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Calibration of the Visible and Near-Infrared Channels of the NOAA-9 AVHRR Using High Altitude Aircraft Measurements from August 1985 and October 1986

Gilbert R. Smith, Robert H. Levin, Robert S. Koyanagi, and Robert C. Wrigley,
Ames Research Center, Moffett Field, California

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Ames Research Center
Moffett Field, California 94035

CALIBRATION OF THE VISIBLE AND NEAR-INFRARED CHANNELS OF THE NOAA-9 AVHRR USING HIGH-ALTITUDE AIRCRAFT MEASUREMENTS FROM AUGUST 1985 AND OCTOBER 1986

Gilbert R. Smith,* Robert H. Levin,* Robert S. Koyanagi,* and Robert C. Wrigley

Ames Research Center

SUMMARY

Visible and near-infrared wavelength sensors mounted on operational satellites now in use do not have on-board absolute calibration devices. One means of establishing an in-orbit calibration for a satellite sensor is to make simultaneous measurements of a bright, relatively uniform scene along the satellite view vector from a calibrated instrument on board a high altitude aircraft. In the work reported here, aircraft data were recorded over White Sands, New Mexico at satellite overpass time. Comparison of the coincident aircraft and orbiting satellite data for the visible and near-infrared wavelength channels of the National Oceanic and Atmospheric Administration (NOAA)-9 advanced very high resolution radiometer (AVHRR) shows that the calibration of the visible channel was unchanged from prelaunch values, but that the near-infrared channel had degraded 6% by August 1985. By October 1986 the visible channel had degraded 13% and the near-infrared channel had degraded 19%.

INTRODUCTION

To make long term studies of global trends feasible, the satellite data user community needs calibrated radiances from the visible and near-infrared-wavelength channels of the instruments aboard geostationary and polar orbiting satellites. The Advanced Very High Resolution Radiometer (AVHRR) on polar orbiting weather satellites has no on-board extended source calibration system for these wavelengths. Assuming a constant target, changes in the observed output of the solar channels of a satellite sensor are most likely to be a result of degradation of the larger foreoptics elements since they are directly exposed to the deteriorating effects of the space environment. Changes in the electronic gain or in detector sensitivity would also alter the output level of the sensor. The best on-board calibration system would be one that monitored instrument performance by utilizing the full optical field of view and all elements of the optical system. An alternative to on-board calibration is the use of bright, relatively uniform target areas on Earth such as White Sands, New Mexico. Simultaneous clear-sky satellite and aircraft measurements are made along the satellite view vector, using a calibrated instrument on board a high-altitude aircraft. The effects of the atmosphere are for the most part empirically included by using this method, and the aircraft measurement becomes a near duplicate of the satellite measurement.

The aircraft radiance is corrected (see Correction for Atmosphere Above the Aircraft) for the small amount of atmosphere above the aircraft and then compared to the coincident collocated satellite sensor radiance measurement, based on prelaunch calibration. The results of this comparison characterize the in-orbit condition of the satellite sensor. A calibration table of in-orbit radiance versus counts can be

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*National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, DC 20233.

produced. The White Sands, New Mexico area is a desirable surface calibration target because the probability for clear skies is great. Also, the characteristics of the atmosphere over White Sands have been well documented for a number of years by resident agencies and many experimenters. The reflectance of the surface of the white sands of New Mexico is considered to be near-Lambertian (i.e., its brightness is dependent primarily on the elevation angle of the observer) because the "grains" of sand are elongated, randomly oriented, flat, clear crystals of gypsum. The dunes that are present and the consequent sun-shadowing do not seriously affect this characteristic of the surface. For calibration measurements, the use of a diffuse surface target such as White Sands is desirable. A diffuse target minimizes the error in the measurement produced by the solid angle difference between the field of view of the satellite instrument in orbit and the high altitude aircraft instrument. An additional advantage of White Sands is that its radiance lies in the higher dynamic range of the satellite instrument.

The NOAA National Environmental Satellite, Data, and Information Service (NESDIS) has conducted several high altitude U-2 aircraft-satellite calibration missions over the White Sands area for GOES (ref. 1) and the Landsat Thematic Mapper (ref. 2). A calibration (ref. 3) of the channels of the NIMBUS-7 Coastal Zone Color Scanner (CZCS) has also been effected by NESDIS using the method described above, but using the same aircraft instrument flown over ocean water. Smith et al. (ref. 4) discussed the results from the August 1985 aircraft flights very thoroughly, whereas the present study arrives at essentially the same results in a somewhat less rigorous fashion. They used LOWTRAN-6 to estimate the effects of the atmosphere above the aircraft while this study uses empirical measurements of atmospheric transmission. The difference in the results of these two approaches was within the calculated 5% experimental error range. This paper is meant to complement the above-mentioned article and to include the October 1986 current NOAA-9 coincident U-2 aircraft data sets.

SATELLITE INSTRUMENT CALIBRATION

Prelaunch calibration of the visible and near-infrared channels of a satellite instrument presents a problem because none of the radiance or irradiance calibration sources available from the National Bureau of Standards (NBS) fill the full aperture of the instrument. The best, most uniform, extended visible source is an integrating sphere (ref. 5) internally illuminated by a series of quartz halogen lamps and painted white with barium sulfate. Sphere sources can be made large enough to fill the aperture of the satellite instrument. However, the NBS does not maintain or supply data for sphere sources. The NOAA/NESDIS 1.07-m-diam sphere source (ref. 5) was used to calibrate the aircraft instrument just prior to, and immediately following, aircraft-data-gathering missions. A similar sphere source, supplied by NASA Goddard Space Flight Center (GSFC), was used by the NOAA-9 satellite instrument vendor to provide a prelaunch calibration. The GSFC and NESDIS sphere sources were both calibrated by the same commercial facility whose source is NBS-calibrated. This common traceability of calibration to NBS is illustrated in figure 1.

FIELD MISSION

A typical NESDIS aircraft-data-gathering field mission is illustrated in figure 2. Not all of the measurements illustrated in figure 2 were conducted during a specific field mission. In 1985 and 1986, data were gathered from the U-2 over White Sands in a direct line with the view vector of the NOAA-9 AVHRR. The NASA Ames U-2 aircraft was flown out of Moffett Field, California.

AIRCRAFT INSTRUMENT

The NESDIS U-2 instrument was a visible and near-infrared wavelength, 1/8-m focal-length-Ebert, rapid-scanning grating, double monocromator (ref. 6) previously flown on the NASA Learjet. The U-2 instrument produces output in counts which are calibrated in radiance. This instrument has seen extensive aircraft usage since 1982 and its reliability and stability have been well documented by NOAA from many laboratory, field-site and in-flight sphere source-calibration measurements. The repeatability of measurement with the instrument is ±0.5%. The nadir footprint (field of view) of the aircraft instrument is about 2.5 × 2.5 km for the U-2 at 19.8 km altitude.

AVHRR DATA

At the vendor's facility, channels 1 and 2 (fig. 3) of the AVHRR are currently calibrated to albedo, rather than radiance using a sphere source. Data privately communicated to the authors from the vendor included channels 1 and 2 output versus sphere radiance. This was converted to radiance in the bandpass of channels 1 and 2. A comparison could then be made with aircraft measured radiance. Figure 4 shows the channels 1 and 2 prelaunch calibration in radiance versus counts, produced from the vendor data. The prelaunch radiance calibration coefficient of channel 1 is 0.0524 and channel 2 is 0.0336. No significant changes have been observed for the zero-count levels for the AVHRR visible channels.

AIRCRAFT DATA—AVHRR CALIBRATION

The U-2 instrument scans the visible and near-infrared wavelength region from 400 to 1050 nm or 0.400 to 1.050 μm. A typical 10-sec spectral scan of U-2 aircraft instrument data is shown in figure 5. The visible and near-infrared spectrum of White Sands is shown along with channels 1 and 2 AVHRR spectral response from figure 3. Aircraft measured radiance is calculated as a convolution of the aircraft instrument spectrum with the figure 3 AVHRR spectral response functions. The aircraft measured, calculated radiances in both channels are typical of those measured by the satellite instrument. A typical White Sands sector of AVHRR channel 2 satellite data is shown in figure 6. The White Sands area is outlined in figure 6 and the satellite data field is in radiance units of mW/[$\text{cm}^2\cdot\text{sr}\cdot\mu\text{m}$]. This data set is based upon the vendor prelaunch calibration. It is necessary to correct the aircraft radiance for the effect of the 5% of the atmosphere above the aircraft. The aircraft radiance will then be equivalent to the surface radiance as viewed by the satellite instrument. This small correction is discussed in the Correction for Atmosphere section. Each figure-6 numerical data point represents the average satellite radiance of a 3 × 3-km area. Thus, the satellite data is correlative to the 2.5 × 2.5-km aircraft data footprint. The figure 6 numerical satellite data points outlined with a parallelogram are the area footprints of the aircraft data. The White Sands brightness is not uniform. A 10% variance in brightness from pixel to pixel can be observed in figure 6. This nonuniformity is utilized as a means to collocate the satellite and aircraft data. A plot of the aircraft footprint radiance versus ground location produces a brightness contour graph of the aircraft data (fig. 7). Each parallel track of satellite pixels (fig. 6) also produces a unique brightness contour. The computer searches the brightness contour of each parallel track of satellite data until it finds a track that matches the contour of the aircraft data. In the entire satellite data field of figure 6, only one track of data has a brightness contour similar to the aircraft data. The latitude-longitude data from both the aircraft and the satellite data sets could be used to produce a preliminary collocation of the data sets but this error is

±1 km, whereas the contour fit error is ±0.5 km. Figure 7 is a plot of radiance vs. ground location for NOAA-9 AVHRR channels 1 and 2, respectively, along with the 65,000-ft altitude, U-2 aircraft measured radiance (corrected to the top of the atmosphere) for channels 1 and 2 of the same surface location. Figure 8 shows the NOAA-9 AVHRR channels 1 and 2 prelaunch calibration radiance versus counts along with the average U-2 radiance calibration, corrected to the top of the atmosphere, for August 1985. At this time the NOAA-9 satellite had been in orbit for 6 months. These data show that channel 1 of the AVHRR was essentially unchanged and channel 2 was degraded 6%.

Data have been processed, in the same manner as above, for the October-November 1986 time period. At this time, the NOAA-9 had been in orbit for 1 year and 8 months. Figure 9 shows the NOAA-9 AVHRR channels 1 and 2 prelaunch calibration radiance vs. counts as well as the average U-2 radiance calibration, corrected to the top of the atmosphere, for October-November 1986. Channel 1 of the AVHRR shows a degradation of 13.3% and channel 2 shows a degradation of 18.9%.

The error of radiance calibration measurement (table 1) is ±2.56%. An error bar of 5% should be applied to both the satellite prelaunch data and the U-2 aircraft data.

GROUND PARAMETER MEASUREMENTS

The August 1985 field mission at White Sands, New Mexico included some of the ground measurements outlined in figure 2. No solar spectra were recorded coincident with the AVHRR. Surface meteorological data, including horizontal visibility, is available for each day. Whenever possible, surface soil moisture (ref. 7) and Rawinsonde observation (RAOB) data to balloon burst were recorded, coincident with satellite overpass.

CORRECTION FOR ATMOSPHERE ABOVE THE AIRCRAFT

Empirical measurement of the zenith-direction atmospheric transmission from space to 11.6 km altitude was made earlier by Arvesen (ref. 8) using calibrated instrumentation on board a high altitude aircraft. In his data set, the atmospheric transmission was found to be above 0.99 for wavelengths larger than 1000 nm and greater than 0.9 for wavelengths larger than 410 nm. The Arvesen data show that the ozone band between 550 and 600 nm decreases the atmospheric transmittance less than 2%. The only other atmospheric absorption detected is the narrow oxygen band at 762 nm. The Arvesen data were extrapolated to the U-2 altitude of 19.2 km and the effect of the day-to-day variable satellite-view vector was included. The residual error was estimated to be ±0.2%. The path radiance contributed by the atmosphere above the aircraft to the satellite radiance was ignored due to the brightness of White Sands. An estimate of the worst case for this path radiance showed it would be less than 0.4% of the satellite radiance in the visible channel. Hence, the combined error resulting from the correction for the atmosphere above the aircraft would be less than 0.5%.

RESULTS

Calibration coefficients have been generated for the data sets. Radiance can be calculated as a product of scene satellite counts minus zero counts, and the calibration coefficient. The zero count for channel 1 is 39 and for channel 2 is 40.

A summary of calculated radiance calibration coefficients for the NOAA-9 AVHRR follows.

	Prelaunch	August 1985	Oct.-Nov. 1986
Channel 1	0.0524	0.0524	0.0599
Channel 2	0.0336	0.0357	0.0414

CONCLUSIONS

The work reported in this paper demonstrates that the visible and near-infrared channels of satellite instruments may be effectively calibrated using high altitude aircraft data. Aircraft data gathered on a regular basis could produce a data set that would monitor the performance of the satellite instrument. This data set would be valuable to the satellite data-user community and would provide validation for the atmospheric-modeling community.

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TABLE 1.- RADIANCE CALIBRATION ERROR ANALYSIS

		Uncertainty
I.	Primary Standard – NBS	
	Wavelength (nm) 400-1050	±2%
II.	Secondary NBS Standard-Optronic Laboratories, Inc.	
	Transfer to 30 in. diam. sphere	±1.5%
III.	Aircraft Spectrometer	
	Wavelength determination	±0.2%
	Electronic noise	±0.1%
IV.	Data Analysis	
	Correction for the atmosphere above the aircraft	±0.4%
	Total radiance uncertainty	±2.56%

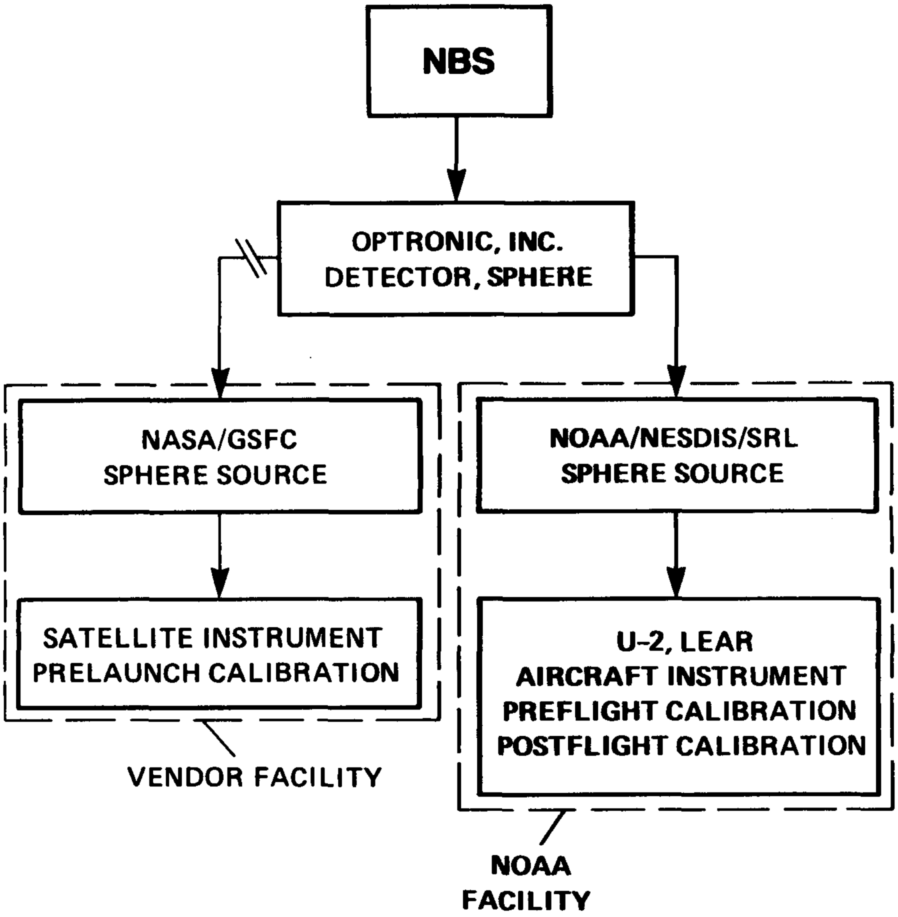


Figure 1.- NBS calibration traceability.

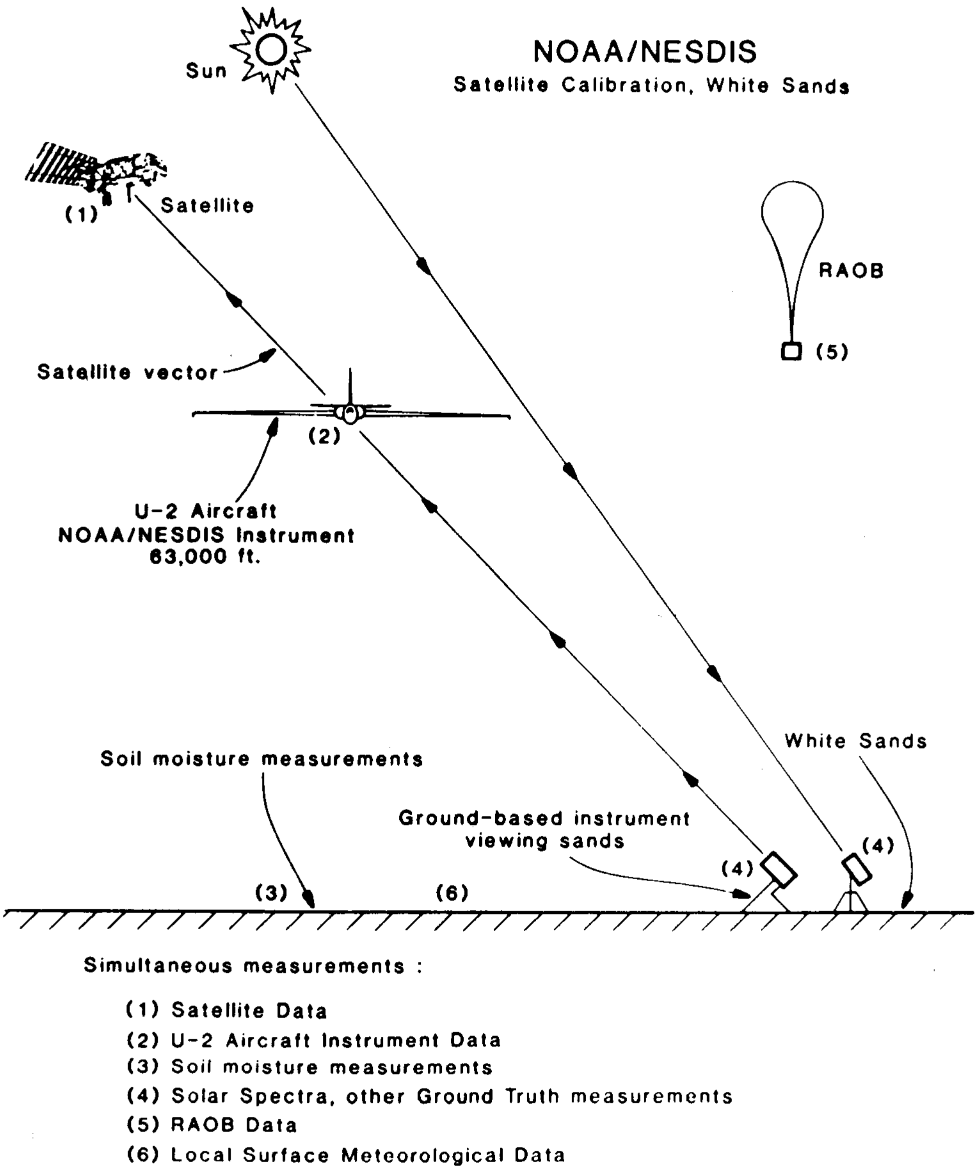


Figure 2.- NESDIS aircraft mission.

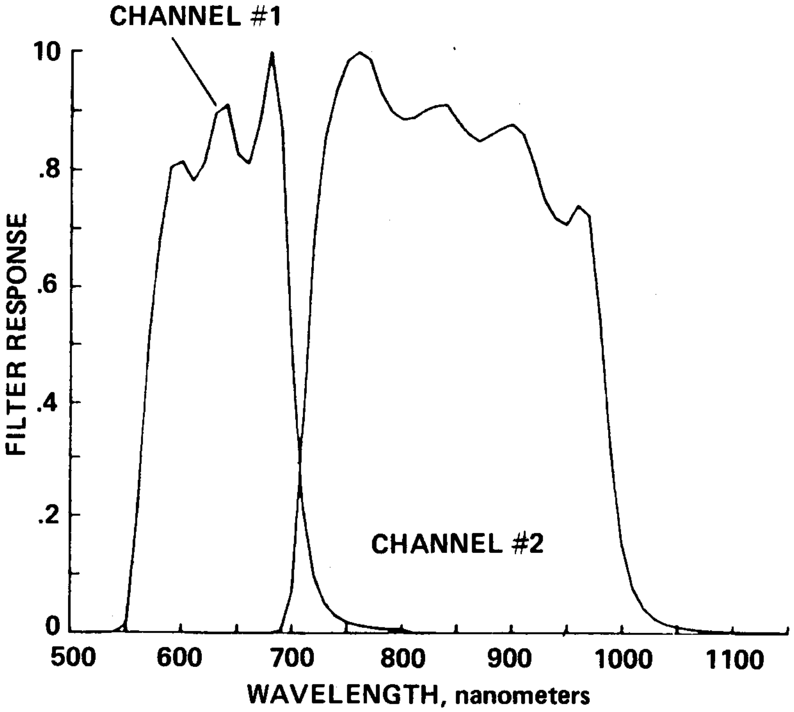


Figure 3.- AVHRR channels 1 and 2 bandpass.

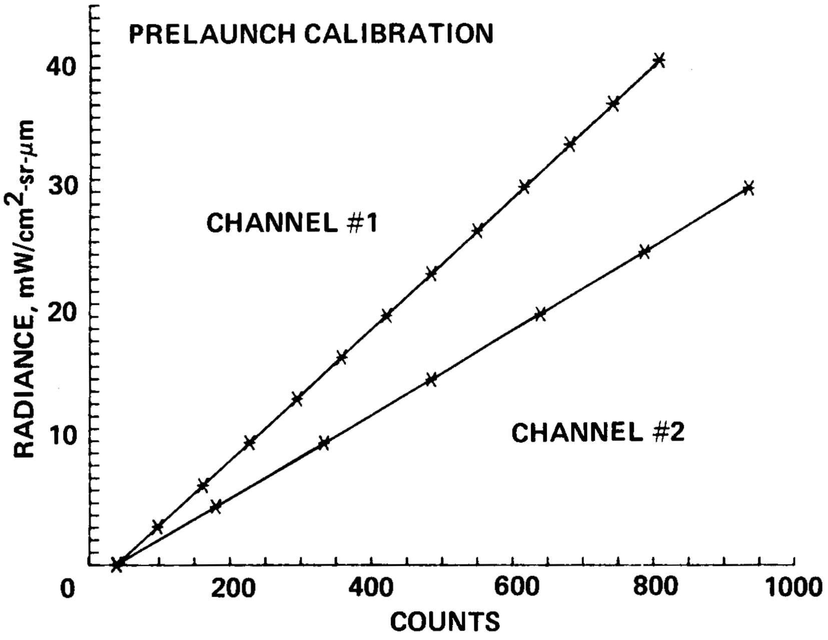


Figure 4.- NOAA-9 radiance vs counts: AVHRR prelaunch calibration.

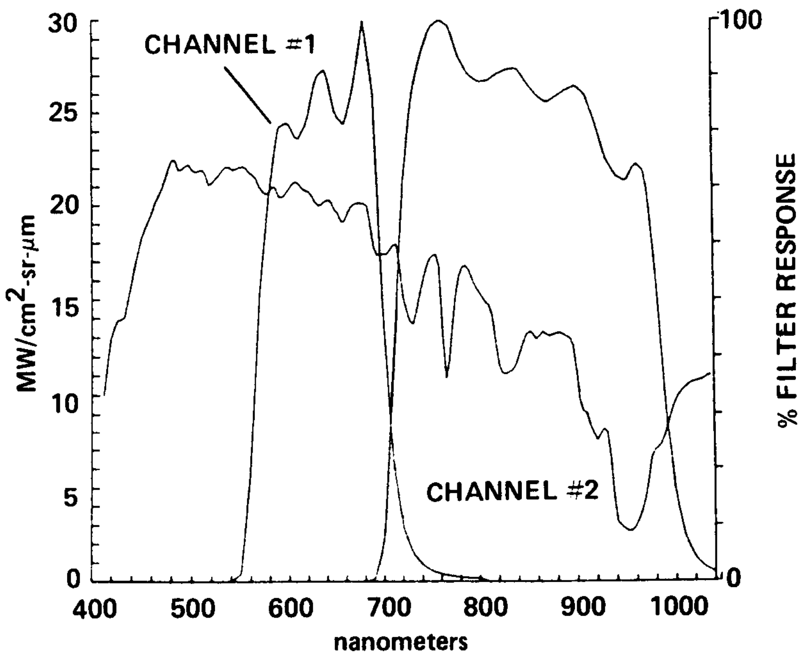
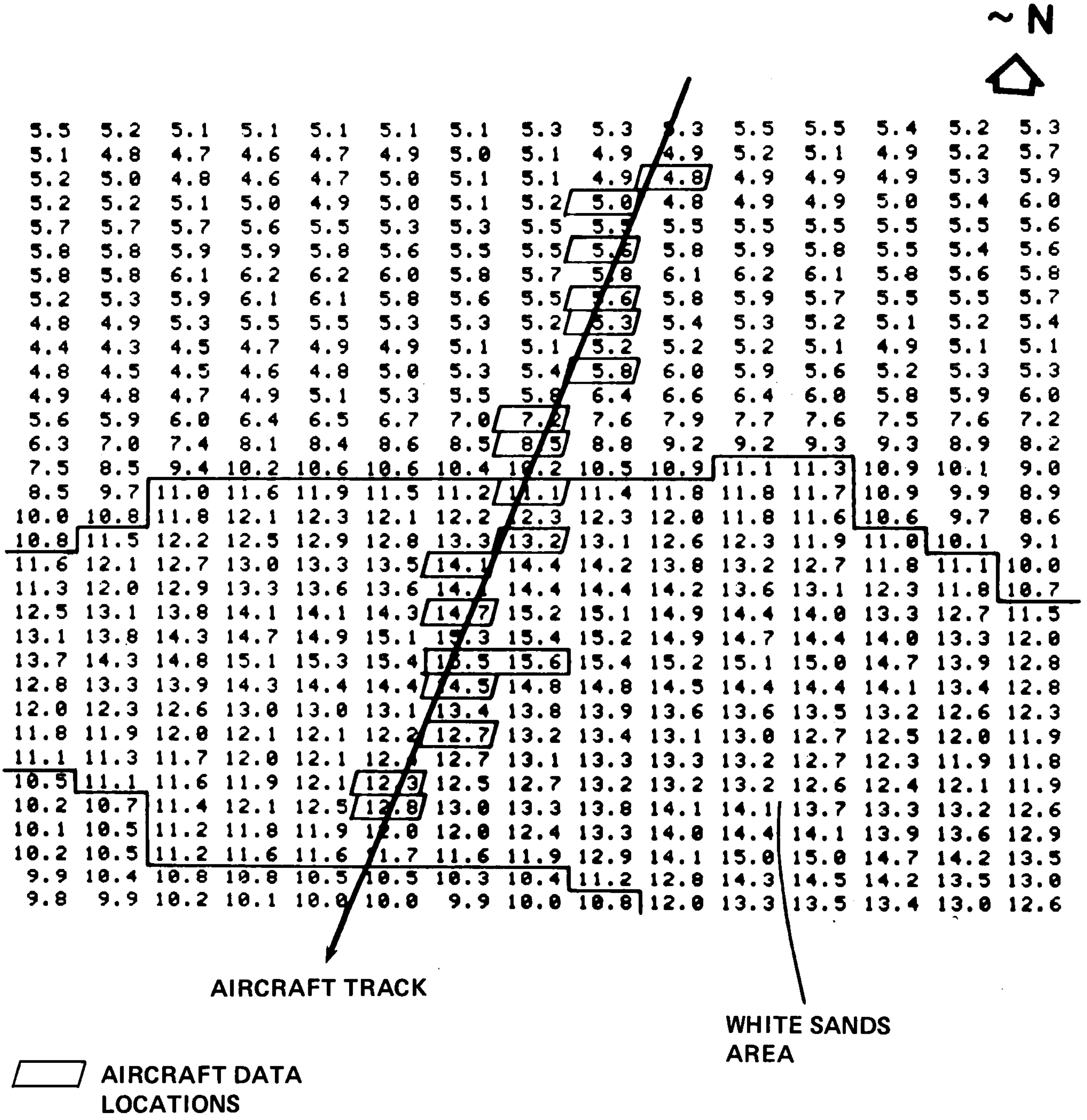


Figure 5.- U-2 aircraft data.



5.5	5.2	5.1	5.1	5.1	5.1	5.1	5.3	5.3	5.3	5.5	5.5	5.4	5.2	5.3
5.1	4.8	4.7	4.6	4.7	4.9	5.0	5.1	4.9	4.9	5.2	5.1	4.9	5.2	5.7
5.2	5.0	4.8	4.6	4.7	5.0	5.1	5.1	4.9	4.8	4.9	4.9	4.9	5.3	5.9
5.2	5.2	5.1	5.0	4.9	5.0	5.1	5.2	5.0	4.8	4.9	4.9	5.0	5.4	6.0
5.7	5.7	5.7	5.6	5.5	5.3	5.3	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.6
5.8	5.8	5.9	5.9	5.8	5.6	5.5	5.5	5.6	5.8	5.9	5.8	5.5	5.4	5.6
5.8	5.8	6.1	6.2	6.2	6.0	5.8	5.7	5.8	6.1	6.2	6.1	5.8	5.6	5.8
5.2	5.3	5.9	6.1	6.1	5.8	5.6	5.5	5.6	5.8	5.9	5.7	5.5	5.5	5.7
4.8	4.9	5.3	5.5	5.5	5.3	5.3	5.2	5.3	5.4	5.3	5.2	5.1	5.2	5.4
4.4	4.3	4.5	4.7	4.9	4.9	5.1	5.1	5.2	5.2	5.2	5.1	4.9	5.1	5.1
4.8	4.5	4.5	4.6	4.8	5.0	5.3	5.4	5.8	6.0	5.9	5.6	5.2	5.3	5.3
4.9	4.8	4.7	4.9	5.1	5.3	5.5	5.8	6.4	6.6	6.4	6.0	5.8	5.9	6.0
5.6	5.9	6.0	6.4	6.5	6.7	7.0	7.2	7.6	7.9	7.7	7.6	7.5	7.6	7.2
6.3	7.0	7.4	8.1	8.4	8.6	8.5	8.5	8.8	9.2	9.2	9.3	9.3	8.9	8.2
7.5	8.5	9.4	10.2	10.6	10.6	10.4	10.2	10.5	10.9	11.1	11.3	10.9	10.1	9.0
8.5	9.7	11.0	11.6	11.9	11.5	11.2	11.1	11.4	11.8	11.8	11.7	10.9	9.9	8.9
10.0	10.8	11.8	12.1	12.3	12.1	12.2	12.3	12.3	12.0	11.8	11.6	10.6	9.7	8.6
10.8	11.5	12.2	12.5	12.9	12.8	13.3	13.2	13.1	12.6	12.3	11.9	11.0	10.1	9.1
11.6	12.1	12.7	13.0	13.3	13.5	14.1	14.4	14.2	13.8	13.2	12.7	11.8	11.1	10.0
11.3	12.0	12.9	13.3	13.6	13.6	14.1	14.4	14.4	14.2	13.6	13.1	12.3	11.8	10.7
12.5	13.1	13.8	14.1	14.1	14.3	14.7	15.2	15.1	14.9	14.4	14.0	13.3	12.7	11.5
13.1	13.8	14.3	14.7	14.9	15.1	15.3	15.4	15.2	14.9	14.7	14.4	14.0	13.3	12.0
13.7	14.3	14.8	15.1	15.3	15.4	15.5	15.6	15.4	15.2	15.1	15.0	14.7	13.9	12.8
12.8	13.3	13.9	14.3	14.4	14.4	14.5	14.8	14.8	14.5	14.4	14.4	14.1	13.4	12.8
12.0	12.3	12.6	13.0	13.0	13.1	13.4	13.8	13.9	13.6	13.6	13.5	13.2	12.6	12.3
11.8	11.9	12.0	12.1	12.1	12.2	12.7	13.2	13.4	13.1	13.0	12.7	12.5	12.0	11.9
11.1	11.3	11.7	12.0	12.1	12.[illegible]	12.7	13.1	13.3	13.3	13.2	12.7	12.3	11.9	11.8
10.5	11.1	11.6	11.9	12.1	12.3	12.5	12.7	13.2	13.2	13.2	12.6	12.4	12.1	11.9
10.2	10.7	11.4	12.1	12.5	12.8	13.0	13.3	13.8	14.1	14.1	13.7	13.3	13.2	12.6
10.1	10.5	11.2	11.8	11.9	12.0	12.0	12.4	13.3	14.0	14.4	14.1	13.9	13.6	12.9
10.2	10.5	11.2	11.6	11.6	11.7	11.6	11.9	12.9	14.1	15.0	15.0	14.7	14.2	13.5
9.9	10.4	10.8	10.8	10.5	10.5	10.3	10.4	11.2	12.8	14.3	14.5	14.2	13.5	13.0
9.8	9.9	10.2	10.1	10.0	10.0	9.9	10.0	10.8	12.0	13.3	13.5	13.4	13.0	12.6

Figure 6.– AVHRR channel 2 data sector White Sands radiance data sector.

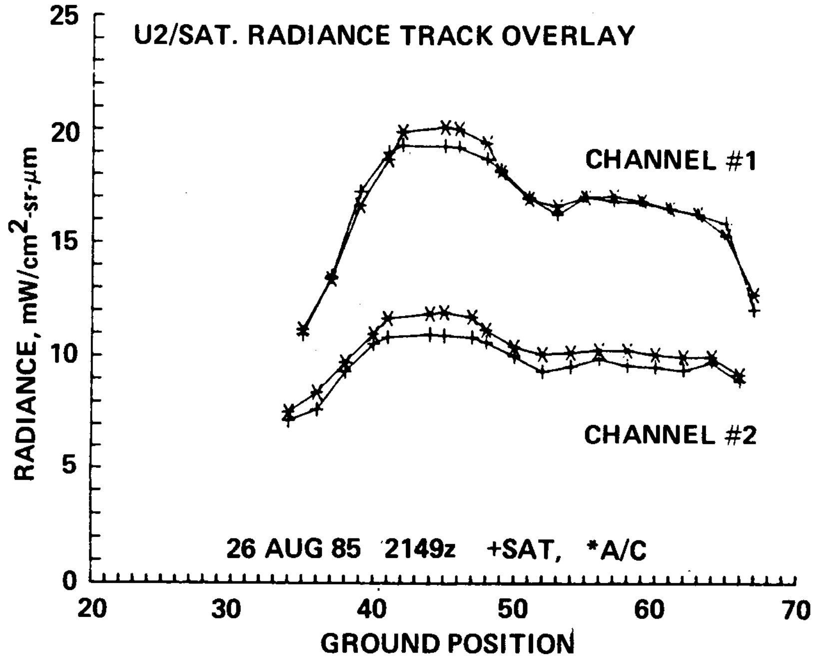


Figure 7.- Brightness contour fit, U-2/satellite radiance track overlay.

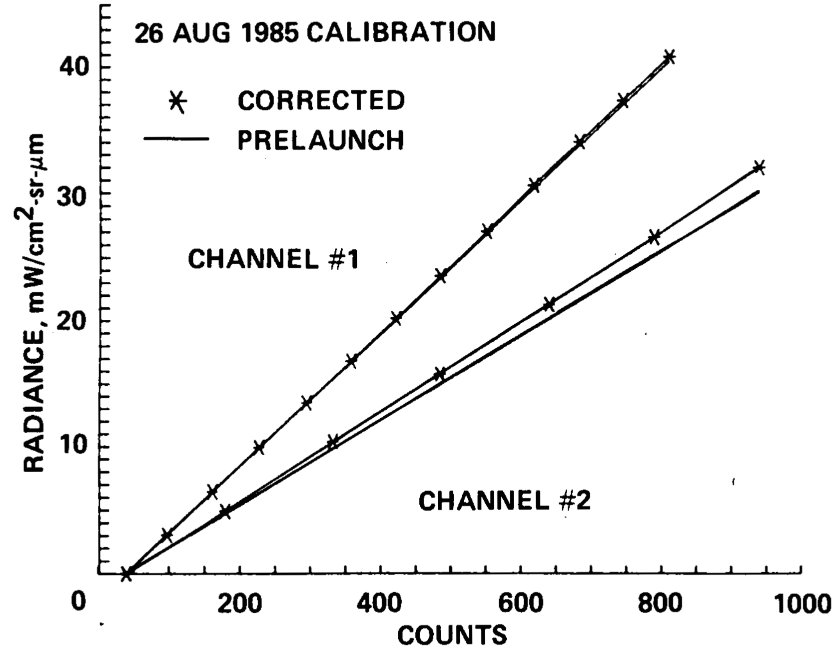


Figure 8.- NOAA-9 AVHRR radiance vs. counts, calibration channels 1 and 2, August 1985.

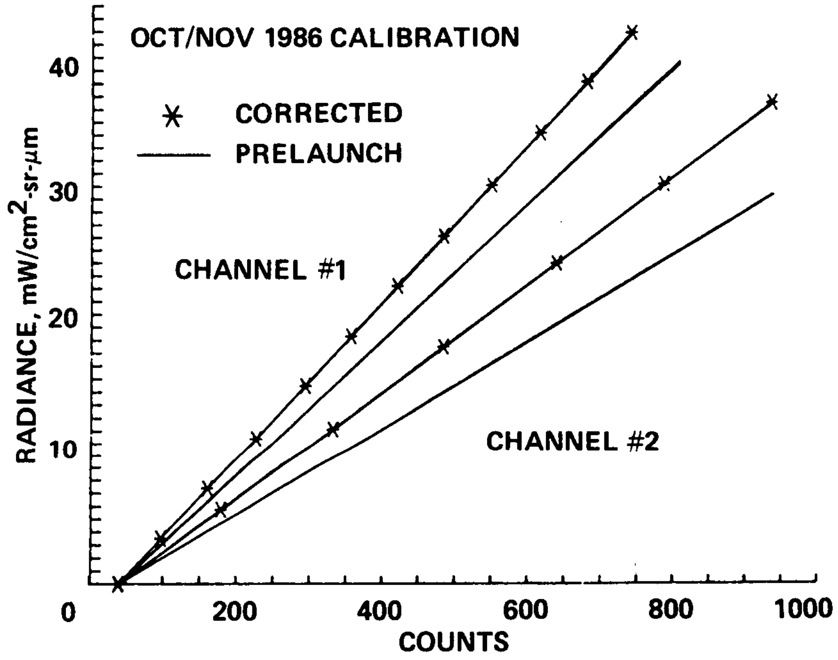


Figure 9.- NOAA-9 AVHRR radiance vs. counts, calibration channels 1 and 2, November 1986.

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Point of Contact: Robert Wrigley, Ames Research Center, MS 242-4, Moffett Field, CA 94035
(415) 694-6060 or FTS 464-6060

16. Abstract

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