Modeling of Atmospheric Effects on the Angular Distribution of a Backscattering Peak

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Abstract—If off-nadir satellite sensing of vegetative surfaces is considered, understanding the angular distribution of the radiance exiting the atmosphere in all upward directions is of interest. Of particular interest is the discovery of those surface reflectance features that may be invariant to atmospheric perturbations. When mono-directional radiation is incident on a vegetative scene, a characteristic angular reflectance signature called the canopy hot-spot, or Heiligenschein, is produced in the retro-direction. We use an analytic model BRDF to describe such a typical angular reflectance peak in the retro-direction. The remotely sensed angular signature is modified by atmospheric extinction of the direct and reflected solar radiation, atmospheric backscattering, and the diffuse sky irradiance incident on the surface. We explicitly demonstrate, however, by radiative transfer calculations through model atmospheres that at least one parameter that characterizes the backscattering peak, namely its angular half width, is invariant to atmospheric perturbations.

I. INTRODUCTION

THE IDENTIFICATION of those characteristics of the spectral or angular reflectance from a surface that are invariant to atmospheric perturbations is of great interest to the remote-sensing community. One such angular signature that has received some notice is the canopy "hot-spot" [3] and [15]. The purpose of this study is to investigate the manner in which an angular signature, such as the canopy "hot-spot," is affected by atmospheric scattering in order to determine its suitability as a remote-sensing diagnostic tool. A similar study has been carried out by Simmer and Gerstl [15]. However, while they were concerned with examining the angular distribution of the reflectance at the top of the atmosphere over all directions, we are exclusively concerned with studying the angular signature of a single retro-reflection peak.

When a rough surface is illuminated by a directional light source with a wavelength considerably smaller than the size of the scattering elements, an intensification of the reflected radiation occurs in a cone around the direction of retro-reflection [4]. This effect is called the canopy hot-spot in agricultural remote sensing [16], the Heiligenschein in atmospheric optics [6], and the opposition effect in planetary physics [7]. The angular width of the canopy hot-spot is a function of the type of vegetative canopy being viewed and ranges from about one to eight degrees [5]. Fig. 1 shows an aerial black-and-white photograph of a canopy hot-spot produced by a coniferous forest. When the view direction is aligned exactly with the retro-solar direction, no shadows are visible. However, as Fig. 1 clearly shows, at all other view directions shadows are contained within the field of view, thereby reducing the overall brightness of the scene. It is this effect that is responsible for the backscattering enhancement in the retro-solar direction. We will describe the angular reflectance signature of such a backscattering enhancement analytically.

II. MATHEMATICAL DESCRIPTION OF SURFACE REFLECTANCE

The complete description of a surface reflectance is given by the bidirectional reflectance distribution function (BRDF) of the surface [12], [3]. It relates the irradiance incident on a surface to the reflected radiance distribution and is defined by [12]

$$\text{BRDF} (\Omega_i, \Omega_r) = \frac{d\psi_r (\Omega_i, \Omega_r)}{\mu_r \psi_i (\Omega_i) d\Omega_i} \quad (1)$$

where $d\psi_r (\Omega_r)$ is the differential radiance reflected into the directions between $\Omega_r$ and $(\Omega_r + d\Omega_r)$ that is due to the irradiance $\psi_i (\Omega_i) \mu_i d\Omega_i$ that is incident from the di-
rections between $\Omega_i$ and $(\Omega_i + d\Omega_i)$. Here, $\mu_i$ is the absolute value of $\cos(\theta_i)$, where $\theta_i$ is the zenith angle of incidence.

Some analytic models that relate the structural characteristics of a vegetative canopy to its BRDF have been reported [4] and [10]. Rather than use one of these models, we created an analytic expression for a BRDF. The chief advantage of this model is that it describes the surface reflectance in terms of three parameters that are both analytically defined and physically meaningful. This model is not intended to describe an actual BRDF. However, with this model we can easily examine how various properties of the reflecting surface interact with the atmosphere to produce the reflectance viewed from the top of the atmosphere.

This model BRDF is given by

$$\text{BRDF}(\mu) = \frac{A}{1 + B - \mu} + \frac{\alpha}{\pi} - 2A \left( (1 + B) \ln \left( \frac{1 + B}{B} \right) - 1 \right)$$

(2)

where $\mu = \cos(\theta_0 + \theta_r)$, $\theta_0$ is the zenith angle of the incident radiation, $\theta_r$ is the zenith angle of the reflected radiation, and $\ln(x)$ means the natural logarithm of $x$. Fig. 2 describes this angular geometry. Note that for these definitions the zenith angle for normally incident radiation and nadir viewing is zero degrees. The hemispherical albedo $\alpha$ of the surface for normally incident radiation is defined by

$$\alpha = 2\pi \int_0^1 \text{BRDF}(\mu) \mu \, d\mu.$$  

(3)

The parameters $A$ and $B$ are related to the angular half width $\mu_h$ and the contrast ratio $K$, where

$$K = \frac{\text{BRDF}(\mu = 1)}{\text{BRDF}(\mu = 0)}$$

(4)

and

$$\text{BRDF}(\cos \theta_h) = \frac{\text{BRDF}(\mu = 1) + \text{BRDF}(\mu = 0)}{2}.$$  

(5)

In terms of these parameters the constants $A$ and $B$ are given by

$$A = \frac{(K - 1)\alpha/\pi}{\frac{2\mu_h - 1}{1 - \mu_h} - K(2\mu_h - 1) + 2(K - 1) \left( \frac{\mu_h}{2\mu_h - 1} \right) \ln \left( \frac{\mu_h}{1 - \mu_h} \right) - 1}$$

(6)

and

$$B = \frac{1 - \mu_h}{2\mu_h - 1}$$

(7)

where $\mu_h$ is equal to $\cos \theta_h$.

For reasons that will later be clear, the model BRDF of (2) is azimuthally independent. It takes on its maximum value when $\mu$ is equal to one. This occurs when the viewing direction is opposite to the direction of incidence, that is, in the direction of the retro-reflection. As the viewing direction moves away from the direction of retro-reflection, the value of the BRDF decreases monotonically. We will refer to that angular region that is within an angular half width of the backscattering peak as the backscattering region.

Fig. 3 shows two examples of the model BRDF for normally incident radiation. In both cases, the values of $K$ and $\alpha$ are set to ten and 0.1, respectively. The angular half width is equal to one degree in one and five degrees in the other. As Fig. 3 shows, decreasing the angular half width increases the rate at which the BRDF decreases from its maximum value in the retro-direction. However, since the hemispherical albedo remains fixed, the values of the BRDF in the backscattering region must increase, and, since the contrast ratio $K$ is also unchanged, the values of the BRDF throughout much of the region outside the backscattering region must also increase. For small angular half widths, the increase in the values of the BRDF outside the backscattering region (required to keep the hemispherical albedo constant) tend to be small because the region of integration is large.

Increasing the contrast ratio $K$, while keeping $\mu_h$ and $\alpha$ fixed, tends to increase the values of the model BRDF in
the backscattering region, while decreasing the values outside the backscattering region. For BRDF's with small angular half widths, this decrease in values is small for the same reason given above.

An examination of (2), (6), and (7) reveals that the model BRDF of (2) can be written as a product of the hemispherical albedo and a function of $K$ and $\theta_s$. Hence, doubling the value of the hemispherical albedo, while leaving the values of $K$ and $\theta_s$ unchanged, will double all the values of the BRDF.

III. METHOD OF CALCULATIONS

All radiative transfer (RT) calculations were performed on CRAY computers at Los Alamos National Laboratory using the discrete-ordinate finite-element code ONE-DANT. This code, originally designed for neutron transport, has been demonstrated to yield accurate results for radiative transfer through the atmosphere [2]. The Shettle and Fenn [14] rural atmosphere model with 90-percent relative humidity was used to describe the atmospheric scattering and absorption parameters. This model was judged to be sufficiently representative and flexible to model the atmospheric conditions often encountered during remote sensing of terrestrial scenes. The atmosphere was divided into five homogeneous layers arranged horizontally above a flat earth. In the top three layers the asymmetry parameters for the Henyey-Greenstein phase functions were also taken from the Shettle and Fenn data. Under the clear air conditions for which remote sensing is normally performed the number of scattering events in the atmosphere is not large; consequently, we expect the atmospheric perturbation of the backscattering peak to be sensitive to the explicit form of the atmospheric scattering phase function. In particular, we expect pronounced sensitivities to the values of the phase function in both the forward and backscattering directions, where, for the highly forward peaked aerosol phase functions, the fit of the Henyey-Greenstein approximation is the poorest. Consequently, in the boundary layer (consisting of the lowest two kilometers), where the majority of the atmospheric scattering takes place, we attempted to represent the phase function as accurately as possible. Fig. 4 shows, for a wavelength of 0.55 $\mu$m, the aerosol atmospheric scattering phase function, as determined by Mie theory, together with a Legendre expansion of the phase function consisting of 250 moments. The parameters and size distributions used in the Mie calculations were taken from the Shettle and Fenn [14] data for a rural atmosphere with 90-percent relative humidity. Although a relative humidity of 90 percent may be rare, we choose this value so that the effect of a backscattering peak in the phase function could be assessed. Due to the high degree of forward scattering in the phase function (Fig. 4 shows that $P(\theta_r = 0$ degrees) $\sim 10^2 P(\theta_r = 180$ degrees $)$), the relative error of the 250 moment expansion is very small in the forward scattering cone and much larger near the backward scattering direction, while the absolute errors are small throughout; therefore, the approximation was judged to be adequate for our purposes. Atmospheric molecular scattering was treated as Rayleigh scattering.

In addition to the requirement on the number of Legendre moments of the phase function, we also require in the discrete-ordinate method that the angular distance between the discrete directions be small enough that the backscattering peak can be resolved. In order to accommodate ONEDANT to these requirements, we decided to perform the RT calculations using one-angle rather than two-angle slab geometry, and, as a consequence, require the surface BRDF to be azimuthally independent. This differs from the calculations reported by Simmer and Gerstl [15] in that they use two-angle geometry throughout. However, for this study it was judged more important to obtain a very accurate representation of the atmospheric scattering and reflectance angular characteristics within the aerosol forward scattering peak and within the surface backscattering peak. 250 Gauss-Legendre discrete directions ($S_2-250$) are sufficient for our purposes. The use of one-angle geometry implies that the radiance must also be azimuthally independent; a condition that is
only satisfied when the solar radiation is normally incident on the atmosphere (in one-angle slab geometry it must be assumed by definition that the solar radiation is incident in a cone about the vertical direction). At present, the incident solar direction must be chosen as one of the discrete directions. We have chosen the discrete direction lying closest to zenith (at 0.55 degrees for 250 Gauss–Legendre quadrature points) for the direction of the solar radiation. In this way, the problem closely approximates an actual problem with the sun at zenith and near nadir observation, and the interpretation of the results is simplified. A comparison of calculations of order $S_r$=250 and $S_r$=498 (where we are able to choose the incident solar zenith angle to be 0.28 degrees) produced a less than 1-percent deviation in the radiances at the top of the atmosphere for all directions, leading us to conclude that $S_r$=250 results are sufficient for our purposes.

In order to investigate the effect of the atmosphere on the transport of a retro-reflection peak through the atmosphere we have made calculations for various atmospheric optical depths, surface BRDF's, and wavelengths. All reflected radiance values are normalized to the incident solar irradiance above the atmosphere, thus facilitating their comparison. More explicitly, we define the reflectance distribution $R(\Omega)$ by

$$R(\Omega) = \frac{\pi \psi_r(\Omega)}{S_0 \cos \theta_i}$$

where $S_0$ is the solar constant (evaluated at the appropriate wavelength), $\theta_i$ is the solar zenith angle measured from the nadir direction, $\psi_r$ is the reflected (upward directed) radiance, and $\Omega$ defines the direction of reflected radiation.

**IV. Results**

*A. Variation in the Angular Half Width*

In Figs. 5 and 6 we examine the influence of varying the angular half width $\theta_i$ of the surface BRDF and the atmospheric optical depth $\tau$ for a wavelength of 0.55 $\mu$m. Both figures show the computed reflectance distribution at the top of the atmosphere for view zenith angles between 0 and 60 degrees and atmospheric total optical depths of 0.41, 0.78, and 1.29. As the view zenith angle approaches 90 degrees, the optical path length through the flat model atmosphere approaches infinity and the validity of slab geometry breaks down at these angles; thus, we have not plotted these results. For the calculations shown in Figs. 5 and 6 we used a surface BRDF with an angular half width of 5 degrees and one degree, respectively. In both cases, contrast ratio $K$ and hemispherical albedo $\alpha$ are set to 10 and 0.1, respectively. Because of the relatively high value of contrast ratio used in this model, we will refer to it as the high contrast model. Although this model is somewhat unrealistic for a canopy hot-spot, it clearly demonstrates the effect of changing the value of the angular half width on the observed reflectance distribution at the top of the atmosphere. For this reason we include it in this report.

The most striking feature of these results is that they all prominently exhibit a backscattering peak in the retro-solar direction above the atmosphere for all the atmospheric conditions considered. Another prominent feature is that as the optical depth increases, the magnitude of the backscattering peak decreases and the level of the background radiance increases, that is, the contrast ratio of the reflectance at the top of the atmosphere decreases with increasing atmospheric optical depth. However, the angular half width of the backscattering peak appears to be virtually unchanged over the range of optical depths considered.

In order to quantify the atmospheric effects on the backscattering peak, we developed an analytical measure of the angular half width of the reflectance distribution at the top of the atmosphere. In the absence of atmospheric ef-
fects the reflectance distribution at the top of the atmosphere would be πBRDF. Hence, if the reflectance distribution in the neighborhood of the backscattering peak is somewhat insensitive to atmospheric effects, the angular distribution of the reflectance in the backscattering region should be well fit by an expression of the form given by (2) for the BRDF. The method used to fit the reflectance distribution to this functional form is based upon the fact that the analytic BRDF described in (2) cannot only be expressed in terms of the three parameters $\alpha$, $\theta_h$, and $K$, but also in terms of its values at any three angles $\theta_e$.

Since we are only interested in describing the reflectance at the top of the atmosphere in the vicinity of the retro-solar direction, we fix $\theta_0$ in (2) to be equal to the solar zenith angle. One value of $\theta_e$ is chosen such that they give the best fit to the reflectance distribution over a given range of view angles. We select the range of view angles over which the reflectance distribution ought to be fit such that the reflectance distribution decreases monotonically throughout, since the BRDF of (2) does likewise. Because it is unlikely that a backscattering peak observed at the top of the atmosphere has a half angular width greater than 10 degrees, we restricted the range of view angles over which the reflectance distribution is fit to be between zero and less than 10 degrees. The average relative error of the approximate fit has been found to be always much less than 1 percent.

Using these three values of $\theta_e$ in (2), three equations with three unknowns can be solved to obtain the value of the associated angular half width $\theta_{hc}$. Table I gives the values, expressed in degrees, for the angular half width $\theta_{hc}$ calculated in this manner. Apparently, the smaller the angular half width of the model BRDF, the less the angular half width of the backscattering peak at the top of the atmosphere.

### Table I

<table>
<thead>
<tr>
<th>$\tau$</th>
<th>$\theta_h$</th>
<th>$\theta_{hc}$</th>
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<tr>
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<td>1.0</td>
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Fig. 7. Reflectance distribution $R(\Omega)$ (in percent) at the top of the atmosphere for atmospheric optical depths of 0.41 (squares), 0.78 (circles), 1.29 (triangles), and 2.69 (crosses) and a wavelength of 0.55 μm, when the coniferous forest model BRDF is used.

Fig. 8. Reflectance distribution $R(\Omega)$ (in percent) at the top of the atmosphere for atmospheric optical depths of 0.41 (squares), 0.78 (circles), 1.29 (triangles), and 2.69 (crosses) and a wavelength of 0.55 μm, when the coniferous forest model BRDF with increased hemispherical albedo is used.

### B. Variation in Hemispherical Albedo and Contrast Ratio

In Figs. 7–9 we examine the effect of varying the surface hemispherical albedo and contrast ratio on the reflectance distribution observed at the top of the atmosphere. Measurements we made of a coniferous forest hot-spot indicate that an angular half width of 3.5 degrees, contrast ratio of 3, and a surface albedo of 0.02 [9] provide a reasonable description of the hot-spot of a coniferous forest in the visible, as shown in Fig. 1 [5]. The results plotted in Figs. 7–9 either use or modify these hot-spot parameters in the analytic BRDF of (2). The results shown in Fig. 7 were produced using this coniferous forest hot-spot model unmodified. For Fig. 8 the surface albedo was changed to 0.06, while keeping the remaining parameters fixed; and in Fig. 9 the contrast ratio was doubled from 3 to 6, while leaving the remaining parameters unchanged. The values of the angular half width of the backscattering...
peak above the atmosphere for Figs. 7–9 are given in Table II. We note that increasing either the contrast ratio or hemispherical albedo of the surface BRDF has the effect of reducing the atmospheric effects on the angular half width of the backscattering peak. As in the previous subsection, we notice that increasing the optical depth of the atmosphere, increases, in all cases, the angular half width of the reflectance distribution at the top of the atmosphere. However, for all cases in the visible this increase is less than 20 percent of the value of \( \theta_{hc} \); and if we restrict ourselves to values of \( \tau \) less than one, the difference is less than 10 percent. For an atmospheric optical depth of 2.69, the backscattering peak is undetectable for all cases in the visible.

### C. Variation in the Wavelength

When the wavelength of the incident radiation changes, both the atmospheric and surface scattering properties change. In the first two kilometers above the earth’s surface the aerosol single scattering albedo is 0.97 at 0.55 \( \mu m \) and 0.95 at 0.86 \( \mu m \), for the Shettle and Fenn rural atmosphere model with 90-percent relative humidity, while the asymmetry parameter changes from 0.73 at 0.55 \( \mu m \) to 0.71 at 0.86 \( \mu m \). These changes produce little change in the aerosol single scattering phase function. However, for the same atmosphere, the aerosol extinction cross section at 0.86 \( \mu m \) is only 62 percent of the extinction cross section at 0.55 \( \mu m \) [14]. Consequently, the atmospheric optical depth at 0.55 \( \mu m \) is larger than at 0.86 \( \mu m \) for all the atmospheric models considered. In the near infrared wavelength region the surface hemispherical albedo of vegetative canopies is higher than in the visible [9], [13], and [18]. In addition, due to increased multiple scattering within the canopy, the contrast ratio decreases. Our measurements indicate that changing the surface hemispherical albedo to 0.10 and the contrast ratio to 1.6 adequately models the hot-spot of a coniferous forest in the near infrared [5]. The angular half width, being primarily a function of the canopy architecture, does not change significantly with wavelength; consequently, we set it equal to 3.5 degrees for all cases in this section.

Fig. 10 shows the results of those calculations and the values of \( \theta_{hc} \) are presented in Table II. Comparison with Figs. 7–9 is difficult with so many parameter differences. However, we note the consistent increase of \( \theta_{hc} \) with increasing atmospheric optical depth. Of greater interest, is, for a given atmosphere and vegetative canopy, the apparent reduction in atmospheric perturbation of the angular half width in the near infrared as compared to that in the visible. Even for an atmospheric optical depth of 0.89 in the near infrared, which corresponds to an optical depth of 1.29 in the visible, the difference between \( \theta_{hc} \) and \( \theta_{e} \) is only 11 percent in the infrared, as compared to the corresponding value of 20 percent in the visible. Perhaps of greater importance for the remote sensing of vegetation is that at an atmospheric optical depth of 1.76 in the near infrared the backscattering peak is still detectable; whereas, at the corresponding atmospheric optical depth of 2.69 in the visible it is not detectable.

### D. Grassland Model

Two of the most frequently encountered land scenes are forested areas and grasslands. In Fig. 11 we show, for the sake of completeness, the reflectance at the top of the atmosphere using a BRDF model that is intended to represent the hot-spot of a grassland in the visible. For this model we set the surface albedo to 0.07 [9], the contrast ratio to 1.5, and the angular half width to 1 degree. These values are consistent with our measurements of the hot-spot produced by grasslands in the visible [5]. The values for the angular half width at the top of the atmosphere for a wavelength of 0.55 \( \mu m \) are listed in Table III. As for all

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**Table II**

<table>
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<tr>
<th>( \tau )</th>
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<th>( \kappa )</th>
<th>( \alpha )</th>
<th>( \theta_{hc} )</th>
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<tr>
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E. Summary of the Computed Results

For all of the results shown in Figs. 5–11 the backscattering peak is clearly detectable above the atmosphere for all except the largest optical depth. The results listed in Tables I–III show that the angular half width is approximately invariant to atmospheric perturbations. The atmospheric optical depth seldom exceeds 1 at visible wavelengths under conditions favorable to remote sensing. If the atmospheric optical depth normal to the surface is one, the atmospheric optical depth $\tau$ for a slant path at 40 degrees from nadir is about 1.29. Consequently, our assumptions of atmospheric optical depths greater than 1.29 at 0.55 $\mu$m and 0.89 at 0.86 $\mu$m are seldom encountered. However, we show results for larger atmospheric optical depths in Figs. 7–11 merely as a limiting case, where atmospheric scattering exceedingly dominates the reflectance distribution above the atmosphere. The major difference between the results shown in Figs. 7–11 and those shown of the high contrast models in Figs. 5 and 6 is that in the latter case the magnitude of the backscattering peak decreases with increasing atmospheric optical depth, whereas in the former case it increases with increasing atmospheric optical depth. We will discuss these differences and other features of these results in the next section.

V. DISCUSSION

Our results demonstrate how, with increasing atmospheric optical depth, the angular signature of a satellite-sensed retro-reflection peak, like a canopy hot-spot, is modified. The aspect of these results that is of greatest importance for remote sensing is the invariance of the angular half width of the backscattering peak to atmospheric perturbations. In order to understand the means by which this invariance occurs, we must first understand how the remote sensing of the backscattering peak through the atmosphere is different from the situation in the absence of the atmosphere.

In the absence of the atmosphere the angular distribution of the backscattering peak is solely created by the interaction of the incident solar radiation with the surface BRDF, neglecting the solar penumbra effect. The presence of the atmosphere creates three important effects on the observation of the backscattering peak from the top of the atmosphere. First, the incident solar radiation intensity is reduced by atmospheric extinction in traveling to the surface and, in a like manner, the reflected radiation intensity is reduced in returning to the top of the atmosphere; second, atmospheric scattering of the direct solar radiation in conjunction with reflection from the surface creates a diffuse source of radiation incident on the surface; third, an additional source of radiation is added to the angular distribution of the backscattering peak by backscattering from the atmosphere. A similar decomposition has been used by others $[1]$, $[11]$, $[17]$.

The influence of these three effects on the reflectance distribution above the atmosphere $R_{\text{top}}$ is then the sum of
three terms

\[ R_{\text{op}} = R_{\text{dir}} + R_{\text{diff}} + R_{\text{back}}. \]  

(9)

\( R_{\text{dir}} \) is that part of the reflectance which is due to direct solar radiation that is only reflected from the surface, \( R_{\text{diff}} \) is that part which is due to diffuse radiation reflected from the surface, and \( R_{\text{back}} \) is that part which is only scattered from the atmosphere and contains no information about the surface. Here

\[ R_{\text{dir}} = \pi \text{BRDF} (\mu_v, \mu_s) \exp \left(-\tau(1/\mu_v + 1/\mu_s)\right) \]

(10)

where \( \mu_v \) is the cosine of zenith angle of the reflected radiation, \( \mu_s \) is the absolute value of the cosine of the zenith angle of the incident solar radiation, and \( \tau \) is the total optical depth of the atmosphere.

The relative importance of these three effects is influenced by the surface BRDF and the scattering and absorption properties of the atmosphere. In Fig. 12 we plot separately the three components of \( R_{\text{op}} \) for the coniferous forest model corresponding to Fig. 7 at an atmospheric optical depth of 0.78. Aside from the magnitude of each of these components, all of the other cases we have considered yield similar results. These results suggest that the reflectance distribution at the top of the atmosphere \( R_{\text{op}} \) might be considered, over the angular width of the backscattering peak, as the sum of a constant and \( R_{\text{dir}} \).

The aerosol phase function as shown in Fig. 4 is highly forward scattering; hence, those view directions that require the incident solar radiation to undergo the smallest cumulative angle of scattering receive the largest amount of radiation. It is a feature of forward scattering aerosol phase functions that accounts for the increase of \( R_{\text{back}} \) with increasing view zenith angle, as shown in Fig. 12. \( R_{\text{diff}} \), on the other hand, can either increase or decrease with increasing view zenith angle. As the view zenith angle increases, both the slant path of the radiation through the atmosphere and the average angle of scattering increase. Increasing the slant path of the radiation through the atmosphere, increases the opportunity for scattering, while, for forward scattering atmospheric phase functions, the amount of radiation scattered into larger scattering angles decreases with increasing scattering angle. At low atmospheric optical depths (below about 0.5), where the number of scattering events is small, \( R_{\text{diff}} \) will generally increase with increasing view zenith angle, despite the larger average scattering angle required. However, at larger atmospheric optical depths, where the number of scattering events is greater, \( R_{\text{diff}} \) will decrease with increasing view zenith angle. As Fig. 12 shows, the rate of these changes in \( R_{\text{back}} \) and \( R_{\text{diff}} \) with view zenith angle tends to be small as compared to the rate of change of \( R_{\text{dir}} \). Hence, as long as the magnitude of \( R_{\text{dir}} \) is not negligible, the angular variation of the total reflectance \( R_{\text{op}} \) with view zenith angle in the neighborhood of the backscattering peak will be largely influenced by the behavior of \( R_{\text{dir}} \) alone.

### A. Effect of Atmospheric Extinction

Over the angular width of the backscattering peak, the difference in atmospheric extinction within the reflected cone of radiation is negligible. Consequently, \( R_{\text{op}} \) as given by (10) accurately manifests the angular characteristics and, in particular, the angular half width of the surface BRDF. As we have indicated above, the value of the reflectance at the top of the atmosphere in the neighborhood of the backscattering peak. To the extent that this is true, the effect of atmospheric extinction on the observed backscattering peak is merely to change the relative magnitude of the backscattering peak above the background. This reduction in amplitude with increasing atmospheric optical depth is evident in Figs. 5–11. Because the atmospheric optical depth at 0.86 \( \mu \text{m} \) is less than at 0.55 \( \mu \text{m} \), the rate of decreasing contrast ratio with atmospheric optical depth is smaller at near infrared (NIR) wavelengths.

### B. Effect of Surface BRDF

The surface BRDF has no effect upon the contribution of \( R_{\text{back}} \) to \( R_{\text{op}} \). Its effect upon \( R_{\text{dir}} \), as shown in (10), is linear; however, its effect upon \( R_{\text{diff}} \) is less straightforward. The relative magnitude of \( R_{\text{diff}} \) is increased by increasing the surface albedo or increasing the amount of atmospherically scattered radiation reaching the ground. However, for the remote sensing of the backscattered peak, the major effect of interest is the broadening of the angular half width produced by the diffuse radiation incident on the surface. This effect is somewhat mitigated by the fact that any model BRDF described by (2) acts like an angular filter within a cone around the retro-direction. Only those directions of incident radiation within a few degrees of each other are correlated through the BRDF. Because the angular distribution of the incident radiation is strongly peaked in the solar direction for the atmospheric optical depths considered, the angular distribution of the reflected radiation in the retro-solar direction is dominated by the irradiance in the incident solar direc-
tion. Therefore, although our model BRDF produces a backscattering peak for every incident direction, only the solar retro-direction shows a predominant backscattering peak. If the downwelling radiation were isotropic, no reflectance peak would be created, even with a peaked BRDF like that given by (2). If, however, only the diffuse part of the downwelling radiation were isotropic, reducing the angular half width of the BRDF (or increasing the contrast ratio $K$) would have no effect upon the angular distribution of the reflected diffuse radiation, while simultaneously increasing the contribution of the direct solar radiation; consequently, increasing the relative value of $R_{dlr}$ compared to that of $R_{dfl}$.

The smaller the angular half width of the BRDF, the more isolated is the reflectance of the incident solar radiation from the reflectance of the incident diffuse radiation, and, consequently, the larger is the relative value of $R_{dif}$ compared to $R_{diff}$ in the retro-solar direction. Thus, the tendency of the diffuse radiation incident on the surface to broaden the angular signature of the backscattering peak is reduced by the angular filtering characteristics of the surface BRDF. Examination of Figs. 5 and 6 and the values, for a given value of $\tau$, of the angular half width of the reflectance at the top of the atmosphere $\theta_{\text{top}}$ listed in Table I, corroborate this statement.

Increasing only the hemispherical albedo of the surface has the effect of increasing the relative values of $R_{dif}$ and $R_{diff}$ compared to that of $R_{back}$, thereby increasing the relative influence of the surface on the total reflectance distribution at the top of the atmosphere. The amount of diffuse radiation incident on the surface will increase when the hemispherical albedo of the surface increases, especially at larger atmospheric optical depths. However, since $R_{dif}$ represents the predominant angular feature in the neighborhood of the backscattering peak, the overall effect is to decrease the atmospheric perturbation within the backscattering region. This is evident by comparing Figs. 7 and 8 and their corresponding values of $\theta_{\text{top}}$ listed in Table II, for a given value of $\tau$.

Increasing the contrast ratio $K$, for a fixed hemispherical albedo, has the effect of increasing the relative brightness of the backscattering region, consequently reducing the probability of radiation being scattered from outside the incident solar direction into the backscattering region. The effect, therefore, is to reduce the relative importance of $R_{diff}$ in the neighborhood of the backscattering peak and increase that of $R_{dif}$, thereby decreasing the atmospheric perturbation of the backscattering peak. This is evident by comparing Figs. 7 and 9 and their corresponding values of $\theta_{\text{top}}$ listed in Table II, for a given value $\tau$.

Despite the fact that the grassland BRDF possesses a larger albedo and smaller angular half width than the coniferous forest BRDF, a comparison of Tables II and III reveals that the atmosphere apparently has a greater effect upon the observed hot-spot of the grassland. This difference obviously is due to the smaller contrast ratio of the grassland BRDF.

The degree with which the BRDF acts like an angular filter is determined by the relative amount of radiation that is scattered from directions outside the backscattering region into the backscattering region. This characteristic is affected by both the angular half width and the contrast ratio. The surface albedo affects the ultimate ability of the BRDF to act as an angular filter by affecting the angular distribution and magnitude of the incident diffuse radiation. Decreasing the angular half width of the BRDF increases its filtering capability, and decreasing the contrast ratio decreases it. Regardless of the value of the angular half width, as the contrast ratio tends to one, the surface behaves increasingly like a Lambertian surface and the ability of the surface BRDF to act like an angular filter vanishes. Apparently, the decrease of the contrast ratio in the grassland model BRDF, despite a decrease in the angular half width, has diminished the angular filter capability of the BRDF as compared to that of the coniferous forest model BRDF.

C. Effect of Atmospheric Backscattering

For small atmospheric optical depths, $R_{\text{back}}$ is primarily due to single scattering. Even though the atmospheric phase function shown in Fig. 4 has a rather pronounced backscattering peak (its value at a scattering angle of 180 degrees is about twice as large as its minimum value), the variation of the atmospheric phase function around the backscattering direction is essentially constant over the angular width of the surface backscattering peak. Hence, the only effect of atmospheric backscattering on the retro-reflection peak is to raise the magnitude of the upwelling radiation across the entire angular cone of the backscattering peak. Consequently, the angular half width of the backscattering region is unaffected by the backscattered radiation. As the atmospheric optical depth increases, the effect of $R_{\text{back}}$ on the angular half width of the backscattering peak tends to be further reduced. This is so because, as the atmospheric optical depth increases, the increased amount of multiple scattering can only decrease the angular variation of the atmospherically backscattered radiation. Of course, for large atmospheric optical depths, atmospheric backscattering will completely obscure the surface.

D. Effect of Wavelength

The results plotted in Figs. 7 and 10 are meant to reflect the differences in the observed backscattering peak of the coniferous forest model in the NIR and visible wavelengths, respectively. The lower value of the contrast ratio in the NIR increases the relative importance of $R_{\text{diff}}$, but the larger hemispherical albedo increases the relative influence of both $R_{\text{diff}}$ and $R_{\text{dif}}$. These factors and especially the reduction of the amount of atmospheric scattering in the NIR lead to an observed backscattering peak above the atmosphere that is generally less affected by atmospheric perturbations at 0.86 $\mu$m than at 0.55 $\mu$m. Comparing Figs. 7 and 10 and the corresponding results listed in Table II bears out this conclusion.

At red and blue wavelengths the hemispherical albedo
of vegetative canopies is lower [9], [13], and [18] than at the wavelength 0.55 \( \mu \text{m} \) in the green, at which our calculations were made. Consequently, one might expect that at other visible wavelengths the retro-reflection region would be more perturbed by the atmosphere than at 0.55 \( \mu \text{m} \).

### E. Effect of Atmospheric Optical Depth

We note in Figs. 5-11 that as the atmospheric optical depth increases, the level of the background reflectance increases. By background reflectance we mean that reflectance observed at the top of the atmosphere which is outside the backscattering peak in angle, or view direction. However, the shape of the backscattering peak is influenced in a more complicated manner. In Figs. 5 and 6 the reflectance values at the backscattering peak decrease with increasing atmospheric optical depth, whereas, in Figs. 7-11 they generally increase with increasing atmospheric optical depth. These results can be understood as due to a competition between the reflectance from the surface and the atmospheric backscattering. The atmospherically backscattered reflectance \( R_{\text{back}} \) increases with increasing optical depth, but, due to atmospheric extinction, \( R_{\text{diff}} \) decreases. On the one hand, the contribution to the reflectance at the top of the atmosphere from the diffuse radiation \( R_{\text{diff}} \) tends to increase with increasing optical depth because of increased scattering, and, on the other hand, it tends to decrease because of the decrease in the amount of radiation reaching the ground. For small atmospheric optical depth, \( R_{\text{diff}} \) increases with increasing atmospheric optical depth. For atmospheric optical depths greater than about one, it decreases with increasing optical depth. However, for the range of atmospheric optical depths we have considered, the contribution from the diffuse radiation is approximately constant for a given model BRDF. Consequently, the resulting reflectance at the top of the atmosphere can be understood primarily as due to a competition between the decreasing values of \( R_{\text{diff}} \) and the increasing values of \( R_{\text{back}} \) with increasing optical depth.

For forward scattering aerosol phase functions, when the sun is in the zenith position, \( R_{\text{back}} \) tends to be smaller within the backscattering region than outside the backscattering region since the scattering angle between the incident solar direction and the view direction is larger. However, the most important difference is that the backscattering peak produced by the incident solar radiation at the surface is much brighter than the reflectance from the surface in any other direction. If the surface is sufficiently bright in the backscattering region, as, for example, in our high contrast models, the decrease in \( R_{\text{diff}} \) with increasing optical depth will be smaller than the increase in \( R_{\text{back}} \). In this case, the backscattering peak will decrease with increasing atmospheric optical depth. Figs. 5 and 6 exhibit this effect. However, if the surface is sufficiently dark in the backscattering region, as, for example, in our coniferous forest and grassland models, the opposite occurs and the backscattering peak rises with increasing atmospheric optical depth. Figs. 7 and 11 display this effect. In Figs. 8-10 the backscattering peak, at lower atmospheric optical depths falls with increasing optical depth, but at larger optical depths, it increases as the atmospheric optical depth increases. These results are a consequence of the bright retro-reflection first dominating the reflectance, and then being obscured by the atmospherically backscattered reflectance.

In summary then, for bright surfaces the major atmospheric effect on the backscattering peak is the extinction of the surface reflectance, which makes the surface appear darker; whereas, for dark surfaces the major atmospheric effect is atmospheric scattering, which makes the surface appear brighter. This effect has also been identified by Kaufman [8] for Lambertian surfaces.

When the sun is not at zenith, the surface BRDF of real and model canopies is not symmetric about the backscattering direction [4]. It is easy to demonstrate that atmospheric extinction introduces an additional asymmetry when the sun is not in the zenith. For angles near the retro-solar direction, the major effect is the increase in slant path through the atmosphere and corresponding increase in atmospheric optical depth. For view zenith angles greater than the solar zenith angle, atmospheric extinction increases further with increasing zenith angle; while for view zenith angles less than the solar zenith angle, atmospheric extinction decreases with decreasing zenith angle. For a constant scattering angle, the influence of atmospheric extinction is therefore not identical on both sides of the retro-solar direction. These factors combine to produce an unsymmetrical reflectance signature. Nevertheless, for effective optical depths less than about one, we do not expect these changes to affect our conclusions about the atmospheric invariance of a retro-reflection peak significantly.

### VI. Conclusion

Employing atmospheric radiative transfer calculations with extremely high angular resolution of the radiance distribution, we analyzed the effects of atmospheric multiple scattering and absorption on the angular distribution of a narrow retro-reflection peak such as the canopy hot-spot or Heiligenschein. Using a realistic aerosol-loaded atmospheric model, our results demonstrate that the angular width of the model hot-spot (for half widths between 1 and 5 degrees and various types of vegetative canopies) is, to within about 10 percent, invariant to atmospheric perturbations for total optical depths of the atmosphere up to 1.0 at 0.55 \( \mu \text{m} \) and up to 0.9 at 0.86 \( \mu \text{m} \). This result is a consequence of the angular filter effect of the surface BRDF and the comparatively broad angular signature of atmospheric backscattering. However, the contrast ratio of the backscattering peak is strongly influenced by atmospheric extinction. As a consequence for satellite-remote sensing, our results indicate that the canopy hot-spot may indeed be classified as an angular reflectance signature whose angular width remains invar-
The characteristic may allow the canopy hot-spot and similar angular signatures to be used as a vegetation identifier in future off-nadir satellite remote-sensing projects.

REFERENCES


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