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THE CORRECTION OF LANDSAT DATA FOR THE EFFECTS OF HAZE, SUN ANGLE, AND BACKGROUND REFLECTANCE

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I. INTRODUCTION

The radiance measured by the Land Satellite (Landsat) multispectral scanner (MSS) in a given channel I, where I = 1,2,3,4, is determined primarily by four quantities:

1. The reflectance ρ_I of the target (i.e., the element of the Earth's surface in the field of view),

2. The solar zenith angle θ_o,

3. The haze level τ_H in the atmosphere, and

4. The average reflectance $\overline{\rho}_I$ of the adjacent areas of the Earth's surface outside the field of view.

In this paper the haze level τ_H is defined as the haze optical depth* at wavelength 0.5 μm. The haze optical depth at other wavelengths λ is denoted $\tau_H(\lambda)$. Normally, in the analysis of Landsat data one wishes to classify certain objects on the Earth's surface on the basis of their reflectance ρ_I. These objects may be in the same Landsat image or may be in several different images separated in space and time. Variations in θ_o, τ_H, and $\overline{\rho}_I$ within a scene or from one scene to another change the data and therefore reduce classification accuracy.

This paper describes a method for simulating the effects of such variations and correcting for them. Simulation and correction are really the same process since correction consists of simulating the MSS response if the value of the Sun angle, haze level, or background reflectance were different from the actual values.

In order to simulate the effect of changes in θ_o, τ_H, and $\overline{\rho}_I$, one must compute the MSS response as a function of these variables and of ρ_I.

An atmospheric model was developed and the Van de Hulst adding method[2] was used to compute the radiances at the MSS for a range of values of θ_o, τ_H, $\overline{\rho}_I$, and ρ_I. This was done for all wavelengths in the MSS bands in steps of 0.01 μm and the resulting radiances corresponding to each band were then multiplied by the MSS response function and integrated over wavelength to obtain the instrument response for that band. It was found that the Landsat gray-scale levels L_I could be written $L_I = A_i(\overline{\rho}_I,\theta_o,\tau_H)\rho_I + B_I(\overline{\rho}_I,\theta_o,\tau_H)$, where A_I and B_I are coefficients which are computed and tabulated for a full range of values for $\overline{\rho}_I$, θ_o, and τ_H. Using these tables it is a simple matter to determine the effect on the Landsat data (i.e., L_I) of a change in any or all of these parameters.

These results allow one to make corrections for changes in θ_o, τ_H, or $\overline{\rho}_I$ if values for these quantities are known for the segments to be corrected. Generally, θ_o is known but τ_H and $\overline{\rho}_I$ are not known. However, if τ_H is known, $\overline{\rho}_I$ can be calculated using the tables described above.

We developed a computer program, the Atmospheric Correction (ATCOR) program, which estimates τ_H from the data itself, computes $\overline{\rho}_I$, and interpolates in the tables of $A_I(\overline{\rho}_I,\theta_o,\tau_H)$ and $B_I(\overline{\rho}_I,\theta_o,\tau_H)$ to find the correction coefficients to make the desired correction. This program is described in section X.

II. THE ATMOSPHERIC MODEL

It is assumed that the atmosphere consists of two homogeneous layers: a Rayleigh scattering molecular layer on top and a Mie scattering haze layer next to the Earth's surface. This is expected to be a good approximation since most of the haze is in the lower 1 km of the Earth's atmosphere while only about 11 percent of the molecular atmosphere is in this region. The two-layer model greatly

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*It is assumed that the reader is familiar with the elements of Radiative Transfer theory. Most of the concepts from Radiative Transfer theory that are used in this paper are discussed in detail in reference 1.

simplifies the calculations. Also, absorption will be neglected, although it can be important in channel 4 of the Landsat data.

In order to define the atmospheric model one must define the scattering diagrams (i.e., phase functions)[1] and the optical depths for the two layers. These quantities completely define the scattering properties of the layers. They are well known for the Rayleigh case[1] and will not be discussed in detail here. For the haze layer, the scattering diagrams and optical depths were calculated from the Mie theory using a haze model due to Reeser.[3] The model is intended to represent a continental type haze and assumes spherical particles with a size distribution given by

$$f(r) = 90 \qquad 0.01\ \mu m \le r \le 0.1\ \mu m$$

$$= \frac{90}{10^4 r^4} \qquad 0.1\ \mu m \le r \le 10.0\ \mu m$$

This distribution corresponds to 100 particles/m^3. The real part of the index of refraction varied from 1.54 to 1.56 in the wavelength interval $0.4\ \mu m \le \lambda \le 1.1\ \mu m$, which is of interest to us. The imaginary part of the index was taken to be zero since we are neglecting absorption. Scattering diagrams for this model were computed for several wavelengths; the one for $\lambda = 0.8\ \mu m$ is shown in figure 1. The scattering diagram changes somewhat with wavelength but this dependence is weak; therefore, the one shown in figure 1 was used for all wavelengths. This considerably reduces the computational effort involved.

The calculations described in this paper were made for haze levels of 0.0, 0.424, and 0.848. The variation of $\tau_H(\lambda)$ with wavelength for the cases $\tau_H = 0.424$ and 0.848 are shown in figure 2. The variation with λ of the Rayleigh optical depth $\tau_R(\lambda)$ is also shown in figure 2.

III. REFLECTION AND TRANSMISSION MATRICES

In what follows, we shall frequently be concerned with reflection and transmission matrices (R and T matrices) which describe the reflection and transmission properties of the plane parallel scattering layers assumed to make up the atmosphere. These layers are assumed to be horizontally homogeneous and to extend to infinity in the horizontal direction. For a layer of optical depth τ_1, the reflection and transmission matrices are defined by

$$R(\mu,\phi;\mu_o\phi_o) = \frac{N(o,+\mu,\phi)}{\mu_o F} \qquad (1)$$

$$T(\mu,\phi;\mu_o\phi_o) = T_{Diff.}(\mu,\phi;\mu_o,\phi_o)+T_o(\mu,\phi;\mu_o,\phi_o) \qquad (2)$$

$$T_{Diff.}(\mu,\phi;\mu_o,\phi_o) = \frac{N_{Diff.}(\tau_1,-\mu,\phi)}{\mu_o F} \qquad (3)$$

$$T_o(\mu,\phi;\mu_o,\phi_o) = \frac{N_o(\tau_1,-\mu,\phi)}{\mu_o F} \qquad (4)$$

Here $N(\tau,\mu,\phi)$ is the radiance at optical depth τ in the direction specified by μ and ϕ, where μ $(o < \mu \le 1)$ is the cosine of the zenith angle θ measured from the normal to the layer, and ϕ is the corresponding azimuth angle. A minus sign in front of μ indicates the direction is downward. The optical depth τ is measured from the top of the layer downward so $N(o,+\mu,\phi)$ is the upward directed radiance at the top of the layer and $N(\tau_1,-\mu,\phi)$ is the downward radiance at the bottom of the layer. The symbols with subscript zero refer to the incident radiation. The incident beam has an irradiance πF through a unit area normal to itself. The subscript Diff. refers to diffusely transmitted radiation; i.e., radiation that has been scattered at least once. N_o is the directly transmitted radiance given by

$$N_o(\tau_1,-\mu,\phi) = \pi F e^{-\tau_1/\mu_o}\delta(\mu-\mu_o)\delta(\phi-\phi_o) \qquad (5)$$

where δ is the Dirac delta function. Note that upward directed radiation is all diffuse so the subscript Diff. is omitted in this case.

IV. THE ADDING METHOD

In order to compute the MSS response for various values of the parameters θ_o, τ_H, ρ_I, and $\bar{\rho}_I$, we first compute the radiance at the MSS for these values of the parameters. This is done by computing the corresponding R-matrix and using Eq. 1 to get the radiance.

The method used to compute the R-matrix is the adding method originally proposed by Van de Hulst.[2,4] It allows one to take the R and T matrices for two separate layers of optical depths τ_1 and τ_2 and construct from them the R and T matrices for the layer of optical depth $\tau_1+\tau_2$ consisting of the two layers, one on top of the other. A special case of the adding method occurs when the two layers are identical. It is then called the doubling method. In the calculations described below, these methods are used to build up R and T matrices for the Rayleigh and aerosol layers that constitute the model atmosphere. The adding method is then used to combine these to obtain R and T matrices for the total atmosphere. Finally, the adding method is used to combine the atmospheric matrices and the R-matrix for the Earth's surface to obtain an R-matrix which describes the reflectance of the overall Earth-atmosphere system. This matrix is somewhat different from the conventional R-matrix since it describes a system which is not horizontally homogeneous.

The principle of the adding method is depicted in figure 3 which shows two scattering layers. It is assumed that the R and T matrices have been obtained for the two layers, and it is desired to obtain the R and T matrices for the two-layer system. In figure 3 the two layers are separated so the upward and downward radiation field where they join can be indicated.

The R and T matrices for the top layer in figure 3 will be denoted R_T and T_T and those of the bottom layer R_B and T_B. It is understood that each matrix is a function of four angular variables which are omitted to simplify the notation. The meaning of the diagram is self-evident: of the incident flux I, a part described by R_1 is reflected by the top layer, and a part described by D_1 is transmitted by the top layer. Of the part described by D_1, a part described by U_1 is reflected by the bottom layer, and a part described by T_1 is transmitted by the bottom layer. The process is continued as shown in the diagram. All the transmission matrices (T_T, T_B, T, D) include both the diffusely and directly transmitted parts. The solution consists in determining R and T, the reflection and transmission matrices for the two layers taken together. The following relations can be read directly from the diagram:

$$\begin{aligned} R_1 &= R_T & D_1 &= T_T \\ T_n &= T_B D_n & U_n &= R_B D_n \\ R_{n+1} &= T_T U_n & D_{n+1} &= R_T U_n \end{aligned} \qquad (6)$$

$$n = 1,2,\cdots$$

By addition we obtain

$$D = \left[1+\left(R_T R_B\right)+\left(R_T R_B\right)^2+\cdots\right]T_T = [1+S]T_T \qquad (7)$$

$$U = R_B D \qquad (8)$$

$$R = R_T + T_T R_B D \qquad (9)$$

$$T = T_B D \qquad (10)$$

The products in Eqs. 6 to 10 stand for double integrals over the intermediate angles. For example, $U = R_B D$ stands for

$$U(\mu_1,\phi_1;\mu_2,\phi_2) = \frac{1}{\pi}\int_o^1\int_o^{2\pi} R_B(\mu_1,\phi_1;\mu',\phi') \cdot D(\mu',\phi';\mu_2,\phi_2)\mu' d\mu' d\phi' \qquad (11)$$

All other products are defined in the same way.

Separating the directly transmitted and diffuse parts of T_T, T_B, D, and T, one obtains:

$$D_{Diff.} = T_{T,Diff.} + Se^{(-\tau_T/\mu_o)} + ST_{T,Diff.} \qquad (12)$$

$$U = R_B e^{(-\tau_T/\mu_o)} + R_B D_{Diff.} \qquad (13)$$

$$R = R_T + e^{(-\tau_T/\mu)} U + T_{T,Diff.} U \qquad (14)$$

$$T_{Diff.} = e^{(-\tau_B/\mu)} D_{Diff.} + T_{B,Diff.} e^{(-\tau_T/\mu_o)} + T_{B,Diff.} D_{Diff.} \qquad (15)$$

We shall assume that we have the solutions for the bottom and top layers in the form of the cosine series

$$R_B(\mu,\phi;\mu_o,\phi_o) = \sum_{m=o}^{N_B} R_B^{(m)}(\mu,\mu_o)\cos m(\phi_o-\phi) \qquad (16)$$

$$T_{B,Diff.}(\mu,\phi;\mu_o,\phi_o) = \sum_{m=0}^{N_B} T_{B,Diff.}^{(m)}(\mu,\mu_o) \cdot \cos m(\phi_o-\phi) \qquad (17)$$

with identical series for R_T and $T_{T,Diff.}$ except that everywhere the subscripts are T instead of B. Most methods of solving the multiple scattering problem for a homogeneous layer, including the doubling method used in this paper, give solutions in this form. The number of components N_B+1 in Eqs. 16 and 17 is the number of components in the cosine expansion of the scattering diagram for the layer. (See Eq. 29 below and the discussion following it.) Substituting Eqs. 16 and 17 and the corresponding series for the bottom layer into Eqs. 12 to 15, one obtains similar series for R and $T_{Diff.}$ describing the two layers taken together:

$$R(\mu,\phi;\mu_o,\phi_o) = \sum_{m=o}^{N} R^{(m)}(\mu,\mu_o)\cos m(\phi_o-\phi) \qquad (18)$$

$$T_{Diff.}(\mu,\phi;\mu_o,\phi_o) = \sum_{m=o}^{N} T_{Diff.}^{(m)}(\mu,\mu_o)\cos m(\phi_o-\phi) \qquad (19)$$

where N is the larger of N_T and N_B. The coefficients $R^{(m)}(\mu,\mu_o)$ and $T_{Diff.}^{(m)}(\mu,\mu_o)$ are given by the following equations:

$$Q_1^{(m)}(u,v) = (1+\delta_{o,m})\int_o^1 R_T^{(m)}(u,z)R_B^{(m)}(z,v)zdz \qquad (20)$$

$$Q_{n+1}^{(m)}(u,v) = (1+\delta_{o,m})\int_o^1 Q_1^{(m)}(u,w)Q_n^{(m)}(w,v)wdw \qquad (21)$$

$$S^{(m)}(u,v) = \sum_{n=1}^{\infty} Q_n^{(m)}(u,v) \qquad (22)$$

$$D^{(m)}_{Diff.}(u,\mu_o) = T^{(m)}_{T,Diff.}(u,\mu_o)+S^{(m)}(u,\mu_o) \cdot e^{-\tau_T/\mu_o}+(1+\delta_{o,m}) \cdot \int_o^1 S^{(m)}(u,v)T^{(m)}_{T,Diff.}(v,\mu_o)vdv \quad (23)$$

$$U^{(m)}(z,\mu_o) = R^{(m)}_B(z,\mu_o)e^{-\tau_T/\mu_o}+(1+\delta_{o,m}) \cdot \int_o^1 R^{(m)}_B(z,u)D^{(m)}_{Diff.}(u,\mu_o)udu \quad (24)$$

$$R^{(m)}(\mu,\mu_o) = R^{(m)}_T(\mu,\mu_o)+e^{-\tau_T/\mu}U^{(m)}(\mu,\mu_o)+(1+\delta_{o,m}) \cdot \int_o^1 T^{(m)}_{T,Diff.}(\mu,z)U^{(m)}(z,\mu_o)zdz \quad (25)$$

$$T^{(m)}_{Diff.}(\mu,\mu_o) = e^{-\tau_B/\mu}D^{(m)}_{Diff.}(\mu,\mu_o)+T^{(m)}_{B,Diff.}(\mu,\mu_o) \cdot e^{-\tau_T/\mu_o}+(1+\delta_{o,m}) \cdot \int_o^1 T^{(m)}_{B,Diff.}(\mu,u)D^{(m)}_{Diff.}(u,\mu_o)udu \quad (26)$$

In Eqs. 23 to 26, τ_T and τ_B are the optical depths of the top and bottom layers, respectively. Only the first few $Q_n^{(m)}(u,v)$ need to be calculated. As n increases, the series for $S^{(m)}(u,v)$ becomes a geometric series and the remaining terms can be approximated by a remainder term.

It will be assumed that the Landsat MSS is pointed vertically downward; i.e., that the look angle is 0.0°. This assumption greatly simplifies the multiple scattering calculations and is quite well justified since the maximum look angle is about 7°. With this assumption, the radiance at the sensor is independent of ϕ and ϕ_o so only the m = o component in Eqs. 16 to 26 needs to be computed.

V. THE DOUBLING METHOD

The doubling method is simply the adding method when the top and bottom layers are the same. By repeated doubling, one can obtain the solution for a thick homogeneous layer if one has the solution for a thin homogeneous layer. One begins with a layer of optical depth τ_1 and "adds" it to itself using the adding method to obtain solutions for a layer of depth $2\tau_1$. By repeating the procedure, one successively obtains solutions for depths $4\tau_1, 8\tau_1, 16\tau_1, \cdots, 2^n\tau_1$ after n doublings.

The initial layer of depth τ_1 can be obtained by any method. Hansen[5] has shown that a good method is to take τ_1 small enough that only first order scattering is important. One then has the solutions

$$R_B(\mu,\phi;\mu_o,\phi_o) = \frac{1}{4\mu\mu_o}\left(\frac{1}{\mu}+\frac{1}{\mu_o}\right)^{-1}\left\{1-\exp\left[-\tau_1\left(\frac{1}{\mu}+\frac{1}{\mu_o}\right)\right]\right\} \cdot P(\mu,\phi;-\mu_o,\phi_o) \quad (27)$$

$$T_{B,Diff.}(\mu,\phi;\mu_o,\phi_o) = \frac{1}{4\mu\mu_o}\left(\frac{1}{\mu}+\frac{1}{\mu_o}\right)^{-1} \cdot \left[\exp\left(\frac{-\tau_1}{\mu_o}\right)-\exp\left(\frac{-\tau_1}{\mu}\right)\right] \cdot P(-\mu,\phi;-\mu_o,\phi_o) \quad (28)$$

with identical expressions for R_T and $T_{T,Diff.}$. In general, $\tau_1 = 2^{-25}$ is small enough for these solutions to be sufficiently accurate. This is the method used in the doubling calculations described in this paper.

In order to perform the numerical calculations, one separates the azimuth dependence by expanding the scattering diagram in a cosine series

$$P(\mu,\phi;-\mu_o,\phi_o) = \sum_{m=o}^{N} P^{(m)}(\mu,\mu_o)\cos m(\phi_o-\phi) \quad (29)$$

where the coefficients $P^{(m)}(\mu,\mu_o)$ are given in reference 1, page 150, Eq. 87. One then has a similar expansion for R_B and $T_{B,Diff.}$:

$$R_B(\mu,\phi;\mu_o,\phi_o) = \sum_{m=o}^{N} R^{(m)}_B(\mu,\mu_o)\cos m(\phi_o-\phi) \quad (30)$$

$$T_{B,Diff.}(\mu,\phi;\mu_o,\phi_o) = \sum_{m=o}^{N} T^{(m)}_{B,Diff.}(\mu,\mu_o) \cdot \cos m(\phi_o-\phi) \quad (31)$$

One then takes $R^{(m)}_T(\mu,\mu_o) = R^{(m)}_B(\mu,\mu_o)$ and $T^{(m)}_{T,Diff.}(\mu,\mu_o) = T^{(m)}_{B,Diff.}(\mu,\mu_o)$ and substitutes into Eqs. 20 to 26 to begin the doubling process. In the calculations described in this paper, only the m = o component was calculated for the reasons given above.

VI. REFLECTION AND TRANSMISSION MATRICES FOR THE ATMOSPHERE

The reflection and transmission matrices that describe the total atmosphere are denoted $R_T(\mu,\mu_o,\lambda)$ and $T_T(\mu,\mu_o,\lambda)$ where the subscript stands for "total." Similarly, $R_R(\mu,\mu_o,\lambda)$ and

$T_R(\mu,\mu_o,\lambda)$ describe the upper Rayleigh scattering layer, and $R_H(\mu,\mu_o,\lambda)$ and $T_H(\mu,\mu_o,\lambda)$ describe the lower haze scattering layer. Here the superscript m has been omitted but it is understood that all these matrices correspond to m = o. The parameter λ has been added to indicate the wavelength. The calculations are carried out for 25 values of μ and μ_o, namely 24 Gauss points plus the value 1.0, and for every value of λ from 0.4 µm to 1.1 µm in steps of 0.01 µm. They are also carried out for three values of τ_H, namely 0.0, 0.424, and 0.848. For a given value of τ_H, the calculations are made for all values of λ. Under the assumptions made above, the only difference between the calculations for different values of λ is that the Rayleigh and haze optical depths are different as shown in figure 2.

The simplest case is for $\tau_H = 0$. Then $R_T(\mu,\mu_o,\lambda) = R_R(\mu,\mu_o,\lambda)$ and $T_T(\mu,\mu_o,\lambda) = T_R(\mu,\mu_o,\lambda)$. The doubling method was first used to obtain the R and T matrices corresponding to Rayleigh scattering layers of optical depth $2^{-24}, 2^{-23}, \cdots, 2^{+11}$. This was done by starting with a Rayleigh scattering layer of optical depth 2^{-25} and doubling 36 times. The larger values of optical depth were not required for this paper but are routinely calculated by the doubling program. The calculation of $R_R(\mu,\mu_o,\lambda)$ and $T_R(\mu,\mu_o,\lambda)$ was begun with the largest value of λ, namely λ = 1.1 µm. The optical depth for the corresponding layer $\tau_R(1.1)$ was obtained (fig. 2) and the matrices $R_R(\mu,\mu_o,1.1)$ and $T_R(\mu,\mu_o,1.1)$, describing a Rayleigh scattering layer of this optical depth, were built up using the adding method to "add" certain previously calculated layers which were selected so that the sum of their optical depths was equal to $\tau_R(1.1)$. Next, $R_R(\mu,\mu_o,1.09)$ and $T_R(\mu,\mu_o,1.09)$ were calculated. Since $\tau_R(1.09)$ is larger than $\tau_R(1.1)$, this involved "adding" more Rayleigh scattering layers to the layer used to compute $R_R(\mu,\mu_o,1.1)$ and $T_R(\mu,\mu_o,1.1)$. This was done as before by using the adding method. This procedure was continued until the calculations had been made for all the selected values of λ. The matrices were stored on tape.

For the cases $\tau_H = 0.424$ and $\tau_H = 0.848$, the procedure was the same except that for each value of λ the matrices $R_H(\mu,\mu_o,\lambda)$ and $T_H(\mu,\mu_o,\lambda)$ were built up [in the same way as $R_R(\mu,\mu_o,\lambda)$ and $T_R(\mu,\mu_o,\lambda)$] and the adding method was used to calculate $R_T(\mu,\mu_o,\lambda)$ and $T_T(\mu,\mu_o,\lambda)$ by "adding" the Raleigh scattering layer on top of the haze layer. Separate tapes containing these matrices were made for $\tau_H = 0.424$ and $\tau_H = 0.848$.

VII. REFLECTION MATRIX FOR THE EARTH-ATMOSPHERE SYSTEM

This section describes the calculation of the R function associated with the Earth-atmosphere system from which the radiance at the MSS can be obtained using Eq. 1. It was assumed that for a given wavelength the Earth's surface is a Lambert reflector with a reflectance $\rho(\lambda)$ for the picture element (pixel) in the field of view at a particular instant and an average reflectance $\overline{\rho}(\lambda)$ for the background (i.e., the area around that pixel). If the whole surface of the Earth, including the pixel in the field of view, had a uniform reflectance $\overline{\rho}(\lambda)$, the desired R-matrix could be obtained from Eq. 25. In this case, the top layer would be described by $R_T(\mu,\mu_o,\lambda)$ and $T_T(\mu,\mu_o,\lambda)$ and the bottom layer would be described by $R_B(\mu,\mu_o,\lambda) = \overline{\rho}(\lambda)$ and $T_B(\mu,\mu_o,\lambda) = 0$. Also, $\mu = 1$ since it was assumed that the MSS was pointed vertically downward. Under these conditions, the m = 0 component of Eq. 25 can be written:

$$R(1,\mu_o,\lambda) = R_T(1,\mu_o,\lambda) + e^{[-\tau_T(\lambda)]}\overline{\rho}(\lambda)D'(\mu_o,\lambda) + 2\int_o^1 T_{T,\text{Diff.}}(1,z,\lambda)U(z,\mu_o,\lambda)z\,dz \qquad (32)$$

where

$$\tau_T(\lambda) = \tau_H(\lambda) + \tau_R(\lambda)$$

$$D'(\mu_o,\lambda) = e^{[-\tau_T(\lambda)/\mu_o]} + 2\int_o^1 D_{\text{Diff.}}(u,\mu_o,\lambda)u\,du \qquad (33)$$

Eq. 32 is not exact because in the derivation of Eq. 25 the top layer was assumed to be homogeneous and in Eq. 32 the top layer is not homogeneous. However, this should cause only a small error which will be neglected in what follows. It is easy to reformulate the theory to treat an inhomogeneous top layer exactly but to date we have not obtained any numerical results for this case.

If one considers the three terms on the right-hand side of Eq. 32, it is clear that the second term represents the radiance that is directly transmitted to the MSS from the target in the field of view and the other two terms represent the path radiance. The first term represents a contribution from the atmosphere alone, and the third term represents a contribution to the path radiance from light that has been scattered by the Earth's surface. Thus, if the reflectance of the pixel in the field of view were changed from $\overline{\rho}(\lambda)$ to $\rho(\lambda)$, the main effect would be to change $\overline{\rho}(\lambda)$ to $\rho(\lambda)$ in the second term on the right hand side of Eq. 32. The effect on the other terms and on $D'(\mu_o)$ should be negligible. Thus, if the reflectance of the pixel in the field of view is $\rho(\lambda)$ and the background reflectance is $\overline{\rho}(\lambda)$, the corresponding reflection matrix is given approximately by:

$$R(\overline{\rho},\rho,\mu_o,\lambda) = R(1,\mu_o,\lambda) + e^{[-\tau_T(\lambda)]}D'(\mu_o,\lambda)[\rho(\lambda)-\overline{\rho}(\lambda)] = a(\overline{\rho},\mu_o,\lambda)\rho(\lambda) + b(\overline{\rho},\mu_o,\lambda) \qquad (34)$$

where

$$a(\bar{\rho},\mu_o,\lambda) = e^{[-\tau_T(\lambda)]} D'(\mu_o,\lambda)$$

$$= e^{[-\tau_T(\lambda)]} U(1,\mu_o,\lambda)\big/\bar{\rho}(\lambda) \qquad (35)$$

$$b(\bar{\rho},\mu_o,\lambda) = R(1,\mu_o,\lambda)-a(\bar{\rho},\mu_o,\lambda)\bar{\rho}(\lambda) \qquad (36)$$

In $\mathcal{R}$, a, and b, the value 1 for μ has been dropped from the list of variables to simplify the notation. It should be noted that the function $\mathcal{R}(\bar{\rho},\rho,\mu_o,\lambda)$ has properties that are different from those associated with reflection functions as they are usually defined. However, for the present calculation, the important point is that the radiance at the sensor is given by

$$N(\bar{\rho},\rho,\mu_o,\lambda) = \mu_o F(\lambda)\mathcal{R}(\bar{\rho},\rho,\mu_o,\lambda) \qquad (37)$$

where $F(\lambda)$ is the solar irradiance at the top of the atmosphere at wavelength λ.

For each of the three values of τ_H, the coefficients $a(\bar{\rho},\mu_o,\lambda)$ and $b(\bar{\rho},\mu_o,\lambda)$ were computed for the 71 values of λ, the 25 values of μ_o, and 50 values of $\bar{\rho}$ ranging from 0.0 to 0.5 in units of 0.01. This was done by using the adding program in the usual way with the top layer described by $R_T(\mu,\mu_o,\lambda)$ and $T_T(\mu,\mu_o,\lambda)$ and the bottom layer described by $R_B(\mu,\mu_o,\lambda) = \bar{\rho}(\lambda)$ and $T_B(\mu,\mu_o,\lambda) = 0$. This produced the matrices $R(\mu,\mu_o,\lambda)$ and $U(\mu,\mu_o,\lambda)$, and the values of these for $\mu = 1$ were used to compute $a(\bar{\rho},\mu_o,\lambda)$ and $b(\bar{\rho},\mu_o,\lambda)$.

VIII. THE LANDSAT MSS DATA

The Landsat MSS data, i.e., the MSS gray-scale levels L_I, are given by

$$L_I = \alpha_I N_I+\beta_I \qquad (38)$$

where α_I and β_I are constants given in table 1 and N_I is the equivalent spectrally flat radiance defined by

$$N_I = \frac{\int N(\bar{\rho},\rho,\mu_o,\lambda)S_I(\lambda)d\lambda}{\int S_I(\lambda)d\lambda} \qquad (39)$$

Here $S_I(\lambda)$ is the response function for band I of the MSS. In principle, $\bar{\rho}$ and ρ are functions of λ. If one assumes they are constant and equal to $\bar{\rho}_I$ and ρ_I across a given band, then

$$N_I = a_I(\bar{\rho}_I,\mu_o)\rho_I+b_I(\bar{\rho}_I,\mu_o) \qquad (40)$$

where

$$a_I(\bar{\rho}_I,\mu_o) = \frac{\int a(\bar{\rho}_I,\mu_o,\lambda)S_I(\lambda)d\lambda}{\int S_I(\lambda)d\lambda} \qquad (41)$$

$$b_I(\bar{\rho}_I,\mu_o) = \frac{\int b(\bar{\rho}_I,\mu_o,\lambda)S_I(\lambda)d\lambda}{\int S(\lambda)d\lambda} \qquad (42)$$

Thus,

$$L_I = A_I(\bar{\rho}_I,\mu_o)\rho_I+B_I(\bar{\rho}_I,\mu_o) \qquad (43)$$

where

$$A_I(\bar{\rho}_I,\mu_o) = \alpha_I a_I(\bar{\rho}_I,\mu_o) \qquad (44)$$

$$B_I(\bar{\rho}_I,\mu_o) = \alpha_I b_I(\bar{\rho}_I,\mu_o)+\beta_I \qquad (45)$$

In the above analysis, the parameter τ_H was not explicitly indicated in order to simplify the notation. However, in the rest of this paper, it will be indicated explicitly for the A_I and B_I coefficients, that is,

$$A_I(\bar{\rho}_I,\mu_o,\tau_H) \equiv A_I(\bar{\rho}_I,\mu_o) \qquad (46)$$

$$B_I(\bar{\rho}_I,\mu_o,\tau_H) \equiv B_I(\bar{\rho}_I,\mu_o) \qquad (47)$$

A complete set of $A_I(\bar{\rho}_I,\mu_o,\tau_H)$ and $B_I(\bar{\rho}_I,\mu_o,\tau_H)$ was computed using Eqs. 41, 42, 44, and 45 for the range of values given above for $\bar{\rho}_I$, μ_o, and τ_H. Also, a complete set of the coefficients C_I given by

$$C_I(\bar{\rho}_I,\mu_o,\tau_H) = A_I(\bar{\rho}_I,\mu_o,\tau_H)\bar{\rho}_I+B_I(\bar{\rho}_I,\mu_o,\tau_H) \qquad (48)$$

was computed. These were required for the ATCOR program described below.

IX. CORRECTIONS FOR CHANGES IN SUN ANGLE, HAZE LEVEL, AND BACKGROUND REFLECTANCE

Assume that we have Landsat data for a segment corresponding to a set of particular values $\bar{\rho}_I'$, μ_o', and τ_H' for $\bar{\rho}_I$, μ_o, and τ_H and that it is desired to "correct" this data so that it corresponds to some other set of values $\bar{\rho}_I''$, μ_o'', and τ_H'' for these parameters. With the first set of parameters, a target of reflectance ρ_I gives rise to a gray-scale level L_I' given by

$$L_I' = A_I(\bar{\rho}_I',\mu_o',\tau_H')\rho_I+B_I(\rho_I',\mu_o',\tau_H') \qquad (49)$$

With the second set of parameters, the same target would give rise to a gray-scale level L_I'' given by

$$L_I'' = A_I(\bar{\rho}_I'',\mu_o'',\tau_H'')\rho_I+B_I(\bar{\rho}_I'',\mu_o'',\tau_H'') \qquad (50)$$

Eliminating ρ_I from Eqs. 49 and 50, we obtain:

$$L_I'' = \mathcal{A}_I L_I' + \mathcal{B}_I \quad (51)$$

where

$$\mathcal{A}_I = \frac{A_I(\bar{\rho}_I'', \mu_o'', \tau_H'')}{A_I(\bar{\rho}_I', \mu_o', \tau_H')} \quad (52)$$

$$\mathcal{B}_I = B_I(\bar{\rho}_I'', \mu_o'', \tau_H'') - \mathcal{A}_I B_I(\bar{\rho}_I', \mu_o', \tau_H') \quad (53)$$

Thus, if the values of ρ_I, μ_o, and τ_H for a segment are known, the data can easily be corrected to correspond to any other values of these parameters. Normally μ_o' is known but $\bar{\rho}_I'$ and τ_H' are not known; and in making the kind of corrections described in this paper, the most difficult task is to determine the values of ρ_I' and τ_H'.

The ATCOR program described in the next section was designed to provide approximate values for $\bar{\rho}_I'$ and τ_H' and to interpolate in the tables of the A_I and B_I coefficients to obtain the appropriate coefficients to correct the data.

X. THE ATCOR PROGRAM

The ATCOR program is based on the assumption that it is possible to obtain a reasonable estimate for the reflectance of those portions of the Earth's surface that correspond to the darkest pixels in a given Landsat segment. The haze level can then be determined from the brightness of these pixels. This question is examined in detail in reference 6. For the present discussion, it will be assumed that a reasonable estimate for the Earth's reflectance corresponding to the darkest pixels can be made.

In the ATCOR program, band 1 is used to determine the haze level because according to our haze model the effect of haze is greatest in this band. The set of "darkest pixels" is obtained by taking the pixel from each line of Landsat data that has the lowest value in band 1. An average minimum value, called $L_{1,MIN}^{(\tau_H)}$ is obtained by averaging the values of L_1 for these pixels. The haze level τ_H is indicated to show that this value of $L_{1,MIN}$ corresponds to the actual haze level τ_H. Also the average value $\bar{L}_1$ for all the band 1 data in the segment is computed. It is assumed that the reflectance $\rho_{1,MIN}$ corresponding to the darkest targets; i.e., corresponding to the value $L_{1,MIN}^{(\tau_H)}$ is known. Next, average minimum values corresponding to $L_{1,MIN}^{(\tau_H)}$ are computed for the cases where the haze level is assumed to be 0.0, 0.424, and 0.848. These are denoted $L_{1,MIN}^{(X)}$ where X takes the values 0.0, 0.424, and 0.848. They are determined as follows. Using the tables for $C_1(\bar{\rho}, \mu_o, X)$, an interpolation is performed on $\bar{\rho}_1$ and μ_o to find the value $\bar{\rho}_{1,X}$ of $\bar{\rho}_1$ that gives $C_1(\bar{\rho}_{1,X}, \mu_o, X) = \bar{L}_1$. Then, using the tables for A_1 and B_1, an interpolation is performed to obtain the coefficients $A_1(\bar{\rho}_{1,X}, \mu_o, X)$ and $B_1(\bar{\rho}_{1,X}, \mu_o, X)$. Finally, $L_{1,MIN}^{(X)}$ is determined from the equation

$$L_{1,MIN}^{(X)} = A_1(\bar{\rho}_{1,X}, \mu_o, X)\rho_{1,MIN} + B_1(\bar{\rho}_{1,X}, \mu_o, X) \quad (55)$$

Using the three calculated values for $L_{1,MIN}^{(X)}$, the value of X that gives $L_{1,MIN}^{(X)} = L_{1,MIN}^{(\tau_H)}$ is determined by interpolation. This value is the estimate of τ_H.

Once τ_H is known, the value of $\bar{\rho}_I$ can be determined. The first step is to calculate the average values for all the data in the segment for bands 2, 3, and 4 so that we have $\bar{L}_I$ for all four bands. Then $\bar{\rho}_I$ is determined using the tables for $C_I(\bar{\rho}_I, \mu_o, X)$ by interpolating to find the value of $\bar{\rho}_I$ for which $C_I(\bar{\rho}_I, \mu_o, \tau_H) = \bar{L}_I$. Finally, the program interpolates in the tables for A_I and B_I to obtain $A_I(\bar{\rho}_I, \mu_o, \tau_H)$ and $B_I(\bar{\rho}_I, \mu_o, \tau_H)$ which are printed out and can then be used with Eqs. 52 and 53 to make the desired corrections. These coefficients correspond to $A_I(\bar{\rho}_I', \mu_o', \tau_H')$ and $B_I(\bar{\rho}_I', \mu_o', \tau_H')$ in Eqs. 52 and 53. One version of ATCOR allows one to input a set of "standard" values for $\bar{\rho}_I$, μ_o, and τ_H and it then computes directly to the $\mathcal{A}_I$ and $\mathcal{B}_I$ coefficients which transforms the segment being processed to correspond to the "standard" conditions.

The ATCOR program was tested on a data set consisting of a number of pairs of acquisitions. Each pair consisted of two acquisitions of the same site, one day apart. The objective was to see if ATCOR could correct for haze level differences when the target was the same. One acquisition was selected as the "training segment" and the other as the "recognition segment." The recognition segment was classified with the LARSYS classifier using

a. Local training

b. Signatures from the training segment corrected by ATCOR

c. Uncorrected signatures from the training segment.

In order to correct the training segment signatures, both segments were processed by ATCOR to obtain the corresponding values of $\bar{\rho}_I, \mu_o, \tau_H$ and then Eqs. 52 and 53 were used to compute the $\mathcal{A}_I$ and $\mathcal{B}_I$ coefficients. These were then used to transform the training data. The results showed that ATCOR generally improved the classifications, by a substantial factor in some cases. This test is described in reference 7. Another test of ATCOR was performed by IBM Corporation.[8] In this test the training and recognition segments were not the same. There was little evidence to indicate that ATCOR had improved the results. However, there was evidence that the local classifications were not very accurate. Therefore, ATCOR may have caused a greater improvement than that indicated by these results. This test is further discussed in reference 9. Finally, ATCOR has been used to study the effects of changes in Sun angle, haze level, and background reflectance for a large number of cases.

XI. REFERENCES

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Table 1. Coefficients for Relating Landsat II data to the Equivalent Spectrally Flat Radiance.

I	α_I (a)	β_I
1	4980	-4.0
2	7471	-4 5
3	8699	-5.2
4	4961	-1.8

[a]The units of α_I are $(w/cm^2\text{-SR-}\mu m)^{-1}$.

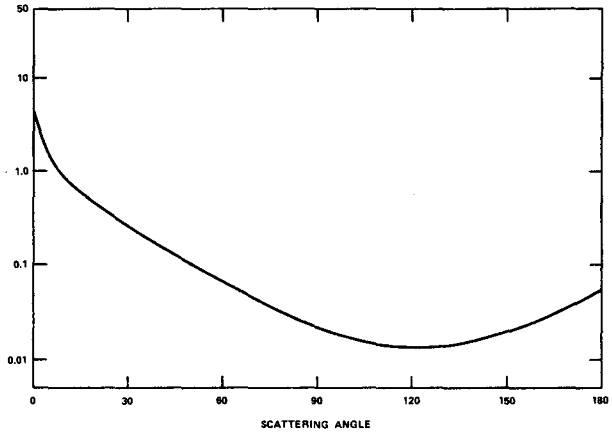

Figure 1. Scattering diagram for haze at wavelength 0.8 μm.

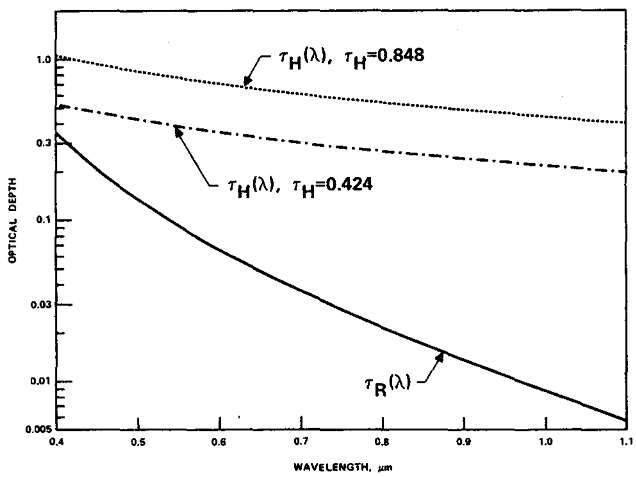

Figure 2. Rayleigh and haze optical depths.

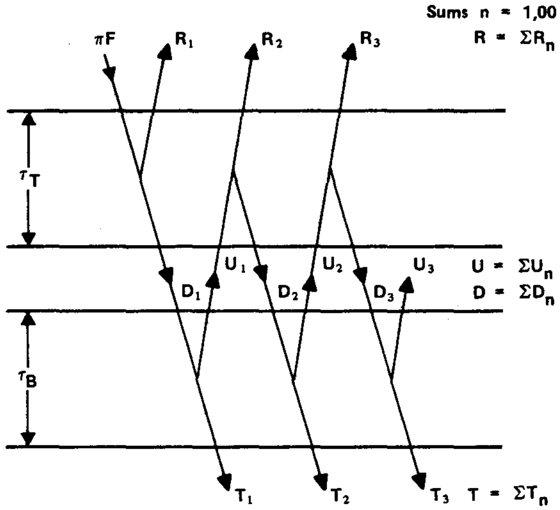

Figure 3. Schematic representation of the adding method.

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