NOAA Technical Report NESDIS 3

Determination of the Planetary Radiation Budget From TIROS-N Satellites

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service

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Arnold Gruber,
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Determination of the Planetary Radiation Budget From TIROS-N Satellites

by

Arnold Gruber, Irwin Ruff, and Charles Earnest

Introduction

With the launching of the TIROS-N series of satellites in 1979, it was necessary to redesign the processing system that produces estimates of the planetary radiation budget. This report will update an earlier report (Gruber, 1977) which provided details of the processing of the pre-TIROS-N satellite data. The main difference between the two systems is that the current procedures operate directly on the incoming data stream where previously the processing was done on a mapped data base in which some processing of the raw data had already been accomplished. Other details concerning the orbital characteristics of the TIROS-N satellite system and the radiometers, as well as improved formulas for estimating flux quantities, are described in this report.

AVHRR Instruments and Data Processing

The AVHRR instruments are mounted on the TIROS-N series of satellites. These satellites are sun-synchronous, having an inclination of about 99°, a nominal height of 833 km, and a period of about 102 minutes. The orbits of this series have either a descending node at about 0730 local time (LT), or an ascending node at about 1430 LT. NOAA-7, the current operational satellite, has an ascending node at 1430 LT. More specific information about the satellite instruments and their calibration is provided by Schwalb, 1978, and Lauritson et al., 1979. In the remainder of this paper, all descriptions and constants will refer to the AVHRR instrument on NOAA-7, unless otherwise specified. AVHRR is a multi-spectral scanner, the NOAA-7 version of which has five channels:

1: .58 to .68 μm
2: .725 to 1.1 μm
3: 3.55 to 3.93 μm
4: 10.3 to 11.3 μm
5: 11.5 to 12.5 μm

Previous versions of the instrument lacked channel 5, as does the recently launched NOAA-8. The response functions are shown in Figure 1, with a plot of channels 1 and 2 on an enlarged scale in Figure 2.

The instantaneous field of view for each channel is approximately 1.4 milliradians. At the nominal altitude of 833 km, this results in a nadir Earth resolution of about 1.1 km. It should be noted that the fields of view of the various channels are not identical and may not be perfectly circular, as may be seen from Table 1. Care should therefore be taken in comparing observations from channels 4 and 5 with each other or with other channels.

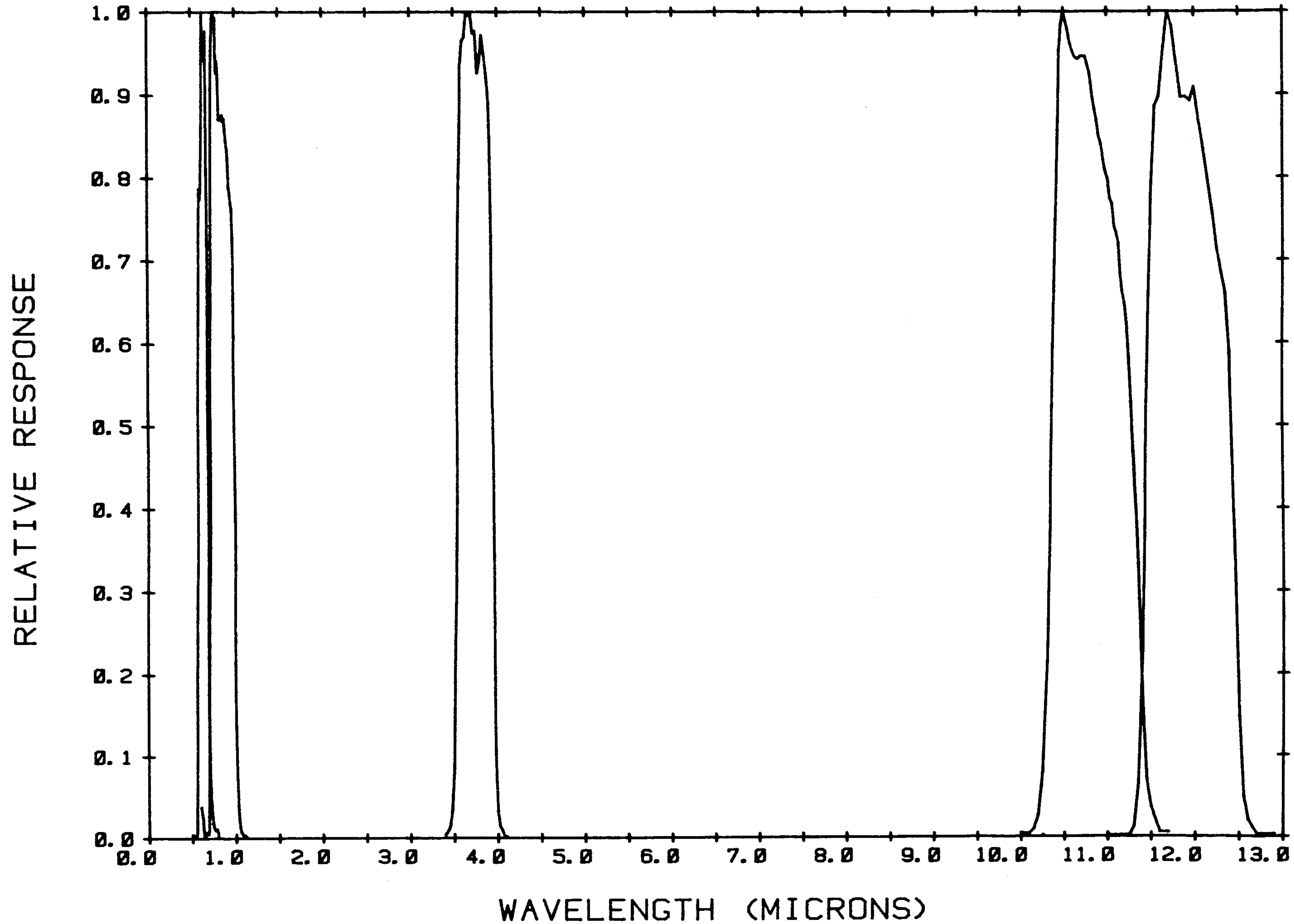

Fig. 1 Spectral response of the five channels of the AVHRR on NOAA 7.

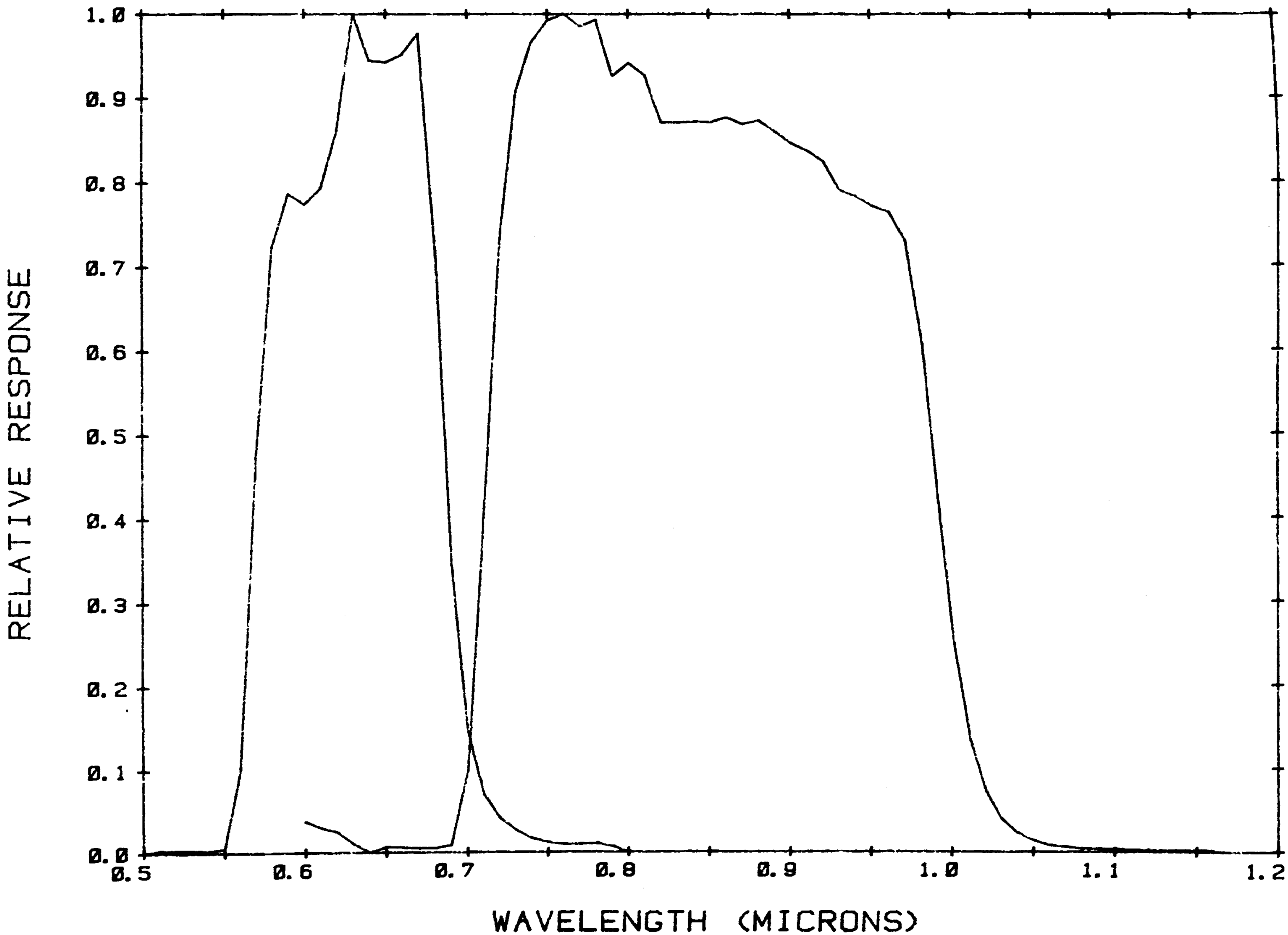

Fig. 2 An enlarged plot of the spectral response of channels 1 and 2.

Table 1: Fields of View for the AVHRR Channels

Channel	Diameter Scan Direction	Diameter Cross-Scan Direction
1	1.443 m. rad.	1.433 m. rad.
2	1.433	1.423
3	1.423	1.423
4	1.28	1.463
5	1.32	1.31

The instrument scan is perpendicular to the orbital plane at a rate of six scans per second. The output of each channel is digitized at the rate of 39,936 samples per second. For each scan 2048 of these samples, centered on nadir, constitute the basic data from the AVHRR. Each sample is termed a local area coverage (LAC) spot. For nominal height the observed swath extends approximately 13° of geocentric arc on either side of the suborbital track. As a result of the combination of field of view and sampling rate, LAC spots overlap, there being 1.36 samples (LAC's) per field of view (see Figure 3).

It is not feasible to use LAC data for routine coverage of large areas because of the large number of data values involved. (For example, one second of data, equivalent to approximately 7 km movement of the subsatellite point, consists of 5 channels x 2048 locations per scan x 6 scans = 61,440 data values.) For much of the routine processing, such as for radiation budget studies, the LAC data are reduced to the form of global area coverage (GAC) data. On a scan line, four contiguous LAC values are averaged for each channel, yielding one set of GAC values. The fifth LAC spot is omitted, the next four values are averaged, and so forth (see figure 3). This process yields 409 GAC spots for that scan line, with the central GAC spot being centered on nadir. The following two scan lines are omitted, and the process is repeated for the third line. GAC lines are thus spaced 1/2 second apart, corresponding to an Earth distance of about 3.3 km. It should be noted that there is nonuniform weighting over a GAC area as a result of the overlap of the LAC samples of which it is composed.

The basic data element used by the radiation budget processing system is an 11 x 11 matrix of contiguous GAC spots, which is termed a GAC target (sometimes also referred to as a 50-km area). The width of a target along the orbital track is 36-37 km, whereas in the direction of scan it varies from 42 to 196 km.

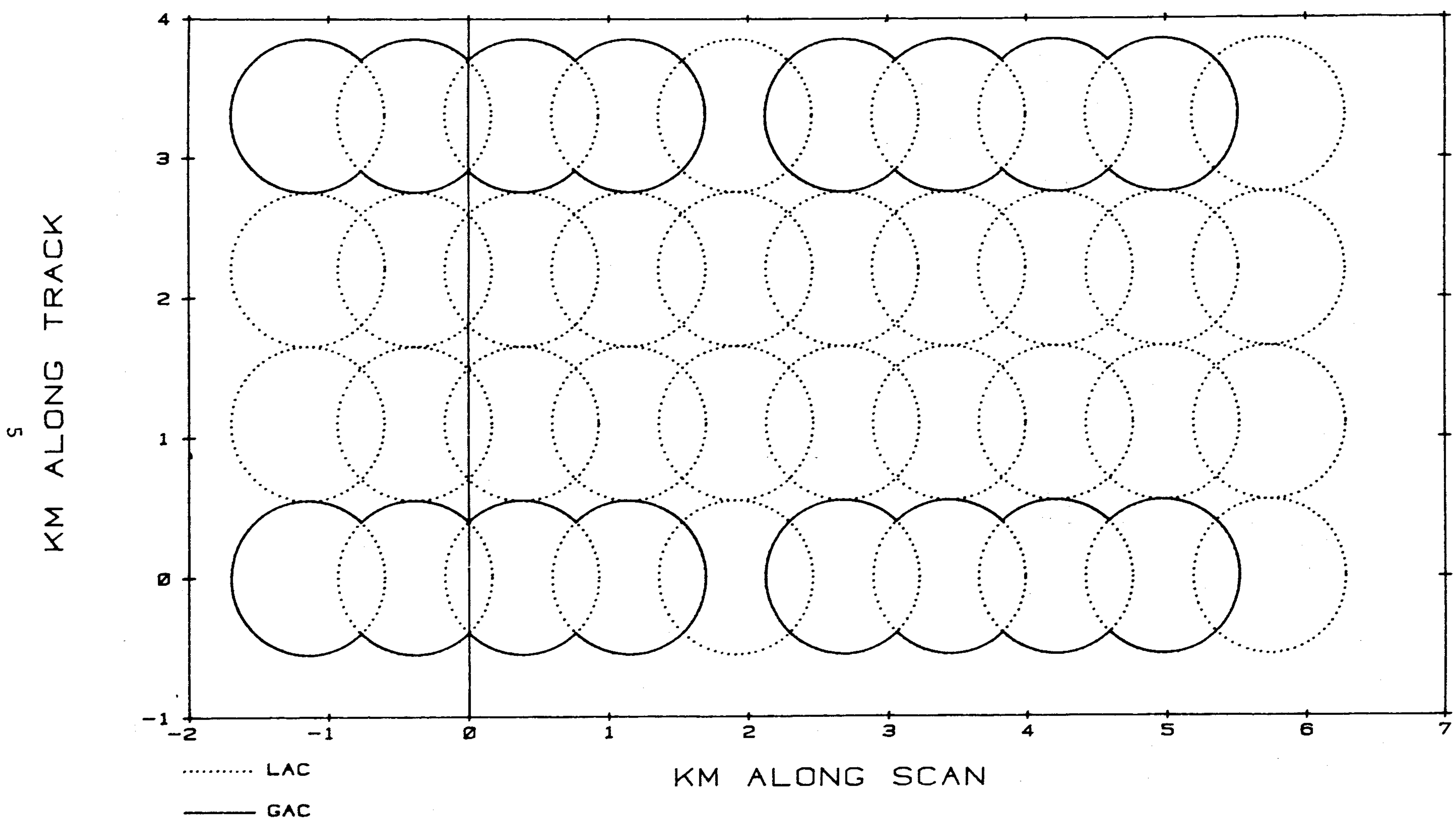

Fig. 3 Local area coverage (LAC) and global area coverage (GAC) spots. LAC spots are dashed and GAC ones are solid.

For reasons connected with operational requirements, each GAC target is centered on a HIRS-2* spot, and a target is passed to the radiation budget system for every such spot. This results in a gap between GAC targets along the orbital track of 4-5 km. Along a scan line there is a slight overlap between targets. If only every other target along a scan line is used in the processing, there is a slight gap.

Although there are four or five channels available on AVHRR, only two are used in the current version of the radiation budget processing system. The absorbed solar energy is determined from the albedo values of channel 1 (.58 to .68μm). These are usually termed the "visible" observations. The emitted terrestrial radiation (referred to as "IR") is obtained from channel 5 (11.5 to 12.5μm) on NOAA-7. Since previous instruments did not have this channel, these values were obtained from channel 4 (10.5 to 11.5μm). However, channel 4 is more transparent to atmospheric moisture than channel 5.

The satellite orbit consists of two equal portions: one when the satellite is northbound, the other when it is southbound. The half that is mostly in sunlight is defined for purposes of processing as being daytime, while the half that is mostly shadowed is defined as being nighttime. Thus, for NOAA-7, daytime is defined as the northbound half of the orbit. The longwave data are processed separately for the daytime and nighttime portions of the orbit, whereas the shortwave data are obviously processed for only the daytime portion.

For both visible and IR data, each GAC target is examined to ascertain the number of individual observations present. If there are less than 60 (about half of the possible number), nothing further is done, and the target is labeled as missing. If there are at least 60 observations present, the values, which are in digital counts, are averaged, and an average count is obtained. The proper calibration equation is then applied to this average value, and an IR radiance or a visible albedo is calculated. At this point in the processing this procedure is legitimate, as digital counts are linearly related to window radiances in the longwave channels 4 and 5 and to spectral albedo in channel 1 and 2.

Outgoing Longwave Radiation

The mean longwave radiance is normalized to a central satellite zenith value using an empirically derived limb-darkening correction (Abel and Gruber, 1977):

$$R(O) = R(\theta) + \left[\alpha_1 + \alpha_2 R(\theta)\right]\left[\sec\theta - 1\right] + \left[\beta_1 + \beta_2 R(\theta)\right]\left[\sec\theta - 1\right]^2 \qquad (1)$$

where 0 is the satellite zenith angle at the center of the GAC target,

$$\alpha_1 = -2.301 \text{ mw}(\text{m}^2 \text{ st cm}^{-1})^{-1},$$

*HIRS2 is the vertical temperature sounder flown on the spacecraft

$$\alpha_2 = 0.04767,$$
$$\beta_1 = 0.1244 \text{ mw}(\text{m}^{-2} \text{ st cm}^{-1})^{-1},$$
$$\beta_2 = -0.002096.$$

The use of a central satellite zenith angle will introduce little error in the final value, since this angle does not vary greatly over a GAC target.

The normalized radiance is converted to a brightness temperature by means of the Planck radiation equation:

$$\frac{c_2 \nu_o}{\ln\left[c_1 \nu_o^3/R(O) + 1\right]} \tag{2}$$

where the constants of the Planck equation are

$$c_1 = 1.191065 \times 10^{-5} \text{ erg cm}^2 \text{ sec}^{-1}$$

and $c_2 = 1.438833$ cm deg.

ν_o is the central wave number for the channel. This will vary not only from channel to channel, but also for the same channel on different instruments, due to slight variations in the response functions. For NOAA-7, channel 5, the value is 840.67 cm^{-1}. It should be noted that in order to maintain dimensional consistency in the Planck equation, it is necessary to convert R(O) from $\text{mw}(\text{m}^2\text{st cm}^{-1})^{-1}$ to erg cm^{-2} st^{-1}. The conversion factor, however, is $10^{-4} \times 10^4$. In practice it is thus possible to use the numerical value of R(O) in the equation without a formal conversion, and to obtain the correct brightness temperature.

A flux equivalent temperature is obtained from

$$T_F = T_B\ (a + bT_B) \tag{3}$$

Table 2 - Coefficients used for the estimation of outgoing longwave flux.

Satellite	Coefficients a	Coefficients b	Remarks
TIROS-N	1.3203	-0.001397	Based on Abel and Gruber (1974).
NOAA-6	1.3203	-0.001397	Based on Abel and Gruber (1979).
NOAA-7	1.2795	-0.0012442	Based on improved radiative transfer model of Ellingson and Ferraro (1983).
NOAA-7	1.2149	-0.001055	Empirical model from Ohring, Gruber and Ellingson (1983).

Table 2 lists values of the coefficients a and b that were used for the different satellites in the TIROS-N series. NOAA-7 coefficients were based on improved radiative transfer calculations (Ellingson and Ferraro, 1983) and then changed when a new set of coefficients were derived by comparison of observed window temperatures and flux values from the Nimbus-7 experiment (Ohring et al., 1983). Finally, an outgoing flux is calculated from the Stefan-Boltzman equation

$$F = \sigma T_F^4 \tag{4}$$

Stefan's constant, $\sigma = 5.6693 \times 10^{-8}$ w m^{-2} deg^{-4}. The flux is given in units of w m^{-2}.

As seen from equations(2)-(4), conversion of radiances to temperature and then application of formulas required to obtain an emitted flux are all nonlinear. Depending on the variability of the observations within a GAC target, it is possible that significant error may arise from the present procedure of calculating the flux for a target from an average value of the counts, rather than by determining a flux for each observation and then averaging the fluxes. A calculation of the nonlinear effect was made by comparing the present procedure against a procedure that estimates the flux at every GAC spot and then averaging. The calculations were done for a sample of NOAA-7 daytime data. The largest difference was about 6 w m^{-2}, occurring in a limited area that was highly variable, i.e., a region where there were combinations of high cloud and cloudfree high temperature surfaces, such as found in the tropics and subtropics. Zonal averages of profiles of the differences are shown in Fig. 4. The largest difference of 1 w m^{-2} occurs in the ITCZ region, as one might expect. Elsewhere differences are less than 1 w m^{-2}. Note, however, that the differences are everywhere positive. This is because the nonlinear relationships between radiance, R(O), and brightness temperature, T_B, (Eq. 2 and Fig. 5) result in systematic overestimates of T_B when calculated for average values of R(O) as compared with window temperatures (T_B) calculated from individual radiance observations. This ultimately results in higher values of T_F (from Eq. 3), and thus higher values of flux (Eq. 4). Also, this effect is large where the range of radiance values is large.

Albedo

In the case of the visible data only linear relationships are involved, so that using a mean count does not introduce any appreciable error. This will not be true if angular corrections (which are a function of surface type) are used to determine the reflected flux.

The calibration equation from counts to albedo provides an estimate of the albedo over the spectral range of the radiometer. The incoming radiation is taken to be the solar constant: i.e., overhead Sun at mean Sun-Earth distance. The solar constant used is based on Thekaekara (1971), having a value of 1353 w m^{-2}. In order to obtain a normalized albedo, it

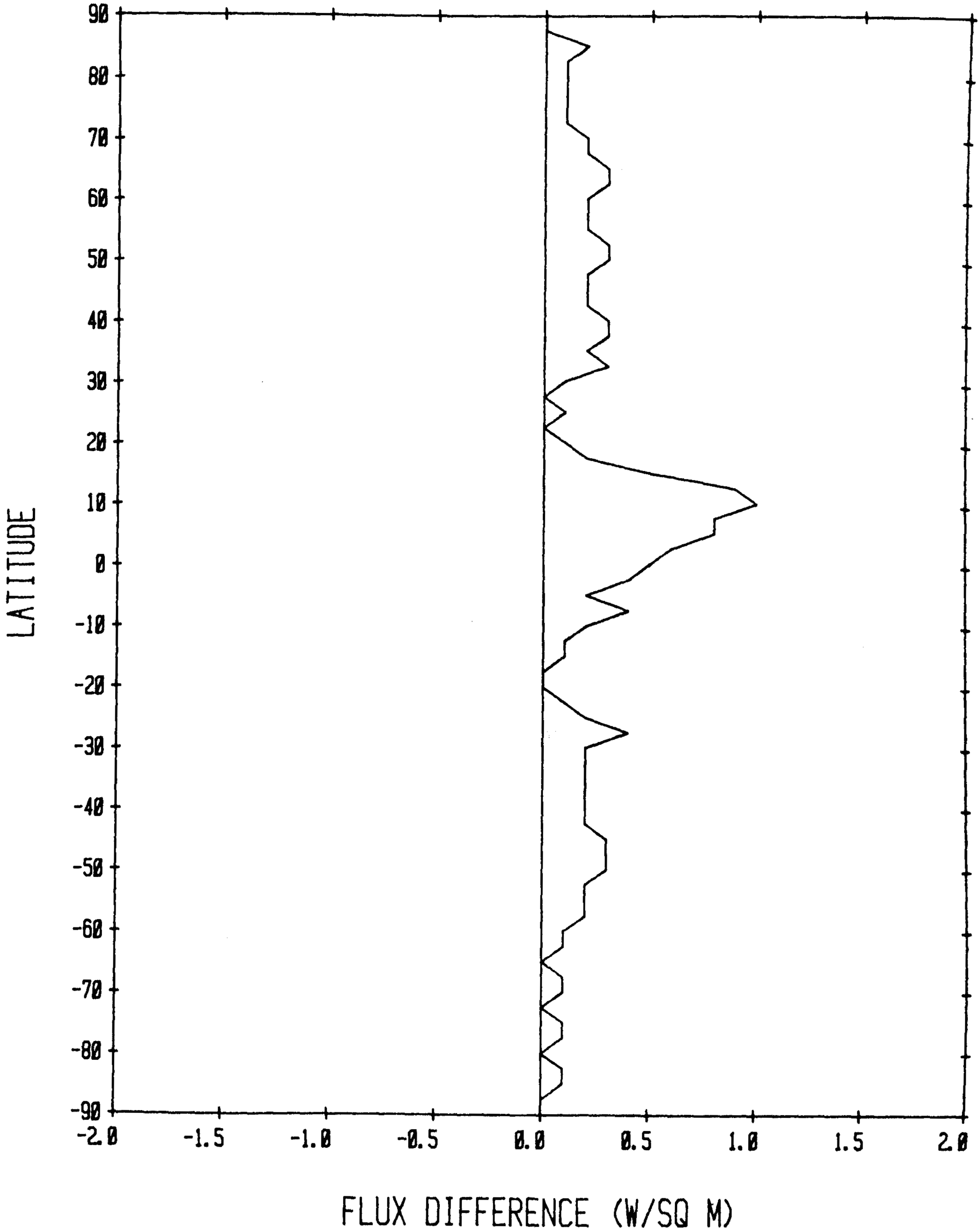

Fig. 4 Zonal average of the emitted flux computed from average radiances minus the average flux computed from each GAC observation.

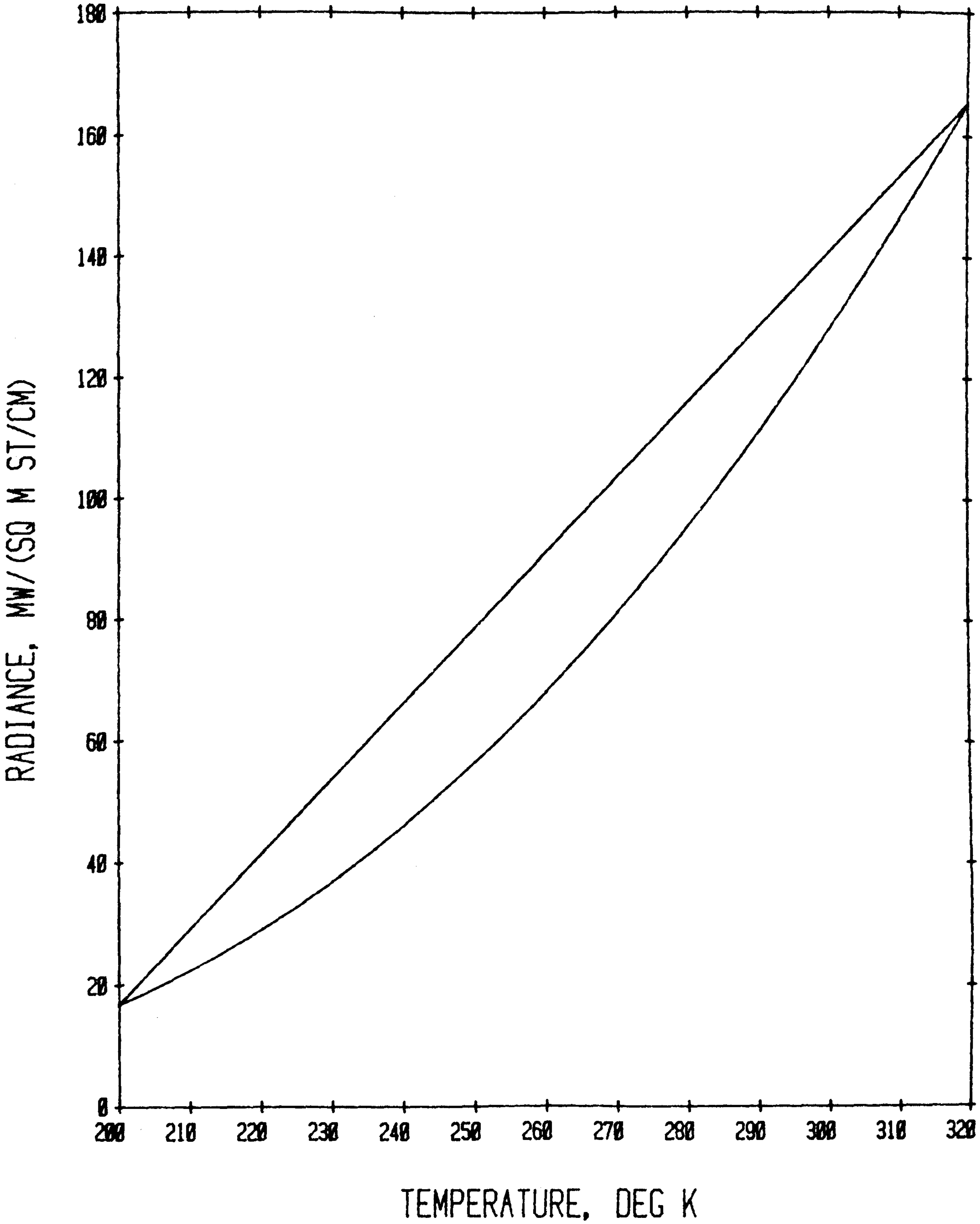

Fig. 5 A plot of radiance versus temperature for the AVHRR Channel 5 (11.5 - 12.5 μ m) (curved line) compared with a linear assumption (straight line).

is necessary to divide the unnormalized albedo by the cosine of the solar zenith angle of the target center and to multiply by the square of the Sun-Earth distance for the time of observation. It is assumed that this value of normalized spectral albedo is equivalent to the broadband albedo and that it remains constant over the day.

The absorbed solar radiation, Ab, is derived from the albedo by use of

$$Ab = (1-A)I_o \tag{5}$$

A is the albedo, I_o the available solar energy. The latter is the amount of radiation incident on the top of the atmosphere over the target on that date, integrated over the day, and divided by one day (in proper units). It is the mean amount of solar radiation striking the atmosphere over the target on that day. It is obviously a function only of solar declination and latitude. The absorbed solar radiation is thus also the mean value in a 24-hour period. It is given in units of w m^{-2}.

Output Products

Thus far the discussion has concerned only individual GAC targets. The global coverage is organized into 125 x 125 square grids which are overlaid on each of the two polar stereographic hemispheres. Each target value is assigned to the closest grid intersection, and all values for each intersection are averaged for a 24-hour period.

Mercator arrays on a 2.5^o x 2.5^o latitude-longitude grid are produced by bi-linear interpolation from the polar stereographic arrays. A value is fitted to a Mercator grid point only if the four surrounding grid points on the polar stereographic grid contain data. Any missing data on the resulting Mercator grid are filled in by interpolation directly in the Mercator array. Interpolated values are flagged with a minus sign.

Each day six longwave radiation arrays are written to a disc archive. There are two 125 x 125 polar stereographic arrays (one for each hemisphere), and one global 2.5^o x 2.5^o Mercator array, for both daytime and nighttime observations.

Two polar stereographic arrays and one Mercator array containing absorbed solar radiation values are written to the archive daily. In addition, there are two polar stereographic arrays containing values of available solar radiation, which are flagged with a minus sign at those locations where the absorbed solar radiation values are missing.

Concluding Comments

The emphasis of this brief report has been on the changes made to the processing system to accommodate the TIROS-N characteristics. Scientifically, we have made only one change: an improved formula for the calculation of broadband emitted flux from window channel radiances. There is, however, a continuing research and development effort for improving the estimates of the radiation budget from the NOAA satellites.

We are currently investigating the possibility of predicting broadband (0.2 - 5.0 μm) reflectances from narrow spectral interval AVHRR channel 1 and channel 2 data (Wydick and Davis, 1983). We are also developing the necessary angle dependencies in our albedo determinations. The results of those activities will be documented in future technical reports.

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