ELSEVIER

Reflectance Factor Retrieval from Landsat TM and SPOT HRV Data for Bright and Dark Targets

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In recent years, there have been many land-surface studies based on visible and near-infrared reflectance values retrieved from the Landsat Thematic Mapper (TM) and SPOT High Resolution Visible (HRV) sensors. Retrieval of reflectance from satellite sensor digital count requires knowledge of the atmospheric conditions and the sensor absolute calibration. In most cases, atmospheric conditions are simulated with a radiative transfer code and sensor calibration coefficients are obtained from preflight sensor calibrations or in-flight calibrations over bright surfaces (such as White Sands, New Mexico, USA, or La Crau, France). Though these procedures are well accepted, there have been few studies specifically designed to validate the accuracy of such reflectance factor retrievals (RFR) for both bright and dark targets. Data from two experiments conducted in an agricultural region in central Arizona were analyzed to quantify the accuracy of RFR from the Landsat TM and SPOT HRV sensors. These data included measurements made with ground-based and aircraft-based four-band radiometers and the NASA Advanced Solid-State Array Spectrometer (ASAS) aboard a C130 aircraft, and TM and HRV images acquired at nadir and off-nadir viewing angles. Results showed that the off-nadir reflectance factors measured using ground- and aircraft-based instruments, including ASAS, were comparable. The RFR from the satellite-based TM and HRV sensors generally resulted in an overestimation of dark target reflectance (up to 0.05 reflectance in the visible) and an underestimation of bright target reflectance (up to 0.1 reflectance in the near-infrared). Even greater error was possible when RFR was based on outdated sensor calibrations, particularly those conducted prelaunch. There was supporting evidence from studies at three sites (White Sands, New Mexico; Maricopa, Arizona; and Walnut Gulch, Arizona) that the Landsat-5 TM sensor sensitivity may have degraded by as much as 20% from the prelaunch calibration. Regarding the potential error in RFR related to recent changes in the processing of Landsat TM data (Level-0 and Level-1) by EOSAT Corporation, we found that the Level-0 data was slightly greater (~2 digital counts) than the Level-1 data for all bands and all targets in our study.

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INTRODUCTION

Spectral images from satellite-based sensors have long been promoted for Earth-monitoring applications, such as land-cover change detection and evaluation of global energy balance. The potential for such applications is growing with the increasing number of Earth-observation satellites in orbit. For example, consider the combined use of images from the Landsat-5 Thematic Mapper (TM) and the Systeme Pour l'Observation de la Terre (SPOT) High-Resolution Visible (HRV) sensors. For a single site, both Landsat and SPOT have repeat coverage of the same target at the same viewing angle every 16 or 26 days, respectively. Furthermore, the orbits of the SPOT-2 satellites were offset to allow more frequent repeat coverage by one of the two sensors. In addition, the SPOT-2 and SPOT-3 HRV sensors are pointable to $\pm 27°$ from nadir along a plane perpendicular to their orbits, thus allowing even more frequent coverage of a specified site than is possible with a

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Table 1. Nominal Spectral Wavelength Bands for the SPOT-2 HRV and Landsat-5 TM Sensors

Spectral Bands	*Center Wavelength (μm)*	*Bandwidth (μm)*
TM1	0.486	0.066
XS1	0.544	0.082
TM2	0.570	0.081
XS2	0.638	0.045
TM3	0.660	0.067
XS3	0.816	0.090
TM4	0.840	0.128
TM5	1.676	0.216
TM7	2.223	0.252

nadir-looking sensor such as TM. By combining the coverage of these three satellites, it is possible to obtain near-daily coverage of a single site at midlatitudes.

The advantage of multisensor applications is not limited to increased temporal coverage. Consider the combined radiometric attributes of TM and HRV sensors (Table 1). First, the TM sensor provides information from the short-wave infrared bands (TM5 and TM7) that cannot be obtained with the HRV sensor. Though those wavelengths are not addressed in the analysis presented here, they are nonetheless important for environmental mapping and monitoring applications. Second, there is some evidence that the subtle difference in the visible and near-infrared (NIR) wavelength bands of the TM and HRV sensors (TM2–TM4 and XS1–XS3) may provide additional information about soil and plant conditions. Guyot and Gu (1992) reported that the combination of the spectral information given by the TM and HRV sensors could be used to improve the discrimination of some targets such as bare soil and soil with low vegetation density. In another study, Gallo and Daughtry (1987) found that the variability of the simple ratio (SR) vegetation index derived from TM and HRV spectral bands increased midway through canopy development (at the time of maximum amounts of green plant matter). On the other hand, they found that the variability in the normalized difference vegetation index (NDVI) was nearly constant for most of the growing season, thus indicating that the NDVI computed by these two sensors was interchangeable for monitoring agronomic changes. These findings, based on simulated data, were supported by work with near-simultaneous TM and HRV images by Hill and Aifadopoulou (1990) and discussed in perspective by Hill (1990). Other advantages of multisensor approaches include increased information obtained by 1) combining nadir and off-nadir views (Qi et al., 1995 and 2) combining fine and coarse resolution (Price, 1987; Moran, 1989).

The disadvantage of multisensor approaches is the sensitivity of these approaches to the absolute radiance calibration of the sensors. In order to combine different sensor outputs in a single analysis, it is necessary to convert sensor output (termed digital count, DC) to values of radiance (L_i) for spectral band i (W m^{-2} sr^{-1}), and in most cases, it is further desirable to correct at-satellite radiance values for effects of illumination and atmospheric path phenomena by computing surface spectral reflectance (ρ_{si}). These radiometric corrections are required in order to isolate the signal from each sensor that is due primarily to changes in surface properties, but they do not account for differences in the spectral wavelength bands of each sensors.

Yet still there are some unanswered questions about the accuracy of calibrations of the TM and HRV sensors, and our ability to retrieve surface reflectance factors from sensor DC. For example:

- Are the published calibration coefficients for the TM and HRV sensors (derived primarily from measurements of high-reflectance sites) applicable to low-reflectance targets such as irrigated agriculture?
- Are the calibration coefficients derived from "raw" DCs applicable to "radiometrically corrected" DCs?
- Has the new processing format of EOSAT Corporation (begun 1 October 1991) affected our ability to use calibration coefficients derived from TM data processed in the old format?
- In validation of reflectance factor retrieval from oblique-viewing SPOT scenes, how do ground-based measurements of surface reflectance compare with surface reflectance factors retrieved from the sensor?

In this article, we shall describe experiments in which we attempted to find answers to these questions regarding the TM and HRV sensors. The next sections provide the background on methods and accuracy of TM and HRV calibration and the history of reflectance factor retrieval (RFR) from TM and HRV DCs. Then, two experiments conducted at the Maricopa Agricultural Center (MAC) south of Phoenix, Arizona, will be described. In one, we obtained two HRV scenes on two consecutive days ($-09°$ and $+25°$ viewing angles) with simultaneous measurements of reflectance in the same viewing and azimuth angles using ground-based and low-altitude airborne instruments. In another experiment, we obtained a TM and HRV scene on the same day with both sensors viewing near-nadir ($\pm 5°$) and simultaneous measurements of ground reflectance with nadir-looking sensors. For both experiments, measurements of atmospheric conditions were made during each overpass. These data sets were designed to build on results from previous experiments at MAC to evaluate our ability to retrieve visible and near-infrared reflectance factors from TM and HRV sensors. Results from these experiments will be evaluated in light of the questions identified above.

BACKGROUND

The background for this work is provided in three sections addressing 1) absolute radiometric calibration of the TM and HRV sensors, 2) results of RFR from TM data, and 3) results of RFR from HRV data.

Absolute Radiometric Calibration of TM and SPOT

Radiometric calibrations of the TM and HRV sensors have been conducted pre- and in-flight. A history of calibration results over time for both sensors shows a trend of decreasing responsivity with time, with the trend more apparent in the shorter wavelength bands (Dinguirard and Henry, 1995; Gellman et al., 1993; Thome et al., 1993). For both sensors, there was a sharp decrease in responsivity shortly after launch and then a period during which the calibration remained relatively stable.

In-flight calibrations are typically reported with an accuracy level of ~6% (Dinguirard and Henry, 1995; Slater et al., 1987). They are generally conducted at high-reflectance sites, such as White Sands Missile Range (WSMR), New Mexico; Edwards Air Force Base (EAFB), California; and La Crau, France, where reflectance values generally exceed 0.1 for visible and NIR wavelengths. The published SPOT HRV calibrations include some results from lower-reflectance targets, but these results are weighted with large uncertainties, thus giving emphasis to the high-reflectance calibration results (Dinguirard and Henry, 1995). Such in-flight calibrations conducted at uniform sites with high-reflectance are useful for determining an absolute radiometric calibration gain and monitoring the sensor degradation with time. However, such studies are less useful for determining the calibration offset, which is critical for the retrieval of surface reflectance factors for dark targets. In fact, based on preflight tests and subsequent in-flight calibrations for predominantly high-reflectance targets, the HRV calibration coefficient is assumed to have a zero offset. For the TM sensor, the offset is measured in-flight with every scan line and reported in the data header.

The history of the TM calibration has become complicated with the implementation of new processing software on 1 October 1991 by Earth Observation SATellite (EOSAT) Corporation. The old software [TM Image Processing System (TIPS)] resulted in three formats: Level-A Unity R-LUT ("raw," with no destriping, radiometric, or geometric corrections), Level-A R-LUT [data were adjusted for detector differences using histogram equalization (destriping) and radiometrically corrected based on the internal calibrator], and Level-P (destriping, radiometric, and geometric corrections were applied). The new software also produces two formats: Level-0 ("raw") and Level-1 ("radiometrically and geometrically corrected"). Since there is very little information published on the new format, there is some question as to whether the calibration coefficients computed for Level-0 can be compared with the historical calibration results for Level-A Unity R-LUT (similarly for Level-1 and Level-P). This leaves one with the following dilemmas:

Level-A: Prior to 1 October 1991, there were several in-flight calibrations performed for TM Level-A Unity R-LUT data (see summaries by Slater et al., 1986; Thome et al., 1993). Though these in-flight calibrations were all conducted for the high-reflectance targets at WSMR and EAFB, results were confirmed for low-reflectance agricultural targets at MAC (Holm et al., 1989). Since 1 October 1991, the results from only one TM calibration at WSMR have been published by Thome et al. (1993). They reported a large difference (close to 20% for TM2) between the calibration coefficients computed shortly after launch from Level-A Unity R-LUT data and a more recent calibration using Level-0 data. They suggested that this difference could be attributed to a change in the foreoptics of the system.

Level-P: Prior to 1 October 1991, there was only one published calibration for TM Level-P TIPS data, based on the preflight calibration of the TM internal calibrator (Markham and Barker, 1986). These data were radiometrically adjusted to a constant radiometric scale during ground processing on the assumption that the internal calibrator was constant in flight. Thus, these calibration coefficients are appropriate for application to Level-A (not Unity R-LUT) and Level-P data generated with the TIPS system. Since 1 October 1991 and the change in the EOSAT processing format [Enhanced Image Processing System (EIPS)], there have been no published in-flight calibration results for TM Level-1 data. However, the calibration coefficients for each Level-1 scene, based on the internal calibrator, are available in the data header from EOSAT. It should be emphasized that it is inappropriate to apply the coefficients published by Markham and Barker (1986) to the Level-1 EIPS data, and it is inappropriate to apply the more-recently published values for the Level-0 EIPS data by Thome et al. (1993) to either the Level-1 EIPS or Level-P TIPS data.

In any case, the postlaunch calibration coefficients obtained at high-reflectance sites for the TM and HRV sensors need to be tested for low-reflectance targets.

This is particularly true for the TM sensor due to the recent change in processing format. The most common method for testing the calibration coefficient of orbiting sensors is to use the sensor calibration coefficients along with measurements of atmospheric characteristics and a radiative transfer program to retrieve surface reflectance factors for a variety of targets. These retrieved reflectance factors can then be compared with careful measurements of surface reflectance using ground-based and low-altitude, aircraft-mounted radiometers over the same target. Unfortunately, differences between the reflectance retrieved from satellite and that measured at the surface can be due to factors other than sensor calibration (Pinter et al., 1990), particularly:

1. Inadequate characterization of inputs to the atmospheric corrections algorithm.
2. Systematic error in surface reflectance measurements.

Nonetheless, results from such studies can provide an insight into the accuracy of the sensor calibration and the accuracy of reflectance factor retrieval methods for low- and high-reflectance targets.

RFR from Landsat TM

Results of reflectance factor retrieval from Landsat TM data have been very promising. Holm et al. (1989) compared ground reflectances measured for several fields of crops and bare soils at MAC with reflectance factors retrieved from four Landsat-5 TM Level-A scenes acquired over a 12-month period during 1984 and 1985. Using calibration coefficients provided by Barker (1986), they found that the root mean square (RMS) differences between ground- and satellite-based reflectance factors were ±0.006, ±0.006, ±0.010, and ±0.009 for TM1–TM4, respectively, and ±0.008 for all bands combined (Fig. 1). In a similar study at MAC with seven TM Level-A scenes acquired during the same 12-month period, Moran et al. (1992) computed an RMS error of ±0.012 reflectance for all targets and bands. Furthermore, they showed that reasonable accuracy could be achieved (RMSE ± 0.02) based on simulated atmospheres rather than on-site atmospheric measurements. All of these results were obtained for targets with reflectances ranging from 0.02 to 0.21 in the TM1–TM3 spectral bands and 0.22 to 0.60 in TM4 spectral band.

More recently, Markham et al. (1992) and Wrigley et al. (1992) reported similar accuracy levels for reflectance factor retrieval from TM Level-P scenes acquired in 1987 and 1989 during the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE). The target was predominately prairie grassland with reflectance factors ranging from 0.06 in the visible to 0.3 in the NIR spectrum. Using the calibration coefficients provided by Markham and Barker (1986), Markham et al. (1992) reported RMS errors of 0.007 reflectance in the visible wavelengths and 0.015 in the NIR for the 1989 scene. Wrigley et al. (1992) tested a simplified atmospheric correction model for the FIFE 1987 and 1989 TM Level-P scenes and reported RMS errors of 0.005–0.010 for TM1–TM3 and 0.02 for TM4 spectral bands.

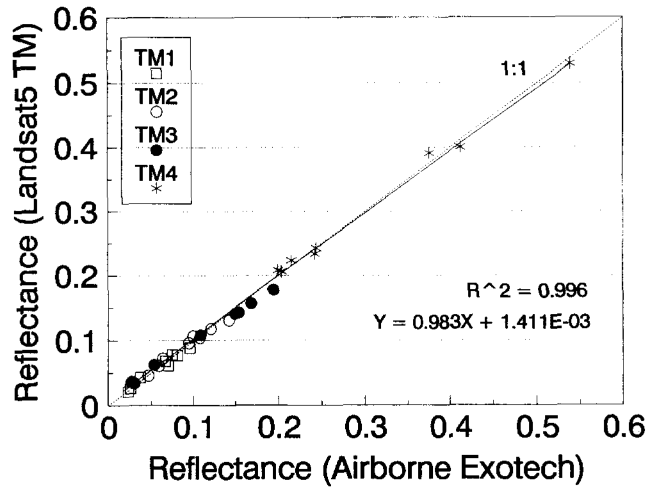


Figure 1. Comparison of Landsat TM reflectance factors with low-altitude aircraft-based radiometer measurements (from Holm et al., 1989), where each symbol represents a measurement over soil or vegetation in each of four spectral bands (TM1–TM4).

Hill and Sturm (1991) tested the accuracy of an image-based atmospheric correction procedure for reflectance factor retrieval from several TM scenes acquired in Italy. Though it appeared they were using data processed similarly to Level-P data, they applied the calibration coefficients of Slater et al. (1987) for Level-A data. They found that the RMS error of retrieved TM reflectance factors (compared with ground measurements for several targets) was 0.016 reflectance. They conducted the same comparison using the prelaunch calibration coefficients, and the RMSE increased significantly, from 0.016 to 0.042 reflectance. Thus, they concluded that the accuracy could be limited more by uncertainties in the TM calibration than the correction method.

Information regarding the calibration offset coefficient can be obtained by looking at the results for targets with very low reflectance, such as vegetation in the visible wavelengths (TM1–TM3). All of the above-mentioned studies reported low RMS errors for TM1–TM3 (of order 0.01 reflectance) for prairie and agricultural targets. Based on these experimental results, one could conclude that the prelaunch estimate of the absolute radiance offset was accurate and has not changed appreciably through 1990.

RFR from SPOT HRV

Validation of RFR from SPOT HRV sensors is more difficult than from TM if the off-nadir views are considered. The accuracy of the validation depends critically

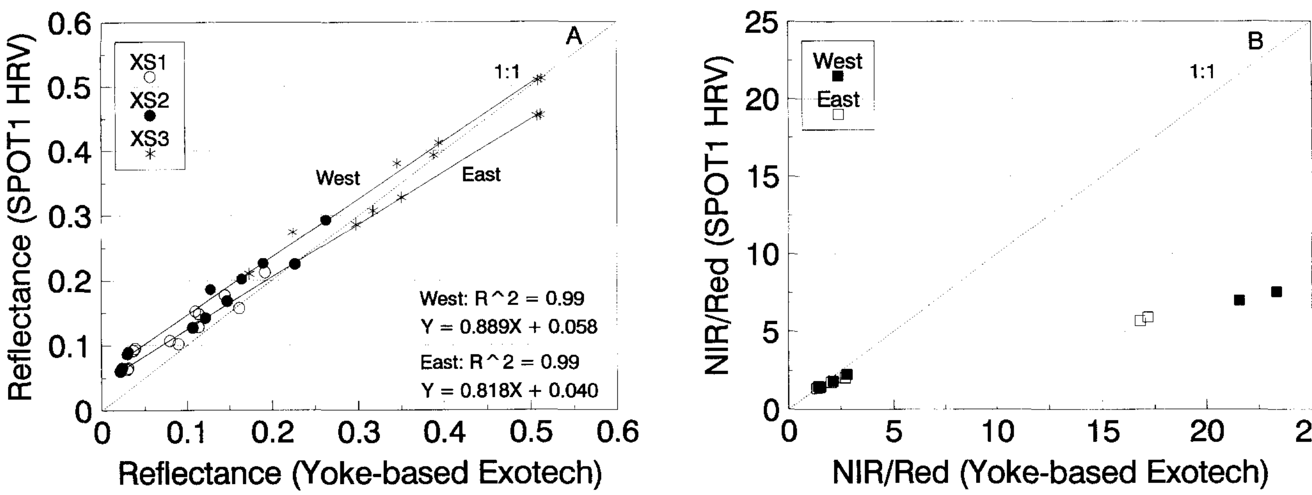


Figure 2. Comparison of SPOT HRV a) reflectance factors and b) simple ratio (NIR / red reflectance) with yoke-based radiometer measurements at oblique view angles (from Pinter et al., 1990), where "west" and "east" designate data with the sensor configuration looking from the west and east, respectively.

on the accuracy of ground bidirectional reflectance factor measurements. For in-flight radiometric calibration studies, targets are selected that have high, uniform reflectance and a near-lambertian scattering characteristics. With these characteristics, the errors associated with the bidirectional reflectance distribution function (BRDF) are minimized. Gu et al. (1992) evaluated the error associated with BRDF effects and concluded that, at the calibration site in La Crau, reflectance measurements could vary by $\pm 10\%$ over a range of viewing angles from 0° to 30°. However, for validation of RFR, the targets are often characterized by low reflectance and extreme nonlambertian scattering (Jackson et al., 1990). Furthermore, since these effects vary with the surface roughness, solar zenith angle, and spectral wavelength band, they must be accounted for during each overpass.

Moran et al. (1990) retrieved reflectance factors from 6 SPOT-1 HRV scenes for bare soil fields at MAC in 1987, 1988, and 1989 with view zenith angles of approximately $\pm 10° - \pm 23°$. They accounted for the BRDF of the soil surface by computing a "view-angle correction" (C_v) based on measurements of the bidirectional radiance along the viewing plane of the HRV and using C_v to convert nadir measurements of surface reflectance (based on ground- and aircraft-based sensors) to off-nadir values for comparison with SPOT HRV data. Their results indicated that the satellite-based reflectance factors were uniformly higher than the ground-based measurement in the visible bands (XS1–XS2) for low-reflectance targets (0.1–0.2 reflectance). Pinter et al. (1990) reported similar results comparing reflectance factors retrieved from two HRV scenes acquired at MAC (reflectances ranging from 0.04 to 0.20 in the visible wavelengths) with measurements of reflectance obtained with an oblique-viewing radiometers mounted on a backpack (Fig. 2). Their results emphasized the large effect that small errors in estimation of surface reflectance have on vegetation indices, such as the simple ratio (ratio of NIR and red reflectance) (Fig. 2b).

These results, and similar findings by Hill and Aifadopoulou (1990), implied that there could be a large offset that was not accounted for in the published HRV sensor calibration. However, in each case, the ground-based measurements were questionable: Moran et al. (1990) measured reflectance using nadir-looking sensors and derived off-nadir values from bidirectional reflectance factor (BRF) measurements at one point; Pinter et al. (1990) measured off-nadir reflectance factors with a ground-based radiometer with 15° field-of-view (that is, an FOV much larger than that of the SPOT HRV sensor). Consequently, it was impossible to determine whether the bias was due to errors in sensor calibration or measurement of surface reflectance.

EXPERIMENTS

Two experiments (MAC-VI and Mini-MAC'92) were conducted as part of a series of experiments at the Maricopa Agricultural Center (MAC). MAC, owned and operated by the University of Arizona, is a 770-ha farm located about 48 km south of Phoenix, dedicated to research and demonstration of farm and crop management. Several large-scale remote sensing experiments have been conducted at MAC due to the large field size (up to 0.27 km × 1.6 km) and favorable weather conditions (Jackson, 1990).

MAC-VI 1991

In the MAC-VI Experiment, a group of scientists from the U.S. Water Conservation Laboratory, University of

Table 2. Summary of Satellite Overpasses and a Subset of the C130 Overflights (at 5300 m AGL) During the MAC-VI Experiment, September 1991

Date	*Platform*	*Sensor*	*Time*	Θ_v[a]	*Weather*
7 Sep	SPOT-2	HRV1	11:34	+25	Cloud-free
8 Sep	SPOT-2	HRV1	11:14	−09	Cloud-free
7 Sep	C-130	ASAS	11:30	Multi	Cloud-free
8 Sep	C-130	ASAS	11:15	Multi	Cloud-free

[a] Θ_v is the angle of incidence of the HRV sensor with the Earth's surface (termed view zenith angle).

Arizona Optical Science Center, University of Arizona Department of Soil and Water Science, and the French INRA and CNET-CRPE research laboratories cooperated to measure atmospheric conditions and bidirectional reflectance factors of a variety of agricultural targets using ground- and aircraft-based sensors, coinciding with the overpasses of the SPOT High Resolution Visible (HRV) sensor and the NASA Advanced Solid-State Array Spectroradiometer (ASAS). The SPOT satellite and coincident ASAS schedules are outlined in Table 2, and the deployment and configuration of all ground- and aircraft-based instrumentation are summarized below.

Yoke-based measurements: Remotely sensed measurements of surface reflectance factors were made over cotton and bare soil targets at MAC on 7 and 8 September 1991. The targets were chosen to meet two criteria: The sites were large (to minimize the adjacency effect), and each site had uniform spectral properties throughout. One target was located in a fallow field where the soil had been recently planed but not laser-leveled. The other target was located in a field of cotton with 80% cover and leaf area index of 4. Each target consisted of a grid of 20-m pixels in a 2×16 array, with the long axis perpendicular to the SPOT orbital path.

Spectral data were collected using an Exotech 4-band radiometer[1] fitted with SPOT HRV filters with a nominal field of view of 15°, suspended about 1 m away from the operator using a backpack-type yoke (Jackson et al., 1987). The yoke was carried along the major axis transects of both the bare soil and cotton target areas during the SPOT overpasses, with the instruments held at a view angle approximating that of the SPOT satellite.

Boom-based measurements: A boom-based device to measure bidirectional reflectance factors (BRFs) was deployed over the bare soil target, providing measurements of surface reflectance factors from −45° to +45° from nadir in 5° increments. Two sets of measurements (forward and reverse) were averaged to minimize changes due to solar zenith angle changes. Measurement sets were scheduled to coincide with the SPOT look-angle axis during the SPOT overpass.

Low-altitude aircraft-based measurements: Aircraft-based spectral data were collected along a route designed to coincide with the time and flight paths of the NASA C130 and the SPOT satellite. Six overflights were conducted on 7 and 8 September. During the SPOT overpass, the flight line was perpendicular to the orbital path of SPOT and the sensors were oriented at two viewing angles which bracketed the SPOT HRV viewing angle within 10°. The aircraft was flown at a nominal altitude of 100 m above ground level (AGL). The airborne Exotech radiometer was fitted with HRV XS filters and 15° FOV lenses.

ASAS measurements: The ASAS sensor is a pushbroom configuration with 29 spectral bands covering a range of wavelengths from 465 nm to 871 nm, with a nominal 15-nm bandwidth (Irons et al., 1991). The sensor can be tilted either forward or backward to allow the sensor to scan the same target from +45° to −45°, with 15° increments. The ground resolution is about 5.5 m×2.3 m when measured from an altitude of 5300 m looking in the nadir direction. The C130 flight line was designed to cover the same bare soil and cotton fields in which the yoke-based instrumentation was deployed. Thus, it was possible to obtain ASAS measurements simultaneously with the yoke-, boom-, and aircraft-based Exotech measurements for the two targets.

Atmospheric measurements: Atmospheric effects on the days of overpasses were characterized by Langley plot measurements to determine total spectral optical depths (Table 3). For the atmospheric correction of the TM and HRV data, total optical depth was partitioned into Mie, Rayleigh, and ozone optical depths with an estimated uncertainty of less than 10% (Biggar et al., 1990). Gaseous transmittance was estimated using the 5S radiative transfer code (Tanré et al., 1990). Columnar water vapor was measured and the 5S code was used to compute sun-to-ground-to-satellite transmittance for correction of at-satellite radiance values for water vapor absorption. Values of optical depth were used as inputs to a radiative transfer model (RTM) (Herman and Browning, 1965; Rahman and Dedieu, 1995) to compute at-satellite radiance (L_i) for several assumed values of surface reflectances (ρ_{si}). The relation between L_i and ρ_{si} over the range of reflectance values 0.0–0.7 allows for linear interpolation with negligible error (Slater and Jackson, 1982). The same approach was used for atmospheric correction of the ASAS data, taking into account the spectral response functions of the ASAS detectors and the lower flight altitude.

Mini-MAC 1992

On 26 July 1992, both Landsat-5 and SPOT-2 passed over MAC with the TM and HRV sensors configured for near-nadir viewing (Table 4). This provided the

[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product or company by the U.S. Department of Agriculture, University of Arizona, LERTS, or NASA.

Table 3. Atmospheric Optical Depth and Transmittance Values in the SPOT-2 HRV Spectral Wavelength Bands Estimated for Times and Dates of SPOT Overpasses on 7 and 8 September 1991 and 26 July 1992

		TM1			TM2			TM3		
DOY	Time	Mie[a]	Ray[a]	Gas[a]	Mie[a]	Ray[a]	Gas[a]	Mie[a]	Ray[a]	Gas[a]
7 Sep 91	11:34	.105	.075	.953	.099	.057	.947	.095	.047	.951
8 Sep 91	11:14	.078	.075	.957	.074	.057	.954	.070	.047	.967
26 Jul 92	11:24	.115	.104	.960	.105	.051	.951	.093	.018	.944

[a] Mie, Ray, and Gas are Mie and Rayleigh optical depth and gaseous transmittance values, respectively.

opportunity to compare RFR from both sensors with little change in atmospheric and surface conditions and sun / sensor / target geometry. It was also an opportunity to avoid the above-mentioned problems associated with validating RFR with an oblique viewing angle. Unlike all previous experiments at MAC, we obtained TM data in the new Level-0 and Level-1 formats.

Similar to the MAC-VI experiment, a target was delimited in a bare soil field covering a uniform area of 4×8 20-m pixels. During both the Landsat and SPOT overpasses, yoke-based Exotech radiometers with the appropriate filters (either TM or HRV) were deployed to measure surface reflectance. An aircraft-based Exotech radiometer was used to measure reflectance over a larger area covering fields of full-cover cotton and alfalfa, wheat stubble, bare soil, and a partial-cover pecan field. As in the MAC-VI experiment, the flight altitude was 100 m AGL to avoid atmospheric effects on reflectance measurements. The flights were designed to trace the flight path and immediately retrace it in reverse order, bracketing the time of the satellite overpass. Thus, measurements over the same field could be averaged to provide an estimate of surface reflectance at the exact time of the Landsat or SPOT overpass. The sky was completely cloud-free from about 9:00 a.m. until well after the last measurements were made. Atmospheric measurements were made in the same way described for the MAC-VI experiment, and the Herman-Browning RTM was used to compute the relation between L_i and ρ_{si} for the TM and HRV sensors.

RESULTS

Comparison of BRF Measured with Yoke- and Aircraft-Based Sensors

In the MAC-VI Experiment, it was necessary to measure the surface reflectance at oblique angles for comparison with the off-nadir data acquired by the SPOT HRV sensors. These measurements were made in three ways:

1. Yoke-based Exotech held at a look angle approximating that of the HRV sensor.
2. Airborne Exotech oriented at two view angles (10° increment) bracketing the view angle of the HRV sensor.
3. Airborne Exotech oriented for nadir viewing, corrected using boom-based BRF measurements to estimate the reflectance at the angle of the HRV sensor.

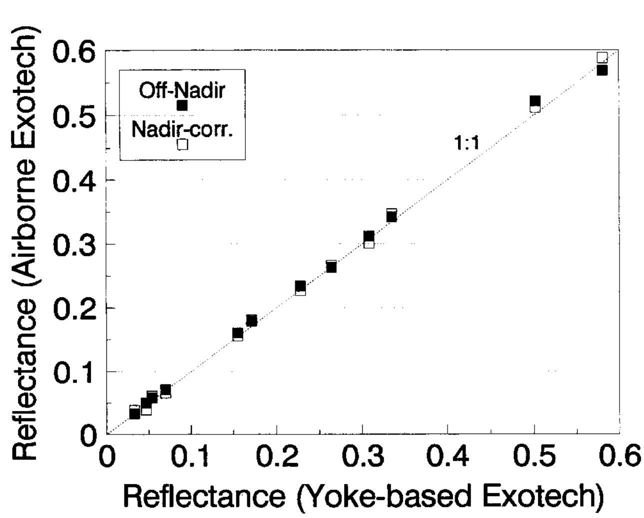
For method 2, the value of reflectance for the viewing angle of the HRV sensor was estimated from the measurements made by the airborne Exotech radiometer from two viewing angles using a linear interpolation. For method 3, nadir-view reflectance measured by the airborne Exotech was multiplied by the ratio of the boom-based measurement of reflectance at the HRV look-angle and reflectance at nadir. A comparison of the

Table 4. Summary of Satellite Overpasses and Low-Altitude Cessna Overflights (at 100 m AGL) during the Mini-MAC Experiment, 26 July 1992

Platform	Sensor	Time	Θ_v[a]
SPOT-2	HRV1	11:24	3.3
Landsat-5	TM	10:26	5.4
Cessna	Exotech	10:26	0.0
Cessna	Exotech	11:24	0.0

[a] Θ_v is the angle of incidence of the HRV sensor with the Earth's surface.

Figure 3. Comparison of yoke-based measurements of reflectance at a look angle approximating that of the HRV sensor with a) aircraft-based measurements with the sensor oriented at the view angle of the HRV sensor and b) aircraft-based measurements with sensor oriented for nadir viewing, corrected using boom-based BRF measurements to estimate the reflectance at the angle of the HRV sensor (Table 2). The 12 data points are measurements from two days, two targets (bare soil and vegetation), and three spectral bands.



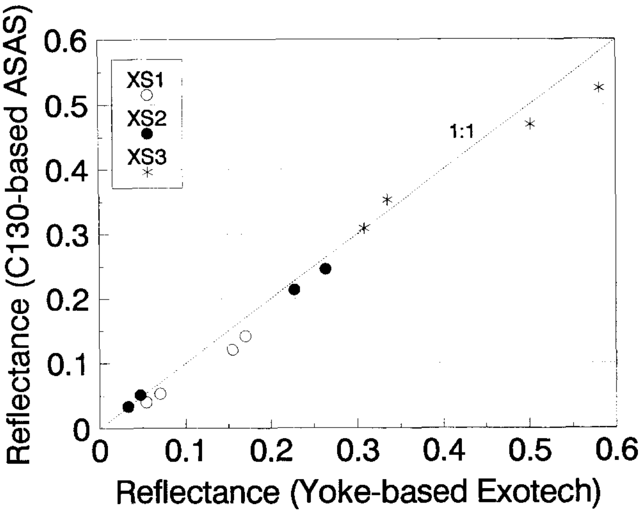


Figure 4. Comparison of reflectances retrieved from ASAS digital counts (integrated over the spectral response of the HRV sensor) with yoke-based measurements with sensors in the same orientation as the HRV sensors (listed in Table 2). The 12 data points are measurements from two days, two targets (bare soil and vegetation), and three spectral bands (HRV XS1–XS3).

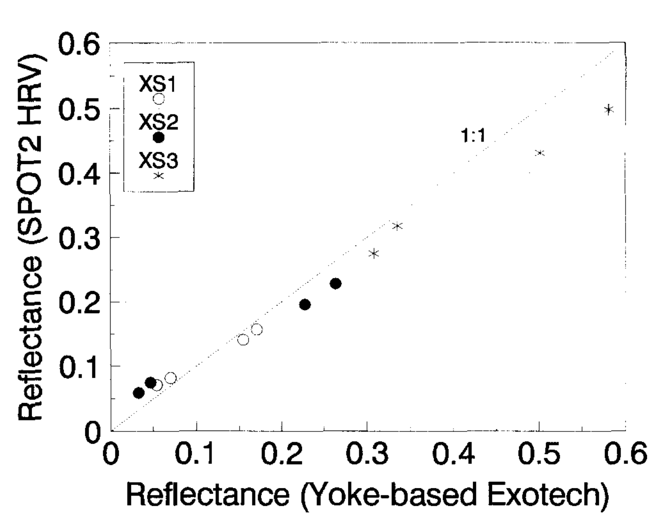


Figure 5. Comparison of reflectances retrieved from SPOT HRV digital counts with yoke-based measurements with the same viewing orientation (Table 2). The 12 data points are measurements from two days, two targets (bare soil and vegetation), and three spectral bands (HRV XS1–XS3).

results shows that the three measurements are similar for all wavelengths and for the two sites (Fig. 3).

In the mini-MAC experiment, nadir-looking ground- and aircraft-based data were acquired over a bare soil site. Data from the two overflights of the aircraft bracketing the time of the Landsat and SPOT overpasses were registered to ground control points in each field. Then, the aircraft-based pixels corresponding with the yoke-based target were extracted and averaged to provide a single measurement of reflectance for the target. The yoke-based data were also averaged to a single measurement, thus providing a comparison between the aircraft- and yoke-based measurements for four bands of two times of day. The differences between yoke- and aircraft-based reflectance measurements were less than 0.005 reflectance in all spectral bands.

To compare the reflectances retrieved from the ASAS data with yoke-based measurements, data from the 29 ASAS spectral bands were corrected for atmospheric effects and integrated over the spectral response of the HRV sensor to estimate the radiance (and reflectance) measured by the HRV sensor. Then, using linear interpolation, values of reflectance were estimated from the ASAS data for the viewing angles the HRV sensor on DOYs 250 and 251. These reflectance factors were compared with yoke-based measurements with the same viewing configuration (Fig. 4). The RMS errors for XS1, XS2, and XS3 for all data combined (two days and two targets) were 0.025, 0.012, and 0.033, respectively.

Results of RFR from SPOT HRV at Oblique Viewing Angles

Using the MAC-VI data set, windows of SPOT HRV data were extracted from the images to coincide with the location of the designated targets in the bare soil and cotton. The DCs were converted to reflectance factors using the calibration coefficients provided by Dinguirard and Henry (1995), the on-site atmospheric measurements, and the SMAC (simplified method for atmospheric correction) radiative transfer code (Rahman and Dedieu, 1995). These were compared with the yoke-based measurements for the same target (Fig. 5). Reflectance factors retrieved from the HRV data were slightly higher than the yoke-based measurements for low reflectance targets and slightly lower for XS3 in the cotton. This trend coincides with results from previous studies at MAC (Fig. 2). The RMS errors for XS1, XS2, and XS3 for all data combined (two days and two targets) were 0.015, 0.031, and 0.057, respectively.

Results of RFR from SPOT HRV and Landsat TM at Nadir Viewing Angles

Using the Mini-MAC'92 data set, aircraft-based measurements of surface reflectance were extracted for bare soil, cotton, and pecans targets. Similarly, HRV and TM DCs corresponding to these same targets were extracted and converted to surface reflectance. RFR was accomplished for both sensors based on the on-site atmospheric measurements and the Herman–Browning radiative transfer code. For the HRV data, the radiance calibration coefficients were provided by Dinguirard and Henry (1995). For the TM data, the radiance calibration coefficients for the Level-0 data were provided from a recent White Sands calibration (Thome et al., 1993). Calibration coefficients for the Level-1 data were provided from unpublished results of a White Sands calibration (K. J. Thome, personal communication). The

Table 5. Summary of Calibration Coefficients for SPOT-2 HRV1 and Landsat-5 TM Used in the Processing of the Mini-MAC'92 Images (26 July 1992)[a]

Source	TM2 or XS1 Slope	TM2 or XS1 Offset	TM3 or XS2 Slope	TM3 or XS2 Offset	TM4 or XS3 Slope	TM4 or XS3 Offset
Landsat-5 TM						
Markham and Barker (1986) (pre-launch 1984)	1.175	−2.8	0.806	−1.2	0.815	−1.5
Thome et al. (1993) (Level-0, August 1992 at WSMR)	1.517	−1.8[b]	1.111	−2.05[b]	0.940	−1.5[b]
K. Thome, personal communication (Level-1, August 1992, WSMR)	1.542	−1.8[c]	1.121	−2.05[c]	0.949	−1.5[c]
Level-1 Tape Header File (26 July 1992, MAC)	1.258	−1.8	0.966	−2.05	0.912	−1.5
Inversion from Mini-MAC'92 data (Fig. 9), Level-1 processing	1.85	−16.3	1.38	−15.5	1.13	−9.1
SPOT-2 HRV1						
Dinguirard and Henry (1995) (postlaunch 1988)	0.990[d]	0.0[e]	0.946	0.0	0.870	0.0
Dinguirard and Henry (1995) (July 1992)	0.910	0.0	0.796	0.0	0.740	0.0
Inversion from Mini-MAC'92 data (Fig. 9)	2.88	−8.85	3.53	−8.64	1.78	−14.2

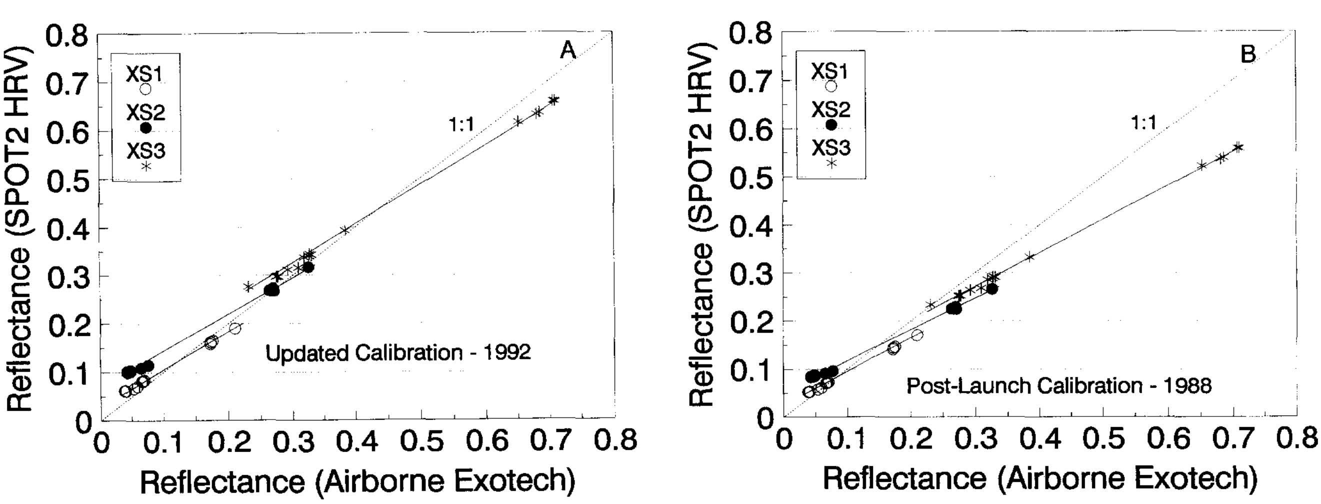
[a] Units of slope are {W m^{-2} sr^{-1} μm^{-1}} / DC, the offset is in units of digital counts (unitless), and radiance (L) can be computed from these coefficients: L = (DC + offset)*slope.
[b] Offset information was unavailable for Level-0 data. Offsets obtained from the Level-1 image header on the same date were assumed to be appropriate and used in this calculation.
[c] Offset taken from measurement of on-board internal calibrator, listed in the Level-1 image header on the tape from EOSAT Corp.
[d] Calibration factors for the SPOT-HRV sensors are generally published for a standard sensor gain of 3; the values listed here have been adjusted for the sensor gain at the time of data acquisition (26 July 1992).
[e] According to prelaunch calibrations, the HRV sensor has a nominal zero offset.

coefficients used for this data set are listed in Table 5. Also, listed are the coefficients for the same sensor based on pre-1991 calibrations and those extracted from the TM Level-1 tape header. These values were included to illustrate the differences in RFR associated with outdated calibration coefficients and the new processing procedures of TM imagery.

The results of RFR from the HRV data with near-nadir configuration look similar to those obtained in previous studies (Fig. 6a). That is, the NIR reflectance was slightly underestimated for high-reflectance targets and the visible reflectance was slightly overestimated for low-reflectance targets. This supported previous studies at MAC (Pinter et al., 1990; Moran et al., 1990). Results with the outdated calibration coefficient from 1988 illustrated the effect of detector deterioration on reflectance factor retrieval (Fig. 6b). In all cases, the satellite-based reflectance factors were lower than those computed with the 1992 calibration coefficients.

The results of RFR from the Level-0 TM data (using calibration factors from Thome et al., 1993) differed from those previously reported for MAC and other sites (Fig. 7). The reflectance factors computed for the low-reflectance sites were substantially higher than the air-

Figure 6. Comparison of reflectances retrieved from SPOT HRV digital counts with aircraft-based Exotech measurements with both sensors in a nadir-viewing configuration, using a) calibration factors from July 1992 and b) calibration factors from immediately after launch 1988 (Table 5). The data points represent measurements from several targets within fields of bare soil, cotton, and pecan trees.



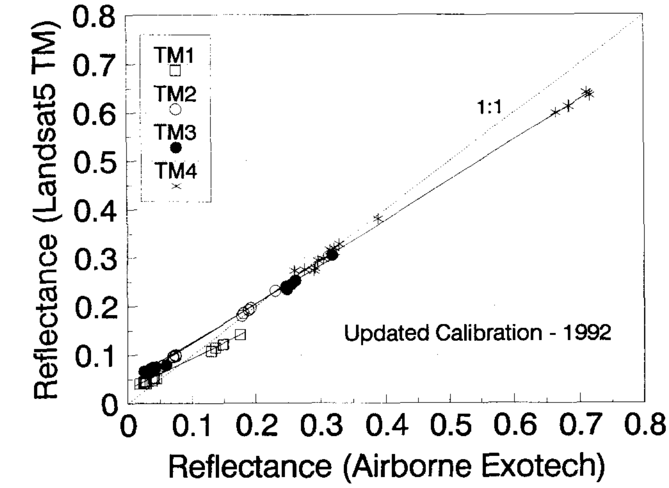


Figure 7. Comparison of reflectances retrieved from Landsat TM Level-0 digital counts with aircraft-based Exotech measurements with both sensors in a nadir-viewing configuration, using calibration factors obtained in August 1992 at WSMR (Table 5). The data points represent measurements from several targets within fields of bare soil, cotton, and pecan trees.

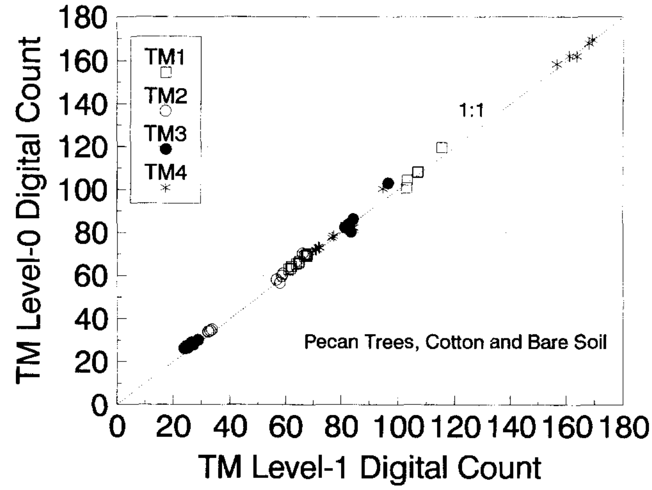


Figure 8. Comparison of Landsat TM digital counts from the 26 July images acquired at MAC and processed with the new EOSAT Level-0 and Level-1 procedures. The data points represent DCs from several locations in a pecan grove, a cotton field, and a fallow field.

craft-based measurements. The overall trend was very similar to the results obtained for the RFR from HRV data for the same day. The results presented in Figure 1 for RFR from TM data in 1985 and 1986 (Holm et al., 1989) showed better agreement for the low- and high-reflectance targets than we found with this data set. However, it should be noted that Holm et al. (1989) included more results from a larger data set that showed a bias toward overestimating reflectance of low-reflectance targets and underestimating reflectance of high-reflectance targets (their Fig. 4), similar to the results presented here. So, though the results were disappointing, they were not unprecedented.

All of the TM data presented up to this point in this analysis were extracted from the TM Level-0 image. In order to address the question of the difference between TM Level-0 and Level-1 DCs, we extracted data from the Level-0 and Level-1 images corresponding to the same ground targets (pecans, cotton, and bare soil). The differences in DC between the two processed images were generally less than 1 DC (Fig. 8). The magnitude of the differences between the two data sets was within the expected error associated with geometric correction resampling and slight misregistration of the image extractions.

It is evident from the similarity between the calibration coefficients obtained at White Sands for Level-0 and Level-1 data (Table 5) and from the similarity between Level-0 and Level-1 data extracted from the MAC scenes (Fig. 8), that the RFR results for Level-1 would be comparable to those for Level-0 data. However, it should be emphasized that the difference between Level-0 and Level-1 data would increase with the nonuniformity of the site because the resampling procedure in the geometric correction affects the radiometry of the image.

DISCUSSION

The question still remains: Are the differences between surface reflectance and satellite-based reflectance due to errors in the atmospheric correction, the measurement of surface reflectance, or the sensor calibration? Based on the good correlation between surface reflectances measured by different methods with different sensors, it appears that the measurement of surface reflectance with yoke- and aircraft-based radiometers is fairly accurate and well within the errors associated with RFR (error $\ll$ 0.1 reflectance). Thus, it is reasonable to focus our attention on effects of atmospheric correction and sensor calibration. This can be accomplished using the Mini-MAC'92 data for which both sensors had similar viewing geometry on the same day for the same targets.

First, we can investigate the error in calibration by assuming that the measurements of surface reflectance and the atmospheric correction were without error. With this assumption, it is possible to back out the calibration coefficients that would be necessary to result in near-zero error in RFR (Fig. 9). For the TM sensor, the following calibration equations would result:

$$\begin{aligned} \text{TM1:}\ L_i &= (\text{DC} - 49.9)1.17, \\ \text{TM2:}\ L_i &= (\text{DC} - 16.3)1.85, \\ \text{TM3:}\ L_i &= (\text{DC} - 15.5)1.38, \\ \text{TM4:}\ L_i &= (\text{DC} - 9.1)1.13, \end{aligned} \qquad (1)$$

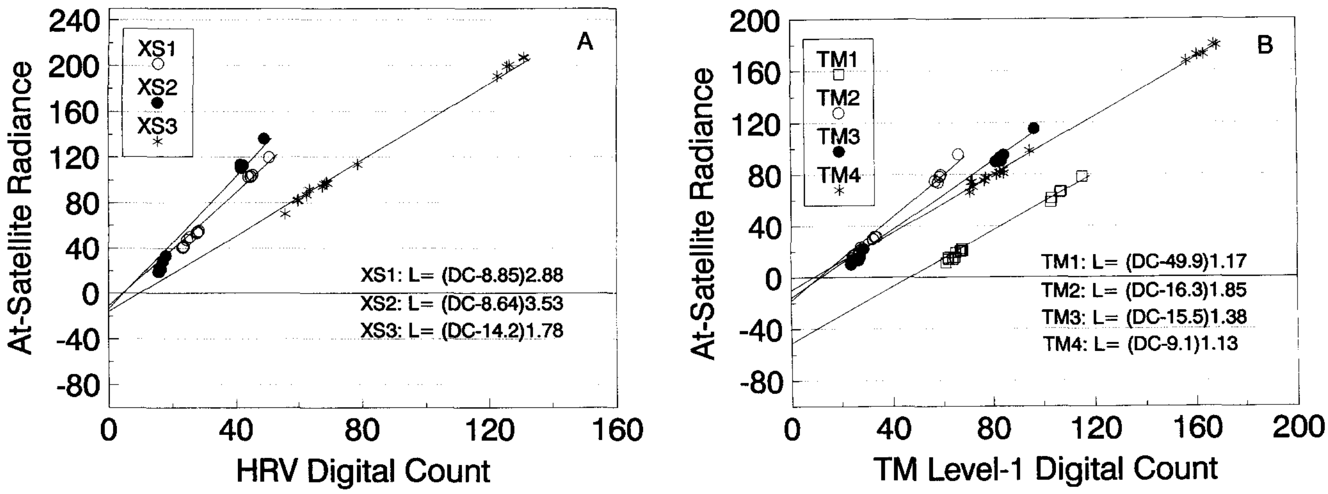


Figure 9. SPOT HRV and Landsat TM calibration coefficients back-calculated from the measurements made at MAC during the Mini-MAC'92 Experiment. At-satellite radiance is presented in units of $Wm^{-2}\ sr^{-1}\ \mu m^{-1}$. The data points represent measurements from several targets within fields of bare soil, cotton, and pecan trees.

where L_i is in units of $W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$. For the HRV sensor, the calibration equations would be

$$\begin{aligned} \text{XS1: } L_i &= (\text{DC} - 8.85)2.88, \\ \text{XS2: } L_i &= (\text{DC} - 8.64)3.53, \\ \text{XS3: } L_i &= (\text{DC} - 14.2)1.78, \end{aligned} \qquad (2)$$

where HRV DC has been corrected to a gain of 3 for comparison with previously published calibration coefficients. These offsets are orders of magnitude larger than the offsets published for the prelaunch calibration. Thus, it might be safe to conclude that the error in RFR is not associated solely with the calibration procedure. It is conceivable, but unlikely, that such large offsets could be the result of optical system degradation that allows stray light to be a major problem. As identified earlier in this text, the error could also be associated with the procedure used for atmospheric correction.

Next, we can consider the errors in atmospheric correction. The methods, models, and instruments used here for atmospheric correction have compared well with other such methods, models, and instruments. Bruegge et al. (1992) compared the results of measuring optical depth using several instruments at one site under controlled conditions and found that all outputs were within 0.01 (midvisible). Moran et al. (1992) compared a variety of radiative transfer codes for use in RFR and found that the 5S, Lowtran, and Herman–Browning codes produced similar results under clear-sky conditions (like those reported here) for the TM spectral bands. Furthermore, these are the instruments and methods chosen for calibration studies at high-reflectance sites such as WSMR and La Crau. Thus, one could conclude that, with the present state-of-the-art RTMs, the results presented here for RFR from TM and SPOT imagery are the best that can be expected. A modification that could improve results would be the inclusion of BRDF properties of the surface in the RTM; most RTMs assume the surface is lambertian. Though this would likely improve atmospheric correction results, it would also add a great deal of complication to the correction process since *a priori* knowledge of the surface BRDF would be required.

Finally, it is informative to compare the results of RFR from C130-based ASAS with those from the satellite-based sensors, TM and HRV. Though the ASAS data were corrected with the same RTM as the satellite-based data, the ASAS reflectances were much closer to yoke-based measurements than were the satellite-based TM or HRV data. These results support the contention that the error in RFR from the TM and HRV sensors is due at least in part to a spectral responsivity change in the satellite-based sensors. There is evidence that both the TM and HRV filters change in transmission characteristics with exposure to a vacuum. The vacuum-induced shift in the spectral response of the SPOT XS2 filter was observed to be about 12 nm, which narrowed the bandwidth and decreased the band sensitivity (M. Dinguirard, ONERA CERT DERO, personal communication). Similar results were found for the TM visible and near-IR filters with shifts in the band center wavelength of up to 7 nm (J. B. Young, Santa Barbara Research Center, personal communication). If the filters changed such that their spectral wavelength band shifted, the path radiance and atmospheric transmission determined with the atmospheric model would be wrong for the band, and the atmospheric correction would consequently be wrong. This could partially explain the results presented here.

CONCLUDING REMARKS

It is appropriate to conclude by revisiting the questions presented in the introduction. Based on the results presented here, the reflectance factors retrieved from TM and HRV sensors using published calibration factors and available RTMs could result in errors of up to 0.05 reflectance (in the visible spectrum) for very low reflectance targets and up to 0.1 reflectance (in the NIR spectrum) for very high reflectance targets. The error appeared to be due to a combination of errors associated with sensor calibration and atmospheric correction.

Regarding the different processing levels of the TM images, the mean absolute difference between Level-1 and Level-0 is 1.9 DC for all bands and all targets. There appears to be a general bias toward Level-0 data being greater than Level-1 (Fig. 8). Due either to sensor degradation or to the new processing technique, the old calibration factors are up to 20% different from the new ones (based on White Sands results and verification at MAC). Thus, the suggestion here is to use the new ones. Using similar validation methods for four TM Level-1 images at a rangeland site southeast of Tucson Arizona, we found that the slopes of the regression equations [Eq. (2)] for TM2, TM3, and TM4 were consistently higher than those published by Markham and Barker (1986) and comparable to those found by Thome et al. (1993) at WSMR (TM2: 1.421, sd 0.029; TM3: 1.135, sd 0.072; TM4: 0.9775, sd 0.071).

Regarding RFR from oblique-viewing SPOT scenes, there were two significant results presented. First, oblique reflectance measurements from yoke-based Exotech, Cessna-based Exotech, and C130-based ASAS compared very well (Figs. 3 and 4). Second, the trends observed in the nadir RFR and the off-nadir RFR were similar (Figs. 5 and 6). Thus, we conclude that conducting calibrations and RFR using the above-described techniques for measuring off-nadir reflectance are appropriate.

Future work should address two issues. First, a rigorous test should be conducted to test the accuracy of RTMs for atmospheric correction of satellite sensor data. Such a test could be conducted for targets of varying reflectance ranging from 0.0 to 0.6 for a single sensor spectral band. This would minimize uncertainties due to band-to-band biases that were present in the agricultural targets used in these studies. Another approach would be to look at very dark surface targets (e.g., ocean) at night to confirm or disprove the large offset values presented in Figure 9. Second, more work is needed to confirm the apparently large offsets in the TM and HRV sensors. Several causes for these apparent offsets have been offered, including optical system degradation resulting in stray light sensitivity, and a spectral responsivity change in the sensor due to exposure to vacuum conditions.

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