Atmospheric Corrections to Satellite Radiometric Data over Rugged Terrain

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Radiometric measurements from satellites in the solar portion of the electromagnetic spectrum can be converted to measurements of surface exittance. Over rugged terrain, the satellite image must be precisely registered to a terrain data set. For small areas a first-order polynomial interpolation scheme is generally satisfactory for the geometric rectification. If there are saturated pixels, a nearest-neighbor procedure is used for the interpolated satellite radiances, otherwise a cubic-convolution algorithm is used. Path radiances and path transmittance are calculated with a simple spectral model, which requires an estimate of the water vapor and aerosol content of the atmosphere.

Introduction

Spaceborne radiometers which measure upwelling radiance in the solar portion of the electromagnetic spectrum can be used to estimate the spatial distribution of surface parameters which are useful in calculating the surface energy budget. In order to properly use the measurements, it is necessary to derive the exittance from the earth's surface. Hence, calculation of the atmospheric path radiance and the atmospheric attenuation of the upwelling surface radiance are necessary. Over terrain of varying elevation, it is generally not true that these quantities are unchanging over the area of interest, so precise registration of the satellite radiometric data with the underlying terrain is necessary.

The method presented here is based upon a simple spectral solar radiation model, with Rayleigh and aerosol scattering, and absorption from aerosols, water vapor, and ozone. Necessary parameters to drive the model are derived from surface measurements (Dozier, 1980). The model is perhaps not as easy to use as some others (e.g., Otterman and Fraser, 1976, Tanre et al., 1979, Otterman and Robinove, 1980), but it is expressly designed for terrain with varying slopes and exposures.

Notation

\(a/Re\) Absorptance/reflectance ratio for atmospheric aerosols
\(E_0\) Solar constant
\(E_d\) Diffuse irradiance
\(E_s\) Direct (beam) irradiance
\(E'\) Irradiance scattered out of incoming beam
\(k_0\) Ozone absorption coefficient
\(k_w\) Water vapor absorption coefficient
\(L\) Radiance
\(M\) Exittance
\(M'\) Surface exittance that is subsequently scattered
\(m_\text{a} (O_3)\) Atmospheric ozone content (mm)
\(P\) Air pressure (Pa)
\(r\) Earth–sun radius vector
\(RN\) Satellite radiance number
\(w\) Precipitable water vapor (mm)

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52 Vanderbilt Ave, New York, NY 10017
0034-4257/81/$03.00 + 1.50
z Altitude (m)
Z Solar zenith angle
α Ångstrom turbidity exponent
β Ångstrom turbidity coefficient
λ Wavelength
ρ_d Bihemispherical reflectance (albedo to diffuse irradiance)
ρ_s Directional-hemispherical reflectance (albedo to beam irradiance)
σ_A Aerosol attenuation coefficient
σ_R Rayleigh scattering coefficient
τ Atmospheric transmittance

Background

Upwelling monochromatic space radiance at the top of the atmosphere has two sources. (1) upward scattering of solar radiation and (2) solar radiation reflected from the surface and subsequently transmitted back through the atmosphere. If the reflected radiance is of equal intensity at all reflection angles and azimuths,

\[ L_{\text{space}}(\lambda) = L_{\text{path}}(\lambda) + \tau(\lambda) \frac{M_{\text{surf}}(\lambda)}{\tau}, \]

(1)

where

\[ M_{\text{surf}}(\lambda) = \rho_d(\lambda) E_d(\lambda) + \cos Z \rho_s(\lambda) E_s(\lambda) \]

(2)

Complications in applying Eqs (1) and (2) are.

(1) Most spaceborne radiometers (e.g., Landsat multispectral scanner, NOAA advanced very high resolution radiometer) are not monochromatic, but measure integrated upwelling space radiance within some broad wavelength band(s)

(2) \( L_{\text{path}}(\lambda) \) varies with the altitude of the surface, the atmospheric attenuation parameters, and the solar angle.

(3) The transmittance function \( \tau(\lambda) \) for upwelling radiance includes attenuation for scattering and absorption. Some of the scattered radiation arrives at the top of the atmosphere over nearby pixels instead of over the pixel from which it left the surface. Moreover \( \tau(\lambda) \) varies with the altitude of the surface.

(4) Surface reflectances \( \rho_d(\lambda) \) and \( \rho_s(\lambda) \) are functions of wavelength, and \( \rho_s(\lambda) \) is also a function of illumination angle. Moreover, the spectral distribution of \( M(\lambda) \) is a convolution of the spectral distributions of irradiance and reflectance.

(5) The surface upwelling radiance varies with the angle and azimuth of reflection. Fortunately, this variation is usually moderate for solar zenith angles less than 50 or 60° (Stowe et al., 1980), and the necessary adjustments can be made after the atmospheric corrections.

Preprocessing of Satellite Radiometric Data

If satellite radiometric data are to be used to derive \( L_{\text{path}}(\lambda) \), they must first be subjected to certain radiometric and geometric transformations. These transformations are collectively described as “preprocessing” since they are a prerequisite to the extraction of usable information. There are two principal requirements which the preprocessing of satellite radiometric data must fulfill.

(1) The data must be converted from their original representation (e.g., digital quantization levels) into measures of radiant power intensity.
(2) Each spaceborne measurement must be correlated with an earth surface location, to account for the influence of spatially varying surface characteristics on the terms in Eqs (1) and (2).

How the preprocessing is implemented is contingent upon the radiometric and geometric characteristics of the particular sensor system from which the data are obtained. In this section, we discuss the relevant characteristics of one commonly used sensor, the Landsat multispectral scanner (MSS) system, and then describe the preprocessing scheme by which we convert these data to space radiance measurements.

In the radiometric domain, spectral radiance levels detected by the MSS are spatially sampled and quantized at 6-bit resolution, and expanded to 7-bits upon CCT (computer-compatible tape) generation for bands 4, 5, and 6 (U.S. Geological Survey, 1979). This leads to the representation of a scene as an array of integer radiance numbers (RNs), ranging from 0–127 (0–63 for band 7). Ideally, the point-by-point conversion of these RNs into space upwelling radiances is accomplished by the following linear transform.

\[
L_{\text{space}}[\text{band}] = L_{\text{thresh}}[\text{band}]
+ \frac{RN[\text{band}]}{RN_{\text{max}}[\text{band}]}(L_{\text{sat}}[\text{band}]
- L_{\text{thresh}}[\text{band}])
\]  

In practice, the conversion is complicated by response variations between the six detectors in a given band (causing the notorious "striping" observable on many MSS images), and by the presence of threshold (\(RN=0\)) and saturated (\(RN=63\) or 127) pixels over the area of interest. Interdetector response variations can be dealt with by statistical equalization, based on either an analysis of a single scene (Landgrebe et al., 1974, Bernstein and Ferneyhough, 1975), or on a multitemporal analysis of several scenes (Potter, 1977). Statistical equalization is an effective method of "smoothing" radiometric errors, but it is undesirable for radiation studies since the original RN-to-radiance transforms would no longer be usable.

Threshold and saturated pixels are a problem in radiation studies since they cannot be assigned radiance levels based on the linear transform described above. In the case of threshold pixels, it is known only that the corresponding radiance is less than or equal to the threshold response of the sensor. Similarly, saturated pixels may represent any value greater than or equal to the saturation level of the sensor. Saturation especially is a significant problem over areas of very high surface reflectance. For example, we have noted 20–40% saturation in MSS bands 4, 5, and 6 over snow-covered terrain in the southern Sierra Nevada.

In the spatial (geometric) domain, the scanning and sampling of the MSS defines a Cartesian coordinate system of lines and samples, by which individual pixels are referenced. Interactions between the scanner, the earth, and the spacecraft cause this coordinate system to be distorted both with respect to geographic coordinate systems, and between successive images of the same location. These distortions fall into two broad categories: systematic (which can be modeled using a priori information), and random (which must be modeled statistically). Mappings between MSS locations and other coordinate systems are usually accomplished by a combination of statis-
tical error minimization (e.g., least squares) and systematic distortion models, applied to a set of control points with known coordinates in both systems (Van Wie and Stein, 1976). This procedure requires a method by which RNs may be assigned to noninteger MSS coordinates (resampling) should such coordinates correspond to a location of interest in the other coordinate system. High-order resampling schemes (such as “cubic convolution”) are available which produce theoretically optimal interpolations of image RNs (Taber, 1973).

There are two major problems associated with the geometric preprocessing of MSS data for space radiance studies. First, the location of accurate image control points is a problem over many of the areas where satellite-derived space radiance data would be most useful. Areas lacking other means of surface exittance measurement are also often lacking in readily locatable cultural features such as highway intersections and agricultural field boundaries. The previously cited example of the southern Sierra Nevada is a case in point. Second, high-order resampling of image RNs is not possible if the interpolation kernel includes threshold and/or saturated pixels, since interpolation by definition requires that the input values be bounded. This leaves zero-order or “nearest-neighbor” resampling as the only usable method under such circumstances. Unfortunately, nearest-neighbor resampling introduces the greatest positional error of any resampling method (Nack, 1977).

Given the above background, the actual preprocessing procedure which we generally employ may now be described. A Landsat MSS CCT is received either with a standard radiometric calibration already applied, or with the necessary parameter values for the user to apply the calibration (U.S. Geological Survey, 1979). No further radiometric calibration is possible at the preprocessing level without corrupting the RN-to-radiance transformation. The data are left in RN format until completion of geometric preprocessing, in order to simplify the recognition of threshold or saturated pixels.

The object of the geometric preprocessing is to register the MSS data to the coordinate system of an area of interest extracted from NCIC Digital Terrain Tapes. The terrain tapes are an excellent database for radiation studies since information on elevation, slope, exposure, and horizon may be derived from them (Dozier and Outcalt, 1979, Dozier et al., 1981). In areas of low relief, the necessary control points may be located on the MSS image and on maps, whose latitude-longitude coordinates may be readily converted to indices in the terrain array. In areas of high relief, which due to remoteness are often associated with less accurate maps, the terrain tapes lend themselves to another method of identifying surface control points. It is possible to synthesize a shaded-relief map by assigning to each point on the terrain grid the cosine of the solar angle (measured from normal to the slope) at that point. If the sun position used to make the shaded relief map corresponds to that of the satellite overpass being registered, then the resulting image of cosines bears a strong resemblance to the satellite image. In particular, the illumination of prominent terrain features such as mountain peaks and ridge lines is the same, which permits these features to be used as control points even when they cannot be accurately located on available maps. Fig-
FIGURE 1. Shaded relief map (a) and Landsat MSS-5 image with systematic distortions removed (b). The area is approximately a 1:5-min quadrangle in the Kesavar Pass–Biffing Lake region of the southern Sierra Nevada in the Kings River drainage, South Fork.
Figure 1 illustrates a satellite image with systematic distortions removed, along with a shaded-relief map of the same general area.

The systematic distortions inherent in MSS data are compensated by removing the distortions from the control point MSS coordinates, and reintroducing them when MSS coordinates are selected for a terrain location. Several sources of systematic distortion have been identified in MSS imagery (Van Wie and Stein, 1976, Bernstein and Ferneyhough, 1975, Kirby and Steiner, 1978). Of these most are either insignificant over areas appreciably smaller than a full MSS frame (e.g., earth curvature, panoramic distortion), or can be treated as continuous and linear over the entire image (e.g., scan skew, earth rotation, oversampling). A distortion which is neither continuous nor insignificant results from the offset between scan swaths (a swath is six scan lines, all of which are collected on a single half-cycle of the scanning mirror). If the global skew resulting from earth rotation is modeled and removed as a continuous function, a "sawtooth" swath-to-swath offset will be apparent (Nack, 1977). This results from mirror motion and earth rotation in the time between samples within a swath (Holkenbrink, 1978). Since the bulk of this distortion is due to the precisely timed interval between sample acquisitions, it is readily removed.

The remaining distortions are subsumed under a first-degree bivariate polynomial, whose coefficients are computed by least squares. A first-degree (affine) polynomial is adequate for a small sub-scene of an MSS frame (on the order of $10^5$ pixels) and has the advantage that control points which are inaccurately located will have anomalously high residuals, and may be removed from subsequent mapping (Wong, 1975). The resulting polynomial is evaluated at each terrain grid location, yielding a corresponding MSS image location. For large areas, direct evaluation of the polynomials at each point may be computationally prohibitive, necessitating some sort of coordinate interpolation scheme (Van Wie and Stein, 1976). This image location is "decorrected" for the within-swath distortion, and an RN value is interpolated or simply fetched, as appropriate. Once a registered image is obtained, the RNs may be converted to $I_{\text{space}}[\text{band}]$ by Eq (3). Figure 2 is an example of a space radiance image which corresponds to known terrain coordinates. The example is from the southern Sierra Nevada, and the corresponding mask of saturated pixels is also shown.

### Path Radiance Algorithm

Total monochromatic radiation scattered out of the solar beam is

$$E'[\lambda] = \frac{E_0[\lambda]}{r^2} \left[ 1 - \exp \left\{ -m_a \left( \frac{\sigma_A[\lambda]}{1 + a/Re} \right) \right\} \right] + \frac{\sigma_R[\lambda]}{P[0]} \left[ \frac{P[z]}{P[0]} \right] \right]. \tag{4}$$

Tabulated data for the solar constant $E_0[\lambda]$ are available from either Thekaekara (1970) or Makarova and Khartintov (1972), although these need to be adjusted to conform with the more recent estimate of $1376 \, \text{W m}^{-2}$ for the integrated solar flux (Hickey et al., 1980). Rayleigh scattering coefficients $\sigma_R[\lambda]$ are from Penndorf (1957), atmospheric path length $m_a$ is calculated by Kasten's (1966).
FIGURE 2  The Landsat image from Fig. 1 corrected to terrain, so that each pixel corresponds to a known coordinate on a digital terrain tape. On the right, (b) is a mask of saturated pixels. Unsaturated radiances in the image range from 0 to 0.175 W m$^{-2}$/um/sr.
method. The aerosol scattering coefficient is parameterized by Ångstrom's (1961, 1964) equation

$$\sigma_A[\lambda] = \beta[z] \lambda^{-\alpha}$$

A commonly accepted value for $\alpha$ is 1.3, with variations from 0.8–2.0 (Leckner, 1978). If $\lambda$ is expressed in nm, $\beta$ ranges from 0 to about 12,500.

Subsequent to scattering, the upwelling radiation is subject to absorption from ozone, water vapor, and aerosols. We assume that, on the average, the scattering takes place from level $P[z]/2$, where $P[z]$ is surface pressure. This altitude ($z_2$) can be found from the hydrostatic equation and the equation of state. The ozone (Kreuger and Minzner, 1974), precipitable water vapor (Yamamoto, 1949), and turbidity (Robinson, 1966) values for the atmosphere above altitude $z_2$ are.

$$O_3[z_2] = O_3[0] 2.5 \times 10^{-5} z_2,$$  

$$w[z_2] = w[0] \left[1 - \exp(-4 \times 10^{-4} z_2)\right],$$  

$$\beta[z_2] = \beta[0] \exp(-5 \times 10^{-4} z_2).$$

Hence the transmittance function for the scattered radiation, integrated over a hemisphere, is

$$\tau[\lambda] = \exp\left[-2 \left(k_0[\lambda] O_3[z_2] + k_w[\lambda] w[z_2]^{1/2} + \frac{(a / Re) \beta[z_2] \lambda^{-\alpha}}{1 + a / Re}\right)\right]$$

If $a/Re=0$, the last term, for aerosol absorption, is omitted. Tabulated values for the absorption coefficients are available for ozone ($k_0[\lambda]$) from Inn and Tanaka (1953) and Leighton (1961), and for water vapor ($k_w[\lambda]$) from Gates (1960) and Gates and Harrop (1963).

Combining Eqs. (4) and (9) leads to the path radiance.

$$\tau L_{\text{path}}[\lambda] = (1 - 0.5 \cos^{1/3} Z) \times \cos Z E'[\lambda] \tau[\lambda].$$

The first term (Robinson, 1966) accounts for the portion of the radiation scattered upward. This equation does not consider the anisotropic nature of path radiance. However, Dave's (1980) spherical harmonics simulations indicate that path radiance vanes little until the nadir angle exceeds 30°.

For a given solar zenith angle and atmospheric attenuation parameters, the path radiance is a function of surface elevation. Hence the integrals over the wavelength range of interest can be calculated for a range of elevations within the area of interest, and the path radiance may then be interpolated for each pixel, provided that each pixel's elevation is known. Sensitivity of path radiance to altitude and atmospheric aerosol content at two different solar zenith angles is shown in Fig 3. The highest Ångstrom $\beta$ value used is 3500, compared to our highest measured values (in the southern Sierra) of 4500. The lower $\beta$ value used is 50, we have measured values below 10. Figure 3 demonstrates that path radiance is quite sensitive to altitude, solar angle, and atmospheric aerosols. Moreover, because of the dependence on altitude, it is likely that a single haze correction factor for an entire scene will be incorrect for areas of rugged terrain.
FIGURE 3 Sensitivity of path radiance to altitude, solar angle, and atmospheric aerosols (a) is for 3000 m elevation (b), whose ordinate scale is the same, is for sea level. In each graph the dashed lines represent 30 May at latitude 36.5° N, the solid lines represent 21 December at the same latitude. In both cases the time of day is that corresponding to the Landsat overpass, about 9:37 AM. For each date the upper curve represents path radiance for \( \beta = 3500 \), the lower curve represents path radiance for \( \beta = 50 \). Both the magnitude and the spectral distribution of path radiance are sensitive to altitude, solar angle, and aerosols.
Figure 4 illustrates dependence of path radiance on precipitable water vapor. Because water vapor absorption is important chiefly beyond 855 nm, the scales on both axes are different than in Fig. 3.

Path Transmittance Algorithm

In order to determine path transmittance with a satellite radiometer measuring upwelling space radiance in broad wavelength band(s), we must make some assumptions about the spectral reflectance of the surface. This does not mean that we need to know the surface albedo (indeed if we did we would hardly need the satellite to measure surface characteristics) but we must have some idea of the relative spectral response. Lacking any information whatever about the surface, we might assume the spectral response to be flat across a wavelength range of measurement, but if we have some information about the nature of the surface we can use it.

For example, for a snow surface we know that the reflectance is similar to the curves, which represent varying snow ages, shown in Fig 5. As the snow ages, the reflectance decreases in the near-infrared due to increasing grain size (O'Brenn and Muns, 1975, Wiscombe and Warren, 1980) and in the visible due to contamination by atmospheric aerosols (Warren and Wiscombe, 1980). Hence, as a first-order approximation, the spectrum of reflectance is approximately the same for new or old snow. For a snow surface, then, we can calculate path transmittance by first calculating the surface irradiance and exittance, using the algorithm in Dozier (1980) and Eq. (4), assuming the reflectance curve is like those in Fig 5 and taking into account any solar angle dependencies.

As this radiation leaves the surface it is scattered and absorbed. The total amount
scattered is

\[ M'\[\lambda\] = M_{surf}[\lambda] \left\{ 1 - \exp \right. \]

\[ \left. \times \left[ -2 \left( \frac{\sigma_A[\lambda]}{1 + a/R_e} + \sigma_R[\lambda] \frac{P[0]}{P[z]} \right) \right] \right\} \]

As before, this scattering takes place on the average from the level \( P[z]/2 \), so the scattered surface exittance which reaches space is

\[ \pi L_{sc}[\lambda] = 0.5 \tau[\lambda] M'[\lambda] \]  \hspace{1cm} (12)

The surface exittance which is neither scattered nor absorbed before reaching space is

\[ \pi L_{direct}[\lambda] = M_{surf}[\lambda] \tau_{musc}[\lambda] \]

\[ \times \exp \left[ - \left( k_0[\lambda](O_3)[z] k_w[\lambda] w[z]^{1/2} \right) \right. \]

\[ \left. + \sigma_A[\lambda] + \sigma_R[\lambda] \frac{P[z]}{P[0]} \right] \]

The \( \tau_{musc}[\lambda] \) term, for absorption by miscellaneous gases, does not necessarily follow Beer's Law so is calculated outside the exponential term (Gates and Harrop, 1963)

Hence Eq (2) for monochromatic space radiance may be rephrased

\[ L_{space}[\lambda] = L_{path}[\lambda] + L_{sc}[\lambda] + L_{direct}[\lambda] \]  \hspace{1cm} (14)

This equation does not help us much, because our space measurements are of \( L_{space} \) integrated over some \( \Delta \lambda \). However, if we have correctly specified the general form of \( \rho_f[\lambda] \) and \( \rho_s[\lambda] \), then our calculations of \( M_{surf}[\lambda] \), \( L_{sc}[\lambda] \), and \( L_{direct}[\lambda] \) at least have the correct relative values. Hence if we integrate these over the desired \( \Delta \lambda \) and drop the wavelength designation,

\[ \tau = \frac{\pi L_{direct}}{M_{surf}}. \]  \hspace{1cm} (15)
The values of \( \tau \) vary with altitude so the simulation has to be carried out for a range of altitudes in the area of interest. Then for any pixel of known altitude, \( \tau \) can be found by interpolation.

**Calculation of Surface Exitance**

By the methods presented in the two previous sections, integrated values for \( L_{\text{path}} \) and \( \tau \) can be found for any wavelength range for any pixel of known elevation. By rearranging Eq. (1) the surface exitance is

\[
M_{\text{surf}} = \frac{\pi [L_{\text{space}} - (L_{\text{path}} + L_{sc})]}{\tau}.
\]

In Fig. 6 we show how \( L_{\text{space}}, L_{\text{path}}, \) and

![Figure 6](image_url)
$M_{\text{surf}}/\pi$ vary with altitude, atmospheric aerosol content, and precipitable water vapor. From this figure it is evident that all three variables are sensitive to altitude and aerosols, so that ad hoc techniques (such as band-ratioing) for estimating surface exittance will not work satisfactorily over a wide range of parameters. For the near-infrared wavelengths where water vapor absorption is the major attenuation factor, corrections for path radiance, but not path transmittance, can probably be ignored.

**Conclusion**

Path radiance and path transmittance vary with the altitude of the surface, atmospheric aerosol and water vapor content, and the nature of the spectral reflectance of the surface. The variations involved are not trivial, and must be

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**FIGURE 7** The difference between upwelling radiance in space and at the surface for MSS band 5, derived from the image in Fig. 2. Values range from 0 to 0.0154 W m$^{-2}$/nm/sr (but almost all of the 0 values are for saturated pixels). For this overpass, field measurements of solar radiation indicated a $\beta$ value of 1100, with 14 mm precipitable water vapor.
calculated explicitly if we are to derive surface exittance data from spaceborne radiometers. Figure 7 shows, for the area in Fig 2, the difference between $L_{\text{space}}$ and $M_{\text{surf}}/\pi$ in MSS band 5, for 13 February 1977, when field measurements of solar radiation in two wavelength ranges (280–2800 nm and 700–2800 nm) indicated a $\beta$ value of 1100 and 14 mm precipitable water vapor. For this band (and for band 6) none of the differences are negative. This indicates that the increased brightness of the image due to path radiance more than compensated for the atmospheric attenuation of the surface signal. This is not true, however, for similar analyses we made for MSS bands 4 and 7, where some of the differences were negative.

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