4. RADIANCE CALIBRATION

Integer count values (CT = 0 - 255) on ISCCP radiance data tapes represent the original radiances, L (watts m^{-2} sr^{-1}), measured by the operational weather satellite imaging radiometers and supplied to the GPC by the SPCs. These radiometers are "narrowband", making measurements in limited ranges of the solar and thermal infrared spectra. The radiances generally depend on location, time and viewing geometry. The radiance calibrations discussed in this section represent the energy **"actually"** measured by the instrument; that is, the effect of the instrument spectral response is **not** removed. In the short wavelength (solar) region of the spectrum, radiance can also be expressed as a (bidirectional) reflectance, R, by dividing L by the effective solar spectral irradiance (E_o) of the radiometers times a factor to correct for the annual variation of the sun-Earth distance, ε, and times the cosine of the solar zenith angle measured at the target: $R = \pi L/\mu_o \varepsilon E_o$. **Scaled radiance** is defined as $L^* = \pi L/E_o = \mu_o \varepsilon R$. Scaled radiance represents the fraction of energy measured by the radiometer assuming that the signal spectrum is the solar spectrum and that the illumination is the annual mean value. High count values correspond to high radiances. In the infrared region of the spectrum, L can be expressed as a brightness temperature, TB, the temperature of a perfect black-body radiating the same amount of energy as measured by the radiometer. High count values correspond to low radiance or brightness temperature. L^* and TB are more convenient quantities because they are more directly comparable when measured by radiometers with slightly different spectral responses. The type of information available to convert the count values to radiances (or their alternates) varies from pre-launch calibration to active on-board calibration. Section 4.1 describes the best available information for each radiometer used by ISCCP and gives the procedure used to convert counts to physical units. These procedures reflect the **nominal** calibration of the radiometers.

A second calibration for each radiometer, the **normalized** calibration, is provided based on a comparison of all geostationary satellite radiometers to the AVHRR flown on the NOAA polar orbiting satellites. Normalization is performed once every three months by comparison of coincident observations; the procedure is briefly described in Section 4.2. and thoroughly documented in Desormeaux et al. (1993).

Obtaining an **absolute** calibration of all the radiometers requires post-launch observations for the solar channels; the infrared channels are well calibrated by on-board sources. Section 4.3 briefly discusses the technique for monitoring the calibrations of the AVHRR and for transferring the calibration standard from one AVHRR to the next. This procedure and its revision are documented more completely in Brest and Rossow (1992) and Brest et al. (1996). Section 4.4 presents a discussion of some additional adjustments to the calibration and the calibration uncertainties. Complete calibration results are reported in WCRP-27 (Rossow et al. 1992) and WMO/TD-No. 736 (Rossow et al. 1996).

4.1. NOMINAL CALIBRATIONS

4.1.1. NOAA POLAR ORBITER (AVHRR)

Data have been obtained from NOAA-7, NOAA-8, NOAA-9, NOAA-10, NOAA-11, NOAA-12 and NOAA-14. All of these satellites except NOAA-8 and NOAA-10 carry a five-channel AVHRR; NOAA-8 and NOAA-10 carry a four-channel AVHRR. Tables 3.2 and 4.1 show the instrument characteristics (Lauritson et al. 1979; Kidwell 1995). The normalized spectral responses of the channels are given in Section 7.2.

Table 4.1. Characteristics of AVHRR

	Bandwidth (μm)			
Channel #	Tiros-N	NOAA-6, 8, 10	NOAA-7, 9, 11, 12, 14	IFOV (mrad)
1	0.55 - 0.90	0.58 - 0.68	0.58 - 0.68	1.39
2	0.725 - 1.10	0.725 - 1.10	0.725 - 1.10	1.41
3	3.55 - 3.93	3.55 - 3.93	3.55 - 3.93	1.51
4	10.5 - 11.5	10.5 - 11.5	10.5 - 11.3	1.41
5	(Ch. 4 repeated)	(Ch. 4 repeated)	11.5 - 2.50	1.41

(1) SOLAR CHANNELS

Pre-launch calibration of the solar channels (Ch. 1 and 2) was performed with a standard calibration lamp viewed through an aperture in an integrating sphere; the calibration lamp is a standard traceable to NBS standards (Lauritson et al. 1979). The spectral output for the source lamp is known, allowing for correction of the calibration to the solar spectrum.

The pre-launch calibration establishes a relation between count values (representing instrument output voltage) and <u>percent</u> scaled radiance for each channel:

$$L^*_i = G_i\ (CT) + Y_i \qquad (4.1)$$

where CT = 0 - 255 and i is the channel number. The coefficients in (4.1) are shown in Table 4.2. Uncertainties are estimated to be about 5-10%.

To obtain radiances the effective solar spectral irradiance for each channel is calculated by integrating over the product of the spectral response functions in Section 7.2 and the annual mean solar irradiance spectrum, Table 7.1.1 (Neckel and Labs 1984). Thus

$$L_i = (E_{oi}/\pi)\, L^*_i / 100 \text{ watts } m^{-2}\, sr^{-1} \qquad (4.2)$$

where values of E_{oi}/π are given in Table 4.2.

Table 4.2. Nominal calibration constants for solar channels on NOAA satellites. See equations (4.1) and (4.2).

Satellite	G_1	Y_1(%)	E_{o1}/π (watts m^{-2} sr^{-1})	G_2	Y_2	E_{o2}/π (watts m^{-2} sr^{-1})
NOAA-7	0.4272	-3.440	56.66	0.4276	-3.488	81.81
NOAA-8	0.4242	-4.162	56.70	0.4240	-4.149	76.96
NOAA-9	0.4254	-3.846	60.91	0.4300	-3.877	79.87
NOAA-10	0.4283*	-4.114*	56.89	0.4231	-3.454	73.20
NOAA-11	0.3624*	-3.730*	58.02	0.3308	-3.390	76.38
NOAA-12	0.4080	-4.130	63.43	0.4120	-4.210	83.13
NOAA-14	0.4460	-4.572	64.42	0.5348	-5.482	79.97

* On 26 May 1989, NOAA changed the channel 1 nominal calibration coefficients for NOAA-10 to G_1 = 0.4235, Y_1 = -3.528 and G_2 = 0.4243, Y_2 = -3.477. On 27 September 1992, NOAA changed the nominal calibration coefficients for NOAA-11 to G_1 = 0.3800, Y_1 = -3.780 and G_2 = 0.3600, Y_2 = -3.600.

(2) INFRARED CHANNELS

Calibration of the infrared channels is done actively on the spacecraft, once per scan, by having the radiometer view space and a standard black-body with a known temperature. Pre-launch measurements of a precision calibration black-body with the radiometer are used to relate the output counts from four thermistors to the temperature of the reference black-body with a fourth order polynomial. This temperature is converted to a radiance by integrating the product of the Planck function and the spectral response functions shown in Section 7.2. NOAA documentation provides calibration in terms of radiance per unit wavelength, J, i.e., L = JB, where B is the radiometer bandwidth. From the spectral response functions in Section 7.2, bandwidths are calculated; results are shown in Table 4.3.

Table 4.3. Nominal calibration constants for infrared channels on NOAA satellites.

Satellite	BW_3 (cm^{-1})	J_{sp}^3 (counts)	BW_4 (cm^{-1})	J_{sp}^4 (counts)	BW_5 (cm^{-1})	J_{sp}^5 (counts)
NOAA-7	287.0	0.0	73.06	-1.176	61.29	-1.346
NOAA-8	262.9	0.0	69.64	-2.784	– – –	– – –
NOAA-9	289.0	0.0	73.96	-3.384	62.18	-2.313
NOAA-10*	272.0	0.0	64.30	0.0	– – –	– – –
NOAA-11	279.0	0.0	77.90	0.0	65.21	0.0
NOAA-12	270.4	0.0	81.10	0.0	64.30	0.0
NOAA-14	285.0	0.0	86.98	0.0	66.31	0.0

*Incorrect bandwidths were used for the nominal calibration of NOAA-10 data from December 1986 through December 1988: B_3 = 277.0 cm^{-1} and B_4 = 66.14 cm^{-1}. This error was corrected by the normalization coefficients. In the new version of the BT dataset, this error does not exist.

The radiometer counts for measurements of space, CT_{sp}, and the on-board black-body, CT_{bb}, are used to calibrate the radiometer by calculating a gain, G_i, and intercept, Y_i:

$$G_i = (J^i_{sp} - J^i_{bb})(CT^i_{sp} - CT^i_{bb})^{-1} \tag{4.3}$$

$$Y_i = J^i_{sp} - G(CT^i_{sp}) \tag{4.4}$$

J_{bb}^i is the reference black-body radiance calculated from its measured temperature and J_{sp} is the radiance of space, adjusted to account for slight non-linearity in the radiometer response. In October 1987, NOAA discontinued use of negative values of J_{sp}^i to correct for the non-linearity of the IR channels; however, the replacement scheme requires use of tables of values not made widely available. An alternative scheme for the calibration of the infrared channels provides better correction for the non-linear responses (Brown et al. 1985; Brown et al. 1993) but requires knowledge of the history of the target temperature (see Rao et al. 1993). Thus, the nominal calibration (using the formulation discussed here) appears to change; however, the normalization to NOAA-9 corrects for this effect.

Table 4.4. Sample values of G_i and Y_i in mwatts m^{-2} sr^{-1} cm.

Satellite	G_3	G_4	G_5	Y_3	Y_4	Y_5
NOAA-7	-0.00617	-0.62141	-0.72617	1.53945	152.93695	178.54785
NOAA-8	-0.00640	-0.65270	——	1.59280	159.2977	——
NOAA-9	-0.00580	-0.66520	-0.78488	1.44247	164.30469	194.97711
NOAA-10	-0.00589	-0.59292	——	1.46467	147.34045	——
NOAA-11	-0.00588	-0.67650	-0.69958	1.45564	167.94104	174.24371
NOAA-12	-0.00625	-0.62144	-0.69932	1.55300	154.54205	174.65582
NOAA-14	-0.00652	-0.65339	-0.72464	1.61714	158.0340	176.9135

Radiance measurements can be converted to brightness temperatures by inverting the relation

$$L_i = \int B(\nu, T)\ \phi_i(\nu)\ d\nu \tag{4.5}$$

where B(v,T) is the Plank function of temperature and frequency, v(cm^{-1}), and φ_i(v) is the normalized spectral response of the radiometer. The conversion table used for ISCCP to convert L_4 into TB_4 is described in Section 7.2. An approximate relation, equivalent to the above for three temperature ranges, is given by Kidwell (1991):

$$TB(J_i) = C_2\bar{\nu}_i\{\ln[1 + C_1\bar{\nu}_i^3 (J_i)^{-1}]\}^{-1} \tag{4.6}$$

where $C_1 = 1.1910659 \times 10^{-5}$ mwatts m^{-2} sr^{-1} cm^4 $C_2 = 1.438833$ cm K, and $\bar{\nu}_i$ represents an effective frequency of the radiometer for a specific temperature range. These values are given in Table 4.5 (in cm^{-1}).

For ISCCP Stage B3 data, the calibration coefficients (G_i and Y_i) for the first scan line in an orbit swath are used for all scan lines in that orbit. Since the calibration actually changes somewhat during the orbit (due to varying thermal environment), the count values are altered so that constant coefficients reproduce the original data. For channels 4 and 5, the change in calibration is no more than 2-3%, occurring primarily when the satellite passes from the night to day side of the Earth. Consequently only the lowest count values actually change. Channel 3 data occasionally exhibit more noise, reflected in rapidly changing calibration coefficients.

Table 4.5. Effective frequency for infrared channels viewing targets with temperatures in three ranges.

		T = 180 - 225K	T = 225 - 275K	T = 275 - 320K
NOAA-7	$\bar{\nu}_3$ =	2668.70	2670.30	2671.90
	$\bar{\nu}_4$ =	926.20	926.80	927.22
	$\bar{\nu}_5$ =	840.10	840.50	840.87
NOAA-8	$\bar{\nu}_3$ =	2631.52	2636.05	2639.18
	$\bar{\nu}_4$ =	913.360	913.865	913.305
NOAA-9	$\bar{\nu}_3$ =	2670.93	2674.81	2678.11
	$\bar{\nu}_4$ =	928.50	929.02	929.46
	$\bar{\nu}_5$ =	844.41	844.80	845.19
NOAA-10	$\bar{\nu}_3$ =	2658.53	2657.60	2660.76
	$\bar{\nu}_4$ =	908.73	909.18	909.58
NOAA-11	$\bar{\nu}_3$ =	2663.50	2668.15	2671.40
	$\bar{\nu}_4$ =	926.80	927.34	927.80
	$\bar{\nu}_5$ =	837.75	838.08	838.40
NOAA-12*	$\bar{\nu}_3$ =	2632.71	2636.67	2639.61
	$\bar{\nu}_4$ =	920.02	920.55	921.03
	$\bar{\nu}_5$ =	836.68	837.03	837.36
NOAA-14*	$\bar{\nu}_3$ =	2638.652	2642.807	2645.899
	$\bar{\nu}_4$ =	958.2603	928.8284	929.3323
	$\bar{\nu}_5$ =	834.4496	834.8066	835.1647

* The effective frequencies for NOAA-12 are defined for slightly different temperature ranges than for the other satellites: 190-230K, 230-270K, and 270-310K, respectively.

4.1.2. METEOSAT

The imaging radiometers on METEOSAT-2, METEOSAT-3, METEOSAT-4 and METEOSAT-5 have three channels with nominal center wavelengths of 0.75 µm, 6.5 µm and 11.7 µm (Morgan 1978). ISCCP calibration information is obtained only for the first and third channels. Radiometer spectral responses are illustrated in Section 7.3. Instrument characteristics are shown in Table 3.2.

(1) SOLAR CHANNEL

Pre-launch calibration tests were performed to define the spectral response of the solar channel and to relate voltage output from the instrument to a known radiance (Hollier 1977). For a given gain setting, i, the sensitivity, $S_{i\lambda}$, is defined by

$$S_{i\lambda} = V_{i\lambda} L_{\lambda}^{-1} \tag{4.7}$$

where the instrument voltage, $V_{i\lambda}$, when illuminated by radiance L_λ, is

$$V_{i\lambda} = K_s (1.2)^i \ \tau_\lambda r_\lambda L_\lambda \qquad (4.8)$$

K_s is the combined sensitivity of the optics and electronics when the gain i = 0, τ_λ is the optics transmittance and r_λ is the detector sensitivity. Thus the total spectral response is given by

$$S_{i\lambda} = K_s (1.2)^i \ \tau_\lambda r_\lambda \qquad (4.9)$$

Pre-launch measurements were made with a monochromatic source, λ = 0.65 µm and L_λ = 31.6 watts m^{-2} sr^{-1}. Using a gain setting of 3, K_s is found to be 0.0280 volts $watts^{-1}$ m^2 sr. The value of $S_{i\lambda}$, normalized by its maximum value, is shown in Section 7.3. The uncertainty of these measurements is estimated to be about 10%. Integration of $S_{i\lambda}$ times the solar irradiance gives the voltage output of the instrument corresponding to its effective solar spectral irradiance. Voltage readings from the spacecraft are related to (8-bit) counts by

$$1\,CT = 0.085\ volts \qquad (4.11)$$

Post-launch comparisons of the METEOSAT-2 solar channel output with aircraft measurements by a precision radiometer gave the following results by K.T. Kriebel:

Table 4.6. Calibration factors for METEOSAT-2 in watts m^{-2} sr^{-1} $count^{-1}$. Counts are 8-bit integers.

Surface Type /	Date of Observation	Calibration Factor
La Mancha /	3 Nov. 1981	1.07
Desert (Tunisia) /	12 Nov. 1981	0.97
Cloud (Altostratus) /	20 Nov. 1981	1.13
Ocean /	3-20 Nov. 1981	1.6 - 2.0

The calibration factors obtained by Kriebel vary because of the difference in the spectral responses of the METEOSAT and aircraft radiometers and their interaction with the differing radiation spectra reflected from different scenes.

Koepke (1982) combined measurements of atmospheric and surface optical properties with radiative transfer calculations to obtain the effective radiances measured by the METEOSAT-1 radiometer. Effective radiances represent the energy actually sensed by the instrument by weighting the signal spectrum by the instrument response function. On the other hand, the calibration values obtained by Kriebel represent calibrations which attempt to remove the effects of the varying instrument spectral sensitivity; however, these calibration coefficients depend on the spectrum of the signal. Our calibration to effective radiances assumes a constant signal spectrum, namely, the solar spectrum at the top of the atmosphere. We adopt Koepke's result for METEOSAT-1 (which compares reasonably with Kriebel's results for specific scenes), but scale to METEOSAT-2 using the ratio of sensitivities suggested by Kriebel, namely 0.87. Note that this ratio is scene independent. Therefore, the ISCCP nominal calibration relation used for METEOSAT-2, 3, 4 and 5 is

$$L^* = (3.641\ 10^{-3})\ (CT - 2) \qquad (4.11)$$

Where CT is an 8-bit count value. The radiance, L, is obtained by multiplying by the effective solar irradiance, Eo/π = 159.28 watts m^{-2} sr^{-1} for METEOSAT-2, 197.32 watts m^{-2} sr^{-1} for METEOSAT-3, and 201.80 watts m^{-2} sr^{-1} for METEOSAT-4, and 197.71 watts m^{-2} sr^{-1} for METEOSAT-5.

(2) INFRARED CHANNELS

Pre-launch calibration of both the IR channel (11.7 μm) and the WV (water vapor) channel (6.5 μm) established a linear relation between output voltage (represented by counts) and radiance (Hollier 1977). The spectral response, defined as for the solar channel, was also measured:

$$S_{i\lambda} = K_T (1.2)^i \; \tau_\lambda r_\lambda \tag{4.12}$$

where $K_T = K_{IR}$ or K_{WV} depending on the channel. The normalized values of $S_{i\lambda}$ are given in Sectio 7.3 for both channels. K_T is obtained from pre-launch measurements of a calibrated black-body at a standard reference temperature of 290K for the IR channel and 260K for the WV channel:

$$K_T = V_{T,i,\Theta} [(1.2)^i \int \tau_\lambda r_\lambda B(\lambda,\Theta) \, d\lambda]^{-1} \tag{4.13}$$

where Θ is the temperature of the black-body, B(λ,Θ) is the Planck function and $V_{T,i,\Theta}$ is the output voltage at gain i. For the IR channel, $V_{T,8,290}$ = 3.09 volts for a detector temperature of 85K and 1.65 volts for a detector temperature of 110K. This gives K_{IR} = 0.11 volts watts^{-1} m^2 sr at 90K. For the WV channel, $V_{T,5,260}$ = 3.35 volts for a detector temperature of 85K and 2.82 volts for a detector temperature of 110K. This gives K_{WV} = 0.91 volts watts^{-1} m^2 sr at 90K. Section 7.3 shows the calculated spectral response for these two channels with the detector temperature maintained at 90K.

Post-launch calibration is monitored in two ways because the on-board calibration procedure does not provide an absolute calibration. The IR channel views the on-board black-body standard by means of a mirror introduced into the optical pathway in the instrument. Consequently, the calibration source is not viewed through the main optics as is the Earth and the Earth view does not involve the mirror used to view the calibration source. The WV channel does not view the calibration source at all.

The IR channel calibration is obtained twice daily by viewing space and the Earth's ocean in cloud free areas. Conventional sea surface temperature measurements by ships, together with a radiative transfer model calculation of atmospheric attenuation, are compared to these IR channel measurements to obtain the second calibration point (a space view provides the first point). Instrument output voltage is converted to count values by a factor 170 $(1.2)^{-i}$counts volt^{-1}, where i is the gain. The two calibration points give a gain, G_{IR}; and an intercept, Y_{IR}. Sample values reported are G_{IR} = 0.046 watts m^{-2} sr^{-1} count^{-1} and Y_{IR} = 5.0 counts. These calibration values are not changed unless the mean bias between the METEOSAT observations and the conventional ship measurements of sea surface temperature exceeds ± 0.5K. However, because the radiative transfer model used in this procedure assumes a sea surface emissivity of unity, instead of the correct value of ≈ 0.98, this procedure biases METEOSAT brightness temperatures by about + 2.5K (Koepke 1980).

The diurnal heating/cooling cycle that the satellite undergoes in orbit introduces shorter term variations in instrument response. In particular, the detector spectral sensitivity varies strongly with temperature. This effect is removed by thermostatic control of the detector temperature to 90K and twice daily observations of the on-board black-body calibration source. The on-board calibration procedure is used to determine a fine adjustment of gain factor, f_{IR}, by

$$f_{IR} = \frac{110}{CT_N} \tag{4.14}$$

where CT_N is the normalized count value measured when the instrument views the on-board black-body which is assumed to be at a temperature of 290K. A typical reported value of f_{IR} is 0.94.

Telemetry count values are converted to radiance units by

$$L_{IR} = f_{IR} \, G_{IR} \, (CT - Y_{IR}) \text{ watts m}^{-2} \text{ sr}^{-1}. \tag{4.15}$$

The spectral response function of the IR channel, together with the Planck function of temperature, is used to calculate radiances measured by this channel when observing a black-body with various temperatures. A table of such values, provided by ESA, is used to convert radiance values to brightness temperatures. To make METEOSAT IR data consistent with all other satellites, the count values in Stage B3 data have been changed to (255-CT), so that high count values represent low radiance or brightness temperature.

The WV channel calibration is performed by comparing simultaneous measurements of high clouds (usually large cumulonimbus towers) by the WV and IR channels. Using the IR channel calibration information and the spectral response functions for the two channels, the radiance measured by the WV channel is calculated from the Planck function. This observation fixes the upper point of the calibration while the lower point is determined from a space view. The gain, G_{WV}, and the intercept, Y_{WV}, are then used to obtain a measure of upper tropospheric humidity from WV channel observations. The humidity is compared to the (arithmetic) mean humidity measured at all standard pressure levels between 700 and 300 mb by co-located radiosonde data. Eliminating any bias between the WV channel and radiosonde humidity provides the calibration of the WV channel. Sample reported values are $G_{WV} = 0.00865$ watts m^{-2} sr^{-1} $count^{-1}$ and $Y_{WV} = 6.0$ counts. No fine adjustment of gain is made for the WV channel.

$$L_{WV} = G_{WV}\,(CT - Y_{WV}) \text{ watts m}^{-2}\text{ sr}^{-1} \tag{4.16}$$

Telemetry count values are converted to radiance units by
The spectral response function of WV channel, together with the Planck function of temperature, is used to calculate radiances measured by this channel when observing a black-body with various temperatures. Count values are recorded as (255-CT).

4.1.3. GOES (VISSR)

The VISSR Atmospheric Sounder (VAS) instrument includes the two-channel imaging radiometer (Visible and Infrared Spin-Scan Radiometer) with nominal center wavelengths of 0.68 µm and 11.6 µm. The spectral responses for GOES-5 (EAST), GOES-6 (WEST), GOES-7 (EAST then WEST) are shown in Section 7.4. The solar channel of the VISSR is actually composed of eight separate detectors sweeping across the Earth in parallel. The infrared part of the instrument makes measurements in twelve spectral bands, with band 8 serving as the standard imaging channel.

The imaging instrument on GOES-8 (EAST) and GOES-9 (WEST), the first in a new series of GOES satellites, has five channels with nominal center wavelengths of 0.65, 3.9, 6.75, 10.7 and 12.0 µm (see Section 7.4). The visible channel is composed eight separate detectors that scan across Earth in parallel. The IR channels are composed of pairs of detectors that scan across Earth in parallel, except for the 6.75 µm channel which has only one detector.

(1) SOLAR CHANNEL

No pre-launch information is available for this channel. Since the VISSRs on GOES-4, 5, 6 and subsequent spacecraft are different instruments from previous VISSRs on SMS-1, 2 and GOES-1, 2, 3, none of the previous pre-launch and post-launch calibration information for GOES (Smith and Loranger 1977; Smith and Vonder Haar 1980; Norton et al. 1980; Smith et al. 1981; Muench 1981) is applicable. A calibration of the solar channel on GOES-6 has been provided by C. Gautier (Frouin and Gautier 1987). Observations of White Sands, New Mexico, which is assumed to have an albedo of 0.69 at 0.565 µm, and of space ($CT_{sp} = 27$) are combined with radiative transfer calculations of atmospheric effects to obtain the following relationship:

$$E = (0.0066818 \pm 0.00043)\,(CT)^2 - 5 \text{ watts m}^{-2} \tag{4.16}$$

where CT = 0-255. This result uses a spectral response function which is an average over the eight channel spectral response functions, giving an effective solar spectral irradiance of 315.83 watts m^{-2}. Subsequent analyses (Frouin and Gautier 1987) adopted a different calibration value; however, normalization of the GOES radiances to the NOAA values eliminates the dependence on this choice of nominal calibration as confirmed in a study by Whitlock et al. (1990) (see also Desormeaux et al. 1993).

Data from the eight separate solar channels are processed to normalize the output from all the channels to a single reference channel. This reference channel is selected as having a maximum dynamic range with little saturation. Observations of large homogeneous targets are used to construct tables relating each channel response to the response of the reference channel. The reference channel for GOES-5 is channel 8, for GOES-6 is channel 2, for GOES-7 is channel 8, for GOES-8 is channel 2 (GVAR numbering convention), and for GOES-9 is channel 3. In ISCCP radiance datasets the output of the eight detectors is averaged to produce a single, lower resolution radiance measurement, which is treated as equivalent to measurements by the reference channel.

The conversion of telemetry count values to radiances makes use of the designed linearity of the instrument with measured radiance, the counts measured for a space view, and the calculated effective solar spectral irradiance based on the spectral responses shown in Section 7.4. Since the solar irradiance tables used here differ slightly from those used by Gautier, we rescale and adopt the following relation between radiance and counts for GOES-6:

$$L = (0.0020)\,(CT)^2 - 1.5 \text{ watts m}^{-2}\text{ sr}^{-1} \qquad (4.18)$$

where CT is an 8-bit count. The scaled radiance is obtained using the solar spectral irradiance for GOES-6 of $E_o/\pi = 94.29$ watts m^{-2} sr^{-1}.

No equivalent calibration information is available for the solar channel on GOES-5. Comparison of one week of observations at the meridian halfway between GOES-5 and GOES-6 (namely 105°W) shows a ratio of solar channel counts = 0.965 and a bias of -10 counts. The space count value for GOES-6 is 27, while the space count value for GOES-5 is 26. Since the ratio is similar to that given by the slightly different spectral responses, the adopted nominal calibration for GOES-5 is that used for GOES-6 adjusted by the difference in solar spectral radiances of the two instruments. Radiance is obtained using the following expression:

$$L = (0.0019)\,(CT)^2 - 1.5 \text{ watts m}^{-2}\text{ sr}^{-1} \qquad (4.19)$$

and scaled radiance is obtained using a solar spectral irradiance for GOES-5, $E_o/\pi = 92.15$ watts m^{-2} sr^{-1}.

Equation (4.18) is also used for GOES-7 with a solar spectral irradiance of $E_o/\pi = 107.8$ watts m^{-2} sr^{-1}.

A processing error occurred in the Stage B3 data for GOES-5 and GOES-6 from July 1983 through May 1984 that is equivalent to adding 0.5 watts m^{-2} sr^{-1} to all nominal VIS radiances or about 0.5% to scaled radiances. Since this "change" is well within the uncertainty of the calibration, no correction was made. This error was eliminated in the new version of the calibration (BT dataset).

For GOES-8 and GOES-9, a pre-launch calibration determines coefficients to convert the count values for each visible channel detector to radiances using a second order equation

$$L_i^* = A\,(b_i + g_{1i}\,CT + g_{2i}\,CT^2) \qquad (4.20)$$

where b_i is the bias correction for each channel, g_{1i} and g_{2i} are the first-order and second-order gains for each channel, and A is a single coefficient used to convert radiances, L, to scaled radiance. These coefficients are not changed after launch (Table 4.7), but count values from each channel are normalized occasionally to a reference channel (Weinreb 1989). In the ISCCP B3 data visible radiance counts are reported as 8-bit count values instead of the original 10-bit counts.

Table 4.7. Visible channel pre-launch calibration coefficients for GOES-NEXT. Gain values have changed for use with 8-bit counts. The solar "constants" are given in watts m^{-2} sr^{-1}.

Satellite	Ref. Channel No.	b_{ref}	g_{1ref}	g_{2ref}	A	E_o/π
GOES-8	2	-15.389000	2.200748	0.0	0.00192979	101.18
GOES-9	3	-16.232590	2.196944	0.0	0.00194180	105.62

(2) INFRARED CHANNEL

Calibration of the IR channel is performed once per week using an on-board black-body source which is viewed directly by the detector (Menzel 1980, 1981, 1983; Menzel et al. 1981). However, the detector views Earth through telescope optics with a transmittance, τ, and an emittance, ε_{space}; thus, the on-board source measurements must be corrected to represent a black-body viewed through the telescope. Pre-launch measurements are used to model the relation between the radiance observed from the on-board source and an external source in terms of the temperatures of various components of the instrument measured by thermistors. The radiance measured by the instrument, which is assumed to be linear in response, is given by

$$E = \frac{V - V_{sp}}{V_{bb} - V_{sp}} \{ E_{bb} + \Sigma c_i (E_{bb} - E_i) \} \qquad (4.21)$$

where V, V_{bb} and V_{sp} are the instrument voltages obtained when viewing an external target, the on-board black-body and space, respectively, and E_{bb} and E_i are the black-body irradiances of the on-board source and eight other instrument components, at temperatures T_b and T_i. The c_i coefficients are obtained from the pre-launch calibration measurements (see Menzel 1981, 1983).

The results of the on-board calibration sequence, expressed in terms of the measured temperatures, T_b and T_i, and voltages, V_{bb} and V_{sp}, are used to calculate tables relating telemetry count values to black-body temperatures. The black-body temperatures are related to the radiances obtained from Eq. (4.21) by integrating the Planck function times the spectral response function. Application of the calibration tables produces count values transmitted to users that are related to black-body temperatures by a constant relationship:

$$\begin{aligned} TB &= 330 - CT/2 \quad \text{for} \quad 0 \le CT < 176 \\ TB &= 418 - CT \quad \text{for} \quad 176 \le CT < 255 \end{aligned} \qquad (4.22)$$

This conversion of count values is valid through March 1987. A table relating brightness temperatures to radiances can be used to obtain radiances.

In April 1987 NOAA changed the telemetry format for GOES data which increased the number of bits used to record VIS radiances from six to eight and IR radiances from eight to ten. In the ISCCP data processing, the extra IR radiance resolution was exploited to produce an eight bit representation with count values nearly linear in radiance rather than linear in brightness temperature. This change made GOES IR data more like data from all other satellites. Table 4.8 gives the brightness temperature values for all counts after and before the change; the change was made in April 1987 for GOES-6 and January 1989 for GOES-7. Since all calibration adjustments are applied to brightness temperatures, users of GOES data in its original format can use the following information to alter brightness temperature values.

Table 4.8. Infrared brightness temperature values corresponding to 8-bit count values used as nominal calibration for GOES-6 from April 1987 onwards and for GOES-7 from January 1989 onwards. Some GOES-6 data in 1987 used the second table, labeled "old".

NEW TABLE

Count Value	Brightness Temperature (K)	Count Value	Brightness Temperature (K)	Count Value	Brightness Temperature (K)
1	345.17	44	318.54	87	301.76
2	333.25	45	318.17	88	301.34
3	332.92	46	317.80	89	300.92
4	332.58	47	317.43	90	300.50
5	332.24	48	317.06	91	300.08
6	331.91	49	316.69	92	299.66
7	331.57	50	316.32	93	299.24
8	331.23	51	315.94	94	298.81
9	330.89	52	315.57	95	298.38
10	330.55	53	315.19	96	297.96
11	330.21	54	314.81	97	297.53
12	329.87	55	314.44	98	297.09
13	329.53	56	314.06	99	296.66
14	329.19	57	313.68	100	296.23
15	328.84	58	313.30	101	295.79
16	328.50	59	312.91	102	295.35
17	328.15	60	312.53	103	294.92
18	327.81	61	312.15	104	294.48
19	327.46	62	311.76	105	294.03
20	327.11	63	311.38	106	293.59
21	326.77	64	310.99	107	293.14
22	326.42	65	310.60	108	292.70
23	326.07	66	310.21	109	292.25
24	325.72	67	309.82	110	291.80
25	325.37	68	309.43	111	291.34
26	325.02	69	309.04	112	290.89
27	324.66	70	308.64	113	290.43
28	324.31	71	308.25	114	289.98
29	323.96	72	307.85	115	289.52
30	323.60	73	307.45	116	289.06
31	323.24	74	307.05	117	288.59
32	322.89	75	306.65	118	288.13
33	322.53	76	306.25	119	287.66
34	322.17	77	305.85	120	287.19
35	321.81	78	305.45	121	286.72
36	321.45	79	305.04	122	286.25
37	321.09	80	304.64	123	285.77
38	320.73	81	304.23		
39	320.37	82	303.82		
40	320.00	83	303.41		
41	319.64	84	303.00		
42	319.27	85	302.59		
43	318.91	86	302.17		

Count Value	Brightness Temperature (K)	Count Value	Brightness Temperature (K)	Count Value	Brightness Temperature (K)
124	285.29	169	261.11	214	227.11
125	284.81	170	260.50	215	226.13
126	284.33	171	259.88	216	225.13
127	283.85	172	259.25	217	224.12
128	283.36	173	258.63	218	223.08
129	282.87	174	257.99	219	222.03
130	282.38	175	257.36	220	220.96
131	281.89	176	256.71	221	219.87
132	281.40	177	256.07	222	218.76
133	280.90	178	255.41	223	217.62
134	280.40	179	254.76	224	219.46
135	279.90	180	254.09	225	215.28
136	279.39	181	253.43	226	214.07
137	278.89	182	252.75	227	212.83
138	278.38	183	252.07	228	211.56
139	277.87	184	251.39	229	210.26
140	277.35	185	250.69	230	208.93
141	276.84	186	250.00	231	207.55
142	276.32	187	249.29	232	206.14
143	275.79	188	248.58	233	204.69
144	275.27	189	247.87	234	203.19
145	274.74	190	247.14	235	201.64
146	274.21	191	246.41	236	200.04
147	273.68	192	245.67	237	198.38
148	273.14	193	244.93	238	196.66
149	272.60	194	244.18	239	194.86
150	272.06	195	243.42	240	192.98
151	271.51	196	242.65	241	191.01
152	270.97	197	241.87	242	188.95
153	270.41	198	241.09	243	186.76
154	269.86	199	240.29	244	184.45
155	269.30	200	239.49	245	181.98
156	268.74	201	238.68	246	179.33
157	268.17	202	237.86	247	176.46
158	267.61	203	237.02	248	173.32
159	267.04	204	236.18	249	169.83
160	266.46	205	235.33	250	165.90
161	265.88	206	234.47	251	161.34
162	265.30	207	233.59	252	155.85
163	264.71	208	232.71	253	148.76
164	264.12	209	231.82	254	138.17
165	263.53	210	230.90	255	118.44
166	262.93	211	229.97		
167	262.33	212	229.03		
168	261.72	213	228.08		

OLD TABLE

Count Value	Brightness Temperature (K)	Count Value	Brightness Temperature (K)	Count Value	Brightness Temperature (K)
1	343.56	48	306.72	95	283.20
2	329.76	49	306.25	96	282.71
3	329.24	50	305.78	97	282.22
4	328.79	51	305.24	98	281.73
5	328.27	52	304.70	99	281.23
6	327.75	53	304.23	100	280.73
7	327.29	54	303.75	101	280.23
8	326.77	55	303.27	102	279.73
9	326.24	56	302.79	103	279.23
10	325.78	57	302.24	104	278.72
11	325.25	58	301.76	105	278.21
12	324.72	59	301.27	106	277.70
13	324.25	60	300.71	107	277.18
14	323.78	61	300.22	108	276.75
15	323.24	62	299.73	109	276.32
16	322.71	63	299.24	110	275.79
17	322.23	64	298.74	111	275.27
18	321.75	65	298.24	112	274.74
19	321.27	66	297.74	113	274.21
20	320.79	67	297.24	114	273.77
21	320.25	68	296.73	115	273.32
22	319.70	69	296.23	116	272.78
23	319.21	70	295.72	117	272.24
24	318.72	71	295.21	118	271.70
25	318.23	72	294.77	119	271.24
26	317.74	73	294.25	120	270.78
27	317.25	74	293.74	121	270.23
28	316.75	75	293.29	122	269.77
29	316.25	76	292.77	123	269.30
30	315.75	77	292.25	124	268.74
31	315.25	78	291.80	125	268.27
32	314.75	79	291.27	126	267.80
33	314.25	80	290.74	127	267.23
34	313.74	81	290.28	128	266.75
35	313.23	82	289.75	129	266.27
36	312.72	83	289.21	130	265.78
37	312.21	84	288.75	131	265.30
38	311.70	85	288.28	132	264.71
39	311.25	86	287.74	133	264.22
40	310.79	87	287.19	134	263.73
41	310.28	88	286.72	135	263.23
42	309.75	89	286.25		
43	309.23	90	285.77		
44	308.71	91	285.29		
45	308.25	92	284.81		
46	307.78	93	284.25		
47	307.25	94	283.69		

Count Value	Brightness Temperature (K)	Count Value	Brightness Temperature (K)	Count Value	Brightness Temperature (K)
136	262.73	180	239.08	224	195.16
137	262.23	181	237.99	225	193.93
138	261.72	182	237.02	226	192.98
139	261.21	183	236.04	227	192.01
140	260.80	184	235.04	228	191.02
141	260.29	185	234.03	229	190.00
142	259.77	186	233.00	230	188.95
143	259.25	187	231.96	231	187.87
144	258.73	188	230.90	232	186.77
145	258.31	189	229.97	233	186.01
146	257.78	190	229.03	234	185.24
147	257.25	191	228.08	235	184.05
148	256.82	192	227.11	236	182.86
149	256.28	193	226.13	237	181.99
150	255.74	194	225.13	238	181.13
151	255.31	195	224.12	239	180.24
152	254.76	196	223.08	240	179.34
153	254.20	197	222.03	241	178.41
154	253.76	198	220.96	242	177.45
155	253.31	199	219.87	243	176.47
156	252.75	200	218.94	244	175.46
157	252.19	201	218.00	245	174.41
158	251.73	202	217.05	246	173.33
159	251.27	203	216.07	247	172.21
160	250.81	204	215.08	248	171.05
161	250.35	205	214.07	249	169.85
162	249.76	206	213.04	250	168.60
163	249.18	207	211.99	251	167.94
164	248.70	208	210.92	252	167.29
165	248.23	209	210.04	253	165.92
166	247.75	210	209.15	254	165.21
167	247.26	211	208.02	255	164.49
168	246.78	212	206.85		
169	246.29	213	205.91		
170	245.80	214	204.94		
171	245.30	215	203.95		
172	244.80	216	202.94		
173	244.30	217	201.91		
174	243.80	218	200.85		
175	243.29	219	200.04		
176	242.78	220	199.22		
177	242.00	221	198.10		
178	240.95	222	196.95		
179	240.03	223	196.07		

Short time scale variations in the calibration, particularly those associated with diurnal heating/cooling cycles of the satellite, are not monitored for GOES-5 through GOES-T (see Desormeaux et al. 1993).

For GOES-8 and GOES-9, IR channel calibrations are performed on-board the spacecraft about once every 10 min by looking at space and a reference blackbody. The instrument views the calibration blackbody through exactly the same optics as it views Earth. The radiance from the blackbody is determined from a cubic function of its measured temperature based on pre-launch laboratory measurements. The results of the calibration sequence are used to determine coefficients to calculate radiances:

$$L_i^* = b_i + g_{1i}\,CT + g_{2i}\,CT^2 \tag{4.23}$$

where b_i is the bias for each channel and g_{1i} and g_{2i} are the first-order and second-order gain factors for each channel. The values of g_{2i} are fixed by a pre-launch calibration of the instrument. In addition, the calibration procedure is used to determine a calibration drift rate that is used to correct the measurements at each pixel and scanline. The radiance values are then scaled to fit the whole dynamic range allowed by the data format and transmitted as standard counts (SC). Conversion of the transmitted count values back to radiances then uses a fixed set of coefficients:

$$J_i = (SC - B_i) / G_i \tag{4.24}$$

where J_i has units of mW m^{-2} sr^{-1} cm and the values of B_i and G_i vary with channel (Table 4.9). For ISCCP, these coefficients are modified for use with 8-bit count values instead of the original 10-bit values.

Table 4.9. Conversion factors for calibrated IR radiances transmitted by GOES-8 and GOES-9.

Channel No.	Wavelength (μm)	B_i	G_i
2	3.7	68.2167	227.3889
3	6.9	29.1287	38.8383
4	10.7	15.6854	5.2285
5	11.5	16.3332	5.0273

Brightness temperatures are obtained from radiances by

$$TB_i = \beta_i\,(c_2 \hat{\nu})[\ln(1 + c_1 \hat{\nu}^3\, J_i^{-1})]^{-1} + \alpha_i \tag{4.25}$$

where $c_1 = 1.191066 \times 10^{-3}$ mWm^{-2} sr^{-1} cm and c_2 = 1.438833 Kcm. The other coefficients are given in Table 4.9.

Table 4.10. Constants to convert IR radiances to brightness temperatures for GOES-8 and GOES-9.

	Channel No.	Detector No.	$\hat{\nu}$ (cm^{-1})	β_i	α_i (K)
GOES-8					
	2	1	2556.65	1.00152	-0.575836
	2	2	2557.15	1.00152	-0.580028
	3	1	1481.85	1.00143	-0.588961
	4	1	934.25	1.00126	-0.313687
	4	2	934.35	1.00122	-0.296247
	5	1	837.05	1.00117	-0.420806
	5	2	836.15	1.00102	-0.341538
GOES-9					
	2	1	2555.15	1.000955	-0.580725
	2	2	2555.15	1.000955	-0.580725
	3	1	1481.75	1.001092	-0.489100
	4	1	934.55	1.001284	-0.377608
	4	2	934.25	1.001264	-0.358734
	5	1	833.95	1.000914	-0.288899
	5	2	834.05	1.000926	-0.296517

4.1.4. GMS (VISSR)

Data from GMS-1, GMS-2, GMS-3, and GMS-4 have been collected for ISCCP; all satellite radiometers consist of four visible and one infrared sensor as the primary set and an identical back-up set. The spectral response functions for the two channels, nominally at 0.65 µm and 11.5 µm, are shown in Section 7.5.

The imager instrument on GMS-5 differs from the previous ones in having a reduced along-line sampling rate for the 11.5 µm channel to make room for the two additional spectral channels at 6.9 and 11.5 µm (see Section 7.5).

Table 4.11. Calibration coefficients used for GMS-1, GMS-2, GMS-3, GMS-4 and GMS-5 reference solar channels.

Parameter	GMS-1	GMS-2	GMS-3	GMS-4	GMS-5
Reference channel number	7	1	5	3	2
Solar scaled radiance	0.30	0.425	0.450	?	?
$ß_0$ (6-bit count)	-0.23764	-0.309	-0.1321	?	?
$ß_1$ (6-bit count)	27.728	28.375	28.370	?	?
Solar count	33	49	42	?	?
Space counts	1	1	1	?	?

(1) SOLAR CHANNEL

Conversion of radiometer output voltages to scaled radiances involves two sets of calibration coefficients (MSC 1984). Telemetry counts are related to instrument voltages by

$$CT = \beta_0 + \beta_1 \sqrt{V} \tag{4.26}$$

where the coefficients $ß_0$ and $ß_1$ are determined daily by insertion of a standard 0 to 5 - volt staircase signal in the telemetry. The instrument voltage is also related to scaled radiance by

$$V = \alpha_0 L^* + V_0 \tag{4.27}$$

where α_0 and V_0 are determined by viewing space and the sun, where the sun is viewed through an energy-reducing prism. Taking the radiance of the sun to be L^*_{sn} and that of space to be $L_{sp} = 0$, Eqs. (4.26) and (4.27) can be combined to give

$$L^* = L_{sn}^* [(CT - CT_{sp})(CT + CT_{sp} - 2\beta_0)][(CT_{sn} - CT_{sp})(CT_{sn} + CT_{sp} - 2\beta_0)]^{-1} \tag{4.28}$$

where CT_{sp} and CT_{sn} are the telemetry counts when viewing these two targets.

Post-launch measurements showed two difficulties: differences in the sensitivity of the four primary and back-up sensors, causing stripes in the images, and rapid variability of the sun calibration signal. Therefore, the solar channel data are normalized to a reference channel (Ch. 7 on GMS-1, Ch. 1 on GMS-2, Ch. 5 on GMS-3, Ch. 3 on GMS-4, and Ch. 2 on GMS-5), where the calibration coefficients for the reference channel are fixed based on a combination of pre-launch and post-launch measurements. These equations are used to construct a table relating telemetry counts (6-bit) to scaled radiance for all solar channels; daily monitoring of the values of $ß_0$ and $ß_1$ can lead to replacement of tables.

Solar channel data for ISCCP represent an average of the measurements from channels 5, 7 and 8 for GMS-1, 1 – 4 for GMS-2, 5 – 8 for GMS-3, 1 – 4 for GMS-4, and 1 – 4 for GMS-5. These average values are rescaled to an 8-bit count scale using

$$L^* = (CT/255)^2 \tag{4.29}$$

These scaled radiance values are converted to radiances using the spectral response functions shown in Section 7.5; the solar spectral irradiances for the reference channels are E_o/π = 113.25 watts m^{-2} sr^{-1} for GMS-1, 114.50 watts m^{-2} sr^{-1} for GMS-2, 119.56 watts m^{-2} sr^{-1} for GMS-3, 122.82 watts m^{-2} sr^{-1} for GMS-4, and 181.31 watts m^{-2} fo GM-5, where

$$L = (E_O/\pi)\, L^* \tag{4.30}$$

(2) INFRARED CHANNEL

Instrument voltage is related to telemetry counts (8-bit) in the same way as for the solar channel (MSC 1984):

$$CT = \beta_0 + \beta_1 \sqrt{V} \tag{4.31}$$

where $ß_0$ and $ß_1$ are determined eight-times daily from the on-board voltage reference signal. Instrument voltage is related to radiance, L, by

$$V = \alpha_0 L + V_0 \tag{4.32}$$

where α_0 and V_0 are determined from eight-times daily observations of space and an on-board black-body of known temperature. These two coefficients are thus given by $V_0 = V_{sp}$ and

$$\alpha_0 = (V_{sh} - V_{sp}) / L_{bb} \tag{4.33}$$

where V_{sp} is the voltage recorded when viewing space (telemetry count CT_{sp} and radiance $L_{sp} = 0$) and V_{sh} is the voltage recorded when viewing the shutter which serves as the on-board reference. The radiance, L_{bb}, is the radiance at the sensor, which depends on the temperatures of various parts of the instrument. The effective temperature of the calibration source is determined by

$$T_{bb} = T_{sh} + k_1 (T_{sh} - T_a) + k_2 (T_{sh} - T_1) \tag{4.34}$$

where

$$T_{sh} = (T_{sh1} + T_{sh2}) / 2 \quad \text{mean shutter temperature} \tag{4.35}$$

A look-up table, calculated using the measured spectral response of the infrared channels and the Planck function, is used

$$T_a = (T_1 + T_2 + T_3) / 3 \quad \text{mean scanner temperature} \tag{4.36}$$

A look-up table, calculated using the measured spectral response of the infrared channels and the Planck function, is used to convert T_{bb} to L_{bb}. The results of the eight-times daily calibration observations are used to produce a table relating count values (8-bit) to radiances and black-body temperatures; these tables are provided with the data. In operation, the backup IR channel is used on GMS-1 and the primary channel is used on GMS-2, GMS-3 and GMS-4. On GMS-5 the primary set of three detectors is used in operation (see Section 7.5).

The coefficients k_1 and k_2 used in construction of the calibration tables were determined from pre-launch calibration measurements; $k_1 = 0.325$ and $k_2 = 0.175$ are used for GMS-1, GMS-2 and GMS-3. Post-launch comparisons of GMS-2 IR measurements and conventional sea surface temperature observations by ships were performed with a model for atmospheric corrections. A small bias (1-2K) was found which varied seasonally, apparently due to changing temperature gradients within the scanner. Because of the uncertainties in both the ship observations and the modeled corrections, no change in calibration was made.

Shorter period variations in calibration due to the diurnal heating/cooling cycle were not monitored for the GMS satellites before 1987; after 1987 diurnal corrections are applied to radiances.

Addendum to Description of GMS-5 Nominal Calibration

GMS-5 began operations in June 1995 using the initial operational calibration coefficients for the nominal calibration. After comparing simultaneous observations at the "window" infrared wavelength (nominally at 11.5μm) from GMS-4 and GMS-5 in August 1996, the Japan Meteorological Agency adjusted the nominal GMS-5 calibration coefficients for both this channel and the new "water vapor" channel (6.9 μm nominal wavelength) slightly. All data after 1 December 1996, including the ISCCP B3 data, use these new coefficients. However, the ISCCP B3 data before this date use the old calibration coefficients for the nominal calibration, which are then normalized to the reference calibration by comparison with NOAA-14 observations. If the ISCCP calibration coefficients (either normalized or absolute) for GMS-5 are to be applied to data from before this date that have been obtained from any other source, the data need to be checked to determine which calibration coefficients have been used. If the calibration coefficients have been used, then the brightness temperature values must be adjusted **by subtracting** the values in the following table before employing the ISCCP coefficients.

Table: Change in GMS-5 brightness temperatures from before 1 December 1996 needed to convert from the new calibration back to the old calibration. First table is for the 11.5µm channel (detector 2) and the second table is for the 6.9µm channel.

	Month/Year	200K	220K	240K	250K	280K	300K	320K
IR 2								
	Jun 95	1.0	1.2	1.4	1.5	1.9	2.1	2.4
	Jul 95	1.0	1.2	1.4	1.5	1.9	2.1	2.4
	Aug 95	0.9	1.1	1.3	1.5	1.8	2.0	2.3
	Sep 95	0.8	1.0	1.2	1.4	1.6	1.8	2.0
	Oct 95	0.8	0.9	1.1	1.3	1.5	1.7	1.9
	Nov 95	0.7	0.8	1.0	1.2	1.3	1.5	1.7
	Dec 95	0.7	0.8	1.0	1.1	1.3	1.5	1.7
	Jan 96	0.7	0.8	1.0	1.1	1.3	1.5	1.7
	Feb 96	0.7	0.8	1.0	1.1	1.3	1.5	1.7
	Mar 96	0.7	0.9	1.0	1.2	1.4	1.6	1.8
	Apr 96	0.8	0.9	1.1	1.3	1.5	1.7	1.9
	May 96	0.9	1.0	1.2	1.4	1.6	1.9	2.1
	Jun 96	1.0	1.2	1.4	1.5	1.9	2.1	2.4
	Jul 96	1.0	1.2	1.4	1.6	1.9	2.1	2.4
	Aug 96	0.9	1.1	1.3	1.5	1.7	1.9	2.2
	Sep 96	0.8	1.0	1.1	1.3	1.5	1.8	2.0
	Oct 96	0.8	1.0	1.2	1.4	1.6	1.8	2.0
	Nov 96	0.8	1.0	1.2	1.4	1.6	1.8	2.0
IR 3								
	Jun 95	0.6	0.8	0.9	1.0	1.2	1.4	1.6
	Jul 95	0.6	0.8	0.9	1.0	1.2	1.4	1.6
	Aug 95	0.6	0.7	0.8	1.0	1.1	1.3	1.4
	Sep 95	0.5	0.6	0.7	0.8	0.9	1.1	1.2
	Oct 95	0.5	0.5	0.6	0.7	0.9	1.0	1.1
	Nov 95	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	Dec 95	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	Jan 96	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	Feb 96	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	Mar 96	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	Apr 96	0.5	0.5	0.6	0.7	0.9	1.0	1.1
	May 96	0.5	0.6	0.7	0.9	1.0	1.1	1.3
	Jun 96	0.6	0.8	0.9	1.0	1.2	1.4	1.6
	Jul 96	0.6	0.7	0.9	1.0	1.2	1.4	1.6
	Aug 96	0.6	0.7	0.8	0.9	1.0	1.2	1.4
	Sep 96	0.5	0.6	0.7	0.8	0.9	1.0	1.2
	Oct 96	0.5	0.6	0.7	0.8	1.0	1.1	1.3
	Nov 96	0.5	0.6	0.7	0.8	1.0	1.1	1.3

4.1.5. INSAT (VHRR)

The Indian National Satellite System (INSAT) was developed by the Indian Space Research Organization to provide, among other services, meteorological imagery to the Indian Meteorological Department. INSAT is a three-axis stabilized satellite operated in geostationary orbit with a sub-satellite longitude of 74.5° E since September 1983. INSAT-1B operated well into 1989 when it was replaced by INSAT-1C (INSAT-2 was launched in the summer of 1992). Only limited data have been obtained from INSAT-1B: twice-daily imagery for January 1986 - March 1988 and eight-times-daily imagery for April 1988 - March 1989.

The INSAT radiometer, called the Very High Resolution Radiometer (VHRR), has four VIS (0.55-0.75 μm) channels with a nadir resolution of 2.75 km and one IR (10.5-12.5 μm) channel with a nadir resolution of 11.0 km. There is also a back-up set of detectors. Radiometer spectral responses are illustrated in Section 7.6.

(1) SOLAR CHANNEL

Little detail is available concerning the pre-launch calibration; which detector set is operational is not known. Average results of pre-launch calibration give the scaled radiance (in percent):

$$L^* = G\,(CT - Y) \qquad (4.37)$$

where CT is an 8-bit count (original INSAT VIS data are reported as 6-bit counts), G = 0.4122 (average primary detector set), G = 0.4203 (back-up detectors), Y = -0.375 (primary) and Y = 0.475 (back-up). Since this information was not available at the time of processing, the ISCCP nominal calibration is

$$L^* = 0.400 * CT \qquad (4.37)$$

Radiances are obtained by multiplying $L^*/100$ by the effective solar constant for the VHRR VIS channel, which is 105.7339 Watts m^{-2} sr^{-2} (for the average spectral response of the primary detector set).

(2) INFRARED CHANNEL

Pre-launch calibrations established relations between counts and radiances for a range of instrument operating temperatures. On-board calibration measurements are used to convert radiance counts into brightness temperature values; these values are converted into standard 8-bit count values with a fixed relationship to brightness temperatures:

$$\begin{aligned} TB &= 179 + (255 - CT_{IR})\ K && 150 \le CT_{IR} \le 253\ K \\ TB &= 284 + 0.127 * (150 - CT_{IR})\ K && 16 < CT_{IR} < 150\ K \qquad (4.39) \\ TB &= 301 + (16 - CT_{IR})\ K && 0 \le CT_{IR} \le 16\ K \end{aligned}$$

The frequency of calibration by on-board measurements is not known.

4.2. NORMALIZED CALIBRATIONS

The second calibration of the ISCCP radiance data is provided by normalizing the geostationary radiometer responses to that of the AVHRR on the primary polar orbiter (Desormeaux et al. 1993). The Satellite Calibration Center (SCC) performs the normalization by comparing nearly simultaneous, co-located images with nearly the same satellite viewing geometry at full resolution (called AC data). Only the visible (0.6 µm) and window IR (11 µm) channels, common to all satellites, are normalized. This analysis is routinely performed once every three months (January, April, July, October) and the results linearly interpolated to the other months. However, when satellite changes occur or other evidence indicates a change, the analysis is performed more frequently. The procedure has five steps (see Desormeaux et al. 1993 for details): (1) image sector selection, (2) image quality checking and preprocessing, (3) mapping and registration, (4) radiance sample selection (e.g., Figure 4.1), and (5) calculation of normalization coefficients (called BC data).

INSAT-1B radiance data were obtained covering the period from April 1988 through March 1989; however, no full resolution samples matched with polar orbiter data (AC data) were provided. Therefore, a special normalization procedure was required that compared overlapping observations between INSAT-1B and METEOSAT-2/3 and GMS-3 (see details in Desormeaux et al. 1993).

Target radiances for each matched pair of images for each month are plotted against each other and a linear least-squares fit calculated. The BC data for each month lists the date and time of each image pair used, the time difference between the geostationary and polar orbiter images, the average solar zenith angle, the total number of targets, the individual target radiances from both satellites, and gives the slope and intercept of the least-squares fit (the normalization coefficients), the correlation coefficient, the rms scatter, mean and maximum/minimum radiances. The GPC uses the BC results to produce a second set of calibration tables for the radiance count values that are given for each radiance image in the B3 and BT datasets. The reported slope and intercept values from the radiance regressions are used to alter the nominal calibration tables:

$$L_N^* = S_{NV}\,(L^*) + I_{NV} \qquad \text{(visible channel)} \qquad (4.40)$$

$$TB_N = S_{NI}\,(TB) + I_{NI} \qquad \text{(IR channel)} \qquad (4.41)$$

where L^* and TB are the nominal and L_N^* and TB_N are the normalized geostationary values of visible scaled radiances and infrared brightness temperatures with respect to AVHRR measurements. Normalized calibrations for the two intervening months between normalizations are obtained by linear interpolation (interpolations can be recognized in the B3 and BT tables by the absence of corresponding rms scatter and maximum/minimum values). Visible channel radiance tables are then obtained from L_N^* by

$$L_N = (E_0/\pi)\, L_N^* \qquad (4.42)$$

IR channel radiance tables are obtained using the conversion tables between temperature and radiance discussed in Section 7.2. If no normalization results are available (only true for extra spectral channels), the normalized calibration tables on B3 data tapes and in the BT datasetsare duplicates of the nominal calibration tables.

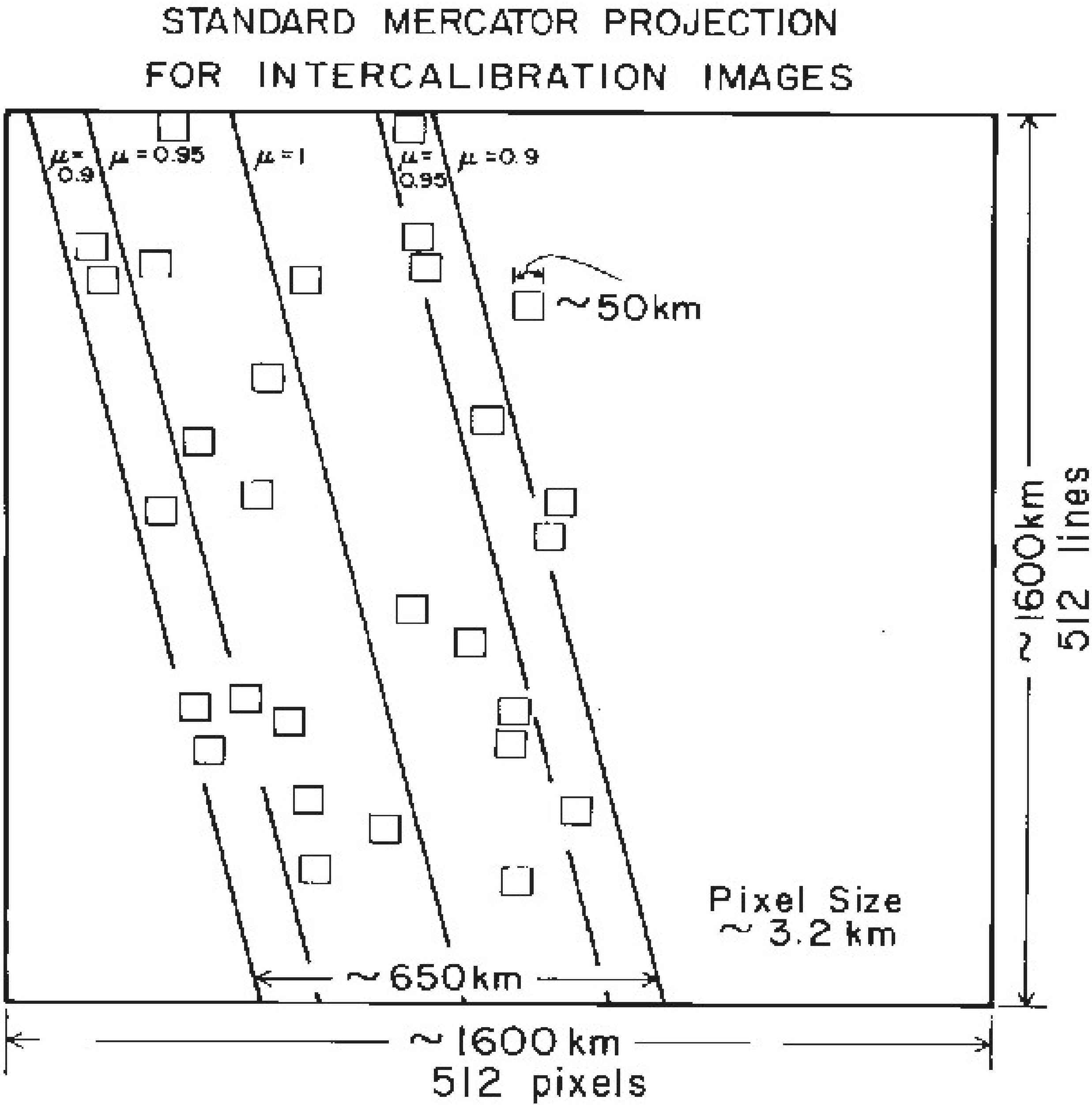

Figure 4.1. Schematic illustrating the viewing geometry of coincident polar orbiter and geostationary images used for radiance normalization. Typical target regions are shown.

4.3. ABSOLUTE CALIBRATION

The infrared channels of AVHRR are routinely and continually calibrated by measurements of space and an on-board calibration thermal source every scan line. This calibration has been thoroughly checked after launch for NOAA-7, NOAA-9 and NOAA-11, providing improved coefficients and corrections for small non-linearities (Rao et al. 1993). These results show small systematic differences between the calibrations of different AVHRRs. ISCCP has adopted the nominal calibration of the NOAA-9 AVHRR infrared channel at 10.7µm as the reference standard. The method for monitoring the infrared calibration and transferring it to other AVHRRs is documented in Brest and Rossow (1992), Brest et al. (1996) and the results given in Rossow et al. (1992, 1996).

Although a thorough pre-launch calibration of the solar channels of AVHRR is performed, no post-launch verification of the calibration is performed operationally. Various techniques have been employed to determine the absolute calibrations of the AVHRR solar wavelength channels and to monitor their variations (e.g., Teillet et al. 1990; Whitlock et al. 1990; Brest and Rossow 1992; Che and Price 1992; Rao et al. 1993). The required corrections are of significant magnitude, sometimes > 10%. The calibration of the NOAA-9 AVHRR is the best determined by comparisons to an absolutely calibrated aircraft instrument: the anchor value is the average of results from three flights conducted within a few days in October 1986 (a singular occurrence). ISCCP uses this calibration of NOAA-9 as the reference standard. The method for monitoring the visible calibration and transferring it to other AVHRRs is documented in Brest and Rossow (1992), Brest et al. (1996) and the results given in Rossow et al. (1992, 1996).

After application of the calibration analysis results to the calibrations of the AVHRRs and the normalization of the geostationary satellite radiometers to the AVHRRs, two kinds of artifacts were still apparent in the first version of the cloud climatology products (C-series data): occasional differences in retrieved quantities between adjacent geostationary satellites producing sudden geographic changes and small changes in global mean quantities associated with changes in the reference AVHRR (e.g., Klein and Hartmann 1993; Rossow and Cairns 1995). In retrospect, these two results show that the geostationary radiometers exhibit sudden calibration changes on time scales of one month (shorter term variations are also apparent, see Desormeaux et al. 1993) and that the various calibration monitoring techniques for the visible channels, including aircraft comparisons (cf. Brest and Rossow 1992), are not precise enough to eliminate significant differences between AVHRRs. The geostationary variations occurred between the routine normalizations performed every three months and show the need for continual monitoring of the calibration of these radiometers. The long-term changes in the AVHRRs demonstrate that the whole Earth, considered as a statistical aggregate of targets, is radiometrically more stable than any available satellite radiometer and varies by less than the uncertainty in available calibration monitoring techniques. Thus, additional adjustments were made to the ISCCP calibrations to reduce these artifacts (Brest et al. 1996).

The final adjustment coefficients are reported as slope and intercept values in the absolute calibration tables in the Stage B3 and BT datasets:

$$L_A^* = S_{AV}\,(L_N^*) + I_{AV} \quad \text{(visible channel)} \qquad (4.43)$$

$$TB_A = S_{AI}\,(TB_N) + I_{AI} \quad \text{(infrared channel)} \qquad (4.44)$$

where L_N^* and TB_N are the normalized values and L_A^* and TB_A are the absolute values of the visible scaled radiance and infrared brightness temperature, respectively.

In Stage B3 and BT data, use of the absolute calibration tables to convert counts to physical quantities provides the best information available to ISCCP on the calibration of these radiometers. The latest version (highest version number on data tapes) is most accurate. For any further updates, consult the ISCCP Web Home Page.

Overall estimates (Brest et al. 1996) of the absolute calibration uncertainties are 7-10% and 1.5% (relative) for visible and infrared, respectively. Most of this uncertainty is in the absolute calibration of the NOAA-9 AVHRR. Relative to the NOAA-9 reference standard, the uncertainties over the whole dataset are about 3-5% and 1% for visible and infrared, respectively. These estimates apply, strictly, to longer-term (month to year time scales) calibration variations. Shorter-term variations are looked for (see description in Desormeaux et al. 1993) and corrected, but the uncertainty for a given time may be similar to the overall uncertainty magnitude.