NOAA Technical Report NESDIS 70

DEGRADATION OF THE VISIBLE AND NEAR-INFRARED CHANNELS OF THE ADVANCED VERY HIGH RESOLUTION RADIOMETER ON THE NOAA-9 SPACECRAFT: ASSESSMENT AND RECOMMENDATIONS FOR CORRECTIONS

Washington, D.C.
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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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Prefatory Note

I have drawn freely from the verbal and written contributions by several members of the Advanced Very High Resolution Radiometer(AVHRR) Pathfinder Calibration Working Group in the preparation of this report on the in-orbit degradation of the visible and near-infrared channels of the AVHRR on board the NOAA-9 spacecraft, reproducing verbatim the greater part of the written contributions in the majority of cases, while exercising some editorial prerogative in others. The first draft of this report was written in November 1992, and circulated among the Working Group members for comments and suggestions. A revised version was prepared taking into consideration the members' comments, and was sent to the Working Group members for further review in early January 1993. The present version reflects the results of this review to the extent practicable. There was general agreement on the recommendations that have been made to account for the observed degradation in the performance of the instrument; however, there was a divergence of opinion on the nature and type of material to be included in the body of the report. While recognizing this as a healthy sign of the democratic process at work, I have taken the final decision on the format and contents of the report in my capacity as the Chair of the Working Group.

C. R. Nagaraja Rao

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ABSTRACT

As part of the NOAA/NASA Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Calibration Working Group activities, the in-orbit degradation of the AVHRR visible (channel 1: $\approx$0.58-0.68μm) and near-infrared (channel 2: $\approx$0.72-1.05μm) channels, which do not have any onboard calibration devices, has been determined for the instrument on the NOAA-9 spacecraft, using the southeastern Libyan desert (21-23°N latitude; 28-29°E longitude) as a time-invariant calibration target. It was found from a statistical analysis of the relevant International Cloud Climatology Project (ISCCP) B3 data obtained over the calibration target that the gains [counts/(W/m^2 μm sr)] in channels 1 and 2 of this instrument had degraded at the rate of 5.9% and 3.5% per year respectively. To facilitate the computation of corrected radiances, the variation in time of the "slope" -- defined as the reciprocal of the "gain"-- in the two channels was determined by anchoring the relative variations of the gain to the "absolute" calibrations based on congruent path aircraft/satellite measurements made over the White Sands area of New Mexico, U.S.A., during October/November 1986. Procedural details for obtaining the correct radiances from the measured signals in the two AVHRR channels, simple user-friendly formulae, and a look-up table are given.

1. Introduction

The NOAA/NASA Pathfinder program has for its primary objective the establishment of accurate, long-term records of environmental parameters that can be used in climate and global change studies. This task entails the generation of atmospheric and surface products such as global cloud climatology, land cover, global aerosol burden, sea surface temperature, etc., that can be used both as diagnostic and prognostic tools in the simulation and assessment of the impact of anthropogenic and natural phenomena on the environment. It is also expected, according to the Memorandum of Understanding executed between NOAA and NASA (1989, 1990), that this program will provide a learning experience in the application of long-term time series and large volume data sets to climate and global change research, and will lead to the definition of community-consensus derived products and to the development of plans to generate and, with user participation, to quality control and validate the same products. As the name implies, it is hoped that the Pathfinder program would prepare the scientific community to explore the uncharted areas of acquisition, storage, analysis, and interpretation of the very large amounts of geophysical data that will result from the multinational, multidisciplinary missions to study Planet Earth, such as the Earth Observing System (EOS) and the Advanced Earth Observing System (ADEOS) planned for coming decades.

It is apparent in this context that the continuous, long-term records of atmospheric and surface data obtained with the meteorological satellites such as the NOAA Polar-orbiting, Operational, Environmental Satellite (POES), the Geostationary Operational Environmental Satellite (GOES), and with the spacecraft flown under the Defense Meteorological Satellite Program (DMSP) should form the core of this climate and global change data base. Thus, separate Pathfinder programs have been established for the Advanced Very High Resolution Radiometer (AVHRR), the Tiros Operational Vertical Sounder (TOVS) suite of measurements, GOES, and the Special Sensor Microwave/Imager (SSM/I) of the DMSP (e.g., Ohring and Dodge, 1993). Initially, the retrospective recalibration, reprocessing, and reinterpretation of operational products generated using these data would be confined to the Pathfinder period, 1981-1991.

The utility of the long-term environmental data records assembled under the Pathfinder programs would essentially be determined by the accuracy and quality (internal consistency and completeness) of the satellite-derived information. In light of this, and since satellite radiometers do degrade in orbit, initially because of the outgassing (e.g., of water vapor from filter interstices) and launch-associated contamination (e.g.,rocket exhaust and outgassing) and subsequently because of continual exposure to the harsh space environment, it is essential to characterize the in-flight performance of satellite sensors, especially of those that do not have any on board calibration devices, as for example, the visible (channel 1: $\approx$0.58-0.68μm) and the near-infrared (channel 2: $\approx$0.72-1.05μm) channels of the AVHRR. Thus, a concerted effort is presently underway to address and quantify the in-flight performance of several of these operational radiometers. A good summary of the various methods presently in use for the post-launch calibration of such sensors is found in Slater (1988), Abel (1990), and in Teillet and Holben (1993).

In light of the above, an AVHRR Pathfinder Calibration Working Group was established, as part of the AVHRR Pathfinder program, in early 1991 to (a) address the degradation of the AVHRR visible and near-infrared channels during the operational life of the spacecraft; and to (b) develop a consistent set of in-flight calibration algorithms for the AVHRR thermal infrared channels centered on $\approx 10.8\mu m$ (channel4) and $\approx 12\mu m$ (channel 5). The membership of the Working Group is made up of representatives of the AVHRR Pathfinder Atmosphere, Land, and Ocean Science Working Groups, and other scientists with interest and experience in the area of calibration, and is listed in Appendix A.

2. The AVHRR Pathfinder Calibration Activity

At the first meeting of the Working Group, held in March 1991, it was decided that the post-launch, in-orbit performance of the AVHRRs on NOAA-7, -9, and -11 spacecraft, the afternoon satellites, would be investigated. This investigation would have for its main components the following:

a. Determination of the relative trends in the calibration of channels 1 and 2, using the southeastern Libyan desert as a time invariant calibration target. The statistical method described in Staylor (1990) would be used. This task would be performed at the NOAA/NESDIS Satellite Research Laboratory, Camp Springs, Maryland, in consultation with scientists at NASA Langley Research Center, Hampton, Virginia. These trends would be compared and reconciled, to the extent practicable, with the results for desert targets obtained by other investigators (e.g., Kaufman and Holben, 1993).

b. Determination of relative trends based on the global International Satellite Cloud Climatology (ISCCP) data sets assembled at the NASA/GSFC Institute for Space Studies (GISS), New York. This task would be performed at NASA/GISS, New York, using the methods described in Brest and Rossow (1992).

c. Absolute calibration using ocean targets. This task would be addressed at NASA/GSFC, Greenbelt, using the methods described in Kaufman and Holben (1992), and Vermote et al. (1990, 1992).

d. Anchoring of the relative trends determined in (a) and (b) above to the absolute calibrations obtained with congruent path aircraft and satellite measurements performed by NOAA and NASA scientists over the White Sands Missile Range (WSMR), New Mexico (e.g., Smith et al., 1988). In addition, the aircraft-based absolute calibrations would also be used as reference points of comparison for absolute calibrations obtained using different techniques. An attempt would also be made to reconcile, to the extent practicable, other post-launch calibrations among themselves and with the aircraft determinations.

e. Development of an appropriate method to implement calibration of the thermal infrared channels (channels 4 and 5); as part of this activity, nonlinearity corrections for these two channels would be developed by a group of NOAA/NESDIS and University of Miami (Florida) scientists initially.

It was decided at the AVHRR Pathfinder Calibration Working Group meeting held on October 5-6, 1992, (NOAA Science Center, Camp Springs, Maryland) that two preliminary reports should be written, one addressing the degradation of the visible and near-infrared channels, and the other the nonlinearity corrections to the thermal infrared channels. Further, these reports would address initially the performance of the AVHRR on the NOAA-9 spacecraft (launch date: December 12, 1984) only so that the reprocessing of the data for the "bench mark" period, April 1987 to November 1988, which falls within the effective, operational life of the AVHRR on the NOAA-9 spacecraft, could commence in January 1993. Accordingly, this report describes the work on the characterization of the in-orbit performance of the visible and near-infrared channels of the AVHRR on board NOAA-9; a companion report (Rao, 1993) describes procedures to implement the nonlinearity corrections in the thermal infrared channels.

2.1 Relative trend determination using the Libyan desert target

The choice of the southeastern part of the Libyan desert (21-23°N latitude; 28-29°E longitude) as a time-invariant target was governed by the following considerations (Staylor 1990): long-term stability, high reflectance combined with low solar zenith angles, surface uniformity, low cloudiness and low precipitation and sufficiently large spatial extent (of the order of a few hundred square kilometers). It is assumed that the radiometer response degrades in time exponentially. Only the upwelling radiances confined to small satellite zenith angles are considered, thereby effectively eliminating the azimuth angle dependency of the upwelling radiance. Under these conditions, the empirical bidirectional reflection model used leads to the equivalent assumption that the "albedo" (AVHRR usage; e.g., Price, 1987; Rao, 1987) or the "scaled radiance" (Brest and Rossow, 1992) or the "reflectance factor" (Rao, 1987) has a power law dependence on a simple function of the cosines of the solar and satellite zenith angles which exhibits reciprocity in the two angular parameters. An iterative procedure, consisting of regressions in succession of (a) the reflectance factor on the simple function of cosines of the satellite and solar zenith angles, and (b) of the natural logarithm of the ratio of the measured to the estimated reflectance factor [from (a) above] on days from launch, yields the apparent degradation per day of the reflectance factor of the desert target, assumed to be time invariant. This is interpreted as the rate of decrease of the gain in units of Counts/[W/(m^2 μm sr)] of the instrument. Using this procedure, the degradation rates of channels 1 and 2 of the AVHRRs on the NOAA-7, -9, -11 spacecraft have been determined, covering the period July 1981 to December 1991 (Rao and Chen, 1993).

Greater details of the statistical method used in the trend analysis and of the bidirectional reflection model are found in Staylor (1990). However, in the present work, the reflectance data-- essentially the measured counts-- were taken from the B3 data of the International Satellite Cloud Climatology Project (ISCCP) (e.g., Schiffer and Rossow, 1983), whereas the NOAA Heat Budget Parameter data (Gruber and Winston, 1978) had been used in the earlier work of Staylor (1990). The entire record of the ISCCP B3 data available for any given satellite has been used in the determination of the degradation rate, as it has been observed that statistical techniques such as the above yield reasonable trends in calibration when the length of record is of the order of a few years (Whitlock et al., 1990). The effects of variations in atmospheric ozone which absorbs in the Chappuis bands in channel 1, and of water vapor which absorbs in channel 2, on the degradation rates are presently being investigated in terms of model simulations.

The validity of the assumption of the time invariance of the Libyan desert target has often been debated. Analysis of multi-year SPOT imagery of the region is supportive of this assumption (Cosnefroy, Briottet, and Leroy, 1993; Henry et al., 1993). Also, based on an analysis of the anisotropy of surface reflection in the general area of the Libyan desert, G. Gutman (personal communication) has shown that, for the range of solar and satellite zenith angles used in the present study, the same bidirectional reflection model can be used for measurements made in both channel 1 and channel 2 in so far as the dependency on the solar zenith, satellite zenith, and azimuth angles is involved.

2.2 An alternative method of trend analysis using a desert target

Kaufman and Holben (1993) have also recently reported on the degradation of channels 1 and 2 of the AVHRR on NOAA-9 using the reflectance measurements made over four different targets located around (25.5°N, 14°E), (25°N, 12°E), (29°N, 25°E) and (26.5°N, 26°E) in the region of the Libyan desert. To minimize the effects of the dependence of the upwelling radiance on the solar zenith angle, and to utilize periods of incidence of low cloudiness and humidity, only reflectance measurements made during the months of August and September 1985, 86, 87, and 88, when the solar zenith angle varies over a moderate range, were utilized to determine the degradation rates by (a) initially determining the variation in time of the apparent reflectance of the targets, assumed to be time-invariant, using the preflight calibration equation; and (b) subsequently anchoring the relative variations to the absolute calibration for 1986 obtained using an ocean target. AVHRR GAC data have been used in this investigation. Results will be presented and discussed in Section 3.

2.3 Trend analysis using the ISCCP global data sets

The ISCCP calibration of the AVHRR (Brest and Rossow, 1992) is performed with a statistical procedure using a number of large area targets which cover significant portions of the globe. These targets cover a wide range of brightness values and a variety of spectral responses. The wide variety of surface types also ensures that the measurements cover a large portion of the dynamic range of the instrument. A fundamental assumption behind this analysis is that the global aggregate of regional variations of surface visible reflectance and the overlying atmosphere is not changing with time, and is not affected by changes in the solar zenith angle associated with the drift in the AVHRR. Since a routine calibration program for satellite radiometers did not exist at the start of the ISCCP, the best available method to monitor calibration was the use of the Earth's surface. Since very accurate data on the reflectivity of various surfaces were also sparse, this analysis provides a calibration relative to a somewhat poorly defined standard. The procedure was designed so that when better information became available it could easily be applied to the entire data set. Using data from U2 aircraft calibration flights obtained in October/November 1986, an absolute calibration for the ISCCP data set has been derived.

A key feature of the statistical procedure, such as used by ISCCP, is that reliance is placed on the constancy of the global aggregate of targets, rather than on the constancy of the surface at any one location. Over 200,000 map grid cells are used (although all the water locations do not provide independent information) to check for calibration changes. Both the statistical variations (means and distributions) of a large number of surface types (9) and various-sized geographical aggregations (27 in all), and changes in each of the 50 x 50 km^2 map grid cells covering the whole globe are monitored. This approach supplies both a massive statistical weight and a sensitivity to different kinds of instrument changes. The former assures that only a change in the instrument would produce a systematic shift of all the measured quantities, whereas the latter enables the detection of changes in instrument linearity and spectral response. To date no changes in statistical regression that would suggest either linearity changes or spectral response changes have been noticed. The resulting calibration measurements represent the best global compromise for all target types and reflectance ranges. By normalizing the entire ISCCP radiance data set to this standard and maintaining constancy over the whole time period, the best approximation to a uniform radiometric standard that is obtainable is ensured.

By combining the results of the ISCCP statistical monitoring of AVHRR calibration with the results from occasional aircraft calibration results (see section 2.4 below), we can obtain an absolute calibration for the entire data set.

2.4 Absolute calibration using congruent path aircraft and satellite measurements

Absolute calibrations based on congruent path aircraft and satellite measurements such as those made over the White Sands Missile Range, New Mexico, are essential as reference points for comparison and enhancement of absolute calibrations obtained using different techniques and for the proper anchoring of the relative trends in the calibration of the two channels obtained from statistical techniques. The basic aspects of the method are briefly described here. Figure 1 illustrates the method, which uses a sunlit, stable, highly reflective and cloud-free target as a transfer standard between a well calibrated spectroradiometer on the aircraft and the radiometer on the satellite. The method requires accurate prediction of the satellite-target viewing geometry, which is necessary to enable the aircraft spectroradiometer to be coaligned with the satellite view vector during satellite overpass. Small corrections must be applied to account for the effects of the atmospheric path between the aircraft and the satellite, and to account for the difference between the footprints of the two instruments on the target. These corrections, and the knowledge of the spectral response function of a given channel of the satellite radiometer, allow the calculation of equivalent sets of radiance values (from the aircraft measurements) and count values (from the satellite measurements) that correspond to the altitude of the satellite radiometer and the field of view of the aircraft spectroradiometer. These sets are augmented in the case of AVHRR by measurements of the counts corresponding to the radiance of space, which is assumed to be zero. A weighted least squares fit between the sets gives the gain (i.e., count output divided by radiance input) -- the reciprocal of the "slope" discussed in Section 3-- of the satellite radiometer's channel as the slope of the best-fit straight line.

The atmospheric correction is minimized by operating the U-2 aircraft in the stratosphere, so that necessary corrections are limited to stratospheric aerosol and stratospheric ozone. In this case the atmospheric correction for reasonable observation geometry is calculated to be less than 3% for channel 1 of AVHRR (and is smaller for channel 2). The corrections may be calculated to adequate accuracy, in the absence of recent additions of aerosols of volcanic origin, by adopting climatological averages for stratospheric composition, and calculating the correction with the LOWTRAN-7 computer code. The aircraft spectroradiometer collects data for a period of approximately 3 minutes. Satellite data encompassing the spatial range of the aircraft data are collected from the satellite radiometer for approximately 5 seconds in the middle of this period, and the method assumes that the two data sets correspond to identical states of scene structure and illumination. It is also assumed that the spectral response functions of AVHRR channels have not changed since being measured before launch, and all observed changes in AVHRR response in orbit can be attributed to changes in gain. Greater details on instrumentation, data acquisition, and footprint correction are found in Smith et al. (1988).

2.5 Absolute calibration using ocean targets

This effort has two major components: (a) derivation of the degradation rate for channel 1 by comparing the measured reflectance factor over ocean targets in the off-glint region with the computed reflectance factor in a representative model of a cloud-free, clear (low turbidity) atmosphere, and (b) intercalibration between channels 1 and 2, using measurements in the highly reflective sunglint region. An ocean target is chosen because of the relative rigor with which radiative transfer in a cloud-free atmosphere bound by a wind-disturbed sea surface can be computed, especially under clear conditions when most of the upwelling radiance is due to molecular scattering. The present technique is a refinement of the earlier work of Kaufman and Holben (1993), the refinement being the inclusion of radiances measured in channel 2 to get better estimates of the aerosol optical thickness to be included in the radiative transfer computations; thus, only the aerosol size distribution function and the refractive index of the aerosol material have to be assumed in the present technique. Gaseous absorption is properly taken into account, and the upwelling radiance, or equivalently, the reflectance factor or albedo is modelled.

The reflectance factor or albedo is also calculated from the measured counts, the offset, and preflight calibration coefficients. The slope of the linear regression between the measured (calculated) and the modelled reflectance factors yields the degradation coefficient as defined in Holben et al. (1990). Preliminary results indicate that this method could generate a much more stable (in time) record of calibration than the earlier ocean technique (Kaufman and Holben, 1993) since the aerosol optical thickness used in the model simulations has minimal ambiguity, resulting in a reduction of the absolute bias introduced by a mean aerosol model which could be very different from the prevalent conditions. It is expected that this technique, when properly developed and implemented, would be able to generate a very good absolute calibration of AVHRR channels 1 and 2 since the technique is essentially free of the adverse effects of the unknown nature of the bidirectional reflection properties of the underlying surface.

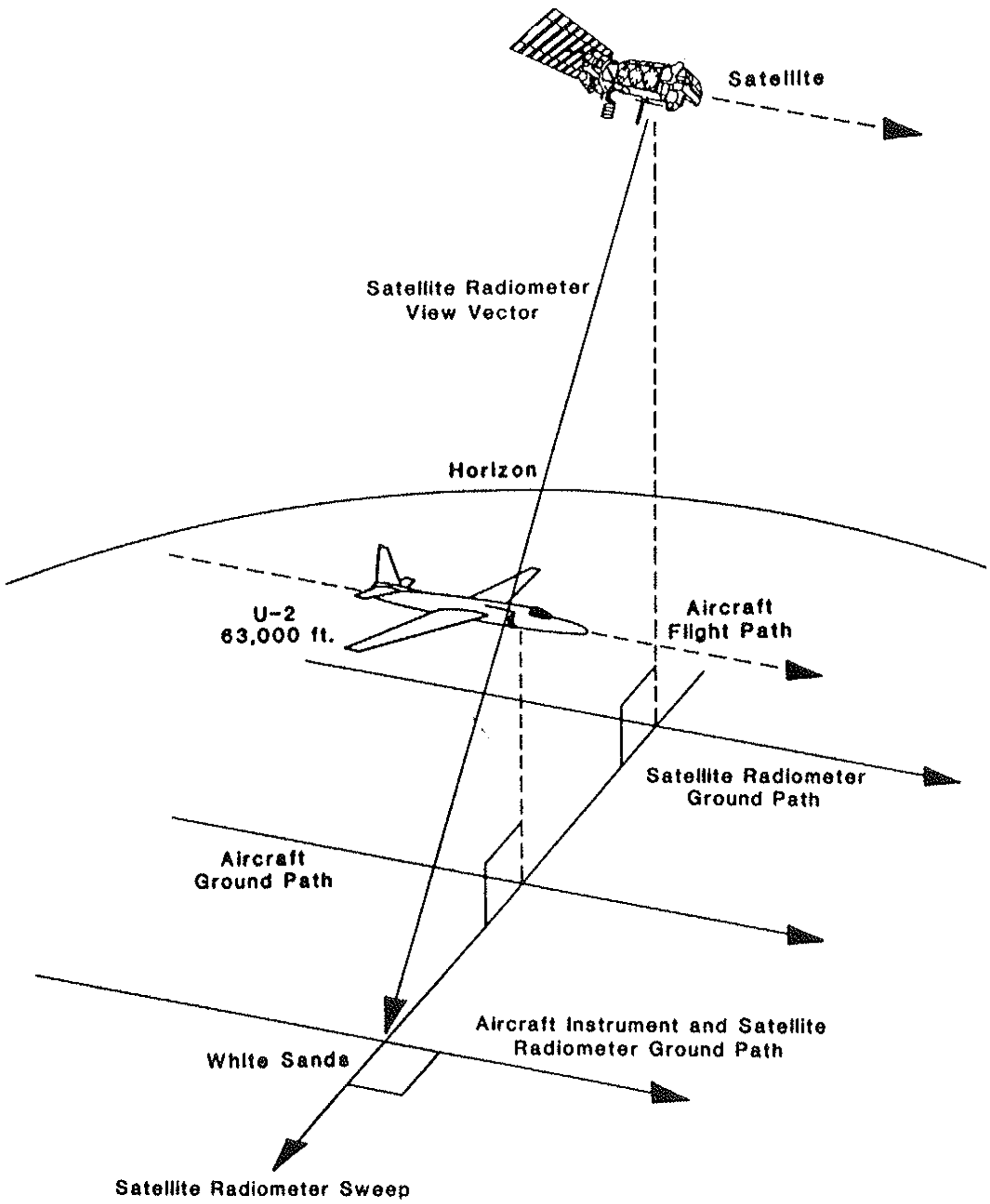

Figure 1. Schematic of the aircraft-satellite congruent path measurements.

(after Smith et al., 1988)

3. Results and Discussion

We shall present and discuss in this section AVHRR calibration information derived from "absolute" or "direct", "indirect", and "relative" methods. It has been the usual convention (e.g., Whitlock et al. 1990; Che and Price 1992) to refer to the congruent path aircraft/satellite technique as the "absolute" or "direct" method; methods which depend upon extensive radiative transfer modelling (surface and overlying atmosphere) are referred to as "indirect" methods; and methods which yield sensor degradation (relative) from statistical analyses of long-term data as "relative." This convention is, however, not very rigid; for example, the results obtained from the ocean target technique (Section 2.5) are also referred to as "absolute" calibrations.

The term "slope" [W/(m^2 μm sr ct)] will be used in this section to indicate the reciprocal of "gain". Thus, increasing values of "slope" --the radiance input required to yield a signal of one count-- in time indicate degradation of the sensor with time. The greater part of the available absolute and indirect post-launch calibration data for channels 1 and 2 of the AVHRR on NOAA-9 are shown in Figs. 2 and 3. These are similar to Figs. 1 and 2 of Whitlock et al. (1990), with the difference that available data up to November 1988 have been included. The data from Whitlock et al. (1990) which have been reproduced in Figs. 2 and 3, as also the NASA/GSFC ER-2 data, were kindly provided by C.G.Whitlock (personal communication). The calibration trends identified as "NOAA Libyan desert" are based on the work performed at the NOAA/NESDIS Satellite Research Laboratory (Rao and Chen, 1993); the ISCCP trend data for channel 1 are drawn from Brest and Rossow (1992); the NASA/GSFC desert data are from Kaufman and Holben (1993); and the USDA "slope" values (Fig. 3) are based on the formulae in Che and Price (1992). The USDA data are a compilation of the gains [counts/(W/m^2 μm sr)] in channels 1 and 2 based on results reported by investigators elsewhere, and will be referred to as "composite" data for convenience; the data were grouped into monthly bins; also, when a single determination of gain was reported for any year, it was assigned to the month of July of that year. A simple regression relationship was established between the gain values and the elapsed time in months from the date of launch. Using these regression relationships, the slope [W/(m^2 μm sr ct)] was calculated as the reciprocal of the gain; greater details are found in Che and Price (op cit). It should, however, be noted that some of these regression relationships, which are the bases for the data labelled "USDA" in Figs. 3 through 5, and in Table 3, have very low values of the coefficient of determination.

The channel 1 trend determined using the Libyan desert target, and the ISCCP channel 1 trend have both been anchored to the <u>mean</u> value of 0.606 W/(m^2 μm sr ct) of the NOAA U2 absolute calibrations of October/November 1986 (Table 1 below) since they are based on the largest number of aircraft/satellite congruent path measurements over a short period of about two weeks. It should however be mentioned that the results reported in Brest and Rossow (1992) have been anchored to an early version of the mean [0.5997W/(m^2 μm sr ct)] of the aircraft absolute calibrations of October/November 1986. The ISCCP trend analysis for channel 2 is not presently available. Detailed descriptions of the techniques employed to obtain the slope values labelled as NASA Sonora desert, NASA LaRC WSMR, Scripps, Georgia Tech, and University of Arizona are found in the literature cited in Whitlock et al. (1990).

Table 1. Slope [W/(m^2 μm sr ct)] values from congruent path aircraft/satellite measurements (C.H. Whitlock, personal communication)

Days from Launch	Platform	Slope Channel 1	Slope Channel 2
257 (Aug 85)	NOAA U2	0.521	0.36
681 (Oct 86)	"	0.600	0.41
682 (Oct 86)	"	0.622	0.41
693 (Nov 86)	"	0.597	0.40
1154 (Feb 88)	"	0.654	0.42
1430 (Nov 88)	NASA/GSFC ER-2	0.660	0.41

Note: The November 1988 measurement falls towards the end of the period of interest.

Pre-launch calibration of the two channels, performed in February 1980, yields values of 0.5249 W/(m^2 μm sr ct) for channel 1 and 0.3515 W/(m^2 μm sr ct) for channel 2.

A subset of the data displayed in Fig. 2 for channel 1 is shown in Fig. 4, along with the "slope" values for channel 1 based on the USDA composite data (Che and Price, 1992); similarly, a subset of the data displayed in Fig. 3 for channel 2 is shown in Fig. 5. These are essentially data that cover the entire, effective operational life of the sensor, and have been compared in some detail later in this section. The uncertainties (see Table 2) furnished by the various authors have not been shown in Figs. 2 through 5 mainly to maintain clarity, and also because of the lack of uniformity in the definition of uncertainty adopted by the various authors (C.H. Whitlock, personal communication).

Pertinent features of the data displayed in Figs. 2 through 5 are:

(a) the scatter in the results of the various "absolute" (or "direct") and indirect methods of post-launch calibration (Figs. 2 and 3);

(b) the NOAA, ISCCP, and the USDA slopes are within ±5% of one another for channel 1; the desert calibration of Kaufman and Holben (1992) gives uniformly larger values of "slope" for both channels than most of the others over the greater part of the period 1985-88 (Figs. 4 and 5);

(c) the NOAA and ISCCP trends, when anchored to the mean value of the October/November 1986 U2-based absolute calibrations, are such that the NOAA

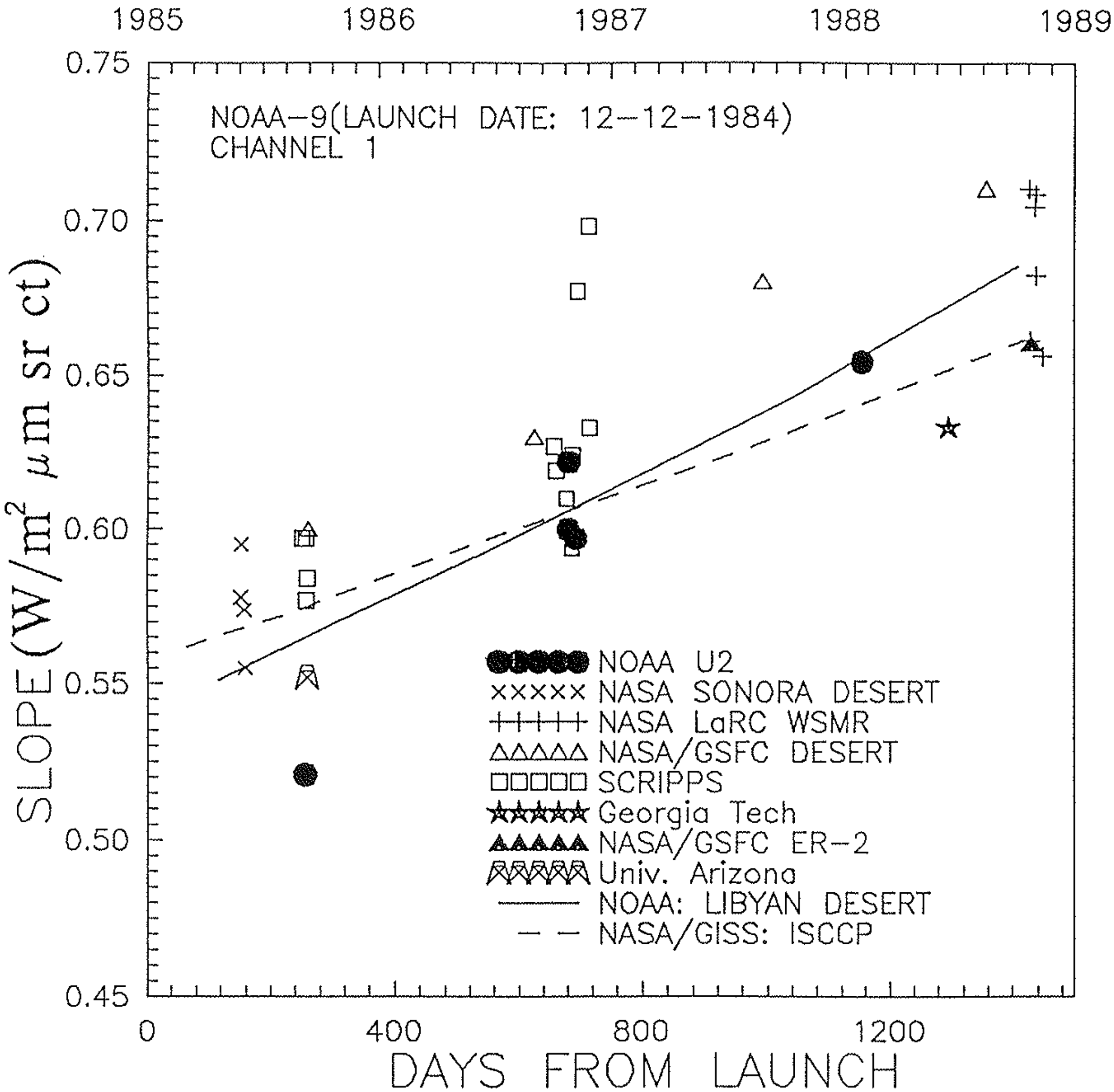

Figure 2. Degradation of AVHRR channel 1; the increasing values of "slope" (the ordinate) indicate the degradation of the instrument (after Brest and Rossow, 1992; Rao and Chen, 1993; Whitlock et al., 1990).

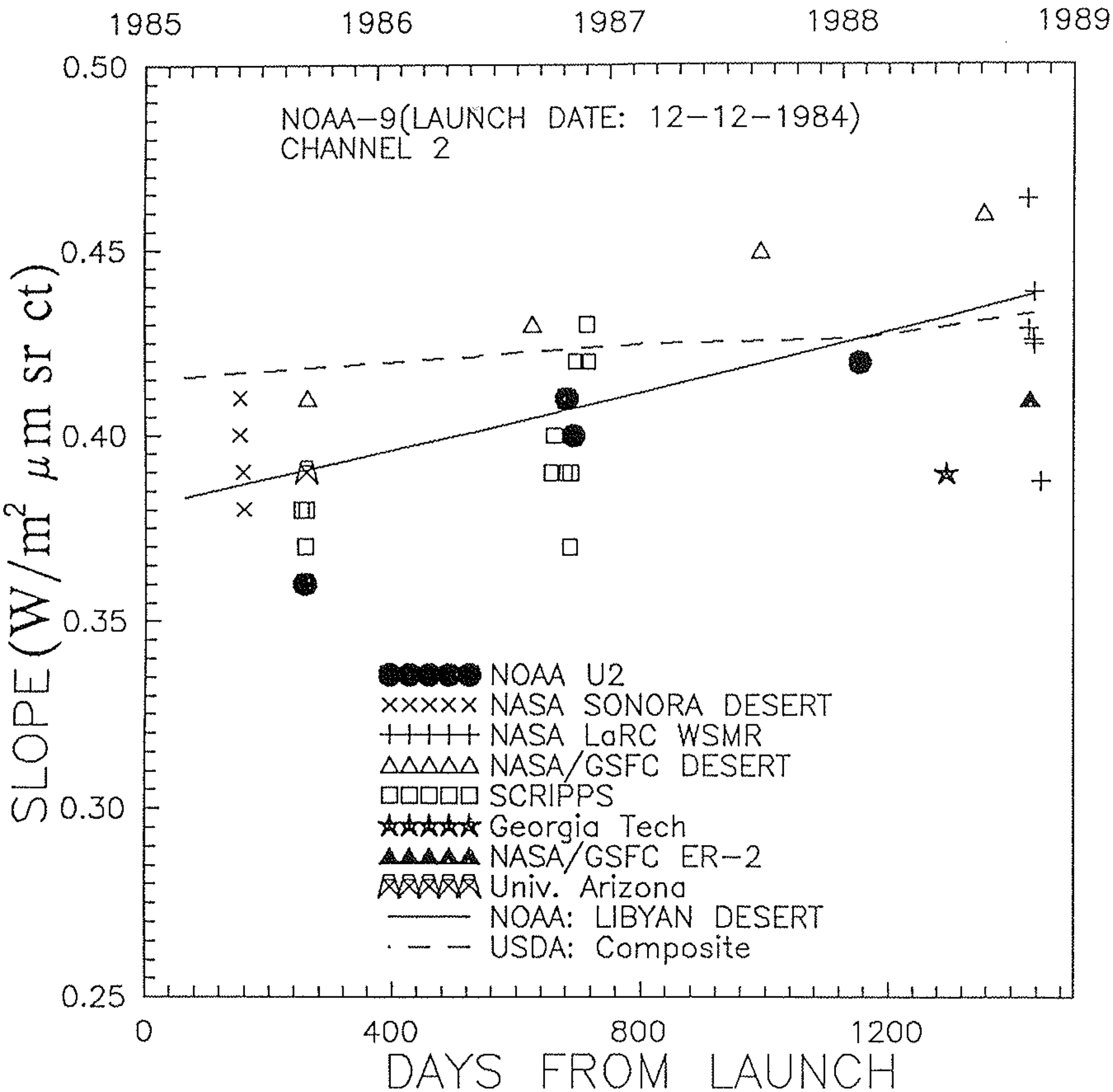

Figure 3. Degradation of AVHRR channel 2; sources of data are the same as for Figure 2; the USDA results (Che and Price, 1992) have also been included.

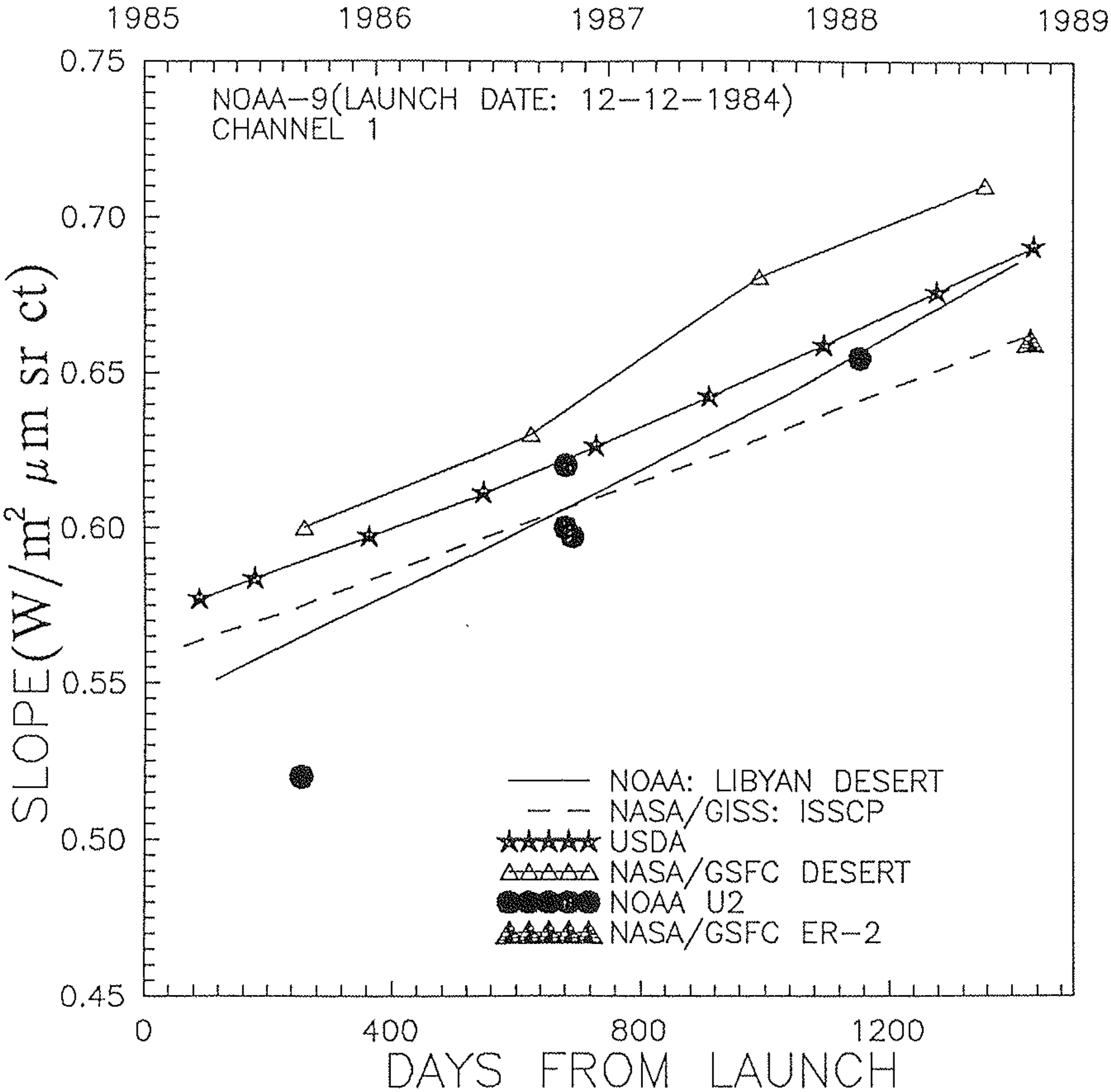

Figure 4. Selected data from Figure 2; in addition, the USDA results (Che and Price, 1992) have also been included.

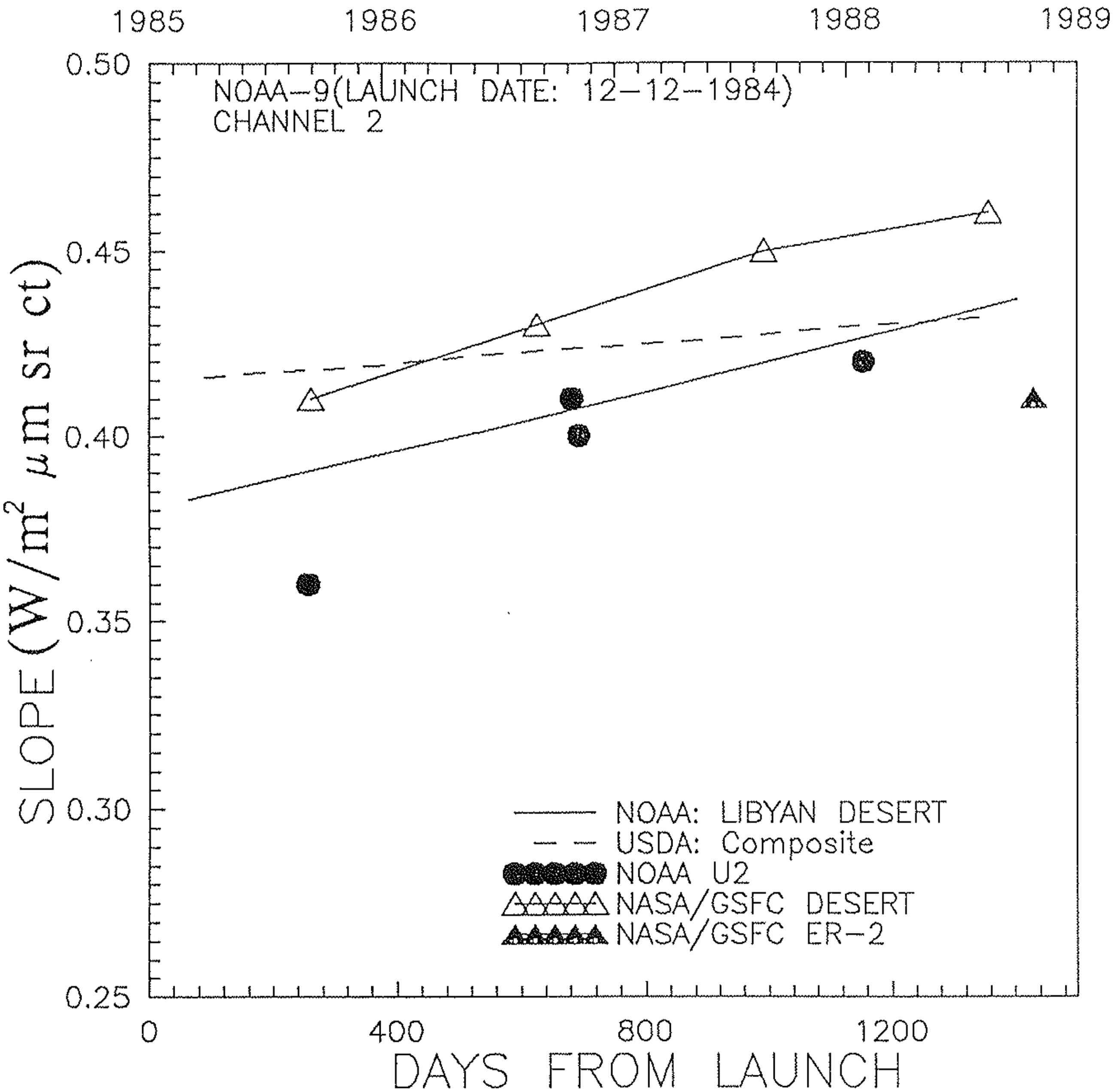

Figure 5. Selected data from Figure 3.

trend passes closer to the February 1988 absolute calibration than the ISCCP trend, whereas the latter is closer to the absolute calibration of November 1988 (Fig. 4);

(d) the very low rate of degradation predicted by the USDA composite data technique for channel 2 compared to either the NOAA trend analysis or the NASA/GSFC desert calibration technique; and the NASA/GSFC calibration results being almost uniformly larger than the NOAA trend analysis results over the entire record (Fig. 5).

These features of the available information on AVHRR degradation, along with the "uncertainties" reported by various authors (Table 2), should be weighed while making recommendations to the user community on corrections to be made to AVHRR channel 1 and 2 data. It should, however, be noted that any comparison of the trends given by the NOAA Libyan desert, ISCCP, NASA/GSFC desert, and the USDA techniques must take into consideration the fact that the NASA/GSFC desert trends have been anchored to an absolute value of slope different from the one to which the NOAA and ISCCP trends have been, and that the USDA trend is based on a simple regression of composite ["direct" and "indirect"] gain values on elapsed time.

Table 2. Estimated uncertainties in the slopes
(C.H. Whitlock, Y. Kaufman, and B. Holben, personal communication)

Method	Uncertainty(%)	
	Channel 1	Channel 2
NOAA/NESDIS U-2	± 5	± 5
Univ. Arizona (Indirect)	± 5	± 5
NASA LaRC (Indirect)	± 7	± 7
Scripps (Indirect)	± 8	± 8
NASA/GSFC (Indirect)	± 5	± 5
NOAA: Libyan Desert (Relative)		
ISCCP (Relative)	± 2(+ U2 error)	

Note 1. According to C.G. Whitlock (personal communication), the uncertainty values were furnished by the various investigators and are the same for the two channels; the descriptive terms within parentheses are taken from Whitlock et al. (1990).

Note 2. Descriptions of the methods used to derive the calibrations labelled "Univ. Arizona", "NASA LaRC", and "Scripps" are found in references cited in Whitlock et al. (1990)

Thus, to bring out more clearly the similarity, or lack of it, among the trends shown in Figs. 4 and 5, we have shown in Fig. 6 the same data normalized to the mean value of the slope in October/November 1986--0.606 [W/(m^2 μm sr ct)] for channel 1 and 0.407

[W/(m^2 μm sr ct)] for channel 2. It is obvious that the renormalized degradations are within about 3% of one another for channel 1; in the case of channel 2, the two desert techniques (Rao and Chen, 1993; Kaufman and Holben, 1993) yield results that are very close to each other, while the USDA values yield a lower rate of degradation overall.

The "slopes" for the two channels corresponding to the mid-point of each month are shown in Table 3. The "ISCCP" values were inferred from the entries in Table 5 of Brest and Rossow (1992) and have been renormalized, as mentioned earlier, to a value of 0.606 [W/(m^2 μm sr ct)] which is the mean of the NOAA U2 absolute calibrations for October/November 1986. The "slope" values labelled "NOAA" are based on the trend analysis using the Libyan desert target (Rao and Chen, 1993); the "USDA" and "NASA" values are based on the formulae given in Table 4 of Che and Price (1992) and Kaufman and Holben (1993) respectively.

It is obvious from the data shown in Figs. 2 through 6 that "direct" calibrations based on congruent radiance measurements from aircraft and satellites have been very infrequent, mainly because of the cost of such missions, and the attendant logistical difficulties, indirect calibrations such as those based on comparison between model simulations and satellite measurements, and on transfer of calibration between a calibrated satellite radiometer and the AVHRR are clustered and not evenly distributed over the length of record. Thus the user community will have to rely on calibration trends determined from statistical trend analyses which have been anchored to the best available absolute calibration, and perhaps to trends calculated from composite data (e.g., Whitlock et al., 1990; Che and Price, 1992) in order to correct for sensor degradation in the retrospective processing of AVHRR data.

There is room for improvement of the various techniques we have described so far for trend analysis and absolute calibrations. The ISCCP trend analysis is based on a global reflectance data set comprising a wide spectrum of surface reflectance values, and a manifold of surface types observed under a variety of illumination and observation geometries. As mentioned earlier, the calibration trend determination is based on the assumption of the constancy of the global aggregate of targets, and not on the constancy of any particular target. In addition, the bidirectional surface reflection models used in the study are presently being improved, and these improvements may also influence the derived degradation rates. Similarly, the global applicability of the trend analysis based on the use of the Libyan desert as a time-invariant target may be questioned as it is based on measurements made over a highly reflecting target illuminated by high to moderate sun, thereby confining the analysis to a finite segment of the dynamic range of the instrument. However, Staylor (1990), while discussing the degradation rate for channel 1, has noted that "An analysis of the combined data from 30°N to 30°S, which includes half of the Earth's surface and many scene types, found that its degradation rates were essentially same as those for the Libyan desert suggesting the rates apply to all scene types."

The absolute calibrations based on congruent measurements from aircraft and satellite put stringent requirements on navigation and alignment of the two measurements, especially in view of the highly variegated nature of terrain features, and surface layer meteorology over the White Sands Missile Range area (C.G. Whitlock, personal communication). The absolute calibrations based on a comparison of model simulations

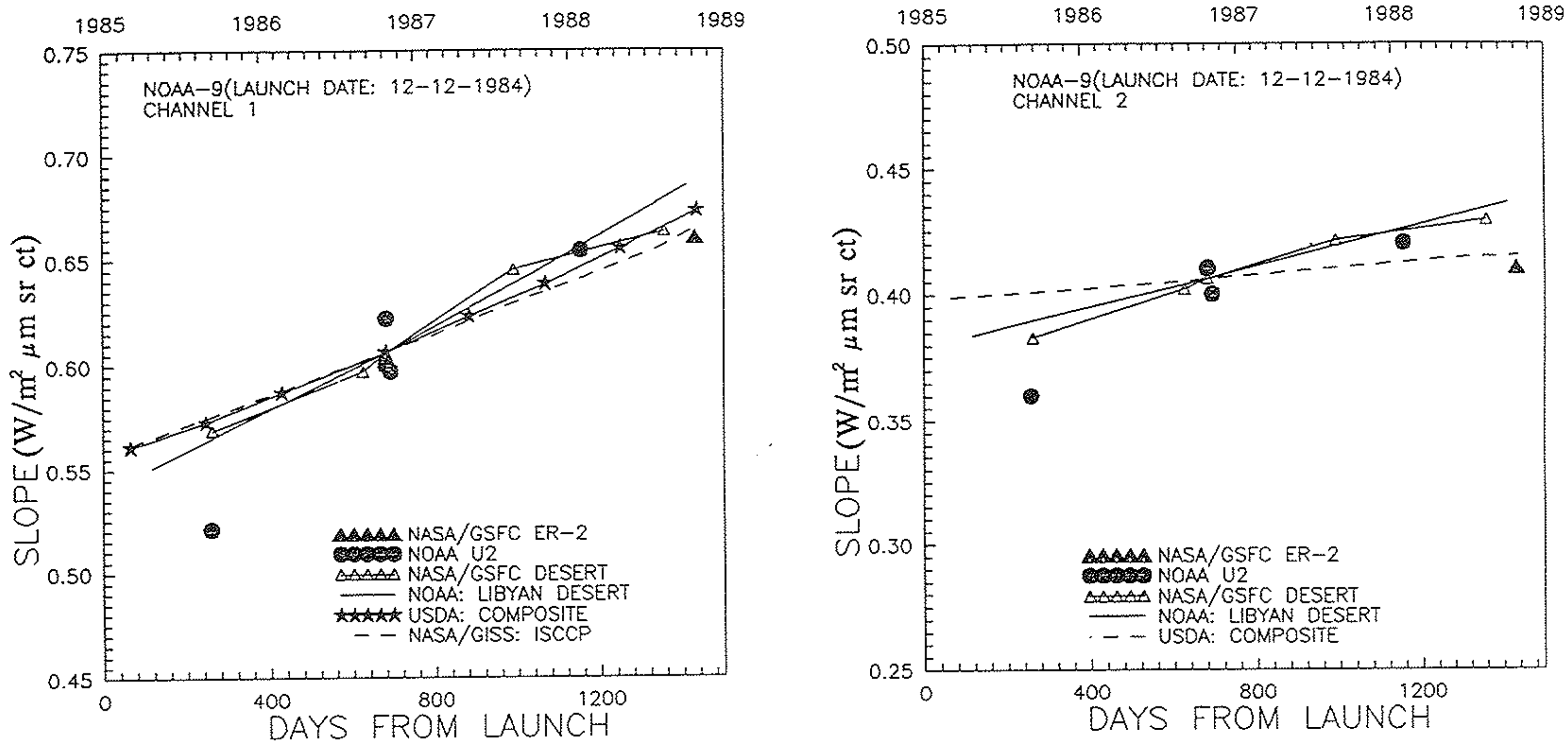

Figure 6. Renormalized data for channel 1 (left) and for channel 2 (right).

Table 3. Slopes ($W \cdot m^{-2} \cdot \mu m^{-1} \cdot sr^{-1} \cdot ct^{-1}$) for channels 1 and 2 of the AVHRR on NOAA-9

Date	Days from launch	Channel 1				Channel 2		
		NOAA	ISCCP	NASA	USDA	NOAA	NASA	USDA
2/15/85	65	0.5465	0.5635	0.5810	0.5753	0.3832	0.4175	0.4156
3/15/85	93	0.5490	0.5657	0.5836	0.5774	0.3842	0.4185	0.4159
4/15/85	124	0.5519	0.5674	0.5863	0.5796	0.3854	0.4196	0.4163
5/15/85	154	0.5546	0.5697	0.5889	0.5817	0.3865	0.4207	0.4167
6/15/85	185	0.5575	0.5719	0.5916	0.5839	0.3877	0.4217	0.4171
7/15/85	215	0.5603	0.5737	0.5944	0.5861	0.3888	0.4228	0.4174
8/15/85	246	0.5631	0.5759	0.5971	0.5883	0.3900	0.4239	0.4178
9/15/85	277	0.5660	0.5782	0.5999	0.5906	0.3912	0.4250	0.4182
10/15/85	307	0.5689	0.5799	0.6027	0.5928	0.3924	0.4260	0.4186
11/15/85	338	0.5718	0.5821	0.6055	0.5951	0.3936	0.4271	0.4190
12/15/85	368	0.5746	0.5844	0.6083	0.5974	0.3947	0.4282	0.4193
1/15/86	399	0.5776	0.5866	0.6112	0.5997	0.3959	0.4293	0.4197
2/15/86	430	0.5806	0.5883	0.6141	0.6020	0.3971	0.4305	0.4201
3/15/86	458	0.5833	0.5906	0.6170	0.6043	0.3982	0.4316	0.4205
4/15/86	489	0.5863	0.5928	0.6200	0.6067	0.3994	0.4327	0.4209
5/15/86	519	0.5892	0.5951	0.6230	0.6090	0.4006	0.4338	0.4213
6/15/86	550	0.5923	0.5973	0.6260	0.6114	0.4018	0.4350	0.4216
7/15/86	580	0.5952	0.5990	0.6290	0.6138	0.4030	0.4361	0.4220
8/15/86	611	0.5983	0.6013	0.6321	0.6163	0.4042	0.4373	0.4224
9/15/86	642	0.6014	0.6035	0.6352	0.6187	0.4055	0.4384	0.4228
10/15/86	672	0.6044	0.6058	0.6383	0.6212	0.4067	0.4396	0.4232
11/15/86	703	0.6075	0.6080	0.6415	0.6237	0.4079	0.4407	0.4236
12/15/86	733	0.6105	0.6103	0.6447	0.6262	0.4091	0.4419	0.4240
1/15/87	764	0.6136	0.6125	0.6479	0.6287	0.4103	0.4431	0.4244
2/15/87	795	0.6168	0.6148	0.6512	0.6313	0.4116	0.4443	0.4247
3/15/87	823	0.6197	0.6170	0.6545	0.6338	0.4127	0.4455	0.4251
4/15/87	854	0.6229	0.6193	0.6578	0.6364	0.4140	0.4467	0.4255
5/15/87	884	0.6260	0.6215	0.6612	0.6391	0.4152	0.4479	0.4259
6/15/87	915	0.6292	0.6238	0.6646	0.6417	0.4165	0.4491	0.4263
7/15/87	945	0.6323	0.6261	0.6680	0.6443	0.4177	0.4503	0.4267
8/15/87	976	0.6356	0.6284	0.6714	0.6470	0.4190	0.4515	0.4271
9/15/87	1007	0.6389	0.6306	0.6750	0.6497	0.4202	0.4527	0.4275
10/15/87	1037	0.6421	0.6329	0.6785	0.6524	0.4215	0.4540	0.4279
11/15/87	1068	0.6454	0.6351	0.6821	0.6552	0.4228	0.4552	0.4283
12/15/87	1098	0.6486	0.6374	0.6857	0.6580	0.4240	0.4565	0.4287
1/15/88	1129	0.6519	0.6396	0.6893	0.6608	0.4253	0.4577	0.4291
2/15/88	1160	0.6553	0.6419	0.6930	0.6636	0.4266	0.4590	0.4295
3/15/88	1189	0.6584	0.6441	0.6968	0.6664	0.4278	0.4603	0.4299
4/15/87	1220	0.6618	0.6464	0.7005	0.6693	0.4291	0.4615	0.4303
5/15/88	1250	0.6651	0.6486	0.7043	0.6722	0.4304	0.4628	0.4307
6/15/88	1281	0.6686	0.6514	0.7082	0.6751	0.4317	0.4641	0.4311
7/15/88	1311	0.6719	0.6536	0.7121	0.6780	0.4329	0.4654	0.4315
8/15/88	1342	0.6754	0.6559	0.7160	0.6810	0.4343	0.4667	0.4319
9/15/88	1373	0.6788	0.6581	0.7200	0.6840	0.4356	0.4680	0.4323
10/15/88	1403	0.6822	0.6605	0.7240	0.6870	0.4369	0.4694	0.4327
11/15/88	1434	0.6857	0.6633	0.7281	0.6900	0.4382	0.4707	0.4331

Note:
NOAA 1,2: Slopes for channels 1 and 2 calculated using the Libyan desert target from Rao & Chen (1993)
NASA 1,2: Slopes for channels 1 and 2 from Kaufman & Holben (1993)
USDA 1,2: Slopes for channels 1 and 2 from Che & Price (1992)
ISCCP 1: Slope for channel 1 from Brest & Rossow (1992) after renormalization

with satellite measurements over ocean targets impose input data requirements which cannot always be met with reasonable effort.

Before we conclude this section, we would like to show some very preliminary results (Figure 7) obtained for the degradation of channel 1 of the AVHRR on NOAA-9 spacecraft using the ocean target technique (Section 2.4). Measurements made over the Indian Ocean off northwestern Australia were used in this study; and the regression line yields the rate of degradation of channel 1 during 1988; the observed rate of degradation of $\approx$ 4.5% per year is lower than the value of $\approx$ 5.9% obtained with the trend analysis using desert targets.

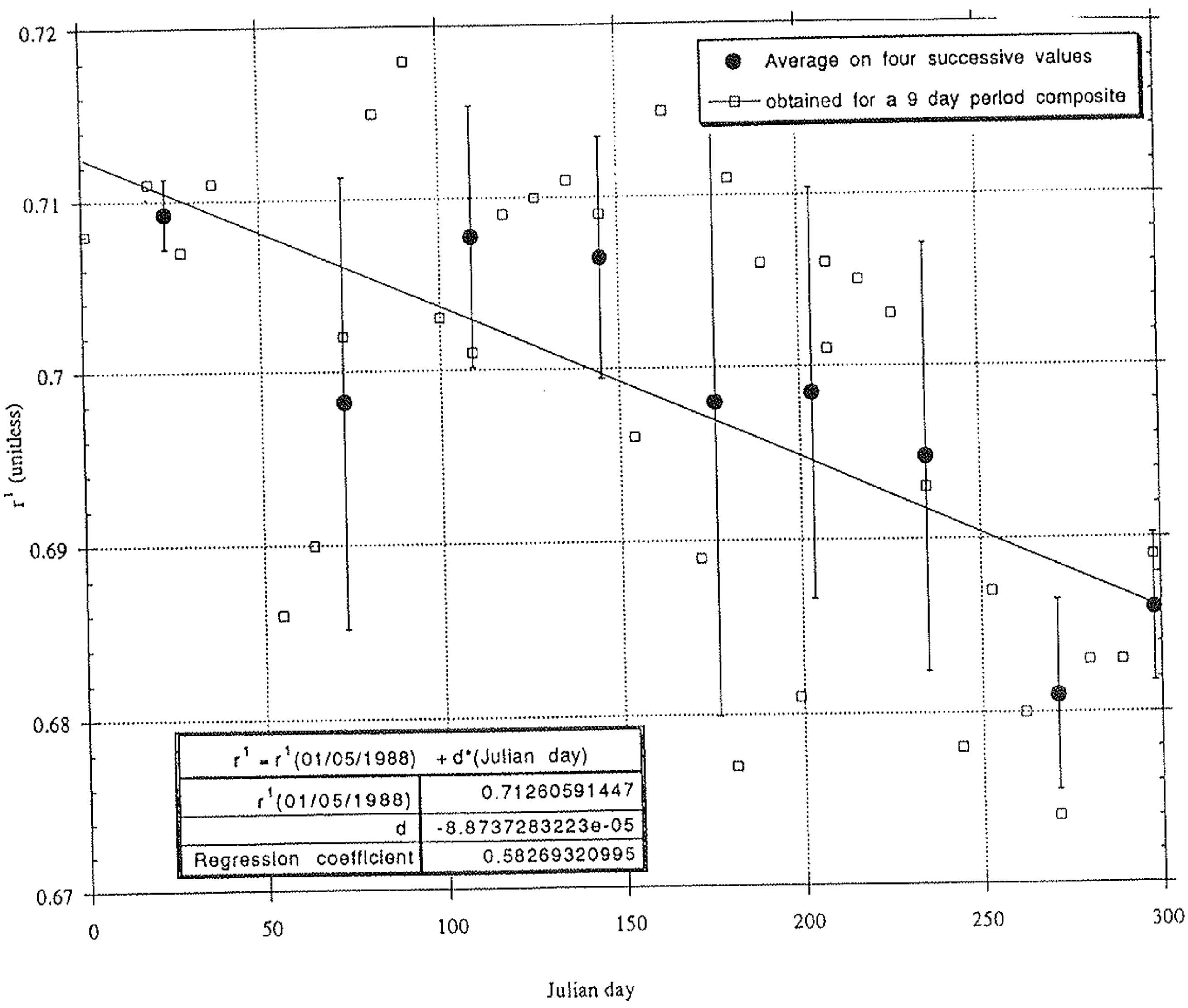

Figure 7. Degradation of AVHRR channel 1 during 1988 from the ocean target technique; the ordinate is the ratio of the pre-launch to actual "slope" values.

4. Recommendations

The recommendations for applying corrections to the radiance measurements made in channels 1 and 2 of the AVHRR on NOAA-9 spacecraft are based on the following considerations:

(a) the recommendations should be based on as large a body of data as is practicable, obtained over a period of time encompassing the greater part of the effective operational life of the sensor;

(b) the results should yield trends, which when anchored to the absolute U2 calibrations of October/November 1986, will be very close to the absolute U2 calibrations of 1988, after making due allowance for the inherent uncertainties in the aircraft-based absolute calibrations;

and (c) they should be based on the same technique for both channels 1 and 2.

In light of the above, it is recommended that the slopes based on the NOAA trend analysis using the Libyan desert target --entries in the "NOAA" column of Table 3-- be used for both channels. The user interested in determining the value of the slope corresponding to a date not listed in Table 3 should use the following formulae:

Channel 1:

$$\text{Slope (days d from launch)} = 0.5465 \times \exp[1.66 \times 10^{-4} \times (d-65)]$$

Channel 2:

$$\text{Slope (days d from launch)} = 0.3832 \times \exp[0.98 \times 10^{-4} \times (d-65)]$$

Linear interpolation between the entries in the "NOAA" column of Table 3 can also be used without serious error.

The slope values thus determined will yield the radiance when multiplied by $[C_{10} - C_0]$ where C_{10} and C_0 are the measured counts (10-bit scale) and "offset" respectively. It has been the practice to use the deep space counts for the offset C_0; the published values for C_0 show some spread, ranging from 36.2 to 38 for channel 1 and from 39 to 40.3 for channel 2. The pre-launch calibration equations yield values of 36.2 for channel 1 and 36.1 for channel 2. In view of this spread in the values, it is recommended that offset values of 37 counts be used for channel 1 and of 39.6 be used for channel 2.

5. Strategy for Future Work

The AVHRR Pathfinder Calibration Working Group recognizes that any calibration method that would provide a uniform calibration over the entire record should have three components: (a) an absolute anchor at as many points in the record as is practicable, (b) statistical trend analyses that would maintain a continuous record between the anchor points, and (c) a procedure to normalize the calibrations of the different AVHRRs to a common base. The anchor points should generally be based on congruent aircraft and satellite measurements over well-characterized target sites. These should also be supplemented by other "absolute" calibrations obtained from different methods such as the ocean target technique (e.g., Mitchell et al. 1992; Vermote et al., 1990; also Abel 1990) to serve as intermediate references in view of the practical considerations of cost and logistics that would limit the frequency of congruent path aircraft and satellite measurements even in the best of times!

Using the above as guidelines, any strategy for future work should address two important aspects of post-launch calibration; these are (a) an examination of the data and results of the various methods to derive gain and intercept in orbit, and (b) the application of physically reasonable constraints to long-term time series of the physical properties of the Earth-Atmosphere system derived from AVHRR measurements. Iterative application of these two procedures may be necessary to obtain a reasonable estimate of the in-orbit performance of the AVHRR. Thus, issues like the error budgets of various calibration techniques, the minimum length of record for statistical trend analysis, and generation of application-oriented calibration information, such as the ratio of the slopes of the two channels required in the determination of normalized vegetation indices should be addressed. An estimate of the physically reasonable natural variabilities of the AVHRR-based environmental products should be furnished by the various AVHRR Pathfinder Science Working Groups so that temporal variations in AVHRR response can be properly isolated. The utility of high clouds as calibration targets to obtain the ratio of calibration changes in channels 1 and 2 should be further explored, bearing in mind that the reflectivity of such high clouds is not very much affected by the effects of water vapor absorption in the overlying atmosphere, and is almost the same in the two channels; however, the effect of variations in atmospheric ozone in the Chappuis bands on the radiances measured in channel 1 should be properly accounted for.

The sense of the working group is that the "calibration" information given to the user should consist of, but should not be limited to, (a) absolute calibrations, (b) simple user-friendly formulae for computation of relative trends over the life of a given sensor, (c) deep space (or offset) counts or intercept information, and (d) ratio of the degradation of the two channels.

The successful implementation of the above strategy for future work in sensor calibration will be dependent upon the assured, long-term commitment of financial and personnel resources by agencies like NOAA and NASA.

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The work reported here was supported by the Information Management Component (NOAA Pathfinder Program Manager: Dr. Arthur Booth) of the Climate and Global Change Program, NOAA Office of Global Programs. Dr.C.H. Whitlock, NASA Langley Research Center, Hampton, Virginia, kindly furnished some of the calibration data shown in Figures 2 through 5. Useful discussions with Dr.G.L. Smith, NASA Goddard Space Flight Center, Greenbelt, Maryland, on the aircraft measurements over White Sands, New Mexico, are herewith acknowledged.

APPENDIX A: The AVHRR Pathfinder Calibration Working Group

The membership of the AVHRR Pathfinder Calibration Working Group is listed below:

Chair:	C.R. Nagaraja Rao	NOAA/NESDIS
Members:	Peter Abel	NASA/GSFC
	Christopher Brest	Hughes STX
	Robert Cess	SUNY, Stony Brook, NY
	Robert Evans	University of Miami, Miami
	Garik Gutman	NOAA/NESDIS
	Yoram Kaufman	NASA/GSFC
	William Rossow	NASA/GSFC/GISS
	Frank Staylor	NASA/LaRC
	Michael Weinreb	NOAA/NESDIS

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