same for both satellite and aircraft resulting in matched viewing and illumination conditions between the two platforms. If these conditions exist, a correction for anisotropy is not required. During October 12, the ER-2 was not exactly on the perpendicular heading resulting in a 15° difference in ϕ between G8 and the MAS at the coincident VZAs. Fortunately, the ER-2 and G9 were more closely aligned, so minimal anisotropic corrections are needed in that analysis.

The GOES and ER-2 data were matched for each 15-min image using the ER-2 data observed within ± 7 min of the time when the GOES viewed the coincident points. At 25°N, the time is roughly 8 min after the nominal image time. Because of the small time difference between the GOES and ER-2 pixels, it is assumed that advection is minimal. Using matched pixels from a series of GOES images should reduce any residual advection effects. The MAS measurement is almost equivalent to that of a satellite. However, the 75-100 hPa of atmosphere above the aircraft contains most of the atmospheric ozone column. At high solar zenith angles, Rayleigh scattering may be significant. Here, it is assumed that Rayleigh scattering above the ER-2 makes a negligible contribution to the outgoing radiance. The ozone absorption is taken into account with the same parameterization used by Minnis et al. (1995) and an ozone loading of 0.3 cm. The absorption optical depth is computed at the observed θ. After correction for anisotropy, ozone absorption, and differences in solar constant and solar zenith angle, the resulting average MAS top-of-the-atmosphere radiance L_e' for each GOES-equivalent pixel is paired with its corresponding GOES pixel. These pairs are then correlated to determine the GOES calibration with respect to the MAS channel-2 calibration. It is assumed that the absorption at 11 µm is negligible above the ER-2 so no additional corrections are made to the infrared data.

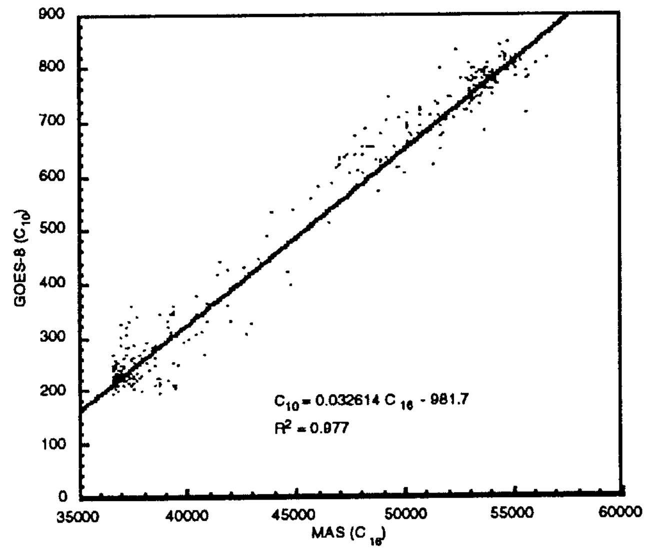

Figure 3. Correlation of ER-2 MAS Band 2 and GOES-8 visible counts for GOES-8 flight leg 2, October 12, 1995.

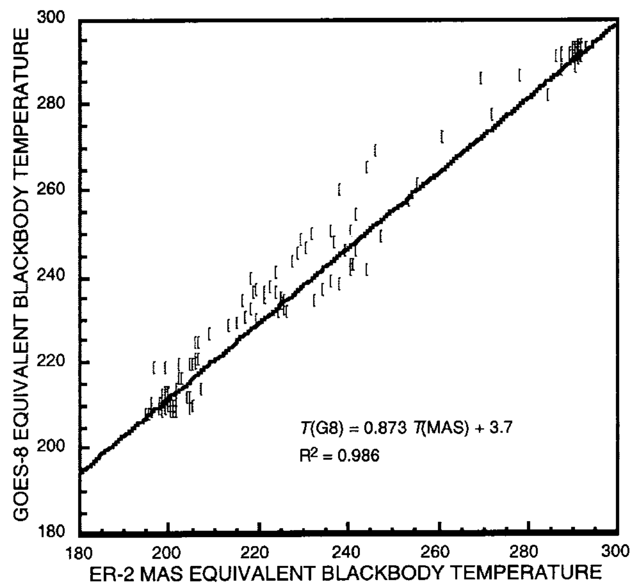

Figure 4. Correlation of ER-2 MAS band 45 and GOES-8 channel 4 temperature data during flight leg 2, October 12, 1995.

Preliminary Results

The scatterplot and resultant regression line are shown in Figure 3 for the G8 and MAS visible data taken during the second G8 flight leg at ~1800 UTC, October 12, 1995. During that leg, the ER-2 passed from an expanse of clear water to solid overcast. The squared correlation coefficient is 0.977 indicating excellent pairing of the data. Count values are used in the correlation at this point because of some remaining uncertainties in the MAS visible channel calibration. When the MAS calibration is completed, the MAS values and, subsequently, the G8 counts can be converted to radiance.

The corresponding plot for the infrared channels is shown in Figure 4. The correlation coefficient of 0.986 is slightly better than that for the visible data as might be expected because of fewer anisotropic effects. The MAS temperatures are lower than the GOES temperatures at the cold end but nearly equal at warmer values. This finding is consistent with a comparison of coincident ER-2 MAS and HIS (High-resolution Interferometer Sounder) performed during late 1994 (C. Moeller, personal communication). A final intercalibration between the two instruments awaits additional corrections to the MAS channel 45 data and the use of data from other flight legs.

Concluding Remarks

This paper has demonstrated a technique for calibrating operational meteorological satellite imager data using aircraft measurements taken over clouds during a field experiment. The analyses will continue using data from the other legs of the October 12 calibration flight as well as the other two satellites. Data taken during the first calibration flight will be used to independently verify the results. Final calibrations cannot be completed until the gains in the MAS channels are well characterized. Additional analyses will be performed to complete the determination of a narrowband-to-broadband albedo conversion formula for application to recent ARM GOES datasets.

The method developed here can be used during most field programs having a well-calibrated imager. It is especially appropriate for flight programs involving the ARM/UAV.

References

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