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Nonlinearity Corrections in Calibration of Advanced Very High Resolution Radiometer Infrared Channels

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The infrared channels of the advanced very high resolution radiometer (AVHRR) are calibrated in-flight with data acquired when the AVHRR views space and a warm target on board. This determines the two coefficients of a linear calibration equation. However, in its 11- and 12-μm channels the response of the AVHRR is nonlinear. If not accounted for, the nonlinearity could cause errors as large as 2°C in inferred scene temperatures. Therefore NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) computes corrections to the brightness temperatures inferred from the linear calibration. This paper describes how the corrections have been calculated at NESDIS since March 1986 and presents the corrections for the AVHRRs on the NOAA 9, 10, and 11 satellites. The corrections are calculated from results of the prelaunch calibration, in which a calibrated laboratory blackbody illuminates the AVHRR. At NESDIS the calculation of the corrections differs from that of Brown et al. (1985) because NESDIS transfers the calibration of the laboratory blackbody to the internal calibration target of the AVHRR, but Brown et al. do not. The absolute radiometric accuracy of AVHRR data that have been corrected for the nonlinearity is approximately 0.55°C, of which 0.35°C is traceable to the calibration of the laboratory blackbody.

INTRODUCTION

The advanced very high resolution radiometers (AVHRRs) [*Schwalb*, 1978], which fly on the NOAA series of polar-orbiting satellites, measure radiation emerging from the Earth's atmosphere in spectral intervals in the visible and infrared portions of the spectrum. The data in the infrared intervals are used, among other things, for inferring sea surface temperatures globally. The AVHRRs on some satellites (e.g., NOAA 9 and 11) have three spectral intervals in the infrared, nominally at 3.5–4.0, 10.5–11.5, and 11.5–12.5 μm, known as channels 3, 4, and 5, respectively. The AVHRRs carried by other NOAA satellites, e.g., NOAA 8 and 10, have channels 3 and 4 but not 5.

The infrared channels are calibrated in-flight from measurements of the radiation emitted by an internal calibration target (ICT) and space [*Lauritson et al.*, 1979]. This gives two points on the calibration curve and would completely determine the calibration, assuming that the response of the AVHRR were linear. After being received at the National Environmental Satellite, Data, and Information Service (NESDIS), data from the AVHRR are checked, preprocessed, and injected into the "1b" data stream [*Kidwell*, 1986], which is available to users both within and outside NESDIS. The 1b data include raw data from the Earth scene, in digital count units, accompanied by slopes and intercepts of linear calibration equations, which may be applied to produce radiances and thence brightness temperatures. However, the responses in channels 4 and 5 are not linear because those channels use photoconductive HgCdTe detectors, which are known to respond nonlinearly under certain conditions (I. L. Goldberg, NASA Goddard Space Flight Center, private communication, 1978). (Channels 1–3 use different detectors and should not be subject to nonlinearity from that source.) In channels 4 and 5 therefore the brightness temperatures determined from the linear calibration may not be accurate enough for determining sea surface temperatures, as neglect of the nonlinearity can cause errors of a degree or more.

The most direct way to handle the nonlinearity would be to use a quadratic calibration equation. (Since the AVHRR lacks a second internal calibration target, the coefficient of the squared term would have to be determined from prelaunch measurements.) However, this approach would require substantial changes to operational software at NESDIS, which was coded originally to implement the linear calibration. Instead, NESDIS computes tables of brightness temperature corrections versus scene temperature, which are disseminated to users in addenda to Appendix B of *Lauritson et al.* [1979]. Users of 1b data may apply those corrections to the scene temperatures they derive from the linear calibration. At NESDIS, we apply the nonlinearity corrections to the brightness temperatures as the first step in retrieving sea surface temperatures [*McClain et al.*, 1985]. Therefore users of sea surface temperatures from NESDIS do not have to concern themselves with the nonlinearity correction.

The method for generating the tables has been changed several times over the years, as problems with them have been pointed out [e.g., *Brown et al.*, 1985]. This paper documents how the corrections are calculated currently at NESDIS. The method follows *Brown et al.* [1985] with one important difference, which will be explained below. The

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first nonlinearity table generated by this method was issued in March 1986 for the AVHRR on NOAA 9, which had been in orbit since December 12, 1984. (There was a nonlinearity table in use before March 1986, but it was generated by a different method.) The current method was also used to generate the correction tables for the AVHRRs on NOAA 10 and 11, which were launched on October 17, 1986, and September 24, 1988, respectively.

PRELAUNCH CALIBRATION

The nonlinearity corrections are calculated from data obtained in the prelaunch calibration at *ITT Aerospace/Optical Division* [1980*a*, *b*, 1981], which is now briefly described. An AVHRR, operating as in orbit, is situated in a thermal/vacuum chamber, where it views a calibrated laboratory blackbody representing the Earth scene and a blackbody cooled to about 77 K simulating the in-orbit space view. The AVHRR's scan mirror rotates at 6 Hz in the cross-track plane, reflecting radiation sequentially from the blackbody "scene," the cooled "space" target, and the AVHRR's ICT to the AVHRR's detectors, whose outputs are amplified, digitized, and recorded. Data are collected as the laboratory blackbody is cycled between 175 and 315 K, in 10 K steps between 175 and 290 K and 5 K steps above 290 K. The entire calibration procedure is carried out for three settings of the AVHRR's baseplate temperature, nominally 10°, 15°, and 20°C.

The laboratory blackbody consists of a cylinder with black-painted honeycomb surfaces on its base (which is the only area viewed by the AVHRR) and walls. Its calculated emissivity is greater than 0.996 [*ITT Aerospace/Optical Division*, 1976]. Both the laboratory blackbody and the target representing cold space are of the same physical construction.

The temperature of the laboratory blackbody is monitored by eight platinum resistance thermometers (PRTs) embedded just below its radiating surface and in good thermal contact with it. This ensures that the PRT readings are a good representation of the actual surface temperature. The PRTs are purchased to a tight tolerance for linearity and change of resistance versus temperature. Once they are received at ITT, each is individually calibrated against a standard Rosemount Engineering PRT in a variable temperature bath. The range of temperatures over which an individual PRT is calibrated depends on its use. For the laboratory blackbody PRTs, the calibration is from 170 K to 330 K in 5 K steps. The data are fitted by least squares to a polynomial relating temperature to PRT output, viz.,

$$T = \sum_{i=0}^{2} a_i X^i$$

where T is temperature, X is count output of the PRT, and a_i are the coefficients determined in the calibration. The standard PRT is periodically sent out for recertification against a standard from the National Bureau of Standards (NBS). This process assures that the temperatures read out by the PRTs are traceable to NBS references.

Together with the high emissivity of the laboratory blackbody and the well-regulated conditions in the surrounding environment, the careful PRT calibration results in a radiometric calibration of the laboratory blackbody that is accurate to within approximately 0.35 K in all channels of the AVHRR [*ITT Aerospace/Optical Division*, 1976]. Most of the uncertainty comes from the temperature measurement and from gradients within the blackbody; nonblackness and the resulting reflection from surrounding elements contribute only approximately 10% of the total uncertainty.

The AVHRR's ICT is a flat plate with a black-painted honeycomb surface. Constraints on size and weight, as well as the fact that its environment cannot be controlled as carefully, prevent it from being as "black" as the laboratory blackbody. Nevertheless, its emissivity is calculated to be at least 0.994 [*ITT Aerospace/Optical Division*, 1976]. The temperature of the ICT is monitored by PRTs at four sites within it. These PRTs are calibrated against the NBS-traceable standard PRT in a manner identical to that of the PRTs in the laboratory blackbody, except that the range of calibration is 278 K to 298 K in 5 K steps. This covers the range of temperatures the ICT assumes in orbit. The accuracy of the ICT calibration is estimated to be better than 0.4 K [*ITT Aerospace/Optical Division*, 1976]. As with the laboratory blackbody, most of the uncertainty comes from the temperature measurement and gradients in the ICT; nonblackness contributes only approximately 20% of the total.

In each of the AVHRR's channels, radiances are computed from the temperatures of the ICT and the laboratory blackbody as convolutions of the Planck function over the AVHRR's spectral response functions. The blackbody's and ICT's emissivities are assumed to be unity in all channels. In actual application the temperature-to-radiance conversions are done with look-up tables, one for each channel, which are precomputed for temperatures between 180 K and 320 K at every 0.1 K.

RECALIBRATION OF PLATINUM RESISTANCE THERMOMETERS

One of the main purposes of the prelaunch calibration is to ensure that the calibrations of the ICT and the laboratory blackbody are consistent. This is necessary if the calibration of the AVHRR in-flight is to be traceable to the laboratory blackbody and thence to NBS references. By consistency, we mean that the radiance of the ICT computed from the temperature measurements of the PRTs embedded in it should be identical to the radiance measured by the AVHRR itself after it had been calibrated against the laboratory blackbody. However, analysis of thermal/vacuum data shows that there can be differences between the radiances determined in those two ways. Expressed in units of brightness temperature, the differences have been as large as 0.7°C for some AVHRRs.

Consistency also implies that if the temperature of the ICT, measured by its PRTs, equalled the temperature of the laboratory blackbody, then the AVHRR will put out the same signal (in counts) when it views the ICT as it does when it views the laboratory blackbody. However, significant differences between those two signals were noticed in the prelaunch calibration data of the NOAA 9 AVHRR (G. Rochard, Centre de Meteorologie Spatiale, Lannion, France, personal communication, 1987), indicating again that the calibrations of the ICT and laboratory blackbody were not consistent.

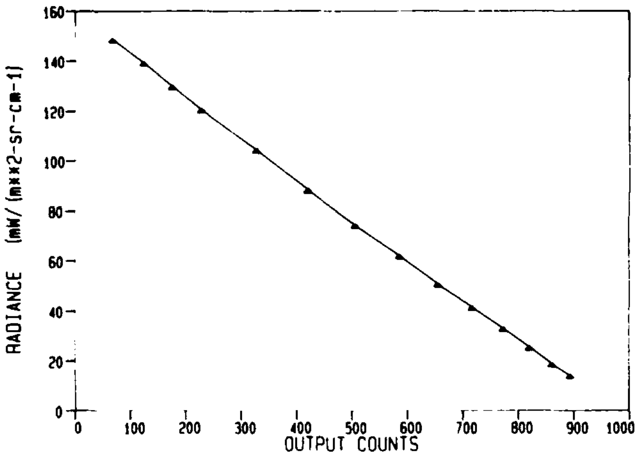

Fig. 1. Calibration curve for channel 4 of NOAA 9 AVHRR.

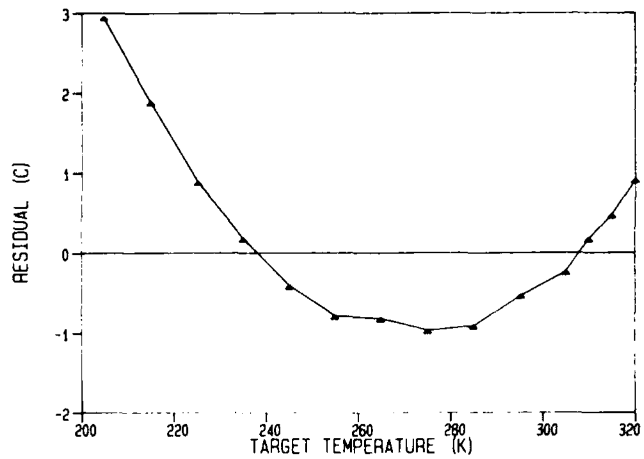

Fig. 2. Residuals from linear fit to calibration curve in Figure 1.

To force consistency, NESDIS modifies the calibration of the PRTs of the ICT as described below. *Brown et al.* [1985], however, do not attempt to achieve consistency between the calibrations of the ICT and the laboratory blackbody. In effect, Brown et al. base the AVHRR calibration in orbit on the NBS calibration of the PRTs of the ICT, whereas our approach bases it on the NBS calibration of the PRTs of the laboratory blackbody. As will be seen below, this difference in approach is the main cause of the differences in the nonlinearity corrections produced by the two groups.

The PRT calibration is modified at NESDIS as follows.

1. The AVHRR calibration, i.e., a table relating target radiance and the output of the AVHRR in digital counts, is generated from the data obtained in the thermal/vacuum tests when the AVHRR viewed the standard blackbody. Figure 1 is a plot of such data for channel 4 of the NOAA 9 AVHRR. For each channel of each AVHRR there will be three tables, one for each of the three baseplate temperatures.

2. The AVHRR's outputs, in digital counts, are averaged over all the times it viewed its ICT during the calibration process. There is a separate average for each baseplate temperature. The averages are then converted to radiances, via interpolation in the AVHRR calibration table, and then to brightness temperatures through the radiance-to-temperature look-up table described previously. This produces a brightness temperature of the ICT in each of the AVHRR's infrared channels for each baseplate temperature. In principle, the brightness temperatures may vary from channel to channel, but in practice we find that they are usually within 0.1 K of each other. The average over channels provides a single brightness temperature of the ICT for each baseplate temperature.

3. Throughout the calibration process, the outputs (in digital counts) of the four PRTs of the ICT had been recorded. The count values are converted to "thermodynamic" temperature via the original PRT calibration. By averaging over the four PRTs, we produce an average thermodynamic temperature of the ICT. All the measurements obtained during the calibration process at each individual baseplate temperature are then averaged. This produces a single average thermodynamic temperature of the ICT for each baseplate temperature. If the difference between this temperature and the average brightness temperature (from step 2) exceeds a predetermined threshold at one or more baseplate temperatures, the PRT calibration will be modified. On the other hand, if the differences at all baseplate temperatures are less than the threshold, then the original calibration is judged to be valid for calibrating the AVHRR in flight and is retained. The value of the threshold is selected empirically from our estimate of the uncertainty in the differences (see below).

4. If the original calibration is not valid, then we modify the calibration (which is in the form of a polynomial) of each PRT by adjusting the constant term, so that in the average over the three baseplate temperatures, the PRT reads out a temperature equal to the brightness temperature measured by the AVHRR. Because the PRT measurements all cluster around the three baseplate temperatures, and because the uncertainties in this process are estimated to be a tenth of a degree or greater, more sophisticated data-fitting procedures are not warranted. One may question why we choose to force equality of average temperatures rather than average radiances in calculating adjustments to the PRT calibration. In principle, it is preferable to base the adjustment on the average radiances. However, because the range of temperatures involved is so small, the adjustments that result from those two approaches differ by no more than a few hundredths of a degree, which is insignificant. On the other hand, it is computationally simpler to work with temperatures.

Note that the modified calibration applies only over the limited range of temperatures the ICT is expected to have in orbit (approximately 10°–20°C) and may be invalid at other temperatures.

THE NONLINEARITY CORRECTION

To demonstrate that the nonlinearity is large enough to warrant a correction, we fitted the calibration data in Figure 1 by least squares to a straight line. The residuals, expressed in units of brightness temperature, are plotted in Figure 2. The pattern is typical of data with curvature. The absolute values exceed 1.0°C at some target temperatures encountered in sea surface temperature measurements. Since accuracy goals for sea surface temperatures are 0.2°–0.3°C [*McClain et al.*, 1985], such errors cannot be tolerated.

The nonlinearity corrections for each channel are calcu-

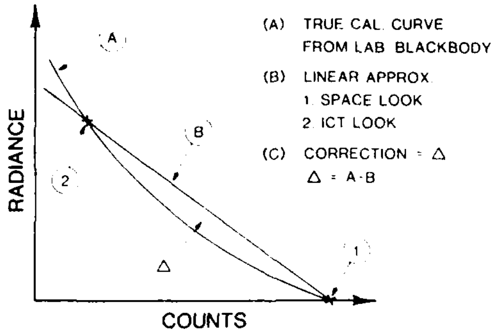

Fig. 3. Illustration of how nonlinearity correction terms are computed.

lated from the prelaunch calibration data as functions of scene temperature. As *Brown et al.* [1985] pointed out, the corrections are also a function of baseplate temperature. Therefore, for each of the three baseplate temperatures at which the prelaunch calibration was done, a separate table of corrections is generated. To find the appropriate correction in practice, the user should interpolate between tables on the temperature of the baseplate or, equivalently, that of the ICT, since they are identical within a fraction of a degree.

Figure 3 illustrates how the nonlinearity corrections are calculated. Curve A represents a "true" AVHRR calibration determined from the laboratory blackbody. Line B represents the linear approximation to the calibration determined from the data collected when the AVHRR viewed the ICT and the 77 K laboratory blackbody ("space"). The radiance of the 77 K target is at least 3 orders of magnitude less than the specified noise in the measurements, so it is taken to be zero. The radiance of the ICT can be computed from the average of the temperatures indicated by the four PRTs embedded in it. Since the calibration of the laboratory blackbody had previously been transferred to the PRTs, the ICT point lies on the true calibration curve. Therefore, with laboratory data (but not flight data), one can also compute the ICT radiance by interpolating in the true calibration relationship to the count value put out by the AVHRR as it viewed the ICT, and in actual practice that is how the calculation is done.

The nonlinearity correction is the difference between the true calibration and the linear approximation. For each channel the corrections are tabulated against scene temperature and baseplate (or ICT) temperature. To apply them to data obtained from the AVHRR in flight, one first derives a scene temperature from the linear calibration and then adds the correction to it. This procedure gives a good estimate of the true brightness temperature of the scene, under the assumption that the nonlinearity is the same in flight as it was before launch.

Previously it was mentioned parenthetically that when the calibration of the ICT is consistent with that of the laboratory blackbody, the ICT point will lie on the true calibration curve, as it is pictured in Figure 3. As a consequence, the correction should be zero when the scene temperature equals the ICT temperature. The corrections produced at NESDIS since 1986 have that property. However, if the ICT calibration were not consistent with that of the laboratory blackbody, the ICT point would not lie on the true calibration curve, and the zero correction would occur at a different scene temperature. Such behavior can be seen in some of the tables produced by NESDIS before 1986 and in those of *Brown et al.* [1985] (see below).

TABLE 1. PRT Temperatures and Brightness Temperatures of ICT

Satellite	AVHRR ID	PRT Temperature, °C	Brightness Temperature, °C	Difference, °C
NOAA 9	S/N 202	9.3	10.0	0.7
		14.3	15.0	0.7
		19.2	19.3	0.1
NOAA 10	F/M 101	9.0	8.7	0.3
		13.9	13.8	0.1
		19.4	19.1	0.3
NOAA 11	S/N 203	9.2	9.2	0.0
		13.9	13.9	0.0
		19.0	19.0	0.0

TABLE 2. Modified PRT Calibration Coefficients

Satellite	AVHRR ID	a_0	a_1	a_2
NOAA 9	S/N 202	277.10	0.051275	1.363×10^{-6}
NOAA 10	F/M 101	276.41	0.051275	1.363×10^{-6}
NOAA 11	S/N 203	276.60	0.051275	1.363×10^{-6}

RESULTS

PRT Recalibration

The prelaunch calibration data used for checking and recalibrating the PRTs were taken from the ITT Alignment and Calibration Data Books [*ITT Aerospace/Optical Division*, 1980*a*, *b*, 1981] for each of the AVHRRs. Table 1 shows the results of checking the original PRT calibration by the procedure described in the previous section. Listed are the average PRT temperature, the average brightness temperature, and their difference for three instruments and three baseplate temperatures. For the NOAA 10 and 11 AVHRRs the differences at the three baseplate temperatures are

TABLE 3. Nonlinearity Correction Terms, in degrees Celsius, for NOAA 9

Scene Temperature, K	Internal Target Temperature, °C					
	Channel 4			Channel 5		
	10.0	15.0	19.3	10.0	15.0	19.3
320	2.35	2.53	2.28	0.82	1.14	1.16
315	1.89	1.97	1.81	0.64	0.83	0.91
310		1.55	1.31		0.71	0.68
305	1.45	1.02	0.88	0.66	0.35	0.47
295	0.82	0.46	0.17	0.45	0.20	0.09
285	0.11	-0.22	-0.48	0.05	-0.09	0.24
275	-0.48	0.61	-0.90	-0.25	0.31	-0.47
265	0.71	-0.84	-1.26	-0.42	0.46	-0.75
255	0.96	-1.25	-1.50	0.63	-0.81	-0.91
245	1.09	1.36	-1.66	-0.76	-0.92	-1.12
235	1.15	1.38	-1.60	1.03	-1.19	-1.31
225	1.32	1.39	1.53	1.14	-1.11	-1.14
215	1.22	1.34	-1.42	-1.24	-1.28	-1.41
205	1.21	1.48	-0.90	-1.43	-1.62	-1.23

TABLE 4. Nonlinearity Correction Terms, in degrees Celsius, for NOAA 10, Channel 4

Scene Temperature, K	Internal Target Temperature, °C		
	8.7	13.8	19.1
320	3.50	2.83	2.54
315	2.93	2.19	1.97
305	1.88	1.34	1.11
295	1.12	0.57	0.12
285	0.20	−0.15	−0.38
275	−0.46	−0.53	−1.08
265	−0.76	−0.93	−1.37
255	−1.33	−1.49	−1.77
245	−1.74	−2.09	−2.26
235	−1.79	−2.20	−2.53
225	−2.22	−2.51	−2.53
215	−2.58	−2.65	−2.80
205	−2.47	−2.88	−3.27

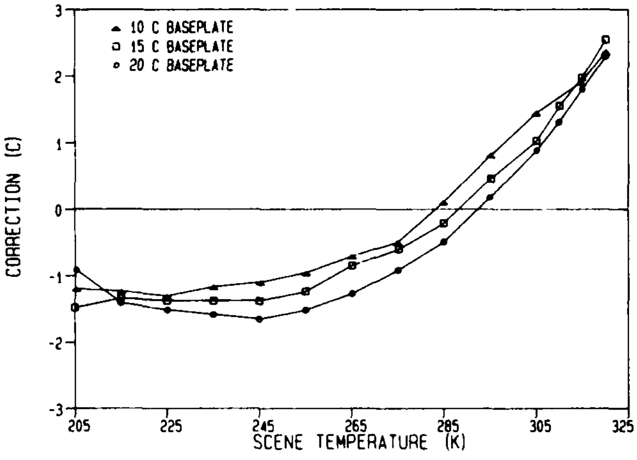

Fig. 4. Nonlinearity correction terms for channel 4 of NOAA 9 AVHRR.

relatively consistent and suggest that the uncertainty in the differences is approximately 0.1°C. The NOAA 9 data appear less consistent (for reasons unknown), suggesting an uncertainty of 0.2°C or more. Adopting the uncertainty values as the recalibration thresholds, we decided that the PRTs of the NOAA 9 and 10, but not NOAA 11, AVHRRs need to be recalibrated.

The recalibration yields a new value of a_0 in the PRT calibration equation. The original (thermodynamic) calibration coefficients that ITT supplied were the same for each of the four PRTs of the ICT, the result of "trimming" the electronics. Since the ICT temperature is computed as an average of the four PRT readings, and since the recalibration is based on the average, it does not matter what the individual polynomials are as long as their average gives the correct brightness temperature. Therefore the same adjustment is made in the calibration equation of each PRT. This maintains the use of a single calibration equation for all four PRTs. The new coefficients are listed in Table 2. (Note that for NOAA 11 the coefficients are unchanged from their original values.)

Nonlinearity Corrections

The nonlinearity corrections for channels 4 and 5 of the AVHRRs on NOAA 9, 10, and 11 are listed in Tables 3–5 and are plotted in Figures 4–8. They were computed from data in the ITT Alignment and Calibration Books [*ITT Aerospace/Optical Division*, 1980*a*, *b*, 1981].

Retest of NOAA 11 AVHRR

The preceding results were derived from data obtained in thermal/vacuum tests conducted in 1980 and 1981. However, the NOAA 11 AVHRR was partially retested in the spring of 1988 after some malfunctioning electronics components were replaced. The infrared channels were recalibrated, but at only one (nominally 15°C) of the three plateaus of the baseplate temperature. Table 6 lists the nonlinearity corrections that resulted.

Comparing Table 6 with the corresponding data in Table 5, one finds that in channel 5 the 1988 correction terms are essentially the same as those from 1981, but in channel 4 there was a significant change. It would be preferable to use the more recent correction terms for channel 4, but with data at just the 15° ICT temperature, they are incomplete. Cor-

TABLE 5. Nonlinearity Correction Terms, in degrees Celsius, for NOAA 11

Scene Temperature, K	Internal Target Temperature, °C					
	Channel 4			Channel 5		
	9.2	13.9	19.0	9.2	13.9	19.0
320	4.81	4.16	3.64	1.43	1.26	1.12
315	4.03	3.43	2.93	1.23	1.03	0.89
310	3.28	2.68	2.20	1.05	0.84	0.70
305	2.56	1.99	1.52	0.85	0.64	0.47
295	1.27	0.82	0.27	0.43	0.28	0.09
285	0.23	−0.20	−0.71	0.07	−0.07	0.23
275	−0.61	−1.06	−1.41	−0.19	−0.34	−0.47
265	−1.22	−1.58	−1.91	0.37	−0.51	−0.60
255	−1.70	−2.08	−2.35	−0.60	−0.77	−0.78
245	−2.02	−2.43	−2.63	−0.72	0.90	−0.92
235	−2.21	−2.42	−2.55	−0.84	−1.02	1.00
225	2.18	2.46	−2.71	0.94	1.06	−1.16
215	−2.17	−2.41	−2.55	−1.12	−1.24	−1.16
205	−1.97	−2.25	−2.12	−1.15	−1.27	−1.23

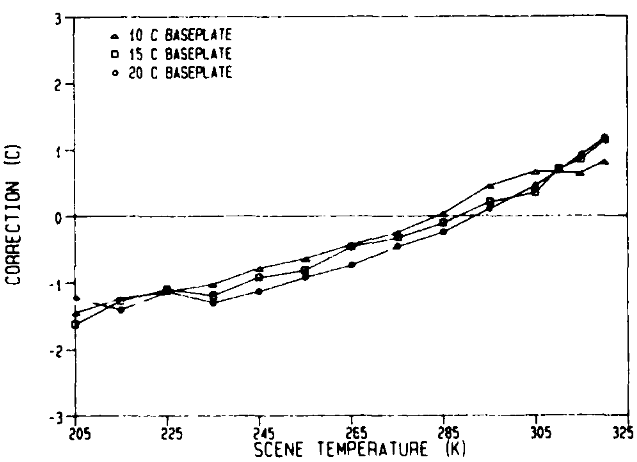

Fig. 5. Nonlinearity correction terms for channel 5 of NOAA 9 AVHRR.

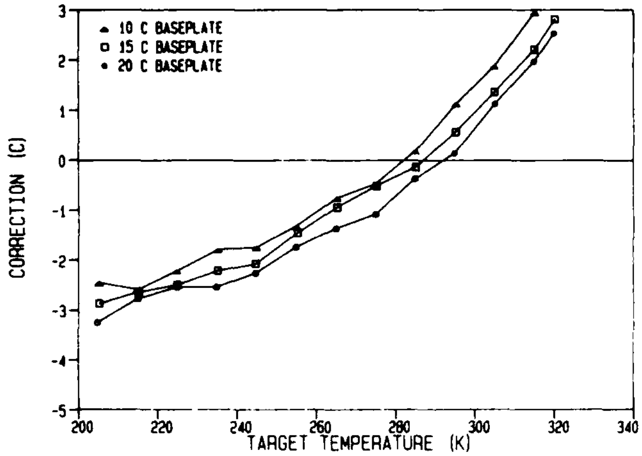

Fig. 6. Nonlinearity correction terms for channel 4 of NOAA 10 AVHRR.

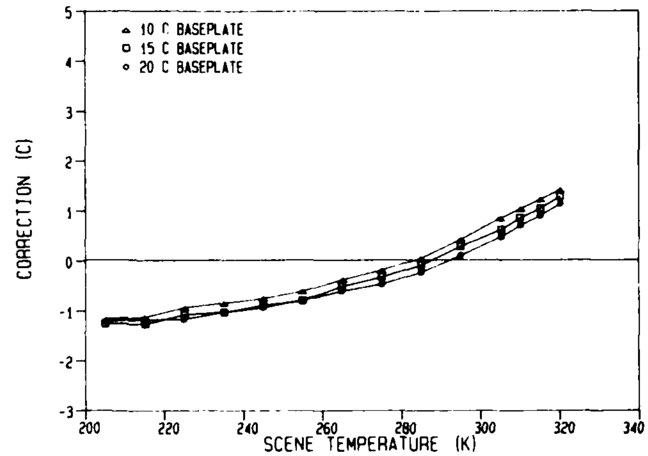

Fig. 8. Nonlinearity correction terms for channel 5 of NOAA 11 AVHRR (based on 1981 data).

rection terms must be available at more than one ICT temperature to permit users to derive in-flight corrections by interpolating on the observed ICT temperature. However, we decided to estimate what the 1988 corrections would have been at ICT temperatures of 10° and 20°C by assuming that between 1981 and 1988 the percent changes in the correction terms were the same at all three ICT temperatures. Using the observed percent changes in the correction terms at the 15° ICT temperature as guide, we can then extrapolate to 1988 the correction terms at the other two ICT temperatures. Table 7 lists the corrections in channel 4 that result. (The data were also smoothed slightly at some scene temperatures below 285 K to compensate for noise amplification in the extrapolation procedure.) The revised corrections in channel 4 (Table 7) along with the original corrections in channel 5 (Table 5) were provided to users in the NOAA 11 amendment to Appendix B of *Lauritson et al.* [1979].

DISCUSSION

In Figures 4–8, the three curves of correction terms versus scene temperature are nearly parallel. This is most apparent with the 1981 NOAA 11 data (Figures 7 and 8), which are the smoothest. If the curves were exactly parallel, then considered as a function of scene temperature minus baseplate temperature, the correction terms would be independent of baseplate temperature. Also, if the calibration were formulated as a quadratic equation, the coefficient of the quadratic term would be independent of baseplate temperature.

We are not certain why the curves for the NOAA 9 and 10 AVHRRs are less smooth than those of the NOAA 11 AVHRR. The variability can be traced back to the raw data, suggesting that the cause is in the test procedure.

The zero crossing of each curve is (within numerical roundoff) at the temperature of the ICT, or baseplate. This is a consequence of the practice at NESDIS of using the calibrated AVHRR to measure the radiance of the ICT, as was described previously. On the other hand, plots of nonlinearity corrections for the NOAA 9 AVHRR from *Brown et al.* [1985], appearing in Figures 9 and 10, illustrate that if this were not done, and if the calibrations of the ICT and the laboratory blackbody were not consistent, the zero crossings would not be at the ICT temperatures.

The magnitudes of the nonlinearity corrections of *Brown et al.* [1985] differ from ours, usually by a fraction of a degree, but in some instances by a degree or slightly more.

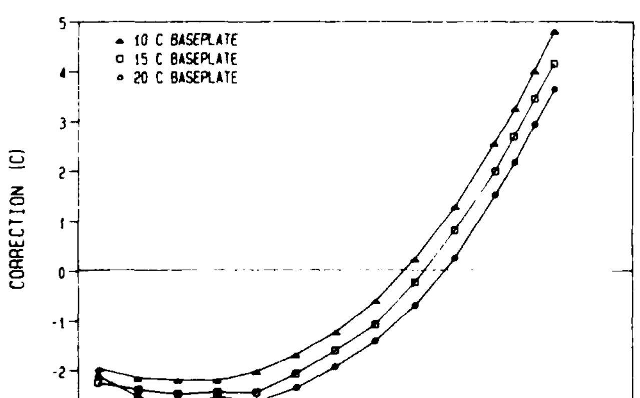

Fig. 7. Nonlinearity correction terms for channel 4 of NOAA 11 AVHRR (based on 1981 data).

TABLE 6. 1988 Nonlinearity Correction Terms, in degrees Celsius, for NOAA 11

Scene Temperature, K	Channel 4	Channel 5
320	3.71	1.37
315	2.98	1.07
310	2.33	0.89
305	1.73	0.66
295	0.68	0.26
285	−0.21	−0.09
275	−0.79	−0.33
265	−1.37	−0.49
255	−1.72	−0.75
245	−2.05	−0.91
235	−2.05	−1.07
225	−2.14	−1.16
215	−2.02	−1.25
205	−1.76	−1.37

Internal target temperature is 14.2°C.

TABLE 7. Revised Nonlinearity Correction Terms in Degrees Celsius, for NOAA 11, Channel 4

Scene Temperature, K	Internal Target Temperature, °C		
	9.2	14.2	19.0
320	4.29	3.71	3.25
315	3.50	2.98	2.55
310	2.85	2.33	1.91
305	2.23	1.73	1.32
295	1.05	0.68	0.22
285	0.24	−0.21	−0.67
275	−0.45	−0.79	−1.15
265	−1.06	−1.37	−1.66
255	−1.41	−1.72	−2.03
245	−1.70	−1.96	−2.22
235	−1.87	−2.10	−2.28
225	−1.90	−2.14	−2.36
215	−1.82	−2.02	−2.20
205	−1.54	−1.76	−1.98

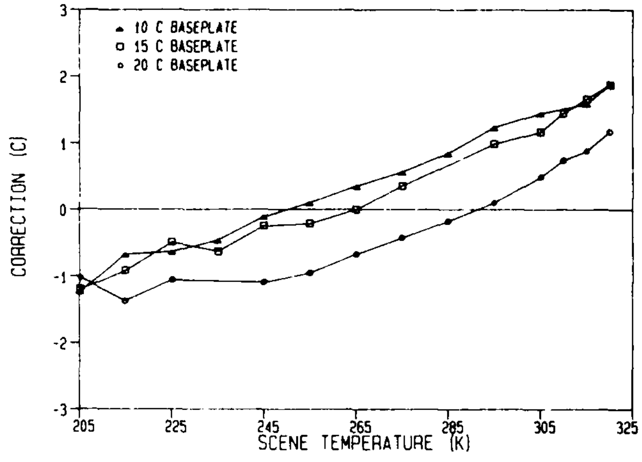

Fig. 10. Nonlinearity correction terms for channel 5 of NOAA 9 AVHRR [from *Brown et al.*, 1985].

As was previously mentioned, the reason is that the in-orbit calibration of Brown et al. is based on the NBS calibration of the PRTs of the internal calibration target, whereas ours is based on the NBS calibration of the PRTs of the laboratory blackbody. However, since both groups tie their nonlinearity corrections to the NBS calibration of the PRTs of the laboratory blackbody, the nonlinearity corrections themselves will tend to compensate for the differences in the in-orbit calibration, with the result that the two approaches will yield scene temperatures that are not so different. (Of course, the nonlinearity corrections must be consistent with the in-orbit calibration; e.g., if the in-orbit calibration is by the approach of this paper, then the user should apply the nonlinearity corrections from this paper.) The only instance where the two approaches may yield significantly different scene temperatures will be where no nonlinearity corrections are made, as in channel 3.

Users of AVHRR data who receive the addenda to Appendix B of *Lauritson et al.* [1979] may note that their NOAA 9 correction terms are slightly different from those in Table 3 of this paper. With one or two exceptions, the differences, when they exist, are of the order of 0.1°C or less.

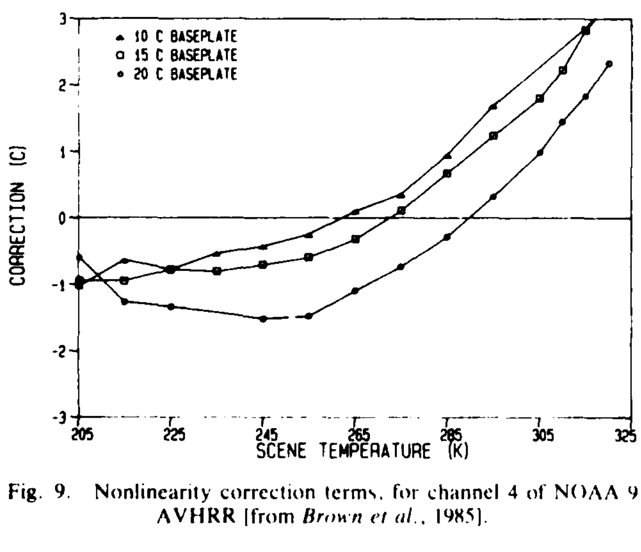

Fig. 9. Nonlinearity correction terms, for channel 4 of NOAA 9 AVHRR [from *Brown et al.*, 1985].

The reason is that for Appendix B the corrections were computed from tapes of raw test data, whereas for this paper the corrections were computed from data in the ITT Alignment and Calibration Books. For the NOAA 10 AVHRR, the correction terms in this paper were issued in December 1989 in a revised addendum to Appendix B. The correction terms for the NOAA 10 AVHRR that appeared in the 1986 addendum to Appendix B are incorrect. The NOAA 11 data in Tables 5 and 7 are in the addendum to Appendix B dated September 20, 1988.

The change in the NOAA 11 nonlinearity correction terms that occurred between 1981 and 1988 is more likely a result of aging of the detectors than the replacement of electronics components. Properties of the HgCdTe detectors may change when they are stored at warm temperatures for long periods. (Once the AVHRRs are in orbit and the detectors are cooled, aging is much less likely to affect their performance.) It is imperative therefore that prelaunch calibration of the instruments be carried out as close as possible to the launch date. That has not been the practice up to now. Final thermal vacuum tests have been carried out anywhere from 6 months to 6 years before launch.

The accuracy of the AVHRR calibration described in this paper is limited a priori by the 0.35°C uncertainty in the calibration of the laboratory blackbody. There is an additional uncertainty from the transfer of the calibration of the laboratory blackbody to the ICT. For the NOAA 10 and 11 AVHRRs, it is 0.1°C or less, but for NOAA 9 it may exceed 0.2°C. Systematic errors in the nonlinearity corrections, estimated from the departure from smoothness in the curves of Figures 4–8, are of the order of 0.1°C or less in the average over all the points. In sum, the uncertainty in absolute accuracy is approximately 0.55°C in channels 4 and 5. We believe that this figure is more realistic than the 0.2°C calibration error estimated by *Brown et al.* [1985]. It should be realized that the accuracy will be degraded further if the properties of the AVHRR change during storage before launch.

These considerations imply that the 0.2–0.3°C accuracy goal for sea surface temperatures is probably not attainable a priori with the AVHRR. In an attempt to attain accuracies closer to the goal, NESDIS makes empirical adjustments to the retrieval coefficients, based on comparisons with temperature measurements from drifting buoys [*Strong and McClain*, 1984]. This minimizes the bias between the skin temperatures sensed by the AVHRR and the bulk water temperatures sensed by the buoys.

Conclusion

Neglect of the nonlinearity in the 11- and 12-μm channels of the AVHRR may cause errors of several degrees in inferred scene temperatures, especially at the high and low extremes. Since the in-flight calibration procedure in these channels is linear, NESDIS provides nonlinearity correction terms tabulated against scene temperature and instrument baseplate temperature. The corrections are calculated once and for all before launch from thermal/vacuum calibration data with the method described in this paper. Because NESDIS uses the thermal/vacuum data to transfer the calibration of the laboratory blackbody to the AVHRR's internal calibration target, the nonlinearity corrections are zero when the scene temperature and the temperature of the internal calibration target are the same. Assuming that the nonlinearity corrections remain valid after launch, the error in absolute radiometric accuracy in the infrared channels of the AVHRR is estimated to be approximately 0.55°C. Of this, approximately 0.35°C is traceable to the calibration of the laboratory blackbody. Changes observed in nonlinearity coefficients for the NOAA 11 AVHRR between 1981 and 1988 suggest that the degree of nonlinearity may change while the AVHRRs are in storage before launch. Therefore the prelaunch calibration should be carried out as close to the launch date as possible.

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