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ITERATIVE ATMOSPHERIC CORRECTION SCHEME AND THE POLARIZATION COLOR OF ALPINE SNOW

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ABSTRACT. Proper characterization of the Earth's surface is crucial to remote sensing, both to map geomorphological features and because subtracting this signal is essential during retrievals of the atmospheric constituents located between the surface and the sensor. Current operational algorithms model the surface total reflectance through a weighted linear combination of geometry-dependent kernels, each devised to describe a particular scattering mechanism. The information content of intensity-only measurements is overwhelmed by instruments with polarization capabilities. Because of their remarkable lack of spectral contrast, the polarized reflectances of land surfaces in the shortwave infrared spectral region (where atmospheric scattering is minimal) can be used to model the surface at shorter wavelengths, where aerosol retrievals are performed.

1. Introduction

Meaningful retrievals of surface and atmospheric properties from remote sensing data rely on accurate radiative transfer models as well as on successful separation of the surface and the atmospheric signals. A straightforward separation of these two contributions is not possible without approximations because of the coupling introduced by multiple reflections. Within a general inversion framework, the problem can be eliminated by linearizing the Radiative Transfer calculation, and making the Jacobian derivative (expressing the sensitivity of the reflectance with respect to model parameters) available at output. We present a general methodology based on a Newton-like iterative search, that eliminates de facto the need of atmospheric correction. We then apply this method to a dataset of special interest recently collected over an alpine snowfield. Confirming that the polarized reflectance of snow is spectrally flat would allow to extend established techniques for aerosol polarimetric retrievals over land to the large portion of snow-covered pixels plaguing orbital observations.

2. Methodology

A common decomposition of the total surface reflectance in a sum of geometry-dependent kernels K_i, weighted by coefficients f_i, follows the RossThick - LiSparse form [1]:

$$\rho = f_{\text{iso}} + f_{\text{vol}} K_{\text{vol}} + f_{\text{geo}} K_{\text{geo}} \tag{1}$$

The first term is a Lambertian contribution with no directional dependence (i.e., kernel-free). The second term represents scattering within dense canopies [2]. The geometric term accounts for shadowing of a Lambertian background from objects of larger size [3].

The polarized portion $F_p(\theta_i)$ of the reflectance generated by most land surfaces is largely determined by the Fresnel laws of reflection [4], function of the incident angle θ_i and the index of refraction of the surface. Corrections to the simple Fresnel model account for geometric effects such as multiple reflections and self shadowing, so that ultimately some function of the Fresnel reflectance is used. Based on the assumption of an isotropic distribution of facets at the surface, a properly normalized model is [5]:

$$R_p = F_P(\theta_i)\,/\,4[\cos(\theta_s) + \cos(\theta_v)] \tag{2}$$

where θ_s and θ_v are the Solar and viewing zenith angles. We allow the weight f_{fresnel} to scale this expression to account for variability in refractive index.

At a given geometry i, the reflectance R_i measured by an optical remote sensor includes the atmospheric contribution and is a certain non-linear function of the kernel weights. To minimize the mismatch between the model $\mathbf{F}$ and the observations, we evaluate the *residuals* $\phi_i = R_i - F_i(\mathbf{f})$ and the scalar *cost function* Φ as the sum of their squares. The condition at minimum $\partial\Phi/\partial f_j = 2\sum_{i=1}^{N} \phi_i \frac{\partial\phi_i}{\partial f_j} = 0$ generates a set of equations solvable by an iterative approach. Pending differentiability and good behavior, F can be expanded in a Taylor series in the neighborhood of the current iteration state $\mathbf{f}^k$. The residuals are then approximated by:

$$\phi_i^k(\mathbf{f}^k) \sim [R_i - F_i(\mathbf{f}^k)] - \sum_{j=1}^{M} J_{ij}^k \delta f_j^k \tag{3}$$

where $\delta f_j^k = f_j - f_j^k$ and J_{ij}^k is the Jacobian, or array of partial derivatives of F_i with respect to each f_j, and from which we derive $\partial\phi_i^k/\partial f_j^k = -J_{ij}^k$. Substituting in the condition at minimum we obtain a new set of linear equations that can be cast in the form of normal equations $(\mathbf{J}^{k,T}\mathbf{J}^k)\delta\mathbf{f}^k = \mathbf{J}^k[\mathbf{R} - \mathbf{F}(\mathbf{f}^k)]$, where the unknown is the increment $\delta\mathbf{f}^k$, the regressor is the departure from the model $\mathbf{R} - \mathbf{F}$ and the matrix involved in the inversion is the Jacobian. The advantage of this approach becomes clear when considering that the latter quantity is a byproduct of the Doubling Adding simulations, output without additional computational cost. At each iteration step k, a new set of model parameters is obtained from the recursive relation $\mathbf{f}^{k+1} = \mathbf{f}^k + \delta\mathbf{f}^k$, and the model run again to obtain a new value for $\delta\mathbf{f}^k$. This procedure is repeated until convergence, essentially applying Newton's method for the search of a minimum. This method is extremely powerful and performs best with smooth functions of low curvature. The convergence is quadratic for functions that are twice differentiable in the neighborhood of a simple root, and can be reached in one iteration in the limiting case of linear functions.

3. Results

To test its performance, we have applied the outlined method to a synthetic scene consisting of a purely Rayleigh atmosphere at 410 nm, where scattering is significant and many of the surface features are washed out. The Solar Zenith Angle (SZA) was set at

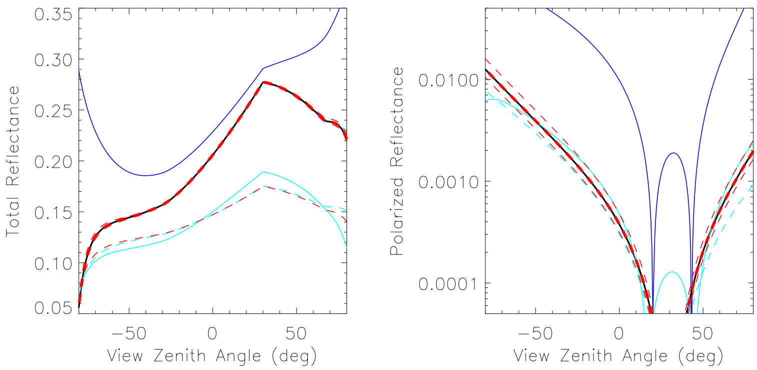

Figure 1. Newton's iterative search for the surface reflectance. Left: total reflectance (see Eq. 1); right: polarized reflectance (see Eq. 2). From the reflectances measured by the RSP (blue), the method converges fast from the initial guess (path radiance-corrected signal, solid cyan curve fitted by the cyan dashed curve) to the unknown surface signal (black). Fits at different iterations are represented by dashed red curves, with the converged answer of increased thickness. Both for total and polarized reflectance, the residuals get very small after a couple of iterations, making it difficult to distinguish between intermediate and final fits.

$30°$. The surface was prepared according to the model in Eqs. (1) and (2) by choosing the following set of parameters: $\{f_{\rm iso}, f_{\rm vol}, f_{\rm geo}, f_{\rm fresnel}\} = \{0.25, 0.19, 0.05, 0.75\}$. The resulting surface reflectance, unknown in real measurements and which we ultimately want to retrieve, is shown with a black curve in Fig. 1 for the total (left panel) and polarized reflectance (right panel). The signal hypothetically collected by an instrument like the RSP while flying at an altitude of 8.5 km along the principal plane is shown by the blue curves.

A first guess for the model parameters is obtained by fitting with a Levenberg-Marquardt type of routine [6] the difference between the observed (total and polarized) reflectance and the (total and polarized) *path radiance*, defined as the radiance scattered into the instrument's field of view without having interacted with the surface. This approximation does not take into account possible effects of multiple interactions between the surface and the atmosphere. It is worthwhile noting the vanishing surface contribution to the polarized reflectance for directions close to backscatter, where Rayleigh processes take over. The cusp in the total reflectance is instead the hotspot signature typical of vegetation models.

When the model is run again with this choice of modeling parameters, the surface signal is found to resemble the first fit (see the almost overlapping red dashed line). The Jacobians output by the code are then used to find the steps $\delta\mathbf{f}$ and update the parameters. A second iteration produces a significantly different signal that already fits the sought surface reflectance very well. Further iterations account for barely distinguishable refinements, until the algorithm stops based on thresholds imposed on the difference in residuals from the previous iteration. This fast convergence is an indicator of the low curvature of the hypersurface represented by the cost function Φ in "residual" space.

4. Case study

During a recent campaign in California, favorable conditions with snow persisting late in the season provided the opportunity to include a few flight legs over the Sierra mountain range in one of the research flights of the Research Scanning Polarimeter. This instrument has served as the airborne prototype of the Aerosol Polarimetry Sensor developed for the Glory satellite mission, and measures the first three Stokes parameters [4] at multiple wavelengths and multiple viewing angles.

The flight took place on 10 June 2010, and resulted in a limited dataset useful to analyze and characterize the signal from snowy alpine surfaces. Of particular interest is the question of whether the polarized reflectance of snow is spectrally flat as that of other land surfaces. This property would allow for the application of the same algorithms already employed in aerosol retrievals from remote sensing data [7], in particular those based of inverse methods.

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