APPLICATION OF HETEROGENEOUS SCENE MODELS TO RETRIEVAL OF LAND SURFACE AND ATMOSPHERIC OPTICAL PROPERTIES FROM SPACE

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ABSTRACT

In this paper we present a method for using multiple-view-angle imagery to retrieve atmospheric aerosol optical properties. Once determined, these optical properties would be used in a surface reflectance retrieval algorithm designed to correct for atmospheric effects. The method makes use of the presence of spatial contrasts within the imagery, and compares the Fourier transforms of the multi-angle images at zero and nonzero spatial frequencies. An initial guess for the aerosol properties is made and corrections for atmospheric effects at zero and nonzero frequencies are performed. The results are then analyzed to establish whether the initial guess was correct. Other than the need to define a relationship between the angular variation of the Fourier transform of the intrinsic surface angular reflectance at the zero and nonzero frequencies, the method assumes no *a priori* knowledge about the aerosols or surface characteristics. Sensitivities to various aerosol parameters are discussed.

1. INTRODUCTION

Development of practical methods for retrieving land surface optical properties (spectral reflectance, directional reflectance, and hemispherical albedo) from remote sensing imagery in the visible and near-infrared would greatly benefit environmental and climatological land processes studies. Retrieval of these surface properties, in general, will require simultaneous determination of the optical depth, single-scattering albedo, and particle size distribution of tropospheric aerosols, so that compensation may be made for the effects of scattering and extinction. Our approach to retrieving these surface and atmospheric characteristics employs 3-dimensional radiative transfer (3DRT) theory to account for a heterogeneous surface reflectance and to model radiative interactions between the surface and the atmosphere in a realistic manner. Our objective is to develop radiative transfer modules that can be used routinely in the processing of data from instruments planned for the Earth Observing System, such as the Multi-angle Imaging SpectroRadiometer (MISR) [1] and the High- and Moderate-Resolution Imaging Spectrometers (HIRIS and MODIS).

Algorithms to retrieve surface and aerosol optical properties, principally using MISR multi-angle, multispectral imagery, are currently being investigated. The particular schemes being considered include a) scene comparison between clear and hazy conditions; b) regression analyses using spectral radiance correlations; and c) 3-dimensional analyses utilizing scene contrast reduction effects. These techniques have been applied previously to nadir view imagery data such as from Landsat. A generalization of these ideas to include off-nadir imagery, such as from MISR, is straightforward and should provide better constraints on the retrieved surface and atmospheric properties. Also, there are potential retrieval techniques which are inherently multi-angular in nature and have no analogy in the more common single-angle algorithms mentioned above. These multi-angle techniques include d) direct field analyses using image spatial filtering and e) multi-angle property invariance (*e.g.*, scene contrast) to constrain the retrieval results. A comprehensive study of the above mentioned techniques is planned to determine which ones are capable of providing the most accurate surface and aerosol parameter retrievals, subject to scene type and condition.

In this paper we present one phase of our research, namely a preliminary investigation of a method for retrieving both atmospheric and surface properties from multi-angle imagery. This method is inherently multi-angular in nature, relying on an interpretation of the angular dependence of the atmospheric radiance upon its optical parameters.

2. RETRIEVAL ALGORITHM

The TOA radiance can be written as [2]

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

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 Eqn. 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; ρ is the spatially-varying surface directional reflectance distribu-

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tion; and the third term, R, is the radiance diffusely transmitted from the surface to space. Additional quantities expressed in the direct radiance term include the total downward directed radiance D. The atmosphere-related quantities in Eqn. 1 are functions of the opacity τ, single-scattering albedo w, vertical distribution of the scatterers, and the scattering phase function. It is also assumed that the atmosphere is horizontally homogeneous over the spatial region being investigated.

Taking the Fourier transform of Eqn.1, the zero spatial frequency expression can be written as [2]:

$$\mathbf{I}(0,0;\mu,\mu_0,\phi-\phi_0) = I_0(\mu,\mu_0,\phi-\phi_0) + \exp(-\tau/\mu) \times$$
$$\times\ \pi^{-1}\int_0^1\int_0^{2\pi} \mathbf{r}(0,0;\mu,\mu',\phi-\phi')D(\mu',\mu_0,\phi'-\phi_0)\ \mu'\ d\mu'\ d\phi' +$$
$$+\ \pi^{-1}\int_0^1\int_0^{2\pi} T(\mu,\mu',\phi-\phi') \int_0^1\int_0^{2\pi} \mathbf{r}(0,0;\mu',\mu'',\phi'-\phi'') \times$$
$$\times\ D(\mu'',\mu_0,\phi''-\phi_0)\ \mu''\ d\mu''\ d\phi''\ d\mu'\ d\phi' \qquad (2)$$

where the boldface fonts indicate the Fourier transform; $\mathbf{r}$ is the Fourier transform of ρ. Here, the diffuse radiance term is written explicitly with T being the upward directed 1-D diffuse transmittance.

Diffuse transmission through the atmosphere filters out the high spatial frequencies due to surface heterogeneity [3]. In this high spatial frequency case, therefore, the Fourier transform of Eqn. 1 can be written as

$$\mathbf{I}(u,v;\mu,\mu_0,\phi-\phi_0) = \exp(-\tau/\mu) \times$$
$$\times\ \pi^{-1}\int_0^1\int_0^{2\pi} \mathbf{r}(u,v;\mu,\mu',\phi-\phi')D(\mu',\mu_0,\phi'-\phi_0)\ \mu'\ d\mu'\ d\phi' \qquad (3)$$

where u and v are the spatial frequencies corresponding to x and y.

It is convenient to express the azimuthal dependence of the surface directional reflectance distribution in some analytic form to facilitate the integration procedure in the equations. For example, we can let

$$\rho(x,y;\mu,\mu',\phi-\phi') = \rho_0(x,y;\mu) + \rho_1(x,y;\mu)\cos(\phi-\phi') \qquad (4)$$

independent of incident angle μ'. Putting the spatial Fourier transform of Eqn. 4 into Eqns. 2 and 3, we obtain

$$\mathbf{I}(0,0;\mu,\mu_0,\phi-\phi_0) = I_0(\mu,\mu_0,\phi-\phi_0) +$$
$$+ \exp(-\tau/\mu)\ [\mathbf{r}_0(0,0;\mu)\ S_0 + \mathbf{r}_1(0,0;\mu)\ S_1(\phi-\phi_0)]$$
$$+ \int_0^1 T_0(\mu,\mu',\phi-\phi_0)\mathbf{r}_0(0,0;\mu')\ d\mu' +$$
$$+ \int_0^1 T_1(\mu,\mu',\phi-\phi_0)\mathbf{r}_1(0,0;\mu')\ d\mu' \qquad (2')$$

and

$$\mathbf{I}(u,v;\mu,\mu_0,\phi-\phi_0) = \exp(-\tau/\mu) \times$$
$$\times\ [\mathbf{r}_0(u,v;\mu)\ S_0 + \mathbf{r}_1(u,v;\mu)\ S_1(\phi-\phi_0)] \qquad (3')$$

where

$$S_0 = \pi^{-1}\int_0^1\int_0^{2\pi} D(\mu',\mu_0,\phi'-\phi_0)\ \mu'\ d\mu'\ d\phi' \qquad (5)$$

and

$$S_1(\phi-\phi_0) =$$
$$\pi^{-1}\int_0^1\int_0^{2\pi} D(\mu',\mu_0,\phi'-\phi_0)\cos(\phi-\phi')\ \mu'\ d\mu'\ d\phi' \qquad (6)$$

and where

$$T_0(\mu,\mu',\phi-\phi_0) = S_0\int_0^{2\pi} T(\mu,\mu',\phi-\phi')\ d\phi' \qquad (7)$$

and

$$T_1(\mu,\mu',\phi-\phi_0) = \int_0^{2\pi} T(\mu,\mu',\phi-\phi')\ S_1(\phi'-\phi_0)\ d\phi'. \qquad (8)$$

Assuming a known relationship between the angular shape of the zero-frequency component of the Fourier-transformed directional reflectance $\mathbf{r}(0,0;\mu,\mu',\phi-\phi')$ and the shape at a non-zero frequency $\mathbf{r}(u,v;\mu,\mu',\phi-\phi')$, it is possible in principle to retrieve the optical properties of the atmosphere. These functions would have the *same* shape, for example, if the surface is characterized by differing albedo from pixel to pixel but the same relative variation in reflectance as a function of view angle. For a radiometrically calibrated, pixel-registered set of imagery at various view angles μ and $\phi-\phi_0$, the retrieval algorithm using the above equations would proceed as follows:

Step 1: Guess an atmosphere and compute the corresponding 1-D path radiance I_0, the upward directed diffuse transmittance T, and the total downward directed radiance D assuming no surface reflectance.

Step 2: Iterate Eqn. 2' to solve for $\mathbf{r}_0(0,0;\mu)$ and $\mathbf{r}_1(0,0;\mu)$. Note that imaging in two azimuthal directions (*e.g.*, fore and aft) is needed to solve for the two functions $\mathbf{r}_0$ and $\mathbf{r}_1$. The surface directional reflectance distribution $\mathbf{r}(0,0;\mu,\mu',\phi-\phi')$ is then constructed according to Eqn. 4 and used to update the total downward directed radiance D, and subsequently to re-calculate the functions S_0, S_1, T_0 and T_1. The iteration procedure for determining $\mathbf{r}_0(0,0;\mu)$ and $\mathbf{r}_1(0,0;\mu)$ is repeated to update the atmosphere-surface functions, continuing this cycle until convergence of the functions is achieved.

Step 3: Solve Eqn. 3' directly for $\mathbf{r}_0(u,v;\mu)$ and $\mathbf{r}_1(u,v;\mu)$ and construct $\mathbf{r}(u,v;\mu,\mu',\phi-\phi')$ using Eqn. 4. The result is compared to $r(0,0;\mu,\mu',\phi-\phi')$ determined from Step 2. Knowing the functional relationship between $r(0,0;\mu,\mu',\phi-\phi')$ and $r(u,v;\mu,\mu',\phi-\phi')$, this comparison is the basis for deciding whether the selected atmosphere in Step 1 is correct or in need of change. If the atmosphere is modified, the whole procedure from Steps 1 through 3 then is repeated until the comparison test is satisfied.

Once the atmospheric parameters are determined, the surface directional reflectance distribution retrieval is straightforward, and makes use of the generalized Fourier domain expression of Eqn. 1, in which the Fourier transform of R includes the spatial frequency dependence of the upward diffuse atmospheric transmittance.

3. RETRIEVAL RESULTS

To investigate the retrieval procedure, a set of images was constructed according to Eqn. 1. Using a Landsat Thematic Mapper image of the Wind River Basin area in Wyoming to specify hemispherical albedo, only one normalized directional reflectance distribution, based on field measurements [4], was used in the image synthesis. (The normalized reflectance for each pixel is the reflectance at each angle divided by the hemispherical albedo.) The view angles selected were based on those planned for the MISR instrument (cosines of the view angle, μ, are 0.3, 0.5, 0.7 and 0.9 for the aftward camera bank and 0.4, 0.6, 0.8, and 1.0 for the forward camera bank). Defining the azimuth angle of the aft direction as zero (and therefore the forward direction as 180°), the sun position was set at a zenith angle of 38° and azimuth angle of 300°. The atmosphere had a small Rayleigh component ($\tau_{ray} = 0.017$) and an aerosol opacity of 0.5. The wavelength was 860 nm. The aerosol single-scattering albedo was set at 1.0 and the scattering phase function, calculated from Mie scattering, was moderately forward scattering (asymmetry factor $g = 0.51$). The vertical distribution of the aerosol was exponential with a scale height of 2 km.

The resulting Fourier transforms of the eight images (computed using a fast Fourier transform, or FFT routine) are presented as amplitude (square root of power) spectra in Figure 1. Since each image was 256 x 256 pixels in size, 128 discrete spatial frequencies in one direction result from the FFT algorithm but only the range of 0 through 5 in frequency index is displayed. The directional dependence of the spatial frequencies was averaged out, producing a scalar spatial frequency s [$= (u^2 + v^2)^{1/2}$].

Since only one normalized directional reflectance distribution exists in the scene, the relationship between $r(0;\mu,\mu',\phi-\phi')$ and $r(s;\mu,\mu',\phi-\phi')$ is straightforward,

$$r(0;\mu,\mu',\phi-\phi') = A(0)\ \rho_{norm}(\mu,\mu',\phi-\phi') \tag{9}$$

and

$$r(s;\mu,\mu',\phi-\phi') = A(s)\ \rho_{norm}(\mu,\mu',\phi-\phi') \tag{10}$$

where $A(s)$ is the amplitude spectrum of the surface hemispherical albedo and $\rho_{norm}(\mu,\mu',\phi-\phi')$ is the directional reflectance distribution normalized to the albedo. Although $A(s)$ is not *a priori* known, the two functions described in Eqns. 9 and 10 have the same angular shape and this is a sufficient condition by which to exercise the retrieval algorithm described in the previous section.

Figures 2 through 5 show the results of a sensitivity study of the retrieved functions $r(0;\mu,\mu',\phi-\phi')$ and $r(s;\mu,\mu',\phi-\phi')$ to atmospheric parameters. The actual curves in the figures are representations of the retrieved functions as defined through Eqn. 4 and were computed at the view angles of the MISR instrument. The retrieved reflectances for both the forward and aftward viewing angles are plotted as a function of $1/\mu$, the secant of the view zenith angle. Goodness of fit between zero and nonzero spatial frequency curves is described by the variance computed in a least squares sense by determining the scaling factor of the nonzero spatial frequency curve.

Figure 2 shows the retrieval results when all atmospheric parameters are guessed correctly. The fact that the fit is not exact is due to the approximation used for the azimuthal dependence of the reflectance distribution as described by Eqn. 4.

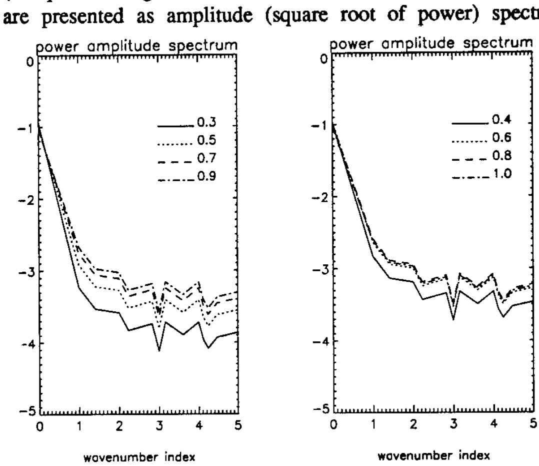

Fig. 1. Spatial frequency spectra of simulated images

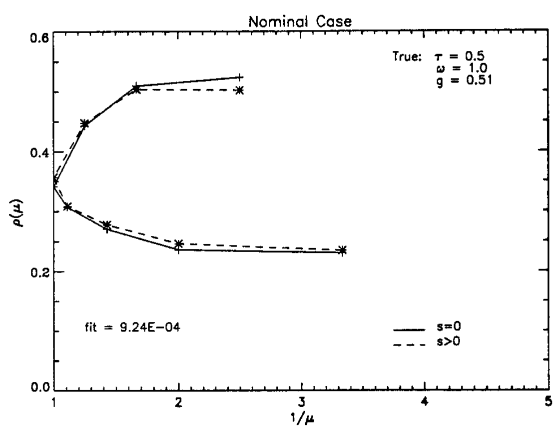

Fig. 2. Retrieval results with correct atmosphere

The effects of errors in the guessed opacity are shown in Figs. 3 and 4. Note that sensitivity is increased when the larger view angles are represented.

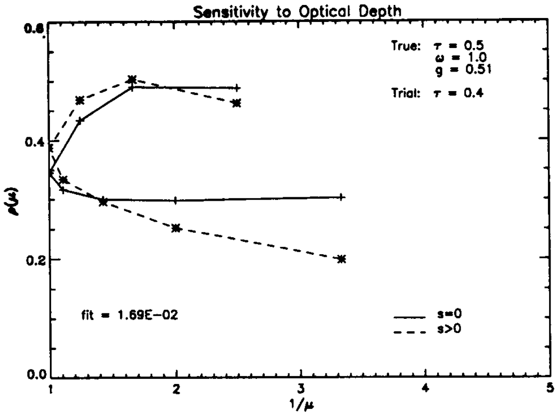

Fig. 3. Retrieval results with underestimated opacity

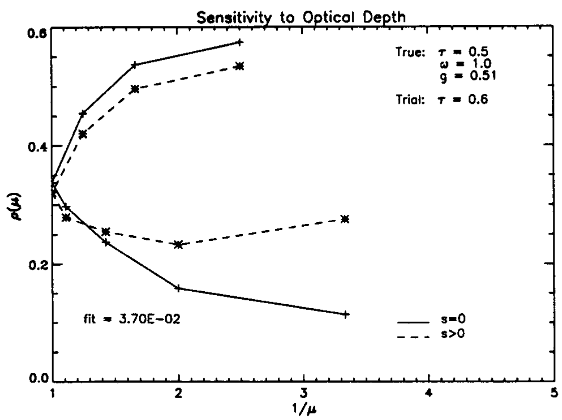

Fig. 4. Retrieval results with overestimated opacity

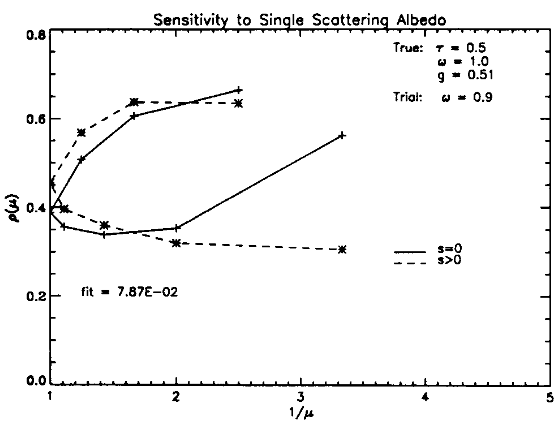

Fig. 5. Retrieval results with error in single scatter albedo

Figure 5 shows the retrieval results when a guess of $w = 0.9$ for the aerosol single-scattering albedo is used. Sensitivity to this parameter is evident only for view angles greater than 60°.

4. CONCLUSIONS

Analyses of radiometrically calibrated, pixel registered imagery obtained from spacecraft instruments with multi-angle viewing capability offer the possibility of retrieving both atmospheric optical properties and surface reflectance properties. Success of the retrieval method outlined in this paper is contingent on the fact that a reasonable determination can be made of a relationship between the angular shape of the directional surface reflectance Fourier transform at zero spatial frequency and at a frequency greater than zero. For the example of a single normalized, non-lambertian directional reflectance in a given set of multi-angle images, the required relationship is easily obtained. When a number of different directional reflectances are present in the imagery, however, as would be the case for typical remotely sensed scenes, determination of this relationship is less obvious and is currently the subject of investigation.

5. REFERENCES

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