Calibration of the Solar Channels of the NOAA-9 AVHRR Using High Altitude Aircraft Measurements

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ABSTRACT

A method for calibrating satellite radiometers is investigated. A calibrated spectral radiometer carried aboard a U2 aircraft at an altitude of 60 000 ft was aligned with White Sands, New Mexico along the same view vector as the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-9 spacecraft at the time of the spacecraft's overpass on 26 August 1985. Both sets of data have been transformed into best estimates of the radiance at satellite altitude inside the footprint of the aircraft radiometer, allowing an estimate of radiance calibration changes in the AVHRR to be made. It is assumed that both instrument systems are linear, that the spectral response function of AVHRR has not changed from its prelaunch value, and that the zero radiance responses of both instruments are accurately known. Extrapolation of the radiances measured from the aircraft to those expected at satellite altitude is achieved by modeling the experimental conditions at White Sands and calculating the ratio of radiances at the two altitudes through the LOWTRAN VI computer program.

Results from data taken within 2 minutes either side of the satellite overpass indicate a 98.9% correlation between the two sets of data, and a change in gain relative to the prelaunch calibration of +2 ± 5% for channel 1 and −2 ± 5% for channel 2 of the NOAA-9 AVHRR. Analysis of other coincident data for the NOAA-9 AVHRR and the aircraft spectral radiometer, including a large dataset from October and November 1986, is now in progress and will establish the day-to-day repeatability of results using this method.

1. Introduction

Applications requiring accurate quantitative measurements of the earth's radiance for their success have increased steadily since the dawn of the satellite era in 1957. The first applications of quantitative data, in 1965, derived the atmospheric temperature profile and the surface temperature from observations in the 15 micron band of CO_2 and the 11 micron window. The observations were calibrated in orbit by measuring the radiometric signal received from an onboard target of accurately known radiance, and from the effectively zero radiance of space. Currently there are applications for accurately calibrated radiances at wavelengths throughout the solar and terrestrial spectra.

The evolution of applications for satellite radiance measurements in the visible spectrum has largely been driven by the needs of weather and climate models for larger and more accurate observational datasets, which are a result of the increasing availability of fast, powerful computers. It is also driven by a strong need to understand the mechanisms underlying decadel changes in the terrestrial environment and, in particular, humanity's growing role in determining the nature of global changes. In the words of Goody (1982),

> The earth is a planet characterized by change, and has entered a unique epoch when one species, the human race, has achieved the ability to alter its environment on a global scale.

The buildup of CO_2 in the atmosphere, and continuing deforestation, particularly in the tropics, are examples of human influence on the drivers of climate change over times measured in decades. Long-term, accurate data bases of climate and other variables are required to give early detection of such changes, and to evaluate their consequences. The crucial need for these has been stressed, for example, in the proposed International Geosphere–Biosphere Program (U.S. National Academy of Sciences 1986) in a major report to the NASA advisory council (Earth System Sciences Committee 1986), and in joint NOAA/NASA reports to the Congress on national research and development plans in remote sensing of the earth and its atmosphere (NOAA/NASA 1985). Unbiased calibration transfer between successive satellite instruments is necessary to achieve this goal. In addition, the calibration bias that develops in single satellite datasets during a multiyear period must be kept less than the precision of a single measurement if the long-term precision of the dataset is to be preserved.

The Advanced Very High Resolution Radiometer (AVHRR) has no onboard calibration system for visible wavelengths, yet several important applications require

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well-calibrated radiances. For example, useful vegetation indices correspond to relative radiance precision of about 1%. Albedo measurements should have an accuracy of better than ±5%, with a goal of ±1% for long-term usefulness. The method reported here has the potential to meet these needs. It is illustrated by a comparison of NOAA-9 AVHRR and coaligned aircraft radiances observed above White Sands, New Mexico on 26 August 1985.

Results from satellite and aircraft radiances collected over water to calibrate the Nimbus 7 Coastal Zone Color Scanner (CZCS) have already been published (Hovis et al. 1985), and illustrate the applicability of the method to a surface target of high horizontal uniformity and low brightness. The present results apply to a surface with low horizontal uniformity and high brightness. For the CZCS shortwave channels, the intended target is the back scattered radiation from the atmosphere, so that the observations were made over ocean. For the AVHRR channels, high brightness targets are required to fill as much of the dynamic range of the channels as possible and to minimize the effects of atmospheric variability. Reflected solar radiation from the dunes of gypsum at White Sands is one of the brightest surface targets available and it has unusually cloud-free and stable atmospheric conditions at most times of the year.

2. Method of calibration

The method described in this paper relies on the capability of a radiance-calibrated spectrometer (Smith et al. 1984) onboard a high altitude aircraft to simultaneously observe the same terrestrial target as the spacecraft radiometer that is to be calibrated. The viewing geometry is illustrated in Fig. 1. We applied the method to the calibration of the NOAA-9 AVHRR channels 1 and 2, which have the spectral responses shown in Fig. 2. In order to achieve a credible calibration, the satellite and aircraft instruments must observe the target along the same view vector, at nearly the same time, through closely matched atmospheric optical depths and with the same optical footprint on the ground. For these measurements, the spectral resolu-

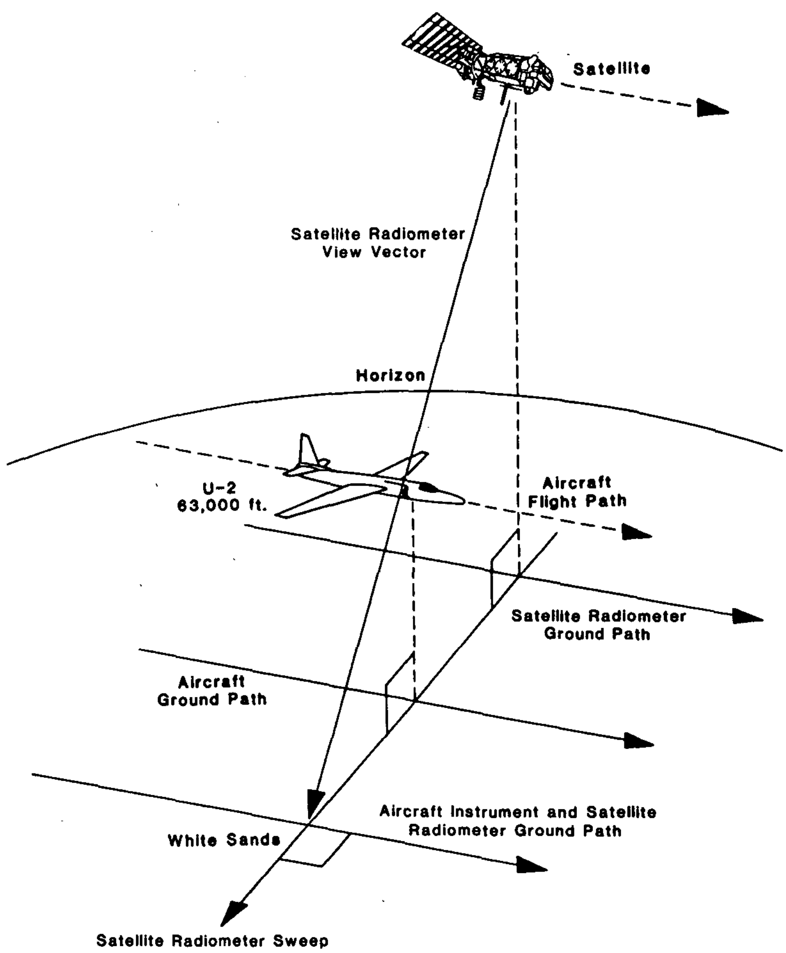

FIG. 1. The basic geometry of the calibration method.

tion of the spectrometer in the aircraft must be capable of resolving the detailed structure of the spectral profile of the satellite radiometric channel, so that the radiance observed by the satellite instrument can be approximated from the spectrum measure aboard the aircraft by convoluting it with the prelaunch spectral response function of the satellite instrument. A precise theoretical atmospheric model (better than ±1% in relative radiance error) must be available to enable extrapolation of the aircraft radiance observations to the top of the atmosphere.

It is desirable that the range of calibration target radiances cover as much of the dynamic range of the satellite radiometer as possible, so that the calibration line, which is the assumed linear relationship between aircraft-measured radiance and the output of the satellite instrument, can be established with the highest accuracy. The White Sands area exhibits a high albedo, or reflectivity to incident spectrally integrated solar radiance in the range 0.5 to 0.7, and relatively stable optical properties throughout the year. The responses of the satellite radiometer and the aircraft spectrometer to effectively zero radiance input are measured at a time close to overpass. This information provides a well defined point on the calibration line, and extends the radiance range of the calibration data considerably.

The direction of the satellite view vector at White Sands is predicted from a computer-generated ephemeris provided by the Satellite Operations Control Center (SOCC) of the National Environmental Satellite, Data, and Information Service (NESDIS). The maximum angle included between the actual and predicted view vectors allowed by this procedure is about 0.3 deg for NOAA polar-orbiting satellites. This uncertainty is similar to that in the pointing of the aircraft spectrometer, which is less than 1 deg (absolute) and ±0.4 deg (relative) for a U2 aircraft at its operating altitude of 63 000 ft MSL (57 000 ft above White Sands).

The time of NOAA polar-orbiting satellite overpasses at White Sands is close to 1440 LST. NOAA-9 overpass time is predictable with an accuracy of ± one sec. The center time of the aircraft pass over White Sands was arranged to be within 1 minute of this time. The correction for the brightness change in the target caused by the apparent movement of the sun during the aircraft pass was small, and did not exceed a rate of a few tenths of one percent per minute. Corrections were made based on the assumption that the surface reflection is Lambertian over small ranges of solar zenith angle.

The aircraft mission was centered on the time of satellite overpass. There were usually 3 passes of the aircraft over White Sands, each pass taking approximately 3 minutes. Alignment of the aircraft for a repeat pass took about 15 minutes. The NOAA-9 satellite passes over the entire White Sands area in approximately 3 seconds. The aircraft flight paths over White Sands were intended to traverse a fixed ground track parallel to the subsatellite track at a constant altitude. This orientation was selected to obtain the longest straight line run over White Sands and because radiance variations as a function of ground track distance traversed by the aircraft possess a particularly well-defined signature, or characteristic shape, along this direction. By searching for the same signature in the satellite-measured radiance field, the uncertainty in relative location of the two radiance fields is greatly reduced. Since the most important geometric requirement for a valid calibration is to ensure that the view vectors from the two instruments are parallel, the nominal aircraft heading is constant. A different wind speed at aircraft altitude from that expected will rotate the aircraft ground track several degrees from its nominal direction. This rotation has little, if any, effect on the accuracy with which the relative location of the two radiance fields can be established.

To obtain spectral equivalence between the satellite and aircraft measurements, the spectrum measured by the aircraft spectrometer was convolved with the spectral filtering function of the satellite channel. For this purpose we assumed the spectral response function measured prelaunch (see Fig. 2) to be valid. This is a reasonable assumption for the AVHRR data presented here, since the multilayer interference filters are temperature-controlled, and the filters and the detector are protected from direct contact with the spacecraft environment. The shapes of the spectral responses of small numbers of similar filters in ambient storage on the ground are known to be stable with time.

The aircraft instrument was a visible wavelength, ⅛ meter Ebert, rapid scanning grating double monochromator. This instrument has been used extensively in aircraft applications since 1982 and its reliability and stability have been well documented by NOAA. From NOAA laboratory, field site and in-flight sphere

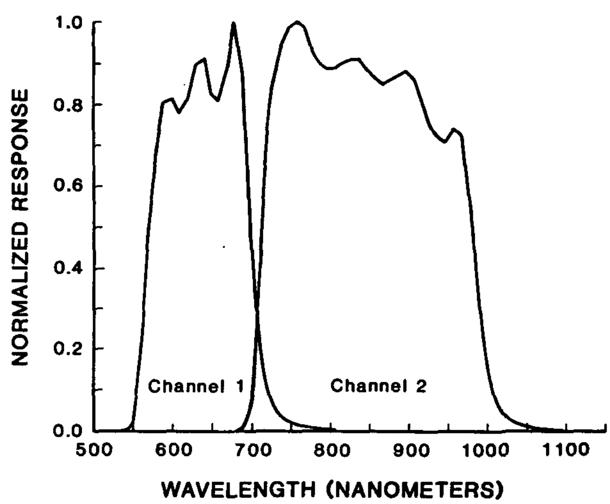

FIG. 2. Spectral response functions for channels 1 and 2 of the NOAA-9 AVHRR.

source calibration measurements, the precision of the radiance calibration is ±1%.

The aircraft spectrometer was radiometrically-calibrated in the NOAA laboratory at Suitland, Maryland, using a 42-inch diameter integrating sphere source (Hovis and Knoll 1983) with a calibration traceable to a NBS 1000 watt lamp irradiance standard. To minimize changes in calibration in flight, the detector and preamplifier of the aircraft instrument were temperature controlled. The quartz viewing window between the radiometer and the outside environment was carefully cleaned on both sides before each flight. Residual changes in radiance calibration were measured with a small (12 inch diameter) integrating sphere source placed outside the viewing window before and after the flight. The 12 inch sphere itself was calibrated in the laboratory against the 42 inch diameter source.

Calculations using the LOWTRAN-6 computer program (Kneizys et al. 1983) showed that corrections required for the different water vapor and oxygen instrument-to-source path lengths involved in the laboratory and field calibrations were entirely negligible for the calibration of wide band visible radiometers.

Examples of the test results are shown in Fig. 3. Flight data collected earlier in 1985 had shown that there was no discernible change in instrument calibration, using the 12 inch diameter source positioned outside the viewing window, between the time immediately before takeoff and immediately after landing for any of four flights. The flight of 26 August 1985, and all subsequent U2 flights, therefore omitted an after-landing calibration with the 12 inch diameter source because of the demonstrated stability of the system response, which exceeded that illustrated in Fig. 3.

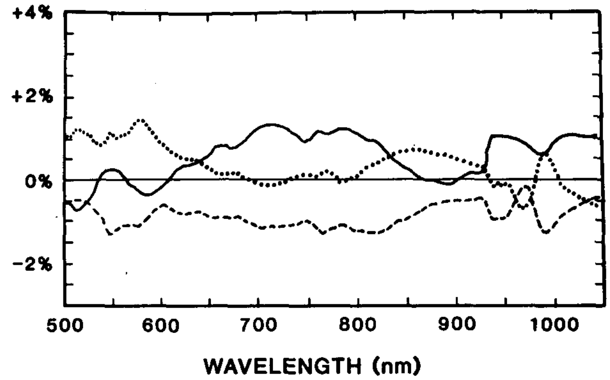

FIG. 3. Deviations in gain of the U2 aircraft spectrometer system, measured for the following dates and sources: 22 August 1985, 12 inch integrating sphere under U2 at NASA/Ames, California (before takeoff), (dotted); 20 August 1985, 12 inch integrating sphere in laboratory at NASA/Ames, California (dashed); 24 November 1985, 42 inch integrating sphere in NOAA laboratory at Suitland, Maryland (solid).

A similar sphere source, supplied by the NASA Goddard Space Flight Center (GSFC), was used to provide a prelaunch calibration of the satellite instrument. Both sphere sources were independently calibrated by Optronic Laboratories. The common traceability of the calibration to the National Bureau of Standards (NBS) is illustrated in Fig. 4. Estimates of

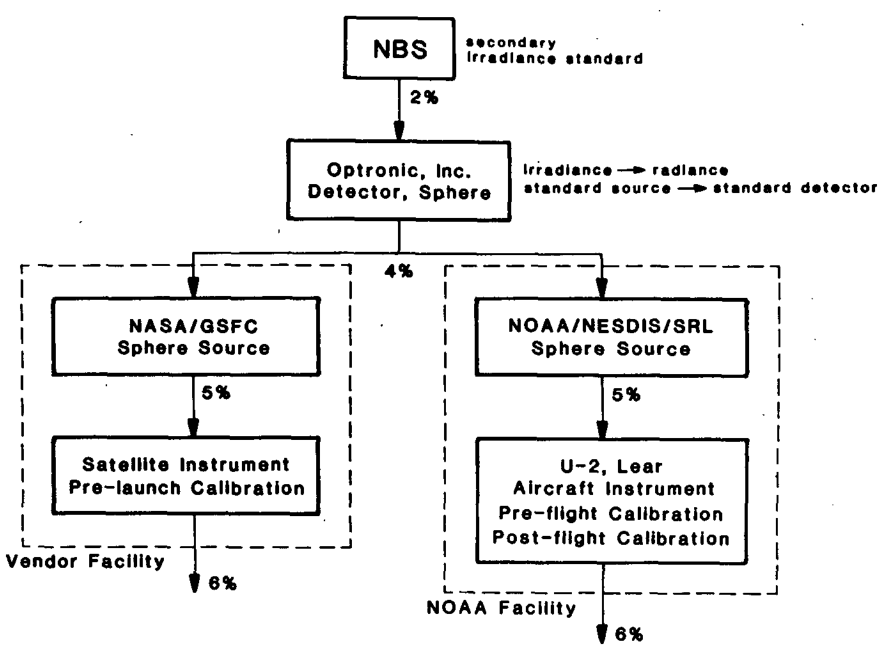

FIG. 4. Traceability of absolute calibration of the aircraft spectrometer and the NOAA-9 AVHRR to NBS standards. The values shown are estimates of maximum absolute error in spectral radiances.

absolute error accumulation as the calibration is transferred are noted in the figure. These estimates are a synthesis of information from sources at NASA/GSFC and at Optronic Laboratories. Both the satellite spectrometer and the aircraft instrument have absolute radiance uncertainties in the range ±6%. However, the relative error between them is estimated to be in the range ±3%.

3. Data analysis

Figure 5 is the AVHRR channel 2 (710–1000 nm) image of the White Sands region at the time of a U2 pass over the area on 26 August 1985. The figure is a visual presentation of a section of the 63 × 80 pixel array of satellite radiances used in the analysis. The aircraft flight path is shown. The satellite overpass and the 3-minute aircraft pass were centered at 2136 UTC.

The first step in the analysis was to correct the aircraft-measured spectrum for a spectral shift experienced in flight. The sources of spectral shift are most likely dominated by the effects of changes in aircraft instrument temperature. The spectral calibration in the laboratory applies at a temperature of approximately 20°C. At U2 cruise altitude (about 19 km above MSL) the spectrometer frame temperature fluctuated in the range 4.3 ± 0.3°C, and the 762 nm O_2 absorption band was observed to have shifted upwards in wavelength by two wavelength steps, or approximately 7 nm. This was corrected by assuming that the temperature change had caused a small (much less than 1 deg) change in the rotational position of the grating. The 762 nm O_2 band center is a sharply defined feature in the aircraft-measured spectrum, and knowledge of its correct wavelength allowed realignment of the complete spectrum to better than a wavelength step.

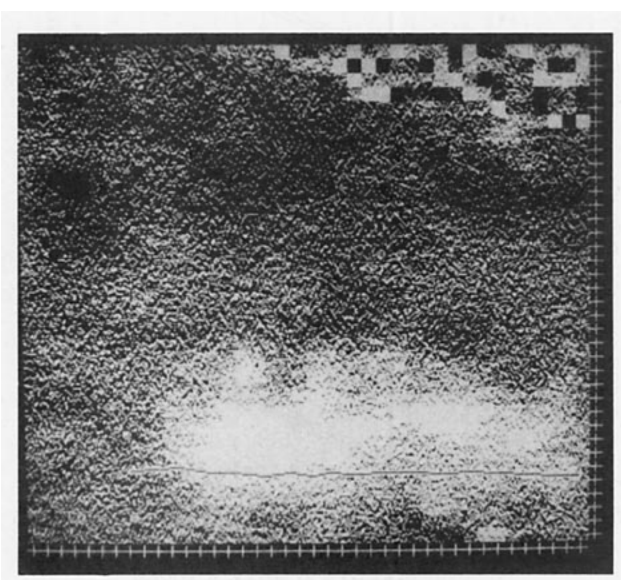

FIG. 5. NOAA-9 AVHRR channel 2 image of White Sands on 26 August 1985. The saturated pixels in the lower right-hand corner illustrate pixel size. The line to the left of center of White Sands represents the common ground target track for the aircraft spectrometer and the AVHRR.

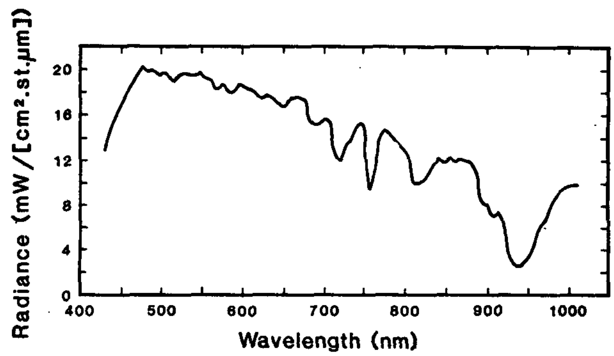

FIG. 6. Calibrated spectrum measured by the aircraft spectrometer over White Sands dunes on 26 August 1985.

The target radiance spectrum as measured from the aircraft (Fig. 6), together with the calculations described below of the ratio of spectral radiance at satellite altitude to that at the altitude of the aircraft (designated the extrapolation spectrum) were used to predict the radiance at satellite altitude. The corrections are relatively small, as is evident in Fig. 7, but they are significant at wavelengths below 750 nm and approach 10% of the observed radiance near 600 nm. The correction acts to reduce the aircraft-observed radiance to obtain an estimate of the satellite-observed radiance along the same view vector. The reduction is expected, since the satellite-directed radiance at aircraft altitude is reduced by absorption as it passes from aircraft altitude to satellite altitude, and is supplemented only by the small amount of solar radiation that is back scattered toward the satellite by the same upper atmospheric layer.

Extrapolation spectra were calculated using the LOWTRAN-6 computer program (Kneizys et al. 1983), atmospheric data from a special radiosonde

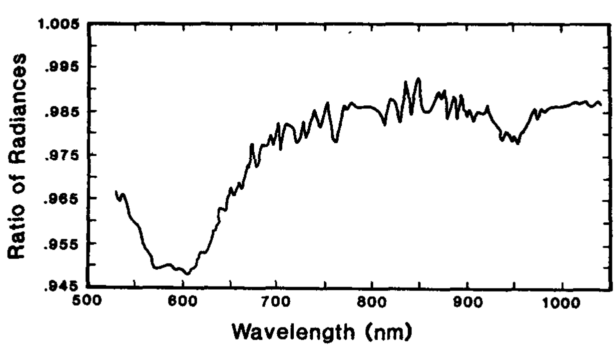

FIG. 7. The ratio of the radiances at NOAA-9 altitude to that at U2 altitude (57 000 ft AGL) for the conditions at the time of NOAA-9 overpass on 26 August 1985. The calculation was made with the LOWTRAN VI computer program.

launched from nearby Holloman AFB at satellite overpass time, and the best available ozone distribution for the White Sands area. The Chappuis band of ozone is the dominant contributor to the magnitude of the extrapolation function in the spectral region covered by channel 1 of AVHRR (550–700 nm), and has a negligible effect at channel 2 wavelengths. The Solar Backscatter Ultra Violet radiometer on the NOAA 7 spacecraft supplied an estimate of the total column ozone and the ozone mass mixing ratio at pressure levels in the range 0.4–30 mb. This information was used to construct a complete ozone profile by forcing the shape of the profile at pressures above 30 mb to conform to that of the midlatitude summer mean profile reported by McClatchey (1971).

The LOWTRAN code calculates atmospheric transmittance and radiance averaged over 20 cm^{-1} intervals from 350 to 40 000 cm^{-1} (250 to 28 500 nm). Molecular and continuum absorption, molecular scattering and aerosol extinction are taken into account with the scattering computed using only single scattering. Representative atmospheric and aerosol models are built into the code, but the option to replace them with user-derived or measured models was exercised here.

Computations were made of the spectral radiances for aircraft and satellite altitudes in 25 cm^{-1} intervals covering the frequency range from 9600 cm^{-1} to 18 925 cm^{-1} (530 to 1040 nm) assuming the surface to be Lambertian with an albedo of 60%. The extrapolation spectra were then obtained by dividing the computer generated radiances at the satellite altitude by that at the aircraft altitude for each frequency. The correction spectrum was also derived for a surface albedo of 30% and compares closely to that obtained for a surface albedo of 60%. The mean differences between the two correction spectra was less than 0.5% with a standard deviation of 0.4% and maximum deviation of 1.6%. Based on these small differences, the correction spectra computed for the 60% surface albedo was utilized for all 18 scans of the White Sands surface.

The line of aircraft radiance data collected during the time interval containing the time of AVHRR overpass of White Sands was selected for analysis. This dataset consisted of 18 spectra at 184 equally spaced wavelengths from 400 to 1040 nm. The location of each aircraft observation in the 63 × 80 pixel array of satellite data was estimated using the approximately known aircraft location, the known location of the highest radiance at White Sands, and the latitude and longitude changes per pixel calculated from the nominal locations of the four corners of the 63 × 80 array.

The estimated locations of the aircraft within the 63 × 80 pixel array have absolute errors in the range ±3 km, and it is necessary to substantially reduce these errors to achieve a useful comparison of the radiance fields. The first step in this process is to use the aircraft data to estimate the radiance that would be observed by the AVHRR, which has a footprint at nadir of approximately 1 km diameter, if it had the 3 km diameter nadir footprint of the aircraft spectrometer. This estimated radiance, R_A^* is calculated from

$$R_A^* = \sum_{i=1}^{184} S_A(\lambda_i)C(\lambda_i)F(\lambda_i) / \sum_{i=1}^{184} F(\lambda_i)$$

where $S(\lambda_i)$ is the measured aircraft spectrum, $C(\lambda_i)$ is the extrapolation spectrum for the path intervening between the aircraft and the satellite, and $F(\lambda_i)$ is the spectral response function of AVHRR channel 1 or 2. This function was measured prelaunch by the manufacturer, ITT.

Other values of R^*, designated R_S^*, may be estimated from the satellite data by interpolating the satellite radiances to a grid of points within the aircraft field-of-view and integrating the interpolated values after they have been weighted by the aircraft field-of-view function. For this purpose, the aircraft field-of-view function was assumed, based on laboratory measurements, to be circular, 3.5 km diameter at nadir, and with a uniform response. Interpolation of the satellite radiances was achieved by assuming that the location of the measured satellite radiance was at the center of each pixel, and then using 2 dimensional lin-

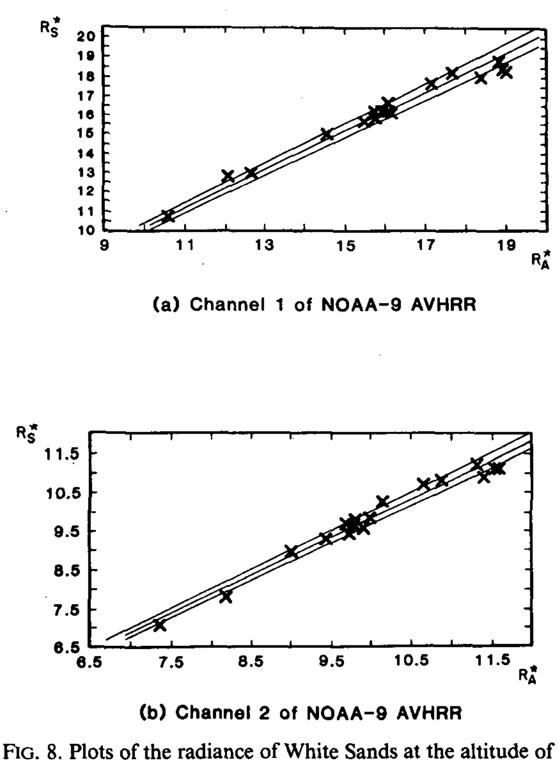

FIG. 8. Plots of the radiance of White Sands at the altitude of the NOAA-9 spacecraft for channels 1 and 2 of AVHRR. The R_s^* and R_a^* are estimates of radiance at satellite altitude within the footprint of the aircraft spectrometer, derived from satellite-measured data and aircraft-measured data, respectively.

ear interpolation from the nearest four pixel center to yield a radiance value at each point in a 7 × 7 grid of points containing the footprint.

The two radiance fields (R_A^* and R_S^*) were optimally aligned by moving and rotating the aircraft path within established physical constraints to obtain the position of maximum correlation coefficient between the 18 sets of R_A^* and R_S^* corresponding to the 18 positions at which the aircraft spectrometer initiated a scan during the pass over White Sands. This was done in steps of 0.1 km in orthogonal directions and for an angular increment of 1 deg.

The R_A^* and R_S^* were then plotted against each other, and it was assumed that the point (0, 0) could be included in the set as an absolutely defined data point. This point corresponds to averaged space view data for the AVHRR and to averaged beam-blocked data for the aircraft spectrometer. The slope of the best fit straight line passing through (0, 0) was assumed to be

$$m = \sum_{i=1}^{18} R_A^*(i) R_S^*(i) / \sum_{i=1}^{18} R_A^*(i)^2$$

and the variance in m was estimated as

$$\sigma_m{}^2 \sim \sigma_{R_S^*}^2 / \overline{R_S^{*2}}.$$

Location accuracy, rather than scatter in the 18 points, contributes most to the uncertainty in m, as will be explained later.

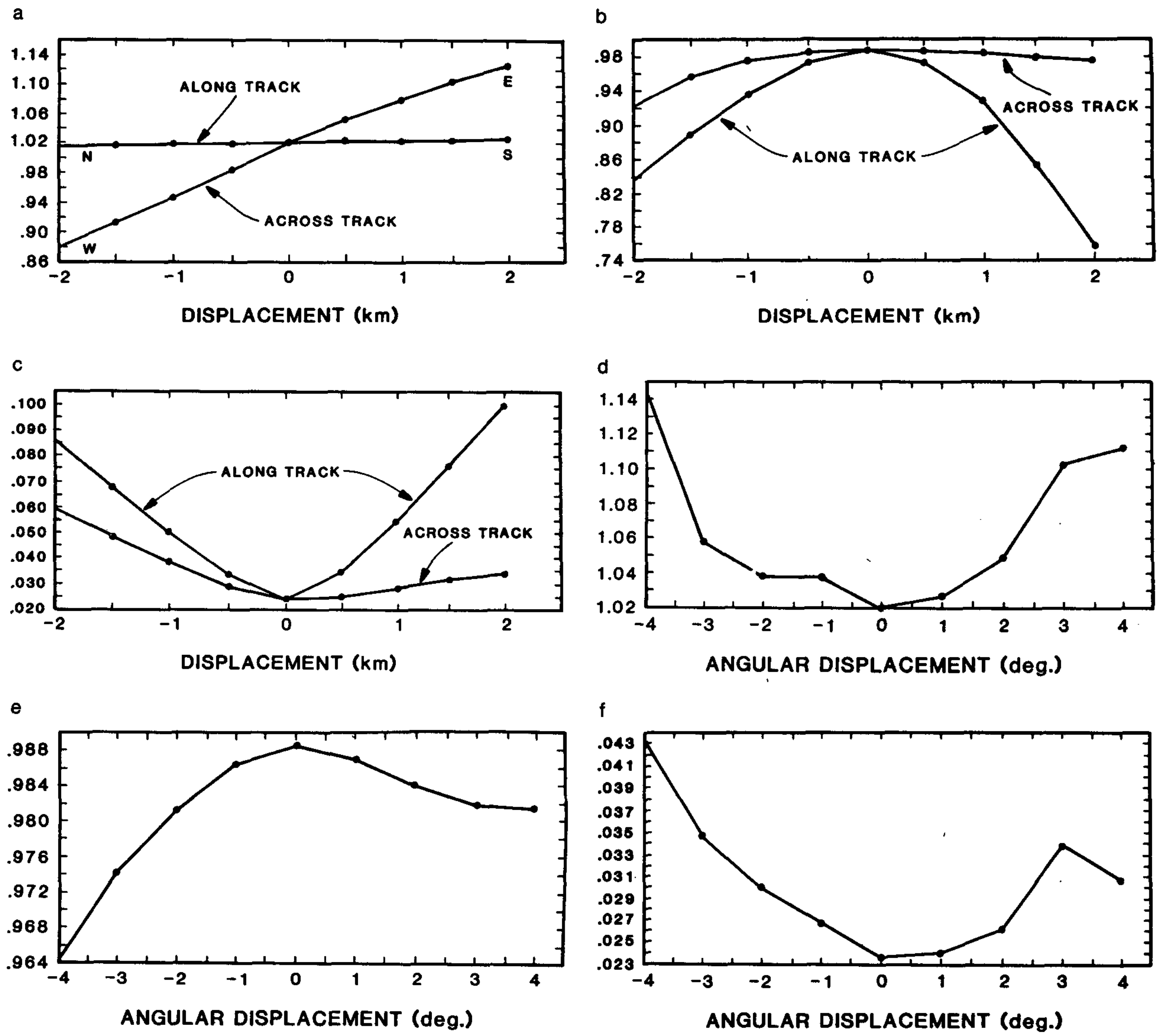

FIG. 9. Sensitivity of the results to changes in colocation of the AVHRR and aircraft spectrometer footprints on the ground. Panels (a)–(c) show the effect of spatial displacement on the derived values of m, C and σ_m, respectively. Panels (d)–(f) show the effect of angular displacement on the same variables.

4. Results and discussion

The experimental conditions on 26 August 1985 at White Sands were good. The official observer at the local weather station ("C" Station, WSMR, NM) reported only a trace of cirrus at an altitude of 25 000 ft, and visibility of 65 miles at the time of satellite overpass (2136 UTC).

Our results for the NOAA-9 AVHRR radiance calibration are shown in Fig. 8. We assumed that the relationship between ordinates and abscissae is linear, and that the line passes through the origin. The zero-radiance response level is well established by frequent measurements onboard the aircraft and the satellite.

The central line drawn in Fig. 8 is a best fit that minimizes the variance of the ordinates about it. The outer lines have a slope which differs from that of the central line, m, by approximately the standard deviation in slope. The value of m is our best estimate of the ratio of AVHRR sensitivity (in counts/unit of radiance) on 26 August 1985 to its prelaunch value.

The precision of these results is determined by the uncertainty in relative location of the satellite and aircraft footprints, as well as by the scatter in the points. Instrumental noise is negligible in this respect. Figure 9 shows the sensitivity of the derived values of m to relative displacements of the two radiance fields along and perpendicular to the subsatellite track, and for relative rotation of the two fields.

The plots show that the correlation coefficient, C, is particularly strongly peaked in the along-track direction. This is not surprising, considering the geometry of Fig. 5. The sharpness of the peak, indicating that the peak can be located to much better than ±1 km, is artificial and is caused by the assumption in the data analysis that the AVHRR radiance measurements apply at the center of each pixel, and that the radiance at intervening points is linearly related to that at centers of the four nearest pixels. The derived value of m is very sensitive to movement across-track, due to the large gradient of satellite-observed radiance in this direction. The correlation coefficient is less sharply peaked along this axis, indicating that the shape of the radiance cross section changes slowly with track displacement along this axis. The derived value of m tends to stabilize at a relatively high value of displacements that position the aircraft track on the along-track axis of the dunes, and the standard deviation in m remains relatively low for such displacements. These effects are also expected from the geometry of the situation.

Sensitivity to angular rotation is shown in Fig. 9d, e and f. The standard deviation in m reaches a minimum at a rotation of 0 deg, the same angle at which C is a maximum. The correspondence of the minimum in m with the maximum C for horizontal and angular displacements indicates that the origin lies very close to the best fit line through the 18 points. This is a requirement for a valid solution, and provides some confidence in the validity of the result. The error budget is summarized in Table 1, the data having been derived from the information in Fig. 9. Since the AVHRR nadir footprint diameter is approximately 1 km, and that of the aircraft is approximately 3 km, it is unrealistic to expect a relative alignment accuracy of much better than 1 km. Assuming a value of ±0.5 km gives an uncertainty in m from all experimental causes, assuming then to be uncorrelated of approximately ±3.5% for both channels.

The absolute error in the radiance measured by the AVHRR or by the aircraft radiometer caused by uncertainties in the external calibration chain was stated in section 2 to be ±6%, and the absolute uncertainty between measurements made by the two instruments was quoted as ±3%.

We conclude that our measurements have established the slope of the best linear fit between R_S^* and R_A^*, m, to approximately ±5%, so that

$$m_1(\text{channel 1}) = 1.02 \pm .05$$

$$m_2(\text{channel 2}) = 0.98 \pm .05.$$

The results indicate that the sensitivities of both AVHRR visible channels on 26 August 1985 were indistinguishable from their prelaunch values. Since the value of m was measured only once for each channel, the stated uncertainty in m does not indicate the repeatability of the value of m estimated from independent datasets. The repeatability of the method is now being investigated with a multiday dataset of NOAA-9 AVHRR and U2 spectrometer measurements collected in October and November 1986.

TABLE 1. Experimental error budget relative to the NOAA secondary radiance standard.

Quantity	Rate of change	Channel 1 and 2 estimated random error components (%)
Motion along subsatellite track	0.3 per km	0.2
Motion perpendicular to subsatellite track	6% per km	3.0
Relative rotation of radiance fields	1% per deg	1.0
Scatter in the 18 points		0.6
Calculated ratio of radiance at aircraft altitude to that at satellite altitude		1.0
U2 system gain stability		1.0
U2 system spectral calibration accuracy		0.2
rms total		3.5

5. Summary

A method for the calibration of satellite-borne visible radiometers has been presented. It employs a radiance-calibrated spectrometer aboard a high-flying aircraft that has the capability of viewing a bright target, such as White Sands, New Mexico, along the same direction and at the same time as the satellite observation. Results indicate that an accuracy of ±5% is possible in estimating the radiometric sensitivity of the satellite radiometer relative to its measured prelaunch value, and that on 26 August 1985 there was no detectable change in the sensitivity of the NOAA-9 AVHRR channels 1 and 2 from their prelaunch (February 1980) values. The accuracy of the results is limited by the accuracy with which the aircraft measurements can be located in the measured radiance field of the satellite radiometer. Analysis of flight data from October and November 1986 is continuing, and results will be available in the near future.

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