Determination of aerosol optical depth and land surface directional reflectances using multiangle imagery

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Abstract. Spectral aerosol optical depths, surface hemispherical-directional reflectance factors, and bihemispherical reflectances (albedos) are retrieved for an area of Glacier National Park using spectral, multiangle imagery obtained with the airborne advanced solid state array spectroradiometer (ASAS). The retrieval algorithms are described and are identical in principle to those being devised for use by the multiangle imaging spectroradiometer (MISR) which will fly on the EOS-AM1 spacecraft in 1998. As part of its science mission, MISR will produce global coverage of both aerosol amounts and land surface reflection properties. The results in this paper represent the initial effort in applying the MISR algorithms to real data. These algorithms will undergo additional testing and validation as more multiangle data become available.

1. Introduction

Knowledge of aerosol characteristics and surface reflection properties on a global basis are essential inputs to the study of atmospheric and biospheric climate processes [Charney et al., 1977; Dickinson, 1983; Mintz, 1984]. The multiangle imaging spectroradiometer (MISR) is a radiometrically calibrated instrument, scheduled for launch in 1998 on the EOS-AM1 spacecraft, which will provide such information in a routine manner [Diner et al., 1991]. It has nine CCD pushbroom cameras to provide images at angles of 70.5°, 60.0°, 45.6°, 26.1°, and 0° relative to nadir, both forward and aftward along the direction of flight. Each camera observes continuously in four spectral bands (443, 555, 670, and 865 nm) and in the global coverage mode will produce imagery with a spatial sampling of 1.1 km and global coverage within 9 days. Operating at an altitude of about 705 km and in a polar orbit, all nine cameras will observe the same ground point within 7 min, guaranteeing that essentially identical atmospheric conditions will exist for each scene viewed at the nine different angles.

To test and validate the aerosol and surface retrieval algorithms which will be used by MISR adequately, it is necessary to have comparable, radiometrically calibrated multiangle imagery. Spacecraft data sets currently available are not well suited to this purpose. Advanced very high resolution radiometer (AVHRR) data, for example, have a footprint size of about 1 km at nadir, similar to that of MISR, but only in a single spectral channel in the visible and one in the near infrared. More importantly, since AVHRR is a cross-track scanning instrument, a set of images of a given region covering a wide range of view angles (up to 55°) can only be obtained using data from different days. An undesirable consequence, for the purpose of testing MISR algorithms, is that each image is probably produced under different atmospheric conditions. ATSR-2 onboard ERS-2 also has a nadir footprint of about 1 km and has two spectral channels (0.65 and 0.85 μm) similar to MISR channels. However, it is a conical scanning instrument, producing two views of a region (one near nadir and another near 55° off nadir in the forward direction) within 2 min of each other. Images at only two view angles are insufficient to represent the range of view angles exercised by the MISR multiangle-dependent retrieval algorithms.

At present the data sets that come closest to simulating MISR-type imagery are those produced by the airborne advanced solid state array spectroradiometer (ASAS) [Irons et al., 1991]. Contiguous spectral bands cover the wavelength region 400–1000 nm and view angle coverage ranges from 70° forward to 55° aftward. The spatial resolution, however, is about 4 m at a typical observing altitude of 5 km, considerably higher than for MISR, and the areal extent of coregistered ASAS scene imagery at the various view angles is of the order of 1 km², about equal in size to a single MISR pixel. Nevertheless, the MISR algorithm for aerosol optical depth retrieval can be applied to the ASAS data because the algorithm depends mainly on there being some spatial contrast within the scene and not particularly on the spatial scale. The spatial scale, however, does affect how the diffuse radiation component of the measured radiance is treated. For ASAS data the diffuse radiance is assumed to be spatially invariant (pixel independent) over the scene, whereas for MISR data, with its coarser resolution, we will assume this component to be spatially variable. Another difference is that MISR takes measurements from above the atmosphere, whereas ASAS observations are made with a nonnegligible amount of atmosphere above the aircraft. We have coded the retrieval algorithms for both aerosol optical depth and surface directional reflectances to handle both types of data.

2. ASAS Data Set Description and Preprocessing

A series of multiangle ASAS images was made of Bowman Lake in Glacier National Park, Montana, at about 1300 LT on February 26, 1992. The lake is at an elevation of 1.25 km and the aircraft flew at an altitude of 4.45 km above sea level with a heading of 235° measured clockwise from true north. The Sun was in the west at a zenith angle of 63.4° and an azimuth angle of 214°, also measured from true north. Thus the aircraft was flying in the general direction of the Sun position, only about 20° azimuth angle from the principal plane. Images at 10
different view angles (70°, 60°, 45°, 30°, and 15° in the forward look direction, nadir, and 15°, 30°, 45°, and 55° in the backward look direction) were obtained in succession along a single flight line. The 559-nm band image with a forward look of 15° is displayed in Figure 1, showing the northeast tip of the ice- and snow-covered lake surrounded by a conifer forest.

Before the multiview angle images could be analyzed for geophysical information by the retrieval algorithms, they first had to be spatially coregistered; that is, the same pixel location in all of the images needed to correspond to the same physical point in the scene. The image coregistration process was done manually, using selected tie points to rubbersheet the off-nadir images to the nadir one. Although the ASAS instrument has an instantaneous swath width of about 2 km at nadir, the effects of aircraft roll and increasing spatial coverage with off-nadir view angle reduced the common swath observed for all 10 view directions to about a 1 km square resulting in a 256 × 256 pixel image for each view. The coregistration accuracy was generally of the order of ±0.2 pixel with a small number of localized areas misregistered by up to 1 pixel. After coregistration of the 10 view angle images for each ASAS spectral band the calibration coefficients were applied, converting digital counts to W m⁻² sr⁻¹ μm⁻¹. The resulting radiometrically calibrated images then were spatially averaged over 4 × 4 pixels to produce a final 64 × 64 pixel image data set. The pixel averaging was done to minimize any coregistration errors, to minimize variable footprint size effects at the different view angles and to increase the signal-to-noise ratio. Although the data set contained images for 29 spectral bands, only those four bands closest to the MISR bands were analyzed (ASAS 475, 559, 673, and 866 nm, hereinafter labeled bands 1 through 4, respectively). The image signal-to-noise ratio for bands 1 through 3 was quite good (~100) but that in band 4 was markedly poorer, because of lower detector sensitivity. The band 4 image also had a coherent noise problem (noticeable periodic streaking appears in a herringbone pattern), mitigated somewhat by the averaging procedure, and a probable calibration problem, discussed later.

3. Aerosol Optical Depth Retrieval

To determine aerosol properties over land using passive remote sensing, it is necessary to have some information about the surface reflectance. If, for example, a large, dark water body exists within a scene, then the water pixel radiances can be interpreted mainly as atmospheric path radiance with only a small, correctable, component due to surface reflectance. Another surface type with presumed known reflectance properties is dense, dark vegetation (DDV), which will play a role in the analysis of EOS-MODIS data [Kaufman et al., this issue] and also MISR data [Diner et al., 1996a] to retrieve aerosol properties. For both dark water and DDV the reflectance is relatively small, allowing modest uncertainties to not unduly affect the accuracy of the aerosol retrieval. In general, however, surface reflectances within a scene are not usually known a priori, so other methods for treating surface reflectance must be investigated. Here two techniques are described which use the scene radiances directly and do not demand any additional information about the surface reflectance properties. However, these techniques cannot guarantee a useful aerosol retrieval for every scene to which they are applied because they both rely on the condition that there be a sufficient number of
pixels which have different bitemporal reflectances (albedos) but very similar directional reflectance shapes. The fact that an analysis of the directional characteristics of the observed radiance is at the heart of these techniques restricts their use to multigange imagery. Algorithms employing both techniques were used in the analysis of the ASAS data to retrieve aerosol optical depth.

3.1. Technique I: Empirical Orthogonal Functions

An aerosol retrieval first was done using an algorithm based on a variation of the technique described by Marionich and Diner [1992]. In the original version of the technique the images were operated upon by a fast Fourier transform (FFT) to generate power spectra as a function of spatial wavenumber and view angle. The angle-dependent power functions of the nonzero wavenumbers then were used to construct empirical orthogonal functions (EOFs) which described the spatially variable, angle dependent surface component of the observed radiance. These EOFs were used as basis vectors in an expansion of the surface component of the image-averaged radiance when an aerosol-laden atmosphere model is introduced in the analysis. The best estimate of the aerosol optical depth is the model which minimized the residuals between the observed multigange radiances and the corresponding model-dependent radiances, computed using the EOF-based surface radiance component.

The variation of the technique used in this study, and which is more closely related to the approach to be adopted with MISR, foregoes the FFT and constructs the EOFs directly from the radiances associated with the individual pixels in the images. To a good approximation the radiance $L_{ASAS}^{ASAS}(\mu, \mu_0, \phi - \phi_0)$ at the ASAS observation level can be written as

$$L_{ASAS}^{ASAS}(\mu, \mu_0, \phi - \phi_0) = L_{ASAS}^{ASAS}(-\mu, \mu_0, \phi - \phi_0) + L_{dif}^{dif}(-\mu, \mu_0, \phi - \phi_0) + L_{dir}^{dif}(\mu, \mu_0, \phi - \phi_0)$$

(1)

where $L_{ASAS}^{ASAS}$ is the radiance field scattered by the atmosphere up to the aircraft without interacting with the surface (i.e., the path radiance) and $L_{dir}^{dif}$ and $L_{dif}^{dif}$ are the radiances directly and diffusely transmitted from the surface to the aircraft, respectively. $L_{ASAS}^{ASAS}$ and $L_{dir}^{dif}$ can be expressed as

$$L_{ASAS}^{ASAS}(\mu, \mu_0, \phi - \phi_0) = \exp(-\tau/\mu_1) \frac{1}{\pi}$$

$$\int_0^1 \int_0^{2\pi} R_c(-\mu, \mu', \phi - \phi') L_{inc}(\mu', \mu_0, \phi' - \phi_0) d\mu' d\phi'$$

(2)

$$L_{dir}^{dif}(-\mu, \mu_0, \phi - \phi_0) = \frac{1}{\pi} \int_0^1 \int_0^{2\pi} \int_0^{2\pi} T(-\mu, -\mu', \phi - \phi')$$

$$\Delta_{ASAS}^{ASAS}(\mu, \mu_0, \phi - \phi_0) = \frac{\mu_0}{\mu_1} L_{inc}(\mu', \mu_0, \phi' - \phi_0) d\mu' d\phi' d\phi'$$

(3)

where $x, y$ are the image pixel coordinates, $\mu$ and $\mu_0$ are the cosines of the view and Sun angles, and $\phi - \phi_0$ is the view azimuth angle with respect to the Sun position. The convention $\mu$ is used for upwelling radiation and $\mu_0$ for downwelling radiation. Also, $\tau$ is the optical depth of the atmosphere between the surface and the aircraft, $L_{inc}$ is the radiance field incident on the surface, $T$ is the upward diffuse atmospheric transmittance from the surface to the aircraft, $R_{ASAS}$ is the spatially variable surface bidirectional reflectance factor (BRF), and $\Delta_{ASAS}$ is the average surface BRF for the image. Note that only $L_{dir}^{dif}$ is assumed spatially variable for the conditions of the ASAS observations. Similar expressions to (1), (2), and (3) also would describe the MISR observations except that both the direct and the diffuse radiation fields would be spatially variable.

The 64 x 64 pixel ASAS scene was subdivided into 4 x 4 subscenes, each with 16 x 16 pixels. Within each of these subscenes a separate aerosol optical depth retrieval was performed for each spectral band and the results for all subscenes then were averaged together. The EOFs required to implement the aerosol retrieval algorithm for each subscene are the eigenvectors associated with the real, symmetric scatter matrix constructed from reduced pixel radiances. Reduced pixel radiances are defined to be ASAS pixel radiances minus the pixel-averaged ASAS radiance, where the average is conducted over the subscene of 16 x 16 pixels. This subtraction process removes any effect of the atmospheric path radiance $L_{ASAS}$ and the diffusely transmitted radiance $L_{inc}$, which are assumed to be the same for each pixel in the subscene. Thus each reduced pixel radiance $J_{x,y}$ at location $x, y$ for each view angle is given by

$$J_{x,y}(-\mu, \mu_0, \phi - \phi_0) = L_{ASAS}^{ASAS}(-\mu, \mu_0, \phi - \phi_0)$$

$$- (L_{ASAS}^{ASAS}(-\mu, \mu_0, \phi - \phi_0)) = L_{dir}^{dif}(-\mu, \mu_0, \phi - \phi_0)$$

$$- (L_{dir}^{dif}(-\mu, \mu_0, \phi - \phi_0))$$

(4)

where the operation angle brackets denote an average over all the pixels in the subscene. $J_{x,y}$, as expressed in (4), can be considered a linear combination of surface functions, $S_{x,y}$, defined to be that component of the measured radiance transmitted from the surface which is spatially variable. For ASAS observations,

$$S_{x,y}(-\mu, \mu_0, \phi - \phi_0) = L_{inc}^{ASAS}(-\mu, \mu_0, \phi - \phi_0)$$

(5)

Following Preisendorfer [1988] the scatter matrix $C$ can be written as

$$C_{ij} = \sum_{x,y} J_{x,y} J_{x,y}$$

(6)

where subscripts $i$ and $j$ are now used to indicate the 10 different viewing geometries. The eigenvectors of $C$ are solutions to the equation given by

$$\sum_{j=1}^{10} C_{ij} f_{nj} = \lambda_{nj} f_{nj}$$

(7)

where $\lambda_n$ is the eigenvalue (real and positive) of $f_{nj}$. In general, there will be 10 eigenvalues and eigenvector solutions with the 10-element eigenvectors forming an orthonormal set; that is,

$$\sum_{j=1}^{10} f_{nj} f_{nj} = \delta_{nm}$$

(8)

where $\delta_{nm}$ is the Kronecker symbol. Thus every 10-element vector $J_{x,y}$ can be expanded in terms of this orthonormal set as
\[ J_{s,y,i} = \sum_{n=1}^{10} A_{n,0}^{i,y} f_{n,i} \]  
(9)

where \( A_{n,0}^{i,y} \) are the principal components,

\[ A_{n,0}^{i,y} = \sum_{i=1}^{10} J_{s,y,i} f_{n,i} \]  
(10)

The eigenvectors are ordered according to the magnitude of the corresponding eigenvalues; that is, \( \lambda_1 > \lambda_2 > \cdots > \lambda_{10} \). The set of vectors \( f_{n} \) is the optimum basis function set to represent the vectors \( J_{s,y} \) in the sense that if only the first \( N \) \( (N < 10) \) eigenvectors are used in the expansion, then the resulting error \( e_N \) is a minimum when compared to the error using the first \( N \) vectors from a different vector basis function set. Here the error \( e_N \) is defined as

\[ e_N = \sum_{s,y} \sum_{i=1}^{10} \left( J_{s,y,i} - \sum_{n=1}^{N} A_{n,0}^{i,y} f_{n,i} \right)^2 = \sum_{s,y} \sum_{i=1}^{10} \left( \sum_{n=1}^{N} A_{n,0}^{i,y} f_{n,i} \right)^2 = \sum_{n=1}^{N} \lambda_n. \]
(11)

Thus, \( f_i \) contributes most to the description of the vectors \( J_{s,y} \) and \( f_{n,i} \), the least.

Now, as an example, if a single BRF shape is able to describe the view angle variability of the surface within a subscene (the individual pixel reflectances, however, being variable), then the reduced pixel radiances are proportional to each other; that is,

\[ J_{s,y,i} = c_i J_{s,y,i} = cf_{i,y}. \]
(12)

In this particular case, the scatter matrix \( C \) has rank 1 and the resulting single EOF \( f_1 \), is proportional to \( J_{s,y} \), this being a limiting form of (9). If the correct atmospheric path radiances \( L_{atm} \) and diffusely transmitted radiance \( L_{diff} \) are subtracted from the pixel-averaged ASAS radiances, then the remaining pixel averaged surface function also must be proportional to \( f_1 \); that is,

\[ \langle L_i^{ASAS} \rangle - L_{i,atm} - L_{i,diff} = \langle S_i \rangle = a_1 f_{i,i} \]
(13)

When knowledge of the correct atmospheric state is not known, (13) then can be used as a criterion to determine the best estimate of the atmospheric state (i.e., aerosol optical depth) by requiring that it produce the minimum deviation \( D_i \) in angular shape between \( \langle L_i^{ASAS} \rangle - L_{i,atm} - L_{i,diff} \) and \( f_1 \). This can be written as

\[ D_i(\text{model, } \tau_{set}) = \sum_{i=1}^{10} \left( \langle L_i^{ASAS} \rangle - L_{i,atm}^{(\text{model, } \tau_{set})} \right) - \left( \langle S_i \rangle - a_1 f_{i,i} \right)^2 \]
(14)

where the summation is over the ASAS view angles, \( L_{i,atm}^{(\text{model, } \tau_{set})} \) and \( L_{i,diff}^{(\text{model, } \tau_{set})} \) are model-generated radiances at a given aerosol optical depth \( \tau_{set} \) and \( a_1 \) is obtained from the general expression

\[ a_n = \sum_{i=1}^{10} \left( \langle L_i^{ASAS} \rangle - L_{i,atm}^{(\text{model, } \tau_{set})} - L_{i,diff}^{(\text{model, } \tau_{set})} \right) f_{n,i} \]
(15)

The computation of \( L_{i,diff} \) requires that the average surface BRF, \( R_s \), for the scene be known or estimated, as indicated in (3). An estimate of \( R_s \), however, can be readily obtained by means of the surface retrieval algorithm described in the following section, using the aerosol model and optical depth being tested. When the algorithm is applied to MISR data, the computation of \( L_{i,atm}^{(\text{ASAS})} \) is not necessary since it is assumed to be spatially variable and therefore is considered with \( L_{i,diff} \) as a component of the surface functions \( S_{i,x,y} \). As such, it is represented along with \( L_{i,x,y}^{(\text{ASAS})} \) by the EOFs.

When more than one BRF shape are represented in the subscene, then (14) is no longer rigorously satisfied. However, since \( (L_i^{ASAS}) - L_{i,atm} - L_{i,diff} \), like \( J_{s,y,i} \), is made up of a linear combination of surface functions \( S_{i,x,y} \), it is desirable to expand it using the EOFs, \( f_{i} \). Therefore

\[ \langle L_i^{(\text{ASAS})} \rangle - \langle S_i \rangle = \sum_{n=1}^{N} a_n f_{n,i} \]
(16)

and (14) can be generalized to

\[ D_i(\text{model, } \tau_{set}) = \sum_{i=1}^{10} \left( \langle L_i^{ASAS} \rangle - L_{i,atm}^{(\text{model, } \tau_{set})} \right) - \left( \langle S_i \rangle - \sum_{n=1}^{N} a_n f_{n,i} \right)^2 \]
(17)

where \( N < 10 \) and the expansion coefficients \( a_n \) again are obtained from (15). As an extension of (14), this expression assumes that there are a few different BRF shapes present within the subscene but each having a variety of reflectances. Because of the ordering of the eigenvalues, a cutoff in the summation of (17) is invoked, using only those eigenvectors with an eigenvalue \( \lambda_n \) greater than 0.05 \( \lambda_1 \). This condition effectively defines the maximum value of \( N \), \( N_{\text{max}} \) with the constraint that \( N_{\text{max}} \) also be less than the total number of eigenvectors. In practice, \( N_{\text{max}} \) should not exceed 3 or 4 since each additional eigenvector used in the expansion described in (17) is very sensitive to the various aerosol models being investigated.

For a given candidate aerosol model \( D_1 \) is computed for each value of \( N \) used in (17), starting with \( N = 1 \) (the first eigenvector only) up through \( N_{\text{max}} \). Varying the model aerosol optical depth, the minimum \( D_i \) for each \( N, D_i^{N} \), defines an estimate of the optical depth \( \tau_N \). The best estimate is defined as a weighted average of all \( N_{\text{max}} \) optical depths,

\[ \tau_{\text{best}} = \left( \sum_{N=1}^{N_{\text{max}}} \frac{1}{D_i^{N}} \cdot \tau_N \right) \left/ \left( \sum_{N=1}^{N_{\text{max}}} \frac{1}{D_i^{N}} \right) \right. \]
(18)

and the weights are the inverses of the \( D_i^{N} \). The effective \( D_1 \) associated with \( \tau_{\text{best}} \) is defined as the weighted average of the \( D_i^{N} \).

\[ \frac{1}{D_i^{N}} = \frac{1}{N_{\text{max}}} \sum_{N=1}^{N_{\text{max}}} \frac{1}{D_i^{N}} \]
(19)

A \( \tau_{\text{best}} \) and a \( D_i^{N} \) are determined for each of the 16 subscenes and used to compute a weighted average optical depth and variance for the scene, with the weights defined as the inverses of the \( D_i^{N} \).
3.2. Technique 2: Similar Surface Types

It is instructive to contrast the EOF technique, described above, with a relatively less efficient but conceptually simpler one, based on similar principles. The technique is to explicitly search for pixels which have the same (or closely similar) surface directional reflectance shapes but different bimodal spherical reflectances (albedos). Comparison of unique pixel pairs, however, rapidly becomes a very time consuming process with increasing size of the comparison area in the image.

For two pixels with similar directional reflectances, labeled 1 and 2, the criterion

\[ I_{i,1}^{\text{ASAS}} - I_{i,2}^{\text{ASAS}} = b(I_{i,1}^{\text{diff}} - I_{i,2}^{\text{diff}}), \]  

(20)

where \( b \) is a constant of proportionality, is satisfied for the correct atmospheric state described by \( L_{i}^{\text{ASAS}} \) and \( L_{i}^{\text{diff}} \). When searching for the correct atmospheric state, (20) can be incorporated into an expression describing the goodness of fit,

\[ D_{2}(\text{model}, \tau_{\text{ext}}) = \sum_{\text{pairs} \rightarrow 1}^{10} [L_{i}^{\text{ASAS}} - L_{i}^{\text{ASAS}}(\text{model}, \tau_{\text{ext}}) - L_{i}^{\text{diff}}(\text{model}, \tau_{\text{ext}}) - b(L_{i,1}^{\text{ASAS}} - L_{i,2}^{\text{ASAS}})]^2, \]

(21)

where \( b \) is determined by least squares. The same subdivision scheme (4 × 4 subscenes) of the ASAS image was also used with this technique, resulting in 32640 unique pixel pairs per subscene. For a given model, it is assumed that the optical depth \( \tau_{\text{ext}} \), which produces the minimum value of \( D_{2} \), is the best estimate of the subscene aerosol optical depth. The best estimate of subscene optical depths are then averaged together as is done for the EOF retrieval technique.

If every pixel is unique in its angular reflectance properties, then \( D_{2} \) is expected to be insensitive to the various atmospheric models being tested and this technique will probably fail.

3.3. Aerosol Analysis of Glacier NP ASAS Data

The aerosol model used in the analysis was assumed to be clean, continental, composed mainly of submicron size water-soluble sulfates and nitrates [d’Almeida et al., 1991]. These types of aerosol particles are generally consistent with in situ measurements made over interior, medium-latitude regions of North America [e.g., Hobbs et al., 1988]. For computational purposes the aerosols were assumed to have a scale height of 1 km within a Rayleigh scattering molecular atmosphere. The multiple scattering, radiative transfer code was a discrete-ordinate, matrix operator type [Grant and Hunt, 1968] which can account for surfaces with non-Lambertian reflectance properties. The model radiances, required by the retrieval algorithms, were computed for various aerosol optical depths, given the appropriate solar angle and view angles, elevation of the scene, and altitude of the observations.

The aerosol optical depth results for the four selected ASAS spectral channels and for the two retrieval techniques are shown in Figure 2. Both techniques give essentially the same results, an optical depth of about 0.03 ± 0.02 at 555 nm, indicating a very light aerosol loading. Also shown is the spectral dependence of the aerosol model, visually scaled to the retrieval results. Apart from the results at 866 nm, the model spectral dependence is consistent with the retrieval results, validating to some degree the choice of the model. The optical depths at 866 nm are larger than expected and show considerably more uncertainty than those at the other wavelengths, a consequence of the larger amounts of random and systematic noise in the imagery and a probable calibration problem, discussed later, which resulted in multangle radiances that are too large. By the nature of the algorithm, a serious calibration problem in any spectral band would affect the associated aerosol optical depth retrieval in a way that cannot readily be anticipated. However, it is not unreasonable to expect that at least a portion of this excess radiance would translate into a larger than expected optical depth.

4. Surface Reflectance Retrieval

Once the atmospheric properties are known, the surface reflectance retrieval is accomplished in a straightforward manner. Since the diffuse radiance at the aircraft level is considered to be spatially invariant over the scene, it is computed first. The retrieval process starts by pixel-averaging the ASAS full scene radiance and retrieving the pixel-averaged surface-reflective radiance. Using (1) through (3), the pixel-averaged ASAS radiance can be written as

\[ \langle L_{i}^{\text{ASAS}}(\mu, \mu_{0}, \phi - \phi_{0}) \rangle = L_{i}^{\text{ASAS}}(\mu, \mu_{0}, \phi - \phi_{0}) + \langle I_{i}^{\text{ATR}}(\mu, \mu_{0}, \phi - \phi_{0}) \rangle + I_{i}^{\text{ATR}}(\mu, \mu_{0}, \phi - \phi_{0}) + \exp(-\tau/\mu) L_{i}^{\text{surf}}(\mu, \mu_{0}, \phi - \phi_{0}) + \int_{0}^{2\pi} \int_{0}^{2\pi} T(\mu, \mu', \phi, \phi') L_{i}^{\text{surf}}(\mu, \mu_{0}, \phi') d\mu' d\phi', \]

(22)

where the pixel-averaged surface-reflective radiance \( L_{i}^{\text{surf}} \) is

\[ L_{i}^{\text{surf}}(\mu, \mu_{0}, \phi - \phi_{0}) = \frac{1}{\pi} \int_{0}^{2\pi} R(\mu, \mu', \phi - \phi_{0}) L_{i}^{\text{surf}}(\mu', \mu_{0}, \phi - \phi_{0}) d\mu' d\phi'. \]

(23)
The integral equation of (22) can be easily solved for $L_{\text{surf}}^{\text{surf}}$ using an iterative approach, once the model generated $I_{\text{atm}}$, $\tau$, and $T$ are defined [Diner et al., 1996b]. Following the determination of $L_{\text{surf}}^{\text{surf}}$, the diffusely transmitted radiance $L_{\text{surf}}^{\text{diff}}$ (the last term in (22)) can be computed. Recall that $L_{\text{surf}}^{\text{diff}}$ was needed when performing the aerosol retrieval. Once $L_{\text{surf}}^{\text{diff}}$ is determined, $L_{\text{surf}}^{\text{diff}}$ is directly transmitted radiance for each pixel can then be calculated using (1). The surface-leaving radiance $L_{x,y}^{\text{surf}}$ is directly related to $L_{x,y}^{\text{surf}}$ that is,

$$L_{x,y}^{\text{surf}}(-\mu, \mu_0, \phi - \phi_0) = L_{x,y}^{\text{surf}}(\mu, \mu_0, \phi - \phi_0)/\exp(-\tau/\mu).$$  

(24)

The surface hemispherical-directional reflectance factor (HDFR), $r_{x,y}$, for each pixel is obtained by ratioing $L_{x,y}^{\text{surf}}$ to the surface-leaving radiance from an ideal Lambertian surface, $L_{\text{lim}}^{\text{surf}}$. The isotropic radiance $L_{\text{lim}}^{\text{surf}}$ is determined from the expression

$$L_{\text{lim}}^{\text{surf}} = \frac{1}{\pi} \int_0^{2\pi} \int_0^1 L_{0}^{\text{inc}}(\mu', \mu_0, \phi - \phi_0) \mu' d\mu' d\phi'$$

$$= \frac{1}{1-s(\rho)} \frac{1}{\pi} \int_0^{2\pi} \int_0^1 L_{0}^{\text{inc}}(\mu', \mu_0, \phi - \phi_0) \mu' d\mu' d\phi'$$

(25)

where $L_{0}^{\text{inc}}$ is the incident radiance on a black surface, $s$ is the bottom-of-atmosphere bihemispherical reflectance, and $\rho$ is the full scene-averaged surface reflectance, all readily computed. Integration of the HDFR $r_{x,y}$ over the viewing hemisphere results in the bihemispherical reflectance (BHR) $\rho_{x,y}$ or albedo. Since $r_{x,y}$ is computed only at the ASAS view angles, this integration is accomplished by assuming that it can be expressed as a two-term expansion in $\phi - \phi_0$. Thus

$$r_{x,y}(-\mu, \mu_0, \phi - \phi_0) = L_{x,y}^{\text{surf}}(-\mu, \mu_0, \phi - \phi_0)/L_{\text{lim}}^{\text{surf}}$$

$$= r_{0,x,y}(-\mu, \mu_0) + r_{1,x,y}(-\mu, \mu_0) \cos(\phi - \phi_0)$$

(26)

$$\rho_{x,y}(\mu_0) = \frac{1}{\pi} \int_0^{2\pi} \int_0^1 r_{0,x,y}(-\mu, \mu_0, \phi - \phi_0) \mu d\mu$$

(27)

Surface HDFR results are shown in Figure 3 for the conifer forest and in Figure 4 for the snow- and ice-covered lake. The corresponding BHR results are listed in Table 1. To consolidate the results, similar surface pixel types were averaged together for both the forest and the lake. The vertical bars in the figures indicate the range of variability over the scene for each surface type. This variability is due in part to actual pixel-to-pixel surface differences (i.e., spotted vegetation or lake snow conditions), evident within the scene, and also to image noise. Band 4 results in particular for both the forest and the lake are about 5 to 10 times more noisy than the other bands, as evidenced in Figure 4 and Table 1.

5. Discussion

The HDFR variation with view angle for the conifer forest shows both forward and backward scattering, resulting in a bowl shape which is typical of this kind of vegetation [Kimes, 1983; Kimes et al., 1985]. The spectral dependence of the BHR for the forest is representative of dense, dark vegetation, i.e., low (<0.05) at visible wavelengths due mainly to chlorophyll absorption and high in the near infrared. The BHR in band 4 equal to 0.49, however, appears too high for this type of canopy. The measurements of Kimes [1983] and Kimes et al. [1985] indicate that it should be in the neighborhood of 0.3. It might seem probable that any snow-covered ground between the trees would increase the BRF to the observed level. However, this does not seem to be the case because the visible bands do

![Figure 3. Retrieved hemispherical-directional reflectance factor (HDFRs) for conifer canopy. Note the change in scale for band 4.](image)

![Figure 4. Retrieved HDFRs for snow- and ice-covered Bowman Lake.](image)

<table>
<thead>
<tr>
<th>Table 1. Scene BHR</th>
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<tr>
<td><strong>Band</strong></td>
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RHR, bihemispherical reflectance.
not appear to be affected. Even the HDRF at nadir view
indicates no significant presence of a snow ground cover, a
condition also observed by Hall et al. [1993] in ASAS data
taken at a neighboring region around St. Mary Lake.

The HDRF variation with view angle for the lake shows
moderate forward scattering, increasing slightly with wave-
length, in agreement with the observations of Salomonson and
Marlatt [1968] for snow. The spectral dependence of the BHR
for a clean snow and ice-covered lake should be fairly uniform
across visible wavelengths with values near unity and a down-
turn in the near IR with amount depending on grain size
[Warren and Wiscombe, 1980]. However, bands 1 through 3
have BHR values about 0.55, suggesting that the snow cover is
contaminated, and band 4 has a BHR value near unity. Cal-
culations by Warren and Wiscombe [1980] indicate that loot
contamination of the snow of only a few ppmw can reduce the
BHR values in the visible to those in Table 1 and produce a
band 4 BHR value about equal to that of band 3. Assuming this
contamination scenario to be valid, this again implies that the
band 4 DRI result is too high, as it was for the forest. To bring
the band 4 BHR values of the two surface types down to their
expected values requires a correction factor of about 0.6 ap-
p lied to the radiances, implying that the calibration coefficient
for this channel is too high by about 67%. Since Table 1 shows
that the lake BHR has a spectral shape similar to that of the
forest an alternative contamination possibility is that dead need-
les from the conifers were strewn about on the snow surface.
To lower the visible BHR of the snow to 0.55 requires that over
40% of the surface was needle litter. If no adjustment is made
in the calibration of band 4 and the BHR for conifers in that
band is taken as 0.49 then the band 4 BHR for the snow would
be 1.33, well in excess of the theoretical limit. Again, if a
calibration correction of 0.6 is applied to the radiances of band
4, then the BRF for snow in that band would be 0.79, in general
agreement with the models of Warren and Wiscombe. Thus
both the soil and the needle litter scenarios require that band
4 radiances be reduced by about the same amount, allowing a
mixing of both types of contamination as another possibility. A
large error in the calibration of band 4 (866 nm) is not unre-
asonable, due to the relatively poor response and nonlinearity of
the ASAS detectors for wavelengths longer than 770 nm [Irns,
1991]. This CID detector array has since been replaced by a
more sensitive CCD array.

When measurements are made with ASAS, it is desirable to
have coincident field measurements acquired within the im-
gaged scene to compare with the aircraft results. There was
some photometer data taken, but it was not of sufficient quali-
ity to validate the small amount of aerosol retrieved from the
ASAS data. Some reflectance data were also obtained on the
lake, but instrument calibration problems have not allowed the
data to be properly analyzed to date (D. K. Hall, personal
communication, 1996).

The approach used here to analyze the multangle image
data sets from ASAS is part of the overall strategy for MISR
data analysis over land. The aerosol optical depth retrieval
technique, using empirical orthogonal functions to describe
the surface directional reflectance, is the third option in a hier-
archy of aerosol retrieval algorithms that will be used on MISR
data. The hierarchy is based on the amount of information
known for a surface type within a scene or region. The first
option is the algorithm which requires that the surface reflec-
tance properties be completely known at one or more MISR
wavelengths. The only surface type that fits this category at

References

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Charnay, J. G., W. G. Quirk, S. M. Chow, and J. Kornfield, A compara-
tive study of the effects of albedo change of drought in semi-arid

d’Almeida, G. A., P. Koepke, and E. F. Shettle, Atmospheric Aerosols:
Global Climatologic and Radiative Characteristics, 561 pp., A.

Dickinson, R. E., Land surface processes and climate-albedo energy

Diner, D. J., C. J. Bruegge, J. V. Martinouich, G. W. Boothwell, E. D.
Danielson, F. I. Floyd, V. G. Ford, L. E. Howland, K. L. Jones, and
M. L. White, A multi-angle imaging spectroradiometer for terres-
trial remote sensing from the Earth Observing System, Int. J. Imaging

Diner, D. J., et al., MISR level 2 aerosol retrieval algorithm theoretical

Duurs, D. J., J. V. Martinouich, C. Borel, S. A. W. Gerstl, H. R.
Gordon, R. Myneni, S. R. Paradise, B. Pinty, and M. Verstraete,
MISR level 2 surface retrieval algorithm theoretical basis, JPL D-11401, Rev. B, 1996b.


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