Radiometric Calibration of Landsat Thematic Mapper Multispectral Images

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ABSTRACT: A main problem encountered in radiometric calibration of satellite image data is correcting for atmospheric effects. Without this correction, an image digital number (DN) cannot be converted to a surface reflectance value. In this paper the accuracy of a calibration procedure, which includes a correction for atmospheric scattering, is tested.

Two simple methods, a stand-alone and an *in situ* sky radiance measurement technique, were used to derive the HAZE DN values for each of the six reflective Thematic Mapper (TM) bands. The DNs of two Landsat TM images of Phoenix, Arizona were converted to surface reflectances. The computed surface reflectance values were compared with the measured surface reflectance values collected at the same time as the Landsat overflights. The average difference between the computed and measured surface reflectance values inside two parking lots were 4.84 and 8.42 percent. For 43 percent of the individual band measurements the accuracy was within 5 percent, even though sub-DN precision was required. Also, the accuracy of the calibration procedure in a temporal sense was good.

INTRODUCTION

GEOMETRIC CALIBRATION CAPABILITIES have evolved at a faster pace than have radiometric ones. Currently, geocoded image data can be generated as a standard product. Geometric corrections due to topographic distortions can be applied on a pixel-by-pixel basis. In the near future, with use of the Global Positioning System and other developing procedures, the geometric calibration of remotely sensed multispectral image data will not be a major problem. However, research is still needed to have the same level of capability available for radiometric calibration. This need is especially true if conversion from top of the atmosphere radiance to surface reflectance is included as part of the calibration procedure, as is the case in this paper.

A digital number (DN)-to-surface calibration procedure is critical to many applications, including those dealing with signature extension (temporally and/or spatially), automatic spectral signature identification, and comparisons between sensors. Some calibration procedures now in use convert image DN values only to top-of-the-atmosphere radiance, referred to as apparent reflectance, and do not correct for atmospheric effects, which can be substantial (Price, 1987; Hall and Chang, 1988; Leprieur *et al.*, 1988). These are sensor calibrations only and not surface calibrations. The term "apparent reflectance" has been used by several authors, but be careful because it can be misleading.

A main objective of this paper is to present and use an equation which converts an image DN to a surface reflectance. A critical part of the equation is the parameter dealing with the additive component of atmospheric scattering. Two simple procedures to correct for this additive component are presented: (1) a stand-alone field independent method, and (2) a simple *in situ* sky radiance measurement technique. This paper discusses these two procedures and compares their radiometric calibration results to measured surface reflectance values.

The stand-alone method to select the atmospheric scattering or haze parameter has been published in a previous paper by the author (Chavez, 1988); however, some improvements have been made and are discussed. The results generated with the second method, which uses simple *in situ* sky radiance measurements to compute the haze correction parameter, are compared with the stand-alone method. Computed surface reflectance values from Landsat Thematic Mapper (TM) DNs are compared with the reflectance values measured in the field during the Landsat overflights.

TEST SITE AND DATA CHARACTERISTICS

SITE

The test site is in the Phoenix, Arizona area. This site was selected because of the variety of atmospheric conditions that occur throughout the year. Usually the atmosphere is clear during the spring and fall and very hazy in the winter due to inversion layers trapping pollutants. The area includes agricultural, urban, and rural environments. Two locations in northwest Phoenix were used to collect field spectral data during the two Landsat overflights–the Metro Center shopping mall and the Turf Paradise horse racing track. These two locations were chosen because they are easy to identify in Landsat TM images (see Figure 1).

The Metro Center parking lot and roof, along with the grass area in the middle of the Turf Paradise racing track, were used as test sites during the first Landsat overflight. The Metro Center parking lot had recently been paved and was dark black with bright white stripes for the parking lanes. On the roof of the shopping mall there was an approximate 60- by 60-metre, or two- by two-pixel, area painted white and very bright. This area was flat with nothing attached to it and seemed to be an ideal target for the calibration project. However, the field spectral data collected implied that it was too bright and that the Landsat TM data might saturate in some of the bands. Once the TM data were received, a quick check verified that it indeed was too bright in TM bands 1 and 3 and saturation occurred at these pixels. Also, due to the scan angle with the roof, it was difficult to tell if a single pure roof pixel was actually imaged; it appeared that the nonroof/parking lot surface could have been included in the pixel average. Consequently, the roof was not used in the analysis.

Radiance measurements of the grass area in the middle of the Turf Paradise racing track were also made on this date. However, because of the limited number of field instruments available, these spectral data were collected slightly over two hours after the first Landsat TM overflight. Not only did the atmospheric conditions change slightly but the grass was being watered on a rotating basis which affected the moisture characteristics. This site was also not used during the first Landsat TM overflight because of these problems.

During the second Landsat overflight, only the Turf Paradise location was used. The parking lot at the Metro Center shop-

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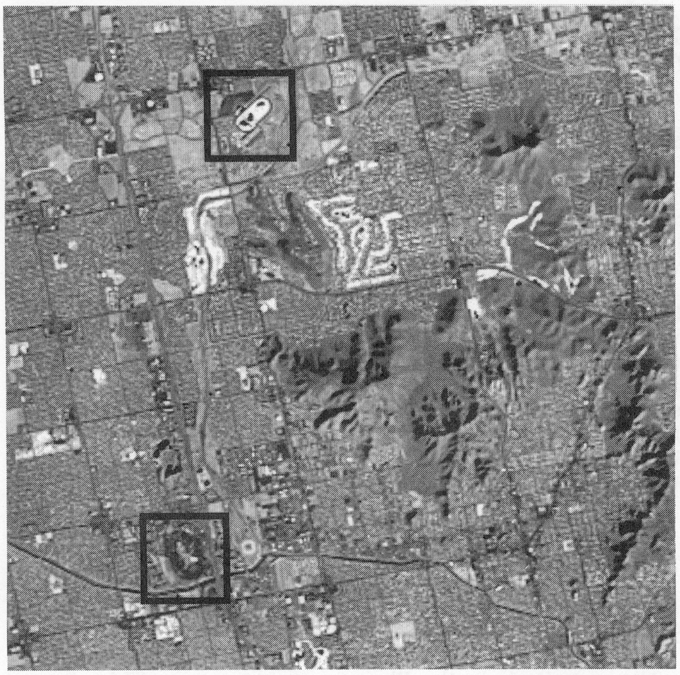

FIG. 1. This black-and-white print was made from the 22 December 1988 Landsat TM band 4 image. The subarea, which is 10.5 km per side, shows both the Turf Paradise race track and Metro Center shopping mall. The race track is inside the boxed area shown at the top center of the print. The darker area within the parking lot and the bright area between the two ponds on the right, inside the race track, were used to make the field surface reflectance measurements. All the grass areas, inside the track and nearby golf courses, are bright because TM band 4 is in the near infrared portion of the spectrum, where vegetation has a high reflectance. The Metro Center shopping mall is inside the box area in the lower left portion of the print. The dark elliptical feature is the surrounding parking lot and roads. Most of the roof is shown as midtone in this print because of its response in TM band 4; however, the few pixels which are bright towards the lower right of the roof includes the area sampled during the 3 October 1988 Landsat overflight.

ping mall was filled with Christmas shopper's cars and the roof was unusable due to the saturation and physical size problems. Field spectral data were collected during the second Landsat overflight in both the Turf Paradise grass area and parking lot. The grass was greener than during the first overflight and more moist due to watering. The Turf Paradise parking lot, not freshly paved like the Metro Center lot, was not as dark and the white stripes were faded. The field spectral data were collected in both the grass and parking lot areas during the Landsat overflight, and so the temporal differences that existed with the data from the first date did not exist with this data set.

The sampling in the field was done so that the average measured radiance values would be as representative as possible of what the Landsat TM imaging system was recording from space. It was easy to do this for the two parking lots but not the grass area. The grass area included exposed soils, a dirt road, and several palm trees; therefore, its surface was not as homogeneous as the parking lots.

FIELD SPECTRAL DATA

Two different instruments were used to collect the field spectral data during the Landsat overflights. One of the instruments was a Barnes Modular Multispectral Radiometer (MMR).* This instrument collects data in eight spectral bands; seven of these bands are similar to the TM bands (Robinson *et al.*, 1979; Jackson *et al.*, 1987; Slater *et al.*, 1987). The second instrument used was an Exotech Model 100-AX radiometer that has four bands that nearly duplicate the first four TM bands. The spectral bands of these two instruments are similar to those of the TM (Slater *et al.*, 1987).

The field spectral data were automatically recorded using the portable acquisition system discussed by Slater *et al.* (1987). The recorded radiance values were converted to reflectance values using two calibrated $BaSO_4$ (barium sulfate) panels. The panels were calibrated using the method described by Jackson *et al.* (1987). The purpose of the field spectral data was to test the accuracy of the method used to compute the surface reflectance from the DN values in the TM images. At the start and end of each sampling session the Exotech radiometer was pointed vertically toward the sky and these radiance measurements were also recorded. These sky radiance values were used, by the second method, to derive atmospheric haze parameters. The sky radiance values were converted to sky reflectance values using the $BaSO_4$ panels (same procedure used to get the measured surface reflectance values). These sky reflectance values were used to derive the equivalent haze DN values.

The areas sampled in the field ranged in size from two by two pixels for the parking lots to two by four for the grass area inside the racing track. The readings were collected as the person carrying the radiometer slowly walked a previously determined grid pattern. The grid patterns were laid out in order to uniformly sample the pixel areas. The radiometer was mounted on a backpack type apparatus that suspended it about one metre to the right side of the operator. This "yoke" system allows measurements to be made quickly, and a large area can be covered. With the 15-degree field of view, the Exotech and MMR radiometers sampled a spot size on the ground of 0.26 and 0.20 metres, respectively (this is affected slightly by the height of the person carrying the yoke). This system and procedure is covered in detail by Slater *et al.* (1987). The Landsat DN values of the measured pixels were averaged, two by two and two by four pixels, and these averages were used in all the computations. Photographs taken in the field were used to help identify the pixels in the TM images that corresponded to the areas sampled during the overflight. Also, the distances to features which were easy to identify in the TM images were measured to help identify the pixels of interest.

A total of 450 MMR readings were averaged to derive the Metro Center parking lot reflectance values and 250 Exotech readings were averaged for the Turf Paradise parking lot. The grass area at Turf Paradise was sampled with the MMR on both dates; 276 readings were collected on the first date and 264 on the second date. Readings of the $BaSo_4$ panels were made before, during, and after the surface areas were sampled. These readings were used to convert from radiance to reflectance as explained by Slater *et al.* (1987) and Jackson *et al.* (1987).

LANDSAT TM DATA

The Landsat TM data used were of the Phoenix area collected on 3 October 1988 and 22 December 1988. The DN values of the test areas in these data sets were converted to surface reflectance values. The sun elevation angles, equal to 90 degrees minus the solar zenith angles, for the October and December dates were 45.1 and 26.9 degrees, respectively. The data were in A rather

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than P format because data that have not been resampled provide better calibration; the cubic convolution resampling process can smear/mix the radiance values of neighboring pixels (Park and Schowengerdt, 1983; Slater, 1984).

DN TO REFLECTANCE CONVERSION EQUATION

The DN values recorded by a multispectral imaging system can generally be represented by the following equation:

$$\mathrm{DN}_i(X,Y) = \mathrm{GAIN}_i \cdot \mathrm{RAD}_i(X,Y) + \mathrm{OFFSET}_i \quad (1)$$

where

- $\mathrm{DN}_i(X,Y)$ is the output digital number for band i at pixel (X,Y);
- GAIN_i is the gain factor used for bank i;
- $\mathrm{RAD}_i(X,Y)$ is the radiance value seen by the detector at pixel (X,Y) in band i; and
- OFFSET_i is the offset factor used for band i.

The following simple relationship is generated when Equation 1 is used to solve for the radiance:

$$\mathrm{RAD}_i(X,Y) = [\mathrm{DN}_i(X,Y) - \mathrm{OFFSET}_i]/\mathrm{GAIN}_i. \quad (2)$$

This equation can be used to correct the data for system gain and offset effects, converting the data from digital numbers to radiance values at the sensor. This correction is very important because the spectral characteristics of a target can be greatly distorted by the system gain and offset values. However, the user must be careful to use the correct gain and offset values. In the case of the TM system, the published preflight gains and offsets are usually not the values used when collecting the image data. The actual values used are stored on the Computer Compatible Tape (CCT) (see *Earth Observation Satellite Company's User's Guide for Landsat TM CCTs*, 1985). The various gains and offsets and their functions are discussed by Barker (1983), Barker *et al.* (1985), Singh (1985), and Slater *et al.* (1987).

The preflight gains and offsets for Landsat-5 and the actual values used for the two Landsat TM images of the Phoenix area are shown in Table 1. The actual values used vary from the preflight values by 6.7 to 21.6 percent. The values shown in Table 1 were generated from both the average internal calibrator values of the entire image and the striping removal correction values (internal calibrator and applied gains and offsets combined). The conversion from DN to radiance is a function of the dynamic range of the radiance in each band. The range for each band on each sensor on each Landsat satellite, for a particular solar zenith angle, is given by Markham and Barker (1986). They discuss Landsat post-launch calibration and include several tables with important information required for Landsat calibration. Spectral characterization of the TM sensors and the radiometric properties of the Landsat Multispectral Scanner (MSS) data are discussed in two other papers (Markham and Barker, 1985 and 1987, respectively). The actual gain and offset values shown in Table 1 are the ones used with the A-tape data that have undergone striping and radiance dynamic range calibration. This is the QCAL format referred to by Markham and Barker (1986). These gain and offset values were used to convert the Landsat TM digital numbers to top-of-the-atmosphere radiance values and represent $\mathrm{RAD}_i(X,Y)$ in Equation 1.

The equation for the detected radiance is made up of a multiplicative and an additive term. Some of the major contributors to the multiplicative term include the surface reflectance of the target at pixel (X,Y) in band i $[R_i(X,Y)]$, the slope conditions at pixel (X,Y) [SLOPE(X,Y)], the sun elevation during data collection [SUN], the multiplicative atmospheric effects in band i at the time the image is recorded [MHAZE_i] – this includes transmission effects, the exoatmospheric spectral irradiance for the given band $[E_i]$, and the Earth-Sun distance [DIST]. The main contributor to the additive term is the haze present in band i, due mostly to the atmospheric scattering caused by the path radiance [HAZE_i]. These factors can be used to obtain a general representation of the radiance parameter in Equation 1 as follows:

$$\mathrm{RAD}_i(X,Y) = [E_i/(\pi \cdot \mathrm{DIST}^2)] \cdot [R_i(X,Y) \cdot \mathrm{SLOPE}(X,Y) \cdot \mathrm{SUN} \cdot \mathrm{MHAZE}_i] + \mathrm{HAZE}_i. \quad (3)$$

This equation can be used to solve for surface reflectance, generating the following equation:

$$R_i(X,Y) = (\pi \cdot \mathrm{DIST}^2) \cdot [\mathrm{RAD}_i(X,Y) - \mathrm{HAZE}_i] / [E_i \cdot \mathrm{SLOPE}(X,Y) \cdot \mathrm{SUN} \cdot \mathrm{MHAZE}_i]. \quad (4)$$

For overall image calibration, rather than pixel-by-pixel calibration, the average topography is usually assumed to be flat and the variable SLOPE(X,Y) is dropped. For the sites used in this project, this was valid because the parking lots and grass area were flat. The multiplicative effects of the atmosphere and how to correct for them in multispectral image data are not discussed in this paper. However, if a high concentration of water vapor exists in the air, the near infrared portion of the spectrum can be substantially affected by absorption. Until an acceptable method is developed for the additive component, which can often be the most significant in arid environments like Phoenix, the multiplicative component, which includes some of the effects of absorption, is assumed to be constant in this project. Also, the assumption is often made that the surface is Lambertian; that is, light is reflected equally in all directions, and the SUN term is set equal to the cosine of the solar zenith angle. The user must be aware that this can present problems

TABLE 1. THIS TABLE SHOWS THE PREFLIGHT AND ACTUAL GAIN AND OFFSET VALUES. THE ACTUAL VALUES WERE THE SAME FOR BOTH THE 3 OCTOBER 1988 AND 22 DECEMBER 1988 LANDSAT TM DATA. THE ACTUAL GAIN AND OFFSET VALUES WERE EXTRACTED FROM THE A-TAPE HEADERS AND THE DETECTORS AVERAGES WERE USED. THESE VALUES ARE USED TO CONVERT FROM THE A-TAPE QCAL DN VALUES TO TOP-OF-THE-ATMOSPHERE RADIANCE VALUES.

TM BAND	PREFLIGHT GAINS	PREFLIGHT OFFSET	ACTUAL GAINS*	ACTUAL OFFSETS
1	15.5525	1.8331	16.5993	2.4899
2	7.8595	1.6896	8.5104	2.3871
3	10.2031	1.8850	12.4074	1.4815
4	10.8206	2.2373	12.2790	1.8418
5	78.7508	3.2893	92.5292	3.4240
7	147.7188	3.2117	175.4878	2.6323

* The difference between the preflight and actual gains for the TM can be large. Therefore, it is important to use the actual rather than the published preflight values. The actual values used incorporate both the internal calibrator and applied gains and offsets.

with non-Lambertian surfaces, especially at high solar zenith angles. Errors due to the assumption of Lambertian reference panels are discussed by Kimes and Kirchner (1982). With the slope and atmospheric multiplicative terms set to unity, and using the cosine of the solar zenith angle (THETA) for SUN, Equation 4 reduces to

$$R_i(X,Y) = (\pi \cdot \text{DIST}^2)\cdot[\text{RAD}_i(X,Y) - \text{HAZE}_i]/[E_i \cdot \cos(\text{THETA})]. \quad (5)$$

This equation is similar, but not equal, to the equation used to convert image DNs to effective or apparent at-satellite reflectances (Begni, 1982; Barker *et al.*, 1985; Markham and Barker, 1986). The only difference is the additive atmospheric scattering term HAZE_i. This term is important, not only for calibration to surface reflectance, but also for temporal and spatial radiometric calibration. The exoatmospheric spectral irradiance term (E_i) can be computed for any spectral window using data published by Neckel and Labs (1984), and the Earth-Sun distance is known.

In this paper, Equation 5 is used to convert multispectral image DN values to surface reflectances. The accuracy of this calibration procedure is tested using two different methods to derive the important HAZE_i term. Without inclusion of this term, the conversion of DN to apparent reflectance can mislead a user into thinking that the resultant pseudo reflectance values are a function of only the surface, when they actually represent a top-of-the-atmosphere condition.

COMPUTATION OF HAZE_i

The effects of the additive component of atmospheric scattering on remotely sensed multispectral digital image data have been extensively studied during the past 15 years. For example, the amount of scattering in the data can affect results generated from multispectral ratioing (Vincent, 1973; Rowan *et al.*, 1974; Holben and Justice, 1981), estimation of forest leaf area index (Spanner *et al.*, 1984), temporal analyses (Chavez *et al.*, 1977; Otterman and Robinove, 1981; Robinove *et al.*, 1981), and signature extension (Carr *et al.*, 1983).

Several different atmospheric scattering or haze removal techniques have been developed for use with digital remotely sensed data (for example, Landsat MSS and TM). Many of these techniques can be grouped into a simple dark-object subtraction method (Vincent, 1973; Rowan *et al.*, 1974; Chavez, 1975). Other more sophisticated methods use various atmospheric transmission models or *in situ* field data, or require specific targets to be present in the image (Ahern *et al.*, 1977; Otterman and Robinove, 1981; Slater *etal.*, 1986). The more sophisticated techniques require information other than the digital image data (path radiance, atmospheric transmission, or optical depth information at locations within the image and area and collected during the satellite's overflight).

Many haze correction techniques involve subtracting a constant DN value from the entire digital image, assuming a constant haze throughout the image. Subtracting a single value from the entire image gives a first-order correction, which is better than no correction, because it removes the major effect of the additive scattering component. A different constant must be used for each spectral band, with a different set of constants used from image to image. However, using a uniform correction for the entire image will leave local errors due to non-homogeneity in the atmosphere.

Stand-Alone Method

The atmosphere influences the amount of electromagnetic energy that is sensed by the detectors of an imaging system, and these effects are wavelength dependent (Curcio, 1961; Turner *et al.*, 1971; Sabins, 1978; Slater *et al.*, 1983). This effect is particularly true for systems, such as the Landsat TM, that record data in the visible and near infrared parts of the spectrum. The atmosphere affects images by scattering, absorbing, and refracting light. Often, the most dominant of these effects is scattering (Siegal *et al.*, 1980; Slater *et al.*, 1983).

A method developed by the author to correct for the additive component of atmospheric scattering uses a relative power law model to predict the haze values for the multispectral bands based on a starting band haze value selected by the user (Chavez, 1988). In this stand-alone method the user selects a starting band dark-object subtraction haze value, typically using the histogram of TM band 1 or 2. The method then utilizes a relative power law scattering model that represents the atmospheric conditions at the time the data were collected. The amplitude of the starting haze value is used as a guide to identify the type of atmospheric conditions that existed during the time the data were collected (very clear, clear, moderate, hazy, or very hazy). The type of atmospheric condition is then matched with a power; the power ranges from 4.00 for very clear to 0.50 for very hazy atmospheres. The selected relative scattering model is used to predict the haze values for the other spectral bands from the selected starting haze value.

The stand-alone method computes DN values for haze correction using a relative scattering model to ensure that the haze values approximate realistic atmospheric scattering conditions. Using the information supplied by Curcio (1961) and Slater *et al.* (1983), and extrapolating to very clear and very hazy atmospheres, one possible set of relative scattering models are

Atmospheric Conditions	Relative Scattering Model
Very Clear	$\lambda^{-4.0}$
Clear	$\lambda^{-2.0}$
Moderate	$\lambda^{-1.0}$
Hazy	$\lambda^{-0.7}$
Very Hazy	$\lambda^{-0.5}$

These models were selected based on the fact that very clear atmospheres are characterized by Rayleigh scattering, moderate atmospheres by Rayleigh and Mie scattering, while very hazy atmospheres are influenced by both Rayleigh and Mie scattering, but with Mie being more important than in moderate atmospheres (Slater *et al.*, 1983, p. 246). The values of the power law functions used to represent the relative scattering models for both Landsat TM and MSS spectral bands are given by Chavez (1988).

The current computer program automatically selects the power to be used from a continuous function generated from the five values shown above using the amplitude of the starting haze value. The program TMHAZE allows the user to change the default power relationship (for example, use a range from 3.00 to 0.70 rather than the default 4.00 to 0.50). This program calculates for the selected power/model the percent of scattering that each band contributes in comparison to the total scattering that occurs within all six bands. For example, with the default relative scattering model of λ^{-4} for a very clear atmosphere, TM band 1 accounts for slightly over 50 percent of the total scattering and TM band 5 for only 0.4 percent. This calculation shows that, for this model, the majority of the additive atmospheric scattering occurs in the visible part of the spectrum for a very clear atmosphere, as expected. The program also shows that, for hazy and very hazy atmospheric conditions, the relative contributions to scattering of TM bands 4, 5, and 7 cannot be ignored (Chavez, 1988).

In this project, the starting haze value was selected from the image DN values using the histogram/dark-object method. If a valid dark-object does not exist in the image, an iteration process can often be used to generate more acceptable values. This is done by iteratively using a lower starting haze value until no over corrections occur. That is, if a starting haze value results in predicted values for the other bands that are higher than some of the actual image DNs, a lower starting haze value must be used. Also, a completely black or zero reflectance surface usually does not exist and a minimum reflectance value of 1 or 2 percent is more realistic. In this project a 1 percent minimum reflectance was assumed.

Sky Reflectance Method

Ideally, a method that uses *in situ* atmospheric measurements should be used to correct for atmospheric effects whenever possible. Papers by Castle *et al.* (1984), Slater *et al.* (1986, 1987), and Holm *et al.* (1989) discuss two projects where this method has been employed with Landsat TM spectral bands. Castle *et al.* and Slater *et al.* used the White Sands, New Mexico area as their test site; Hom *et al.* used the Maricopa Agricultural Center, located approximately 48 km south of Phoenix, Arizona, as their test site. The atmospheric measurements and correction procedure used by both projects were identical. The procedure required the determination of the optical properties of the atmosphere and the reflectance of the surface in each band of interest at the time the satellite collects the image data (Holm *et al.*, 1989). Atmospheric information was used to determine the total, Raleigh, Mie, and ozone optical depths. The average optical depths for water and carbon dioxide were determined for TM bands 4, 5, and 7 in order to correct for absorption effects. The optical depth data and the measured surface reflectance values were then used as input to a radiative transfer code. The output allows a correction for atmospheric effects that includes both scattering and absorption.

In this research, besides the simple field independent stand-alone method described in the previous section, a second technique based on *in situ* sky/atmosphere measurements was also used. However, the *in situ* atmospheric measurements were simple and straightforward in comparison to those used by Castle *et al.*, Slater *et al.*, and Holm *et al.* The *in situ* measurements were simply the sky radiance values collected by turning the field radiometers over and pointing them vertically toward the sky. These readings were used to compute the spectral characteristics/reflectance of the atmosphere during the time the image data were collected (i.e., the color of the sky). The measured sky radiance values were converted to sky reflectance values using the measurements of the $BaSO_4$ panels; the panel measurements were made right before and after the sky measurements. The assumption was made that the down and up path of the radiance seen by the satellite was twice the down path seen at the surface, so half the computed sky reflectance values were used. It is assumed that the measured sky radiance comes only from the atmosphere and so the computed sky reflectance is equal to the $HAZE_i$ reflectance (shown as SKY REF in Table 4). A computer program (TM2REF) that converts from DNs to reflectances, using the equations shown earlier, is used to compute the DN value that correspond to the sky reflectance of each band (shown as SKY DN in Table 4). Notice that the sky reflectance values can be plotted/used to check the type of curve/model represented by the measured sky radiance values. The plans are to do this with many different readings and compare them to the relative power law models currently being used.

DISCUSSION AND RESULTS

This section contains a short discussion on the DN resolution requirements to achieve an absolute accuracy of less than 5 percent error for each Landsat TM band. This discussion is followed by a presentation of the $HAZE_i$ computation results and a comparison of the stand-alone and in-situ sky radiance measurements. Next, the results of the computed versus measured surface reflectance values are presented. The accuracy of the calibration procedure is examined in a temporal sense by using the October TM data to predict the December measured surface reflectance values for the Turf Paradise parking lot.

Accuracy Requirements

To understand the level of accuracy being generated by the method presented in this paper, an examination of the requirements in terms of DN resolution needed to achieve an absolute accuracy of 5 percent or better in computing surface reflectances is discussed. It is important to realize that we are talking about 5 percent error and not 5 percent reflectance. The 5 percent error level is used because it is the approximate goal of several current calibration procedures; also, it can be difficult to get below this value in absolute accuracy. The level of accuracy achievable is influenced by several factors, including the solar zenith angle at the time the image data are collected and the amplitude of the surface reflectance (5 percent of a low surface reflectance is smaller, and so more difficult to achieve, than 5 percent of a high surface reflectance).

Equation 5 shows that the radiance value received at the sensor is proportional to the cosine of the solar zenith angle; therefore, the maximum possible apparent reflectance that can be recorded for a given band will be a function of the solar zenith angle. The term apparent reflectance is used because the atmospheric effects are included and is the term used by previous authors. The maximum possible reflectance determines the amount of reflectance per DN and the DNs per 1 percent reflectance (i.e., reflectance resolution in terms of DNs). Therefore, a difference of 1 percent reflectance between the computed and measured reflectance will translate to a different level of accuracy in terms of DNs in two images recorded with different solar zenith angles. That is, the reflectance per DN resolution will affect the calibration accuracy. This difference can be seen in Table 2 with the 3 October 1988 and 22 December 1988 TM images that have 7.32 DNs and 4.84 DNs per 1 percent reflectance, respectively. Another important factor that affects the DN resolution and, therefore, the accuracy is the amplitude of the surface reflectance. This is because the effect of a small error, either computed or measured, affects the results of low reflectance values more than it does high reflectance values.

Table 2 shows the resolution, in DNs, needed for each band in both the 3 October 1988 and 22 December 1988 TM images to achieve an absolute accuracy of within 5 percent error. This information is shown for hypothetical reflectance values ranging from 2 to 40 percent; 2 percent reflectance is for a very dark surface, while 40 percent reflectance is for a bright surface. Notice that, in order to get an error under 5 percent for the lower reflectance values, sub-DN resolution is required. The amplitude of most of the surface reflectance values used in this project, parking lots and grass area, are less than 10 percent.

$HAZE_i$ Computation Results

As mentioned earlier, the correction for the $HAZE_i$ term in Equation 5 is important to calibrate the Landsat TM DN values to surface reflectance. Table 3 shows the results, in DNs, of using the stand-alone procedure to derive the $HAZE_i$ values. The default relative scattering model for a very clear atmosphere was used (power equal to 4.00). Table 3 shows the percent of scattering contributed by each TM band, the cumulative percent of scattering, the predicted haze value in TM band 1 DNs, and the actual $HAZE_i$ values in DNs to be used for each band. The final values are generated by adjusting the predicted values for the individual band's gain, offset, and solar irradiance differences (Chavez, 1988). This information is shown for both the 3 October 1988 and 22 December 1988 TM images.

The very clear atmosphere condition was selected by the TMHAZE program for both the October and December images because of the amplitude of their starting haze value (44.68 for

TABLE 2. THIS TABLE SHOWS THE EQUIVALENT RESOLUTION IN DNS REQUIRED TO ACHIEVE AN ABSOLUTE ACCURACY OF 5 PERCENT FOR REFLECTANCE VALUES RANGING FROM 2 TO 40 PERCENT FOR THE 3 OCTOBER 1988 AND 22 DECEMBER 1988 TM DATA. THE TOP PORTION SHOWS BOTH THE REFLECTANCE PER 1 DN AND DNS PER 1 PERCENT REFLECTANCE. THESE VALUES ARE AFFECTED BY THE SOLAR ZENITH ANGLE; THEY THEN DETERMINE THE DN RESOLUTION REQUIRED FOR LESS THAN A 5 PERCENT ERROR. THE BOTTOM PORTION SHOWS THE REFLECTANCE, 5 PERCENT OF THE GIVEN REFLECTANCE, AND THE EQUIVALENT DN VALUE THAT CORRESPONDS TO 5 PERCENT IN EACH OF THE TM BANDS (TO GET THE ERRORS UNDER 5 PERCENT, THE RESOLUTION IN DNS MUST BE LESS THAN OR EQUAL TO THE VALUES SHOWN).

	OCTOBER		DECEMBER	
TM	REF PER DN	DNS PER REF	REF PER DN	DNS PER REF
1	0.1367	7.32	0.2068	4.84
2	0.2853	3.51	0.4316	2.32
3	0.2298	4.35	0.3478	2.88
4	0.3454	2.90	0.5226	1.91
5	0.2188	4.57	0.3311	3.02
7	0.3395	2.95	0.5138	1.95

OCTOBER

		EQUIVALENT DN					
REF (%)	5%	TM1	TM2	TM3	TM4	TM5	TM7
2.00*	0.10	0.73	0.35	0.44	0.29	0.46	0.29
5.00*	0.25	1.83	0.88	1.09	0.72	1.14	0.74
8.00	0.40	2.93	1.40	1.74	1.16	1.83	1.18
10.00	0.50	3.66	1.75	2.18	1.45	2.29	1.47
15.00	0.75	5.49	2.63	3.26	2.17	3.43	2.21
20.00	1.00	7.32	3.51	4.35	2.90	4.57	2.95
30.00	1.50	10.97	5.26	6.53	4.34	6.86	4.42
40.00	2.00	14.63	7.01	8.70	5.79	9.14	5.89

DECEMBER

		EQUIVALENT DN					
REF (%)	5%	TM1	TM2	TM3	TM4	TM5	TM7
2.00*	0.10	0.48	0.23	0.29	0.19	0.30	0.19
5.00*	0.25	1.21	0.58	0.72	0.48	0.76	0.49
8.00	0.40	1.93	0.93	1.15	0.77	1.21	0.78
10.00	0.50	2.42	1.16	1.44	0.96	1.51	0.97
15.00	0.75	3.63	1.74	2.16	1.44	2.27	1.46
20.00	1.00	4.84	2.32	2.88	1.91	3.02	1.95
30.00	1.50	7.25	3.48	4.31	2.87	4.53	2.92
40.00	2.00	9.67	4.63	5.75	3.83	6.04	2.89

*Notice that, to get the error under 5 percent at the lower reflectance values, sub-DN resolution is required. Most of the reflectance values used in this project, parking lots and grass area, are less than 10 percent.

TABLE 3. THIS TABLE SHOWS THE RESULTS OF THE PROGRAM TMHAZE FOR BOTH THE 3 OCTOBER 1988 AND 22 DECEMBER 1988 LANDSAT TM IMAGES OF THE PHEONIX AREA. THE COMPUTED DN HAZE VALUES WERE USED TO CORRECT FOR ATMOSPHERIC SCATTERING WHEN CONVERTING FROM DNS TO SURFACE REFLECTANCE VALUES. THESE HAZE VAUES WERE COMPUTED USING THE STAND-ALONG PROCEDURE.

OCTOBER				
TM	BAND % SCATTER	CUM % SCATTER	PREDICTED HAZE	ACUTAL DN HAZE
1*	50.5	50.5	43.17	44.68
2	28.4	78.9	24.29	13.16
3	14.7	93.6	12.59	8.46
4	5.9	99.5	5.03	4.11
5	0.4	99.9	0.32	3.47
7	0.1	100.0	0.10	3.25
DECEMBER				
TM	BAND % SCATTER	CUM % SCATTER	PREDICTED HAZE	ACTUAL DN HAZE
1	50.5	50.5	33.33	35.16
2	28.4	78.9	18.75	10.55
3	14.7	93.6	9.72	6.96
4	5.9	99.5	3.89	3.68
5	0.4	99.9	0.25	3.43
7	0.1	100.0	0.08	3.24

*TM band 1 was used as the starting haze value (SHV) band. The minimum DN values were 52 and 40 but, because of the assumption that the darkest object is not absolute black (zero reflectance), the 1 percent reflectance values were used. For example, a SHV of 35.16 (40.00 − 4.84) was used in the December calculations because 1 percent reflectance in TM band 1 is equal to 4.84 DNs (see Table 2).

October and 35.16 for December). The same model was used for both images because a starting haze value of 45 or less is considered a very clear atmosphere by the procedure. As shown in Table 3, with the given relative scattering model, TM band 1 accounts for 50.5 percent of the total scattering while 93.6 percent occurs within TM bands 1, 2, and 3 (visible portion of the spectrum). Both the percent scattered by each individual band and the predicted haze values give the relative spectral characteristics of the selected model.

The 22 December 1988 date was selected because the atmospheric conditions are usually affected by pollution at this time of year. However, due to stormy weather for the 3 days prior to 22 December, the atmosphere was much cleaner than normal (approximately that of 3 October); the December data were still used because surface reflectance values were collected in the field during the Landsat TM overflight and were needed to make a comparison with the October data.

As discussed earlier, the sky radiance measurements collected during the Landsat TM overflights were used to derive the $HAZE_i$ DN values for each band. These $HAZE_i$ values were compared with the computed values generated with the stand-alone procedure. The values were compared in both reflectances and DNs and the results are shown in Table 4. The table shows that both methods generated similar $HAZE_i$ values. In fact, the results for the December data are almost identical (within a fraction of a DN for the four bands measured by the Exotech radiometer). For the 3 October 1988 data the $HAZE_i$ values derived using the stand-alone procedure would have matched the *in situ* sky radiance derived $HAZE_i$ values better if a less Rayleigh relative scattering model had been used (power equal to 3.00 rather than 4.00).

Computed Versus Measured Reflectance

Table 5 shows the results of the data collected on 3 October 1988 in the Metro Center parking lot (see Figure 1). The MMR was used to make the measurements so that information was available for all six reflective bands. The difference between the computed and measured surface reflectance values for TM bands 1, 3, 5, and 7 were at the sub-DN level. The percent of error for these four bands, with the given surface reflectance values and solar zenith angle, were 1.77, −0.91, 0.96, and 3.22 percent, respectively. Negative percent of error is used to indicate that the computed value is less than the measured value. Notice that for TM band 7 even with sub-DN accuracy (0.62) the amount of error was 3.22 percent. The difference between the computed and measured surface reflectance values for TM bands 2 and 4 were −2.49 and 3.23 DNs; these values correspond to errors of −8.95 and 13.25 percent, respectively. For the six TM bands the average error was 4.84 percent.

Table 6 shows the results of the data collected on 22 December 1988 in the Turf Paradise parking lot. The Exotech radiometer was used to make these measurements so information was available only for TM bands 1, 2, 3, and 4. The only band that had a difference between the computed and measured surface reflectance values with sub-DN accuracy was TM band 2 (−0.52). However, due to the reflectance per DN resolution, the 1.48 DN difference of band 1 gave it an error similar to band 2; the percent of error for bands 1 and 2 were 4.61 and −2.96 percent. Again, notice that even with sub-DN accuracy TM band 2 had a three percent error. The differences between the computed and measured surface reflectance value for TM bands 3 and 4 were 2.96 and 2.72 DNs. With the given solar zenith angle and their surface reflectance amplitudes, these values corresponded to errors of 12.03 and 14.08 percent for bands 3 and 4. The average error for the four bands was 8.42 percent. Note that the errors for bands 5 and 7 were low at the Metro Center parking lot and perhaps would have been similar at this site (TM bands 5 and 7 are affected less by the additive component of scattering than are TM bands 1, 2, and 3).

Table 7 shows the results of the data collected on 22 December 1988 in the Turf Paradise grass area. The MMR was used to make the measurements so that information was available for the six reflective TM bands. The only band that had a difference between the computed and measured surface reflectance values at sub-DN accuracy was TM band 7 (0.51); this corresponded to an error of 3.61 percent. Band 2 had a difference of 1.03 DN that was

Table 4. This Table Shows the 3 October 1988 and 22 December 1988 Sky Reflectance Measurements and Their Equivalent $HAZE_i$ values in DNs (SKY DN). The $HAZE_i$ DN Values Computed Using the Stand-Along Method (TMHAZE with the Default POWER = 4.00) Are Shown for Comparison ($HAZE_i$ DN). These Values Were Converted to Reflectance and Are shown as $HAZE_i$ REF; they Should Be Compared with the Computed Sky Reflectance. The Exotech Radiometer Was Used to Make the Measurements so Information Was Available only for TM Bands 1, 2, 3, and 4.

OCTOBER

TM	SKY REF*	$HAZE_i$ REF**	DIFF REF	SKY DN	$HAZE_i$ DN	DIFF DN
1	6.70	6.15	0.55	49.02	45.00	4.02
2	4.34	3.75	0.59	15.21	13.16	2.05
3	2.69	1.94	0.75	11.70	8.46	3.24
4	2.36	1.42	0.94	6.83	4.11	2.72

*All reflectance values are times 100 to show as percents.
**If POWER = 3.00 had been used rather than the default value of 4.00 the TMHAZE reflectance values would have been equal to 6.15, 4.26, 2.49, and 1.88 for TM bands 1. to 4, respectively. These values translate to TM HAZE DN values of 45.00, 14.93, 10.83, and 5.44, respectively. For $HAZE_i$ values these figures make a better match between the two methods and indicate that the scattering was less Rayleigh and more Mie. However, the computed surface reflectance values are not as acccurate.

DECEMBER

TM	SKY REF*	$HAZE_i$ REF	DIFF REF	SKY DN	$HAZE_i$ DN	DIFF DN
1	7.32	7.27	0.05	35.39	35.16	0.23
2	4.46	4.55	−0.09	10.33	10.55	−0.22
3	2.76	2.42	0.34	7.94	6.96	0.98
4	2.16	1.92	0.24	4.14	3.68	0.46

*December sky reflectance values are slightly larger than the October values but the DN values are lower because the solar zenith angle was 63.1° on 22 December and 44.9° on 3 Ocotber.

TABLE 5. THIS TABLE SHOWS THE METRO CENTER SHOPPING MALL PARKING LOT RESULTS OF THE DATA COLLECTED ON 3 OCTOBER 1988. SHOWN ARE THE MAXIMUM REFLECTANCE POSSIBLE WITH THE GIVEN SUN ANGLE (INCLUDING HAZE), REFLECTANCE PER DN, SURFACE REFLECTANCE AS MEASURED IN THE FIELD, AVERAGE LANDSAT TM DN VALUE OF THE SURFACE MEASURED, DN REPRESENTING THE $HAZE_i$ VALUE USED IN THE CORRECTION AND DERIVED USING THE STAND-ALONE METHOD (FROM TABLE 3), REFLECTANCE COMPUTED FROM THE AVERAGE DN VALUE OF THE SURFACE CORRECTED WITH THE GIVEN STAND-ALONG $HAZE_i$, DIFFERENCE BETWEEN THE MEASURED AND COMPUTED REFLECTANCE, THE EQUIVALENT DIFFERENCE IN DNS, AND THE PERCENT OF ERROR OF THE COMPUTED VERSUS MEASURED REFLECTANCE VALUES. NOTE, THE PERCENT OF ERROR VALUES ARE THOSE GENERATED USING FOUR DECIMAL PLACES AND THEN ROUNDED-OFF TO TWO PLACES; THEREFORE, THE VALUES SHOWN MAY NOT BE EXACTLY EQUAL TO THOSE DERIVED USING THE VALUES IN THE TABLE. THE MMR WAS USED TO MAKE THE MEASUREMENTS SO INFORMATION WAS AVAILABLE FOR TM BANDS 1, 2, 3, 4, 5, AND 7.

TM	MAX REF POSSIBLE*	REF PER DN	MEASURED REF*	AVE DN**	DN HAZE**	COMPUTED REF	DIFF REF	DIFF DNS	% ERROR (COMP-MEAS)/MEAS
1	34.9	0.1367	6.79	95.25	44.68	6.91	0.12	0.88	1.77%
2	72.8	0.2853	7.94	38.50	13.16	7.23	−0.17	−2.49	−8.95%
3	58.6	0.2298	8.30	44.25	8.46	8.23	−0.08	−0.33	−0.91%
4	88.1	0.3454	8.43	31.75	4.11	9.55	1.12	3.23	13.25%
5	55.8	0.2188	7.70	39.00	3.47	7.77	0.07	0.34	0.96%
7	86.6	0.3396	6.58	23.25	3.25	6.79	0.21	0.62	3.22%
									AVERAGE = 4.84%

*All reflectance values are times 100 to show as percents. The maximum refletance possible is affected by the solar zenith angle, which affects the reflectance per DN.
**AVE DN represent the DN values extracted from the A-tape which are the raw QCAL values. The DN HAZE values are DNs on the A-tape representing the haze correction parameters, in QCAL DNs, used for the given bands; they are in A-tape format and have the gain, offset, and spectral irradiance effects of that band.

TABLE 6. THIS TABLE SHOWS THE TURF PARADISE PARKING LOT RESULTS OF THE DATA COLECTED ON 22 DECEMBER 1988. SHOWN ARE THE MAXIMUM REFLECTANCE POSSIBLE WITH THE GIVEN SUN AGNLE (INCLUDING HAZE), REFLECTANCE PER DN, SURFACE REFLECTANCE AS MEASURED IN THE FIELD, AVERAGE LANDSAT TM DN VALUE OF THE SURFACE MEASURED, DN REPRESENTING THE HAZE VALUE USED IN THE CORRECTION AND DERIVED USING THE STAND-ALONE METHOD (FROM TABLE 3), REFLECTANCE COMPUTED FROM THE AVERAGE DN VALUE OF THE SURFACE CORRECTED WITH THE GIVEN STAND-ALONE HAZE, DIFFERENCE BETWEEN THE MEASURED AND COMPUTED REFLECTANCE, THE EQUIVALENT DIFFERENCE IN DNS, AND THE PERCENT OF ERROR OF THE COMPUTED VERSUS MEASURED REFLECTANCE VALUES. THE EXOTECH RADIOMETER WAS USED TO MAKE THE MEASUREMENTS SO INFORMATION WAS AVAILABLE ONLY FOR TM BANDS 1, 2, 3, AND 4.

TM	MAX REF POSSIBLE*	REF PER DN	MEASURED REF*	AVE DN**	$HAZE_i$ DN**	COMPUTED REF	DIFF REF	DIFF DNS	% ERROR (COMP-MEAS)/MEAS
1	52.7	0.2068	6.64	68.75	35.16	6.95	0.31	1.48	4.61%
2	110.1	0.4316	7.65	27.75	10.55	7.42	−0.23	−0.52	−2.96%
3	88.7	0.3478	8.55	34.50	6.96	9.58	1.03	2.96	12.03%
4	133.3	0.5226	10.11	25.75	3.68	11.53	1.42	2.27	14.08%
5	84.4	0.3311	---	41.25	3.43	12.52	---	---	---
7	131.0	0.5138	---	26.25	3.24	11.82	---	---	---
									AVERAGE = 8.42%

*All reflectance values are times 100 to show as percents. The maximum reflectance possible, which determines the reflectance per DN, is affected by the solar zenith angle. These values are higher than the October ones because the sun elevation is lower.
**AVE DN represent the DN values extracted from the A-tape. The DN HAZE values are DNs on tape representing the haze correction parameters used for the given band; they are in A-tape format and have the gain, offset, and spectral irradiance effects of that band.

equal to an error of 7.71 percent. Both TM bands 4 and 5 had a difference between the computed and measured reflectance values of about seven DNs. However, due to the high surface reflectance of these two bands, the percent of errors were 8.52 and 11.95, respectively. In contrast, TM bands 1 and 3 had differences of 6.08 and 4.99 DNs that corresponded to errors of 38.34 and 38.20 percent. These percent of errors are large because the surface reflectance values in bands 1 and 3 are very low, 3.28 and 4.54, respectively.

As noted earlier, with low surface reflectance, a small error in either the computed or measured values can generate a large percentage error. These two cases, bands 1 and 3, were the only ones encountered with such large errors between the computed and measured values. Most other errors were under 10 percent, with almost half under 5 percent. Determination of the exact cause of these large errors will require further research. Both the very low surface reflectance and the field sampling may have contributed to the problem. However, note that the parking lots both had low surface reflectances, and better results were generated. The main difference between the parking lots and grass area was that a more homogeneous surface existed on the parking lots, perhaps allowing a more representative sampling. Because the grass area was actually a combination of grass, exposed soils that included a dirt road, and palm trees, a representative sampling may not have been made.

TM bands 2, 4, 5, and 7 generated results similar to those in the parking lots. The average error for the six TM bands was 18.05 percent due to the large errors in TM bands 1 and 3; the average error excluding TM bands 1 and 3 was 7.95 percent. If the problem was due to the $HAZE_i$ values used then TM band 2 should also have a large error. In addition, the Turf Paradise parking lot, very close to the grass area, also used the same $HAZE_i$ values and generated lower errors.

Table 8 shows, for the Turf Paradise parking lot, the computed surface reflectance values generated from the 3 October 1988 Landsat TM data and the measured surface reflectance values

TABLE 7. THIS TABLE SHOWS THE RESULTS OF THE DATA COLLECTED ON THE GRASS AREA IN THE MIDDLE OF THE TURF PARADISE HORSE RACING TRACK ON 22 DECEMBER 1988. SHOWN ARE THE SURFACE REFLETANCE AS MEASURED IN THE FIELD, AVERAGE LANDSAT TM DN VALUE OF THE SURFACE MEASURED, DN REPRESENTING THE $HAZE_i$ VALUE USED IN THE CORRECTION AND DERIVED USING THE STAND-ALONE METHOD (SAME VALUES USED FOR THE TURF PARADISE PARKING LOT), REFLECTANCE COMPUTED FROM THE AVERAGE DN VALUE OF THE SURFACE CORRECTED WITH THE GIVEN STAND-ALONE $HAZE_i$, DIFFERENCE BETWEEN THE MEASURED AND COMPUTED REFLECTANCE, THE EQUIVALENT DIFFERENCE IN DNS, AND THE PERCENT OF ERROR OF THE COMPUTRED VERSUS MEASURED REFLECTANCE VALUES. THE MMR WAS USED TO MAKE THE MEASUREMENTS SO INFORMATION WAS AVAILABLE FOR TM BANDS 1, 2, 3, 4, 5, AND 7.

TM	MEASURED REF*	AVE DN	$HAZE_i$ DN	COMPUTED REF	DIFF REF	DIFF DNS	% ERROR (COMP-MEAS)/MEAS
1	3.28	57.1	35.16	4.54	1.26	6.08	38.34%
2	5.79	25.0	10.55	6.24	0.45	1.03	7.71%
3	4.54	25.0	6.96	6.27	1.73	4.99	38.20%
4	42.80	78.6	3.68	39.15	−3.65	−6.98	−8.52%
5	19.43	55.1	3.43	17.11	−2.32	−7.01	−11.95%
7	7.27	17.9	3.24	7.53	0.26	0.51	3.61%
						AVERAGE ERROR =	18.05%

*All reflectance values are times 100 to show as percents. Note that the average error without TM bands 1 and 3 is 7.95 percent.

TABLE 8. THIS TABLE SHOWS THE TEMPORAL RESULTS OF THE CALIBRATION PROCEDURE USING THE TURF PARADISE PARKING LOT. SHOWN ARE THE OCTOBER AVERAGE DN VALUES, THEIR CORRESPONDING APPARENT REFLETANCES (STILL INCLUDES ATMOSPHERIC EFFECTS), THE COMPUTED OCTOBER TMHAZE REFLECTANCE VALUES, AND THE COMPUTED OCTOBER SURFACE REFLECTANCES (AVERAGE DN APPARENT REFLECTANCES CORRECTED FOR SCATTERING USING THE COMPUTED TMHAZE VALUES). ALSO SHOWN ARE THE MEASURED DECEMBER SURFACE RECFLECTANCE VALUES, THE DIFFERENCE BETWEEN THE COMPUTED AND MEASURED REFLECTANCES IN BOTH REFLECTANCE AND EQUIVALENT OCTOBER DN VALUES. THE PERCENT OF ERRORS IN THE COMPUTED VERSUS MEASURED VALUES ARE ALSO SHOWN. THE EXOTECH RADIOMETER WAS USED TO MAKE THE MEASUREMENTS SO INFORMATION WAS AVAILABLE FOR ONLY TM BANDS 1, 2, 3, AND 4.

TM	AVE DN	AVE DN REF*	$HAZE_i$ REF	OCTOBER COMPUTED REF	DECEMBER MEASURED REF	DIFF REF**	DIFF DNs	% ERROR (COMP-MEAS)/MEAS
1	97.25	13.29	6.15	7.14	6.64	0.50	3.66	7.53%
2	39.75	11.24	3.75	7.49	7.65	−0.16	−0.56	−2.09%
3	48.75	11.20	1.94	9.26	8.55	0.71	3.09	8.30%
4	35.25	12.17	1.42	10.75	10.11	0.64	1.85	6.33%
								AVERAGE = 6.06%

*All reflectance values are times 100 to show as percents.
**Notice that if the October computed are compared with the December computed (shown in Table 6) reflectance values the differences in reflectances are 0.19, 0.07, −0.32, and −0.78 percent, respectively for TM bands 1, 2, 3, and 4. These correspond to an average percent of error difference of 3.44 percent between the two dates (sub-DN precision).

made on 22 December 1988. Surfaces reflectance measurements were made at the Turf Paradise parking lot only on 22 December 1988. However, the surface characteristics of the parking lot should have been similar on 3 October 1988. No cars were parked in the lot on either day. We were physically on the Turf Paradise parking lot on both dates and visually it appeared the same (no major changes such as re-paving or striping). The information in Table 8 is used to view the calibration results on a temporal basis. The differences between the October computed and December measured reflectance values are 3.66, −0.56, 3.09, and 1.85 October DNs for TM bands 1, 2, 3, and 4, respectively. These values correspond to errors of 7.53, −2.09, 8.30, and 6.33 percent, respectively, with an average error of 6.06 percent for the four bands. These values are valid only if the assumption is made that the surface reflectance values of the parking lot were the same on both dates.

CONCLUSIONS

An equation to convert multispectral image DNs to surface reflectances was presented. The equation includes corrections for the system gain and offset values, solar irradiance, Earth-Sun distance, solar zenith angle, and the additive atmospheric scattering component. The calibration procedure was applied to Landsat TM data, but the algorithm is general in nature and can be used with other remotely sensed multispectral image data.

Two different methods were used to compute the critical $HAZE_i$ component for the scattering correction. Both the stand-alone and *in situ* sky radiance measurement techniques generated similar $HAZE_i$ values for the Landsat TM data used in this study. However, if the user is in the field with a radiometer, the *in situ* sky radiance measurements should be collected for use in the $HAZE_i$ computations, especially if the image to be used will not have a valid dark-object needed by the stand-alone method.

For the two homogeneous parking lots, the overall average accuracy using the stand-alone method was within 10 percent error, and within 5 percent error for 43 percent of the individual measurements. The accuracy of the results is affected by the amplitude of the surface reflectance, the solar zenith angle, and the field sampling.

Potential problems are that in some cases the starting haze value can be difficult to select, a constant atmospheric scattering is assumed for the entire image (as is true with many current methods), and the power law exponent versus starting haze values amplitude needs to be refined. Future research will include developing a method to compute a multiplicative atmospheric component correction, which should be important in humid environments, and to compare sky reflectance curves with those generated using power law models.

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REFERENCES

Ahern, F. J., D. G. Goodenough, S. C. Jain, V. R. Rao, and G. Rochen, 1977. Landsat atmospheric corrections at CCRS, *Proceedings of the Fourth Canadian Symposium on Remote Sensing*, Quebec City, May, pp. 583–595.

Barker, J., 1983. Relative radiometric calibration of TM reflective bands: *Landsat-4 Science Characterization Early Results*, NASA Conference Publication 2355, Vol. III, pp. 1–29.

Barker, J. L., D. L. Ball, K. C. Leung, and J. A. Walker, 1983. Prelaunch absolute radiometric calibration of the reflective bands on the Landsat-4 protoflight Thematic Mapper, *Landsat-4 Science Characterization Early Results*, NASA Conference Publication 2355, Vol. II, pp. 277–393.

Begni, G., 1982. Selection of the optimum spectral bands for the SPOT satellite, *Photogrammetric Engineering and Remote Sensing*, Vol. 48, No. 10, pp. 1613–1620.

Carr, J. R., C. E. Glass, and R. A. Schowengerdt, 1983. Signature extension versus retraining for multispectral classification of surface mines in arid regions, *Photogrammetric Engineering and Remote Sensing*, Vol. 49, No. 8, pp. 1193–1199.

Castle, K. R., R. G. Holm, C. J. Kastner, J. M. Palmer, P. N. Slater, M. Dinguirard, C. E. Ezra, R. D. Jackson, and R. K. Savage, 1984. Inflight absolute radiometric calibration of the Thematic Mapper, *Proceedings, IEEE Transactions on Geoscience and Remote Sensing*, Vol. GE-22, No. 3, pp. 251–255.

Chavez, P. S., Jr., 1975. Atmospheric, solar, and MTF corrections for ERTS digital imagery, *Proceedings of the American Society of Photogrammetry Fall Technical Meeting*, Phoenix, Arizona, p. 69.

———, 1988. An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data, *Remote Sensing of Environment*, Vol. 24, pp. 459–479.

Chavez, P. S., Jr., G. L. Berlin, and W. B. Mitchell, 1977. Computer enhancement techniques of Landsat MSS digital images for land use/cover assessments. *Proceedings of the Sixth Remote Sensing of Earth Resources Symposium*, Tullahoma, Tennessee, pp. 259–275.

Curcio, J. A., 1961. Evaluation of atmospheric aerosol particle size distribution from scattering measurement in the visible and infrared, *Journal Optical Society of America*, Vol. 51, pp. 548–551.

EOSAT, 1985. *User's Guide for Landsat Thematic Mapper Computer-Compatible Tapes*, Earth Observation Satellite Company, c/o Code 435.7, Goddard Space Flight Center, Greenbelt, MD 20771.

Hall, D. K., and A. T. C. Chang, 1988. Reflectances of glaciers as calculated using Landsat-5 Thematic Mapper data, *Remote Sensing of Environment*, Vol. 25, pp. 311–321.

Holben, B., and C. Justice, 1981. An examination of spectral band ratioing to reduce the topographic effects on remotely sensed data, *International Journal Remote Sensing*, Vol. 2, No. 2, pp. 115–133.

Holm, R. G., M. S. Moran, R. D. Jackson, P. N. Slater, B. Yuan, and S. F. Biggar, 1989. Surface reflectance factor retrieval from Thematic Mapper data, *Remote Sensing of Environment*, Vol. 27, pp. 47–57.

Jackson, R. D., M. S. Moran, P. N. Slater, and S. F. Bigger, 1987. Field calibration of reference reflectance panels, *Remote Sensing of Enviornment*, Vol. 22, pp.145–158.

Kimes, D. S., and J. A. Kirchner, 1982. Irradiance measurement errors due to the assumption of a Lambertian reference panel, *Remote Sensing of Environment*, Vol. 12, pp. 141–149.

Leprieur, C. E., J. M. Durand, and J. L. Peyron, 1988. Influences of topography on forest reflectance using Landsat Thematic Mapper and digital terrain data, *Photogrammetric Engineering and Remote Sensing*, Vol. 54, No. 4, pp. 491–496.

Markham, B. L., and J. L. Barker, 1985. Spectral characterization of the Landsat Thematic Mapper sensors, *International Journal of Remote Sensing*, Vol. 6, No. 5, p. 697–716.

———, 1986. *Landsat MSS and TM post-calibration dynamic ranges, exoatmospheric reflectances and at-satellite temperature*, EOSAT Landsat Technical Notes, No. 1, August, 8 p.

———, 1987. Radiometric properties of U.S. processed Landsat MSS data, *Remote Sensing of Environment*, Vol. 22, pp. 39–71.

Neckel, H., and D. Labs, 1984. The solar radiation between 3300° and 12500°, *Solar Physics*, Vol. 90, pp. 205–258.

Otterman, J., and C. J. Robinove, 1981. Effects of the atmosphere on the detection of surface changes from Landsat Multispectral Scatter data, *International Journal Remote Sensing*, Vol. 2, No. 4, pp. 351–360.

Park, S. K., and R. A. Schowengerdt, 1983. Image reconstruction by parametric cubic convolution, *Computer Vision, Graphics, Image Processing*, Vol. 23, pp. 258–272.

Price, J. C., 1987. Calibration of satellite radiometers and the comparison of vegetation indices, *Remote Sensing of Environment*, Vol. 21,pp. 15–27.

Robinove, C. J., P. S. Chavez, Jr., D. Gehring, and R. Holmgrem, 1981. Arid land monitoring using Landsat albedo difference images, *Remote Sensing Environment*, Vol. 11, pp. 133–156.

Robinson, B. F., M. E. Bauer, D. P. Dewitt, L. F. Silva, and V. C. Vanderbilt, 1979. Multiband radiometer for field research, *SPIE*, Vol. 196, pp. 8–15.

Rowan, L. C., P. H. Wetlaufer, A. F. H. Goetz, F. C. Billingsley, and J. H. Stewart, 1974. *Discrimination of Rock Types and Detection of Hydrothermally Altered Areas in South-Central Nevada by the Use of Computer-Enhanced ERTS Images*, U.S. Geological Survey Professional Paper 883, 35 p.

Sabins, F. F., Jr., 1978. *Remote Sensing Principles and Interpretation*, Freeman, San Francisco, 18 p.

Siegal, B. S., A. R. Gillespie, and J. E. Skaley, 1980. *Remote Sensing in Geology*, Wiley, New York, 120 p.

Singh, A., 1985. Postlaunch corrections for Thematic Mapper 5 (TM-5) radiometry in the Thematic Mapper Image Processing System (TIPS), *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9 (Special LIDQA issue), pp. 1385–1390.

Slater, P. N., F. J. Doyle, N. L. Fritz, and R. Welch, 1983. Photographic systems for remote sensing, *Manual of Remote Sensing*, Second Edition, American Society of Photogrammetry, Vol. 1, Chap. 6, pp. 231–291.

Slater, P. N., 1984. The importance and attainment of absolute radiometric calibration, *Proceeding of SPIE Critical Review of Remote Sensing*, Vol. 475, pp. 34–40.

———, 1985. Radiometric considerations in remote sensing, *Proceedings of IEEE*, Vol 73, No. 6, pp. 997–1011.

———, 1987. Reflectance- and radiance-based methods for the in-flight absolute calibration of multispectral sensors, *Remote Sensing of Environment*, Vol. 22, pp. 11–37.

Slater, P. N., S. F. Biggar, R. G. Holm, R. D. Jackson, Y. Mao, M. S. Moran, J. M. Palmer, and B. Yuan, 1986. Absolute radiometric calibration of the thematic Mapper, *SPIE*, Vol. 6, pp. 2–8.

Spanner, M. A., D. L. Peterson, M. J. Hall, R. C. Wrigley, D. H. Card, and S. W. Running, 1984. Atmospheric effects of the remote sensing estimation of forest leaf area index, *Proceedings of Eighteenth International Symposium on Remote Sensing of Environment*, Paris, France, pp. 1295–1308.

Turner, R. E., W. A. Malila, and R. F. Nalepha, 1971. Importance of atmospheric scattering in remote sensing, *Proceedings of Seventh International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, pp. 1651–1697.

Vincent, R. K., 1973. Spectral ratio imaging methods for geological remote sensing from aircraft and satellites, *Proceedings of the American Society of Photogrammetry, Management and Utilization of Remote Sensing Data Conference*, Sioux Falls, South Dakota, pp. 377–397.