NOAA Technical Report NESDIS 78

POST-LAUNCH CALIBRATION OF THE VISIBLE AND NEAR INFRARED CHANNELS OF THE ADVANCED VERY HIGH RESOLUTION RADIOMETER ON NOAA-7, -9, AND -11 SPACECRAFT

Washington, D.C.
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U.S. DEPARTMENT OF COMMERCE
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U.S. DEPARTMENT OF COMMERCE
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National Oceanic and Atmospheric Administration
D. James Baker, Under Secretary

National Environmental Satellite, Data, and Information Service
Robert S. Winokur, Assistant Administrator

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Prefatory Note

This is the third in a series of reports on work performed under the NOAA/NASA Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Calibration Activity. While the first two reports (NOAA Technical Reports NESDIS 69 and 70) summarized the recommendations of the NOAA/NASA AVHRR Pathfinder Calibration Working Group, this report describes work done at the Satellite Research Laboratory, NOAA/NESDIS Office of Research and Applications, on the development of post-launch inter-satellite calibration linkages for the AVHRRs on NOAA-7, -9, and -11 spacecraft. These linkages are crucial to the establishment of long-term records of operational products based on measurements made with the three AVHRRs. The formulae for the calculation of calibrated radiances and albedos (AVHRR usage) given in this report have already been implemented in AVHRR products such as NOAA's Clouds from AVHRR (CLAVR) and Normalized Difference Vegetation Index climatology, and in the generation of the NOAA/NASA Pathfinder AVHRR Land Data Set. In addition, the work described here has been reviewed by several scientists, including some members of the AVHRR Pathfinder Calibration Working Group. However, I wish to reiterate, in my capacity as the Chair of the Working Group, that this report summarizes the results obtained at NOAA/NESDIS Satellite Research Laboratory.

C. R. Nagaraja Rao

C.R. Nagaraja Rao

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ABSTRACT

The absence of onboard calibrators or stability monitors renders difficult the post-launch calibration of the visible (channel 1; ≈0.58-0.68μm) and near-infrared (channel 2: ≈0.72-1.1μm) channels of the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-7, -9, and -11 spacecraft, and necessitates the use of vicarious calibration techniques. Thus, using the southeastern Libyan desert as a radiometrically stable calibration target, the relative rates of degradation of the two channels have been evaluated. The annual degradation rates, in percent, for the two channels are respectively: 3.6 and 4.3 (NOAA-7); 5.9 and 3.5 (NOAA-9); and 1.2 and 2.0 (NOAA-11). Using the relative degradation rates thus determined, and absolute calibrations based on congruent path aircraft/satellite radiance measurements over White Sands, New Mexico, the variation in time of the gain or "slope" of the AVHRR on NOAA-9 has been established. Interrelationships among the radiances measured by the three AVHRRs have been developed, using the AVHRR on NOAA-9 as a normalization standard. Formulae for the calculation of calibrated radiances and albedos (AVHRR usage) are given for the three AVHRRs, as are a few examples of their application.

1. Introduction

One of the main objectives of the National Oceanographic and Atmospheric Administration (NOAA)/National Aeronautics and Space Administration (NASA) Advanced Very High Resolution Radiometer (AVHRR) Pathfinder program is the establishment of long-term, accurate records of environmental products such as vegetation cover, cloud morphology, aerosols, and sea surface temperature generated from broad-band spectral measurements made by the AVHRRs onboard the NOAA-7, -9, and -11 spacecraft (Ohring and Dodge 1992). There is evidence (e.g., Staylor 1990; Whitlock et al., 1990) that the in-orbit performance of the AVHRR visible (channel 1; ≈0.58-0.68μm) and near-infrared (channel 2: ≈0.72-1.1μm) channels, which have no onboard calibration devices, degrade in time, initially because of the outgassing (e.g., water vapor from filter interstices) and launch-associated contamination (e.g., rocket exhaust and outgassing), and subsequently because of the continued exposure to the harsh space environment. It was thus recognized at the inception of the NOAA/NASA Pathfinder program that: (a) the in-orbit degradation of the AVHRR visible and near-infrared channels should be evaluated and appropriate correction algorithms developed, and (b) interrelationships among the radiance measurements made by the three AVHRRs should be established so that continuity of record of the environmental products for the Pathfinder period, 1981-present, would be ensured. Accordingly, we wish to present and discuss here: (a) the degradation rates that we have determined for the three radiometers; (b) development of interrelationships among the radiances measured by the three radiometers, using the AVHRR on NOAA-9 as a normalization standard; and (c) the resulting formulae for the calculation of the upwelling radiances and albedos (AVHRR usage).

2. Degradation Rates

2.1 General

Relative changes in the gains of the three AVHRRs, expressed in units of Counts(ct)/[W/(m^2 sr μm)], or equivalently, the relative changes in the "slope", the reciprocal of gain, expressed in units of W/(m^2 sr μm ct), were determined using the southeastern part of the Libyan desert (21-23°N latitude; 28-29°E longitude) as a radiometrically stable calibration target. It is assumed that the isotropic albedo, defined as $(\pi I_i/F_{i0}\mathrm{Cos}\theta_0)$, does not vary in time; here I_i and F_{i0} are respectively the in-band upwelling radiance and the extraterrestrial solar irradiance in the i^{th} channel; and θ_0 is the solar zenith angle. This is a reasonable assumption since the highly variable atmospheric contribution to the upwelling radiance at the top of the atmosphere is small compared to the contribution of the radiation reflected by the bright desert surface (e.g., Brest and Rossow 1992; Kaufman and Holben 1993). The recent work of Cosnefroy et al. (1993), and Henry et al. (1993) on the radiometric stability of desert targets also lends support to this assumption.

The International Satellite Cloud Climatology Project (ISCCP) B3 data (Schiffer and Rossow 1983) for the region of the calibration target were used in the present study; the data comprised the measured counts in the visible, near-infrared, and thermal infrared channels of the AVHRR; the satellite and solar zenith angles, and the azimuth angle of observation; the latitude and longitude of the Global Area Coverage (GAC) pixel; and the date of measurement. A variant of Minnaert's reflection law (Minnaert 1941; Barkstrom 1972; Staylor 1990) was used to characterize the dependence of the upwelling radiance on the solar and satellite zenith angles. Following a scheme suggested by Staylor (1990) where it is assumed that the degradation of the radiometer in time is exponential in its nature, the degradation rates are estimated from solutions of the following equation:

$$Y = AX^{B}\exp(-kd) \quad (1)$$

where

- Y: $\rho^2(C_{10} - C_0)\cos\theta$;
- C_{10}: measured signal in 10-bit counts;
- C_0: offset in 10-bit counts;
- ρ: Earth-Sun distance in astronomical units for the date of measurement;
- X: $\cos\theta\cos\theta_o/(\cos\theta + \cos\theta_0)$, θ and θ_o being the satellite and solar zenith angles respectively;
- k: daily rate of the degradation of the gain of the radiometer, assuming it to be exponential in time;
- d: days after launch of the spacecraft; and
- A,B: regression parameters.

Standard numerical techniques (e.g., Powell 1970) were used to determine the value of the daily degradation rate, k. We have confined our attention to the B3 data corresponding to satellite zenith angles ≤14° to minimize the effects, if any, of the azimuthal dependence of the upwelling radiation at the top of the atmosphere. Greater details of the method of determination of the degradation rates; of the quality control criteria adopted to detect the presence of clouds; and of the ISCCP B3 data used are found in Rao and Chen (1993).

2.2 The AVHRRs on NOAA-7, -9, and -11 Spacecraft

The degradation rates k for the two channels of the three AVHRRs, determined using the method outlined in the previous section, and the relevant meta-data are shown in Table 1; the k values yield the rate at which the albedo of a surface, set equal to unity (1) on the day of launch, would apparently decrease in time, all other conditions remaining unaltered, because of the degradation of the radiometer. Thus, the corrected albedo can be obtained from the uncorrected albedo on day d after launch by multiplying the latter(uncorrected albedo) by exp(kd).

We have compared in Table 2 the annual rates of degradation obtained in the present study, based on the daily degradation rates listed in Table 1, with results reported by researchers elsewhere; this comparison is only representative and not complete. The choice of the data for comparison was mainly governed by our desire to compare our results with those obtained over similar desert calibration targets (Staylor 1990; Kaufman and Holben 1993); with the results of statistical analysis of a large body of global reflectance data (Brest and Rossow 1992); with results based on composite calibration data (Che and Price 1992); and with those based on measurements made over a variety of targets (Santer and Sharman 1993; Mitchell et al. 1992). Staylor (1990) used the Heat Budget Parameter (HBP) data (Gruber and Winston 1973) for a broad region of the Libyan desert in his work. Kaufman and Holben (1993) used the AVHRR GAC data (spatial resolution: ≈4 km; temporal resolution: daily and monthly means) for several sites located in the Libyan desert to establish the rate at which the ratio of the pre-launch value of the "slope" to its actual value varied in time. Brest and Rossow (1992) based their findings on statistical analysis of a large body of ISCCP global reflectance data, assuming that "the global aggregate of regional variations of surface visible reflectance is not changing with time;" their results indicate that the visible channel of the AVHRR on NOAA-7 did not exhibit any

Table 1. Relative degradation rates for the visible and near-infrared channels of the AVHRRs on NOAA-7, -9, and -11 spacecraft

Space-craft	Launch date	Dates of data availability	Number of data points	Degradation rate(k) per day Ch.1	Ch.2
NOAA-7	6/23/81	8/81 - 12/84	84	0.000101	0.000120
NOAA-9	12/12/84	1/85 - 12/88	86	0.000166	0.000098
NOAA-11	9/24/88	1/89 - 12/91	83	0.000033	0.000055

Note: Each data point is the average of measurements made over approximately 35 pixels in the 1°x2° area of the calibration target in the course of a day; the entries in the "Number of Data Points" column give the number of days of appropriate data availability.

perceptible in-orbit degradation over the period July 1983 to January 1985. Che and Price (1992) used a composite of post-launch calibration results given by several authors, using different techniques, and established linear regression relationships between the published values of gains (or "slopes"), and elapsed time in months since launch of the spacecraft, assuming similarity in the degradation of different AVHRRs. Santer and Sharman (1994) have used measurements of upwelling radiances over desert surfaces, stratus cloud decks, ocean targets, and model simulations to derive the degradation rates. The relatively high degree of correspondence between our results and those reported by Staylor (1990) and Kaufman and Holben (1993) is to be expected since similar techniques and calibration targets located in the broad region of the Libyan desert were used in all of these studies. It should be reiterated that the annual relative degradation rates given above are essentially the rates at which the albedo of an Earth scene decreases in the course of one year from its initial value at the beginning of the one-year period.

Table 2. Comparison of annual relative degradation rates (in per cent) reported by different authors

Source	NOAA-7 Ch.1	NOAA-7 Ch.2	NOAA-9 Ch.1	NOAA-9 Ch.2	NOAA-11 Ch.1	NOAA-11 Ch.2
Present Work	3.6	4.3	5.9	3.5	1.2	2.0
Staylor (1990)	3.5	-	6.0	-	-	-
Kaufman and Holben (1993)	4.2	5.6	5.7	3.1	1.3	2.9
Brest and Rossow (1992)	0 (7/83 to 1/85)	-	4.6	-	-	-
Che and Price(1992)	4.4	4.6	5.0	6.7	6.7	3.9
Santer and Sharman (1994)	4.7	4.7	7.5	4.5	-	-
Wu and Zhong (1994)	-	-	5.8	4.6	-	-

Note 1: The degradation rates based on the work of Kaufman and Holben (1993) represent averages over a 3-year period.

Note 2: The AVHRR on NOAA-7 was assumed to be stable over the period July 1983 - January 1985 in Brest and Rossow(1992).

2.3 Time Dependence of the Absolute Calibration of the AVHRR on NOAA-9 Spacecraft

The in-orbit degradation of the visible and near-infrared channels of the AVHRR on NOAA-9 spacecraft has been studied very extensively (e.g. Whitlock et al., 1990) by researchers employing a variety of techniques since its effective operational life (≈1985-1988) encompassed important, international, multi-agency, multi-platform experiments such as the First ISCCP Regional Experiment (FIRE), and the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE). Also, the availability of the results of several aircraft/satellite congruent path measurements over White Sands, New Mexico (U.S.A.) (Smith et al., 1988), employing a well-calibrated radiometer onboard a U-2 aircraft, made it possible to translate the relative degradation rates into variations in time of the gain or "slope." Accordingly, in the present study, the relative degradations (see Table 1) of the two channels were anchored to the absolute calibrations based on aircraft/satellite measurements made during October/November 1986 to determine the rate of variation of the "slope" in time. The resulting expressions for the calculation of radiances I_d (in units of W m^{-2} sr^{-1} μm^{-1}) on day d after launch, are:

Channel 1:

$$I_d = 0.5465 \times \exp[1.66 \times 10^{-4} \times (d - 65)](C_{10} - C_0) \quad (2)$$

Channel 2:

$$I_d = 0.3832 \times \exp[0.98 \times 10^{-4} \times (d - 65)](C_{10} - C_0) \quad (3)$$

C_0 has been given values of 37.0 and 39.6 in channels 1 and 2 respectively, and d is taken to be zero on the day of launch. Also, the effective counts (C_{10} - C_0) have been normalized to mean Earth-Sun distance in the above formulae; it should be noted that the "slope" on day d for either channel, in units of W/(m^2 sr μm ct), is obtained by dividing the corresponding expression for I_d (Eq. 2 or 3) by (C_{10} - C_0). The time-dependent slopes thus derived have been recommended to the user community by the NOAA/NASA AVHRR Pathfinder Calibration working group (Rao et al., 1993).

3. Inter-satellite Calibration Linkages

We have used the AVHRR on NOAA-9 as the normalization standard to establish interrelationships among the visible and near-infrared radiances measured by the three AVHRRs. The method is based on the use of matched data sets consisting of the measured counts, satellite zenith and solar zenith angles, and the dates of measurements over the southeastern part of the Libyan desert which was used as the calibration target in the present study. The following selection criteria were used to generate two sets of matched data, one for the NOAA-7/NOAA-9 combination, and the other for the NOAA-9/NOAA-11 combination:

a. The solar zenith angle, θ_o, and the satellite zenith angle, θ, for the measurements made by the AVHRRs on NOAA-7 and NOAA-11 should be within 1° of the corresponding angles for measurements by the AVHRR on NOAA-9; and

b. The two measurements should have been made in the same calendar month, with the days of the month being as close to one another as was practicable, to allow for seasonal variations, if any, in the radiometric characteristics of the target; it was further recognized, in the light of the requirement set in (a) above, that the same-month measurements could be in different years of the effective operational life of the relevant spacecraft. It is thus likely that the measurements made by the AVHRR on either NOAA-7 or NOAA-11 in a given calendar month in the i^{th} year in orbit of the relevant spacecraft could be matched with the measurements made by the AVHRR on NOAA-9 in the same calendar month, but falling in a different (j^{th}) year in orbit of NOAA-9.

These selection criteria resulted in 11 sets of matched data for the NOAA-7/NOAA-9 combination, and 10 sets of matched data for the NOAA-11/NOAA-9 combination. Each set of matched data consisted of the solar and satellite zenith angles, measured counts in either channel for the given AVHRR (NOAA-7 or NOAA-11), the counts for the corresponding measurements by the AVHRR on NOAA-9, and the dates of measurement. Only data corresponding to solar zenith angles ≤60° have been included.

The method of normalization of the AVHRRs on NOAA-7 and NOAA-11 to the AVHRR on NOAA-9 is illustrated below, using the NOAA-7/NOAA-9 matched data set as an example:

a. For either channel, the effective counts (C_{10} - C_0) were corrected for the NOAA-7 AVHRR degradation, using the k values listed in Table 1; the elapsed time in days, d, since launch was calculated from the known dates of launch and of the measurements in the matched data set.

b. The matched, calibrated radiance measured by the AVHRR on NOAA-9 was calculated, using either Eq. 2 or Eq. 3 as was appropriate.

c. A linear regression relationship was established between the NOAA-9 radiances from (b), and the corrected effective counts for the NOAA-7 AVHRR from (a).

The regression relationship established in (c) above links the AVHRR on NOAA-7 to the AVHRR on NOAA-9, and yields the "slope", in units of W/(m^2 sr μm ct), for the given channel on the day of launch of NOAA-7. The AVHRR on NOAA-11 was linked to the AVHRR on NOAA-9 in a similar manner. The noticeable feature of the regressions, displayed in Fig. 1, is the very high value of the correlation coefficient, R. The resulting formulae for the calculation of radiances are given in Table 3 below.

Staylor (1990) has established linkages among the visible channels (channel 1) of the AVHRRs on NOAA-6, -7, and -9, using the instrument on NOAA-7 as the normalization standard. Starting with the regions of overlap in the X variable in the plots of Y on X (Eq. 1), he determined adjustment factors (multipliers) for Y that would force the regression plots for the radiometers on NOAA-6 and -9 to coalesce with the regression plot for the AVHRR on NOAA-7. The ratio of the adjustment factors he has given for the AVHRRs on NOAA-7 and NOAA-9 is 1.07 which is very close to the ratio (1.064) of the channel 1 slopes for the day of launch (d = 0) listed in Table 3 for the two AVHRRs. Brest and Rossow (1992) have also established a linkage between the visible channels of the AVHRRs on NOAA-7 and -9, using reflectance data from the two satellites, obtained over a three-week overlap period from January 18 to February 8, 1985; it should however be noted that they have assumed that there was no perceptible degradation in the performance of NOAA-7 AVHRR channel 1 over the period from the middle of 1983 to early 1985.

The albedo (AVHRR usage) or reflectance factor(Rao 1987) or scaled radiance (Brest and Rossow (1992)], given by ($100\pi I_i/F_{i0}$), is currently being used in a wide variety of applications of AVHRR data; to facilitate this activity, we have listed in Table 4 below the formulae for the calculation of the albedos; the extraterrestrial solar spectral irradiance values given by Neckel and Labs (1984) were used in the conversion of the radiance formulae (Table 3) to the albedo representation; the conversions are effected by multiplying the radiances by ($100\pi w_i/F_{i0}$), w_i being the equivalent width of the i^{th} channel.

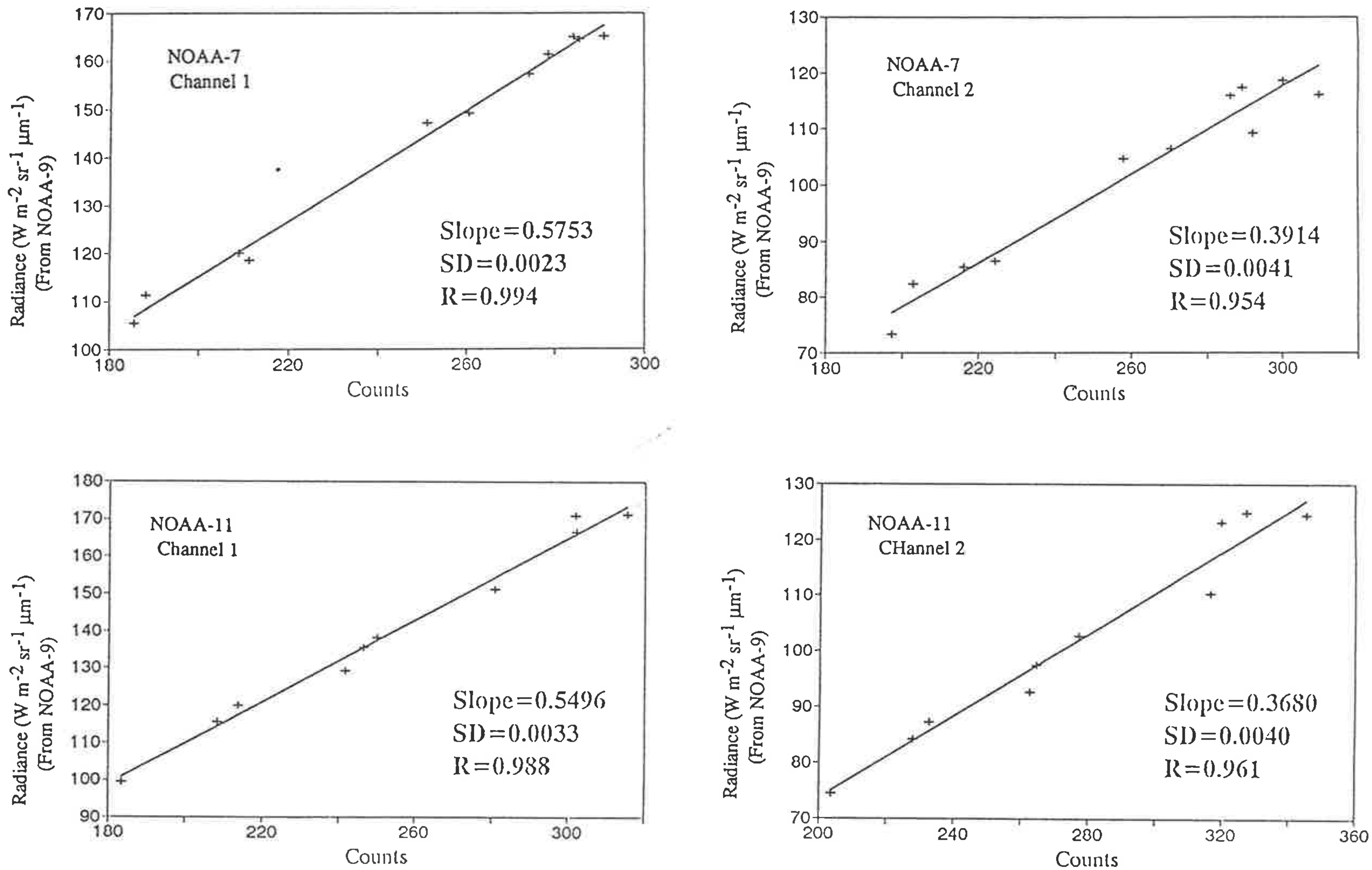


Figure 1. Inter-satellite calibration linkages

Table 3. Formulae for the calculation of calibrated radiances

Spacecraft	Radiance $(W/m^2\ sr\ \mu m)$
NOAA-7	
Channel 1	$0.5753 \times \exp(1.01 \times 10^{-4} \times d) \times (C_{10} - 36)$
Channel 2	$0.3914 \times \exp(1.20 \times 10^{-4} \times d) \times (C_{10} - 37)$
NOAA-9 (Set A)	
Channel 1	$0.5465 \times \exp[1.66 \times 10^{-4} \times (d - 65)] \times (C_{10} - 37)$
Channel 2	$0.3832 \times \exp[0.98 \times 10^{-4} \times (d - 65)] \times (C_{10} - 39.6)$
NOAA-9 (Set B)	
Channel 1	$0.5406 \times \exp(1.66 \times 10^{-4} \times d) \times (C_{10} - 37)$
Channel 2	$0.3808 \times \exp(0.98 \times 10^{-4} \times d) \times (C_{10} - 39.6)$
NOAA-11	
Channel 1	$0.5496 \times \exp(0.33 \times 10^{-4} \times d) \times (C_{10} - 40)$
Channel 2	$0.3680 \times \exp(0.55 \times 10^{-4} \times d) \times (C_{10} - 40)$

Table 4. Formulae for the calculation of calibrated AVHRR albedos

Spacecraft	Albedo (per cent)
NOAA-7	
Channel 1	$0.1100 \times \exp(1.01 \times 10^{-4} \times d) \times (C_{10} - 36)$
Channel 2	$0.1169 \times \exp(1.20 \times 10^{-4} \times d) \times (C_{10} - 37)$
NOAA-9 (Set A)	
Channel 1	$0.1050 \times \exp[1.66 \times 10^{-4} \times (d - 65)] \times (C_{10} - 37)$
Channel 2	$0.1143 \times \exp[0.98 \times 10^{-4} \times (d - 65)] \times (C_{10} - 39.6)$
NOAA-9 (Set B)	
Channel 1	$0.1039 \times \exp(1.66 \times 10^{-4} \times d) \times (C_{10} - 37)$
Channel 2	$0.1136 \times \exp(0.98 \times 10^{-4} \times d) \times (C_{10} - 39.6)$
NOAA-11	
Channel 1	$0.1060 \times \exp(0.33 \times 10^{-4} \times d) \times (C_{10} - 40)$
Channel 2	$0.1098 \times \exp(0.55 \times 10^{-4} \times d) \times (C_{10} - 40)$

Note: The two sets of formulae given for NOAA-9 yield the <u>same</u> radiances/albedos; the quantity exp (-65k) occurring in Set A has been incorporated into the numerical coefficient appearing at the beginning of the formulae in Set B to render their format the same as that of the formulae for the AVHRRs on NOAA-7 and NOAA-11.

We have given in Table 5 the values of w_i and F_{i0} used in the conversion of the radiance formulae given in Table 3 to the albedo (AVHRR usage) representation (Table 4).

Table 5: Equivalent widths and in-band extraterrestrial solar irradiances

Spacecraft	w_i (μm)		F_{i0} (Wm^{-2})	
	Ch.1	Ch.2	Ch.1	Ch.2
NOAA-7	0.108	0.249	177.5	261.9
NOAA-9	0.117	0.239	191.3	251.8
NOAA-11	0.113	0.229	184.1	241.1

It is felt that the attainable accuracies in the radiance or albedo calculated using the formulae we have given (Tables 3 or 4) are at best comparable to the estimated accuracies of the order of a few percent (G. Smith, personal communication) of the Fall 1986 aircraft-based absolute calibrations of the AVHRR on NOAA-9 which we have used as the normalization standard in the present work. The relative degradation rates and the time-dependent slopes for the two channels of the three AVHRRs are shown in Fig. 2.

4. Applications

We shall examine in this section the validity of the radiance/albedo formulae given in Tables 3 and 4 in the following manner. To evaluate the reasonableness of using the AVHRR on NOAA-9 as a normalization standard, we shall first compare the variation in time of the "slopes" of channels 1 and 2 of the AVHRR on NOAA-11, derived from these formulae, with the absolute calibrations based on congruent path aircraft/satellite radiance measurements (Abel et al., 1993), and with the results reported by other investigators. We shall also examine the long-term time series of surface albedos, and the Normalized Difference Vegetation Index (NDVI) for the southeastern Libyan desert calibration site. We shall illustrate the applications of the calibrated radiance/albedo formulae to the reprocessing of NDVI data for other locations, and to NOAA's "Clouds from Advanced Very High Resolution Radiometer" (CLAVR) product.

4.1 The AVHRR on NOAA-11 Spacecraft

Abel et al. (1993) have measured the upwelling radiance from an ER-2 aircraft over the White Sands area of New Mexico, U.S.A., since late 1988 during satellite overpasses to evaluate the post-launch performance of the AVHRR on NOAA-11 spacecraft. We have shown in Fig. 3 these aircraft-based calibrations, along with the "slopes" determined using the formulae in Table 3, and the results of other investigators. The noticeable feature is that our results are within one standard deviation of the mean values of the majority of aircraft-based absolute calibrations in both channels. It is felt that this behavior can be taken as an indicator of the viability of both the method we have used to develop interrelationships among the three radiometers, using the

Degradation of AVHRR

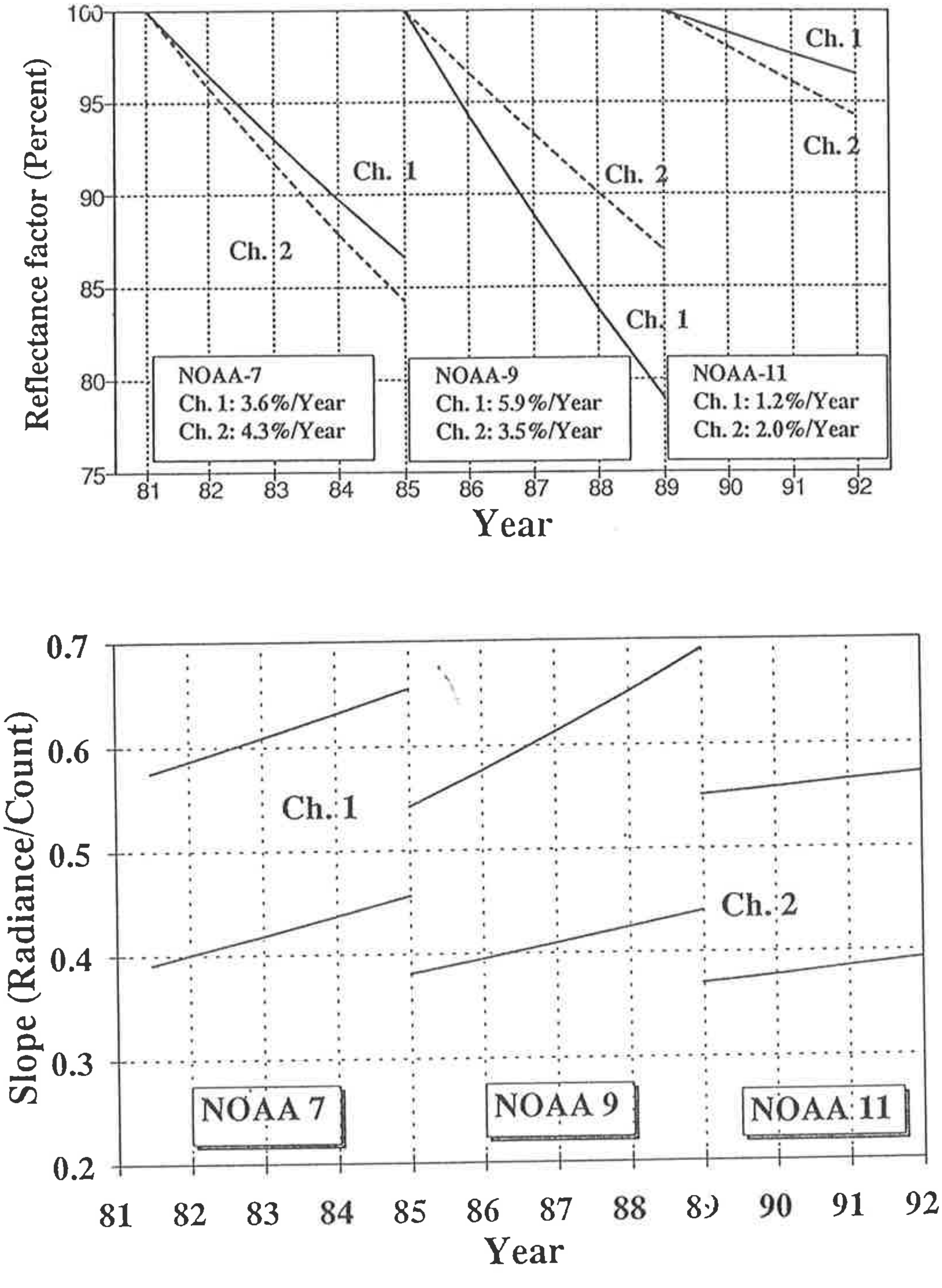


Figure 2. Relative degradation rates(top) and time-dependent slopes(bottom) of channels 1 and 2 of the AVHRRs on NOAA-7, -9, and -11 spacecraft

AVHRR on NOAA-9 as a normalization standard, and of the congruent path aircraft/satellite technique of absolute radiometer calibrations. It should also be noted that the AVHRR on NOAA-9 had in turn been anchored to aircraft-based absolute calibrations performed in 1986 over the same site (White Sands area, New Mexico, U.S.A.).

Our experience to date with the post-launch calibration of the AVHRR on NOAA-9, and with the development of inter-satellite calibration linkages, and validation of the same in the manner described above point to the crucial role played by absolute radiometric calibrations based on congruent path aircraft/satellite radiance measurements. We feel that such absolute calibrations should be made at regular intervals to provide anchors or normalization standards to AVHRR calibrations based on different, vicarious techniques. Thus, they (aircraft-based absolute calibrations) should be an integral part of any sustained post-launch calibration of the AVHRR visible and near-infrared channels.

4.2 Southeastern Libyan Desert Calibration Site

The matched data sets which were used in the establishment of interrelationships among the three AVHRRs and in the derivation of the radiance formulae given in Table 3 comprised about 15% of the ISCCP B3 data for the southeastern Libyan desert calibration site--sandy, non-agricultural, uninhabited land (Chi-Bonnerdel 1976)--which we have used to determine the degradation rates of the two channels of the AVHRRs on the NOAA-7, -9, and -11 spacecraft (Section 2). We thus felt it may be scientifically meaningful to examine the differences between the applications of pre- and post-launch calibrations to the entire ISCCP B3 data for this site. Accordingly, we have shown in Fig. 4 the isotropic albedos $[100\pi I_i/(F_{i0}\text{Cos}\theta_0)]$ in the two channels, calculated using the pre-launch calibration coefficients (e.g., Kidwell 1993), and the formulae given in Table 4. The spurious downward trend in the albedos, resulting from the application of the pre-launch calibration coefficients to the effective counts measured by the radiometer, which has degraded in time, is very obvious in both channels. On the other hand, the application of the formulae in Table 4, which account for the in-orbit degradation of the radiometers, results in considerable improvement, and also establishes continuity among the three AVHRRs. The mean value and standard deviation (in parentheses) of the albedo of the site, as measured by the three AVHRRs, after correction for the in-orbit degradation of the radiometer, are shown in Table 6; also included under the "All Data" heading are the mean value of the albedo and its standard deviation calculated using all of the data for the three satellites together. The noticeable feature is that the variation of the mean value of the albedo in both channels is about 0.5% in magnitude over a period of about 10 years, with the dispersion (standard deviation/mean value) being of the order of 2 to 3%; this can be taken as an indicator of the radiometric stability of the southeastern Libyan desert calibration site. It should, however, be noted that channel 2 data are generally noisier than channel 1 data because of the uncertainties introduced by the variations in the columnar water vapor content.

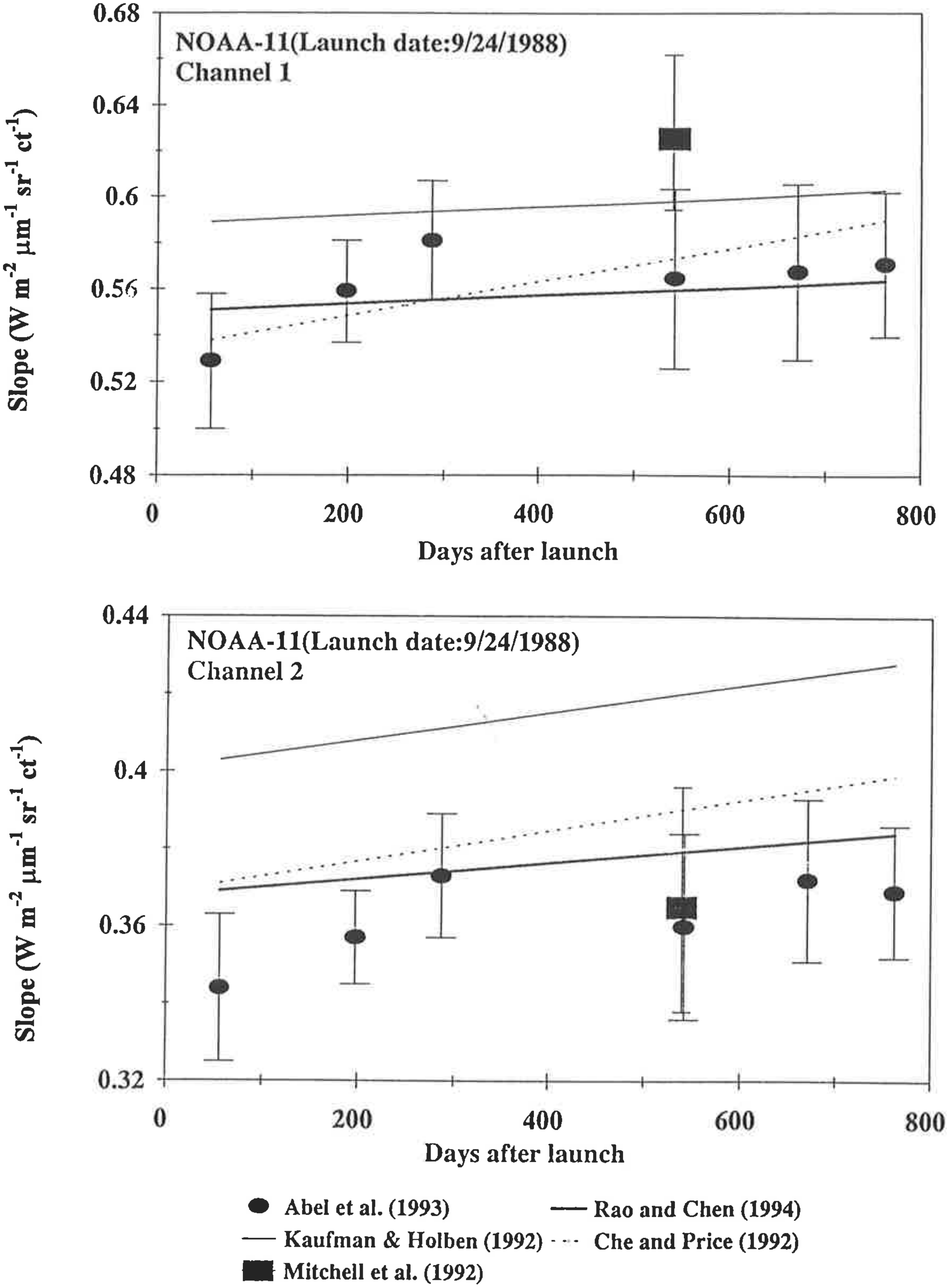


Figure 3. Comparison of the "slopes" determined using the southeastern Libyan desert target (present work; solid line) with aircraft-based absolute calibrations (Abel et al. 1993) and with the results of other investigators

Table 6. Albedo of the southeastern Libyan desert calibration site

	Albedo (per cent)			
	NOAA-7	NOAA-9	NOAA-11	All Data
Channel 1	37.5(0.5)	37.9(0.6)	38.0(0.8)	37.8(0.7)
Channel 2	42.2(1.2)	42.7(1.5)	42.9(1.5)	42.6(1.5)

The resulting NDVI for this region, defined as the ratio $(\alpha_2 - \alpha_1)/(\alpha_2 + \alpha_1)$ where α_i is the albedo in the i^{th} channel, is shown in Fig. 5. The improvements resulting from making proper corrections for the in-orbit radiometer degradation are obvious, especially in the transition from one spacecraft to the next. We have shown for purposes of comparison the NDVIs calculated using the albedo/radiance formulae given in Kaufman and Holben (1993) and in Che and Price (1992). Even though the method used by Kaufman and Holben (1993) to establish interrelationships between the three AVHRRs is similar to what we have adopted here, their "slope" values, while exhibiting time trends very similar to ours, lead to NDVI values which are somewhat larger. The use of the formulae given by Che and Price (1992) also generally results in larger values of NDVI, especially during the period covered by NOAA-9.

4.3 Ranchland in Brazil

It can be rightfully argued that the illustrations given above are really not indicative of the validity of the inter-satellite calibration linkages we have developed since a part (≈15%) of the ISCCP B3 data for the region of the southeastern Libyan desert calibration target was used to develop these linkages. Thus, as a test--perhaps limited--of the general applicability of the calibrated radiance/albedo formulae (Tables 3 and 4), we used them to calculate the corrected albedo and NDVI for Bage (29.9°S; 55.6°W), located in ranchland in southern Brazil near the border with Uruguay. Sheep and cattle ranching is the primary activity in the region. The NOAA Global Vegetation Index (GVI) data (Tarpley 1991) were used; the weekly composited data consist of the integral channel 1 and 2 counts for the day with the maximum difference between the two, and the relevant values of the solar and satellite zenith angles, and geographical location of the GVI map cell with a nominal spatial resolution of 16 km at the equator. Retention of only the daily data for which the difference between the channel 1 and 2 signals is maximum screens for clouds to a certain extent. The data have been utilized in the form they were furnished (G. Gutman, personal communication) without any additional cloud screening or quality control; however, only data corresponding to solar zenith angles ≤60° have been included. We have shown in Fig. 6 the reprocessed long-term record of visible and near-infrared albedos, and the resulting calibrated NDVI for the relevant GVI map cell. The continuity and uniformity of the long-term records of albedo and NDVI are once again apparent, even though the GVI data appear to be noisy. It should also be recognized that uncertainties in the albedos are amplified in the corresponding NDVIs, the amplification being larger the lower the NDVI.

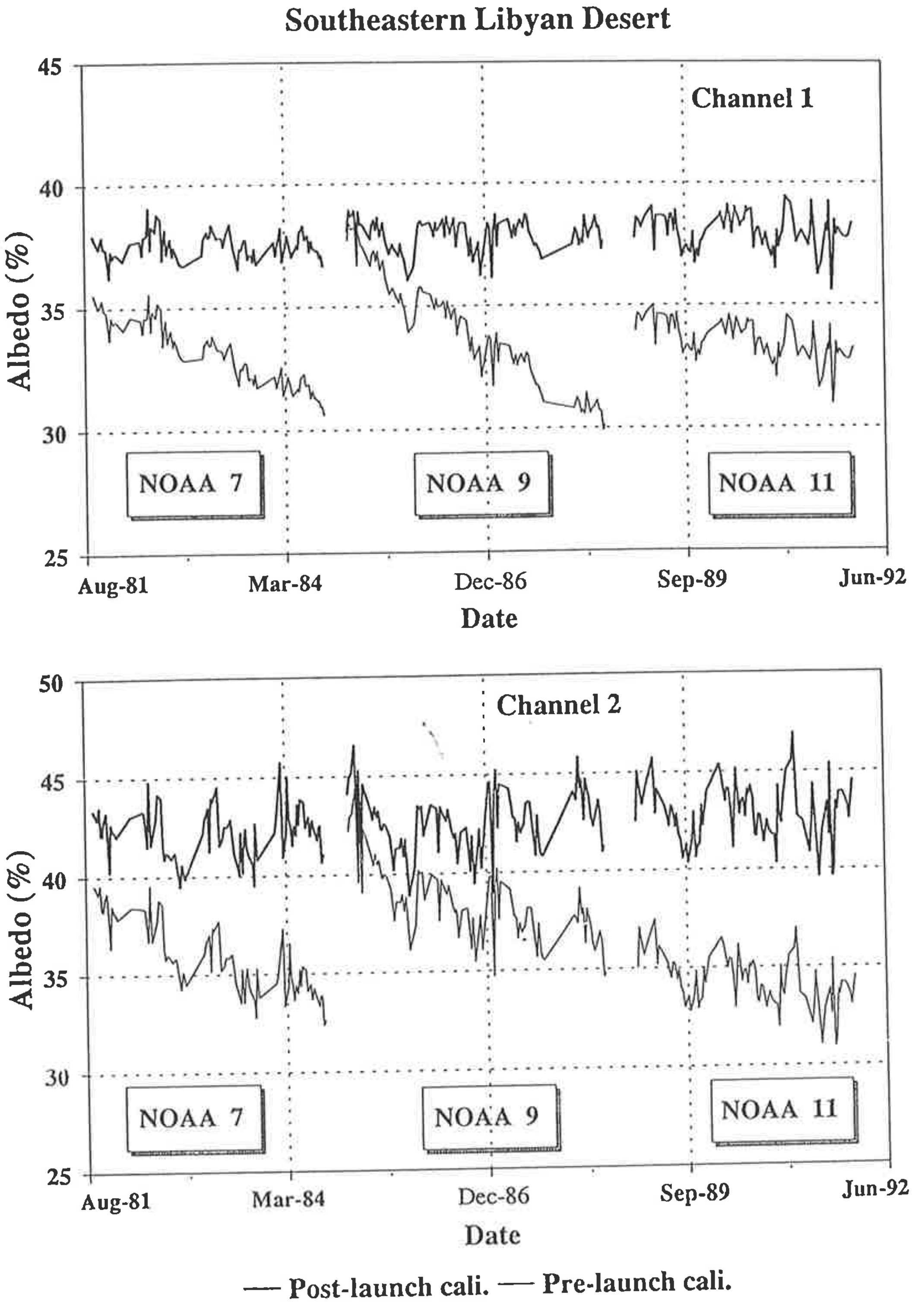


Figure 4. Isotropic albedo in channel 1(top) and channel 2(bottom) of the southeastern Libyan desert

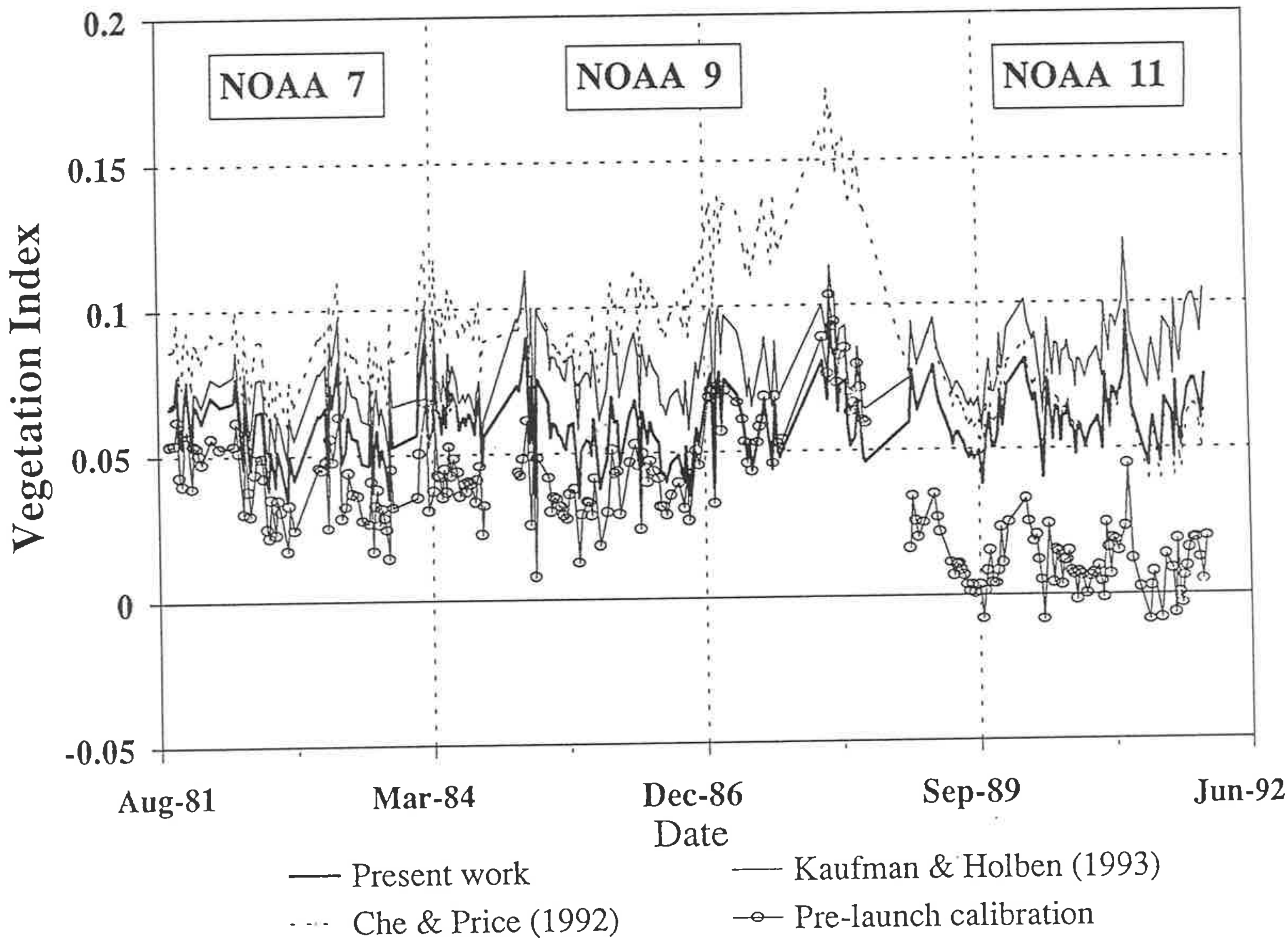
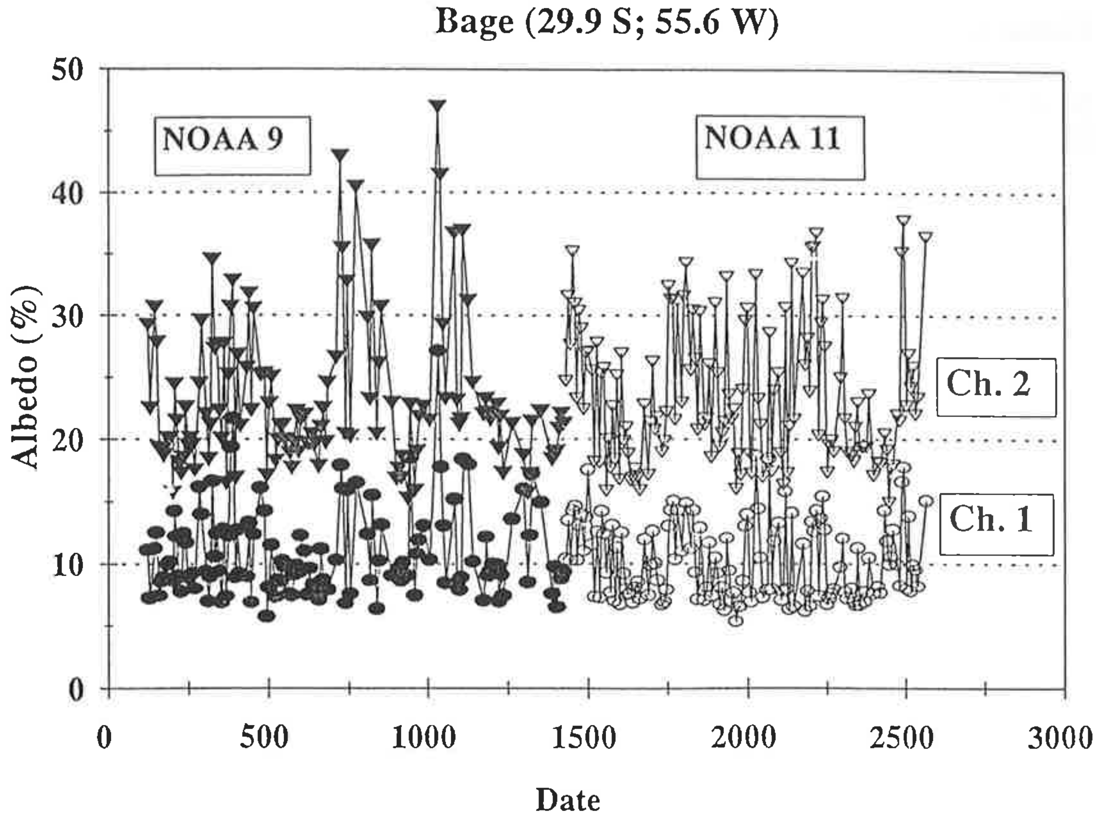


Figure 5. Normalized Difference Vegetation Index for the southeastern Libyan desert



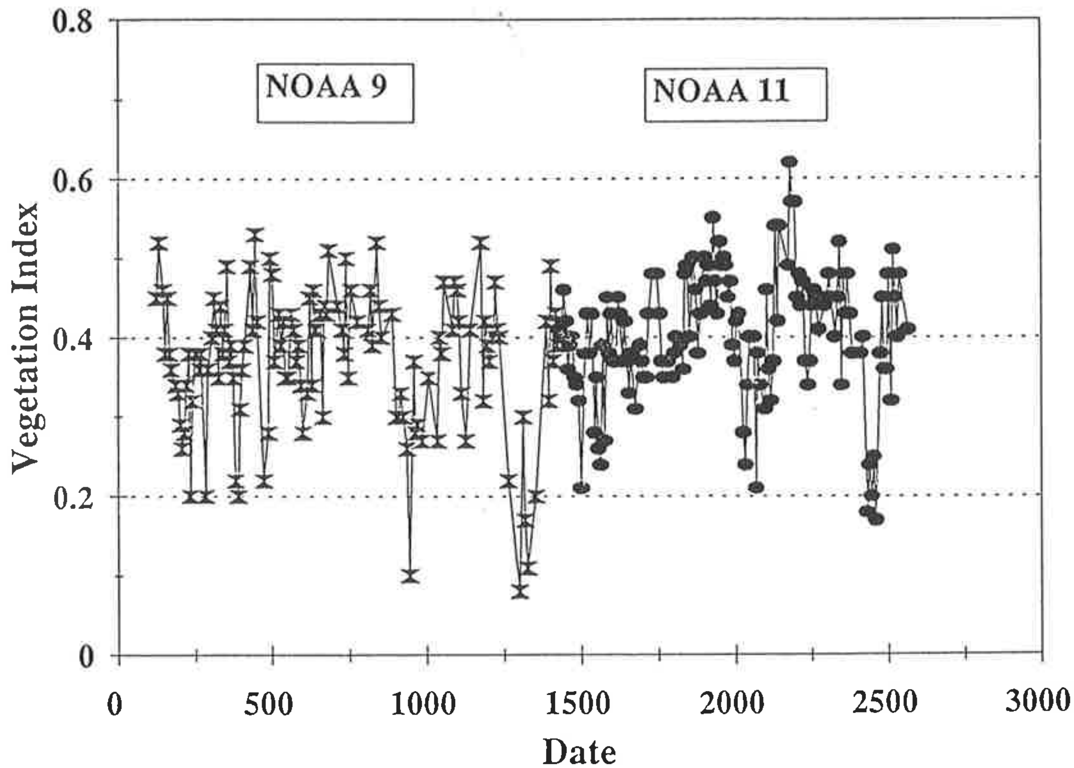


Figure 6. Isotropic albedos(top) and Normalized Difference Vegetation Index(bottom) for Bage, Brazil

4.4 Clouds from Advanced Very High Resolution Radiometer (CLAVR)

Since November 1993, "Clouds from Advanced Very High Resolution Radiometer (AVHRR)" has become an experimental product at NOAA/NESDIS. In the allocation of pixels in a given scene to the "clear", "partly cloudy", and "cloudy" categories in this product, thresholds based on the albedos in AVHRR channels 1 and 2 play a crucial role. Thus, for the region of north-eastern Africa (including the Libyan desert and the Mediterranean; about 1000 km on the side) on November 3, 1993, the apportionment of pixels to the three categories using the pre-launch calibration coefficients, and the formulae given in Tables 3 and 4 (post-launch calibration) for the two channels of the AVHRR on NOAA-11 is shown below in Table 7.

Table 7. CLAVR cloudiness categories (in per cent) for north-east Africa

Category	Pre-launch calibration	Post-launch calibration
Clear	49.4	48.8
Partly cloudy	32.2	27.2
Cloudy	18.4	24.0

It is apparent from the entries in Table 6 that the greatest impact of the differences between the pre- and post-launch calibration coefficients is on the allocation of pixels to the "partly cloudy" and "cloudy" categories.

5. Conclusion

We wish to conclude with the statement that the validity and usefulness of the inter-satellite calibration linkages we have established, and of the radiance and albedo formulae we have given can be evaluated only after they have been applied to the reprocessing of long-term records of different AVHRR-derived environmental products for the Pathfinder period; several activities along these lines are presently underway both within NOAA, and at other institutions elsewhere. It should also be remembered that the improvements brought by the use of the inter-satellite calibration linkages we have furnished are also determined by the nature of the data (e.g., skewness, composite nature) to which they are applied, and the approximations and assumptions made in the product-generation algorithms.

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