Thematic Mapper Thermal Infrared Calibration

John R. Schott and *William J. Volchok*
Digital Imaging & Remote Sensing Laboratory/SPAS, Rochester Institute of Technology, One Lomb Memorial Drive, P.O. Box 9887, Rochester, NY 14623

ABSTRACT: TM band 6 data from Landsat-4 and Landsat-5 are analyzed by correcting the observed radiance for the spectral characteristics of the sensor, along with atmospheric propagation parameters derived from LOWTRAN models. The resultant surface radiance values or surface temperatures are compared to surface temperatures derived from underflight and ground truth data. Correlation of these data indicate that significant systematic error is evident in the satellite-derived surface temperatures. Evaluation of the expected error introduced by the LOWTRAN modeling technique results in compensation of some of this systematic error. The remaining error indicates that the satellite internal calibration, specifically the sensor gain, corrections are not completely compensating for gain shifts.

INTRODUCTION

THIS PAPER REPORTS on the initial results of a study with a two-fold purpose. The first objective was to evaluate the postlaunch radiometric calibration of the Landsat Thematic Mapper (TM) band 6 data. The second objective was to determine to what extent surface temperatures could be computed from the TM band 6 data using atmospheric propagation models. To accomplish this, ground truth data were compared to a single TM-4 band 6 data set. This comparison indicated satisfactory agreement over a narrow temperature range. However, systematic errors were apparent which could not be adequately evaluated using only the available ground truth data. Subsequently, a thermal infrared line scanner mission was flown under the satellite on 22 June 1984 in the vicinity of Rochester, NY (Plate 1). The underflight data permit direct measurement of surface temperature over large areas for direct correlation with the spacecraft data. In addition, the underflight data can be used to measure atmospheric effects for comparison to the atmospheric propagation models. This study indicates that the satellite is experiencing postlaunch shifts in gain which are not being adequately compensated for at the present time. The magnitude of this effect on the one data set studied is an increase in apparent gain of approximately 43 percent. This would result in significant errors in predicted temperatures. However, if underflight data or appropriate surface truth are available, then the sensor can be calibrated to yield surface temperatures. In the present study, the residual error for 48 points over a 26°K temperature range was 2°K. No attempt to significantly improve this result through systematic analysis of outliers or correction for recognized errors in some of the ground truth data has been attempted to this point. So we would expect this to be an upper bound on the error in use of the TM band 6 data if underflight calibration is used. It is not yet clear whether the gain shift is consistent or observable from TM housekeeping data such that it could be corrected in the computer compatible tape (CCT) P-data. Further analysis of additional underflight data is planned in an effort to address this question.

EXPERIMENTAL BACKGROUND

As part of the National Aeronautics and Space Administration (NASA) Heat Capacity Mapping Mission (HCMM) experiment, the U.S. Air Force Cambridge Research Laboratory's LOWTRAN code was used to produce atmospheric models in an attempt to evaluate the postlaunch radiometric response of the Heat Capacity Mapping Radiometer (HCMR). Bohse *et al.* (1979) describe how surface radiometric readings were used in conjunction with radiosonde data to predict the radiance at the top of the atmosphere using atmospheric propagation models. As a result of these analyses, NASA offset the prelaunch calibration values for this sensor by −5.5°K (NASA, 1980). Similar studies five months later indicated that the offset should be moved back to the original value (Subbarayudu, 1979). These results indicated that either initial shifts in the HCMR response function were compensated for by long term calibration drift, and/or the variances exhibited were due to atmospheric effects insufficiently accounted for by the atmospheric propagation models. Schott (1979) found that atmospheric effects could be accounted for by imaging at multiple altitudes with an aerial infrared line scanner. Using this profile technique, Schott and Schimminger (1981) successfully calibrated the HCCM satellite resulting in radiometric calibration of the

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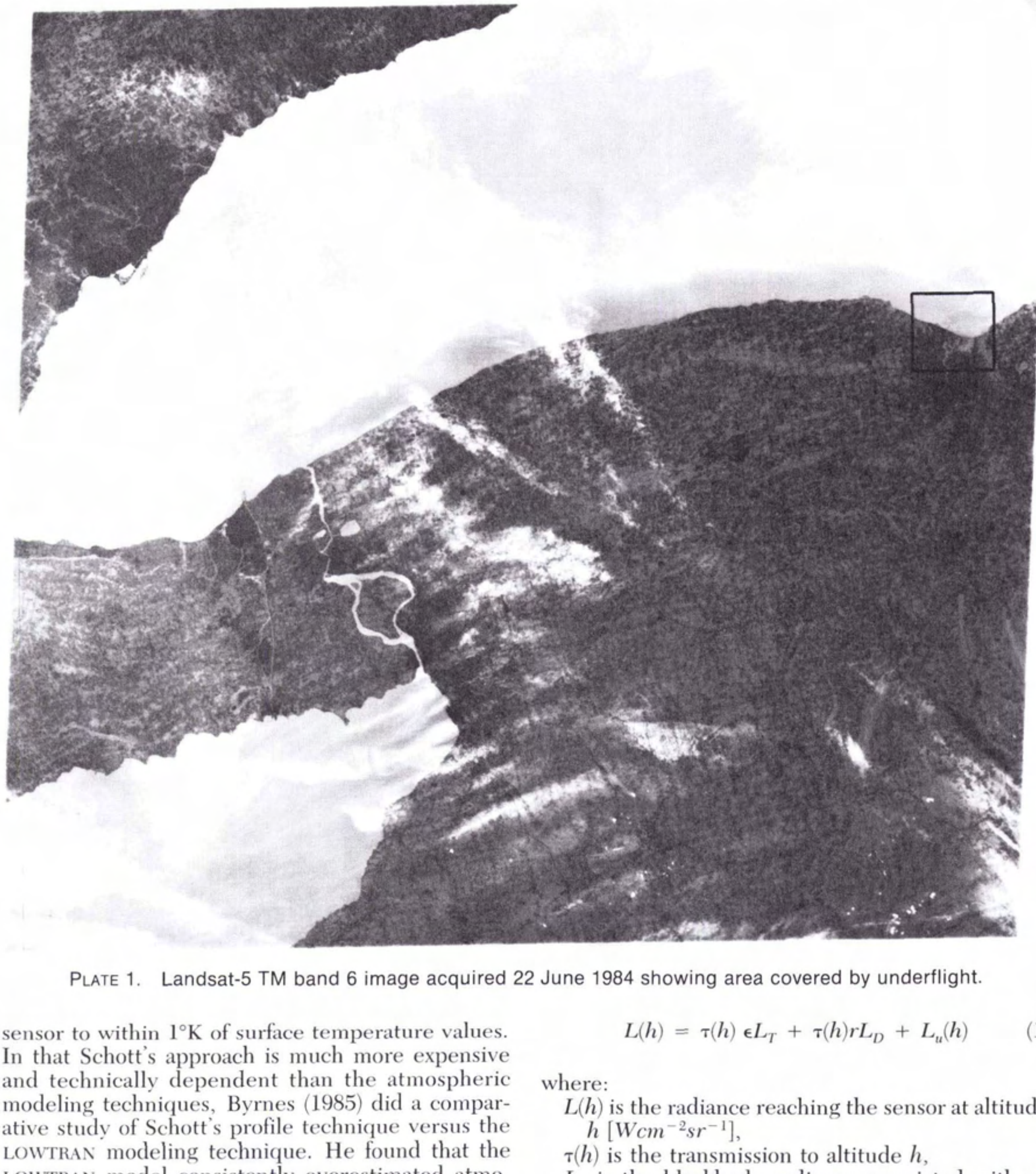


PLATE 1. Landsat-5 TM band 6 image acquired 22 June 1984 showing area covered by underflight.

sensor to within 1°K of surface temperature values. In that Schott's approach is much more expensive and technically dependent than the atmospheric modeling techniques, Byrnes (1985) did a comparative study of Schott's profile technique versus the LOWTRAN modeling technique. He found that the LOWTRAN model consistently overestimated atmospheric transmittance with respect to the profile technique. In the current study, both the profile and a modified LOWTRAN technique were applied to the satellite data in an effort to check the sensor postlaunch calibration and evaluate the effectiveness of the radiation propagation models in estimation of atmospheric effects.

THEORETICAL BACKGROUND

The radiance reaching an airborne or satellite sensing system can be expressed as (c.f., Figure 1):

$$L(h) = \tau(h)\, \epsilon L_T + \tau(h) r L_D + L_u(h) \qquad (1)$$

where:

- $L(h)$ is the radiance reaching the sensor at altitude h $[Wcm^{-2}sr^{-1}]$,
- $\tau(h)$ is the transmission to altitude h,
- L_T is the blackbody radiance associated with an object on the ground with temperature T $[Wcm^{-2}sr^{-1}]$,
- ϵ is the emissivity of the surface observed,
- r is the reflectivity of the surface observed ($r = 1 - \epsilon$),
- L_D is the downwelled radiance from the sky integrated over the hemisphere above the surface $[Wcm^{-2}sr^{-1}]$ and,
- $L_u(h)$ is the upwelled radiance from the air column between the surface and the sensor at altitude h $[Wcm^{-2}sr^{-1}]$.

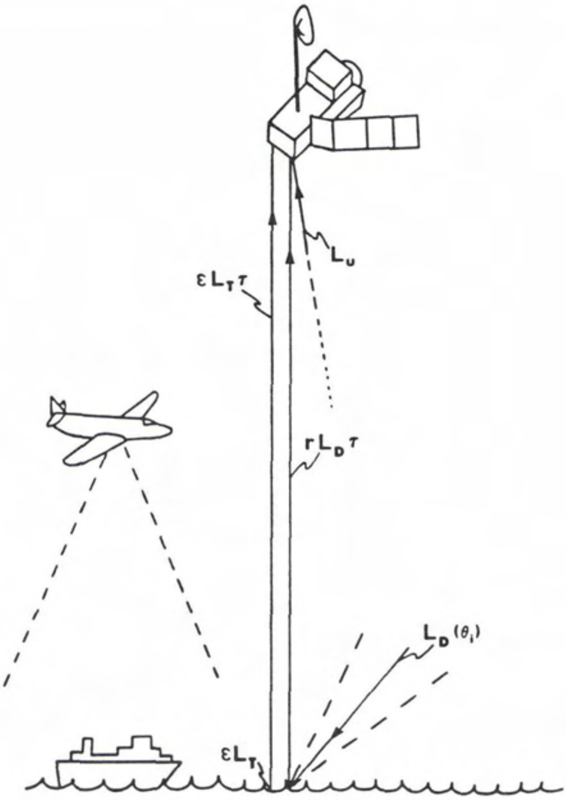


FIG. 1. Illustration of Energy Paths for Radiance Reaching a Satellite Sensor.

All the parameters in Equation (1) are the integrated values over the bandpass of interest.

LOWTRAN Technique

To compute the kinetic temperature of an object, it is necessary to solve Equation (1) for L_T and then solve the Planck radiation equation to find T (this is simplified with a look-up table). For the Landsat case, the transmission, τ, and path radiance, L_u, were computed using the LOWTRAN propagation model. The model was modified using the approach suggested by Ben-Shalom (1980). The atmospheric model was defined using radiosonde data from a sonde released from Buffalo, NY at 7 a.m. on the dates of the overpass. These data were modified to adjust the low altitude values to reflect the conditions occurring at Rochester, NY (60 miles away) at 9:30 a.m. when the satellite passed overhead. The value of L_D was obtained by computing the radiance a sensor on the ground would receive if it looked to space at an angle θ from the normal. From these $L_D(\theta,\phi)$ values, L_D is obtained by numerical integration of the contribution from each point on the hemisphere above the sample, i.e.,

$$L_D = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} [L_D(\theta,\phi) \cos(\theta) \sin(\theta)\, d\theta\, d\phi]/\pi \quad (2)$$

where ϕ is an azimuth angle.

The emissivity and reflectivity values are a function of material type. In this study, direct comparisons to kinetic temperature were made only for water and an emissivity value of 0.986 was used (Saunders, 1967).

The spectral radiance values computed by the modified LOWTRAN code and Equation (1) were cascaded with the sensor response function to yield the integrated radiance values observed by the sensor i.e.,

$$L_\beta(h) = \left[\int_{\lambda_1}^{\lambda_2} L_\lambda(h)\beta_\lambda d\lambda / \int_{\lambda_1}^{\lambda_2} \beta_\lambda\, d\lambda \right] (\lambda_2 - \lambda_1) \quad (3)$$

where:

$L_\beta(h)$ is the integrated radiance observed by the sensor incorporating the spectral response characteristics of the sensor $[Wcm^{-2}sr^{-1}]$,

$L_\lambda(h)$ is the spectral radiance reaching the sensor as computed by the modified LOWTRAN code $[Wcm^{-2}sr^{-1}\mu m^{-1}]$,

β_λ is the relative spectral responsivity of the detector (Markham and Barker, 1983) and,

λ_1 and λ_2 are the passband limits of the sensor $[\mu m]$.

Revised atmospheric transmission and path radiance values were also computed using the LOWTRAN code incorporating the sensor's spectral characteristics.

To compute water surface temperatures from satellite data, the digital counts were converted to blackbody equivalent radiance values using the sensor calibration data supplied by NASA i.e.,

$$L_\lambda = ((R_{max} - R_{min})/255)DC + R_{min} \quad (4)$$

where:

L_λ is the mean spectral radiance over the bandpass of interest incorporating the sensor response function $[mWcm^{-2}sr^{-1}\mu m^{-1}]$,

R_{max} and R_{min} are the maximum and minimum scene radiance from the Landsat CCT header $[mWcm^{-2}sr^{-1}\mu m^{-1}]$,

DC is the TM band 6 digital count.

The surface radiance values were then computed using the revised transmission and path radiance values according to Equation (1). The surface temperature values could then be computed by reverse analysis of the Planck equation (incorporating sensor effects).

The conversion process can be simplified using an equation developed by Lansing and Barker* (1983) for TM-4 band 6, as:

* N.B. This fit was not used here but is in excellent agreement with the look-up tables used in this analysis.

$$T = K_2/(Ln(K_1/L + 1)) \quad (5)$$

where:

L = spectral radiance $[mWcm^{-2}sr^{-1}\mu m^{-1}]$
K_1 = 67.162 $[mWcm^{-2}sr^{-1}\mu m^{-1}]$ K_2 = 1284.3K for TM-4 (Lansing and Barker, 1983)
K_1 = 60.776 $[mWcm^{-2}sr^{-1}\mu m^{-1}]$ K_2 = 1260.56K for TM-5 (NASA, 1984).

Profile Technique

The LOWTRAN technique can also be used to calibrate thermal infrared aircraft data. However, its accuracy is not as well defined. The underflight data were, therefore, calibrated using the profile method developed by Schott (1979). This method has been repeatedly tested and demonstrated to yield predicted temperatures within 0.4°K (standard error) of the kinetic temperature values.

This method involves repeated overflights of selected target objects at varying altitudes. The image data recorded at each altitude are converted to radiance data using internal systems calibration. The radiance data from each of several objects with different radiance levels are plotted against observation altitude. The shape of the functional relationship between the radiance reaching the sensor and altitude is defined by LOWTRAN. The profile data are then fitted to zero altitude by least squares fit to curves whose shape is defined by LOWTRAN. Figure 2 illustrates the least squares fit of the LOWTRAN models to specific profile data points. Note the change in the LOWTRAN model curve due to corrections in radiosonde data. For any altitude sampled, it is then possible to express the radiance observed for each object i as:

$$L_i(h) = \tau(h)\, L_i(0) + L_u(h) \quad (6)$$

where:

$L_i(h)$ and $L_i(0)$ are respectively the radiance reaching the sensor at altitude h from the ith object and the radiance on the ground from the ith object, i.e.,

$$L_i(0) = \epsilon_i L_T + r_i L_D \quad (7)$$

A linear regression of $L_i(h)$ against $L_i(0)$ for several objects with varying radiance levels yields the transmission and path radiance terms (c.f., Equation 6). This process can be repeated at each altitude to characterize the atmospheric transmission and path radiance as a function of altitude. At any given altitude all the imaged data can be converted to surface radiance values once $\tau(h)$ and $L_u(h)$ are known. The downwelled radiance term L_D can be determined by the LOWTRAN method previously described or by an empirical method described by Schott (1979). (N.B. an error analysis demonstrates that for most cases L_D need only be known to approximately 10 percent of the actual value.) The equivalent blackbody radiance L_T and associated kinetic temperature can then be found by evaluation of Equation (7) and the Planck blackbody radiation equation. This analysis was only done for water because of its well-defined emissivity. In cases where objects other than water were studied, the surface radiance values, $L_i(0)$, were converted directly to apparent temperature through the Planck equation, i.e., apparent surface radiometric temperatures are compared.

EXPERIMENTAL APPROACH AND RESULTS

The first data comparisons were made using ground truth data and predicted water surface temperatures for 29 points in Lake Ontario. The Landsat data were acquired on 13 September 1982 by the Landsat-4 satellite. The surface data were acquired by the Canada Center for Inland Waters (CCIW) as part of a regularly scheduled sampling program. The CCIW data were acquired over a 5-day interval encompassing the satellite overpass. The latitude and longitude of each surface sample were converted to image coordinates and the corresponding band 6 digital count was converted to observed radiance. The observed radiance was then corrected for sensor response function, atmospheric effects, and surface emissivity to yield expected water temperature values. The results of this experiment were quite encouraging. The standard error in the predicted temperature was 1.48°K over a range of 8°K. Standard error is expressed as:

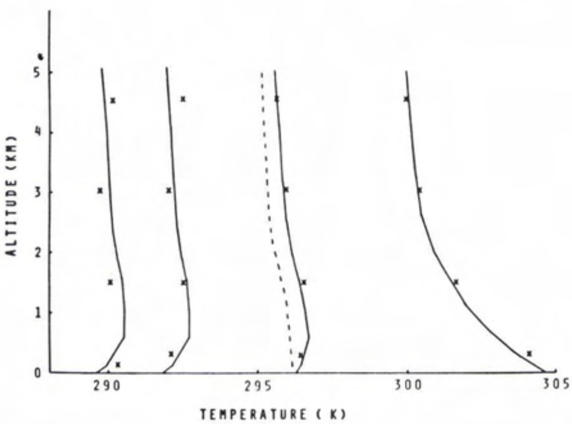
$$S = [\Sigma(\hat{T}_i - T_i)^2/N]^{1/2} \quad (8)$$

where:

$\hat{T}_i$ is the predicted temperature of the ith sample,
T_i is the measured temperature of the ith sample,
N is the number of samples.

It is important to note that care must be used in employing this approach. If the LOWTRAN model had not been properly adjusted and the sensor response function not included, the standard error would have increased to 3.14°K for this data set (Schott, 1983).

When the data from this experiment were plotted (c.f., Figure 3), an additional concern was raised. Although the data samples have small residual errors, it is apparent that systematic error exists which is masked somewhat by the narrow range in temperature. The LOWTRAN model applied to the Landsat data appears as though it would underestimate high temperature values and overestimate low temperature values. There are three potential sources of this systematic error. First, the onboard gain calibration of the sensor could be in error. Second, the LOWTRAN model could be improperly accounting for the atmospheric transmission. Third, the large footprint of the satellite (some pixel averaging was done which would augment this problem) could be obscuring the temperature extremes sensed by the surface vessel. Any or all of these error sources could be contributing to the residual systematic error illustrated in Figure 3. The initial



x - PROFILE DATA

— CORRECTED LOWTRAN MODEL FOR ROCHESTER, 9:53 AM

--- UNCORRECTED LOWTRAN MODEL, BUFFALO, 7:00 AM

FIG. 2. Plot of Apparent Temperature at Altitude for Profile Data and LOWTRAN Models, 22 June 1984.

data set could not separate out these potential sources of error.

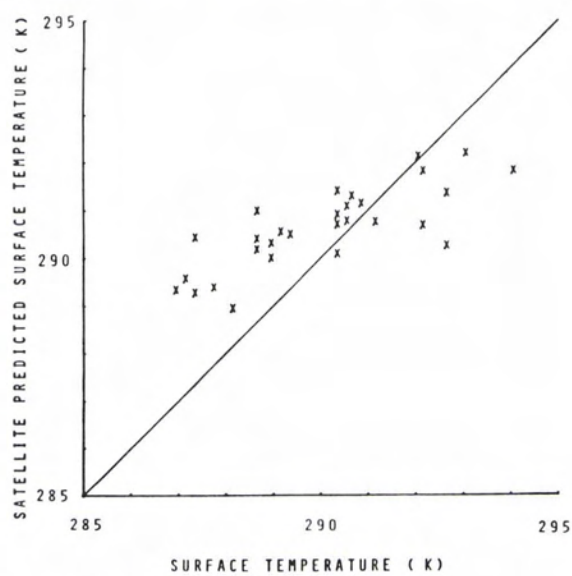
To evaluate the sources of error, aircraft underflight data were acquired in conjunction with a satellite overpass of 22 June 1984. In this case, the satellite data were from Landsat-5. The aircraft carried an infrared line scanner equipped to sense in the 8–14 μm bandpass as well as in the slightly narrower bandpass of the satellite. An instrumentation problem precluded the use of the narrow bandpass data so the 8–14 μm data were used in the subsequent analysis. Also, once again, a limited number of ground truth points were available from a regularly scheduled CCIW cruise.

The aircraft underflight data were analyzed and atmospheric transmission and path radiance values were computed. These values were obtained for altitudes of 4.5, 3.0, 1.5, and 0.3 Km. These atmospheric parameters were then used to compute the surface radiometric temperature for 20 objects in the scene, with uniform temperature, and which were large enough to be easily identified on the TM band 6 image. The 4.5 Km data were used for this purpose to better approximate the TM footprint. (A 1.1 milliradian IFOV scanner was flown yielding a 50 meter footprint with sampling done over an area of approximately 250 meters in diameter.) Ground truth data were also available for 28 points in Lake Ontario where the CCIW had taken surface temperature readings over a 3-day period, including the morning of the overpass. These data points are included in much of the subsequent analysis. However, because of the point nature and because they were not taken exactly when the overpass took place, the accuracy of these data is not known. The profile data, on the other hand, have a demonstrated accuracy of 0.4°K for water temperature measurements and 0.7°K for all surfaces.

The TM band 6 image was sampled by visual location of the points where the profile data set was sampled. A rectilinear coordinate transformation was generated for a portion of the image containing the CCIW data. The longitude and latitude were then converted to scene coordinates, and the TM scene was sampled at these locations.

The scene radiance at the satellite for each point sampled was then computed and converted to surface temperatures by Equation (1) to determine the surface radiance and look-up tables to compute the corresponding temperature. These values are plotted against the measured surface temperatures in Figure 4. These results indicate a good fit to the data, but a systematic error in the slope opposite to that observed for the TM-4 band 6 results is apparent.

To attempt to identify the source of this error the radiance computed at the spacecraft was regressed against the surface radiance values computed from the profile technique. The slope of this relationship should yield the atmospheric transmission over the bandpass according to Equation (6). The result of this analysis yielded an observed atmospheric transmission value of 0.996 when only the profile data are considered and a value of 1.32 if the CCIW data are included. These numbers are obviously impossibly high and must result from either surface temperature measurement errors or sensor calibration



X FROM SURFACE VESSEL

FIG. 3. Plot of Observed Surface Temperature and Predicted Surface Temperature for 13 September 1982 (Landsat-4). A perfect correlation line is plotted for reference.

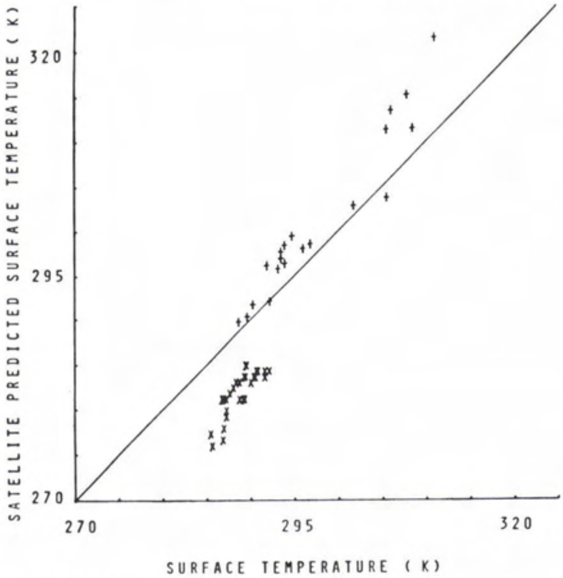


FIG. 4. Plot of Observed Surface Temperature and Predicted Surface Temperature for 22 June 1984 (Landsat-5). A perfect correlation line is plotted for reference.

errors. Since the profile calibration technique has been demonstrated to result in errors in surface temperature of less than 0.7°K and the error in CCIW data is unknown (due to temporal variations) only profile results were considered in the next step of the analysis.

An error propagation study showed that the error in transmission calculations due to errors in temperature measurement using the profile technique would only result in errors of ±0.04 transmission units. This could not account for the high apparent transmission observed by the spacecraft. It appears that on this date the effective gain on the sensor is too high. The following analysis describes an effort to attempt to compute the magnitude of the increase in apparent sensor gain.

The multiplicative error in gain can be expressed as:

$$m' = \tau_o/\tau_a \tag{9}$$

where:

m' is the multiplicative gain factor that must have been applied to yield the observed systematic error,

τ_o is the observed atmospheric transmission assuming no error in the data (i.e., 0.996 for the profile data set),

τ_a is the actual atmospheric transmission.

The error in the atmospheric transmission values computed by the modified LOWTRAN code was evaluated by comparing the transmission values computed by the profile technique with those computed by LOWTRAN. This was done for data in the 8–14 μm spectral band obtained on several dates at altitudes ranging from fractions of a kilometer to several kilometers. In all cases the radiosonde data and sensor spectral response functions were included as described in the theoretical background section. These data indicated that actual atmospheric transmission (as computed by the profile techniques) could best be estimated from the LOWTRAN data as:

$$\tau_a = \tau_L(0.877 \pm 0.087) \tag{10}$$

where:

τ_a is the estimate of atmospheric transmission and,

τ_L is transmission predicted by LOWTRAN.

Assuming this relationship holds in the 10.45–12.43 μm bandpass of the TM-5 band 6 sensor, then we can estimate the value of the atmospheric transmission, τ_a, the sensor should have observed. With the LOWTRAN predicted value of 0.793 for the transmission in the TM-5 band 6 bandpass, the best estimate of atmospheric transmission is $\tau_a = 0.695 \pm 0.06$. The excess gain on the system for this data set can be computed from Equation (9) to be between 1.32 and 1.57 (best estimate 1.43). It is not clear from this limited data set whether the error is time stable or not. Comparison with future data sets will attempt to evaluate this.

CONCLUSIONS

The radiometric calibration of the Landsat-5 TM band 6 data appears to have a systematic error in the gain. This error for the 22 June 1984 data analyzed here is manifest as an excess gain factor of about 1.43. If this were not accounted for, the root mean square error (c.f., Equation 8) in predicted surface temperature for the 48 samples studied would have been in excess of 6°K. When the 22 June 1984 satellite data were regressed against measured surface temperatures, the residual error was 2°K for 48 points with a temperature range of 26°K. This indicates that the satellite can be reasonably well calibrated if underflight data and/or appropriate ground truth data are available. The source of the gain shift in the spacecraft has not been fully defined, although it is probably due to moisture accumulation on optical surfaces which may be correctable by more frequent outgasing (Barker, J., NASA Goddard, personal communication, 1985). The rate of change of the error and the limits on its magnitude are not yet clearly defined. The limited data analyzed for TM-4 band 6 indicate that similar systematic gain errors may also have existed. However, the direction and magnitude of the observed shift in the TM-4 data could be explained by errors in the surface temperature estimates and errors generated by the atmospheric propagation models. In closing, we should point out that the TM band 6 data have considerable value in observing the thermal properties of the earth surface but that caution should be employed where absolute radiance levels are of interest.

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ANNOUNCEMENT

Remote Sensing Applied to Monitoring and Management of Wetlands

Louisiana State University, Baton Rouge
4-5 October 1985

This Annual Fall Meeting of the Mid-South Region is being organized by the Mid-South Region of the American Society for Photogrammetry and Remote Sensing and the Remote Sensing and Image Processing Center of the Louisiana State University. It will be preceded by a one-day workshop on Photointerpretation of Wetlands on 3 October, conducted by LSU faculty and specialists from the USGS.

David L. Evans, Program Coordinator
School of Forestry, Wildlife, and Fisheries
Louisiana State University
Baton Rouge, LA 70803
Tele. (504) 388-6826