Abstract -- MISR is scheduled for launch in 1998 on the EOS AM 1 platform. The algorithms needed to analyze data from this instrument are currently being tested, using both simulated data and data currently available from the airborne ASAS multi-angle instrument. The data processing can be divided into three major, sequential segments. The first segment retrieves the necessary atmospheric properties over the scene. These results then are used in the second segment to retrieve the surface spectral HDRFs on a pixel-by-pixel basis for the scene. Finally, the HDRFs are used with a linearized three parameter BRF model in the third algorithm segment to retrieve the corresponding spectral BRFs. Results of the retrieval algorithms are presented using simulated MISR data.

INTRODUCTION

The Multi-angle imaging Spectroradiometer (MISR) is a radiometrically calibrated instrument, scheduled for launch in 1998 on the EOS-AM 1 platform into a sun-synchronous polar orbit. It has nine CCD array cameras, each with a fixed-view angle at the surface, ranging between 70.5° forward and 70.5° aftward, with each camera observing in four spectral bands (443, 555, 670, and 865 run). The spatial sampling of the imagery will be 1.1 km with a swath width of about 360 km, MISR will provide information about aerosol and surface directional reflectance properties on a global basis [1].

The algorithms which are to be used to routinely analyze the multi-angle image data from MISR are currently being tested on simulated MISR data and data from the airborne Advanced Solid-State Array Spectroradiometer (ASAS). These algorithms can be separated into three major segments which are used sequentially. The first segment retrieves the aerosol spectral optical depth and information on the aerosol type [2, 3], which are needed to characterize the radiative properties of the atmosphere over the scene (for MISR the scene size is a 17.6 km x 17.6 km region). This information then is used as input to the second segment, which retrieves the surface spectral hemispherical-directional reflectance factors (HDIRFs) and spectral bihemispherical reflectances (BHIRs) [2,4] on a pixel-by-pixel basis for the scene. For MISR the pixel size is 1.1 km x 1.1 km). Finally, the HDRFs are used in the third algorithm segment to retrieve the corresponding spectral bidirectional reflectance factors (BRFs) and the spectral directional-hemispherical reflectances (DHIRs) [4]. This conversion from HDRF to BRF, i.e., removing the effects of direct sunlight, needs to be facilitated with the use of a BRF model since the multi-angle data will have a very limited range of solar zenith angles. The BRF model used is a linearized, three parameter model which is currently being tested on both field and simulated reflectance measurements.

This paper assumes that the atmospheric properties are known (i.e., they have been retrieved from the multi-angle image data using the first segment of the algorithm) and places the emphasis on the surface reflectance retrieval algorithm segments. Results are presented for simulated MISR data.

THEORY

The top-of-atmosphere (TOA) radiance $L_\lambda$ at wavelength $\lambda$ can be written as

$$L_\lambda(^-\mu,\mu_0,\phi-\phi_0) = \frac{L_\lambda^{atm}(-\mu,\mu_0,\phi-\phi_0)}{12\pi} + \exp(-\tau_\lambda) \rho J_\lambda^{surf}(-\mu',\mu_0,\phi'-\phi_0)d\mu'd\phi'$$

where $\mu$ and $\mu_0$ are the cosines of the view and Sun zenith angles and $\phi$ and $\phi_0$ is the view azimuthal angle with respect to the Sun position. The convention $-\mu$ and $\mu$ is used for upwelling and downwelling radiation, respectively. On the right-hand-side of Equation (1) $L_\lambda^{atm}$ is the radiance field scattered by the atmosphere to space without interacting with the surface (i.e., the path radiance), $\tau_\lambda$ is the optical depth of the atmosphere, $L_\lambda^{surf}$ is the surface-leaving radiance, and $J_\lambda$ is the upward diffuse transmittance. Equation (1) describes the relationship between the TOA radiance $L_\lambda$ and the surface-leaving radiance $L_\lambda^{surf}$.
**HDRF and BHR Retrieval.**

Assuming the atmospheric parameters in Equation (1) are known, \( L_{\lambda}^{surf} \) can be easily determined by means of an iteration procedure, as described below. Once \( T_{\lambda}^f \) is determined the HDRF, \( r_{\lambda} \) and the surface irradiances, then can be expressed as

\[
r_{\lambda} (-\mu, \mu_0, \phi - \phi_0) = \frac{L_{\lambda}^{surf}(-\mu, \mu_0, \phi - \phi_0)}{E_{\lambda}^{\prime}(\mu_0)} \quad (2)
\]

where \( E_{\lambda}^{\prime} \) is the surface irradiances. From the radiant exitance \( M_{\lambda} \), defined as

\[
M_{\lambda} = \frac{12\pi}{\hbar} L_{\lambda}^{surf} (-\mu, \mu_0, \phi - \phi_0) \mu d\mu d\phi \quad (3)
\]

the BHR, \( A_{\lambda}^{hem} \), is given by the ratio

\[
A_{\lambda}^{hem} (\mu_0) = \frac{M_{\lambda} (\mu_0)}{E_{\lambda}^{\prime}(\mu_0)} \equiv \frac{M_{\lambda} (\mu_0)}{F_{\lambda}^{black}(\mu_0) + s_{\lambda} \cdot M_{\lambda} (\mu_0)} \quad (4)
\]

where \( s_{\lambda} \) is the bottom-of-atmosphere bihemispherical reflectance and \( F_{\lambda}^{black} \) is the black-surface irradiance (independent of surface reflection properties). It is related to the actual surface irradiance \( F_{\lambda} \) by the highly accurate expression,

\[
F_{\lambda} (\mu_0) \approx \frac{F_{\lambda}^{black}(\mu_0)}{1 - s_{\lambda} \cdot A_{\lambda}^{hem}(\mu_0)} \quad (5)
\]

An excellent initial guess for \( L_{\lambda}^{surf} \) in the iteration procedure can be obtained from Equation (1) by removing \( L_{\lambda}^{surf} \) from the integral. Thus,

\[
L_{\lambda}^{surf}(0) (-\mu, \mu_0, \phi - \phi_0) = \frac{L_{\lambda} (-\mu, \mu_0, \phi - \phi_0) \cdot L_{\lambda}^{atm} (-\mu, \mu_0, \phi - \phi_0)}{\exp (-\tau_{\lambda} / \mu) + t (-p)} \quad (6)
\]

where

\[
t (-p) = \int_0^{12\pi} T_{\lambda} (-\mu, -\mu', \phi - \phi') \ d\mu' \ d\phi' \quad (7)
\]

An initial guess for the 11111 from Equation (4) implies a guess for \( M_{\lambda} \), which can be obtained from Equation (3). The integral in Equation (3) is best easily done by assuming that the surface radiance \( L_{\lambda}^{surf} \) can be expressed as a two term cosine series in \( \phi - \phi_0 \).

\[
L_{\lambda}^{surf} (-\mu, \mu_0, \phi - \phi_0) = L_{0,\lambda}^{surf} (-\mu, \mu_0) + L_{1,\lambda}^{surf} (-\mu, \mu_0) \cos (\phi - \phi_0) \quad (8)
\]

Thus,

\[
M_{\lambda}^{(0)} (\mu_0) = \int_0^{12\pi} L_{0,\lambda}^{surf} (-\mu, \mu_0) \mu d\mu \quad (9)
\]

where, for any iteration \( n \) and using Equation (8)

\[
\int_0^{12\pi} L_{0,\lambda}^{surf} (-\mu, \mu_0) \mu d\mu = \frac{L_{\lambda}^{surf} (-\mu_0, \phi_0 - \phi_0) \cos (\phi - \phi_0)}{\cos (\phi - \phi_0) \cos (\phi - 4')} - \frac{\int_0^{12\pi} L_{\lambda}^{surf} (-\mu, \phi_0 - \phi_0) \cos (\phi - \phi_0)}{\cos (\phi - \phi_0) \cos (\phi - 4')} \quad (10a)
\]

\[
\int_0^{12\pi} L_{1,\lambda}^{surf} (-\mu, \phi_0 - \phi_0) \mu d\mu = \frac{L_{\lambda}^{surf} (-\mu, \phi_0 - \phi_0)}{\cos (\phi - \phi_0) \cos (\phi - 4')} \quad (10b)
\]

there, \( \phi_0 \) and \( 4' \) are the two azimuth angles for each fore-aft MISR camera pair.

Once \( L_{\lambda}^{surf} \) is computed, the surface radiance \( L_{\lambda}^{surf} \) can be updated via the iterations using Equation (7),

\[
\exp (-\tau_{\lambda} / \mu) \cdot L_{\lambda}^{surf}(n + 1) (-\mu, \mu_0, \phi - \phi_0) = \int_0^{12\pi} T_{\lambda} (-\mu, -\mu', \phi - \phi') L_{\lambda}^{surf} (-\mu, \mu_0, \phi - \phi_0) \ d\mu' \ d\phi' \quad (11)
\]

The upward diffuse transmittance \( T_{\lambda} \) in Equation (11) is expressed as a two term cosine series in \( \phi - \phi_0 \) such that

\[
T_{0,\lambda} (-\mu, -\mu') = \int_0^{2\pi} T_{\lambda} (-\mu, -\mu', \phi - \phi') d\phi' \quad (12a, b)
\]

\[
T_{1,\lambda} (-\mu, -\mu') = \int_0^{2\pi} T_{\lambda} (-\mu, -\mu', \phi - \phi') \cos (\phi - \phi') d\phi' \quad (12a, b)
\]

Once \( L_{\lambda}^{surf} \) is updated, it then is used to compute a new \( M_{\lambda} \) and a new \( A_{\lambda}^{hem} \). The iteration proceeds until convergence is reached. This is normally evaluated by noting the change in \( A_{\lambda}^{hem} \).
BRF and DIFR Retrieval.

The BRF, $R_\lambda$, is related to the 1 DDIR, $r_\lambda$, through the expression

$$F_\lambda (\mu_0) = r_\lambda (-\mu, \mu_0 \phi - \phi_0)$$

$$= \sum_{h} R_\lambda (-\mu, \mu', \phi - \phi') L_{\lambda}^{inc} (P', \mu_0 \phi' - \phi_0) \mu' d\mu' d\phi'$$

\[ \text{(13)} \]

where $L_{\lambda}^{inc}$ is the radiance incident on the surface. Separating $L_{\lambda}^{inc}$ into direct and diffuse components, Equation (13) can be rewritten as

$$F_\lambda (\mu_0) = r_\lambda (-\mu, \mu_0 \phi - \phi_0)$$

$$= E_\lambda^{dir} (\mu_0) R_\lambda (-\mu, \mu_0 \phi - \phi_0)$$

\[ \text{(14)} \]

$$+ \sum_{h} R_\lambda (-\mu, 11', \phi' \phi') L_\lambda^{diff} (\mu', \mu_0 \phi' \phi_0) \mu' d\mu' d\phi'$$

\[ \text{(15)} \]

where $L_\lambda^{diff}$ is the diffuse radiance incident on the surface and $E_\lambda^{dir}$ is the direct radiance. They can be expressed as

$$E_\lambda^{dir} (\mu_0) = \mu_0 F_0^{\lambda} \exp (-\tau/\mu_0)$$

\[ \text{(16)} \]

Where $F_0^{\lambda}$ is the exo-atmospheric radiance and $7 = \lambda'$ and $7$ describe the downwelling diffuse transmittance in terms of a two term cosine series in $\phi \phi_0$. Note that the last term in Equation (16) represents approximately the downwelling radiance due to multiple reflections between the atmosphere and the surface. Inserting this expression for $L_\lambda^{diff}$ in Equation (14) and rearranging terms,

$$R_\lambda^{m+1} (-\mu, \mu_0 \phi - \phi_0) = \frac{E_\lambda (\mu_0) - r_\lambda (-\mu, \mu_0 \phi - \phi_0)}{E_\lambda^{dir} (\mu_0)}$$

$$- \frac{E_0^{\lambda} \cos (\phi - \phi_0)}{2 \pi E_\lambda^{dir} (\mu_0)} \int_{0}^{1} R_\lambda^{m} (-\mu, \mu') T_{\lambda, \lambda'} (\mu', \mu_0) \mu' d\mu'$$

$$- \frac{E_0^{\lambda}}{2 \pi E_\lambda^{dir} (\mu_0)} \int_{0}^{1} R_\lambda^{m} (-\mu, \mu') T_{\lambda, \lambda'} (\mu', \mu_0) \mu' d\mu'$$

\[ \text{(17)} \]

Equation (17) is written as an iterative scheme to determine $R_\lambda$. Note that $R_\lambda$ within the integrals is also described by a two term cosine series in $\phi \phi_0$ with coefficients as defined in Equation (12a, b). These coefficients subsequently are replaced by equivalent functions, $R_\lambda^{m}$ and $R_\lambda^{m}$ generated from a BRF model, because of the lack of measurements concerning the variation of $R_\lambda$ with $p'$.

The BRF model used is that of Rahman et al. [5], modified to allow a nearly linearizable least squares fitting analysis. This model has been shown to work sufficiently well for this purpose [6], and is described by

$$R_\lambda^{m} (-\mu, \mu_0 \phi - \phi_0)$$

$$= r_\lambda (-\mu, \mu_0 \phi - \phi_0)$$

$$- \frac{1}{1 - R_\lambda^{m}} \sum_{h} \exp (b \cos \Omega) h_\lambda (-\mu, \mu_0 \phi - \phi_0)$$

\[ \text{(18)} \]

with three free parameters $(r_0, \lambda, k_2, b_\lambda)$. The function $h_\lambda$ is a factor to account for the hotspot,

$$h_\lambda (-\mu, \mu_0 \phi - \phi_0) = 1 + \frac{1 - r_0}{1 + G (\mu)}$$

\[ \text{(19)} \]

$$G (\mu) = \frac{1 - \mu_0^2}{\mu^2}$$

\[ \text{(20)} \]

and $\Omega$ is the scattering angle defined by

$$\cos \Omega = p \mu + \sqrt{1 - \mu^2} \sqrt{1 - \mu_0^2 \cos (\phi - \phi_0)}$$

\[ \text{(21)} \]

To determine the coefficients $R_\lambda^{m}$ and $R_\lambda^{m}$ for use in Equation (17), (11C model $R_\lambda^{m}$ in Equation (18) is fitted to the current iteration of the BRF, $R_\lambda^{m}$, to obtain the current iteration of the three model parameters. This fitting is most easily done by comparing the logarithms of $R_\lambda^{m}$ and $R_\lambda^{m}$ in a least squares sense. Once the three parameters are determined, the BRF model then can be evaluated at all necessary angles in order to compute $R_\lambda$, and $R_\lambda^{m}$.

The initial guess for $R_\lambda$ is set equal to the 1 DDIR, $r_\lambda$. Once convergence is achieved for $R_\lambda$ via Equation (17), the DDIR then is evaluated from the expression,

$$A_\lambda^{dir} (\mu_0) = 2 \int_{0}^{1} R_\lambda^{m} (-\mu, \mu_0) \mu d\mu$$

\[ \text{(22)} \]

where $N$ is the last iteration count and $R_\lambda^{m}$ is computed using the formula displayed in Equation (16a).
Application of the retrieval algorithms described in the previous section was accomplished using simulated MISR data. The TOA radiances were computed using a multiple scattering, discrete ordinate, radiative transfer code [7] and included both Rayleigh and aerosol scattering. The computations were performed for the MISR red wavelength at 0.670 μm and the nine MISR viewing zenith angles (0°, 5°, 10°, ±26.1°, ±60.0°, and ± 70.5°), symmetrically placed about the nadir in a single nadir-azimuth angle plane. The solar zenith angle was 55° and the azimuth angle difference between the Sun position and the forward-looking views were set at three values: 30°, 60° and 90° (i.e., perpendicular to the principal plane). The aerosol was specified to be a sulfate/nitrate type (accumulation mode) with phase function asymmetry parameter g = 0.628, single scattering albedo \( \omega = 1.0 \), and optical depths \( \tau_\text{a} = 0.4 \) and 0.5.

Eleven different surface types, listed in Table 1, were used in the MISR TOA radiances calculations. The BRF's for these surfaces were derived from field measurements [8-10] which covered a wide range of both viewing angle and solar zenith angle. These BRF's then were incorporated into the radiative transfer code to simulate a realistic, coupled surface-atmosphere system.

Table 1: Surface Type Characteristics

<table>
<thead>
<tr>
<th>Case</th>
<th>Surface Type</th>
<th>BRF (670 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Soil</td>
<td>0.186</td>
</tr>
<tr>
<td>2</td>
<td>Grassland</td>
<td>0.318</td>
</tr>
<tr>
<td>3</td>
<td>Steppe Grass</td>
<td>0.211</td>
</tr>
<tr>
<td>4</td>
<td>Hay Wheat</td>
<td>0.228</td>
</tr>
<tr>
<td>5</td>
<td>Irrigated Wheat</td>
<td>0.063</td>
</tr>
<tr>
<td>6</td>
<td>Hardwood Forest</td>
<td>0.035</td>
</tr>
<tr>
<td>7</td>
<td>Pine Forest</td>
<td>0.038</td>
</tr>
<tr>
<td>8</td>
<td>Lawn Grass</td>
<td>0.058</td>
</tr>
<tr>
<td>9</td>
<td>Corn</td>
<td>0.082</td>
</tr>
<tr>
<td>10</td>
<td>Soybean</td>
<td>0.034</td>
</tr>
<tr>
<td>11</td>
<td>Orchard Grass</td>
<td>0.077</td>
</tr>
</tbody>
</table>

**Example 1:** The \( \hat{\text{BRF}} \) was retrieved for each surface type from the simulated multi-angle TOA radiances with \( \tau_\text{a} = 0.4 \), assuming that the atmospheric properties are ideally known (i.e., no error). Figure 1 shows the retrieval deviation for the eleven surface types and for the three different view-sun azimuth angles. The deviation \( \delta \) is defined as

\[
\delta = \frac{1}{9} \sum_{n=1}^{9} \left| r^{\prime} \left( -\mu_n, \mu_0, \phi_n - \phi_0 \right) - r \left( -\mu_n, \mu_0, \phi_n - \phi_0 \right) \right|
\]

(23)

**Example 2:** Using the same simulated MISR dataset, the \( \hat{\text{BRF}} \)'s were again retrieved, but assuming an aerosol optical depth of 0.35 instead of the true value of 0.4. The results are shown in Figure 2.

Figure 1. Retrieved \( \hat{\text{BRF}} \) with correct atmosphere.

Figure 2. Retrieved \( \hat{\text{BRF}} \) with incorrect aerosol amount.

This difference of 0.05 is the expected error in retrieved aerosol optical depth using MISR observations. As such, the \( \hat{\text{BRF}} \) deviations shown in Figure 2 are the errors expected from the MISR experiment. Notice that the accuracy for the darker surface types (case number 5 through 11) decreased by about an order of magnitude whereas the brighter surfaces were somewhat less affected.
Example 3: Using the simulated MISR dataset with $\tau_{aot} = 0.5$ and a Sun-view azimuth angle difference of $30^\circ$, Figure 3 shows both IIDRF and BRF retrieval results.

![Figure 3. Comparison of IIDRF and BRF retrievals.](image)

For each of the eleven surface types, an IIDRF retrieval was performed using the correct atmosphere and also one in which the aerosol optical depth was in error by 0.05. Starting from the retrieved IIDRFs, obtained using the correct atmosphere, a BRF retrieval was then performed for each case. Figure 3 shows that the expected IIDRF errors are generally comparable to or larger than the actual difference between the IIDRF and BRF.

**SUMMARY**

The algorithms to be used by MISR to retrieve the surface IIDRF and BRF from radiometrically calibrated multi-angle imagery are currently being tested on simulated MISR data and airborne ASAS data. The results from the simulated MISR data show that the intrinsic accuracy of the IIDRF retrieval algorithm is limited mainly by the accuracy of the information on the atmospheric optical properties and not by the limited viewing geometry of the observations. Also, the expected atmospheric property uncertainties will generally tend to mask any differences in the IIDRF and the BRF.

**ACKNOWLEDGMENTS**

The author would like to express his appreciation to Brian Rheingans for his assistance in the graphical aspects of this work. This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

**REFERENCES**


