ATMOSPHERIC CORRECTION OF HIGH RESOLUTION LAND SURFACE IMAGES

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ABSTRACT

Algorithms to correct for atmospheric scattering effects in high spatial resolution land surface images require the ability to perform rapid and accurate computations of the top-of-atmosphere diffuse radiance field for arbitrarily general surface reflectance distributions (which may be both heterogeneous and non-lambertian) and atmospheric models. We have been developing such algorithms, using 3-dimensional radiative transfer (3DRT) theory. We describe the methodology used to perform the 3DRT calculations, demonstrate how these calculations are used to perform atmospheric corrections, and illustrate the sensitivity of the retrieved surface reflectances to atmospheric structural parameters.

Keywords: Atmospheric Corrections, Radiative Transfer

1. INTRODUCTION

A determination of true surface reflectance using high resolution (tens to hundreds of meters/pixel), radiometrically calibrated satellite land images must correct for the atmospheric effects of (1) extinction due to molecular and aerosol scattering and absorption, (2) path radiance introduced by scattering from the atmosphere, and (3) horizontal diffusion of radiation leaving the surface (the adjacency effect). The latter effect is particularly important for scenes containing reflectance contrasts, *e.g.*, near coastal boundaries or inland bodies of water. Part of the process of retrieving surface reflectance includes computing top-of-atmosphere (TOA) diffuse radiance for an arbitrary atmospheric model overlaying an arbitrary surface reflectance distribution. If the model atmosphere is defined to be horizonally homogeneous, the atmospheric extinction and the path radiance can be computed using a standard 1-dimensional radiative transfer (1DRT) algorithm. The determination of the radiance arising from photons diffusely transmitted from the surface to space, however, must be computed using a 3-dimensional radiative transfer (3DRT) algorithm and is generally the most time consuming element of the atmospheric correction scheme.

In this paper we describe our progress in generating fast algorithms for computing the diffuse radiance and also in retrieving surface reflectance. Fast algorithms are a necessity if image correction for 3-D atmospheric effects is to be performed on a routine basis. This will be especially true in the Earth Observing System (Eos) era of remote sensing when vast quantities of image data will be obtained daily and must be analyzed in a timely fashion. Our current 3DRT algorithms are now comparable in speed to standard 1-D diffuse radiance algorithms, with negligible loss of accuracy compared to our earlier versions. Our ultimate goal is a rapid algorithm that can be applied routinely to data acquired by the High- and Moderate-Resolution Imaging Spectrometers (HIRIS and MODIS) on Eos-A, and the Multi-angle Imaging SpectroRadiometer (MISR), an instrument investigation also selected for Eos-A (Diner *et al.*, 1989).

We also demonstrate the sensitivity of retrieved reflectances to uncertainties in knowledge of atmospheric parameters and compare retrieved surface reflectances using both 1- and 3-D techniques. These results illustrate the relative importance of 3DRT effects and also the ease with which the 3-D retrieval procedure can be applied in atmospheric correction of images.

2. OPTICAL TRANSFER FUNCTION

The 3-D diffuse radiance field can be represented as the convolution of an atmospheric point-spread, or blurring, function with the surface illumination distribution. We can then write the expression for the TOA radiance as (Diner and Martonchik, 1985):

$$\begin{aligned} I(x,y;\mu,\mu_0,\phi-\phi_0) &= \\ & I_0(\mu,\mu_0,\phi-\phi_0) + \exp(-\tau/\mu) \times \\ & \times \pi^{-1}\int_0^1\int_0^{2\pi}\rho(x,y;\mu,\mu',\phi-\phi')D(\mu',\mu_0,\phi'-\phi_0)\ \mu'\ d\mu'\ d\phi' + \\ & + R(x,y;\mu,\mu_0,\phi-\phi_0) \end{aligned} \quad \{1\}$$

where I is the TOA radiance as a function of surface spatial coordinates x and y, cosines of the view and illumination angles μ and μ_0, and the relative solar azimuth angle $\phi-\phi_0$. The first term on the right-hand-side of Eq. 1, the atmospheric path radiance I_0, is the radiance reflected by the atmosphere without any surface interaction; the second term is the direct radiance field, the field which is not scattered or absorbed by the atmosphere upon leaving the surface; and the third term, R, is the diffuse radiance field. The atmosphere-related quantities in Eq. 1 are functions of the opacity τ, single-scattering albedo w, vertical distribution of the scatterers, and the scattering phase function.

The diffuse radiance field can be expressed as

$$R(x,y;\mu,\mu_0,\phi-\phi_0) = \pi^{-1} \int_0^1 \int_0^{2\pi} T(x,y;\mu,\mu',\phi-\phi') \otimes S(x,y;\mu',\mu_0,\phi'-\phi_0)\ d\mu'\ d\phi' \qquad \{2\}$$

where S is the reflected surface illumination distribution, T is the atmospheric point-spread function (or upward diffuse transmittance), and the symbol ⊗ denotes a convolution over x and y. The reflected surface illumination distribution, in turn, is defined as

$$S(x,y;\mu',\mu_0,\phi'-\phi_0) = \int_0^1 \int_0^{2\pi} \rho(x,y;\mu',\mu'',\phi'-\phi'')D(\mu'',\mu_0,\phi''-\phi_0)\mu''d\mu''d\phi'' \qquad \{3\}$$

where D is the total downward directed radiance at the surface and ρ is the spatially-varying surface directional reflectance distribution. Multiple reflections between the atmosphere and surface give rise to some dependence of D on the average value of ρ.

The characteristic width of the point-spread function (PSF) is on the order of the effective scale height of the scatterers in the atmosphere (Diner and Martonchik, 1985). The atmosphere therefore behaves as a low-pass spatial frequency filter and, as such, the computation of the diffuse radiance field may be performed more efficiently in the spatial Fourier transform domain. The Fourier analog of the atmospheric PSF is the optical transfer function (OTF), which is generally complex, except for nadir viewing, whence the OTF is real and equivalent to its modulus, known as the modulation transfer function (MTF). In this special case both the PSF and OTF are circularly symmetric.

If the atmosphere is horizontally homogeneous, both the path radiance and the direct radiance field can be computed using a standard 1DRT algorithm since the downward directed radiance, D, has, to a good approximation, no horizontal variability. The diffuse radiance field, as noted above, is best calculated in the Fourier domain. Therefore, taking the Fourier transform of Eq. 2, we find

$$\overline{R}(u,v;\mu,\mu_0,\phi-\phi_0) = \pi^{-1} \int_0^1 \int_0^{2\pi} \overline{T}(u,v;\mu,\mu',\phi-\phi')\ \overline{S}(u,v;\mu',\mu_0,\phi'-\phi_0)\ d\mu'\ d\phi' \qquad \{4\}$$

where the overbars indicate the Fourier transform, u and v are the spatial frequencies corresponding to x and y, and the convolution operation has transformed into multiplication. Note that the OTF at zero spatial frequency, $\overline{T}(0,0;\mu,\mu',\phi-\phi')$, is just the 1-D upward diffuse transmittance and is calculated using the same 1DRT code used to calculate path radiance. As such, all orders of scattering are automatically computed. For spatial frequencies not equal to zero, however, the OTF is more efficiently computed using the method of successive orders of scattering, where we find that truncating the computations after two atmospheric scattering events is a sufficiently accurate representation of the total OTF.

The shape of the OTF is sensitive to a number of atmospheric structural parameters, including the opacity and scale height of molecular and aerosol scatterers, and the asymmetry parameter of the aerosol phase function. This sensitivity to the atmosphere plus the large number of OTF values needed, corresponding to the different spatial wavenumbers, makes the OTF computation algorithm the largest consumer of time in the diffuse radiance calculation. An investigation of ways to appreciably reduce the OTF computing time without significantly affecting accuracy resulted in the following measures: (1) treating the double scattering events as isotropic scattering, (2) creating look-up tables for the various functions particular to the OTF calculation (Diner and Martonchik, 1984a, 1984b), and (3) interpolating the OTF in spatial frequency using empirical functions fitted to values calculated at only a few wavenumbers. These measures, together, resulted in two orders of magnitude increase in the computational efficiency of the OTF. The OTF for the atmospheric model described in the next section is shown in Fig. 1. The viewing angle is nadir so that the function is circularly symmetric in spatial frequency, and the incident angles have been integrated over the hemisphere in correspondence with a lambertian surface reflectance.

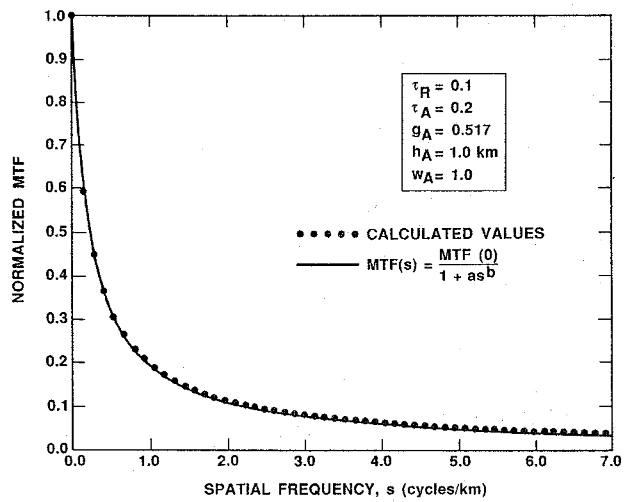

Figure 1. Optical transfer function calculated at the discrete spatial frequencies (dots) and using an empirical three-point interpolating function (solid line)

3. SURFACE REFLECTANCE RETRIEVAL

The simulated scene studied in this paper was generated from part of a radiometrically calibrated Landsat Thematic Mapper image of the coastal region near Los Angeles. The radiance values of the selected portion (256 x 256 pixels at 30-m resolution) of the TM image were transformed to effective lambertian albedo and the darkest pixel value then subtracted from the whole scene, resulting in a simulated no-atmosphere surface scene in which the darkest pixel is black. An arbitrary, normalized reflectance distribution can be introduced at this point to create a more realistic surface. However, in order to see, unambiguously, the magnitude of the adjacency effect in the following surface reflectance retrievals, the reflectance distribution for the scene studied in this paper was taken to be lambertian for all pixels in the image. The model atmosphere used to calculate simulated TOA radiances was horizontally homogeneous with two scattering components: (1) Rayleigh scattering molecules with an opacity, τ_R, of 0.1, a scale height, h_R, of 8 km and a single-scattering albedo, w_R, of unity and (2) a Mie scattering aerosol with an opacity, τ_A, of 0.2, a scale height, h_A, of 1 km, a single-scattering albedo, w_A, of unity and a phase function asymmetry parameter, g_A, of 0.517. The wavelength was assumed to be 550 nm. The viewing geometry was nadir with the sun angle 38^o off of nadir.

Because the surface reflectance distribution is lambertian, Eq. 4 can be written as

$$\overline{R}(u,v;\mu,\mu_0,\phi-\phi_0) = \overline{\rho}(u,v)\ \overline{T}(u,v;\mu,\phi)\ D(\mu_0,\phi_0) \qquad \{5\}$$

where

$$\overline{T}(u,v;\mu,\phi) = \int_0^1\int_0^{2\pi} \overline{T}(u,v;\mu,\mu',\phi-\phi')\ d\mu' d\phi' \qquad \{6\}$$

and

$$D(\mu_0,\phi_0) = \pi^{-1}\int_0^1\int_0^{2\pi} D(\mu'',\mu_0,\phi''-\phi_0)\mu'' d\mu'' d\phi'' \qquad \{7\}$$

Taking the Fourier transform of Eq. 1, we then have

$$\overline{I}(u,v;\mu,\mu_0,\phi-\phi_0) = I_0(\mu,\mu_0,\phi-\phi_0)\delta_{u0}\delta_{v0} + \exp(-\tau/\mu)\ \overline{\rho}(u,v)\ D(\mu_0,\phi_0) + \overline{T}(u,v;\mu,\phi)\ \overline{\rho}(u,v)\ D(\mu_0,\phi_0) \qquad \{8\}$$

where δ_{ij} is a Kronecker delta. This expression can immediately be recast as an algorithm for surface reflectance retrieval:

Step I. Fourier transform the image to be corrected from the spatial domain to the frequency (wavenumber) domain.

Step II. Compute $\overline{\rho}(u,v)$,

$$\overline{\rho}(u,v) = \frac{[\overline{I}(u,v;\mu,\mu_0,\phi-\phi_0) - I_0(\mu,\mu_0,\phi-\phi_0)\delta_{u0}\delta_{v0}]}{[\exp(-\tau/\mu) + \overline{T}(u,v;\mu,\phi)]\ D(\mu_0,\phi_0)} \qquad \{9\}$$

where the path radiance I_0, the direct transmittance $\exp(-\tau/\mu)$, the OTF $\overline{T}$, and the downward directed radiance D are calculated from *a priori* knowledge of the basic atmospheric structural parameters. Since D has a slight dependence on the average albedo, $\overline{\rho}(0,0)$, Eq. 9 can be iterated for the case $u,v = 0$ to obtain both D and $\overline{\rho}(0,0)$.

Step III. Fourier transform $\overline{\rho}(u,v)$ back to $\rho(x,y)$.

Since Eq. 9 includes both measurements [the Fourier transform of the radiance image $I(x,y;\mu,\mu_0,\phi-\phi_0)$] and quantities calculated from supposedly known atmospheric quantities, any uncertainty in the atmospheric quantities will result in corresponding uncertainty in the retrieved surface reflectance $\rho(x,y)$. Using the simulated Landsat-based image described above, we show in Figs. 2 - 5 retrieved surface reflectance sensitivity results to each of four basic aerosol parameters: scale height, single-scattering albedo, phase function asymmetry factor, and optical depth.

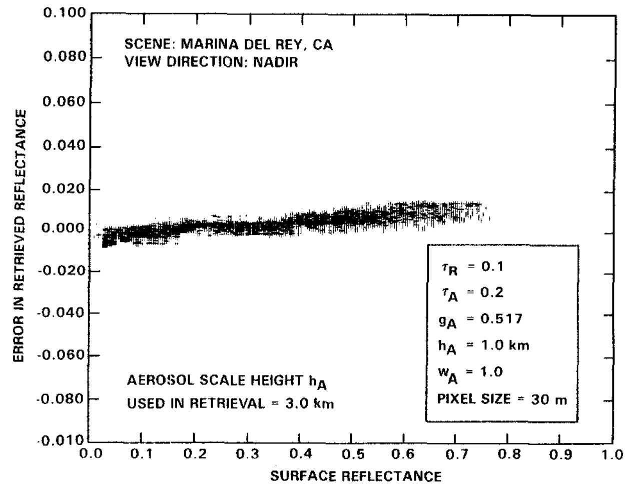

Figure 2. Surface reflectance retrieval with error in aerosol scale height

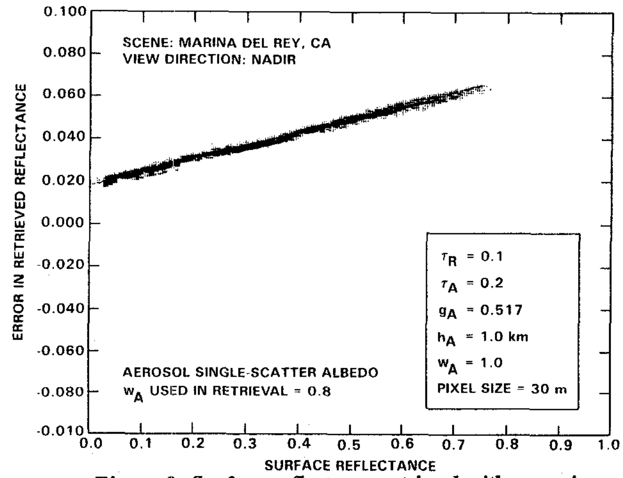

Figure 3. Surface reflectance retrieval with error in aerosol single-scattering albedo

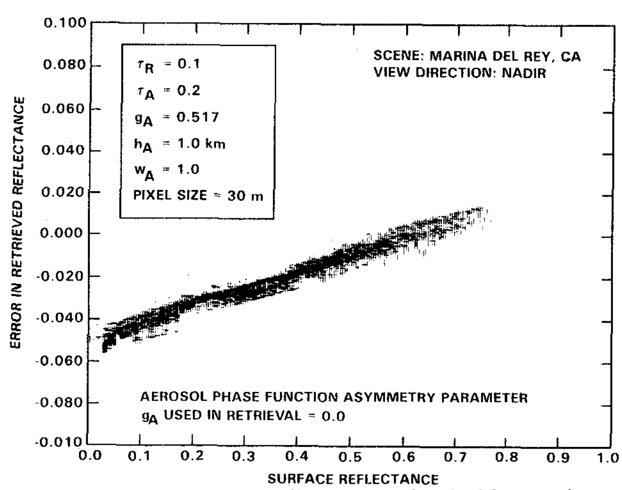

Figure 4. Surface reflectance retrieval with error in aerosol phase function

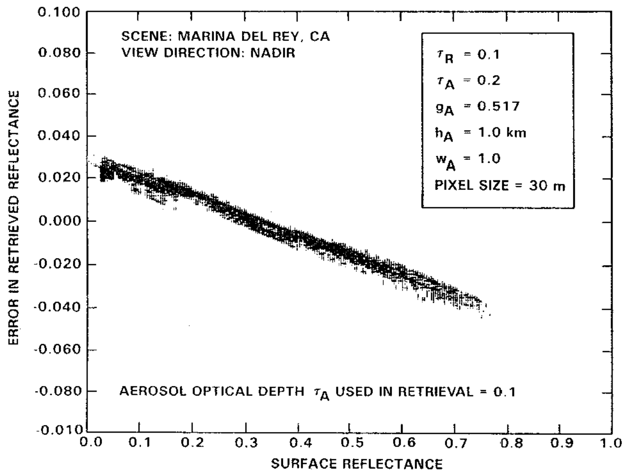

Figure 5. Surface reflectance retrieval with error in aerosol optical depth

These results show that significant errors in surface reflectance can occur if the atmospheric conditions are not determined well enough. However, a potentially more important source of error is ignoring the 3DRT effects and using a 1-D retrieval scheme. From Eqs. 1, 6, and 7 we can write the 1-D retrieval algorithm as

$$\rho(x,y) = \frac{[I(x,y;\mu,\mu_0,\phi-\phi_0) - I_0(\mu,\mu_0,\phi-\phi_0)]}{[\exp(-\tau/\mu) + \overline{T}(0,0;\mu,\phi)] \quad D(\mu_0,\phi_0)} \qquad \{10\}$$

where $\overline{T}(0,0;\mu,\phi)$ is equivalent to the 1-D upward diffuse transmittance.

Figure 6 shows the retrieved surface reflectance of the simulated scene using Eq. 10.

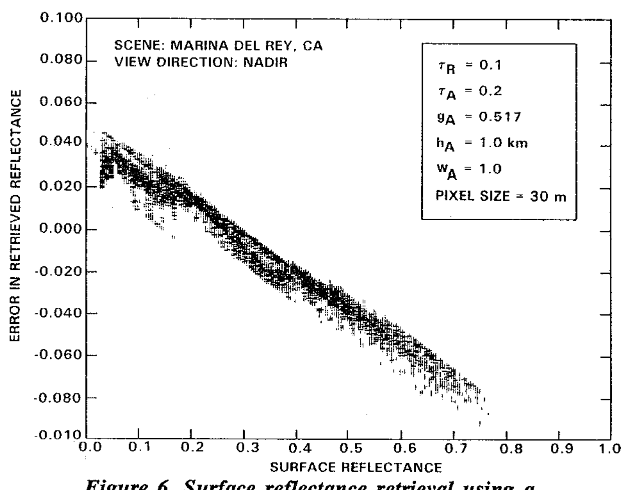

Figure 6. Surface reflectance retrieval using a 1-dimensional retrieval scheme

Comparing the results of Fig. 6 with those of Figs. 2 - 5 shows that ignoring the adjacency effect by using a 1-D retrieval can result in significantly more error in the retrieved surface reflectance than imprecise knowledge of the structure of the atmosphere. This is especially true in for those regions of a scene where albedo contrast is large.

4. CONCLUSIONS

Retrieval of surface reflectance, taking into account 3-D radiative transfer effects, requires the computation of the optical transfer function (or, alternatively, the point-spread function) of the atmosphere. Considerable progress has been made in simplifying the OTF computational process, allowing a two orders of magnitude increase in speed and making that part of the retrieval algorithm timewise comparable to the necessary 1-D computations. We expect additional improvements in speed in both the 1- and 3-D aspects of the algorithm in the future. Using Landsat-based, simulated satellite imagery, we have demonstrated the sensitivity of retrieved surface reflectance to basic atmospheric structural parameters and also compared results using both a 1-D and a 3-D retrieval approach. For scenes with high albedo contrast we find that using a 1-D algorithm and having perfect knowledge of the atmosphere can introduce more error into the surface reflectance retrieval than using a 3-D algorithm and knowing the atmosphere to a far less perfect but more reasonable degree.

5. REFERENCES

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