Sensitivity of surface reflectance retrieval to uncertainties in aerosol optical properties

P. M. Teillet, G. Fedosejevs, F. J. Ahern, and R. P. Gauthier

We formulate a procedure to investigate the sensitivity of surface reflectances retrieved from satellite sensor data to uncertainties in aerosol optical properties. Aerosol optical characteristics encompassed in the study include the aerosol optical depth, the Junge parameter (i.e., spectral dependence), and the imaginary part of the refractive index (i.e., aerosol absorption). The study includes both clear and hazy atmospheric conditions, wavelengths of 0.550 and 0.870 μm, three solar zenith angles, and five viewing geometries. Key results are presented graphically in terms of accuracy requirements on the aerosol property under consideration for a 5% uncertainty in predicted surface reflectance.

Introduction

The estimation of surface reflectance is one of the goals of remote sensing, particularly if one is attempting to retrieve biophysical or geophysical parameters from the data. Because of the effects of the Earth's atmosphere, one usually uses a radiative transfer code to retrieve surface reflectance from spaceborne observations. Radiative transfer is a complex physical process that can be modeled reasonably accurately. However, a large number of parameters are required for results that agree well with the experiment to be obtained. Many of the parameters can be specified accurately from *a priori* knowledge. Among these are the illumination and viewing geometries at the time of a given measurement. Others are less well known.

In this study our purpose was to determine the level of uncertainty that can be tolerated in the specification of three parameters describing atmospheric aerosol conditions and still achieve a relatively small uncertainty (5%) in the estimation of surface reflectance from satellite sensor data. The three parameters are the aerosol optical depth, the Junge parameter (which can be used to describe the wavelength dependence of optical depth), and the imaginary part of the index of refraction (used in the determination of aerosol absorption).

The authors are with the Canada Centre for Remote Sensing, 588 Booth Street, Ottawa, Ontario K1A 0Y7, Canada.

Received 28 October 1992; revised manuscript received 26 August 1993.
0003-6935/94/183933-08$06.00/0.

Many operational methodologies for surface reflectance retrieval assume that path radiance is estimated from the satellite image itself, typically by the use of a dark-target approach.[1,2] To examine the sensitivity of this process to uncertainty in the specification or determination of the three aforementioned aerosol parameters, we used simulations based on the Herman radiative transfer code.[3]

The optical characteristics of aerosols are primarily determined by the particle size distribution, which dictates the scattering function (computed with Mie theory in the Herman code), and by the complex index of refraction of the scattering and absorbing particles. A convenient representation of the size distribution function for the purpose of this study is the power-law expression of Junge[4]:

$$\frac{dN}{dr} = Cr^{-(\nu+1)}, \tag{1}$$

where N is the number of particles per unit volume up to radial size r, and C is a constant. Aerosol investigations at a variety of locations have verified that the power law is a good representation of particle size distribution.[5] Values of the Junge exponent ν are typically between 3 and 4 for continental aerosols.[5] For aerosols following a power-law size distribution as in Eq. (1), the relationship between aerosol optical depth and wavelength also follows a power law[5]:

$$\delta_a(\lambda) = A\lambda^{-\alpha}, \tag{2}$$

where λ is the wavelength, δ_a is the aerosol optical depth, A is a turbidity coefficient, and

$$\alpha = \nu - 2. \tag{3}$$

Thus, the observational determination of α allows one to infer the Junge power-law exponent in the aerosol size distribution.

The complex index of refraction is expressed as follows:

$$m = m_r - m_i i, \tag{4}$$

where the real component m_r is of the order of 1.5 and the imaginary component m_i is in the range 0.005–0.01 for basic aerosol components at visible and near-infrared wavelengths. A procedure was formulated as a way to study the sensitivity of surface reflectance retrieval to variations in the Junge parameter ν, and in the imaginary part of the refractive index m_i (i.e., aerosol absorption).

The radiance observed by a sensor in a given spectral band in the solar reflective part of the spectrum can be written as

$$L^* = L_t + L_s + L_a, \tag{5}$$

where L_t is the radiance from the target surface directly transmitted through the atmosphere to the sensor, L_s is the radiance from the surface surrounding the target scattered by the atmosphere to the sensor, and L_a is the radiance scattered by the atmosphere itself without reflection by the surface. The target surface reflectance is assumed to be Lambertian, and the surround reflectance is assumed to be identical to that of the target. The intrinsic atmospheric radiance L_a is sometimes referred to as the path radiance. However, as the target radiance L_t is the component of primary interest for remote sensing of surface characteristics, the path radiance was considered to be the sum of the remaining terms, $L_s + L_a$, in this investigation.

It was assumed initially that there was no error in the path radiance estimate and no error in the measurement of apparent radiance by the sensor (i.e., no calibration error). Subsequently, the sensitivity analysis was also extended so that we could assess the impact of uncertainty in the retrieved path radiance, expressed in terms of perturbations in the aerosol optical depth, on the determination of surface reflectances from satellite sensor data. The study encompassed both clear and hazy atmospheric conditions, wavelengths in the green (0.550 μm) and the near-infrared (0.870 μm), three solar zenith angles, and five viewing geometries.

Analysis Methodology and Results for the Junge Parameter Sensitivity Study

Extensive observational monitoring carried out North of Ottawa, Canada has shown that atmospheric optical conditions in that area fall into two distinct cases, corresponding to clear and hazy sky conditions.[6] The mean aerosol optical depth at 0.550 μm for the clear case was 0.0553 with a standard deviation of 0.0167, whereas for the hazy case it was 0.331 (corresponding to a meteorological visibility of ~14 km) with a standard deviation of 0.192. When the spectral dependence of the aerosol optical depth is modeled as a power law, corresponding to a Junge size distribution, the Junge exponent is 3.55 for the clear case, with a standard deviation of 0.50, and it is 3.58 for the hazy case, with a standard deviation of 0.34. The two aerosol cases were treated separately in the sensitivity analyses undertaken in this study. For brevity, only results for the hazy case are emphasize, because of their greater interest.

We first generated reference results by running the Herman code (H-Code) at 0.550 μm for the full atmosphere (from sea level to satellite altitude) with the nominal input parameters listed in Table 1 (also see Fig. 1, step A). In particular, nadir viewing and a solar zenith angle of 45° were assumed. The aerosol optical depths δ_a and Junge parameters ν were taken to be the mean values from the aforementioned observational data set. Thus the nominal values are $\nu_0 = 3.55$ (case I) and $\nu_0 = 3.58$ (case II), and $\delta_{a0}(550) = 0.0553$ (case I) and $\delta_{a0}(550) = 0.331$ (case II). The nominal value for the complex index of refraction was taken to be $m_0 = 1.5 - 0.0075i$. H-Code output values for apparent radiance at the sensor and path radiance were recorded for use as reference values in the sensitivity analysis.

For a variety of surface reflectances between 0.005 and 1, and for the clear and hazy cases treated separately, the procedure for testing sensitivity to uncertainties in the Junge parameter ν was as follows. For a perturbed value of ν and constant m_0, the aerosol optical depth $\delta_a(550)$ was adjusted and the H-Code run until the reference path radiance was obtained (Fig. 1, step B). With the resulting value of $\delta_a(550)$, the predicted surface reflectance was then varied until the code yielded the reference apparent

Table 1. Input Conditions for the Herman Code Run for the Reference Case Used in the Initial Sensitivity Analysis[a]

Wavelength (μm)	0.550 (0.870)	
Solar zenith angle (deg)	45	
Solar azimuth angle (deg)	135	
Solar distance (A.U.)	1	
View angle	Nadir	
Terrain elevation	Sea level	
Aerosol size range (μm)	0.02–5.02	
Aerosol vertical distribution	Elterman[b]	
Aerosol refractive index	1.5–0.0075i	
Pressure (mb)	1013.25	
Rayleigh optical depth	0.0966 (0.01516)	
Ozone optical depth	0.0267 (0)	
Surface reflectances	Variable between 0.005 and 1	
	Clear	Hazy
Aerosol optical depth $\delta_a(550)$	0.0553 (0.0286)	0.331 (0.1639)
Junge parameter ν	3.55	3.58

[a]Standard values for the Rayleigh[7] and ozone[8,9] optical depth components were used. The values in parentheses refer to inputs used for code runs at 0.870 μm.

[b]Ref. 10.

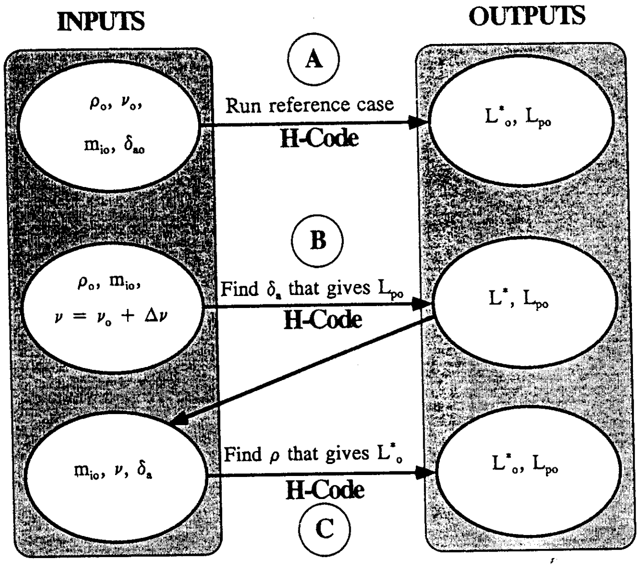

Fig. 1. Schematic representation of the Junge parameter sensitivity study.

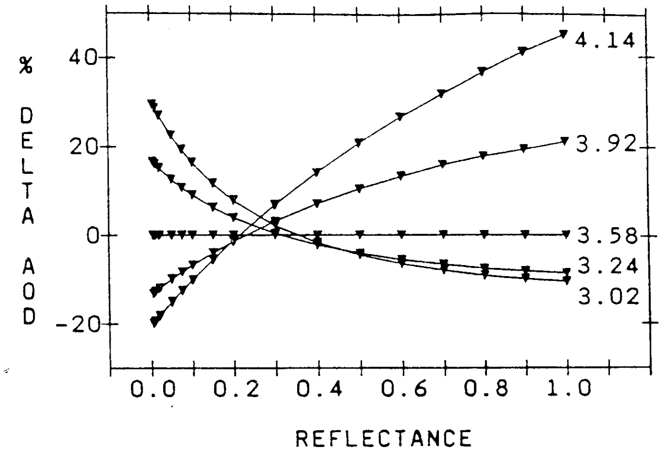

Fig. 2. $\delta_a(550)$ percent change (% DELTA AOD) required to recover the reference path radiance as a function of surface reflectance and the indicated Junge parameter cases (ranging 3.02–4.14), for the hazy atmospheric condition (case II) at 0.550 μm.

radiance at the sensor (Fig. 1, step C). This procedure was repeated for various ν values, and the error in predicted surface reflectance (compared with the reference input value) was monitored with respect to variations in ν. The ν values were chosen to be the nominal reference value ν_0 and four other values consisting of $\nu_0 \pm 1\sigma$ and $\nu_0 \pm 1.645\sigma$ (90% confidence interval), where the standard deviations σ were based on the observational data set. Extensions of the calculations to other illumination and viewing angles and to a different wavelength are described later in the paper.

Adjusting $\delta_a(550)$ to Obtain the Reference Path Radiance

As we mentioned in the previous paragraph, our first step in the procedure was to vary the aerosol optical depth $\delta_a(550)$ and run the H-Code until the reference path radiance L_{p0} was obtained. In practice, we accomplished this by running the code for a grid of $\delta_a(550)$ values, fitting the results with a second-order polynomial that described $\delta_a(550)$ as a function of path radiance, and then solving the polynomial at L_{p0}. Note that a separate computation was carried out for each surface reflectance case for each given value of ν used in the analysis.

The percent change in $\delta_a(550)$ required to recover L_{p0} is plotted as a function of surface reflectance in Fig. 2, where the different curves are for the different Junge parameter cases. The biggest adjustments to $\delta_a(550)$ occur at low and high reflectances. The plot also emphasizes the zone of insensitivity around surface reflectance values of 0.2, where uncertainty in the ν parameter (i.e., the slope of the aerosol size distribution) has little effect on the relationship between path radiance and aerosol optical depth.

Adjusting Surface Reflectance to Obtain the Reference Apparent Radiance at the Sensor

Our next step in the procedure was to vary the input surface reflectance until the H-Code output the reference apparent radiance at the sensor, L_0^*. The adjusted value of $\delta_a(550)$ determined in the previous step was used as an input for the code runs. The approach used here was running the code for a grid of surface reflectance values (bracketing the reflectance value under consideration), fitting the results with a second-order polynomial that described surface reflectance as a function of apparent radiance at the sensor, and then simply solving the polynomial at L_0^*. As before, a separate computation was carried out for each surface reflectance case for each given value of ν used in the analysis.

Analogously to Fig. 2, the percent change in surface reflectance required to recover L_0^* is plotted as a function of surface reflectance (Fig. 3). The results given in Fig. 3 pertain to the hazy atmospheric condition (case II). Case I results for the clear atmospheric state (not shown) indicate that errors in

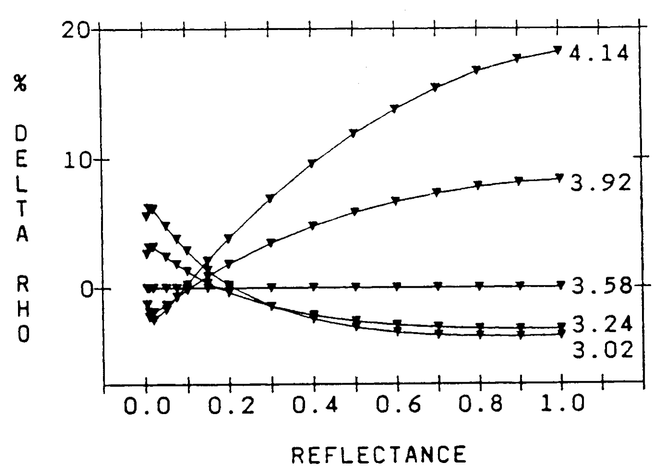

Fig. 3. Percent change in surface reflectance (% DELTA RHO) required to recover the reference apparent radiance as a function of surface reflectance and the indicated Junge parameter cases (ranging 3.02–4.14), for the hazy atmospheric condition (case II) at 0.550 μm.

predicted surface reflectance are approximately an order of magnitude less than those found for case II.

Discussion of Results

In the case of the clear atmosphere (not shown), errors in predicting surface reflectance are well within 5% (i.e., $|\Delta\rho/\rho| < 0.05$, where ρ is the surface reflectance), regardless of the magnitude of the surface reflectance. Thus the value of the Junge parameter ν does not have to be well known. In the case of a hazy atmosphere (Fig. 3), the retrieval of higher reflectance values is affected more greatly by uncertainties in ν. A different representation of the results for the hazy case is given in Fig. 4, which portrays accuracy requirements on ν for a 5% uncertainty in predicted surface reflectance. This figure indicates that it is only for relatively bright targets (i.e., $\rho > 0.4$) that ν has to be known to better than one standard deviation at 0.550 μm.

Analysis Methodology and Results for the Refractive Index Sensitivity Study

The approach for testing sensitivity to uncertainties in the imaginary part of the refractive index m_i parallelled the procedure used for the Junge parameter analysis at 0.550 μm (Fig. 1). For a given value of m_i, the aerosol optical depth $\delta_a(550)$ was varied and the H-code run until the reference path radiance L_{p0} was obtained. With the resulting value of $\delta_a(550)$, the input surface reflectance was than varied until the code yielded the reference apparent radiance at the sensor $L_0{}^*$. These steps were repeated for various m_i values, and the error in predicted surface reflectance (compared with the reference input value) was monitored with respect to variations in m_i. The m_i values were chosen to be the nominal reference value, $m_{i0} = 0.0075$, and four other values consisting of 0.0025, 0.0050, 0.0100, and 0.0125. A separate computation was carried out for each of the surface reflectance cases and for both the clear and hazy atmospheric states.

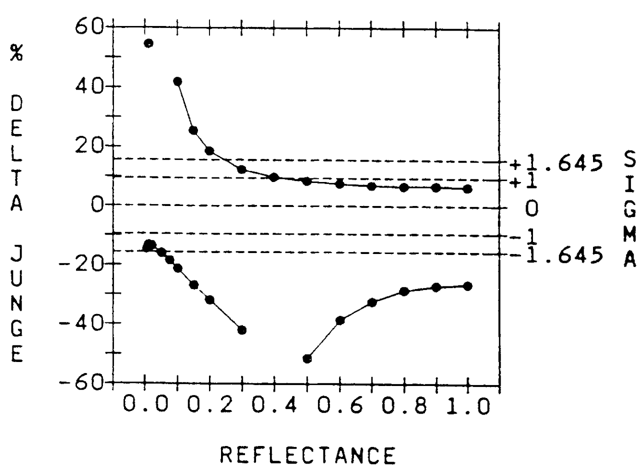

Fig. 4. Accuracy requirement on the Junge parameter (% DELTA JUNGE) for a ±5% error in predicted surface reflectance, for the hazy atmospheric state (case II) at 0.550 μm; SIGMA is the standard deviation (see text).

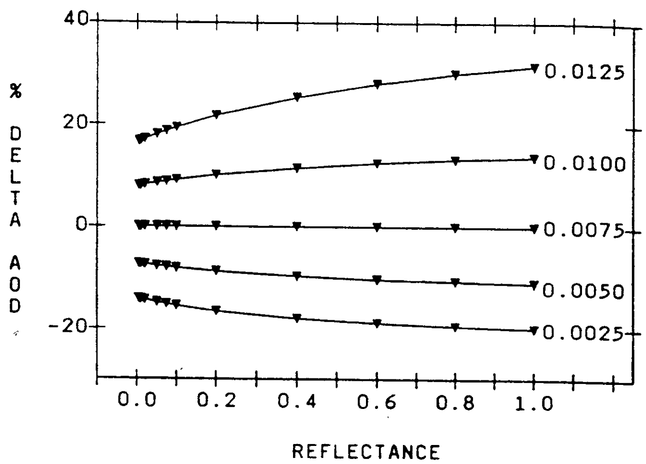

Fig. 5. $\delta_a(550)$ percent change (% DELTA AOD) required to recover the reference path radiance as a function of surface reflectance and the indicated values of the imaginary part of the refractive index (ranging 0.0025–0.0125), for the hazy atmospheric condition (case II) at 0.550 μm.

The percent change in $\delta_a(550)$ required to recover L_{p0} is plotted as a function of surface reflectance in Fig. 5, where the different curves are for the different refractive index cases. Unlike the Junge parameter results (Fig. 2), Fig. 5 shows that the adjustments to $\delta_a(550)$ depend on surface reflectance and refractive index in a more straightforward manner. There is no special range of surface reflectances for which there is a zone of insensitivity. In other words, unlike the situation for the Junge parameter study (Fig. 2), there are no surface reflectances for which uncertainty in the m_i parameter has little effect on the aerosol optical depth required to recover L_{p0}. Figure 5 is for the hazy atmospheric state; results for the clear atmospheric state (not shown) yield percent changes in $\delta_a(550)$ of approximately half of those obtained for the hazy case.

The percent change in surface reflectance required to recover $L_0{}^*$ is plotted as a function of surface reflectance in Fig. 6. This figure portrays the results of the refractive index sensitivity analysis at 0.550 μm for the hazy atmosphere condition (case II). Errors in predicting surface reflectance are generally within 10% (i.e., $|\Delta\rho/\rho| < 0.1$) and are within 5% for a reasonable range of m_i values (0.005 to 0.010), regardless of the magnitude of the surface reflectance. In the clear atmosphere case (not shown), errors in predicting surface reflectance are within 1%; therefore, the value of the imaginary part of the refractive index m_i does not have to be well known. A different representation of the results for the hazy case is given in Fig. 7, which illustrates accuracy requirements on m_i for a 5% uncertainty in predicted surface reflectance. This figure shows that m_i only has to be known to within 30–40% for any target reflectance value (at 0.550 μm).

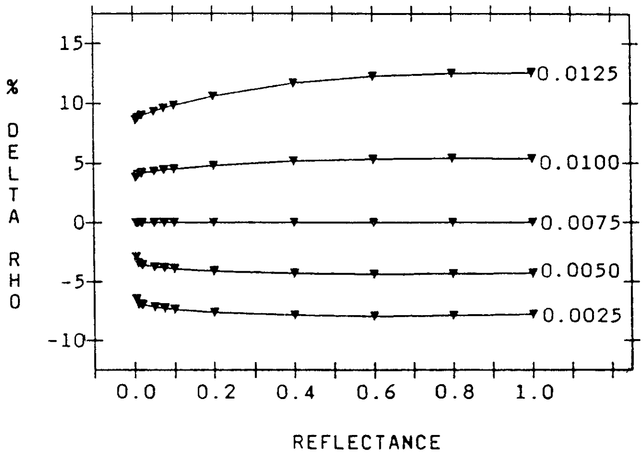

Fig. 6. Percent change in surface reflectance (% DELTA RHO) required to recover the reference apparent radiance as a function of surface reflectance and the indicated values of the imaginary part of the refractive index (ranging 0.0025–0.0125), for the hazy atmospheric condition (case II) at 0.55 μm.

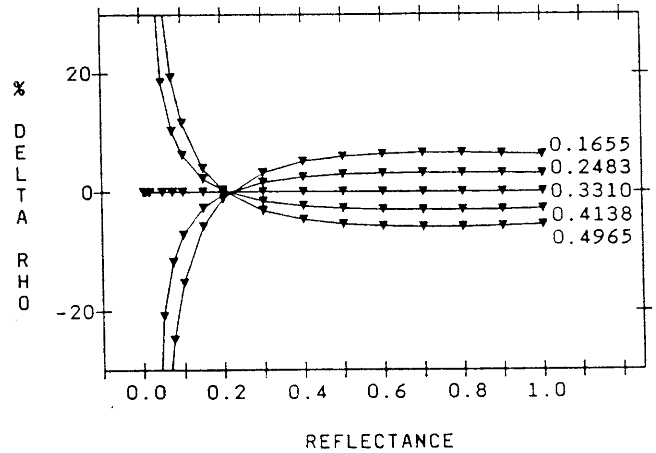

Fig. 8. Percent change in surface reflectance (% DELTA RHO) required to recover the reference apparent radiance at the sensor as a function of surface reflectance and the indicated aerosol optical depth values (ranging 0.1655–0.4965), for the hazy atmospheric condition (case II) at 0.550 μm.

Impact of Uncertainty in Aerosol Optical Depth Estimates

For both the Junge parameter and the refractive index sensitivity studies, it was assumed that there is no error in the path radiance estimate, which in practice is either estimated from the imagery itself or is derived from ground-based measurements of aerosol optical depth. Therefore, it was also of interest for us to examine the impact of errors in the estimated path radiance, expressed in terms of uncertainties in the aerosol optical depth, on the retrieval of surface reflectances. The same reference case was used (Table 1). With the ν_0 and m_{i0} values fixed, we varied the $\delta_a(550)$ values and ran the H-Code for each $\delta_a(550)$ case, adjusting the input surface reflectance until the reference apparent radiance, $L_0{}^*$, was obtained. Thus the error in predicted surface reflectance was monitored with respect to uncertainties in $\delta_a(550)$. The $\delta_a(550)$ values were chosen to be the nominal reference values of 0.0553 (case I) and 0.331 (case II) and six other values perturbed by ±10%, ±25%, and ±50% from the reference value. A separate computation was carried out for each surface reflectance case and for both the clear and hazy atmospheric states.

Figures 8 and 9 show the results for the hazy case at 0.550 μm. The largest errors in predicted surface reflectance are for the lowest reflectance of 0.005, where the relative errors can be several hundred percent, although the absolute errors are only of the order of 0.01 or 0.02 in reflectance. Figure 9 shows that it is only for targets with reflectances of less than 0.1 that $\delta_a(550)$ has to be known to better than 25% if a 5% uncertainty in predicted surface reflectance is required. Under hazy atmospheric conditions, there is little tolerance for error in aerosol optical depth if one is interested in retrieving the reflectance of dark

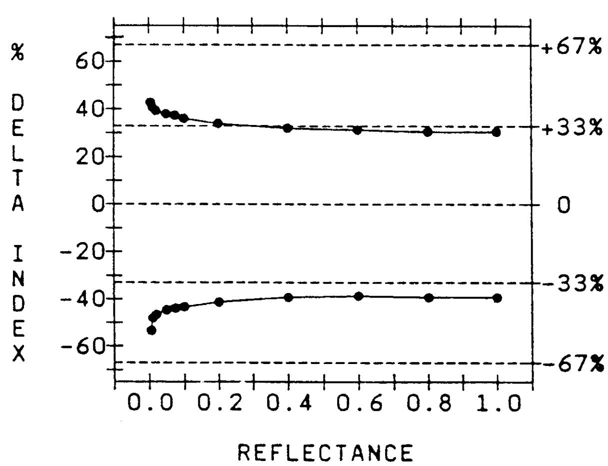

Fig. 7. Accuracy requirement on the imaginary part of the refractive index (% DELTA INDEX) for a ±5% error in predicted surface reflectance, for the hazy atmospheric state (case II) at 0.550 μm.

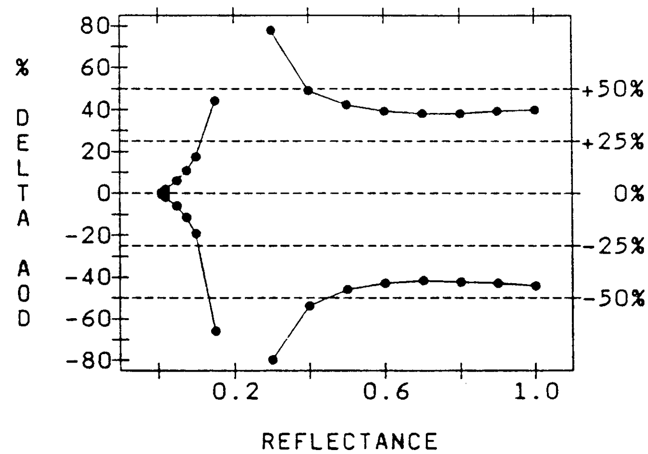

Fig. 9. Accuracy requirement on the aerosol optical depth (% DELTA AOD) for a ±5% error in predicted surface reflectance, for the hazy atmospheric state (case II) at 0.550 μm.

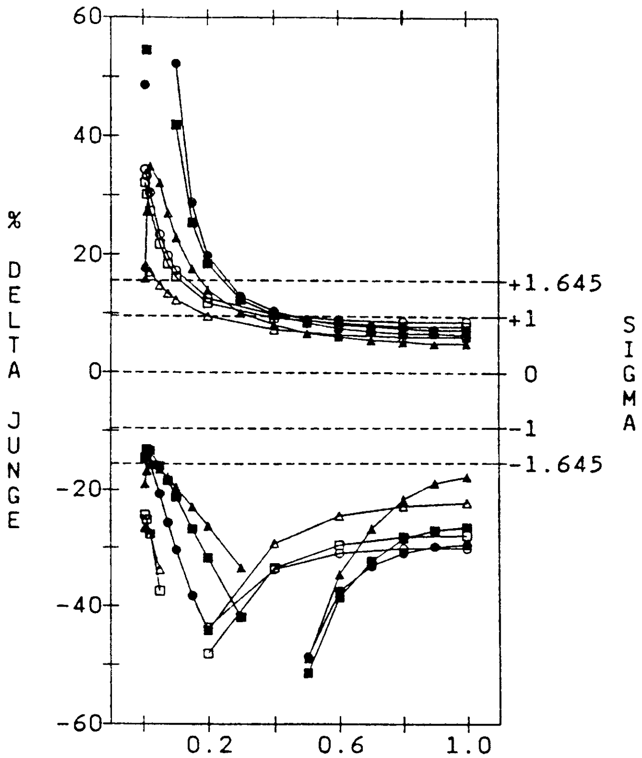

Fig. 10. Accuracy requirement on the Junge parameter (% DELTA JUNGE) at solar zenith angles of 25° (circles), 45° (squares), and 65° (triangles), for the hazy atmospheric state (case II) at 0.550 μm (filled symbols) and 0.870 μm (empty symbols).

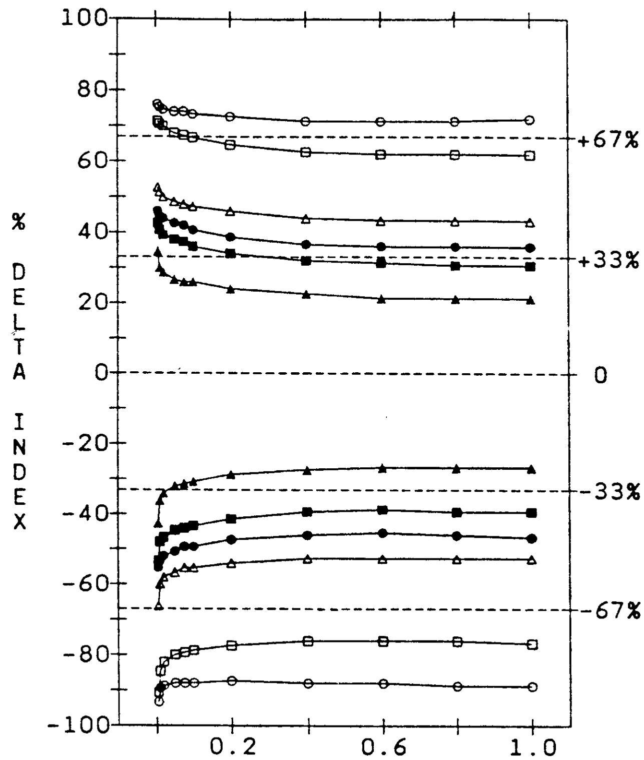

Fig. 11. Accuracy requirement on the imaginary part of the refractive index (% DELTA INDEX) at solar zenith angles of 25°, 45°, and 65°, for the hazy atmospheric state (case II) at 0.550 and 0.870 μm. The symbols are defined as in the caption for Fig. 10.

targets to within 5% relative uncertainty. In the clear atmosphere case (not shown), errors in predicting surface reflectance are within 5%, except for reflectances below 0.05 where errors can range 5–70%.

Extensions to Other Geometries and Another Wavelength

The sensitivity analyses described in the previous sections pertain to a wavelength of 0.550 μm, a solar zenith angle of 45°, and a nadir viewing angle. The entire sequence for the hazy atmospheric state was repeated for solar zenith angles of 25° and 65° (nadir viewing), as well as for off-nadir viewing angles of 25° and 55° in both forward scattering (0° relative azimuth) and backscatter directions (180° relative azimuth) for a solar zenith angle of 45°. Finally, the full study for the hazy atmospheric state, including all geometries, was redone for a wavelength of 0.870 μm, a near-infrared wavelength in which aerosol scattering is predominant compared with gas absorption in the atmosphere.

The analysis involved point calculations such that for non-Lambertian surfaces the variable geometry results were still valid even though a Lambertian surface was assumed. The results for a non-Lambertian surface as a function of illumination and viewing geometry would simply follow a modified trajectory through the same sensitivity analysis solution space. The radiative transfer runs also assumed that the surround reflectance was identical to that of the target. For a non-Lambertian surface, the effective angular integration of the surrounding surface reflectance can yield a lower or higher surround reflectance compared with that of the target. This usually has a second-order or lesser effect on radiative transfer computations and should not affect the general validity of the sensitivity analysis results.

The results presented in the following sections are portrayed as above in terms of accuracy requirements on the Junge parameter ν, the imaginary part of the refractive index m_i, and the aerosol optical depth δ_a for a 5% uncertainty in predicted surface reflectance in each instance.

Results for Other Solar Zenith Angles

The effect of increasing the solar zenith angle (nadir viewing) is to make the accuracy requirements on all three parameters, ν, m_i, and δ_a, more stringent for all values of surface reflectance. As shown in Fig. 10, the Junge parameter at 0.550 μm has to be known to better than one standard deviation for retrieval of surface reflectances ρ above 0.3 to a relative uncertainty of 5%, if the solar zenith angle is 65°, compared with $\rho > 0.4$ for 25° or 45°. From Fig. 11 it is evident that the imaginary part of the refractive index at 0.550 μm only has to be known to within 25% at best for any target reflectance if the solar zenith angle is 65°. Finally, as the solar zenith angle is increased to

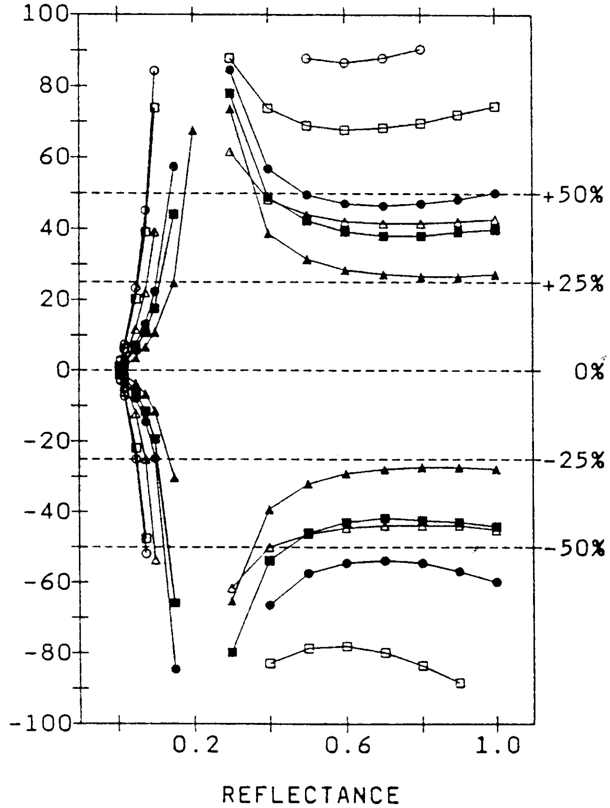

Fig. 12. Accuracy requirement on the aerosol optical depth (% DELTA AOD) at solar zenith angles of 25°, 45°, and 65°, for the hazy atmospheric state (case II) at 0.550 μm and 0.870 μm. The symbols are defined as in the caption for Fig. 10.

65°, it is only for darker targets with $\rho < 0.1$ that $\delta_a(550)$ has to be known to better than 20% (Fig. 12) if a 5% uncertainty in predicted surface reflectance is required.

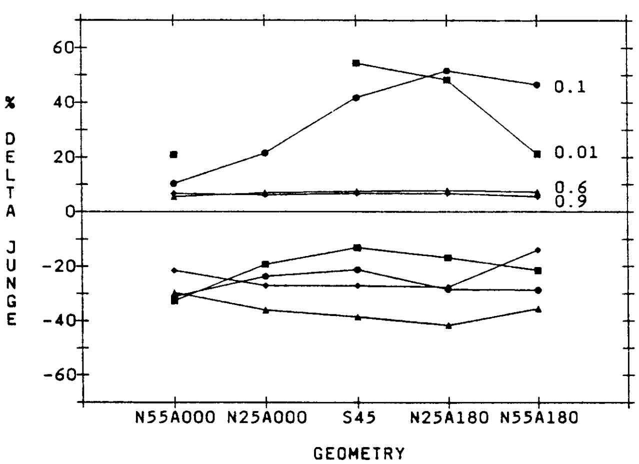

Fig. 13. Accuracy requirement on the Junge parameter (% DELTA JUNGE) as a function of view-angle geometry and the indicated surface reflectance cases (ranging 0.01–0.9), for the hazy atmospheric state (case II) at 0.550 μm and for a solar zenith angle of 45° (S45). The view-angle geometries are noted on the horizontal axis, where nadir is denoted as S45 and the off-nadir cases are 25° and 55° (N25 and N55) in the forward scattering (relative azimuth A000) and backscatter (relative azimuth A180) directions.

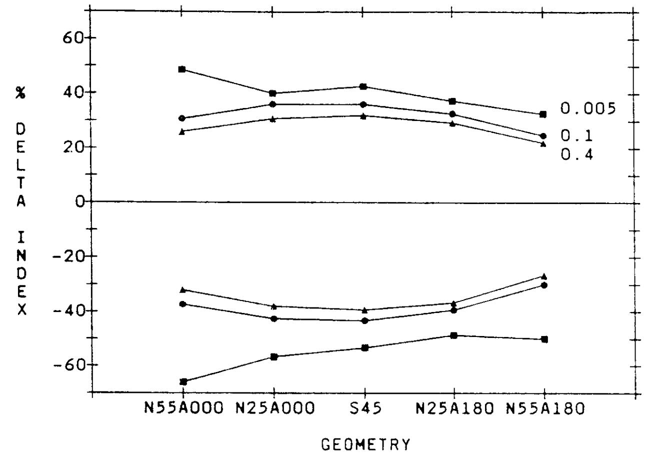

Fig. 14. Accuracy requirement on the imaginary part of the refractive index (% DELTA INDEX) as a function of view-angle geometry and the configurations outlined in Fig. 13, for the indicated surface reflectance cases (0.005, 0.1, 0.4).

Near-Infrared Results for Variable Solar Zenith Angle

As for results at 0.550 μm, the effect of increasing the solar zenith angle at 0.870 μm is to make the accuracy requirements on all three aerosol parameters more stringent for any reflectance. The dependence of the Junge parameter accuracy requirement on solar zenith angle is less at 0.870 μm than it is at 0.550 μm, but it is slightly more stringent overall (Fig. 10). This stringent behavior shifts in reflectance space such that the maximum tolerance in accuracy requirement occurs at lower reflectances at 0.870 μm than at 0.550 μm. In contrast, in the case of the imaginary part of the refractive index, the dependence of the accuracy requirement on solar zenith angle is greater at 0.870 μm than it is at 0.550 μm, but it is less stringent for all reflectances and all Sun angle cases examined (Fig. 11). The latter situation is also true of the accuracy requirement on the aerosol optical depth at 0.870 μm (Fig. 12).

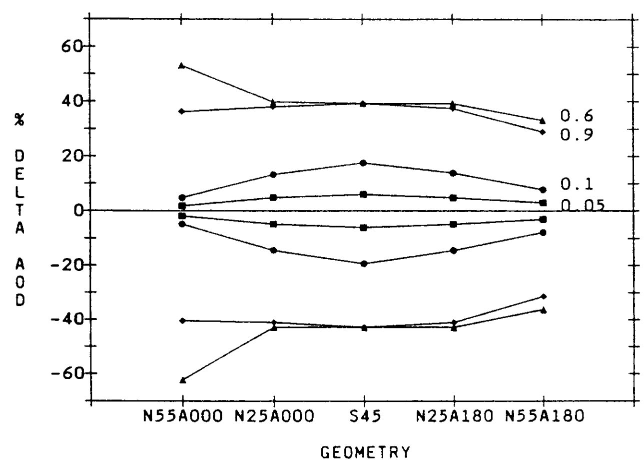

Fig. 15. Accuracy requirement on the aerosol optical depth (% DELTA AOD) as a function of view-angle geometry and the configurations outlined in Fig. 13, for the indicated surface reflectance cases (ranging 0.05–0.9).

Results for Off-Nadir View Angles

In general, the effect of off-nadir viewing is to make the accuracy requirements on all three parameters, ν, m_i, and δ_a, more stringent for almost all values of surface reflectance, at both the visible and the near-infrared wavelengths. The cases examined were for the hazy atmospheric state with off-nadir viewing angles of 25° and 55° in both forward scattering (0° relative azimuth) and backscatter directions (180° relative azimuth) for a solar zenith angle of 45°. Figures 13–15 illustrate the results at 0.550 μm for selected values of surface reflectance. Asymmetries between forward scattering and backscattering behaviors occur in only a few cases corresponding to low surface reflectances. The results at 0.870 μm (not shown) bear the same relationship to those at 0.550 μm, as did the results for variable solar zenith angle. In other words, the dependence of the ν accuracy requirement on view angle geometry is less at 0.870 μm but slightly more stringent overall, whereas in the case of m_i and δ_a the dependence of the accuracy requirement on view angle is greater at 0.870 μm but less stringent overall.

Concluding Remarks

We carried out computations using the Herman radiative transfer code to investigate the sensitivity of surface reflectances derived from satellite sensor data to uncertainties in aerosol optical depth properties. Accuracy requirements were determined for each of the aerosol characteristics investigated, based on a 5% relative uncertainty in retrieved surface reflectance.

Results were first obtained at 0.550 μm for nadir viewing and a solar zenith angle of 45°. The Junge parameter sensitivity analysis indicates that it is only for relatively bright targets ($\rho \geq 0.4$) and hazy atmospheric conditions that the Junge parameter has to be known to better than 10%. The refractive index sensitivity study at 0.550 μm indicates that, even for hazy atmospheric conditions, the imaginary part of the refractive index only has to be known to within 30–40% for any target reflectance. Under hazy atmospheric conditions, it is only for reflectances less than 0.1 that aerosol optical depth at 0.550 μm has to be known to better than 25% if a 5% uncertainty in predicted surface reflectance is required. However, there is little tolerance for error in aerosol optical depth when one is retrieving reflectances for dark targets ($\rho < 0.05$), in terms of relative uncertainty. Fortunately, the *absolute* uncertainty in reflectance for darker targets is still small and the accuracy requirements on aerosol optical depth will be less stringent in practice than indicated here.

The effect of increasing the solar zenith angle is to make the accuracy requirements on all three aerosol parameters more stringent for all values of surface reflectance, at both the visible and the near-infrared wavelengths. Results in the infrared (at 0.870 μm) as compared with those in the visible indicate that radiative transfer computations are generally more sensitive to Junge parameter variations and less sensitive to variations in the refractive index and the aerosol optical depth. The effect of off-nadir viewing is to make the accuracy requirements on all three aerosol parameters more stringent compared with nadir for almost all surface reflectances. Nevertheless, accuracy requirements are less sensitive to viewing geometry than they are to solar zenith angle.

The authors thank B. M. Herman for the use of his radiative transfer code, one of the anonymous reviewers for constructive comments, and A. Kalil for word processing of the manuscript.

References

1. F. J. Ahern, D. G. Goodenough, S. C. Jain, V. R. Rao, and G. Rochon, "Use of clear lakes as standard reflectors for atmospheric measurements," in *Proceedings of the Eleventh International Symposium on Remote Sensing of Environment* (Environmental Research Institute of Michigan, Ann Arbor, Mich., 1977), pp. 711–755.
2. M. S. Moran, R. D. Jackson, P. N. Slater, and P. M. Teillet, "Evaluation of simplified procedures for retrieval of land surface reflectance factors from satellite sensor output," Remote Sensing Environ. **41,** 169–184 (1992).
3. B. M. Herman and S. R. Browning, "The effect of aerosols on the Earth-atmosphere albedo," J. Atmos. Sci. **32,** 158–165 (1975).
4. C. E. Junge, *Air Chemistry and Radioactivity* (Academic, New York, 1963).
5. E. J. McCartney, *Optics of the Atmosphere: Scattering by Molecules and Particles* (Wiley, New York, 1976).
6. F. J. Ahern, R. P. Gauthier, P. M. Teillet, J. Sirois, G. Fedosejevs, and D. Lorente, "An investigation of continental aerosols with high spectral resolution solar extinction measurements," Appl. Opt. **30,** 5276–5287 (1991).
7. P. M. Teillet, "Rayleigh optical depth comparisons from various sources," Appl. Opt. **29,** 1897–1900 (1990).
8. D. Tanré, C. Deroo, P. Duhaut, M. Herman, J. J. Morcrette, J. Perbos, and P. Y. Deschamps, *Simulation of the Satellite Signal in the Solar Spectrum,* (Laboratoire d'Optique Atmosphérique, Université des Sciences et Technique de Lille, Villeneuve d'Ascq Cédex, France, 1986).
9. D. Tanré, C. Deroo, P. Duhaut, M. Herman, J. J. Morcrette, J. Perbos, and P. Y. Deschamps, "Description of a computer code to simulate the satellite signal in the solar spectrum: the 5S Code," Int. J. Remote Sensing **11,** 659–668 (1990).
10. L. Elterman, "UV, visible, and IR attenuation for altitudes up to 50 km," Environ. Res. Paper 285, AFCRL-68-0153 (U.S. Air Force Cambridge Research Laboratories, Hanscom Field, Bedford, Mass. 1968).