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Semi-Annual Status Report

The Absolute Radiometric Calibration of the Advanced Very High Resolution Radiometer

(NASA-CR-182755) THE ABSOLUTE RADIOMETRIC CALIBRATION OF THE ADVANCED VERY HIGH RESOLUTION RADIOMETER Semiannual Status Report (Arizona Univ.) 17 p CSCL 08B

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INTRODUCTION

This is the semi-annual status report for NASA Grant NAG5-859 covering the period of October 1987 to April 1988.

During the latter half of this period the following papers, in part supported by this grant, were prepared for presentation at the April 1988 SPIE Orlando Conference entitled *Recent Advances in Sensors, Radiometry, and Data Processing for Remote Sensing*.

Radiometric Calibration Requirements and Atmospheric Correction

P. N. Slater

Abstract:

The need for independent, redundant absolute radiometric calibration methods is discussed with reference to the Thematic Mapper. Uncertainty requirements for absolute calibration of between 0.5% and 4% are defined based on the accuracy of reflectance retrievals at an agricultural site. It is shown that even very approximate atmospheric corrections can reduce the error in reflectance retrieval to 0.02 over the reflectance range 0 to 0.4.

Laboratory Calibration of Field Reflectance Panels

S. F. Biggar, J. Labed, R. P. Santer,
P. N. Slater, R. D. Jackson, and M. S. Moran

Abstract:

A method used for calibrating field reflectance panels in the visible and shortwave infrared wavelength range is described. The directional reflectance factor of painted barium sulfate ($BaSO_4$) panels is determined. The reference for this method is the hemispherical reflectance of pressed polytetrafluoroethylene (halon) powder prepared according to National Bureau of Standards (NBS) directions. The panels and a radiometer are mounted on rotation stages to measure the reflectance factor at different incidence and view angles. The sensor can be any laboratory or field filter radiometer small enough to mount on the apparatus.

The method is used to measure the reflectance factors of halon and $BaSO_4$ panels between 0.45 and 0.85 micrometers. These reflectance factors are compared to those measured by a field apparatus. The results agree to within 0.013 in reflectance at incidence angles between 15 and 75 degrees.

Accounting for Diffuse Irradiance on Reference Reflectance Panels

R. D. Jackson, P. N. Slater, and M. S. Moran

Abstract:

Measurements of surface reflectance factors in the field are usually made under conditions of total (direct and diffuse) irradiance. However, the reference panel reflectance factor $R(0^o/\Theta)$ used to convert the target measurement to reflectance is frequently determined using only direct irradiance. A method for determining the diffuse-irradiance reflectance factor, $R_{dif}(0^o/\Theta)$, of a calibrated field-reference panel from a knowledge of the direct-irradiance reflectance factor, $R_{dir}(0^o/\Theta)$, is described. The magnitude of the error involved if only the direct irradiance reflectance factor is known, usually from laboratory calibration, was found to vary from - 2% to + 5%, depending on zenith angle, atmospheric conditions, and the particular reflectance panel used.

In-Flight Radiometric Calibration of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)

James E. Conel, Robert O. Green, Ronald E. Alley, Carol J. Bruegge, Veronique Carrere, Jack S. Margolis, Gregg Vane, Philip N. Slater Stuart F. Biggar, R. D. Jackson and M. S. Moran

Abstract:

A reflectance-based method was used to provide an analysis of the in-flight radiometric performance of AVIRIS. Field spectral measurements of the atmosphere using solar radiation were used as input to atmospheric radiative transfer calculations. Four separate codes were used in the analysis. Three include multiple scattering, and the computed radiances from these for flight conditions were in reasonable agreement. Code-generated radiances were compared with AVIRIS-predicted radiances (based on two laboratory calibrations, pre- and post-season of flight) for a uniform highly-reflecting natural dry lake target. The post-season AVIRIS calibration constants were found to give the best agreement with models that include multiple scattering. From spectrometer A, the radiance predicted was about right. The other three spectrometers (B, C, D) returned values systematically 20 - 30% low.

The attached paper by Teillet et al. that describes work done to date on AVHRR calibration was also presented.

In addition some radiometer calibrations were conducted for B. L. Markham, F. M. Wood Jr., and S. P. Ahmad, the results of which were mentioned in their paper entitled "Radiometric calibration of the reflective bands of NS001-Thematic Mapper simulator and Modular Multispectral radiometers (MMR) at the same conference.

In addition to the authors of this report, the following have participated in the associated field work: S. F. Biggar, D. I. Gellman, B. J. Grant, and M. Smith from the Optical Sciences Center, and R. D. Jackson and M. S. Moran from the USDA Water Conservation Laboratory in Phoenix.

STATUS OF AVHRR CALIBRATION

The following table lists the status of AVHRR calibration work. We are presently involved in the data reduction for the February 1988 calibration campaign at White Sands for NOAA-9 and NOAA-10. We are planning a trip to Rogers (dry) Lake at Edwards Air Force Base in mid-June for some further AVHRR calibrations. In the fall, we plan to return to White Sands as part of a large calibration activity, including NASA and NOAA for AVHRR, TM, and SPOT calibrations.

Status of AVHRR Calibration Analyses (April 1988)

NOAA-9 and NOAA-10 AVHRR data sets. The bracketed number after the date refers to the number of days since launch. WSMR is the White Sands Missile Range in New Mexico and EAFB is Edwards Air Force Base in the Mojave Desert of California.

NOAA-9 AVHRR Data Sets

Date	Site	Reference Sensor	Analysis Status
1985.08.28 (260)	WSMR	TM	Completed (Methods 1 and 3)
1986.10.14 (672)	EAFB	--	Completed (Method 2)
1987.05.04 (874)	EAFB	--	Completed (Method 2)
1987.05.05 (875)	EAFB	--	Completed (Method 2)
1988.02.10 (1157)	WSMR	TM, HRV	In Progress

NOAA-10 AVHRR Data Sets

Date	Site	Reference Sensor	Analysis Status
1987.03.27 (192)	WSMR	TM	Completed (Methods 1 and 3)
1987.03.28 (193)	WSMR	HRV	In Progress
1987.07.17 (305)	WSMR	HRV	In Progress
1987.09.13 (363)	EAFB	--	Planned
1988.02.09 (512)	WSMR	next day TM, HRV	In Progress

924-23 SPIE Conference Orlando April, 1988

Absolute radiometric calibration of the NOAA AVHRR sensors

P. M. Teillet,[1*] P. N. Slater,[1] Y. Mao,[1] Y. Ding,[1] B. Yuan,[1] R. J. Bartell,[1] S. F. Biggar,[1] R. P. Santer,[1+] R. D. Jackson,[2] and M. S. Moran.[2]

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ABSTRACT

Three different approaches are described for the absolute radiometric calibration of the two reflective channels of the NOAA AVHRR sensors. Method 1 relies on field measurements and refers to another calibrated satellite sensor that acquired high-resolution imagery on the same day as the AVHRR overpass. Method 2 makes no reference to another sensor and is essentially an extension of the reflectance-based calibration method developed at White Sands for the in-orbit calibration of Landsat TM and SPOT HRV data. Method 3 achieves a calibration by reference to another satellite sensor, but it differs significantly from the first approach in that no ground reflectance and atmospheric measurements are needed on overpass day. Calibration results have been obtained using these methods for four NOAA-9 AVHRR images and for one NOAA-10 AVHRR image. A significant degradation in NOAA-9 AVHRR responsivity has occurred since the prelaunch calibration and with time since launch. The responsivity of the NOAA-10 AVHRR has also degraded significantly compared to the prelaunch calibration. The suitabilities of using Method 2 with the Rogers Dry Lake site in California and using Methods 1 and 3 at White Sands are discussed. The results for Method 3, which requires no field measurements and makes use of a simplified atmospheric model, are very promising, implying that a reasonable calibration of satellite sensors may be relatively straightforward.

1. INTRODUCTION

An increasing number of remote sensing investigations require radiometrically calibrated imagery from NOAA Advanced Very High Resolution Radiometer (AVHRR) sensors. Although a prelaunch calibration was done for these sensors, there is no proper capability for monitoring any changes in the in-flight absolute calibration for the visible and near infrared spectral channels. Hence, the possibility of using the reflectance-based method[1] developed at White Sands for in-orbit calibration of Landsat Thematic Mapper (TM) and SPOT Haute Resolution Visible (HRV) data to calibrate the AVHRR sensor has been under investigation. Three different approaches have been considered.

1.1 Method 1: Ground and atmospheric measurements and reference to another calibrated satellite sensor (Figure 1).

Ground-based reflectance measurements can be made over terrain areas corresponding to numerous Landsat TM or HRV pixels, but such measurements become impractical for the calibration of the AVHRR image data with pixel dimensions of 1.1 km by 1.1 km or greater. An alternative is to acquire AVHRR imagery of White Sands on the same day that a TM or HRV calibration has been carried out on the basis of ground reflectance factor and atmospheric measurements at Chuck Site in the alkali-flat region of White Sands. The methodology then takes advantage of the accurate calibration results for TM bands 3 and 4 or HRV bands 2 and 3 to effect a calibration of AVHRR channels 1 and 2. More specifically, a relatively uniform area corresponding to one or more AVHRR pixels is selected in the alkali-flat region and average digital counts are extracted for these AVHRR pixels and for pixels from the matching area in the TM or HRV imagery. With the help of radiative transfer computations and bidirectional reflectance data for the gypsum surface at White Sands, radiance at the entrance aperture of the AVHRR sensor is predicted. The analysis takes into account differences in spectral response, sun angle, and viewing geometry between the TM or HRV and AVHRR data acquisitions.

1.2 Method 2: Ground and atmospheric measurements with no reference to another sensor (Figure 2).

The second approach is more closely analogous to the original reflectance-based approach used at White Sands to calibrate the TM or HRV sensors. It is based on detailed ground and atmospheric measurements near the time of AVHRR overpass, but it necessarily assumes the reflectance values to be representative of the whole pixel since these ground measurements can only encompass a portion of one AVHRR pixel. The availability of aircraft data can assist in the selection of an appropriately uniform area for this purpose. Although this method is not likely to be as accurate as the first, it has the distinct advantage of not requiring nearly coincident data acquisition from two different sensors.

1.3 Method 3: No ground and atmospheric measurements but reference to another sensor (Figure 3).

As with the first method, this approach achieves a calibration of the first two AVHRR channels by reference to another satellite sensor such as the TM or HRV on the same day. However, it differs significantly in that no ground and atmospheric measurements on the overpass day are needed. Instead, a standard data set of atmospheric conditions is used to approximate the actual atmosphere and historical bidirectional reflectance data are used to adjust for differences in illumination and viewing geometries. The same atmospheric parameters are adopted to estimate surface reflectance from the TM or HRV imagery and then to predict radiance at the AVHRR sensor from that surface reflectance (suitably adjusted for bidirectional effects and spectral bandpass differences). Because of this two-way use of the atmospheric model, errors introduced in one direction will be compensated to some extent in the reverse direction so that reasonable calibration results may be obtained if the procedure is not overly sensitive to the choice of atmospheric model. If it proves to be viable, this approach will be a valuable one because it will facilitate in-orbit sensor calibration without the complexity and expense of field measurements.

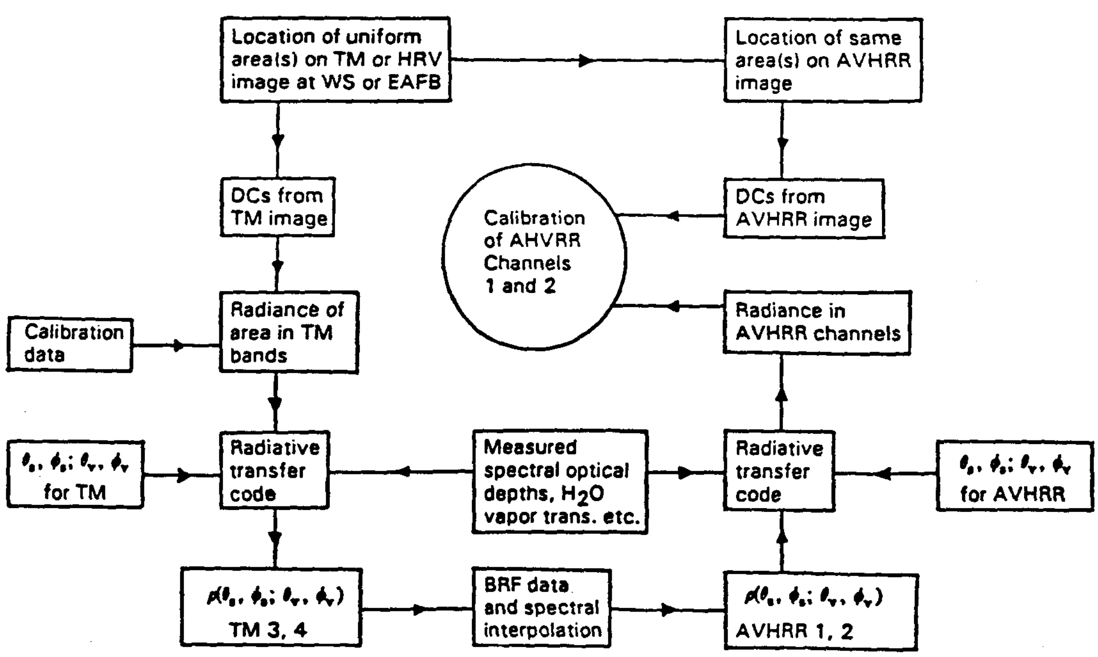

Figure 1. "Method 1" calibration approach: ground and atmospheric measurements and reference to another calibrated satellite sensor.

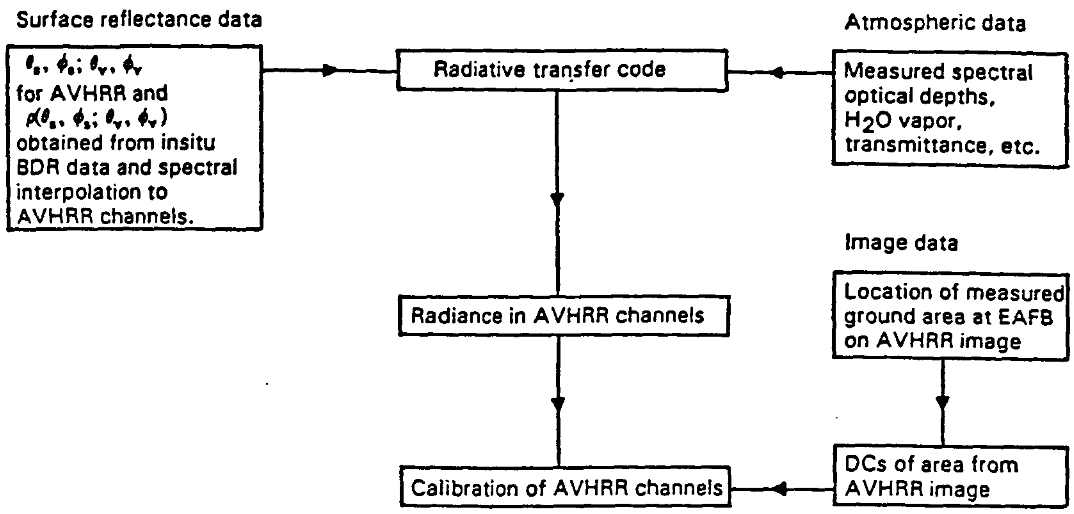

Figure 2. "Method 2" calibration approach: ground and atmospheric measurements without reference to another sensor.

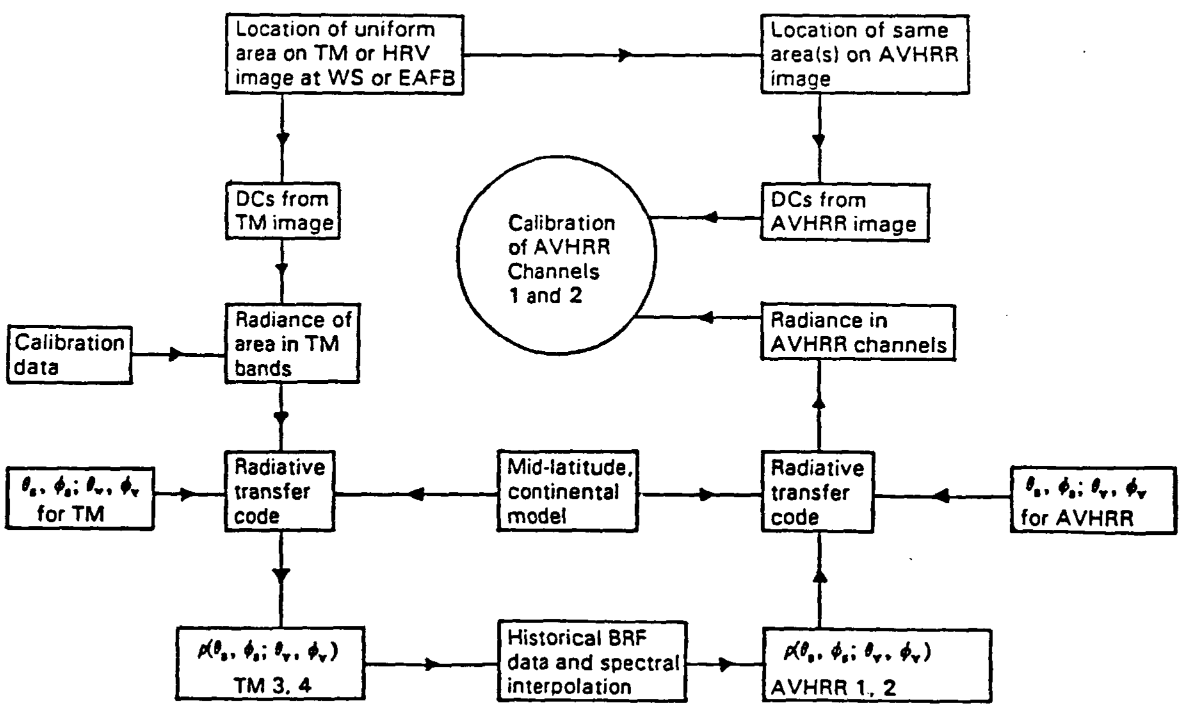

Figure 3. "Method 3" calibration approach: no ground and atmospheric measurements but reference to another satellite sensor.

2. NOAA-9 AND NOAA-10 AVHRR DATA SETS

The methods described in the previous section have been applied to several data sets involving NOAA-9 and NOAA-10 AVHRR imagery. The principal characteristics of these two sensor systems are listed in Table 1. As indicated in the table, prelaunch radiometric calibrations were performed many years prior to launch.

The collection of data sets involving ground-based measurements and/or same-day coverage of a test area by more than one satellite sensor is difficult to accomplish. The logistics and expense of field measurement campaigns as well as ever-present limitations due to weather severely reduce the number of data sets suitable for calibration work. An additional constraint in the case of AVHRR coverage of a given site is the possibility of large off-nadir view angles, which are not used if they exceed 40 to 45 degrees. Nevertheless, several AVHRR data sets have been acquired (Table 2) over the last few years during calibration experiments at White Sands, New Mexico and at the Rogers Dry Lake at Edwards Air Force Base (EAFB) in California. The work at EAFB has been concerned with calibration of airborne sensors and so there is no reference to another satellite sensor for that site (Method 2). At the White Sands Missile Range (WSMR), the main efforts have been directed towards in-flight calibration of the Landsat TM and SPOT HRV sensors.[1,2] Hence, TM or HRV image data are used as the reference in Method 1 and Method 3 analyses. To date, calibration results have been obtained for four NOAA-9 AVHRR cases (August 28, 1985; October 14, 1986; May 4, 1987; May 5, 1987) and for one NOAA-10 AVHRR case (March 27, 1987).

Table 1. Principal characteristics of the NOAA-9 and NOAA-10 AVHRR sensor systems. The indicated spectral bandpass limits are nominal values; the spectral response profiles of the two sensors actually differ somewhat.

	NOAA-9 AVHRR	NOAA-10 AVHRR
Prelaunch Calibration:	approx. February, 1980	approx. March, 1977
Launch Date:	December, 1984	September, 1986
Orbit:	sun-synchronous ascending node (day)	sun-synchronous descending node (day)
Equatorial Crossing:	14:30	07:30
Nadir Resolution:	1.1 km	1.1 km
Scan Angle Range:	± 55.4°	± 55.4°
Spectral Bands (μm):	Ch. 1 (0.58-0.68) Ch. 2 (0.725-1.1) Ch. 3 (3.55-3.93) Ch. 4 (10.3-11.3) Ch. 5 (11.5-12.5)	Ch. 1 (0.58-0.68) Ch. 2 (0.725-1.1) Ch. 3 (3.55-3.93) Ch. 4 (10.3-11.3)
Quantization:	10 bit	10 bit

Table 2. NOAA-9 and NOAA-10 AVHRR data sets. The bracketed number after the date refers to the number of days since launch. WSMR is the White Sands Missile Range in New Mexico and EAFB is Edwards Air Force Base in the Mojave Desert of California.

NOAA-9 AVHRR Data Sets			
Date	Site	Reference Sensor	Status
1985.08.28 (260)	WSMR	TM	Completed (Methods 1 and 3)
1986.10.14 (672)	EAFB	--	Completed (Method 2)
1987.05.04 (874)	EAFB	--	Completed (Method 2)
1987.05.05 (875)	EAFB	--	Completed (Method 2)
1988.02.10 (1157)	WSMR	TM, HRV	Planned
NOAA-10 AVHRR Data Sets			
Date	Site	Reference Sensor	Status
1987.03.27 (192)	WSMR	TM	Completed (Methods 1 and 3)
1987.03.28 (193)	WSMR	HRV	In Progress
1987.07.17 (305)	WSMR	HRV	In Progress
1987.09.13 (363)	EAFB	--	Planned
1988.02.09 (512)	WSMR	next day TM, HRV	Planned

3. ANALYSIS PROCEDURES

3.1 Method 1 analysis for NOAA-9 AVHRR on August 28, 1985 at WSMR

A geometric registration procedure was used to match the relevant portions of the TM and AVHRR images of White Sands. From the superimposed images, a relatively uniform area of two by two AVHRR pixels was selected in the alkali-flat region. The digital counts for this area and for the corresponding area in the TM imagery were extracted and averaged.

In order to relate the TM radiance values (corresponding to the aforementioned TM digital counts for the AVHRR test area) to ground reflectance factors, a series of atmospheric model computations were carried out using the Herman radiative transfer code.[3] The Rayleigh and aerosol optical depths required by the code were determined from an analysis of Langley plots, in which the log voltages from solar radiometers were plotted against air masses for the satellite overpass day. The result of this step is a set of surface reflectance factors in the TM bands over a much larger area than could be measured using ground-based techniques.

At the NOAA-9 satellite overpass time of 21:27 Coordinated Universal Time (UT), the solar zenith angle was 39.85 degrees, whereas at the Landsat-5 satellite overpass time of 17:08 UT, the solar zenith angle was 35.95 degrees. Moreover, the off-nadir view angle was 23.6 degrees for the AVHRR sensor and about one degree for the TM sensor. Thus, in order to obtain values relevant to the AVHRR conditions, corrections were applied to the TM band 3 and 4 reflectance factors on the basis of bidirectional reflectance (BRF) measurements made for the gypsum surface at a variety of solar zenith angles at White Sands on March 15, 1986. The reflectance factors were further adjusted to the central wavelengths of AVHRR channels 1 and 2.

Atmospheric parameters and surface reflectances for the two AVHRR channels were then input to the Herman radiative transfer code for the return pass through the atmosphere. The result is predicted radiance at the entrance aperture of the AVHRR sensor in each channel. Both for this step and the earlier pass down through the atmosphere for TM, an additional adjustment was applied to correct for gaseous absorption. More specifically, the French "5-S" atmospheric program[4] was run to obtain the total gaseous transmittance for four gases (H_2O, O_3, CO_2, and O_2).

3.2 Method 2 analysis for NOAA-9 AVHRR on three dates at EAFB

Although it makes no reference to another imaging sensor, the Method 2 calibration approach relies on ground-based measurements of atmospheric conditions and surface reflectance made at the site on the day of an overpass with the techniques used at White Sands.[1] Solar radiometer measurements were made next to Rogers Dry Lake at EAFB on October 14, 1986, May 4, 1987, and May 5, 1987. On October 14 and May 5, reflectance factor measurements were made on the dry lakebed over a 320 meter by 80 meter target area related to another experiment. The ground reflectance data were collected using a Barnes MMR in spectral bands similar to the Landsat TM bandpasses. Reflectance factors were computed using a calibrated barium sulfate panel and an average reflectance was computed for the entire target area in each band.

The atmospheric radiative transfer computations require a surface reflectance value as one of the inputs in any given spectral band. However, the measured reflectance factors were acquired with nadir viewing geometry and usually not at AVHRR overpass time (and hence at a different sun angle). Thus, the reflectance factors were corrected to be appropriate for the sun and view angle geometries for the NOAA-9 AVHRR overpasses of EAFB on each of the three dates. These corrections were made with the help of BRF measurements made on the dry lakebed at a variety of solar zenith angles on May 5, 1987, May 6, 1987, and September 14, 1987. A final adjustment was made to the reflectance factors to correspond to the central wavelengths of AVHRR channels 1 and 2. The use of the Herman and "5-S" codes is as described earlier in the Method 1 approach.

Bright and dark features were identified in SPOT HRV and Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) imagery,[5] acquired at other times for the EAFB area, that were also distinguishable in the AVHRR scenes. The features used for this purpose were not likely to have changed places in time and were sufficiently numerous to minimize the effect of systematic geometric distortions. The location of the ground measurement site on the dry lakebed could then be estimated visually in the AVHRR imagery using relative distances and triangulation. Digital image analysis facilities were used for this purpose. The corresponding "best estimate" digital counts were then interpolated from image values in channels 1 and 2.

The surface at Rogers Dry Lake is quite flat for many kilometers in all directions but its reflectance characteristics are reasonably uniform only in a limited area, roughly 1 3/4 kilometers in the predominantly East-West direction. Thus, although that part of the dry lakebed provides a large uniform target for high-resolution sensors, it can accommodate the area of one AVHRR pixel only for off-nadir view angles less than 35 degrees relative to vertical at ground level (the approximate pixel dimensions on the various dates are listed in Table 3). Because this site is not easy to pin-point in the AVHRR imagery, digital counts were also obtained by interpolation for locations plus or minus half a pixel away in the direction of the strongest radiance gradient.

Table 3. Sun and view angle geometries for the NOAA-9 and NOAA-10 AVHRR overpasses. The nadir view angles are relative to vertical at ground level and view azimuth angles are in the satellite direction from the ground location.

Date	Overpass Time (U.T.)	Solar Zenith (Degrees)	Solar Azimuth (Degrees)	Solar Distance (A.U.)	Off-Nadir View (Degrees)	View Azimuth (Degrees)	Approximate Pixel Dimensions (km)
1985.08.28	21:27:00	39.9	242.1	1.0098	23.6	259	1.4 x 1.3
1986.10.14	21:46:55	53.0	221.6	0.9972	44.5	259	2.2 x 1.6
1987.05.04	22:29:54	40.7	252.8	1.0087	15.3	79	1.3 x 1.2
1987.05.05	22:19:03	38.5	250.8	1.0087	31.3	79	1.6 x 1.3
1987.03.27	15:15:45	62.7	107.0	0.9979	21.5	281	1.3 x 1.2

3.3 Method 3 analysis for NOAA-9 AVHRR on August 28, 1985 at WSMR

Although the data flow for this method schematically resembles that of Method 1, it differs considerably in nature in that no ground-based measurements of atmospheric conditions and surface reflectance are required. The actual atmosphere is approximated by a standard set of atmospheric conditions and the "5-S" atmospheric model is invoked as a simpler and faster code to use. Historical BRF data are used to adjust TM reflectance factors to the illumination and viewing geometries pertinent to the AVHRR overpass. In other respects, the analysis procedure is identical to Method 1.

It is also of interest to test the sensitivity of Method 3 to the assumed atmospheric characteristics. In particular, the "5-S" code allows the user to easily modify input specifications for visibility, aerosol model, and atmospheric profile.[4,6] The different cases examined are listed in Table 4. The nominal case for the White Sands area is 100 kilometer visibility, continental aerosols, and a mid-latitude summer profile.

Table 4. Sensitivity analysis selections for input to the "5-S" code used in Method 3 calibration analyses.

Visibility (km)	Aerosol Model	Atmospheric Model
200	Continental	Mid-Latitude Summer
100	Continental	Mid-Latitude Summer
50	Continental	Mid-Latitude Summer
23	Continental	Mid-Latitude Summer
200	Maritime	Tropical
100	Maritime	Tropical
50	Maritime	Tropical
23	Maritime	Tropical
200	Continental	Sub-Arctic Winter
100	Continental	Sub-Arctic Winter
50	Continental	Sub-Arctic Winter
23	Continental	Sub-Arctic Winter

3.4 Method 1 and Method 3 analyses for NOAA-10 AVHRR on March 27, 1987 at WSMR

Compared to the Method 1 and Method 3 analyses for NOAA-9 AVHRR, the only differences in the case of the NOAA-10 AVHRR concern image data manipulation. Unlike the situation with NOAA-9, the NOAA-10 AVHRR and the Landsat TM sensors acquire images from similar orbital configurations (descending orbit). Thus, no significant rotation was necessary to superimpose the two image data sets and the main factor to be dealt with was the different off-nadir viewing angles involved.

The other difference is not inherent to the NOAA-10 AVHRR sensor but rather concerns the adoption of a different procedure for selecting common areas in the TM and AVHRR scenes. More specifically, the TM scene was examined on a digital image display for relatively uniform patches greater than one AVHRR pixel in extent. Ten such locations were identified, seven in the alkali-flat region for use in the actual analysis and three in the dunes area for comparison. Block averages of 45 pixels by 41 lines (corresponding to the size of one AVHRR pixel) were obtained in TM bands 3 and band 4 image data centered in each of the ten areas. The central locations were then identified in the registered AVHRR imagery and corresponding digital counts were obtained from AVHRR channels 1 and 2. Because each of the uniform image patches were well over one AVHRR pixel in extent and only one AVHRR sample was taken from each such area, problems due to mis-registration should have been minimized. Figure 4 shows that there is some merit to this approach. It plots digital counts from AVHRR channel 1 against TM band 3 and AVHRR channel 2 against TM band 4 after geometric registration, with linear regressions yielding coefficients of determination of 0.993 and 0.984, respectively. By means of such graphs, outliers could be removed from further analysis. However, all seven points were kept for the purposes of this exploratory work.

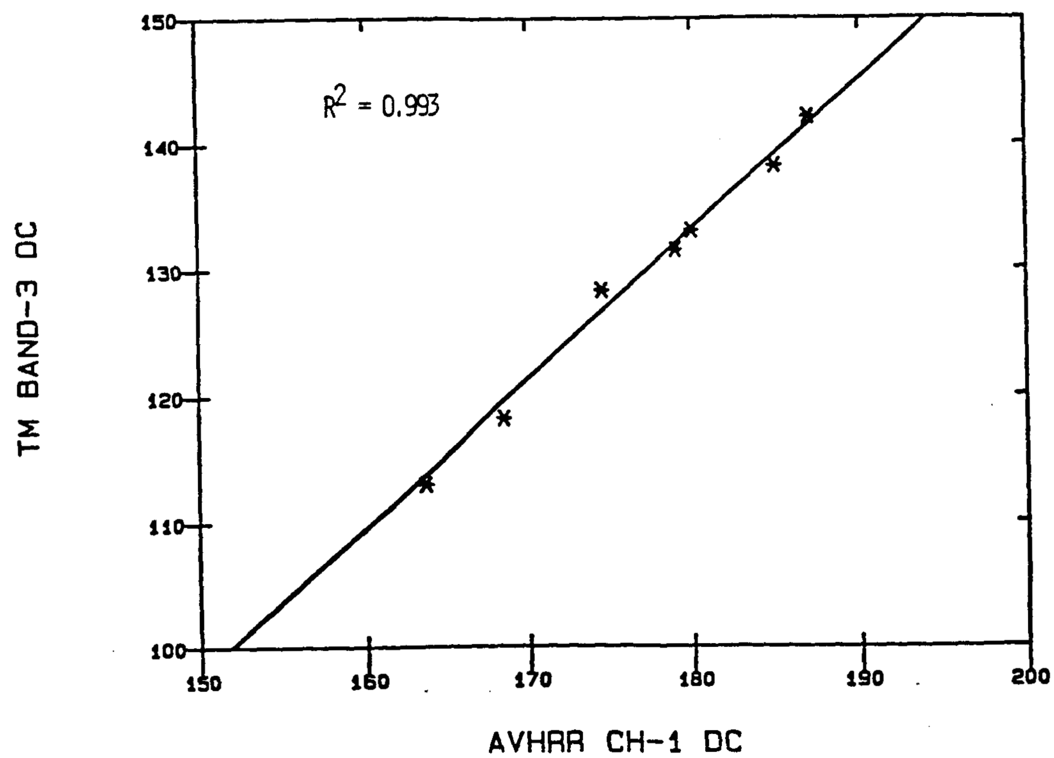

Figure 4(a). Comparison of digital counts from AVHRR channel 1 and TM band 3 on March 27, 1987 for seven locations in the alkali-flats region at White Sands after geometric registration. The straight line is a linear regression fit.

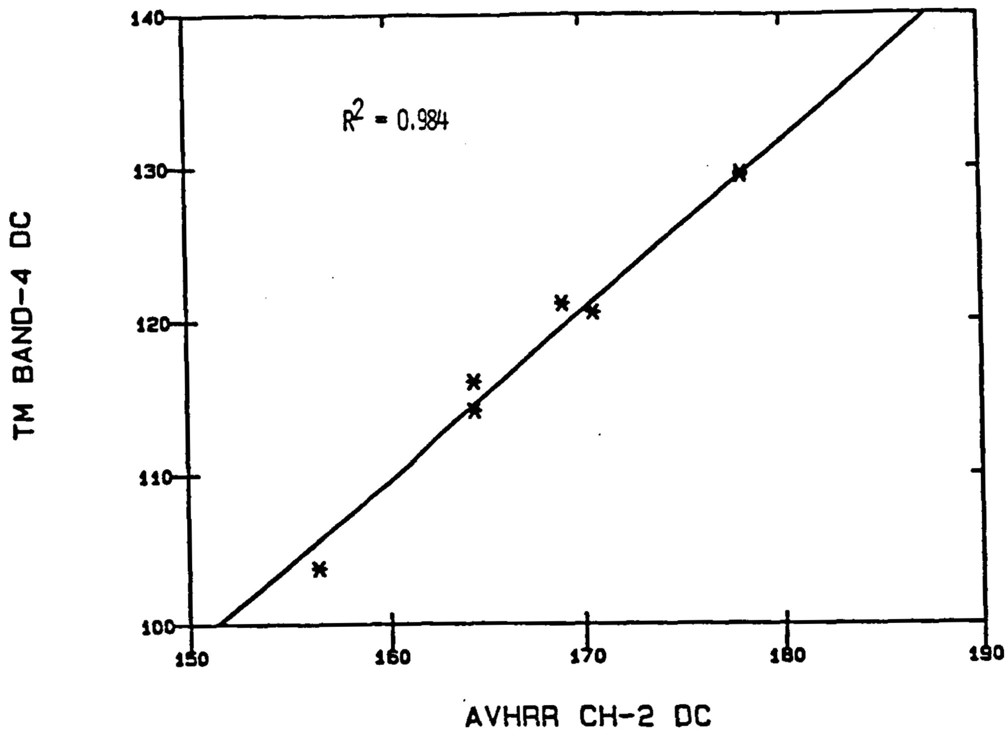

Figure 4(b). Comparison of digital counts from AVHRR channel 2 and TM band 4 on March 27, 1987 for seven locations in the alkali-flats region at White Sands after geometric registration. Two points fall in the same place (the brightest location) and so only six points are distinguishable in the plot. The straight line is a linear regression fit.

4. RESULTS

4.1 NOAA-9 AVHRR Calibration

Absolute calibration coefficients for the reflective channels of the NOAA-9 AVHRR are listed in Table 5 and portrayed as a function of time in Figures 5(a) and 5(b). It is evident that the sensor's responsivity has degraded significantly with time, with the greater change occurring in channel 2. That the gain coefficients in October 1986 should be somewhat higher than in May 1987 is largely due to the difficulty in making a precise BRF correction for the earlier date when the off-nadir view angle was nearly 45 degrees, but also partly due to the problem of having a

Table 5. NOAA-9 AVHRR radiometric calibration results. For Method 2 at EAFB, results are given in parentheses for locations plus or minus half a pixel away in the scan direction. Gain coefficients are in units of $Wm^{-2}sr^{-1}\mu m^{-1}count^{-1}$.

Date	Method	Channel 1 Gain		Channel 2 Gain	
Prelaunch		0.5243		0.3286	
1985.08.28	1	0.552		0.390	
1986.10.14	2	0.703	(0.654, 0.732)	0.470	(0.437, 0.491)
1987.05.04	2	0.674	(0.649, 0.697)	0.447	(0.430, 0.462)
1987.05.05	2	0.666	(0.631, 0.705)	0.436	(0.413, 0.463)

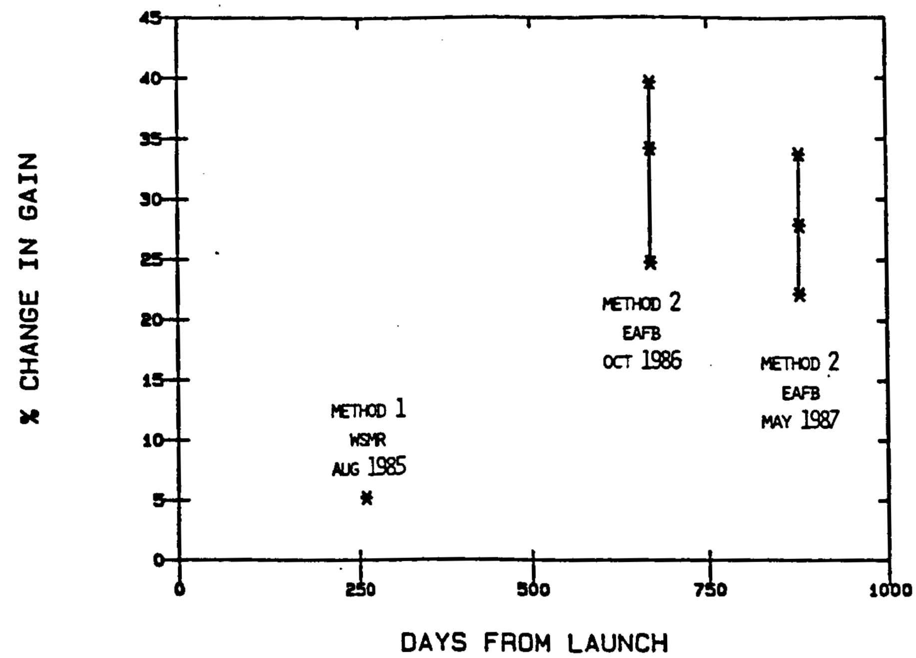

Figure 5(a). NOAA-9 AVHRR channel 1 calibration results expressed as percent change in gain as a function of time. In Method 2 cases at EAFB, results for locations plus or minus half a pixel away in the scan direction give rise to the error bars. The May 1987 results are averages from May 4 and May 5.

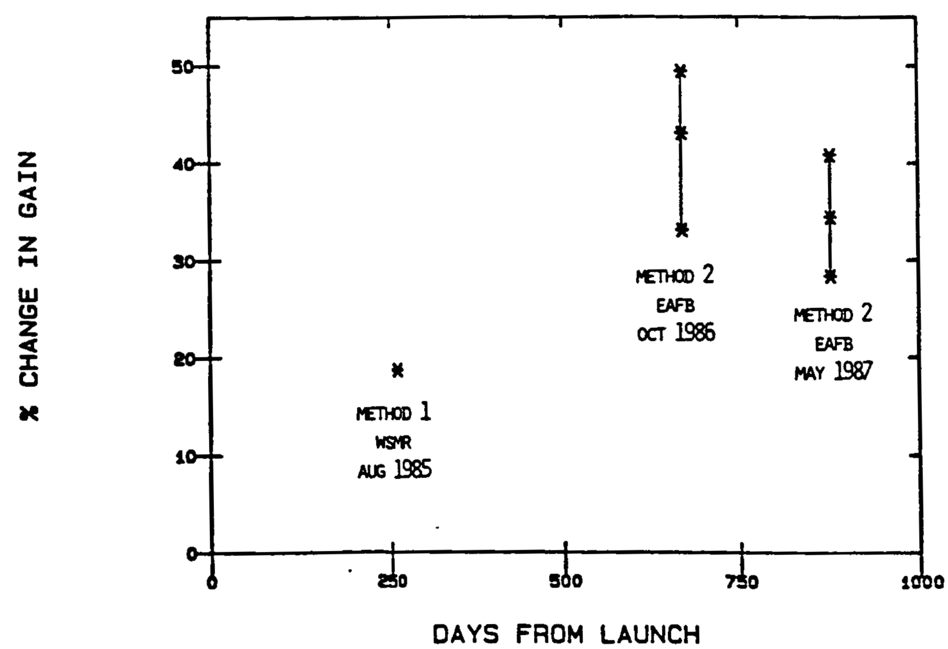

Figure 5(b). As for Figure 5(a), except for NOAA-9 AVHRR channel 2.

2.2 kilometer pixel dimension in the scan line direction, which exceeds the size of the uniform reflectance patch at EAFB. The results for May 4 and May 5, 1987 are reasonably consistent. Although the same surface reflectance measurements were used for both days since no reflectance measurements were made on May 4th, different atmospheric parameters were used and the off-nadir view angles differed considerably (Table 3). No detailed error analysis has been carried out for the Method 1 approach, but a rough estimate indicates an uncertainty on the order of 5 percent.

Method 3 and Method 1 calibration results on August 28, 1985 are compared in Table 6. Lacking any knowledge of atmospheric conditions at White Sands, the standard conditions would be assumed to be a mid-latitude summer profile with continental aerosols and a visibility of 100 km. The difference between the two methods in that case would be 1.6% in channel 1 and 2.7% in channel 2. There appears to be very little sensitivity to the assumed visibility and a slight sensitivity to a change to a moister atmosphere (tropical) with maritime aerosols. The greatest effect in this regard occurred in channel 2 with a change to a drier atmosphere (sub-arctic winter). Notable differences between the two methods also arise if no corrections are made for sun angle, view angle, and wavelength differences between the TM and AVHRR conditions.

Table 6: Method 3 calibration results for NOAA-9 for August 28, 1985. M.L.S. = Mid-Latitude Summer; S.A.W. = Sub-Arctic Winter; Trop. = Tropical; Cont. = Continental; Marit. = Maritime. "Matched" refers to 5S runs using measured aerosol and Rayleigh optical depth values. Gain coefficients are in units of $Wm^{-1}sr^{-1}\mu m^{-1}count^{-1}$.

Visibility (km)	Atmospheric Profile	Aerosol Model	Channel 1 Gain	Difference from Method 1	Channel 2 Gain	Difference from Method 1
200	M.L.S.	Cont.	0.540	-1.5%	0.373	-2.7%
100	M.L.S.	Cont.	0.540	-1.6%	0.373	-2.7%
50	M.L.S.	Cont.	0.539	-1.7%	0.373	-2.8%
23	M.L.S.	Cont.	0.539	-1.9%	0.372	-2.9%
200	Trop.	Marit.	0.544	-0.9%	0.370	-3.5%
100	Trop.	Marit.	0.544	-0.9%	0.370	-3.4%
50	Trop.	Marit.	0.545	-0.7%	0.371	-3.2%
23	Trop.	Marit.	0.548	-0.2%	0.372	-2.9%
200	S.A.W.	Cont.	0.535	-2.4%	0.389	+1.5%
100	S.A.W.	Cont.	0.535	-2.5%	0.389	+1.5%
50	S.A.W.	Cont.	0.534	-2.6%	0.389	+1.4%
23	S.A.W.	Cont.	0.533	-2.8%	0.388	+1.2%
With no BRF and no λ adjustment:						
200	M.L.S.	Cont.	0.535	-2.6%	0.362	-5.6%
50	M.L.S.	Cont.	0.534	-2.7%	0.362	-5.7%
"Matched"	M.L.S.	Cont.	0.541	-1.3%	0.382	-0.2%
	Method 1 results:		0.549		0.383	
	Prelaunch values:		0.5243		0.3286	

4.2 NOAA-10 AVHRR Calibration

Absolute calibration coefficients based on Method 1 for the reflective channels of the NOAA-10 AVHRR on March 27, 1987 are given in Table 7. Compared to prelaunch values, the mean gain coefficients for the seven alkali-flats locations represent degradations of 21% and 35% in the responsivities of channels 1 and 2, respectively. Results for the dunes differ considerably from those for the alkali-flats, probably because the BRF corrections based on data acquired at Chuck Site are not applicable to the dunes area. Conversely, the consistency between results for the various alkali-flats locations indicates that the

Table 7. NOAA-10 AVHRR radiometric calibration results based on Method 1 for March 27, 1987 at White Sands. The first seven locations listed are in the alkali-flats region. Gain coefficients are in units of $Wm^{-2}sr^{-1}\mu m^{-1}count^{-1}$.

Location	Channel 1 Gain	Channel 2 Gain
#1	0.603	0.445
#2	0.626	0.467
#3	0.623	0.472
#4	0.621	0.464
#5	0.633	0.474
#6	0.606	0.460
#7	0.629	0.473
Mean	0.621	0.465
Std. Dev.	0.019	0.016
Prelaunch	0.5115	0.3454
#1 (dunes)	0.686	0.509
#2 (dunes)	0.675	0.504
#3 (dunes)	0.624	0.476

BRF corrections can be extended widely in that region of White Sands. Method 3 and Method 1 calibration results on March 27, 1987 are compared in Table 8. As for the case discussed in the previous section, results from the two methods are generally within a few percent of each other. The greatest difference occurs in channels 2 if the atmosphere is assumed to be a sub-artic winter model.

5. DISCUSSION

A significant degradation in NOAA-9 AVHRR responsivity has occurred since the prelaunch calibration and with time since launch. As of May 1987, the change has been on the order of 25 to 30 percent in channel 1 and approximately 35 percent in channel 2. The analysis of more recent data sets is needed to update and further characterize the degradation. In this regard, a data set involving TM, HRV, and AVHRR imagery is currently being assembled after a successful field trip to White Sands on February 8-10, 1988.

Table 8: Method 3 calibration results for NOAA-10 for March 27, 1987. M.L.S. = Mid-Latitude Summer; S.A.W. = Sub-Arctic Winter; Trop. = Tropical; Cont. = Continental; Marit. = Maritime. Gain coefficients are in units of $Wm^{-2}sr^{-1}\mu m^{-1}count^{-1}$.

Visibility (km)	Atmospheric Profile	Aerosol Model	Channel 1 Gain	Difference from Method 1	Channel 2 Gain	Difference from Method 1
200	M.L.S	Cont.	0.631	+1.6%	0.481	+3.4%
100	M.L.S.	Cont.	0.628	+1.1%	0.479	+3.0%
50	M.L.S.	Cont.	0.625	+0.6%	0.475	+2.2%
23	M.L.S.	Cont.	0.622	+0.2%	0.467	+0.4%
200	Trop.	Marit.	0.635	+2.3%	0.475	+2.2%
100	Trop.	Marit.	0.634	+2.1%	0.473	+1.7%
50	Trop.	Marit.	0.634	+2.1%	0.471	+1.3%
23	Trop.	Marit.	0.634	+2.1%	0.470	+1.1%
200	S.A.W.	Cont.	0.618	-0.5%	0.506	+8.8%
100	S.A.W.	Cont.	0.616	-0.8%	0.504	+8.4%
50	S.A.W.	Cont.	0.613	-1.3%	0.500	+7.5%
23	S.A.W.	Cont.	0.609	-1.9%	0.492	+5.8%
With no BRF and no λ adjustment:						
200	M.L.S.	Cont.	0.618	-0.5%	0.461	-0.9%
50	M.L.S.	Cont.	0.613	-1.3%	0.455	-2.2%
	Method 1 results:		0.621		0.465	
	Prelaunch values:		0.5115		0.3454	

With only one data set analyzed so far, the analysis of additional data sets is needed to assess any changes in NOAA-10 AVHRR calibration. As of March 1987, the degradation from the prelaunch calibration is on the order of 21 percent in channel 1 and 35 percent in channel 2.

There are some limitations to the use of Method 2 with the Rogers Dry Lake site at Edwards Air Force Base. The uniform area is limited to one AVHRR pixel (for nadir view angles less than 35 degrees relative to vertical at ground level) and is surrounded by terrain of much brighter and much darker reflectance on either side. In addition, unlike the gypsum at White Sands, the surface is not very lambertian so that accurate BRF corrections are important. (It should also be noted that the radiative transfer codes used assume lambertian reflectance.) Method 2 using the Rogers Dry Lake site is not likely to be able to track gain changes less than about 10 percent.

In both Methods 1 and 3, corrections for sun angle, view angle, and spectral differences between the higher resolution data and the AVHRR data are important, as is a good calibration of the high resolution sensor. For the data sets analyzed to date, the alkali-flats area at White Sands has proven to be quite suitable for the Method 1 and Method 3 approaches.

As far as Method 3 is concerned, results are generally within 1 to 3 percent of Method 1 for the conditions usually expected at White Sands. The method is not very sensitive to assumed visibility and hence aerosol optical depth, but it does show some sensitivity to the assumed atmospheric profile and hence water vapor, especially in channel 2. Nevertheless, the results for Method 3, which requires no field measurements and makes use of a simplified atmospheric model, are very promising. Because the results from this approach compare favorably with the more detailed methods and are not overly sensitive to assumed atmospheric conditions, the implication is that a reasonable calibration of satellite sensors may be possible by transfer, without the necessity of making ground-based measurements. In this way, it would be relatively straightforward to monitor occasionally (and retrospectively as well) the status of AVHRR sensor radiometric responses.

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