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INTERCOMPARISON OF THE OPERATIONAL CALIBRATION OF GOES-7 AND METEOSAT-3/4

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1. INTRODUCTION

Meteosat-3 is now positioned at 75 W and is calibrated operationally by using Meteosat-4 measurements as reference radiances in an area viewed by both satellites (de Waard et al., 1992). The Meteosat-3 calibration procedure is inherently noisy; recent work suggests methods to reduce the variability of the Meteosat-3 calibration coefficient. This note describes current operational procedures for calibrating GOES-7 and Meteosat-3/4 and reports on the intercomparison of radiance measurements from these geostationary satellites. The GOES-7 calibration, which occurs every spin (.6 seconds), was used to verify improvements in the Meteosat operational calibration procedures performed twice daily .

2. GOES-7 CALIBRATION

The VAS (Visible Infrared Spin Scan Radiometer Atmospheric Sounder) is a thirteen channel passive radiometer onboard the Geostationary Operational Environmental Satellite (4 through 7) which measures visible reflectances at 1 km resolution and infrared radiances in twelve spectral bands from 4 microns out to 14.5 microns at either 8 or 16 km resolution (depending on channel). For more information on the VAS, see Montgomery and Uccellini, 1985. The VAS detector responds to the combined radiation from the target and the telescope, or it responds to the radiation from an internal blackbody when a calibration shutter is inserted. The foreoptics components of the VAS telescope (mirrors, baffles, mirror masks) thus contribute to the background when the Earth or space is measured, but they do not contribute to calibration blackbody measurements. These foreoptics contributions to the background radiation are estimated with a radiative model and thermistor measurements of foreoptics temperatures (ranging between 15 and 35 C). If the blackbody had been external to the VAS, the determination of the VAS telescope contributions to the background radiation would have been unnecessary, and the calibration procedure would have been much simpler.

The VAS calibration involves measurements of radiation from space, an internal blackbody, and the target on earth (Menzel et al., 1981). The equations governing these measurements are

$$V_z = a\,[t\,R_z + (1 - t)\,R_v] + b, \qquad (1)$$

$$V_{bb} = a\,R_{bb} + b, \qquad (2)$$

$$V_e = a\,[t\,R_e + (1 - t)\,R_v] + b \qquad (3)$$

where V is the output voltage of the detector, R is the input radiance, a is the responsivity of the detector, t is the transmittance of the VAS telescope, b is the detector offset voltage, z denotes space, bb denotes the internal blackbody, e denotes the target on earth, and v denotes the VAS telescope contributions to the background radiation. Space and blackbody looks occur every spin (0.6 seconds).

Assuming the input radiance from space is negligible, we write for the target radiance

$$R_e = \frac{V_e - V_z}{V_{bb} - V_z} \, \frac{[R_{bb} - (1 - t)\,R_v]}{t} \,. \qquad (4)$$

R_v is determined by monitoring the temperatures of eight selected components of the telescope foreoptics. The transmittance t is calculated from the reflectivities, emissivities, and obscuration fractions of the various telescope components, that have been determined before launch; Menzel (1980) cites a value of 61% (within 2%).

The radiance emanating from a component of known temperature in a given band of known spectral response is determined by the normalized convolution of the Planck function and the spectral response function. Appendix A discusses a simple adjustment to the Planck function which takes the spectral bandwidth of a given channel into account.

The blackbody radiance is calculated from the measured temperature within the blackbody cone, T_{bb}, the emissivity of the shutter cavity, ϵ, and its temperature, T_{sc}, using the relation

$$R_{bb} = (1-\epsilon)\,R(T_{bb}) + \epsilon\,R(T_{sc})\,. \qquad (5)$$

The radiance of the VAS telescope has been modeled so that Eq (4) reads

$$R_e = \frac{V_e - V_z}{V_{bb} - V_z} \,\{R(T_{bb}) + \sum_j C_j\,[R(T_{bb}) - R(T_j)]\}, \qquad (6)$$

where the sum Σ_j runs over seven telescope foreoptics components that contribute appreciably to the background radiation, plus the shutter cavity with C_{sc} equal to $-\epsilon/t$. The term in the brackets { } represents the equivalent blackbody radiance, had it been placed external to the telescope, which we denote by R_{ebb}. The C_j are constants determined from reflectivities, emissivities, and obscuration fractions and are constrained by the relation

$$\sum_j{}' \, C_j = \frac{(1 - t)}{t} \,. \qquad (7)$$

where the sum Σ'_j runs over the seven telescope foreoptics components, but does not include the shutter cavity.

The contributions of the foreoptics components to the measured radiance when viewing the earth are 39% of the total signal, when the earth and the telescope are roughly at the same temperature (between 15 and 35 C).

The calibration algorithm is implemented for each spectral band in the following way. The detector voltage, V_i, measured in response to incident radiation is adjusted with a cubic fit so that it accommodates small non-linearities in the detector response. This adjusted response, X_i, is converted to a radiance value, R_i, by writing

$$R_i = slope * X_i - intercept \quad (8)$$

where i indicates space, blackbody, or earth. This linear relationship is calculated for every spin of the VAS using

$$slope = R_{ebb} / [X_{bb} - min (X_{zeast}, X_{zwest})], \text{ and} \quad (9)$$

$$intercept = slope * min (X_{zeast}, X_{zwest}). \quad (10)$$

The minimum of the adjusted space responses east and west of the earth, (X_{zeast}, X_{zwest}), is used to avoid influences of the sun or the moon. The radiance value for a given pixel is converted to a ten bit integer using a linear relationship (estimated prelaunch) that allows nominal scenes to activate nine of the available ten bits. All VAS instruments during their functioning days have been calibrated every spin as just described.

The conversion from radiance to brightness temperature for the nominal range of observed earth-atmosphere temperatures (200 C to 330 K) is easily performed with accuracy to better than .2% with adjusted Planck functions. Appendix A provides more details.

The nonlinearity correction implicit in Eq (8) and the calibration coefficients C_j from Eq (7) should be adjusted seasonally to accommodate the changing nominal temperature of the VAS telescope. Currently the summer coefficients are used year round. Using the summer values to calibrate the winter data introduces an offset of several tenths of a degree Centigrade (primarily in the longwave infrared window channel).

Diurnal trends in the calibration are tracked very well; measurements of presumed isothermal areas of the ocean remain constant within a few tenths of a degree Centigrade throughout the day. GOES-7 Multi-Spectral Image (MSI) calibration parameters for the IR window (band 8 at 11.2 um) have been investigated for eclipse and non-eclipse days. During a non-eclipse day, the VAS foreoptics temperatures remain steady within a few degrees and the slope is constant within 0.1%, while the intercept is within 0.8%. During an eclipse day, some of the VAS foreoptics experience up to a 10 C temperature excursion and the slope remained constant within 1.5% and the intercept within 2.8%. On an eclipse day, using the 00 UTC slope and intercept values at 09 UTC would have caused a brightness temperature error of approximately 1 C (Schmit and Menzel, 1992b). The line-by-line VAS calibration algorithm compensates very well for changes in the foreoptics temperatures.

The VAS onboard GOES-7 has been used to construct a time series of average radiances (for 9 x 9 field of view areas) near the North Pole for three years beginning in late 1988. This analysis (Schmit and Menzel, 1992a) of mean radiances revealed that the mean summer radiance values nearly repeat from year to year. For example, channel 3 at 14.2 microns shows mean summer radiance peaks of 57.6, 57.1, and 57.7 mW/(m^2-ster-cm^{-1}) for the summers of 1989, 1990 and 1991, respectively. This consistency of the VAS measurements indicate a long-term stability within .3 C.

3. METEOSAT-4 CALIBRATION

Meteosat is a geostationary satellite equipped with a three channel passive radiometer that measures visible reflectances and infrared radiances in spectral bands at 6.4 (water vapor, WV) and 11.5 (infrared window, IRW) microns. Sub-satellite spatial resolution is 2.5 km in the visible and 5.0 km in the infrared. For more information on the Meteosat see ESA, 1987. At the European Space Operations Centre (ESOC), calibration is performed with computed reference radiances performing the role of the blackbody in the VAS calibration. Both the IR and WV channels are operationally calibrated with radiances calculated from radiative transfer models.

For the infrared radiometer channels, the radiance R_{sat} may be associated with a measured count via a linear relationship:

$$R_{sat} = a\,(C - C_z) \qquad (11)$$

where a is the calculated calibration coefficient, C the measured count and C_z the count when viewing space. The calibration coefficient is calculated from the relation

$$a = \frac{R_{ref} - R_z}{C_{ref} - C_z} \qquad (12)$$

where R_{ref} is the radiance calculated from the radiative transfer model, R_z is the radiance from space assumed to be negligible, and C_{ref} and C_z are the corresponding counts detected by the Meteosat-4 radiometer.

The calibration establishes a functional relationship between the measured digital counts and the radiances. The calibration of the thermal infrared channels (IR window at 10.5 - 12.5 um and WV at 5.7 - 7.1 um) must be monitored continuously, since significant short term changes in radiometer response may occur due to aging, contamination, or heating cycles (Jones and Morgan, 1981).

Both the IR and the WV channels are calibrated operationally at ESOC using radiative transfer models and correlative data on temperature and humidity. Although calibration programs are run twice a day, the actual calibration coefficients are changed only when significant changes occur. The calibration data is disseminated to users along with the digital image data.

For the operational calibration of the IR channel at ESOC, measured counts of cloud free scenes over the ocean are associated with calculated radiances at the top of the atmosphere (Gaertner, 1988). The radiances are computed with a radiative transfer code (Schmetz, 1986) from the sea surface temperature analysis from the National Meteorological Centre (NMC) in Washington and forecast profiles of the atmospheric temperature and humidity from the European Centre for Medium range Weather Forecast (ECMWF). The method provides consistent and precise measures of the IR calibration and is well suited for monitoring short term fluctuations. The absolute accuracy of the calibration is sensitive to cloud contamination of clear sky radiances (Gaertner, 1988 and 1989); careful identification of the clear sky scenes allows the operational calibration precision to be on the order of 1% (De Waard et al., 1992). The calibration coefficient, a, which is equivalent to the slope in the VAS calibration algorithm, changes by less than 0.5% between calibration events every twelve hours (about the same stability as found in the VAS slope).

For the water vapor channel, calibration coefficients are obtained from a linear regression of collocations between the satellite measured counts and radiances calculated with a radiative transfer model from conventional radiosonde profiles (Schmetz, 1989). Only radiosondes from clear or low cloud areas are considered for the calibration; the water vapor channel is not sensitive to low level clouds. Calibration coefficients are derived twice per day (1200 and 2400 UT) at ESOC. The WV calibration coefficient is steady to about 2.5% between calibration events; this variation is larger than one would expect from a spinning radiometer and is probably due to the variable quality of the upper tropospheric humidity measurements from radiosondes.

4. METEOSAT-3 CALIBRATION

The IR and WV calibrations for Meteosat-3 at 50 West are obtained twice per day indirectly via cross-calibration with Meteosat-4 at 0 longitude. Thus R_{ref} for Meteosat-3 in Eq (12) is determined from Meteosat-4 calibrated radiance measurements, rather than the model calculation of R_{ref} used for Meteosat-4. An area of 400 x 400 pixels is selected in simultaneous images from both satellites and a mean radiance is computed for Meteosat-4 using the operational calibration. The area for cross-calibration is selected half way between the two satellites. Azimuthal isotropy of the atmospheric water vapor over the selected area is assumed. A correction for the different spectral response functions is performed. The information on calibration is distributed to the user within the header of the disseminated digital image formats. The Meteosat-3 calibration coefficients vary between calibration events by 5.5% for IRW and by 6.3% for WV

5. GEOSTATIONARY SATELLITE COMPARISON RESULTS

Simultaneous collocated radiance measurements from different geostationary satellites were compared to indicate the effectiveness of the calibration procedures. Both infrared window and the water vapor channels were investigated. To mitigate the effects of atmospheric correction, radiance measurements at the equator in areas equally distant from either satellite were selected. Thus, GOES-7 (viewing from 111 W) and Meteosat-3 (viewing from 75 W) radiance measurements over an area centered at 93 W were compared; Meteosat-4 (viewing from 0 W on the Greenwich meridian) and Meteosat-3 radiance measurements over an area centered at 37.5 W were compared. The comparison area is enclosed by 5 degrees latitude and 3 degrees longitude centered on the equator. The radiance measurements were projected into a common satellite view angle to assure similar cloud cover in the area and then averaged. Figure 1 shows the IRW brightness temperature comparisons at three hourly intervals for three days. The GOES-7 minus Meteosat-3 brightness temperature differences range from 2.3 to -1.2 and show considerable change after each Meteosat-3 calibration event (at 8 and 20 UTC). The problem lies in the variation in the Meteosat-3 calibration coefficient from one calibration event to another. The Meteosat-4 minus Meteosat-3 brightness temperature differences show similar behavior during the first four days, suggesting that GOES-7 and Meteosat-4 are in basic agreement; the departure on the last day could be due to extremely cloudy conditions in the calibration area.

6. IMPROVED CALIBRATION FOR METEOSAT-3

After further investigation, the Meteosat-3 calibration procedure was changed in the following way. First, the vicarious Meteosat-3 calibration via Meteosat-4 was adjusted so that the radiance measurements from both satellites were remapped into a geostationary projection at 37.5 W longitude. Inspection of scenes without adjusting for the different satellite view angles often showed different cloud amounts and hence different radiance measurements; without adjustment for the satellite view angles Meteosat-4 could not be used as a reference radiance measurement for Meteosat-3. Second, the calibration coefficient, a, was smoothed to mitigate the effects of abrupt changes. The smoothing algorithm uses the last ten calibration events to determine a gaussian distribution for the coefficients, then the last five coefficients are averaged with that gaussian weighting. More explicitly, the mean coefficient, a_m, and the standard deviation from that mean, σ_m, are calculated from the last ten calibration events. Then the smoothed calibration coefficient, a_s, is calculated from the weighted mean of the last five calibration events; thus

$$a_s = \sum_{j=1}^{5} a_j \, G(a_j, a_m, \sigma_m) \Big/ \sum_{j=1}^{5} G(a_j, a_m, \sigma_m), \qquad (13)$$

where G denotes the Gaussian distribution given by

$$G(a_j, a_m, \sigma_m) = \exp[(a_j - a_m)^2/(2\ \sigma_m^2)]. \qquad (14)$$

This smoothing allows the coefficients to indicate real changes that occur over several days during eclipse, but still maintain adequate smoothing in non-eclipse times.

Figure 2 shows the coefficients for days 169 to 182 in 1993 using the new algorithm (view adjusted radiances and coefficient smoothing over the last five calibration events) in comparison to the original coefficients. The new coefficients vary by 0.3% at the most between calibration events (in contrast to 5.5% for the original algorithm); slow trends are captured but noise is minimized. Some of this remaining variation may be due to the differing scenes (mostly cloudy or mostly clear) that are used in the Meteosat-4 reference measurements; the uncompensated 1% nonlinearity in the Meteosat-3 IRW detector response will bring about larger calibration coefficients for clear (warm) scenes than for cloudy (cold) scenes.

Figure 3 shows the GOES-7 minus Meteosat-3 brightness temperature differences for days 175 through 178 in 1993, using the original and the new calibration procedures. The original procedure shows a range of 2.0 C to -1.2 C (similar to the data of days 146 to 149), while the new procedure reduces the range to 1.5 C to -0.1 C (mean difference is .6 C). The new calibration procedure has halved the disagreement between the GOES-7 and Meteosat-3 sensors.

Some of remaining difference between the GOES-7 and Meteosat-3 brightness temperature values can be ascribed to the different atmospheric absorption caused by the different IRW spectral response functions of the two sensors. Figure 4 shows the differing brightness temperatures that are measured by GOES-7, Meteosat-3, and Meteosat-4 for a tropical standard atmosphere (4 cm column moisture in the atmosphere). For a viewing angle of about 20 degrees, GOES-7 is about .5 C warmer than Meteosat-3, in very good agreement with the .6 C mean difference in the observed brightness temperatures for days 175 through 178.

7. COMPARISON WITH POLAR ORBITING SATELLITES

The geostationary satellites can only be calibrated directly with respect to one another if their earth views have some overlap. However the polar orbiting High resolution Infrared Radiation Sounder (HIRS) offers a fixed reference for all of the geostationary satellites. The nineteen channel HIRS has both an infrared window and a water vapor channel (for more information on the HIRS, see Smith et al., 1979). An example of polar and geostationary radiance comparison is presented here.

The GOES and HIRS data are compared with histograms of brightness temperatures of similar spectral channels from the two sensors for an area near the GOES sub-satellite point (Schmit and Herman, 1992). This method minimizes viewing angle differences and the need for high accuracy navigation. Figure 5 shows the two histograms over the same region on July 1, 1991 for both the GOES-7 VAS and NOAA-11 HIRS IRW brightness temperatures, respectively. Both capture the peaks associated with the low cloud and the clear ocean. Sensor resolution differences account for some of the discrepancies. The mean brightness temperature difference is smaller than 0.5 C. The collocation in time was less than 30 minutes.

Favorable comparisons between Meteosat-3 and NOAA-12 IRW window data have also been found. Mean values were within 1 C. Thus the polar orbiter data are also indicating good consistency of GOES-7 and Meteosat-3 radiances.

8. CONCLUSIONS

As expected, improved performance of the Meteosat-3 calibration is possible when the calibration procedure is adjusted so that intercalibration with Meteosat-4 radiances is done at the same satellite view angle and the calibration coefficients are smoothed over the past five calibration events. This paper shows GOES-7 minus Meteosat-3 brightness temperature differences are 0.6 C on the average when viewing the same area at the equator; scatter about this mean is 0.6 C. Spectral differences in the two infrared windows would account for 0.5 C of this difference. This suggests several recommendations.

* For the operational Meteosat-3 vicarious calibration using Meteosat-4 reference radiances, the satellite data should be navigated to the same satellite view angle (preferably one exactly between the two satellites, eg. 37.5 W for the current positions of Meteosat-3 at 75 W and Meteosat-4 at 0 W).

* The calibration coefficients for both Meteosat-3 and Meteosat-4 should be smoothed to alleviate the effects of scene differences and detector non-linearity; a gaussian distribution from the last ten calibration events has been used to determine a weighted mean of the last five calibration coefficients and has demonstrated greatly improved results.

* The calibration coefficient for both Meteosat-3 and Meteosat-4 should be changed at most once per day (close to 00 UT) so that diurnal changes in the measured brightness temperatures better reflect changes in the earth-atmosphere system.

On August 11, 1993, the ESOC adopted these recommendations and their operational calibration of Meteosat-3 and -4 has been changed accordingly.

APPENDIX A. ADJUSTED PLANCK FUNCTIONS

The Planck function provides a means to determine monochromatic radiance as a function of temperature for a given wavenumber (or wavelength). To accommodate the spectral bandwidth of the satellite sensor measurements, the wavenumber is chosen to be the median value, vm, in the spectral response function, and the temperature, T, in the Planck function is adjusted to

$$tc1 + tc2 * T \qquad \text{(A1)}$$

where tc1 and tc2 are determined in a least squares fit over a temperature range of 200 to 330 K. Thus the function becomes

$$B(v_m,T) = c1 * v_m{**}3 \; / \; [\exp(c2 * v_m \; / \; (tc1 + tc2 * T)) - 1] \qquad \text{(A2)}$$

where c1 = 1.191066 E-5 mW/m2/ster/cm-4 and c2 = 1.43883 deg C / cm-1. The following Table indicates the values for GOES-7, Meteosat-3, Meteosat-4, and Meteosat-5 IRW and WV channels.

Table: Coefficients for Adjusted Planck function calculation of temperature and radiance for infrared window and water vapor channels. GOES-7 is indicated by G-7 and Meteosat-3/4/5 is indicated by M-3/4/5.

Channel	v_m	tc1	tc2
G-7 IRW	894.5	0.3408	.9973
G-7 WV	1488.0	0.6448	.9977
M-3 IRW	876.0	0.9065	.9967
M-3 WV	1549.2	4.3185	.9903
M-4 IRW	882.4	0.8275	.9870
M-4 WV	1601.1	3.2265	.9927
M-5 IRW	883.0	0.9613	.9966
M-5 WV	1612.2	3.5381	.9920

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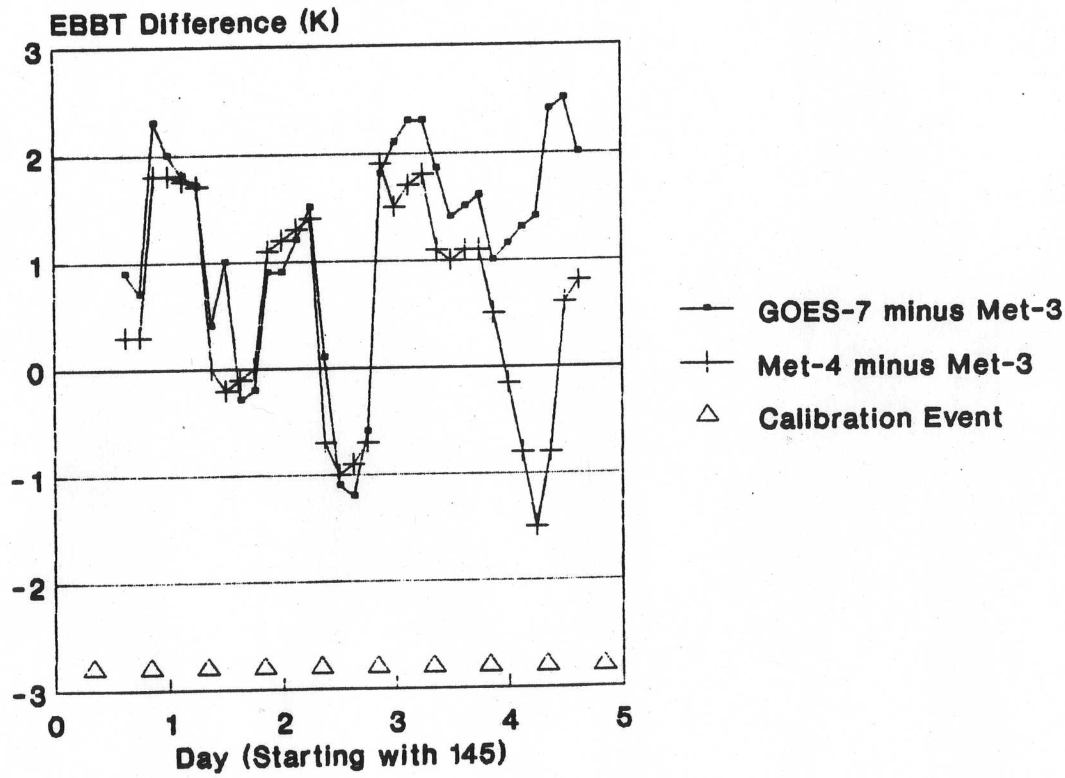


Figure 1. Infrared window brightness temperature (EBBT) differences in the measured GOES-7 minus Meteosat-3 radiances as well as the Meteosat-4 minus Meteosat-3 radiances for days 145 to 149 in 1993 at three hour intervals. The 12 hourly Meteosat-3 calibration events are indicated at the bottom. Calibration is performed using the original algorithm.

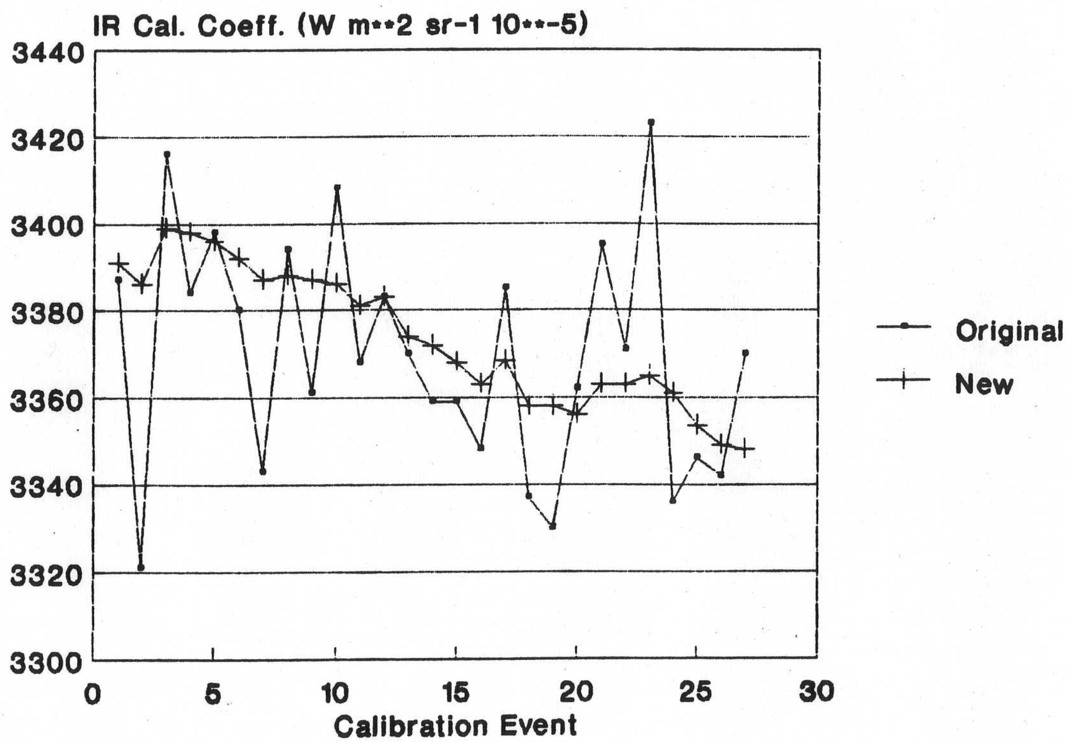


Figure 2. Meteosat-3 calibration coefficients evaluated twice daily for days 169 to 182 in 1993. Results from the original algorithm and the new algorithm are shown.

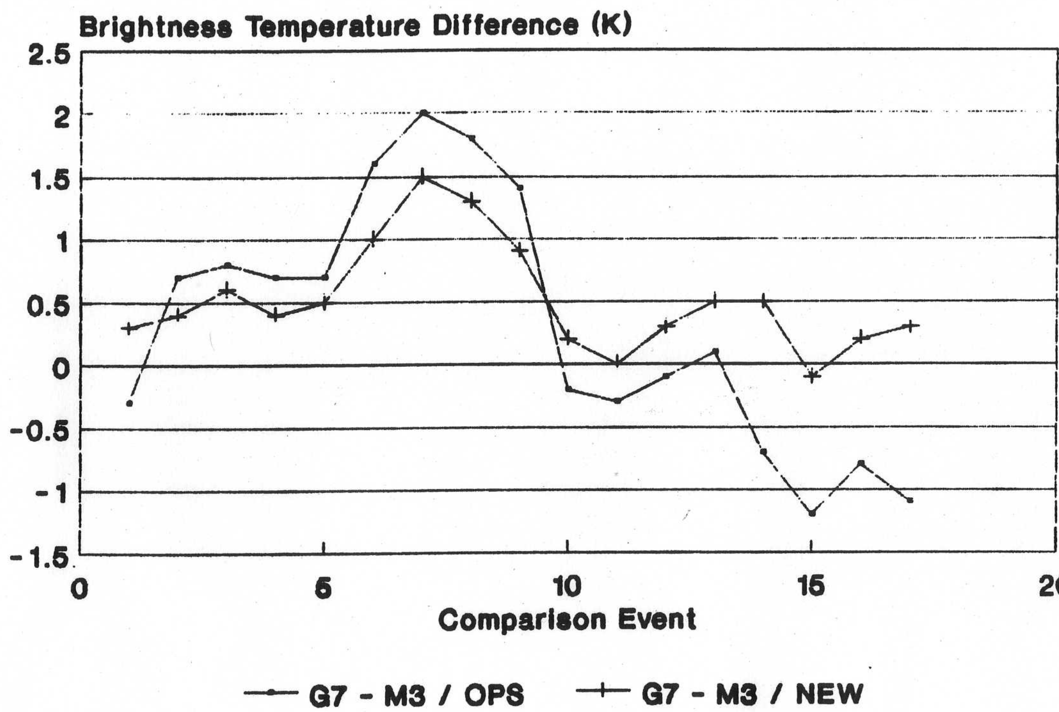


Figure 3. Brightness temperature differences in the measured GOES-7 minus Meteosat-3 infrared window radiances using the original and the new calibration algorithms for days 175 to 178 in 1993. The comparisons occured at three hour intervals.

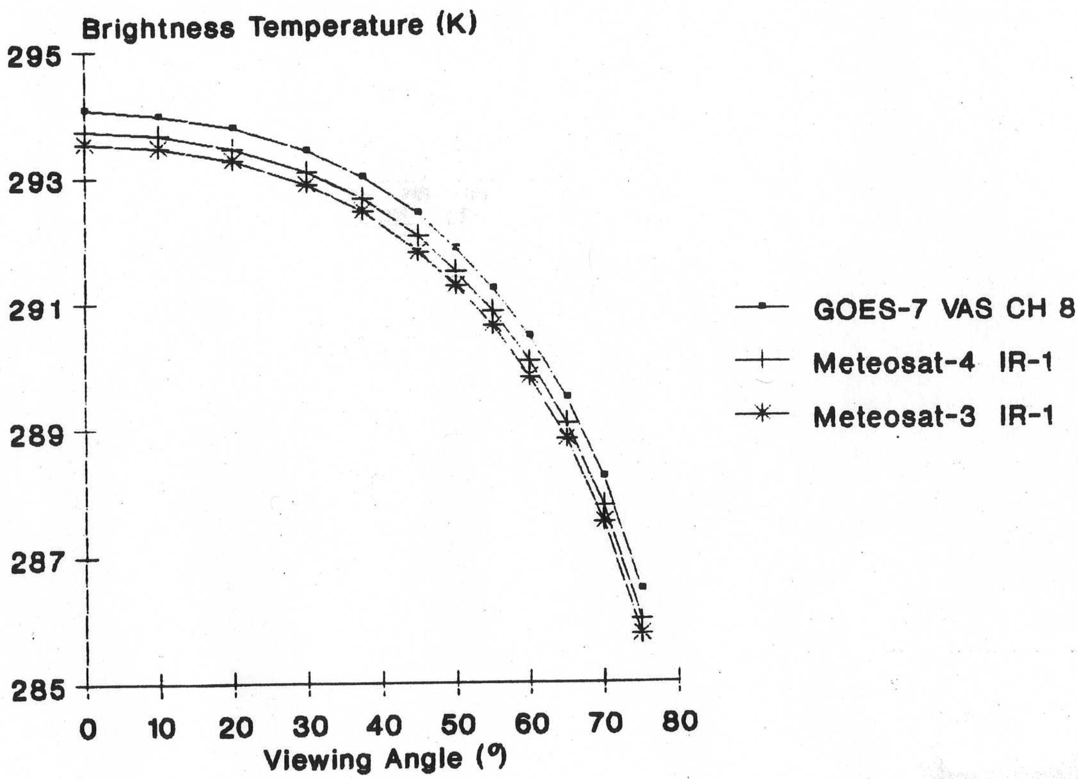
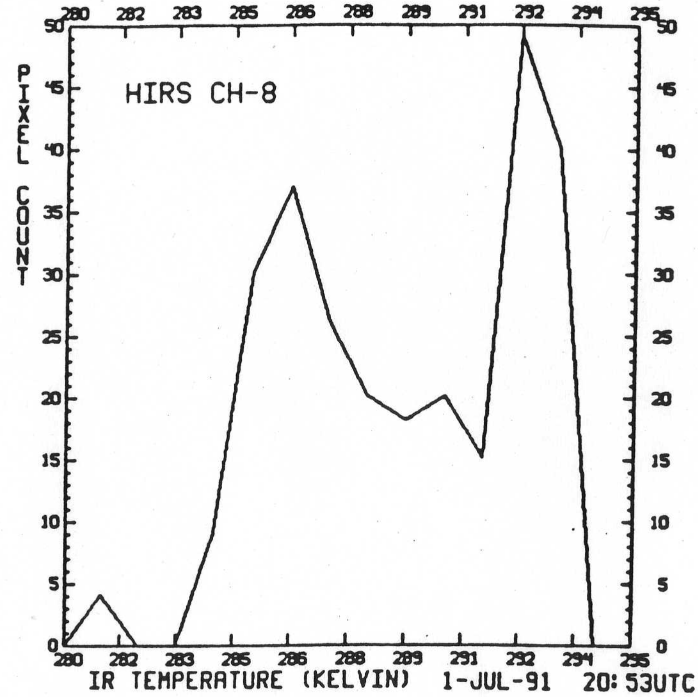


Figure 4. Brightness temperatures measured by GOES-7, Meteosat-3, and Meteosat-4 for a tropical standard atmosphere as a function of satellite viewing angle. Differences are due to the different spectral response functions of the sensors.



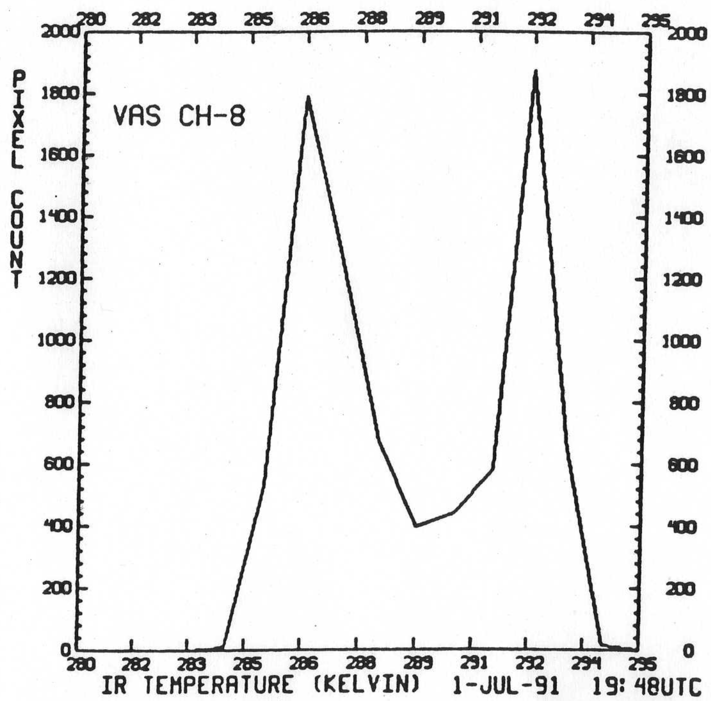


Figure 5. Histograms over the same region for both the GOES-7 VAS and NOAA-11 HIRS IRW brightness temperatures.

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