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Assessment of operational techniques for estimating visible spectrum contrast transmittance

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Abstract

Approximate solutions appropriate for real time calculations of directional path radiance and atmospheric contrast transmittance were developed and tested using an extensive data base gathered with a specially instrumented aircraft. The high-resolution, simultaneous optical and meteorological measurements were made in a broad range of environmental conditions and diverse geographical areas in the United States and western Europe. Modelling techniques based upon these data yield computationally fast and consistent results of reasonable accuracy. The effects of the natural variations in environmental physical parameters upon the calculations of spectral contrast transmittance are examined through systematic application of the modelling techniques. Comparative analyses are made of the changes in the visible spectrum contrast transmittance associated with typical changes in some of the relevant parameters such as the depth and density of the low-level haze layer, aerosol absorption, surface spectral reflectance, solar zenith angle and viewing path.

Introduction

The degradation of visible image contrast along a viewing path of increasing length is governed by (1) the attenuation of the inherent background and object radiances by air molecule and aerosol particle scattering and absorption, and (2) the generation of path radiance by molecular and aerosol scattering of ambient light into the path of sight. Direct measurements of radiance and aerosol concentration profiles for selected path segments cannot be made simply and inexpensively. Thus, operational estimates of contrast transmittance must be derived from model calculations that are based upon estimated variables, including the distribution of aerosol particles and their directional scattering and absorption properties. In this paper, we present the results of a systematic series of calculations designed to help identify the relative effects of the changes or uncertainties in relevant physical parameters upon the contrast transmittance of hazy, cloud free paths of sight.

Model for the calculation of contrast transmittance

The equation for apparent spectral radiance of the background b at altitude z and range r in the direction defined by zenith angle θ and azimuth angle ϕ is[1]:

$$ {}_bL_r(z,\theta,\phi) = T_r(z,\theta)\ {}_bL_o(z_t,\theta,\phi) + L_r^*(z,\theta,\phi) \qquad (1)$$

where ${}_bL_o$ is the inherent background radiance at target altitude z_t, T_r is path transmittance, and L_r^* is the spectral path radiance generated by the scattering of light reaching the path from all directions.

The spectral contrast transmittance is given[1] directly by the product of ratio of the inherent and apparent (${}_bL_r$) background radiances and the path transmittance as follows,

$$ C_r(z,\theta,\phi)/C_o(z_t,\theta,\phi) = T_r(z,\theta)\,{}_bL_o(z_t,\theta,\phi)/{}_bL_r(z,\theta,\phi) \qquad (2)$$

where $C_r = ({}_tL_r - {}_bL_r)/{}_bL_r$ is the apparent target contrast at path length r and $C_o(z_t,\theta,\phi) = ({}_tL_o - {}_bL_o)/{}_bL_o$ is the inherent target contrast at altitude z_t.

A computationally fast technique for the calculation of atmospheric path radiance and contrast transmittance was developed[2,3] through analysis of an extensive series of optical/meteorological measurements gathered by the Visibility Laboratory with an instrumented aircraft deployed in the United States and Europe. Model input parameters are the number of atmospheric layers, the average optical scattering ratio and single scattering albedo for each layer, solar zenith angle, representative wavelength, extra-terrestrial solar irradiance and surface reflectance. The computer code calculates the path radiance and contrast transmittance for any selected slant path.

Modelling approximations include the representation of the vertical profile of total volume scattering coefficient, $s(z,\lambda)$ by the profile of optical scattering ratio, $Q(z,\lambda) = s(z,\lambda)/s_R(z,\lambda)$ where s_R is the Rayleigh scattering coefficient, thus normalizing with respect to wavelength and pressure altitude. Under conditions of complete mixing within a given atmospheric layer, $Q(z,\lambda)$ would be constant in the layer. The aircraft measurements reveal large variability in $Q(z)$ depending upon the aerosol particle source strength and the nature of the convective and turbulent mixing processes. The model computer code will accept specification of as many layers as warranted by available observations. However, a prominent feature of most aircraft measured profiles[4] in the daytime, following the dispersion of surface ground based temperature inversions, is the strong tendency for good mixing with constant $Q(z)$ in the primary haze layer and again in the overlying troposphere. So that a simple 2-layer troposphere model assuming a constant $Q(z)$ in each layer provides a good first approximation of the scattering ratio profile on a majority of sunny days over inland areas.

Another special element of the model calculations involves the specification of the single scattering phase function for each layer. To the extent that the detailed information about the phase function is known for a given layer, it can be incorporated directly into the model determinations. But in the absence of such detailed information, an approximation for the phase function is used that was developed and tested using the experimental data base. The phase functions are represented by two-term Henyey-Greenstein functions (see Kattawar[5], 1975), whose coefficients in turn are approximated by continuous functions[3] of the Mie scattering ratio, $Q(z)-1$, for each layer. The functions are bounded by the theoretical Rayleigh phase function for a clear atmosphere and a phase function representative of clouds or fog for very large $Q(z)$.

The series of airborne measurements served to validate individual model components as well as to test the overall model performance characteristics. Shown for example in Fig. 1 are profiles of total volume scattering coefficient measured near Meppen, Germany for three spectral bands: 2 - a narrow band blue filter centered near 475 nm, 3 - a narrow band red filter centered near 660 nm, and 4 - a broad band photopic filter centered near 550 nm. The relatively abrupt transition in scattering coefficient between the primary haze layer and the relatively clear air aloft that is evident in all 3 profiles is a typical feature of the daytime soundings measured over continental United States and Europe.

Calculations of the sky and terrain radiance distributions based upon the measured scattering coefficient profile for this flight are shown in Figs. 2 and 3 in comparison with the radiance distributions measured by the instrumented aircraft. The agreement shown between calculated and observed radiance values is representative in general of model performance. This midday flight was made under conditions of isolated patches of middle clouds and scattered thin cirrus. Moderate haze extended to 1.3 km and the surface visibility was near 15 km. The solar zenith angle averaged about 44 degrees. The $\theta > 90^\circ$ segments of the observed radiance distribution looking downward from an altitude of 200m, shown in Fig. 2, reflect significant fluctuations that are caused by changes in the inherent reflectance of the underlying surface which varied from dark woods to open fields. As shown in Fig. 3, the influence of the surface reflectance variations on the radiance is greatly smoothed by the effects of the intervening atmosphere as measured from an altitude of 6 km by the scanning radiometer, which has a 5-degree field of view. The measured directional radiance values at 6 km for viewing angles near the sun were subject to significant stray light error and are not shown in the comparison. A prominent characteristic of the radiance distribution at 6 km is the bright horizon sky radiance which in this case had equivalent brightness in the upsun ($\phi = 0^\circ$) and downsun ($\phi = 180^\circ$) azimuth directions.

Sensitivity of spectral contrast transmittance to selected changes in physical parameters

A systematic series of model calculations were made to illustrate the effects of typical variations in physical parameters upon the slant path transmittance and the corresponding range of object detection. For this purpose, a two-layer atmosphere was assumed, consisting of a primary haze layer of varying optical depth and absorption, and an overlying upper troposphere-stratosphere layer of relatively clear air with a constant optical scattering ratio of 1.3 and a single scattering albedo of 0.97. The trial calculations were carried out for an assumed wavelength of 550 nm. The responses in contrast transmittance to parameter changes would be similar for other visible wavelengths but would vary systematically for the same aerosol loading in the haze layer due primarily to the wavelength dependence of both the total optical depth and the single scattering phase function.

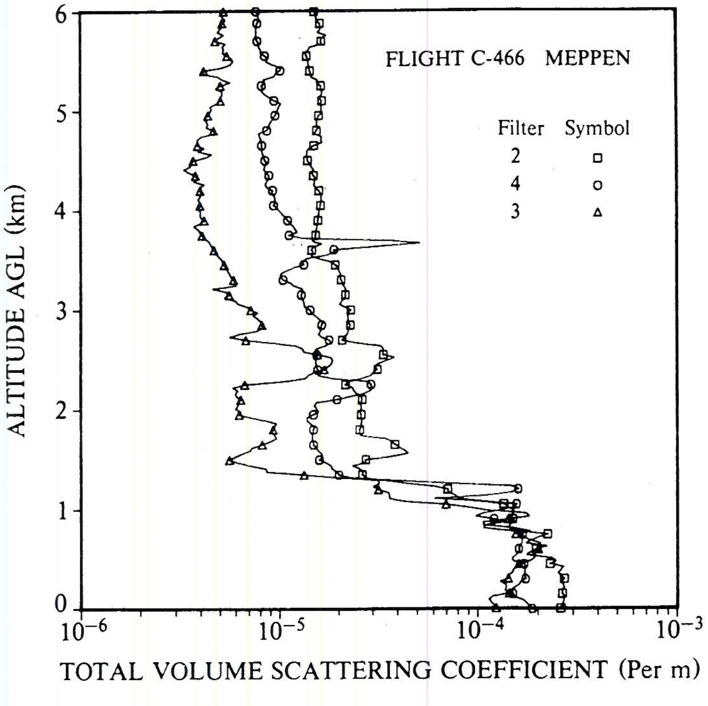

Figure 1. Measured profiles of total volume scattering coefficient, where 2 is the narrow band blue filter (475 nm), 3 is the narrow band red (660 nm), and 4 is the broad band photopic (550 nm). Aircraft measurements were made over Meppen, Germany, 15 August 1978.

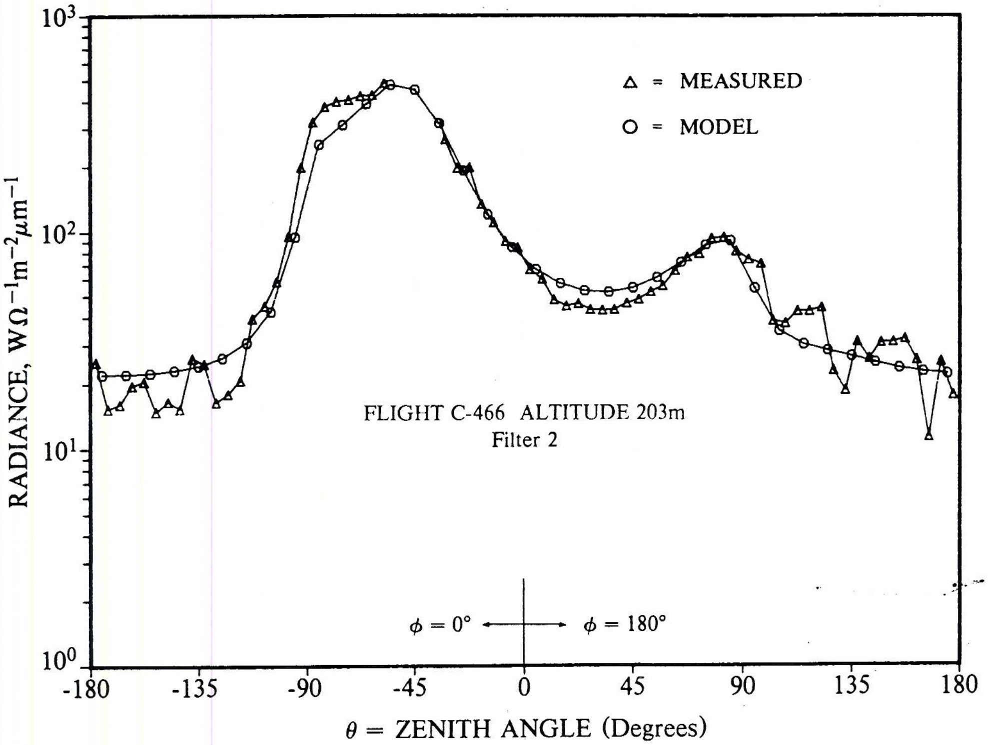

Figure 2. Comparison of measured and calculated sky and terrain radiance distributions at 200 m.

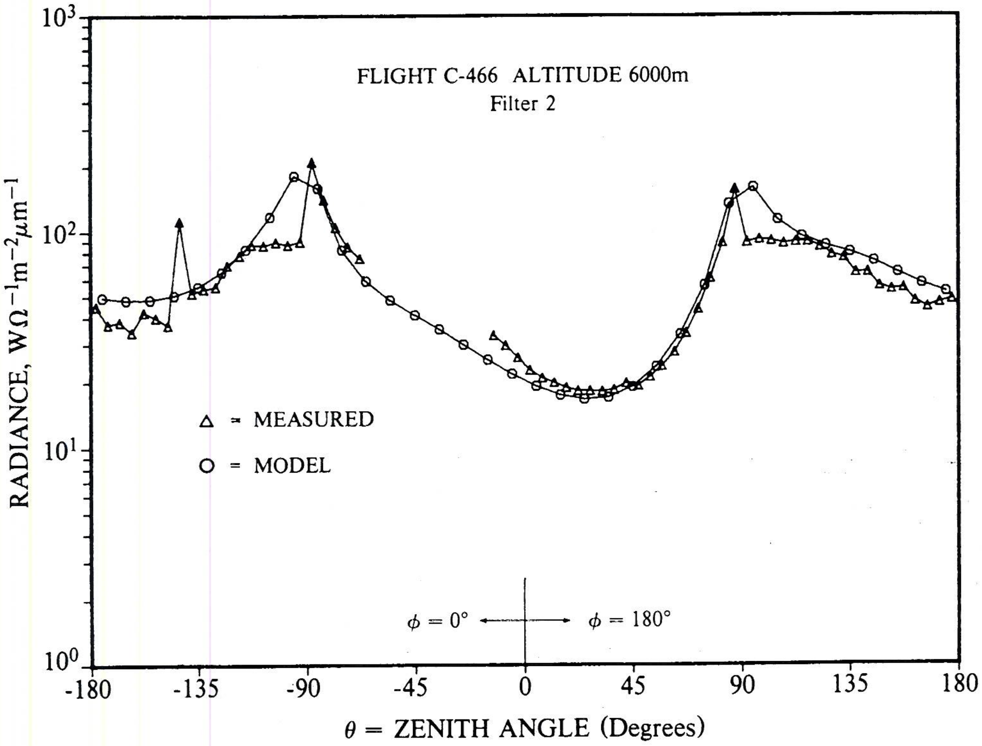

Figure 3. Comparison of measured and calculated sky and terrain radiance distributions at 6000 m.

Results are shown for a range of haze layer depth, aerosol concentration and absorption, and for selected values of surface reflectance and solar zenith angle. The parameters are varied individually while holding each of the other variables constant and equal to their values for an assumed reference atmosphere as follows; solar zenith angle = 60°, surface reflectance = 0.10, single scattering albedo = 0.97, and optical scattering ratio in the haze layer = 13 which corresponds to a horizontal surface equivalent visibility of about 20 km assuming a threshold contrast of 5 percent. The vertical extent of the haze layer for the reference atmosphere was assumed to be 3 km except that a few comparative calculations were made also for an assumed haze layer top at 500m altitude while holding the overall optical thickness the same as for the 3 km case.

Object at the earth's surface and the sensor at 6 km.

From Eq. (2), we observe that the contrast transmittance, $T_c = C_r/C_o$, of a viewing path extending downward from the sensor to an object at the earth's surface is given by the product of the path beam transmittance, T_r, and ratio of the inherent background radiance of the surrounding surface and the apparent background radiance as measured at the sensor, ${}_bL_o/{}_bL_r$. It follows that the contrast transmittance decreases with an increase in the extinction optical thickness of the viewing path in concert with both a decrease in $T_r(z,\theta)$ and an increase in the path radiance contribution, L_r^*, to ${}_bL_r$ (see Eq. 1). The responses of T_c, for the case with the object at the surface and the sensor at 6 km, to changes in optical depth, τ, and to changes in the cosine of the zenith viewing angle are shown in Fig. 4. Since we have assumed that the surface reflectance obeys Lambert's law, the asymmetry of T_c in the upsun and downsun viewing directions is small and is caused only by the directional changes in the direct solar backscattering component of the path radiance, L_r^*. Except for viewing angles near the horizon, the calculated T_c from the surface to 6 km decreases more or less in direct proportion to the increase in slant path distance.

For diagnostic purposes let us define a target acquisition range (TAR) where the contrast transmittance reduces to 10 percent. Illustrated in Fig. 5 are the calculated changes in TAR that correspond to selected changes in the physical variables. Again we assume a target located at the earth's surface and a sensor altitude of 6 km. The calculations were made for an azimuth viewing angle of 180°. The calculated TAR for the reference atmosphere is 13.5 km. Comparing responses of the TAR to the departures of the individual parameters from their values given by the reference atmosphere, we note that a 25 percent increase in TAR is associated with about a 25 percent decrease in the optical thickness of the haze layer. On the other hand about a 50 percent increase in optical thickness is required for a 25 percent decrease in TAR. The dotted line shown in Fig. 5 for the relationship of TAR with optical thickness depicts the calculated TAR for an haze layer top at 0.5 km in lieu of the 3 km altitude assumed for the reference atmosphere. Notice that the TAR differs only by approximately 15 percent for a haze layer with the greatly reduced vertical extent but with increased extinction so as to yield the same optical thickness.

With regard to other parameters, the results show that changes in ln TAR are directly proportional to the changes in the cosine of the solar zenith angle. For example, in rough measure the change in solar zenith angle during a one-hour period in the midmorning or afternoon in middle latitudes will result in about a 25 percent change in TAR for the reference atmosphere. Notice also that a 25 percent decrease in TAR results from an increase in haze layer absorption from the small amount associated with clear remote atmospheres (single scattering albedo = 0.97) to the large amount corresponding to urban atmospheres (single scattering albedo = 0.63).

For objects viewed against a terrain background, the TAR has a significant direct dependence upon the surface reflectance. For example, the calculated TAR decreases by 25 percent as the surface reflectance changes from the value associated with a brown field (0.10) to a value representative of a grass field (0.06).

Object at 6 km and the sensor at ground level

Diagnostic model calculations of T_c and TAR for an object at 6 km when viewed against a sky background from the earth's surface are shown in Fig. 6 and 7. The reference atmosphere and selected changes to the reference atmosphere are the same as for the sensitivity analysis described in the preceding paragraphs. In contrast with downward paths of sight, the calculated contrast transmittance of upward paths have large asymmetry in the upsun and downsun directions because of the enhanced path radiance generated by the increased scattering of sunlight at forward scattering angles. As shown in Fig. 6, the calculated T_c reduces to less than 10 percent for an azimuth viewing direction directly upsun when the total optical depth is 0.5 or larger. In the downsun direction ($\phi = 180°$), T_c has only a modest variation with zenith viewing angle for angles less than about 70°.

A strong dependence of target acquisition range in the downsun direction upon the optical thickness of the haze layer is evident in the results shown in Fig. 7. A change in thickness of only 10 percent, holding other parameters of the reference atmosphere constant, results in about a 25 percent change in TAR. A marked sensitivity of the TAR to changes in solar zenith angle is also found. The observed decrease in TAR with an increase in solar altitude stems from the associated increase in the path radiance component of apparent background radiance. In comparison with the results shown in Fig. 5, the TAR for objects viewed against a sky background illustrated in Fig. 7 show significantly less response to changes in the single scattering albedo of the haze layer and changes in surface reflectance.

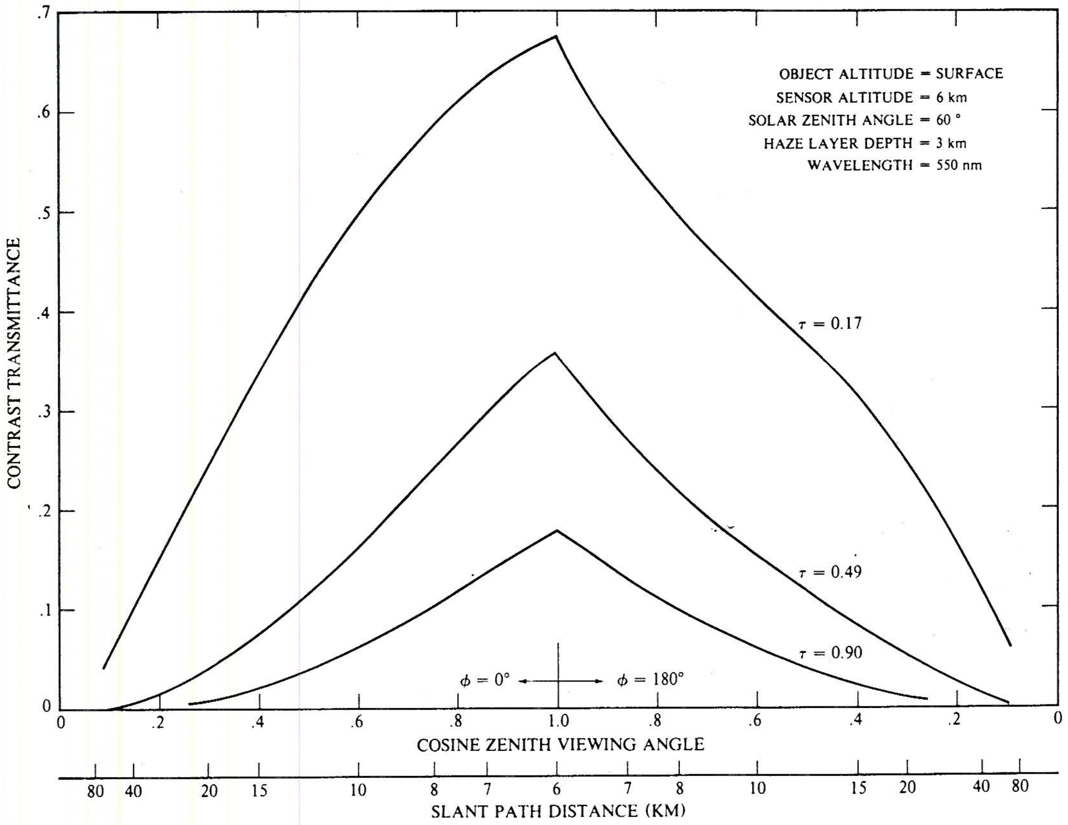

Figure 4. Diagnostic calculations of contrast transmittance as a function of zenith viewing angle for a target viewed against a terrain background. Values of τ refer to total atmosphere optical depth.

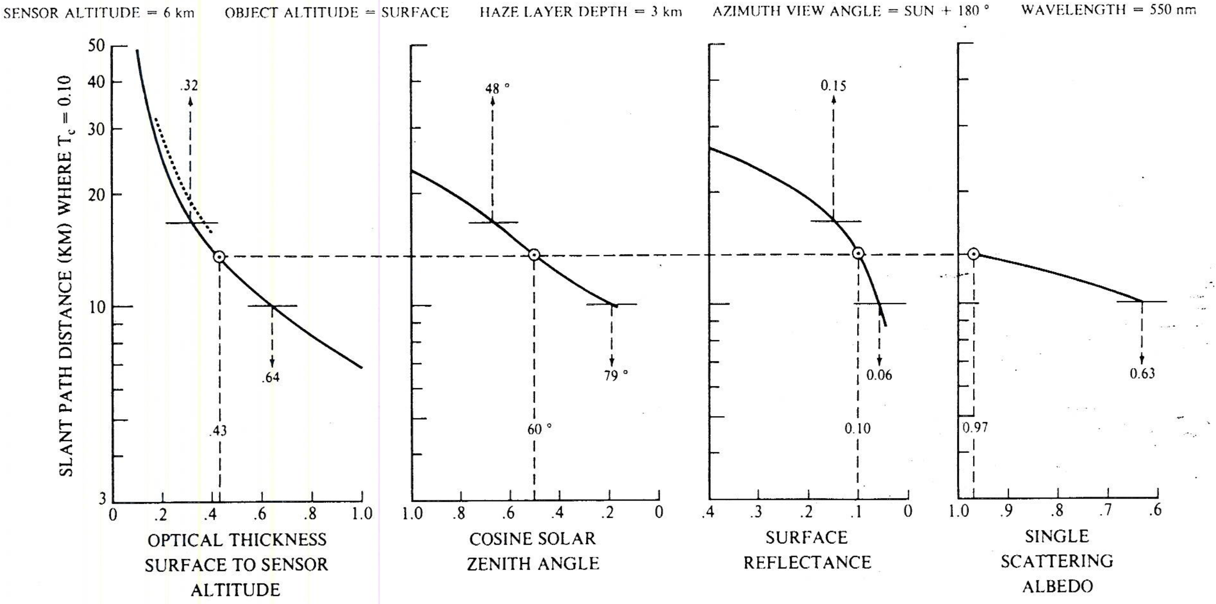

Figure 5. Variations in target acquisition range ($T_c = 0.10$) associated with departures of selected parameters from the assumed reference atmosphere values. The horizontal dashed line denotes parameter values for this reference atmosphere. The horizontal bars identify values of parameters corresponding to a change of ±25 percent from the slant path distance where $T_c = 0.10$ for the reference atmosphere, *i.e.* 13.5 ± 3.4 km.

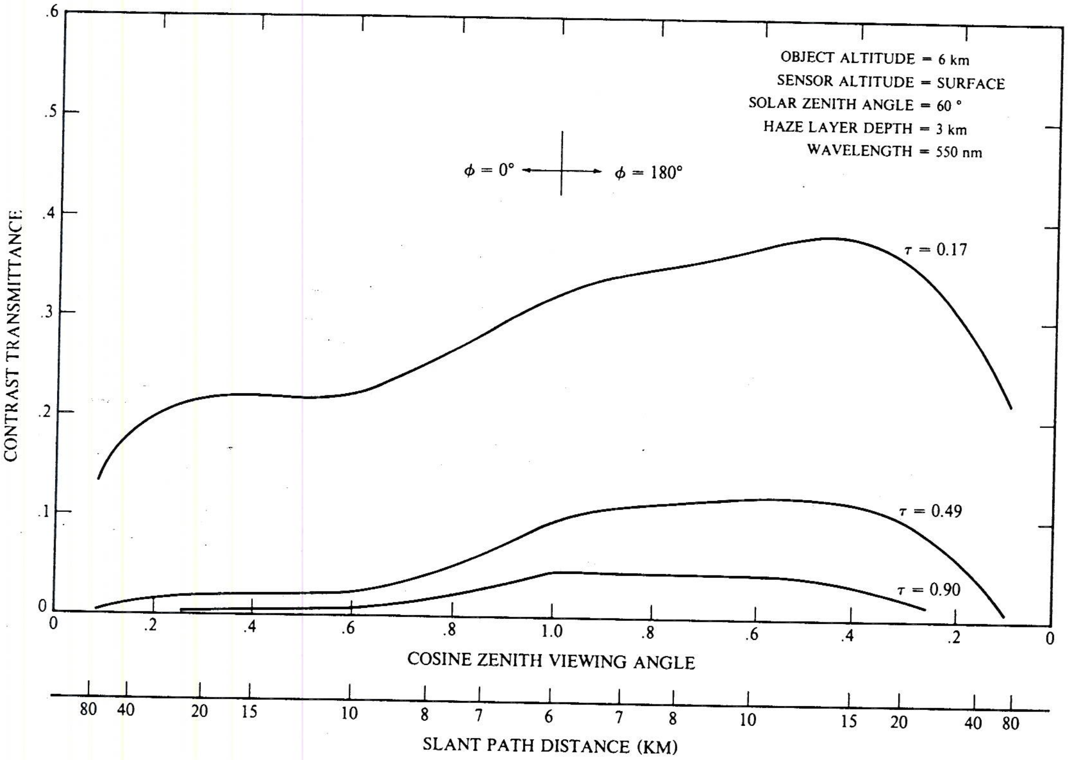

Figure 6. Same as figure 4 except for a target viewed against a sky background.

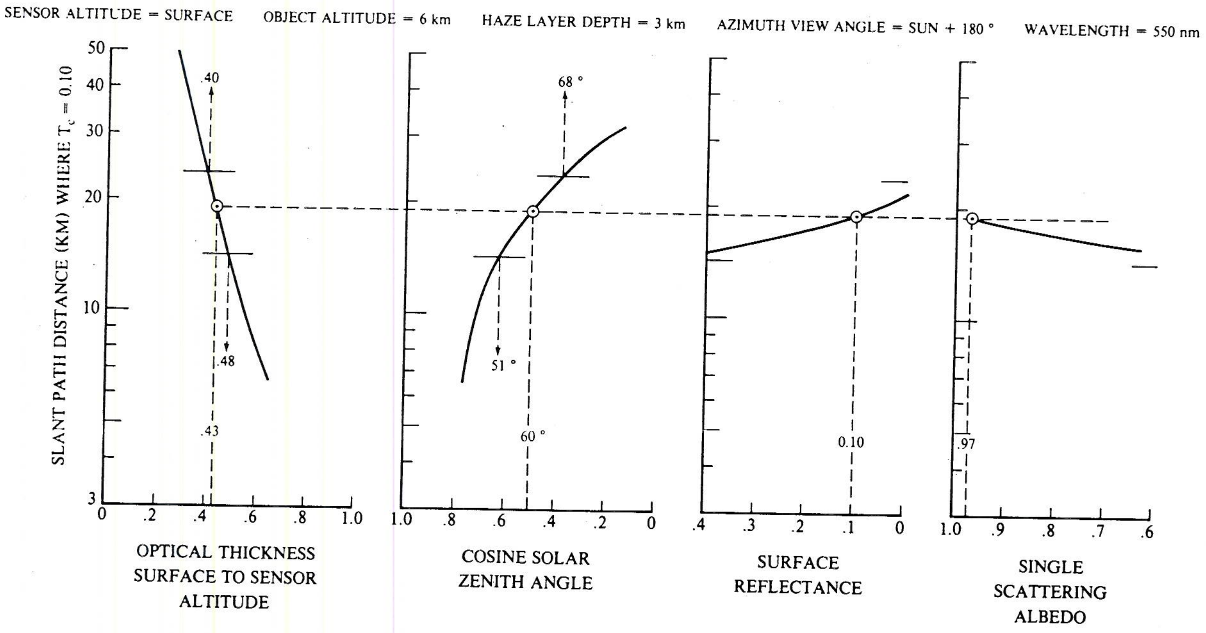

Figure 7. Same as figure 5 except for a target viewed against a sky background.

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