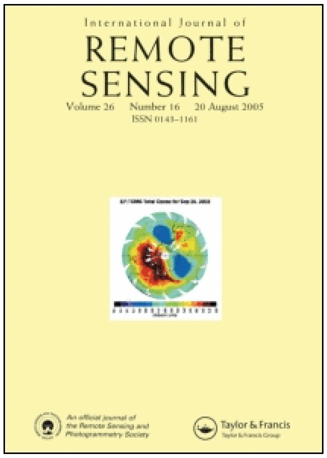

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Irradiance-based cross-calibration of Landsat-5 and Landsat-7 Thematic Mapper sensors

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Irradiance-based cross-calibration of Landsat-5 and Landsat-7 Thematic Mapper sensors

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Abstract. On 2 June 1999 Landsat-5 and Landsat-7 passed over north-central Nebraska collecting Thematic Mapper (TM) data for essentially the same spatial location, with an acquisition time differing by less than 20 min. At the Niobrara Nature Preserve, Nebraska site, two multifilter rotating shadowband radiometers (MFRSRs), a Cimel sunphotometer, a Microtops sunphotometer, and an ASD-FR spectroradiometer were used to take ground-based readings. This dataset offered a unique opportunity to absolutely calibrate both instruments, and also to cross-calibrate TM with Enhanced Thematic Mapper Plus (ETM+) the new thematic mapper aboard Landsat-7. ModTran3 radiative transfer code, based on the Nebraska datasets, was calibrated to match observed atmospheric transmittance and diffuse-to-global ratios, employing ground reflectance values, for each individual overpass. Having replicated those conditions, models were then extrapolated to satellite orbits, and exoatmospheric irradiances calculated. Finally, by obtaining actual imagery from each satellite, a cross-calibration comparison of the two satellites' TM sensor's responses was made.

1. Introduction

This paper will document the instrumentation, data collection procedures and results of a field campaign conducted at the Niobrara Nature Preserve (Niobrara) in north central Nebraska on 2 June 1999. The campaign was designed to collect a ground-based dataset that would allow for a vicarious calibration of both Landsat-7 (L-7) and Landsat-5 (L-5). L-7 was launched from Vandenberg Air Force Base on 15 April 1999. Prior to establishing its worldwide reference system orbit, both L-7 and the L-5 satellite collected Enhanced Thematic Mapper Plus (ETM+) and Thematic Mapper (TM) data on that date, for the same Niobrara spatial location,

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with an acquisition time differing by less than 20 min. Because the difference between acquisition times for both satellites was minor, this experiment was also designed to allow for a comparison of imagery from both satellites to be made. Representatives from Earth Resources Operation System (EROS) Data Centre (EDC) and from the science team at South Dakota State University (SDSU) took part in the experiment.

First, this paper specifically discusses procedures used to obtain ground-based measurements of downwelling irradiance, upwelling radiance and reflectance taken at the Niobrara site by the SDSU science team. Downwelling data were collected using two multifilter rotating shadowband radiometers (MFRSRs) produced by Yankee Environmental System®. Upwelling radiance and reflectance values were derived from measurements made using a single FieldSpec FR portable general purpose spectroradiometer (ASD-FR) produced by Analytical Spectral Devices, Inc.

The method used to perform the dual calibrations was both an irradiance- and reflectance-based approach (Slater *et al.* 1987, Thome *et al.* 1998), where results of measurements made with the above instruments were used as constraints in creating a subsequent radiative transfer code. This code, created by the SDSU science team using PCModWin3 (MODTRAN) software produced by the Ontar® Corporation, will be described in the second part of this paper. The modelling code first attempted to replicate the observations as recorded by the ground-level instruments and then, having satisfactorily reproduced those conditions, the model was then used to predict radiance values at the satellite sensor altitude. The paper details constraint data, and inputs that were varied to make the model's output match actual ground conditions. Resultant top of atmosphere (TOA) radiance values will also be given.

The third part of the calibrations involved analysing actual Niobrara imagery from both L-5 and L-7 that were acquired simultaneously with the collection of ground data during the dual overpass. For ETM+ and TM bands, respectively, digital numbers (DNs) corresponding to the target area were obtained. Calibration files associated with those particular scenes were used to derive bias values, and historical detector gain data were used to make corrections to those target area DN values. Initial digital values obtained corresponding to the target area, and corrections for gains and biases that were made are also given in this part.

Field data were collected in a high, open meadow (approximate area 0.7 km^2 and elevation 0.76 km) at the Nebraska site as shown in figure 1. A target area of 150 m × 150 m was centred in this meadow, which acted ideally as a large, spatially homogeneous region, being somewhat flat with native prairie grass as the primary ground cover. Five separate TM and ETM+ detectors sampled this large target area. On the morning previous to overpass, incident skies had been somewhat cloudy and hazy, but a later inspection of actual imagery confirmed visual observations of clear skies at scene acquisition time, suggesting low aerosol loading. The site selection and ultimate sky conditions during overpass were ideal for the approaches to calibration used in this experiment.

Two MFRSR instruments, SDSU's unit 316 and unit 318, were used in this experiment to report the direct, diffuse and global components of solar irradiance at seven different wavelengths, ultimately using five to derive inputs for later modelling efforts. The five channels used and their corresponding wavelengths are: channel 2 at 415 nm, channel 3 at 500 nm, channel 4 at 615 nm, channel 5 at 673 nm and channel 6 at 870 nm. Each channel of the MFRSR instruments has a bandwidth of 10 nm. The shadowband of each instrument acted to alternately expose and shade the instrument's diffuser, enabling measurement of all three irradiance components

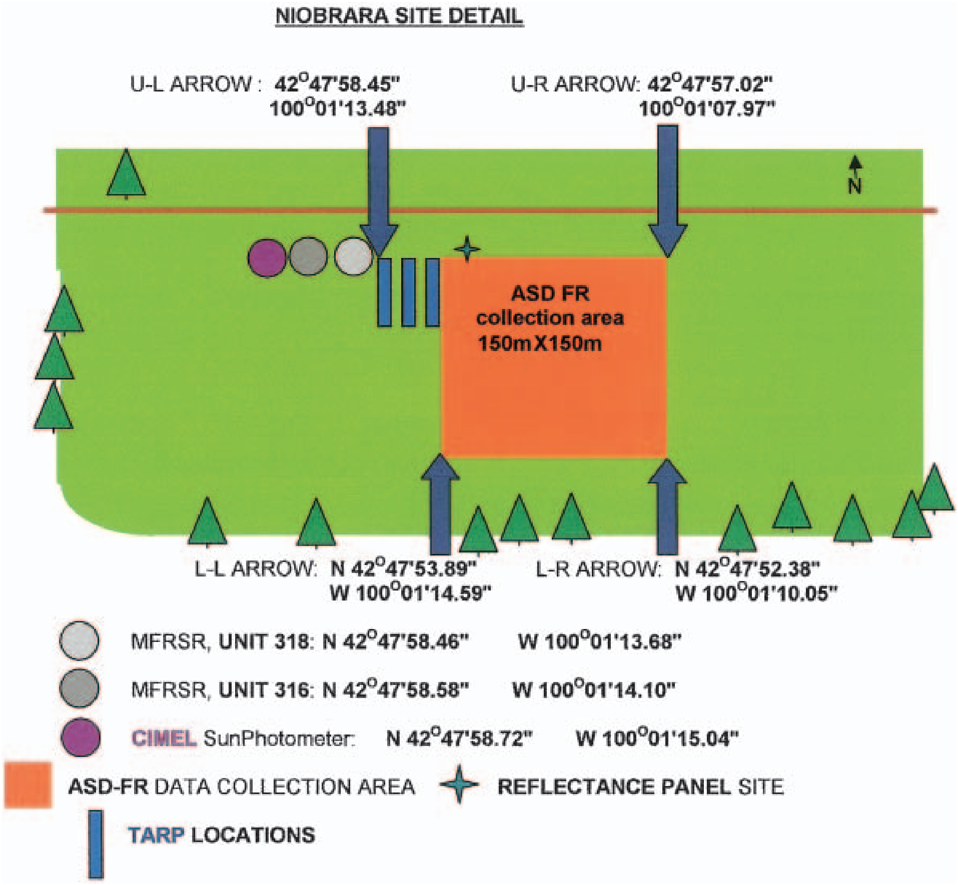

Figure 1. Site detail of Niobrara, Nebraska, target area.

using the same detector (internal software actually subtracts the angular corrected diffuse component value from the global irradiance to obtain the direct horizontal component). Measurement of both total and diffuse irradiance components using the same detector acted to minimize the introduction of systematic errors.

Accompanying software, combined with the initial programming capabilities of these units, allowed for numerous corrections and computations to be made with each dataset obtained. Cosine corrections due to solar angles (which are continuously updated and reported as part of each dataset), and Earth–Sun distance corrections were made. A TOA solar radiance value was also calibrated at each channel (distinct wavelength) of the instrument by means of a Langley regression analysis performed using MFRSR software, with the final TOA calibration used in this experiment being based on several historical, instrument-specific regressions (Yankee Environmental Systems, Inc. 1995a, b, Ontar Corporation 1997).

Both MFRSR instruments were erected at the field site on the evening prior to the two midday overpasses. This was done to enable sufficient data collection for a date-specific Langley analysis and subsequent TOA radiance values to be internally calibrated. These two radiometers recorded each of their three measures at 15 s intervals, and were run a full 40 min after the last satellite had passed.

On the morning of the overpass, an area of 150 m × 150 m was flagged as the target area, and three blue tarps (covering a 30 m × 30 m rectangle) were placed adjacent to this area to ensure pinpointing the exact location in the satellite imagery. The blue tarps significantly changed the DN value of a single pixel in both of the satellite scenes (noting that a scene pixel covers the same 30 m × 30 m area) and thus enabled location of the Niobrara target area by a visual inspection of those 2 June 1999 images. According to interpretation of calibration files by officials at EDC, L-5 was at nearest proximity (and capturing Niobrara imagery) at 12:02:14 cdt (Central Daylight Time) and similarly L-7 at 12:16:59 cdt.

The ASD-FR general purpose spectroradiometer was used at the times of overpass to sample the target area's light field. Measurements were made covering a 350–2500 nm spectral range. This instrument has three separate spectrometers, which converted incident photons into a digitized voltage measure that were post-processed into radiance values. Radiance values derived from the ASD-FR were obtained using an 8° cosine receptor attached to the end of the fibre optic cable. This foreoptic was pointed toward the ground and a height of 2 m was maintained as the field was canvassed. From the time of 11:41 until 12:19 cdt the entire field area was covered twice using the ASD-FR, and 9000 samples over that spectral range of 350–2500 nm were taken, with approximately 750 files recorded. Using a raw DN mode, an average of 50 samples was recorded at distances of approximately 10 m, with each record composing a file. The entire 150 m × 150 m target area was covered twice in this fashion.

Immediately after the radiance mode collections were made, the ASD-FR portable spectroradiometer was switched to a reflectance mode and, with the use of a 'white reference' panel, reflectance values were also calculated. In this mode, 1500 samples over the entire spectrum were measured. Reflectance measures were obtained in the same physical manner as DN values were recorded in the radiance mode, once again traversing the field, and 30 subsequent reflectance files were created.

Reflectance is a measure of the fraction of incident light that is reflected from a surface. The reflectance values recorded at the Niobrara field site are inherent properties of its vegetative cover, and independent of the light source. Because the ASD-FR can measure only light intensities, the SDSU Spectralon® panel, with a known reflectance value, was used to calculate field reflectance using a ratio of the ground cover radiance to that of the calibrated panel. This reference panel served as the white reference mentioned above. By computing the ratio of the raw field spectrum to that of the panel, characteristics of the instrument and the light source were cancelled out, and reflectance values for the target area obtained for that same 350–2500 nm spectral range.

The SDSU calibration panel used as a standard (white reference) at Niobrara has had accurate absolute reflectance measurements obtained by the University of Arizona Remote Sensing Group in 1997 (Schiller and Hawks 1997). Those absolute measures were obtained by comparison of the panel (a 45 cm × 45 cm two-piece composite) to a pressed halon panel prepared according to US National Institute of Standards and Technology (NIST) standards. The absolute reflectance as a function of illumination angle for the SDSU Spectralon panel is given in table 1. The angle referenced is that of the Sun's angle at times of overpass.

White reference measures were also conducted, and recorded, intermittently while collecting radiance files (ordering noted in site detail, figure 2), and immediately before reflectance data were collected. These white references were used to ensure optimal field measures of up-welling radiance.

Table 1. SDSU Spectralon panel reflectance values derived by the University of Arizona Remote Sensing Group in 1997. Wavelengths shown were chosen to compare with TM-band wavelengths. Illumination angles listed capture Sun zenith angles during times of Niobrara overpasses.

	Wavelength (nm)					
Illumination angle	500	550	650	860	1646	2208
25°	1.039	1.038	1.034	1.039	1.037	1.017
30°	1.034	1.032	1.031	1.034	1.031	1.01

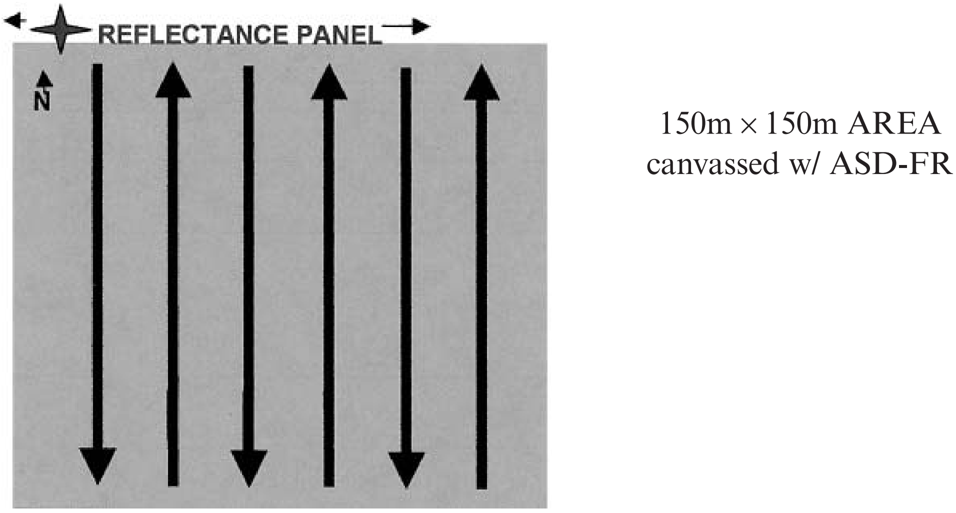

Figure 2. Diagram of ASD-FR field-pass routes for data collection within target area.

A chronological ordering for the collection of ASD-FR ground data in the target area is as follows: On a first pass, the entire field (target area) was walked with the ASD-FR operated in the raw DN mode. A white reference was first taken, then the field was walked from north to south on a first pass, traversed again south to north, another white reference was taken, followed by crossing the field on four more passes taking additional measures. A third white reference immediately followed that first canvassing of the complete target area, and a second complete pass of the field, still in a raw DN (radiance) mode, was conducted in the same fashion as the first. On a third and final measure of the target area, the ASD-FR was reconfigured to reflectance mode. After a fifth white reference dataset was collected, the western side of the target area was walked from north to south and back again creating two sets of reflectance files. Traversing each of the six rows combined to separate the field evenly, having approximately 18.5 m distance between each pass. Each of the passes referenced above was composed of a set of 15 records, taken at 15 m intervals along the path, each of which averaged 50 spectral samples. Each row pass, measuring up-welling radiance using the raw DN mode of the ASD-FR, combined to create 12 files, or a record of approximately 9000 radiance samples, between the times of 11:41 cdt and 12:20 cdt. Similarly, the surface reflection record created on 2 June

1999 between 12:24 cdt and 12:29 cdt in that Niobrara target area was based on approximately 1500 spectra measures from 350–2500 nm.

2. Data extraction

Each of the MFRSR units recorded three irradiance component measurements for each of the five channels (wavelengths) of interest, at 15 s intervals during the overpasses. Each line of output recorded for those intervals had a time value, the cosine of the zenith angle, and then the data from the unit in sequential order, first listing total-horizontal measurements for each channel, followed by the diffuse-horizontal components, followed by the direct-normal component regressions (Yankee Environmental Systems, Inc. 1995a, b, Ontar Corporation 1997). Accompanying software was used to apply angular corrections to these datasets based on an instrument-specific, factory cosine calibration. A time stamp accompanies each record, and was used to isolate a 4 min interval surrounding each overpass (L-5 and L-7), for each of the two instruments. For the specific times when L-5 and L-7 were capturing conditions in the Niobrara meadow, as seen from space, the shadowbands were recording conditions on the ground that allowed for calculation of a transmittance value and a diffuse-to-global ratio.

3. Transmittance

Transmittance is a measure of the fraction of incident light that passes through a material. In transfer code modelling, the light source is that of the Sun, and the material, or medium, that it passes through is the atmosphere. Transmittance values vary with wavelength, and indicate atmospheric conditions that actively dissipate that TOA energy (scatter light) as it travels to and is incident upon the Earth's surface. It is used as a primary criterion to match in initial attempts at atmospheric modelling, and allows for further parameters to be set. In using the shadowband data to calculate this ratio, the direct normal component recorded by the MFRSR in the binary file is first angular corrected and then adjusted for variations in the Earth–Sun distance (AU corrected). This value (I) is then divided by a TOA irradiance value (I_{zero}) obtained by Langley regression analysis from numerous unit-specific datasets.

Numerous Langley sets were used for a more accurate characterization of the instrument. Again, with the Langley analysis being based on actual MFRSR unit measures, and having been performed internally using the MFRSR software, each instrument was relatively calibrated. The final transmittance value used to create and check subsequent radiative transfer code for this calibration process was based on a 4 min average surrounding each satellite overpass, and then by averaging those two transmittance values from each of the two instruments as shown in equation (1).

$$\text{Transmittance} = \frac{I}{I_{zero}} \tag{1}$$

The transmittance values obtained at L-5 and L-7 overpass times are given in tables 2 and 3, respectively.

4. Diffuse-to-global ratio calculation

The second value calculated from MFRSR field measures is the diffuse-to-global ratio. It is an indication of how much energy is scattered in the atmosphere, and not arriving incident to the ground on a direct path from the Sun. In terms of instrument

Table 2. L-5 overpass: MFRSR calculated transmittance values. Accepted value is average of both units 316 and 318, with values from each an average of the 4 min interval surrounding L-5's scene centre time.

	Ch2 415 nm	Ch3 500 nm	Ch4 615 nm	Ch5 673 nm	Ch6 870 nm
Unit 316	0.649	0.793	0.838	0.876	0.976
Unit 318	0.639	0.763	0.839	0.874	0.938
Average	0.644	0.778	0.839	0.875	0.957

Table 3. L-7 overpass: MFRSR calculated transmittance values. Accepted value is average of both units 316 and 318, with values from each an average of the 4 min interval surrounding L-7's scene centre time.

	Ch2 415 nm	Ch3 500 nm	Ch4 615 nm	Ch5 673 nm	Ch6 870 nm
Unit 316	0.656	0.798	0.841	0.877	0.977
Unit 318	0.646	0.767	0.841	0.875	0.938
Average	0.651	0.782	0.841	0.876	0.957

Table 4. L-5 overpass: MFRSR calculated diffuse-to-global ratios. Accepted value is average of both units 316 and 318, with values from each an average of the 4 min interval surrounding L-5's scene centre time.

	Ch2 415 nm	Ch3 500 nm	Ch4 615 nm	Ch5 673 nm	Ch6 870 nm
Unit 316	0.226	0.133	0.075	0.062	0.051
Unit 318	0.228	0.132	0.076	0.061	0.050
Average	0.227	0.132	0.076	0.061	0.050

Table 5. L-7 overpass: MFRSR calculated diffuse-to-global ratios. Accepted value is average of both units 316 and 318, with values from each an average of the 4 min interval surrounding L-7's scene centre time.

	Ch2 415 nm	Ch3 500 nm	Ch4 615 nm	Ch5 673 nm	Ch6 870 nm
Unit 316	0.219	0.128	0.071	0.059	0.048
Unit 318	0.223	0.127	0.073	0.058	0.047
Average	0.221	0.128	0.072	0.058	0.047

irradiance values, it is the measured diffuse-horizontal component ($I_{\text{D-H}}$) divided by the measured total-horizontal component ($I_{\text{T-H}}$) as shown in equation (2). Again, this ratio enabled modelling efforts to capture the true nature of the prevailing atmospheric conditions and, after creating such code, served as the match criterion of replicating ground conditions before the modelling was propagated to the TOA.

$$\text{Diffuse/global ratio} = \frac{I_{\text{D-H}}}{I_{\text{T-H}}} \tag{2}$$

Diffuse-to-global ratios are given in tables 4 and 5.

5. ASD-FR data

The ASD-FR was used to record radiance and reflectance values found within the field site (Analytical Spectral Devices, Inc. 1994). As previously indicated, extensive sampling of ground conditions was conducted using this device. Reflectance values, shown in figures 3 and 4, were input into the transfer code to precisely shape and match the model to the field measurements at those overpass instances, and

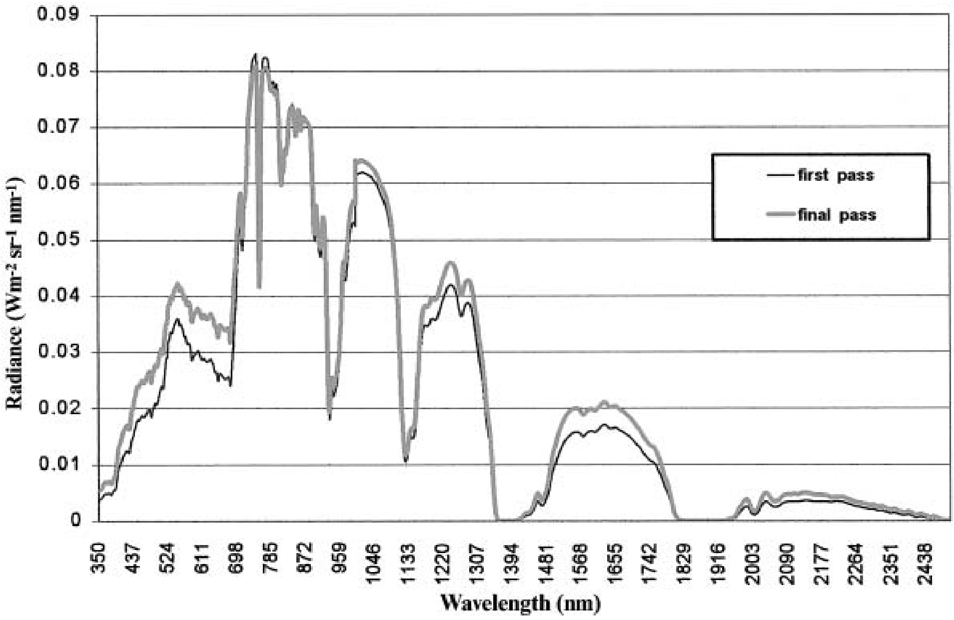

Figure 3. ASD-FR Niobrara radiance data showing measured change in up-welling radiance values from beginning of collection to final radiance-mode field pass.

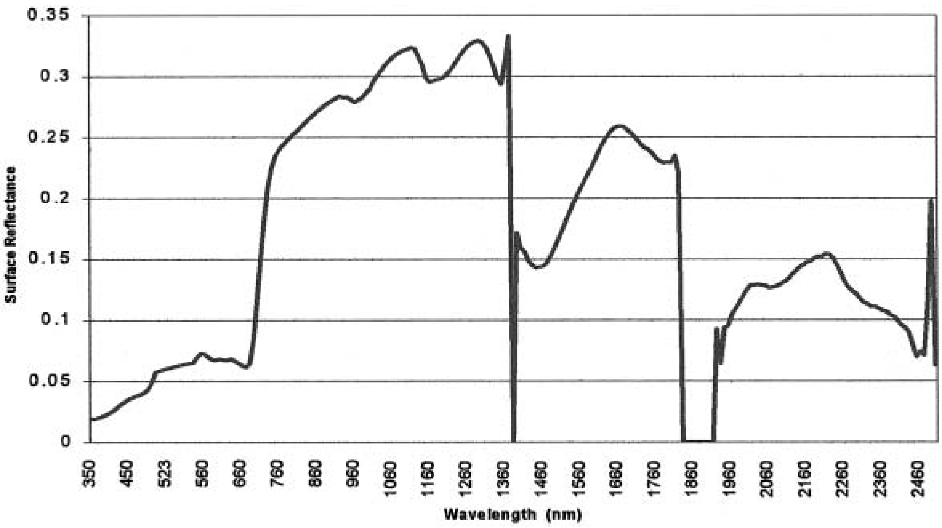

Figure 4. ASD-FR Niobrara surface reflectance values.

radiance values were used in comparison with the final ground-based model again to ensure that recorded conditions had been captured and replicated accurately.

6. Radiative transfer code modelling

Radiative transfer code based on the Niobrara data was developed using Ontar Corporation's PCModWin3 (MODTRAN) software and two versions, one for L-5 and one for L-7, were created. For each separate satellite version, transmittance-mode models were created and refined to match MFRSR-calculated transmittance values for each overpass incident. From these two transmittance codes, appropriate values for a necessary surface range input were derived, and subsequently used in the creation of the second set of radiance-mode models. The two sets of radiance-mode models (one for each satellite) were further refined to initially match MFRSR-based diffuse-to-global ratios at corresponding overpass times. Final acceptance of the radiance-based models came from their agreement with on-site radiance values obtained using the ASD-FR during the satellites' data acquisition times.

7. Transmittance mode models

The first radiative transfer code attempted to match Niobrara MFRSR calculated transmittance values using MODTRAN3 in a transmittance mode of execution. Inputs that were fixed within the model were the use of the 1976 US Standard Model Atmosphere with a choice of the slant path to space type of atmospheric path. The aerosol model used was a user-defined model with a visibility of 23 km. This choice of aerosol model allowed for the use of calculated aerosol optical thickness inputs that were based on relevant Niobrara ground data. This calculation process was perhaps the most involved of all efforts to create a successful transfer code, and is described in detail below.

Aerosol extinction inputs allowed the MODTRAN models to best replicate atmospheric conditions at Niobrara on 2 June 1999, and subsequently to achieve an acceptable fit when compared with ground data values. The attenuation of radiant energy as it passes through the atmosphere is referred to as extinction. Those transmittance values obtained using SDSU shadowband data were the starting point for calculating MODTRAN extinction input values.

Average transmission values (T) during a 4 min interval surrounding both (L-5 and L-7, respectively) overpasses were calculated, and then an average value for the two MFRSR units was calculated as above.

Those unit-average transmittance values for channel 2 (415 nm) and channel 6 (870 nm), both of which allow for aerosol extinction, were used to calculate total extinction (τ_{tot}) using the equation

$$T = e^{-\tau m} \tag{3}$$

where $m = 1/\cos\theta$ (θ = zenith angle at overpass). Cosine values were obtained directly from overpass-time-specific MFRSR datasets. Solving this equation for both channels and both overpasses yielded

$$\tau_{tot} = -\ln(T)\cos(\theta) \tag{4}$$

Then, knowing that total extinction is the sum of Rayleigh extinction (τ_{ray}) and aerosol extinction (τ_{aer}), the Rayleigh component was needed to finally isolate the desired aerosol component

$$\tau_{tot} = \tau_{ray} + \tau_{aer} \tag{5}$$

Rayleigh extinction was calculated using two separate equations. The first solution was obtained using the known Niobrara altitude, and the second solution was solved using known air pressure for the site and time.

The wavelength-specific equation to solve for Rayleigh extinction using known altitude obtained using a Global Positioning System receiver (GPS) at the target site was

$$\tau_{\mathrm{ray}} = (0.008735)(\lambda^{-4.08})(e^{-0.0001184z}) \quad (6)$$

where λ equals input wavelength in microns, and altitude (z) set equal to the altitude of 759.8 m at the Niobrara target site.

The second method of calculating a wavelength-dependent Rayleigh extinction coefficient used the atmospheric pressure value $P/P_0 = 0.9019$ for 2 June 1999 from National Oceanic and Atmospheric Administration (NOAA) reports at nearby Valentine, Nebraska. The equation used was

$$\tau_{\mathrm{ray}} = (0.008735)(\lambda^{-4.08})(e^{-0.0001184P/P_0}) \quad (7)$$

Pressure data used were time-correlated with respective overpass incidents. This calculation was then compared with the altitude-based value, and acted as a check.

By subtracting this calculated Rayleigh extinction from the total extinction values obtained for channels 2 and 6 (415 nm and 870 nm, respectively) of the MFRSRs, an aerosol extinction value for those two channels was derived. The Ångström power law was then used to predict aerosol extinction coefficients at specified MODTRAN input. The equation used was

$$\tau_{\mathrm{aer}} = \beta\lambda^{-\alpha} \quad (8)$$

Using newly derived ordered pairs to solve for alpha (α) and beta (β), inputs at specified MODTRAN wavelengths were calculated using that equation, and then those values were normalized with respect to the 0.55 μm wavelength (as expected by the model). Extinction coefficients are given in table 6.

Table 6. Total extinction values were derived from transmittance values and used to calculate aerosol extinction coefficients. Rayleigh extinction values for channels 2 and 6 calculated using both altitude and air pressure. Calculated L-5 and L-7 aerosol extinction values are equal to the total extinction minus Rayleigh extinction.

	L-5 average		L-7 average	
	Ch2 415 nm	Ch6 870 nm	Ch2 415 nm	Ch6 870 nm
Transmittance	0.644	0.957	0.651	0.957
Total extinction (τ)	0.386	0.038	0.385	0.0390
Rayleigh extinction (τ_{ray})				
Calculated using altitude	0.289	0.014	0.289	0.014
Calculated using P/P_0	0.285	0.014	0.285	0.014
Aerosol extinction (τ_{aer})				
Calculated using altitude	0.097	0.024	0.096	0.025
Calculated using P/P_0	0.101	0.024	0.100	0.025

The seasonal modifications to aerosols input parameter was set at spring–summer and the upper atmospheric aerosols (30–100 km) input was set at background stratospheric.

The input parameter in the MODTRAN transmittance model that is adjusted to force the output to best match with above MFRSR transmittance values was the surface range for the boundary layer. After all other constraint inputs have been entered and subsequent models run, that surface range parameter acted as the 'fine tune' adjustment. Other constraint inputs included ground altitude of the target area (0.76 km, GPS) and the altitude of the MFRSR units (0.762, 2 m above ground level). The Sun zenith angle at the midpoint of scene acquisition (28.94°, as obtained from the Astronomical Applications Department of US Naval Observatory's web page (US Naval Observatory)), along with GPS measured latitude, longitude and time, were also input into the transmittance models.

What the transmittance mode models of the Niobrara event accomplished was a determination of a surface range parameter that could then be transferred to modelling in the radiance mode of MODTRAN. Again, having all other inputs described being fixed within the model, this boundary range for surface layer parameter was adjusted with each model until model transmittance values matched MFRSR calculated values, minimizing combined error at the five wavelengths under consideration. Changing this input parameter acted to change aerosol profiles at altitudes near the Earth's surface and, in relation to output diffuse-to-global ratios, acted to increase or decrease their magnitude. The final accepted transmittance models for both L-5 and L-7 had a surface range value of 150 km. Transmittance models for L-5 and L-7 are shown in figures 5 and 6.

8. Radiance mode models

Having determined the necessary surface range parameter using the transmittance mode of MODTRAN, new models could then be created, switching to a radiance

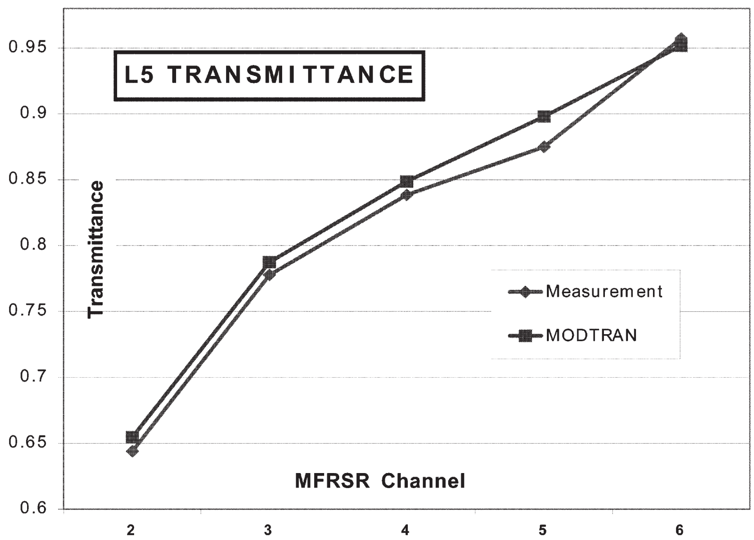

Figure 5. Graphical comparison of MFRSR calculated L-5 transmittance values and MODTRAN Niobrara transmittance-mode models.

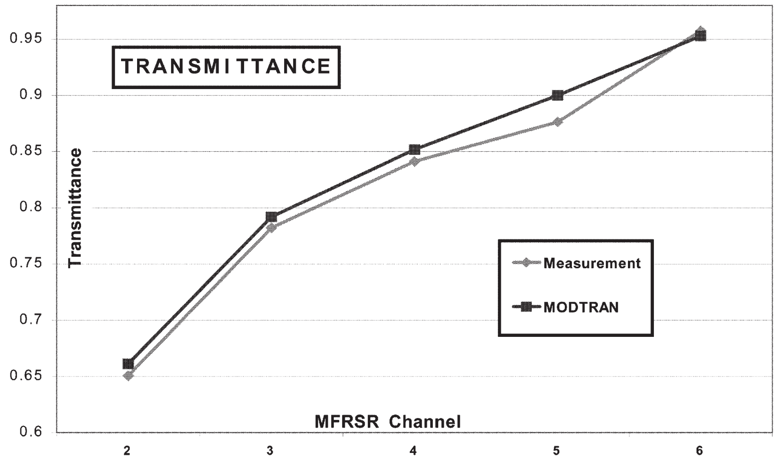

Figure 6. Graphical comparison of MFRSR calculated L-7 transmittance values and MODTRAN Niobrara transmittance-mode model.

mode, to match primarily MFRSR-based diffuse-to-global ratios and ultimately to replicate ground-based radiance values. Necessary inputs defining 2 June 1999 ground conditions during overpass events were again entered along with the above calculated extinction coefficients. Also added to the new models were the ground-based reflectance values measured using the ASD-FR. Those reflectance inputs allowed for a precise fitting of L-5 and L-7 radiance model outputs to measured field data.

Radiance mode parameters best describing Niobrara conditions again used the MODTRAN 1976 US Standard Model Atmosphere with a slant path to space atmospheric path and a radiance with scattering mode of execution. Both radiance models also used the multiple scattering option. In choosing to use multiple scattering, more than one scattering event is allowed, with the two primary sources being molecular scattering and particle (aerosol) scattering. Molecular scattering is a significant factor in the visible wavelength regions, and particle (aerosol) scattering can play a significant role out into the near- and mid-infrared regions. The final model used a disort scattering algorithm with four streams within the multiple scattering input. As in transmittance modelling, the aerosol model was user defined, again allowing for the previously calculated aerosol extinction coefficients to be input at specified wavelengths. Spring–summer season-dependent and background stratospheric upper-atmosphere modifications were also made to that aerosol model within the code. Necessary Sun angles, site and observer altitude, and day of year were also input.

The surface albedo input card of MODTRAN allowed for using a reflectivity that could be varied as a function of wavelength, and the ASD-FR measured target area values were input. Surface albedo was defined here as being the reflectivity of the radiating surface at the start of the path. In both L-5 and L-7 radiance mode models, 100 Niobrara reflectance values were entered in the spectrum ranging from 350–1800 nm to create models that covered bands 1–5 of the TM (and ETM+) sensors.

Because of technical problems encountered at Niobrara due to equipment overheating, separate band 7 radiance models were created for both L-5 and L-7 overpass incidents. Input parameters in those radiance mode models were the same as for bands 1–5, with the exception of creating a separate set of 50 reflectance inputs (surface albedo card in MODTRAN). Reflectance values used for L-5 and L-7, band 7, models were based on a simple ratio of field radiance measures to a particular white reference that was not heat corrupted within that particular spectrum. (Reflectance values were input over a range of 1950–2425 nm, which encompasses band 7 for both TM and ETM+ sensors.)

Adjusting the surface range parameter was necessary due to the fact that surface albedo input was fixed by inputting measured surface reflectance values. Past modelling efforts by the science team adjusted that input parameter to achieve an acceptable match to diffuse-to-global ratios. In this experiment, a compromise had to be reached. By adjusting the surface range parameter, agreement between the transmittance mode models and MFRSR-calculated transmittance was offset, but the difference was only minor. Past experience indicated that the MFRSR overcompensates for solar aureole effects, so it was determined that actual diffuse-to-global ratios should be higher than the ratios based on Niobrara MFRSR field data. Minimizing errors between model outputs and field-based calculations for both transmittance and diffuse-to-global ratios was the criterion for accepting a final surface range value. Figure 7 shows diffuse-to-global ratios for various surface range values in comparison to field measurements for L-7. Figure 8 gives the best match between model and measurement.

As a final assurance check of both L-5 and L-7 ground-level radiance models, a comparison to Niobrara ASD-FR radiance values was made, and the model was shown to have a good fit to those datasets as shown in figure 9.

The radiance mode models were considered acceptable after differences between MODTRAN output and those obtained from MFRSR field data were minimized. It is important again to note that these models had the observer height parameter set at 2 m, the same as the height of the MFRSR instruments in the field. Seeing that an acceptable match had been achieved, those radiance values (r_{surface}) were

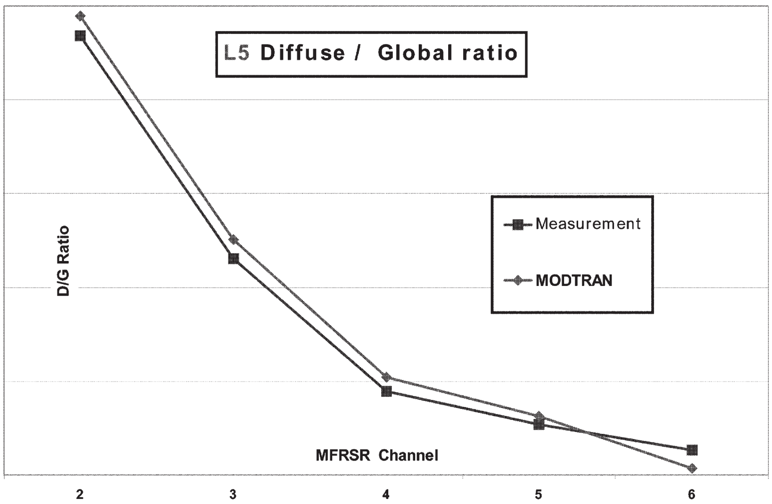

Figure 7. Graphical comparison of MFRSR measured L-5 diffuse-to-global values and MODTRAN models.

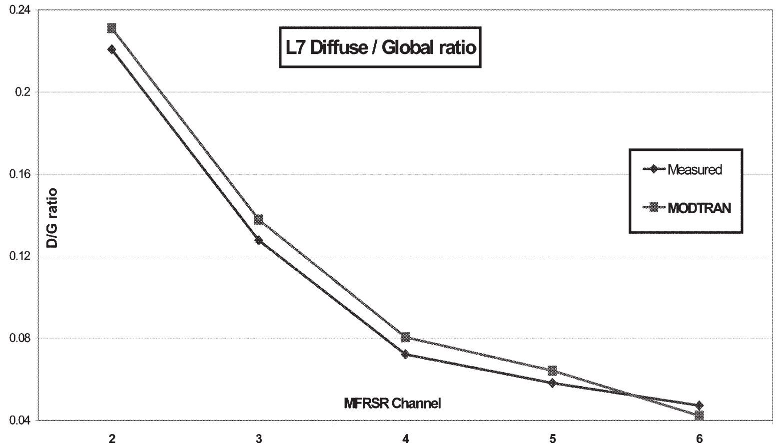

Figure 8. Graphical comparison of MFRSR measured L-7 diffuse-to-global values and MODTRAN models.

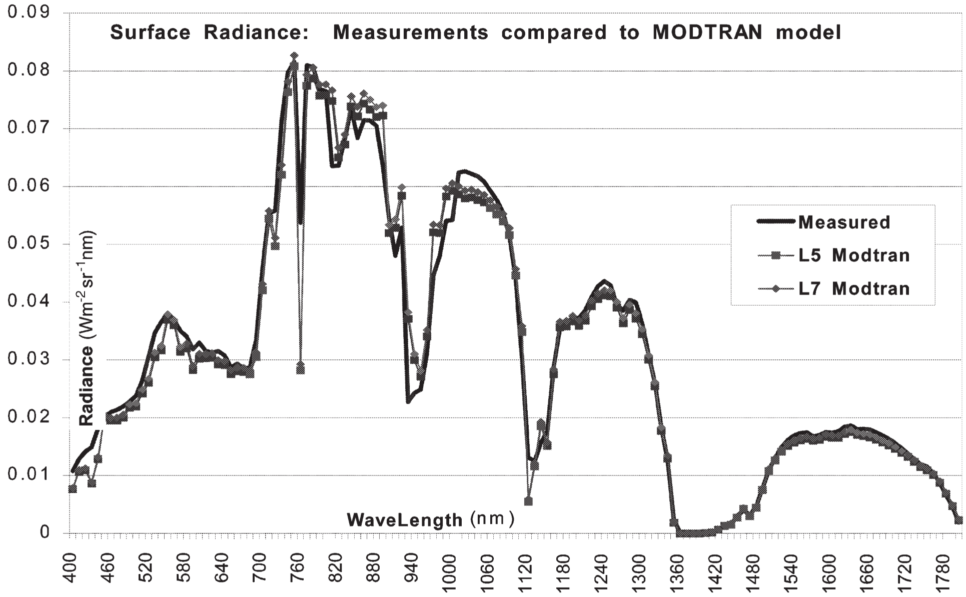

Figure 9. Comparison of measured surface radiance and MODTRAN model.

then propagated to the satellite level by changing that parameter to 100 km, or to the TOA. The equation used to compute at sensor radiance was

$$r_{\mathrm{sensor}} = Tr_{\mathrm{surface}} + r_{\mathrm{path}} \tag{9}$$

where r_{surface} is up-welling surface radiance and r_{path} is path radiance.

Having changed the models to compute radiance values at an exoatmospheric level, it was necessary to determine how the satellite sensors actually recorded those values. To make this determination, relative spectral response (RSR) curves reported by Markham in the L-7 Calibration Parameter File (Markham 1999) were consulted. They served to define the effective bandwidth for each band of each respective satellite. After TOA radiance values were extracted for each band, those values were interpolated using appropriate TM and ETM+ RSR curves. Figure 9 shows up-welling radiance measurements predicted by the MODTRAN model in comparison with measured up-welling radiance.

9. Satellite data extraction

The equation associated with obtaining correct DN values from imagery is

$$DN_{COR} = \frac{DN_{RAW} - \text{bias}}{\text{gain}_{REL}} \tag{10}$$

Detector bias must be removed and differences in relative detector gain must be normalized. Implementing the above equation involved three separate efforts of extracting data from satellite imagery. The first step examined Niobrara scenes from both L-5 and L-7. The target area was easily located by visually observing the single adjacent pixel brightened by the blue tarps, and DN values (DN_{RAW}) within the 150 m × 150 m area were recorded. This was done on a band-by-band basis for both scenes. Because the tarps corrupted adjacent pixels in both scenes, a 120 m × 150 m area was ultimately considered in the calibration efforts. A check of adjacency effects was also made via a comparison of the average DN values found within the target area to a histogram of DN values found in a larger 2 km^2 area centred about that target area. It was found that site pixel values were not significantly different from adjacent pixel values.

The second extraction of data from imagery was a calculation of relative detector gains (gain_{REL}). Gain values for each scene were collected in a detector-specific process by matching detectors with line numbers of the images based on scan lines. For L-5 Niobrara imagery, an unpublished work at EDC was used (Benson and Morfitt 1999). In that study, historical gain values had been tracked from 1985 to 1993 and values for June 1999 were extrapolated band by band for each TM detector. For the ETM+, the Calibration Parameter File (CPF) was referenced for the latest (June 1999) L-7 detector gain values. With all relative detector gain calculations, only values for detectors involved with acquisition of imagery within the 150 m × 150 m target area were used. For gain values used in this calibration effort, a normalized, relative detector gain was calculated by dividing that specific detector's gain value by the average gain value for all detectors involved in the target-site scene.

The final satellite-specific bias values needed were obtained from the calibration files associated with both L-5 and L-7 Niobrara scenes. This data extraction was also done on a band-by-band, detector-specific basis. Based on the line number (corresponding to a specific detector) capturing target site imagery, 500 pixel values from that same numbered line of the associated calibration file were averaged. Those values constituted band-specific bias values on a detector-by-detector basis.

10. Band gain calculation

The final step in this calibration effort was deriving band gain values for bands 1–5 and band 7 of the TM and ETM+ sensors. Band gain is a ratio, relating scene DNs to radiance values. For those bands considered, band-detector-specific bias values were subtracted from individual pixel DNs line by line. Those values were then divided by their corresponding normalized detector gains. Having removed relative gain and bias effects detector by detector, target area pixel DN values were averaged. This average DN value representing the target area was divided by

RSR corrected at-sensor radiance to obtain the desired band gain value in units of DN/radiance. Average band gains are shown in table 7.

11. Conclusions and error analysis

Band gains obtained from the Niobrara campaign are compared with L-7 prelaunch calibration values in table 8. The results are generally in good agreement with differences less than 5%, with the exception of band 4 which differs by approximately 10%. This lack of agreement may be attributable, at least in part, to a drift error within the MFRSR units.

Gain comparisons for L-5 are shown in figure 10. Here the asterisks indicate vicarious calibrations completed by the Remote Sensing Group of the Optical Sciences Center at the University of Arizona. The final calibration in the figure indicates the results obtained from the Niobrara campaign. The solid line represents estimates of instrument gain based on the internal calibrator. The data clearly indicate a non-constant gain over the lifetime of the instrument. Good agreement exists with the exception, again, of band 4 and of band 7. Differences in band 7 may be due to the limited spectral coverage afforded by the MFRSR units and the necessary extrapolations may not have been accurate.

The SDSU MFRSR units used at the Niobrara site were factory calibrated in the autumn/winter of 1998. Transmittance and diffuse-to-global ratio values used differed by no more than 3% between both units. On the individual unit basis, both ratios varied by less than 0.2% during 4 min intervals surrounding overpass incidents

Table 7. Calculated L-5 TM and L-7 ETM+ band gain values. L-7 bands are all set in high gain.

	Average band gains (DN/[W m^{-2} sr^{-1} μm^{-1}])	
Band	L-5	L-7
1	1.221	1.244
2	0.662	1.201
3	0.904	1.570
4	0.980	1.378
5	7.681	7.323
7	16.91	23.34

Table 8. Comparison of Niobrara L-7 ETM+ calibration with CPF calibration. L-7 bands are all set in high gain.

	L-7 average band gains (DN/[W m^{-2} sr^{-1} μm^{-1}])	
Band	CPF	Niobrara
1	1.211	1.244
2	1.161	1.201
3	1.519	1.570
4	1.533	1.378
5	7.601	7.323
7	22.55	23.34

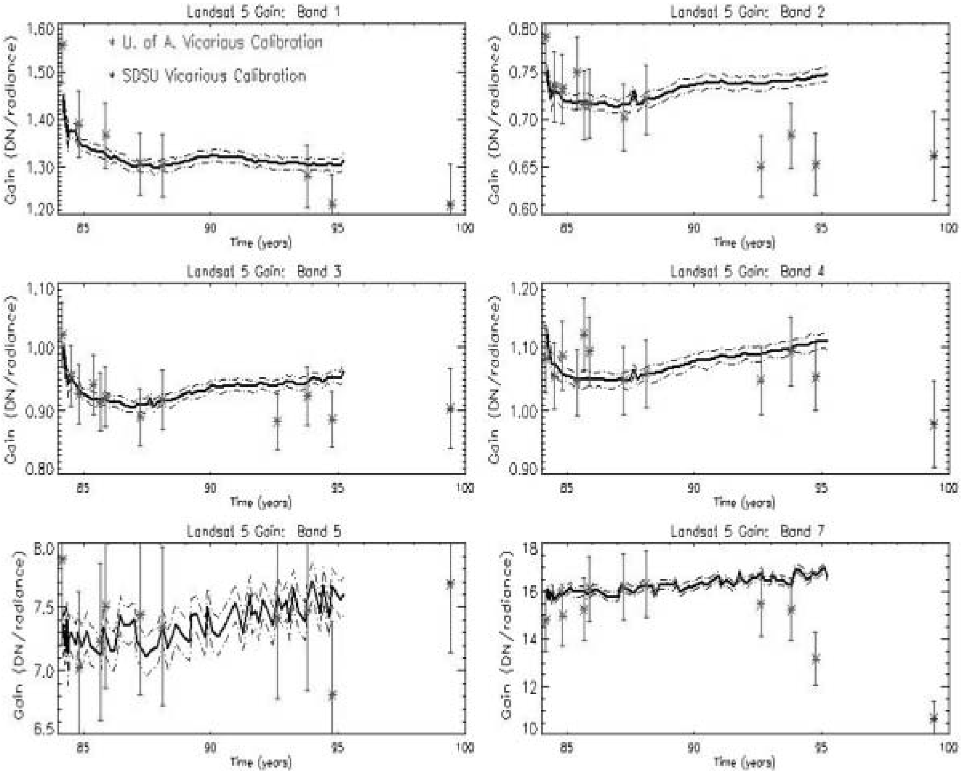

Figure 10. Comparison of Niobara L-5-bend gains with University of Arizona. Remote Sensing [Group's previous calibrations.]

for both units. Up to eight Langley regressions were used for each MFRSR band in the calculation of transmittance, and those values had standard deviations of less than 5% for all channels. Although further analysis is warranted, preliminary calculations place the absolute accuracy of the units at less than 5%. Other similar calibration efforts have claimed errors of less than 4% (Brown *et al.* 2001).

The ASD-FR was factory calibrated in the spring of 1999 and is claimed to have an error of 2% or less. Field data used in this calibration were time-centred about overpass incidents, so the accuracy is strictly based on that spectroradiometer's performance. ASD-FR units were continually optimized during Niobrara data collection to account for changing atmospheric conditions. A NIST standardized calibration of the SDSU reflective panel put errors in reflectance calculations based on that standard at less than 4% (Schiller and Hawks 1997). Calibrations done at SDSU, combined with the field data obtained in this Niobrara campaign, place errors at less than 5% within the visible range (Brown *et al.* 2001).

The radiative transfer code introduces error through the introduction of calculated extinction coefficients. The values used here were calculated in two ways using both altitude and air pressure measures. Comparisons were made to two other sunphotometers used on that day, and all values considered were within 10% of one another. Comparison of the radiance mode models created in MODTRAN to MFRSR-based diffuse-to-global ratios showed differences of up to 15% for one unit at 870 nm, but most errors were under 10%. Propagating ground-based calculations to TOA has been shown not to significantly propagate errors found in those models using an at-surface altitude (Biggar *et al.* 1994).

In this report, a first ground-based calibration of L-7 ETM+ imagery has been accomplished with results fairly consistent with prelaunch values. Clearly further campaigns are necessary to establish the gain of the ETM+. Results also indicate that L-5 gain has been fairly stable since 1987. Results from this campaign are in general agreement with what has been reported by others with the possible exception of bands 4 and 7. Both instruments could benefit from regular vicarious calibration campaigns so that gain can be more accurately calculated and monitored.

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