Atmospheric modeling for space measurements of ground reflectances, including bidirectional properties

D. Tanre, M. Herman, P. Y. Deschamps, and A. de Leffe

A fairly accurate analytical expression of the measured reflectance is established for the general case of a non-Lambertian and nonuniform ground by separating the atmospheric and surface effects. The signal is nearly linear in the function of intrinsic atmospheric reflectance, the actual target reflectance, and two average ground reflectances, angular and spatial, to be defined. Contrast reduction by the atmosphere, defined in the cases of Lambertian and directional ground reflectances, has been evaluated using this formulation.

1. Introduction

The three main mechanisms by which terrestrial atmosphere perturbs the measurements of ground reflectances from space are (1) aerosol and molecular backscatterings change the measured target reflectances, (2) for nonuniform sites the measurement is altered by the contribution of the target background, and (3) the bidirectional properties of the target reflectance are partially smoothed over by the atmospheric scattering processes.

The study of these different atmospheric effects has been considerably developed. Atmospheric models assuming the ground to be uniform and Lambertian have been studied extensively. These computations give the intrinsic atmospheric radiation for quite varied conditions and also permit the evaluation of contrast degradation for sites of large dimensions or for small targets in a uniform background. Several attempts have been made to account for the diffuse radiation field corresponding to a nonuniform ground albedo with the aid of the adding procedure, the Fourier transformation method, or the invariant imbedding technique. Finally, the influence of the bidirectional character of the reflectance has also been studied.

These studies improve our knowledge of various atmospheric and surface effects, but their influences are most frequently considered separately. These effects generally occur simultaneously, and it is of interest to specify their relative importance in the function of experimental conditions (sun elevation, aerosol content, wavelength, type of target reflectance) and to evaluate measurement sensitivity to the variations of these conditions within the framework of multitemporal, multangular, or multispectral observations. Consider a mean atmosphere above a ground for which the reflectance \( \rho_s(M,S_0,S) \) depends upon the point \( M \) and upon the incidence and observation directions \( S_0 \) and \( S \). The apparent reflectance \( \rho_a^*(M,S_0,S) \) of \( M \), observed from a satellite in direction \( S \) when the sun is in direction \( S_0 \), will depend not only upon the actual target reflectance \( \rho_s(M,S_0,S) \) and the atmospheric reflectance \( \rho_a^*(S_0,S) \) but also upon spatial and angular mean reflectances to be defined (see, e.g., Refs. 10 and 11). An exact numerical simulation of the actual problem is obviously out of the question, but the study of a simple case of a uniform and Lambertian ground proves sufficient to give fairly precise answers to the following questions:

Which are the mean reflectances to be defined and how are they related to experimental conditions?

To what extent is the measurement a linear function of these mean reflectances?

What are the relative contributions of these quantities to the apparent reflectance \( \rho_a^*(M,S,S_0) \); and how do these contributions vary in function of observation conditions.
II. Signal Analysis in the Case of a Homogeneous Lambertian Surface

Let it be given that the ground is of uniform Lambertian reflectance. The atmosphere and particularly the atmospheric aerosol concentration are assumed to be horizontally uniform. This study deals with monochromatic quantities, but subscript \( \lambda \) will be omitted to simplify notation. Last, rather than being expressed as radiance \( I \), the various quantities will be expressed exclusively in terms of equivalent reflectance defined as

\[
\rho^* = \frac{\Pi}{\mu_{\alpha}},
\]

where \( f \) is the solar flux at the top of the atmosphere, and \( \Theta_0 = \arccos \mu_0 \) is the zenithal solar angle.

It is practical to express the signal received by the satellite in the function of successive orders of radiation interactions in the coupled ground–atmosphere system.\(^{10,11}\) If \( \rho \) is the ground reflectance, the apparent reflectance is written

\[
\rho^*(M,\theta_0,\phi) = \rho_a(\mu_0,\mu,\phi) + \exp(-\tau/\mu_0) \rho \exp(-\tau/\mu) \]

\[
+ E(\mu_0) \rho \exp(-\tau/\mu) \]

\[
+ [\sum_{n=1}^{\infty} \exp(-\tau/\mu_0) + E(\mu_0)] \rho E'(\mu)
\]

\[
\times \rho \exp(-\tau/\mu) + E'(\mu),
\]

(2)

where \( \tau \) is the optical thickness of the atmosphere,
\( \Theta = \arccos \mu \) is the zenithal viewing angle,
\( \phi \) is the azimuthal angle,
\( \rho_a(\mu_0,\mu,\phi) \) is the intrinsic atmospheric contribution in terms of reflectance [Fig. 1(a)],
\( \rho \exp(-\tau/\mu_0) \times \exp(-\tau/\mu) \) is the term that contains the information resulting from direct solar radiation reflected by the target [Fig. 1(b)],
\( \rho E(\mu_0) \exp(-\tau/\mu) \) is the contribution resulting from diffuse downward solar radiation attaining the ground at point \( M \) [Fig. 1(c)], and
\( \rho [\exp(-\tau/\mu_0) + E(\mu_0)] E'(\mu) \) represents the first-order contribution of the target background [Fig. 1(d)].

The geometrical series in Eq. (2) corresponds to higher orders of interaction with the ground, the term \( [\exp(-\tau/\mu_0) + E(\mu_0)] \rho E'(\mu) \) corresponds to radiation having interacted \( n \) times with the ground [Fig. 1(e)].

Equation (2) is also written as

\[
\rho^*(M,\theta_0,\phi) = \rho_a(\mu_0,\mu,\phi) + \frac{\rho}{1 - \rho} [\exp(-\tau/\mu_0) + E(\mu_0)] E'(\mu).
\]

(3)

For a homogeneous atmosphere, functions \( E(\mu_0) \) and \( E'(\mu) \) are identical in accordance with the reciprocity principle

\[
E(\mu) = E'(\mu).
\]

(4)

Due to the presence of aerosols, the real atmosphere is inhomogeneous, but Eq. (4) is numerically well verified and will be accepted for the remainder of this paper. Equation (3) is written as

\[
\rho^*(M,\theta_0,\phi) = \rho_a(\mu_0,\mu,\phi) + \frac{\rho}{1 - \rho} [\exp(-\tau/\mu_0) + E(\mu_0)] E'(\mu).
\]

(5)

In accordance with the above definitions, the normalized quantities \( E'(\mu_0) \) and \( r \) are given by

\[
E(\mu_0) = \frac{1}{\mu_0} \int_0^{2\pi} \int_0^1 I_2(\tau,\mu_0,\mu,\phi) \mu d\mu d\phi,
\]

(6)

where \( I_2(\tau,\mu_0,\mu,\phi) \) is the downward diffuse radiance at the bottom of the atmosphere for \( \rho = 0 \), and

\[
r = \frac{1}{\pi} \int_0^{2\pi} \int_0^1 I^*(\tau,\mu) \mu d\mu d\phi,
\]

(7)

where \( I^*(\tau,\mu) \) is the downward radiance at the ground level for the case of an incident upward isotropic radiation at the bottom of the atmosphere \( [I^*(\tau,\mu) = 1] \).

III. Signal Analysis in the Case of a Non-Homogeneous Non-Lambertian Ground Surface

Let it now be assumed that the ground reflectance depends upon the target \( M \) and the observation and incidence directions and thus is written \( \rho(M,\mu_0,\mu,\phi) \). In this case, Eq. (2) is no longer exact but remains interesting. Each of the terms (1) implicitly defines the different spatial and angular averages that must be made for \( \rho(M,\mu_0,\mu,\phi) \), (2) gives the weight of these averages in the total signal, and (3) allows one to estimate the linearity of the measured signal. Equation (2) is now written as

\[
\rho E(\mu_0) \exp(-\tau/\mu) \times \rho \exp(-\tau/\mu) \quad \rho [\exp(-\tau/\mu_0) + E(\mu_0)] E'(\mu).
\]
The first three terms of this development are precisely defined:

\[ \rho_\lambda(\mu_\lambda,\phi) \text{ is still the intrinsic atmospheric reflectance (} \rho = 0). \]

\[ \rho(M,\mu_\lambda,\mu,\phi) \exp(-\tau/\mu_\lambda) \exp(-\tau/\mu) \text{ gives direct information about the target.} \]

\[ \rho(M,\mu_\lambda,\mu,\phi)E(\mu) \exp(-\tau/\mu) \text{ rigorously allows us to define an average angular reflectance of the target } M \text{ as} \]

\[ \bar{\rho}(M,\mu_\lambda,\mu,\phi) = \frac{1}{E(\mu_\lambda)} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \rho(M',\mu_\lambda,\mu,\phi')I_2(\tau,\mu_\lambda,\mu',\phi')d\mu'd\phi'. \]  

\[ \text{(9)} \]

\[ \rho(M,\mu_\lambda,\mu,\phi) \exp(-\tau/\mu) \text{ E(} \mu \text{) defines the average reflectance of the environment } \langle \rho(M,\mu_\lambda,\mu,\phi) \rangle \text{ in the same way, but this definition is not so easily formulated. If } t(\mu,x,y) \text{ is the contribution to } E(\mu) \text{ per unit area of ground at a point } M' \text{ with horizontal coordinates } (x,y), \text{ a reasonable definition of } \langle \rho \rangle \text{ seems to be} \]

\[ \langle \rho(M,\mu_\lambda,\mu,\phi) \rangle \text{ E(} \mu \text{) [exp(} -\tau/\mu_\lambda \text{-} \tau/\mu \text{) + E(} \mu_\lambda \text{)] defines the average reflectance of the target } M \text{ as} \]

\[ \langle \rho(M,\mu_\lambda,\mu,\phi) \rangle \text{ E(} \mu \text{) [exp(} -\tau/\mu_\lambda \text{-} \tau/\mu \text{) + E(} \mu_\lambda \text{)] defines the average reflectance of the target } M \text{ as} \]

\[ \rho(M,\mu_\lambda,\mu,\phi) = \rho_\lambda(\mu_\lambda,\mu,\phi) + \rho(M,\mu_\lambda,\mu,\phi) \exp(-\tau/\mu_\lambda) \exp(-\tau/\mu) \]

\[ + \bar{\rho}(M,\mu_\lambda,\mu,\phi) \exp(-\tau/\mu)E(\mu_\lambda) + \langle \rho(M,\mu_\lambda,\mu,\phi) \rangle [E(\mu_\lambda) + \exp(-\tau/\mu_\lambda)]E(\mu) \]

\[ + \langle \rho(M,\mu_\lambda,\mu,\phi) \rangle r \left[ \frac{\bar{\rho}(M,\mu_\lambda,\mu,\phi) \exp(-\tau/\mu) + \langle \rho(M,\mu_\lambda,\mu,\phi) \rangle E(\mu)}{1 - \langle \rho(M,\mu_\lambda,\mu,\phi) \rangle r} \right] [E(\mu_\lambda) + \exp(-\tau/\mu_\lambda)]. \]  

\[ \text{(8)} \]

\[ \text{IV. Atmospheric Functions} \]

In order to define the dependence of atmospheric functions \( \rho_\lambda(\mu_\lambda,\mu,\phi), E(\mu), \text{ and } r \), it is necessary to calculate intrinsic atmospheric radiances for different experimental conditions and different atmospheric models. The considered atmospheric models consist of a Rayleigh atmosphere to which is added a variable aerosol concentration. Optical thickness and phase function for Rayleigh scattering have been adopted from the estimations of Hoyt.\(^1\) The aerosol scattering properties correspond to the aerosol model used by McClatchey et al.\(^3\) The particle scattering cross section and the phase function were computed from the size distribution using Mie theory. For this, the refractive index of the particles was assumed to be real (that is, no absorption) and equal to 1.50. Table I gives the corresponding optical thicknesses for visibilities of 5 km, 10 km, 23 km, and 30 km. The vertical profiles of aerosol concentration are the ones given by McClatchey et al. for visibilities of 5 km and 23 km. In fact the aerosol vertical profile only slightly affects the radiation field, and the main parameter remains the optical thickness. The radiances were computed by the successive orders of scattering method.\(^4\) The computations were made for four wavelengths (\( \lambda = 450 \text{ nm}, 550 \text{ nm}, 650 \text{ nm}, \text{ and } 850 \text{ nm} \)) and four zenithal solar angles (\( \theta_0 = 15^\circ, 41.4^\circ, 60^\circ, \text{ and } 75.5^\circ \)). By using these computations, \( E(\mu_\lambda) \) and \( r \) can be obtained directly from Eqs. (6) and (7).
Table II. Function \( r \) for Four Wavelengths and for Three Atmosphere Models

<table>
<thead>
<tr>
<th>Wavelength (( \text{nm} ))</th>
<th>Molecular atmosphere</th>
<th>Turbid atmosphere (( V = 23 \text{ km} ))</th>
<th>Turbid atmosphere (( V = 5 \text{ km} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>0.1685</td>
<td>0.2128</td>
<td>0.3080</td>
</tr>
<tr>
<td>550</td>
<td>0.0807</td>
<td>0.1403</td>
<td>0.2432</td>
</tr>
<tr>
<td>650</td>
<td>0.0438</td>
<td>0.1038</td>
<td>0.2066</td>
</tr>
<tr>
<td>850</td>
<td>0.0157</td>
<td>0.0698</td>
<td>0.1608</td>
</tr>
</tbody>
</table>

Table III. Function \( E(\mu) \) for Several Zenithal Angles (\( \mu = \cos \Theta \))

<table>
<thead>
<tr>
<th>Solar zenith angle ( \Theta ) (deg)</th>
<th>Wavelength (( \text{nm} ))</th>
<th>Molecular atmosphere</th>
<th>Turbid atmosphere (( V = 23 \text{ km} ))</th>
<th>Turbid atmosphere (( V = 5 \text{ km} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>450</td>
<td>0.0992</td>
<td>0.2847</td>
<td>0.4822</td>
</tr>
<tr>
<td>41.4</td>
<td>450</td>
<td>0.1235</td>
<td>0.3065</td>
<td>0.5107</td>
</tr>
<tr>
<td>60</td>
<td>450</td>
<td>0.1723</td>
<td>0.3707</td>
<td>0.5206</td>
</tr>
<tr>
<td>75.5</td>
<td>450</td>
<td>0.2793</td>
<td>0.4457</td>
<td>0.4616</td>
</tr>
</tbody>
</table>

Table IV. Atmospheric Contribution \( \rho_a(\mu_0,\mu,\phi) \) for Vertical Observation (\( \mu = 1 \))

<table>
<thead>
<tr>
<th>( \lambda_\text{nm} )</th>
<th>( \Theta^\circ )</th>
<th>Rayleigh ( V = 23 \text{ km} )</th>
<th>( V = 5 \text{ km} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>15</td>
<td>0.0838</td>
<td>0.1000</td>
</tr>
<tr>
<td>550</td>
<td>15</td>
<td>0.0367</td>
<td>0.0567</td>
</tr>
<tr>
<td>650</td>
<td>15</td>
<td>0.0184</td>
<td>0.0266</td>
</tr>
<tr>
<td>850</td>
<td>15</td>
<td>0.0061</td>
<td>0.0208</td>
</tr>
<tr>
<td>450</td>
<td>60</td>
<td>0.0988</td>
<td>0.1281</td>
</tr>
<tr>
<td>550</td>
<td>60</td>
<td>0.0448</td>
<td>0.0708</td>
</tr>
<tr>
<td>650</td>
<td>60</td>
<td>0.0228</td>
<td>0.0454</td>
</tr>
<tr>
<td>850</td>
<td>60</td>
<td>0.0077</td>
<td>0.0250</td>
</tr>
</tbody>
</table>

The values obtained for \( r \) and \( E(\mu) \) are recorded, respectively, in Tables II and III. The following formulas, based on the Eddington method, have been proven to give a good approximation of \( r \) and \( E(\mu) \) and can be extended to other aerosol models:

\[
r \approx (0.92r_p + \alpha T_p) \exp(-r_p) \exp(-(r_p + T_p)),
\]

(12a)

\[
E(\mu) \approx \exp(-\mu) \exp[(0.52r_p + \beta T_p)/\mu - 1],
\]

(12b)

with \( \alpha = 1 - (\cos \Theta) \) and \( \beta = \cos \Theta (1 + (\cos \Theta)) \), where \( (\cos \Theta) \) is the anisotropy factor of the aerosol scattering phase function. This factor remains quite constant (about 0.5) for most of the aerosol models, and variations of \( r \) and \( E(\mu) \) as a function of wavelength are mainly due to variations of \( T_p \).

Table IV gives some values of \( \rho_a(\mu_0,\mu,\phi) \). \( \rho_a \) increases with decreasing wavelengths and visibilities, and values higher than 0.1 may be found at shorter wavelengths. A parameterization of \( \rho_a \) is not convenient because of the variable angular effects. Also, the intrinsic contribution \( \rho_a \) only modifies the absolute level of the measured reflectances and does not change the relative contributions of the other terms.

Figure 2 represents the relative contributions \( A, B, \) and \( C \) of reflectances \( \rho, \tilde{p}, \) and \( (\rho) \) vs the zenithal solar angle \( \Theta \) when viewing at the nadir for three wavelengths (450 nm, 550 nm, and 850 nm) and three optical thicknesses corresponding to visibilities of 10 km, 23 km, and 30 km. The results are interpolated from Table III. It is clear that, except for exceptional visibilities and near IR wavelengths, the contributions of the three terms are of the same order.

In a first approximation, the results in Fig. 2 are representative of the atmospheric effects due to a given optical thickness \( T_p \) and are independent of the particle model used for the computations. Apart from knowing \( \rho_a(\mu_0,\mu,\phi) \), the atmospheric parameter to be determined in order to define Eq. (11) is thus the aerosol optical thickness \( T_p \) at the wavelengths used.

V. Average Reflectances

The sensitivity of averages \( \tilde{\rho} \) and \( \langle \rho \rangle \) to the atmospheric properties is more difficult to evaluate, since it depends upon the exact nature of the target or site involved.

The bidirectional effect was studied with the aid of the experimental results of Kriebel\(^\text{15}\) corresponding to the reflectance of the savannah at \( \lambda = 520 \text{ nm} \). By introducing these experimental values of \( \rho(\mu_0,\mu,\phi) \) and the radiances \( I_\text{a}(\tau,\mu_0,\mu,\phi) \) obtained in the theoretical computations into Eq. (9), \( \tilde{\rho} \) was computed for different solar incidence angles, for different viewing angles, and for three atmospheric models: Rayleigh, \( V = 23 \text{ km} \), and \( V = 5 \text{ km} \) at \( \lambda = 450 \text{ nm} \) and 850 nm. The values thus obtained for \( \tilde{\rho} \) are found in Figs. 3(a) and 3(b) as a function of the actual values of reflectance \( \rho \).

It is clear that the variations of \( \tilde{\rho} \) between visibilities of 5 km and 23 km are rather small and that the knowledge of coefficient \( B \) [Eq. (11)] is sufficient for definition of the contribution of the bidirectional effects. However, the strongly directional atmospheric radiation corresponding to aerosol scattering reduces the degradation of the signal obtained for the pure molecular scattering.

From Fig. 3 it may be seen that \( \tilde{\rho} \) preserves partly the bidirectional effect of \( \rho \) and could be approximately written as

\[
\tilde{\rho} = \rho_0 + \alpha \rho,
\]

(13)

with \( a = 0.1 \) for the Rayleigh scattering and \( a \) between 0.3 and 0.5 for \( V = 5 \text{ km} \) and \( V = 23 \text{ km} \); \( a \) would generally depend upon the degrees of anisotropy of both the atmospheric scattering and the ground reflectance; \( a \) would tend to 0 for an isotropic scattering or a specular reflection; and \( a \) would be close to 1 for a strong forwards-scattering and a near Lambertian reflectance.
Fig. 2. Relative contributions \( A, B, \) and \( C \) of reflectances \( \rho, \tilde{\rho}, \) and \( \langle \rho \rangle \) vs the zenithal solar angle, for a vertical observation (\( A \) is represented by a solid line, \( B \) is represented by a dashed line, and \( C \) is represented by a dotted line).
Spatial average reflectance \( \langle \rho \rangle \) was evaluated by considering the case of a ground composed of two infinite half planes with uniform Lambertian reflectances \( \rho_1 \) and \( \rho_2 \). The computation of \( \langle \rho \rangle \) was made by using the approximation of primary scattering for the evaluation of \( t(\mu, x, y) \) in Eq. (10). Figure 4 gives the values of \( \langle \rho \rangle \) thus obtained for the three above defined atmosphere models and at wavelengths 450 nm and 850 nm. The residual interaction cannot be entirely neglected, particularly in the critical zone of 500 m, but, if one notes that the weighting of \( \langle \rho \rangle \) is from 40% to 20% between visibilities of 5 km and 23 km, the linearity of Eq. (11) remains quite accurate in the first approximation.

VI. Application: Definition of Spatial or Directional Contrast

In what follows, we attempt to generalize the notion of contrast reduction in the case of bidirectional reflectance properties. Contrast reduction is defined as the variation of the available signal after atmospheric degradation, as compared with the original signal. If \( \rho_1 \) and \( \rho_2 \) are the exact reflectances in two different measurement conditions, and \( \rho_1^* \) and \( \rho_2^* \) are the measured apparent reflectances [Eq. (1)], the contrast reduction \( R \) is expressed as

\[
R = \frac{\rho_1 - \rho_2}{\rho_1^* - \rho_2^*}.
\]  

which allows expression of the information loss when viewing through the atmosphere. Spatial contrast is obtained by giving reflectance values \( \rho_1 \) and \( \rho_2 \) for two neighboring targets for which the atmosphere can be considered identical. This notion will be extended to include the case of a target having bidirectional reflection properties. In this case, \( \rho_1 \) and \( \rho_2 \) correspond to different incidence or viewing angles for the same target. For the sake of practicability, it will be considered that the bidirectional measurements are made under fixed illumination conditions with an observation angle \( \pm 0^\circ \) in the incidence plane.

The effects due to the term \( \rho_a \) [Eq. (2)] will be neglected, which is rigorously exact for the spatial contrast; in the case of bidirectional measurements, however, \( \rho_a \) is dependent upon geometrical conditions and perturbs the measurement, but this effect will not be evaluated here. The effects due to the multiple interactions between the ground and the atmosphere will also be neglected. In order to evaluate contrast reduction, we consider the following cases:

1. Spatial contrast between Lambertian sites of large dimensions \( \langle \rho \rangle = \rho = \rho \). From Eqs. (11) and (14) we obtained

\[
R = \frac{\rho_1^* - \rho_2^*}{\rho_1 - \rho_2}.
\]

This case typically corresponds to the remote sensing
of the ocean and other large uniform areas such as a desert or forest. The results in Fig. 4 show that the uniform area must have a minimum dimension of several kilometers.

(2) Spatial contrast between Lambertian targets of small dimensions ($\tilde{\rho} = \rho; \langle \rho \rangle$ = constant):

\[
R = A + B, \\
R = [\exp(-\tau/\mu_0) + E(\mu_0)] \exp(-\tau/\mu). 
\]  
This case corresponds to the definition of the contrast reduction in remote sensing commonly found when the broken ground is of small dimensions (on the order of 100 m, see Fig. 4).

(3) Directional contrast for sites of large dimensions. It is obvious that only the direct flux of the solar radiation is useful in the measurement of the bidirectional reflectance properties. However, it is seen in Figs. 3(a) and 3(b) that a small fraction $a$ of the diffuse flux preserves the directional properties of the target. If the site is homogeneous over large dimensions, these properties are also partly preserved for the contribution of directions other than the direction of observation. Thus

\[
R = [\exp(-\tau/\mu_0) + aE(\mu_0)] \exp(-\tau/\mu). 
\]  

The following values of $a$ were adopted from the results of the example dealing with the savannah [Figs. 3(a) and 3(b)]:

- $a = 0.1$ for the Rayleigh scattering,
- $a$ varying linearly from 0.3 to 0.5 between 450 nm and 850 nm for an atmosphere containing aerosols.

(4) Directional contrast for targets of small dimensions. The background contributes in a constant (or random) way to the directional effect, thus

\[
R = [\exp(-\tau/\mu_0) + aE(\mu_0)] \exp(-\tau/\mu). 
\]

(5) The extreme case of a perfectly specular reflection can also be considered as the limit of contrast degradation

\[
R = \exp(-\tau/\mu_0) \exp(-\tau/\mu). 
\]

The contrast reductions corresponding to the different cases above are plotted as a function of wavelength (450–850 nm) in Figs. 5(a)–5(c). The geometrical conditions are incidence at 41.4° and observation at +30° in the plane of incidence. The results correspond to three atmosphere models: Rayleigh atmosphere, which represents an ideal case and the best

Fig. 5. Contrast reduction vs wavelength for three atmosphere models: (1) large Lambertian targets; (2) small Lambertian targets; (3) and (4) are the same as (1) and (2) but for the directional reflectance of the savannah, and (5) specular reflectance.
possible atmospheric conditions; visibility of 23 km, which represents good standard conditions in remote sensing; visibility of 5 km, generally considered to be the lowest limit in remote sensing problems.

The contrast between Lambertian sites of large dimensions (case 1) is always relatively good ($R > 0.5$), even for 5-km visibility. In all other cases, contrasts deteriorate much more rapidly for 23-km or 5-km visibility. The contrasts become inferior to 0.5 for $\lambda = 500$ nm in the case of 23-km visibility and for $\lambda = 850$ nm in the case of 5-km visibility.

It is particularly interesting to note that the loss of contrast in directional effects (cases 3 and 4) is about the same as the loss of spatial contrast in the case of neighboring sites of small dimensions (case 2). This should allow the feasibility of bidirectional reflectance measurements to be evaluated by a study of the spatial contrast between sites of small dimensions as obtained in present remote sensing measurements. Measurement of the bidirectional properties of the target thus seems possible if given that the measurement is limited to good atmospheric conditions and to the upper limit of the visible spectrum. It must nonetheless be remembered that we have not taken into account the variations of $\rho_a$ as a function of the geometrical conditions. In a rough analysis, the $\rho_a$ variations expressed as reflectance are on the order of 0.05. This limits measurements to well-defined bidirectional reflectances, which in practical terms means the study of vegetation in the near IR region.

VII. Conclusion

A fairly accurate analytical expression of the measured reflectance was established for the general case of a non-Lambertian and nonuniform ground. The signal is quite linear as a function of the intrinsic atmospheric reflectance, the actual target reflectance, and two average reflectances, angular and spatial. These two average reflectances remain slightly dependent upon atmospheric properties. For atmospheric corrections, it appears that, except for the intrinsic atmospheric reflectance, the only unknown necessary for the definition of the relative weights of these different terms is the total optical thickness.

Other problems have not been studied here. The relationship between the average angular reflectance and the true reflectance should be generalized to include other types of directional reflectances, and the sensitivity of the average spatial reflectance to the aerosol distribution, for example, should be studied.

The formulation of the signal as described can be quite practical. In particular, it allows a fast and simple evaluation of the different notions of contrast and, more generally, should be useful in the optimization of the correction algorithms for a given type of measurement.

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References