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MONTE CARLO ANALYSIS OF SEARCHLIGHT SCATTERING MEASUREMENTS

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by
Michael B. Wells

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Task No. 762107
Work Unit No. 76210701

Scientific Report No. 3

31 May 1968

Contract Monitor
Robert W. Fenn
Optical Physics Laboratory

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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
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MONTE CARLO ANALYSIS OF SEARCHLIGHT SCATTERING MEASUREMENTS*

Michael B. Wells

ABSTRACT

A Monte Carlo analysis was made of measurements of the scattered light from a searchlight beam. These measurements, reported by Elterman (AFCRL-66-828), were performed to determine the aerosol properties of the atmosphere for altitudes below 35 km. Elterman derived altitude profiles of the aerosol attenuation coefficient from the measured response data by use of single scattering theory for Rayleigh and aerosol particle scattering. A study was made using the LITE-I Monte Carlo code to investigate the effects of multiple scattering and ozone absorption on the measured response data for 0.55μ wavelength light. Also studied was the effect on the calculated receiver response that results from the use of different aerosol phase functions in the Monte Carlo calculations. The Monte Carlo calculations showed that the effects of multiple scattering and ozone absorption were approximately equal in magnitude, but opposite in effect, thus one can conclude that the neglect of ozone absorption and multiple scattering did not introduce any significant error in Elterman's calculations of the aerosol attenuation coefficient profiles. The major source of error in determining the aerosol attenuation coefficient profile from single scattering theory was found to be in the use of an aerosol phase function that was measured at a different time and geographical location than that used for the searchlight experiment.

* Presented as paper ThD 20 at the 1967 Annual Meeting of the Optical Society of America.

INTRODUCTION

At the 1966 Annual Meeting of the Optical Society of America, Dr. L. Elterman[1] of the Air Force Cambridge Research Laboratories reported on the results of a searchlight scattering experiment which had been performed at White Sands, New Mexico for the purpose of determining the aerosol properties of the atmosphere for altitudes to 35 km. He presented several aerosol attenuation coefficient profiles which he had computed from the measured receiver response data by use of the expression

$$E_{rp} = CT_r T_p[\beta_r P_r(\phi_s) + \beta_p P_p(\phi_s)]$$

where:

E_{rp} = instrument response (volts)

C = proportionality constant (volts cm steradian)

T_r = Rayleigh transmission for both slant paths

T_p = aerosol transmission for both slant paths

β_r = Rayleigh attenuation coefficient (km^{-1})

β_p = aerosol attenuation coefficient (km^{-1})

$P_r(\phi_s)$ = normalized Rayleigh phase function ($steradian^{-1}$)

$P_p(\phi_s)$ = normalized aerosol phase function ($steradian^{-1}$)

ϕ_s = scattering angle

The constant C was determined by Elterman by assuming that at an altitude of 35 km. the receiver response resulting from aerosol scattering was negligible and could be neglected. By assuming that the aerosol phase function is known, it is possible to determine $\beta_p(h)$ since $T_p(h)$ can be expressed in terms of $\beta_p(h)$. Since β_p exists in the transmission equation as an exponent, the solution for β_p is not analytic. Elterman used an iterative-convergent procedure to determine β_p from the measured response data.

The iteration was started using the aerosol attenuation coefficient for 0.55μ light as tabulated in the Atmospheric Attenuation Model, 1964 by Elterman[2]. The aerosol phase function, $P_p(\phi_s)$, as used in the calculation for β_p was derived from measurements reported by Reeger and Siedentopf[3] in an atmosphere having a meteorological range of 30 km. The Rayleigh attenuation coefficient variation with altitude for 0.55μ light was also taken from the Atmospheric Attenuation Model tabulations reported by Elterman[2].

Several of the aerosol attenuation coefficient profiles that were computed by Elterman[4] from the measured searchlight scattering data are shown in Fig. 1. For comparison, the Rayleigh and ozone attenuation coefficients from Ref. 2 are also shown in Fig. 1. The four aerosol attenuation coefficient profiles shown in Fig. 1 illustrate that there is considerable structure in the aerosol coefficient as a function of altitude. It is seen in Fig. 1 that ozone is relatively unimportant at low altitudes, but for altitudes above $\approx$18 km the ozone coefficient is larger than the Rayleigh attenuation coefficient.

A review of the equation used by Elterman to compute β_p from the measured response data shows that there are at least three possible

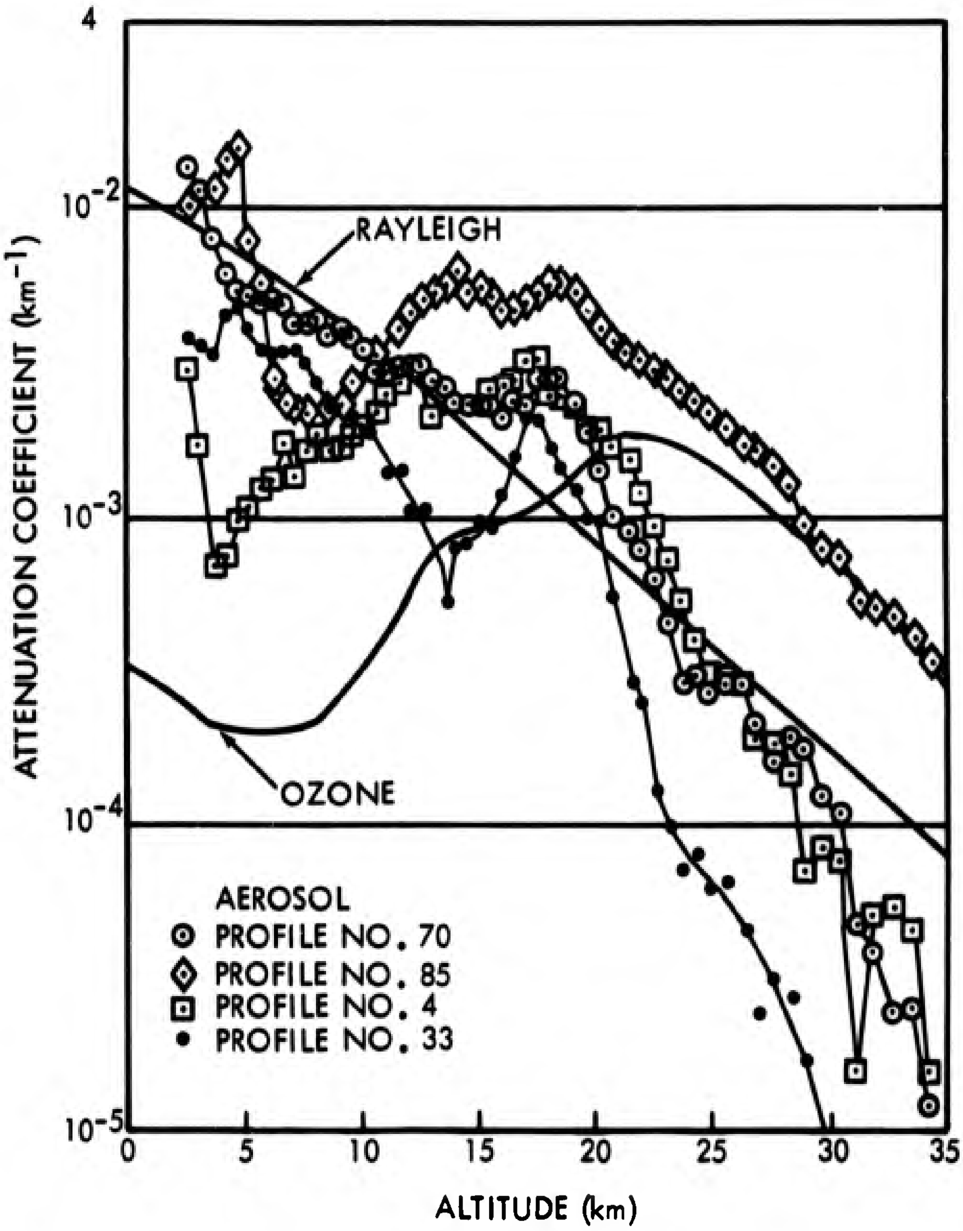

Fig. 1. Attenuation Coefficient Profiles

sources of error in the calculational method. An error could have been introduced by the neglect of the effect of multiple scattering of the light scattered from the searchlight beam. Another source of error is the neglect of ozone absorption in the calculation. A third possible source of error is the error that could result from the fact that the Reeger-Siedentopf phase function might not adequately represent the aerosol phase function that existed during the period of time required for each individual scan of the searchlight beam.

A study was undertaken to evaluate the effect of these three possible sources of error on Elterman's calculations of the aerosol attenuation coefficient profiles. LITE-I[5], a Monte Carlo procedure, was used to evaluate the effects of multiple scattering, ozone absorption, and aerosol size distribution on the searchlight scattering data.

CALCULATIONAL METHOD

In the LITE-I code the life histories of photons are traced as they leave the searchlight beam. At each collision an estimate is made of the scattered intensity that would reach the receiver. The atmosphere is defined in LITE-I in terms of the mean-free-path distance from ground level to height h, the ratio of the sum of the Rayleigh and aerosol attenuation coefficients to the extinction coefficient as a function of altitude and the ratio of the Rayleigh to the sum of the Rayleigh and aerosol attenuation coefficients as a function of altitude. At every collision the photon being followed is forced to undergo a scattering event with a weight W given by

$$W = W'\beta_s(h)/\beta_{ext}(h)$$

where

W'	=	weight before collision
$\beta_s(h)$	=	sum of the aerosol and Rayleigh attenuation coefficients at altitude h
$\beta_{ext}(h)$	=	extinction coefficient at altitude h.

The type of scattering event is selected at random by generating a random number between 0 and 1 and then determining if it is less than or equal to the ratio, $\beta_r(h)/\beta_s(h)$. If it is, then the collision is taken to be a Rayleigh scattering event. If not, then the collision is taken to be an aerosol scattering event.

The phase functions for aerosol and Rayleigh scattering are input to LITE-I for use in computing the intensity at a receiver after each collision and to select at random the direction after each collision to the next collision.

The searchlight scene geometry is shown in Fig. 2. The searchlight beam was defined in the LITE-I calculations in terms of a point source located at an altitude of 1.39 km emitting 0.55μ light in a beam defined by a beam divergence of 2°. The beam was oriented so that it had an elevation angle of 75°. The receiver was placed in a plane containing the beam at an altitude of 2.76 km and a horizontal range of 30.2 km from the source. The scattered radiation was recorded at the receiver in terms of the polar angle ψ about the source-receiver axis and an azimuthal angle which was defined in a plane perpendicular to the source-receiver axis.

To study the effect of neglecting ozone absorption in Elterman's analysis of the searchlight scattering data, single scattering calculations were run for atmospheres with and without ozone. The aerosol attenuation coefficient profile for two of the atmospheres studied are shown in Fig. 3. These profiles were computed by Elterman from the searchlight data for 0058 hrs on 13 April 1964 and 2325 hrs on 11 June 1964. They will be designated as profiles 53 and 85, respectively. The aerosol phase function used in Elterman's calculations was derived from the searchlight scattering measurements reported by Reeger and Siedentopf[3]. The Monte Carlo single scattering calculations in which ozone absorption was neglected were found to be in good

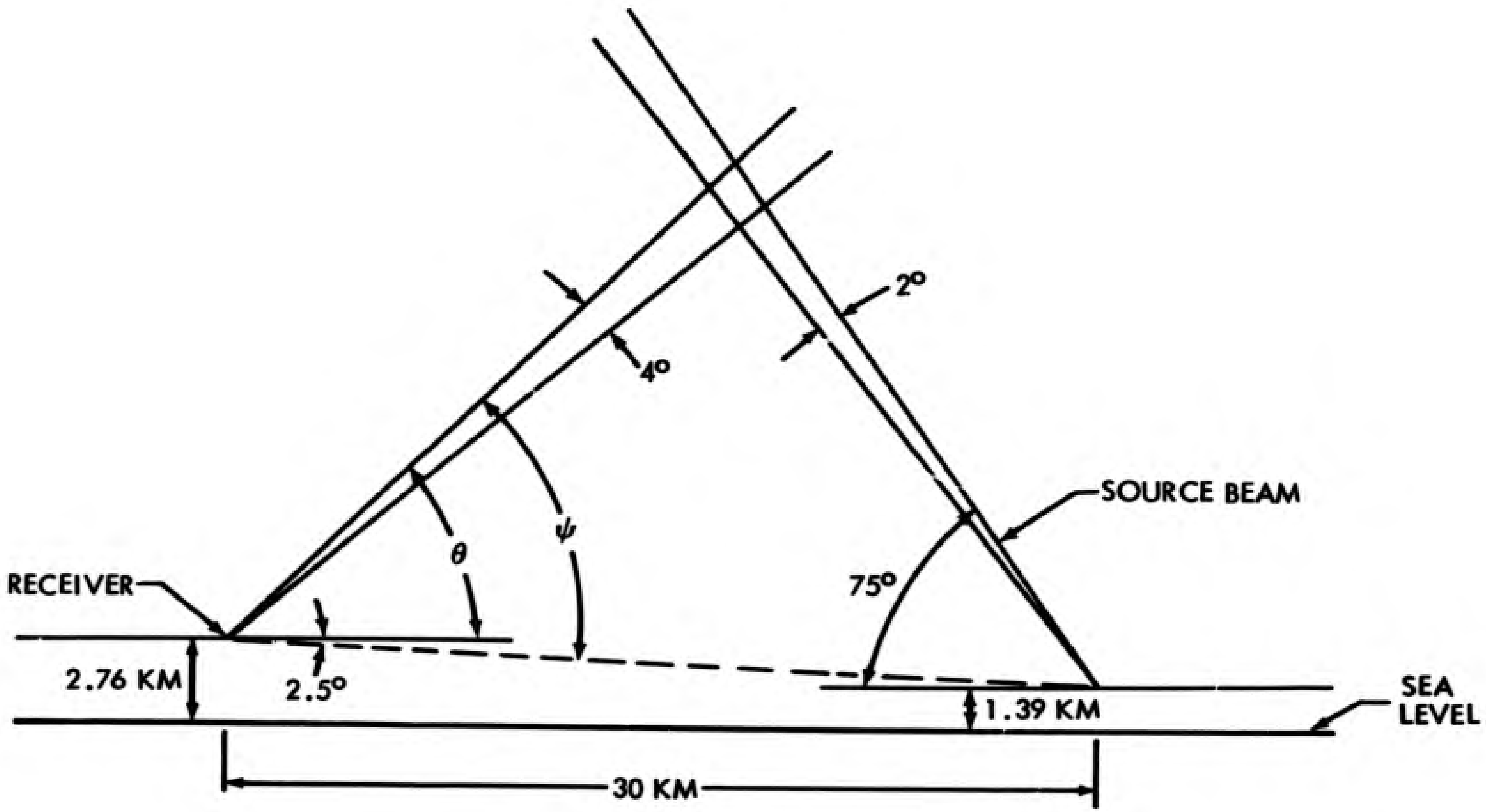

Fig. 2. Searchlight Scene Geometry

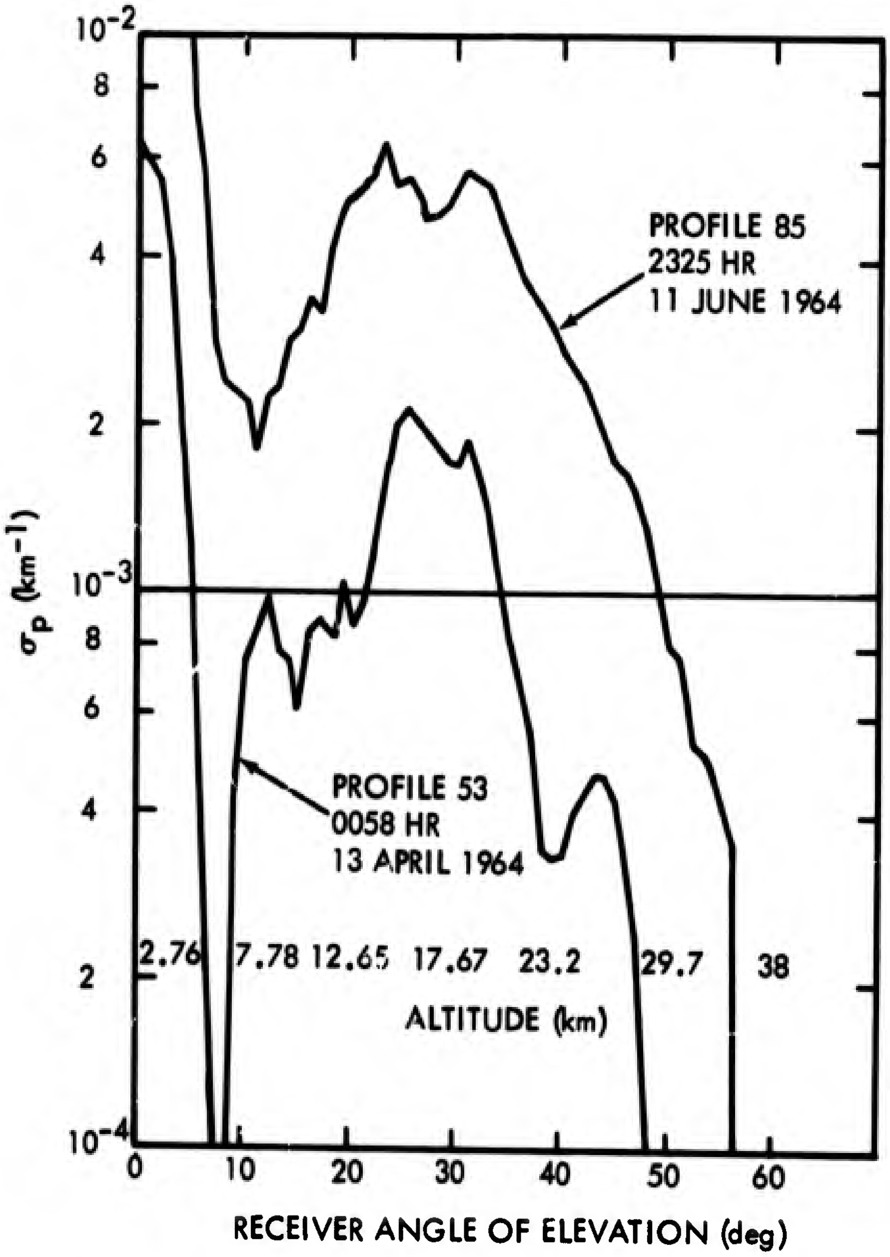

Fig. 3. Aerosol Attenuation Coefficient Profiles 53 and 85

agreement with the shapes of the measured response data as a function of the receiver angle of elevation for each of the aerosol attenuation coefficient profiles studied. The single scattering calculations in which ozone absorption was included were found to produce scattered intensities as a function of the receiver angle of elevation that were lower in magnitude than those calculated when ozone absorption was neglected. The percent decrease in the single scattered intensities as a function of the receiver angle of elevation that results from the addition of ozone to the atmosphere is shown in Fig. 4 for Profiles 53 and 85. It is seen that the addition of ozone to the atmosphere results in a decrease in the scattered intensities that varies by less than 1 percent at a receiver elevation angle of 0° to about 6.1 percent at a receiver angle of elevation of 54°.

Although the aerosol coefficients as given by Profile 85 are a factor of 2 to 22 greater than those given by Profile 53, the single scattered intensities for Profile 85 did not vary by more than 38 percent from those computed for Profile 53. A comparison of the single scattering calculations for profile 85 and 53 indicate that a sizeable error in the calculated aerosol attenuation coefficient could result from the neglect of ozone absorption in the calculation of the aerosol coefficient.

Monte Carlo calculations were run to determine the effect of multiple scattering on the intensities at the receiver as a function of the receiver angle of elevation. The calculations included the

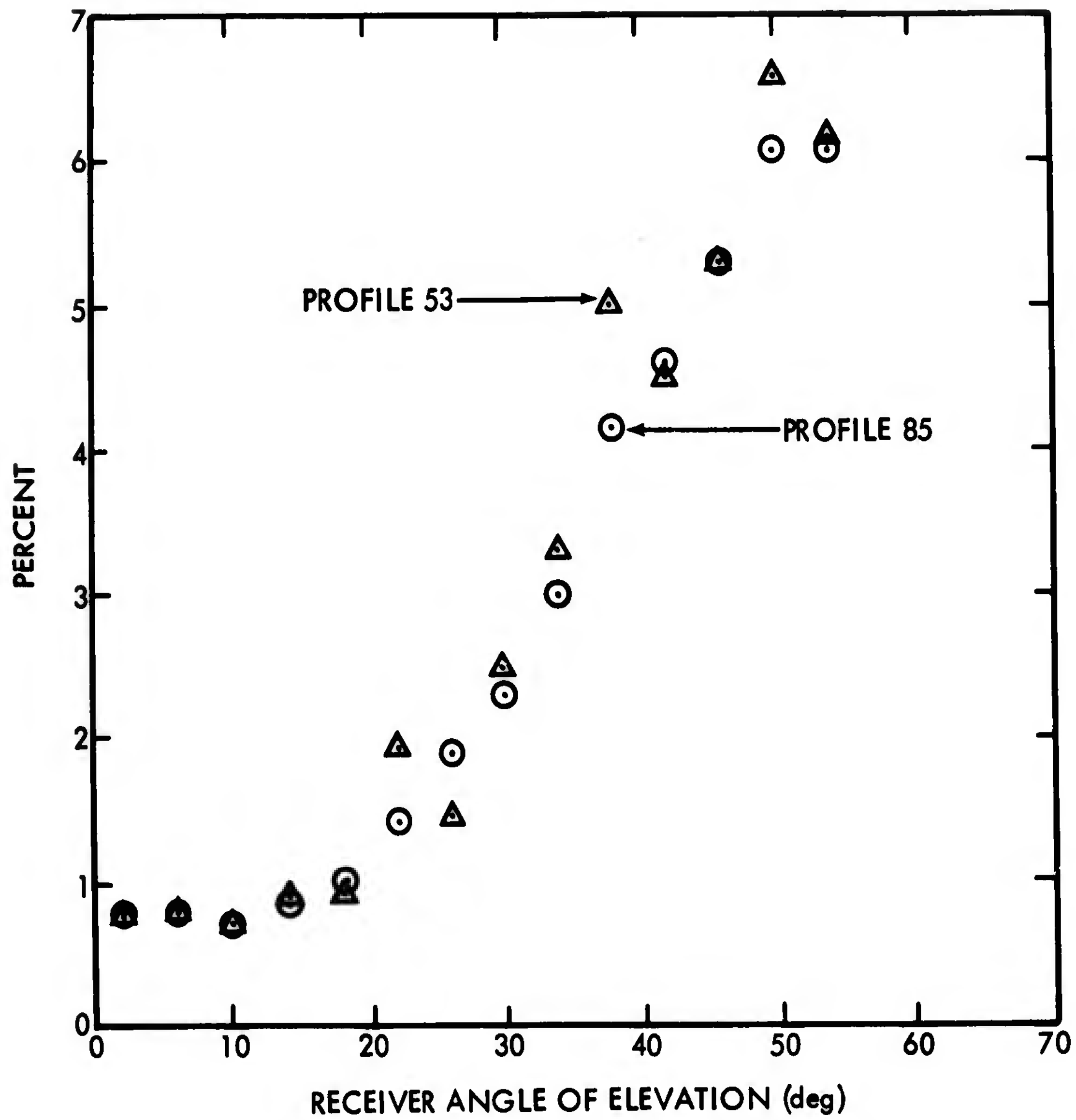

Fig. 4. Percent Decrease in Single Scattered Intensity Resulting from Addition of Ozone to the Atmosphere

effect of ozone absorption. The phase function for aerosol scattering was taken to be that derived from Reeger and Siedentopf's measurements. It was found that the importance of multiple scattering increased as the receiver angle of elevation was increased. These calculations showed that the combined effect of multiple scattering and ozone absorption resulted in scattered intensities at the receiver that varied with the receiver angle of elevation in the same manner as that computed by single scattering when ozone absorption was neglected.

Fig. 5 presents a comparison of the multiple scattering calculations with the measured response data for four different scans of the searchlight beam. The Monte Carlo calculated data were normalized to the measured data at a receiver angle of elevation of 18° for each profile. It is seen that the variation of the calculated intensities with the receiver angle of elevation is in good agreement with the measured data for each of the four sets of measured data.

From an examination of the equation used by Elterman to compute the aerosol coefficient profiles from the measured response data it appears that a sizeable error could result from the assumption that the aerosol phase function, $P_p(\phi_a)$ is adequately described by the aerosol phase function derived from Reeger and Siedentopf's measurements. The aerosol particle size distribution is usually expressed by an equation of the form $n(r) = cr^{-\nu}$ with the value of the exponent ν being dependent on the visibility. The exponent ν ranges from about 2 to 5 with a value of 4 usually used for a visibility of about 25 km at ground level. The aerosol phase function which was derived from Reeger and Siedentopf's

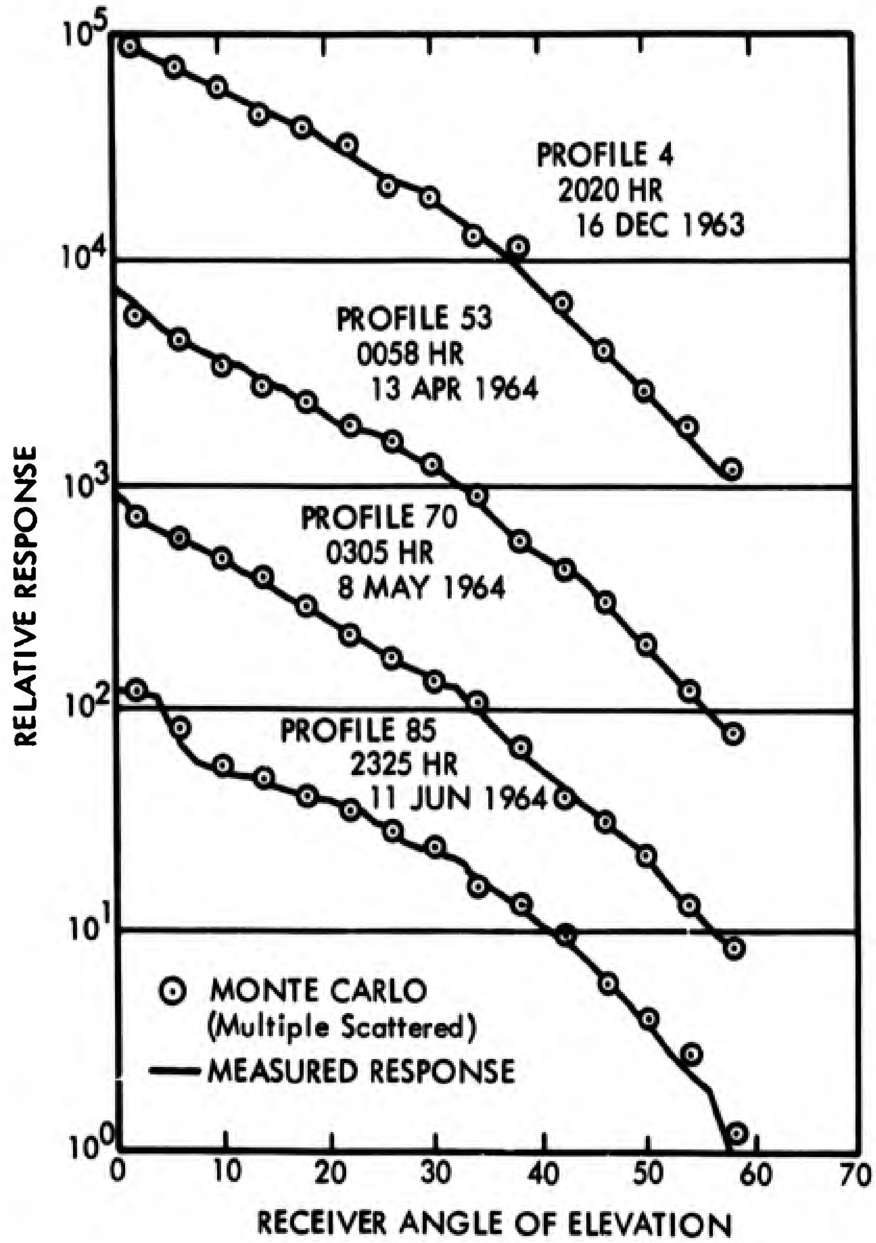

Fig. 5. Comparison of Calculated and Measured Receiver Response

measurements is for a visibility of 30 km. In the scattering angle range for which single scattering is involved in the searchlight measurements there are significant differences in the magnitude of the normalized aerosol phase function for values of ν between 2 and 5. Fig. 6 shows the variation of the normalized aerosol phase functions with the scattering angle for the size distribution $n(r) = c\ r^{-\nu}$ when for $\nu = 2$, 3, and 4. The phase functions shown in Fig. 6 were computed from Mie data for spherical particles with an index of refraction of 1.5. For comparison, the Reeger-Siedentopf aerosol phase function and the Rayleigh phase function are also shown in Fig. 6.

Multiple Scattering calculations were run for several of Elterman's aerosol coefficient profiles, taking into account ozone absorption, and using the aerosol phase functions shown in Fig. 6. A comparison was made of the results obtained from the LITE-I calculations for Profile 85 when using the aerosol phase function for $\nu = 4$ with that obtained using the Reeger-Siedentopf aerosol phase function. This comparison showed that an approximate 30 percent increase in the normalized aerosol phase function in the scattering angle interval between 75° and 145° resulted in only a 15 percent increase in the scattered intensities at the receiver. A multiple scattering problem that was run for Profile 70 using the aerosol phase function for $\nu = 2$, which in the range of scattering angles between 75° and 135° varies from the Reeger-Siedentopf aerosol phase function by factors of 1.59 to 3.1, produced scattered intensities that were only 15 to 20 percent less than those obtained from the problem using the Reeger-Siedentopf aerosol phase function.

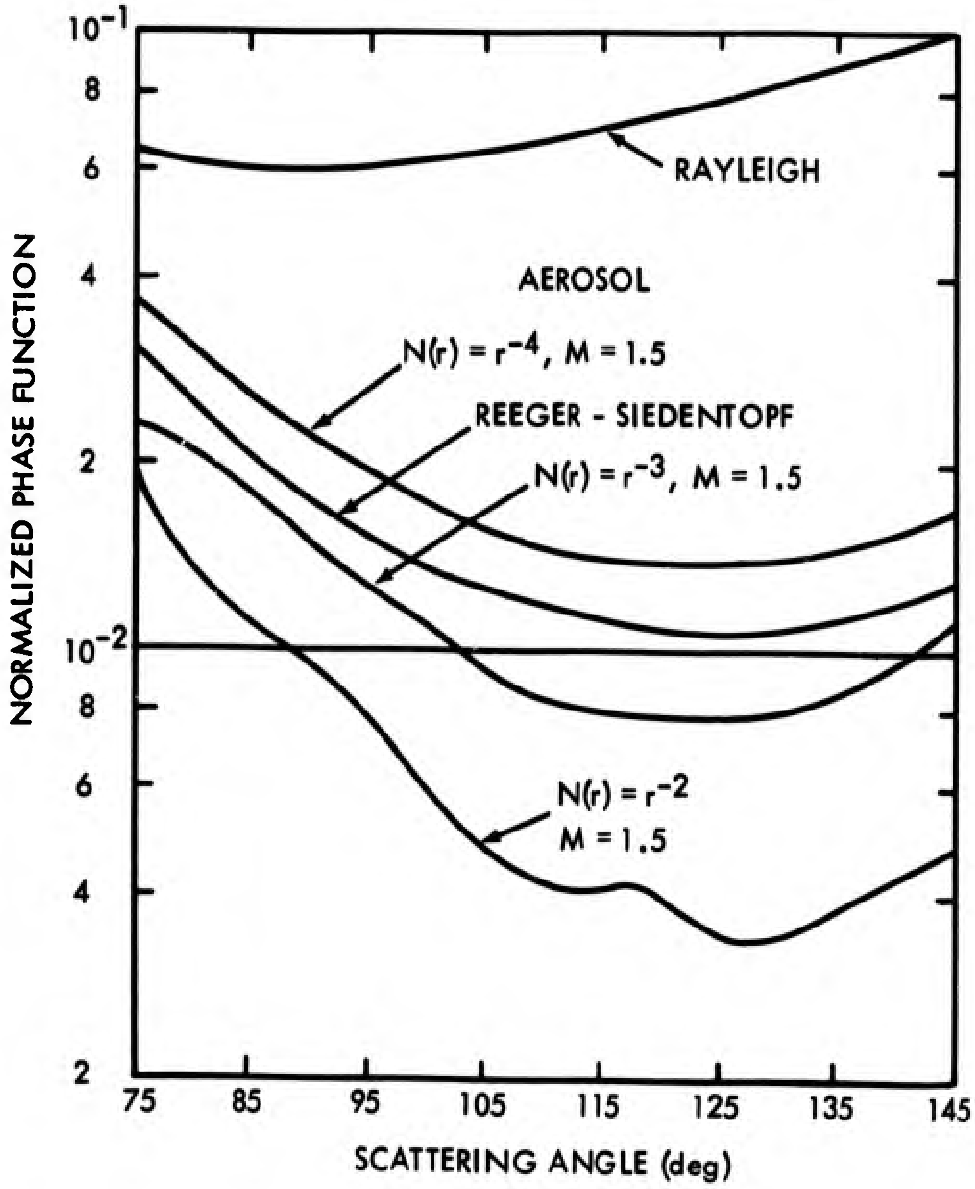

Fig. 6. Normalized Phase Functions for Aerosol and Rayleigh Scattering of 0.55 Micron Light

Plots were made of the multiple scattered intensities as a function of the receiver angle of elevation that were computed for several of the aerosol coefficient profiles using aerosol phase functions for $\nu = 2$, 3, and 4. These plots showed that the sensitivity of the Monte Carlo calculations to changes in the aerosol phase function model used in the calculations was less than 25 percent even when there were as much as a factor of 3.5 change in the magnitude of the normalized aerosol phase function.

It appears then that the major source of error in determining the profile of the aerosol attenuation coefficient from the measured response data by use of single scattering theory lies in the knowledge of the aerosol phase function.

CONCLUSIONS

To summarize it can be stated that the results of the Monte Carlo calculations showed that the effects of ozone absorption and multiple scattering are approximately equal in magnitude, but opposite in effect. Therefore one can conclude that the neglect of ozone absorption and multiple scattering did not introduce any significant error in the calculation of the aerosol attenuation coefficient profiles.

The study of the sensitivity of the LITE-I calculations to changes in the aerosol phase function indicated that the magnitude and shape of scattered intensities as a function of the receiver angle of elevation were dependent on the particular aerosol phase function used in the calculations. It is evident from an examination of the LITE-I calculations using different aerosol attenuation coefficient profiles that the sensitivity of the scattered intensities to changes in the aerosol phase function is dependent on the ratio of the Rayleigh to the aerosol coefficients.

The determination of the error in an aerosol attenuation coefficient profile that resulted from the use of the Reeger-Siedentopf aerosol phase instead of the one that existed during the period of time required to scan the searchlight beam is complicated by the fact that the real aerosol phase function is not known. Since Elterman has estimated that the ground level visibility was approximately 30 km during the evenings in which the searchlight scattering measurements were taken, it is felt that the aerosol phase function derived from the Reeger-Siedentopf measurements was as good a choice as any for use in analyzing the searchlight scattering data.

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