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AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

**Empirical Determination of
Scattered Light Transport
Through the Lower Atmosphere**

GEORGE F. RILEY

SEP 9 1968

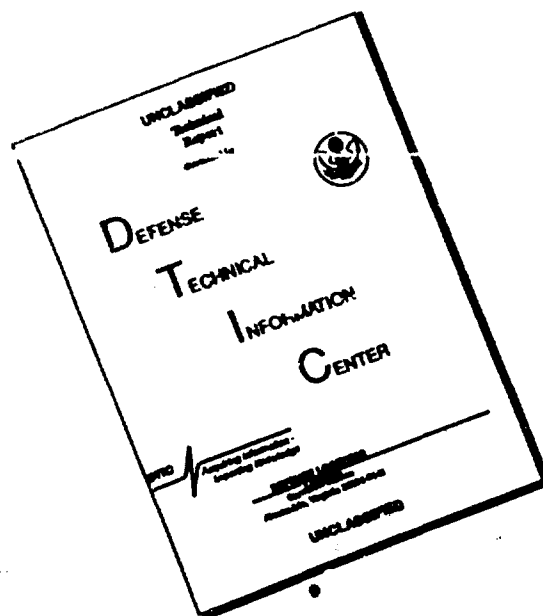
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Empirical Determination of Scattered Light Transport Through the Lower Atmosphere

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Abstract

The transmissivity of the lower atmosphere for thermal radiation from an isotropic source to a flat receiver was obtained as a function of the distance of the receiver from the source and various meteorological conditions. The functional relationship is as follows:

$$T_T = e^{-\sigma R} + R^2 \left(A e^{-3.1 R} + B e^{-1.12 R} + C e^{-\alpha R} \right)$$

where R is the distance between the source and receiver and σ , A , B , C and α are determined by the prevailing meteorological conditions. The first term accounts for the attenuation of the direct beam by "scattering out" and absorption of the radiation, and the remaining terms account for the radiation received due to "scattering in".

The results of this investigation are based on data taken over ranges (R) from 0.2 to 25 km with values of σR between 0.02 and 40.

Preface

This report was completed during the fall of 1965 and utilized by AFCRL as an internal document until now. Recently there have been several requests for it and suggestions that it be published. No new data have become available in the interim.

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Empirical Determination of Scattered Light Transport Through the Lower Atmosphere

1. INTRODUCTION

This paper is concerned with the propagation of scattered visible flux in the lower atmosphere. Researchers have taken experimental data over the past 10 years, and from their data empirical formulae were derived for the scattered intensity dependence on range and the direct beam extinction coefficient (Eldridge and Johnson, 1962; Cantor and Petriw, 1964; Gibbons et al, 1961, 1962; Lane, 1965). In most cases the data were taken under different meteorological and range conditions, hence the existing formulae most properly apply only to a specific set of parameters. Table 1 presents the various optical thicknesses and slant ranges associated with the available data. Some overlap does exist in the conditions under which the data were taken. In this study all of the data will be analyzed as a single entity, with equal weight being given to each set of transmission data. The objective is to determine a single empirical formulation that will be a valid representation of all the existing data.

2. BASIC CONCEPTS AND DEFINITIONS

For a light source radiating isotropically through 4π steradians (sr) in a vacuum, the irradiance (H) at a distance (R) from the center of the source is

(Received for publication 9 May 1968)

Table 1. Comparison of Conditions Under Which Data Were Taken

| | ELDRIDGE & JOHNSON (1962) | CANTOR & PETRIW (1964) | GIBBONS et al (1961, 1962) | LANE (1965) |
|--|---|--|---|---|
| RANGE | 0.28 - 8 km | 0.2 - 7 km | 1.7 - 27 km | 1.6 - 25 km |
| NUMBER OF STATIONS | 4 - 5 | 4 | 8 | 5 - 7 |
| DIRECT BEAM EXTINCTION COEFFICIENT (σ) | 0.04 0.05 0.06 0.16 0.58 13. 15. 16. | 0.4 0.56 0.70 0.95 1.1 1.5 2.0 2.29 | 0.022 0.027 0.038 0.040 0.065 0.066 0.080 | No Clouds 0.16 0.21 0.24 0.40 0.60 0.97 3.2 Clouds 0.06 0.30 0.64 0.87 1.2 1.4 21. |

$$H = \frac{P}{4\pi R^2} \text{ W/cm}^2 \quad (1)$$

where P is the power dissipated in the source as electromagnetic radiation. The source radiant intensity is defined as $J_o = P/4\pi$, or in terms of the irradiance (H) produced at a range (R) can be written as

$$J_o = HR^2 \text{ W/sr} . \quad (2)$$

Theory and experimental observations of the irradiance from such a source imbedded in a uniform medium in which scattering and absorption can occur, show that the power per steradian in the direct beam decreases exponentially with distance from the source; for example,

$$H_D R^2 = J_o e^{-\sigma R} \quad (3)$$

where σ is defined as the direct beam extinction coefficient. The total irradiance impinging on a detector is composed of a "scattered-in" component plus a direct beam contribution; for example,

$$H_T = H_D + H_S . \quad (4)$$

The transmissivity (or transmission) is defined as the ratio of the total irradiance at a certain distance from an isotropic source in the presence of a scattering and absorbing medium to the irradiance from the same source at the same distance in a vacuum. From this definition and the preceding equations it follows that the transmission of the direct beam is

$$\tau_D = e^{-\sigma R} = H_D R^2 / J_0 \quad (5)$$

With the aid of Eqs. (2) and (4) the amount of "scattered-in" flux can be cast in the form of a fraction of the total unattenuated beam:

$$\tau_S = H_S R^2 / J_0 \quad (6)$$

The total effective transmission of the medium can be written as

$$\begin{aligned} \tau &= \tau_D + \tau_S \\ &= e^{-\sigma R} + H_S R^2 / J_0 \end{aligned} \quad (7)$$

Measurements were made of the total irradiance on wide-angle detectors and of the "scattered-in" irradiance under various meteorological conditions at several ranges. From such measurements, the quantity $\ln(H_D R^2)$ can be plotted against R and thus J_0 can be obtained from the $R = 0$ intercept. Once J_0 has been determined the direct beam extinction coefficient (σ) can be obtained by solving Eq. (3).

An alternate (and usually less certain) method of determining σ for the visible spectrum is to use a measured visual range (Smithsonian Meteorol. Tables, 1951). The visual range is defined as the value of R for which the direct beam transmission is 2 percent, hence

$$\begin{aligned} \ln 0.02 &= \sigma V \\ \sigma &= 3.91/V \end{aligned} \quad (8)$$

where $\ln = \log_e$, V is the visual range, and σ is expressed in reciprocal units. This latter method was used only in the case of Lane's data (Lane, 1965) where the total irradiance was given as a function of distance together with the visual range. Hence the "scattered-in" irradiance had to be calculated. The principle uncertainty in this method arises when the visual range is established by means of an eyeball estimate of the visibility (e. g., the range at which there is liminal contrast between

a reasonably large object and its background). Gibbon's experience (Gibbons, 1967) is that the visibility as commonly observed is about one-half the visual range.

3. ANALYSIS OF EXPERIMENTAL DATA

Experiments were performed in the lower atmosphere by Eldridge and Johnson (1962), Gibbons (1966), Cantor and Petriw (1964), and Lane (1965). Essentially, all of these studies consisted of a light source and several detector stations at various ranges from the source. The total flux and the "scattered-in" flux were measured directly, and the flux due to the direct beam only was obtained by subtraction. In the Eldridge-Johnson experiment, since the detector was photographic film, the direct beam and scattered components were measured directly. The direct flux in all cases was observed to be attenuated exponentially in its passage through the atmosphere. The scattered component, H_S , does not behave as nicely. Values of H_S/J_0 as a function of R were obtained from all of the above mentioned experiments.

Examination of a plot of $\ln(H_S/J_0)$ versus R indicates that it can be approximated by the sum of three exponential functions; for example,

$$\frac{H_S}{J_0} = \frac{H_1}{J_0} e^{\sigma_1 R} + \frac{H_2}{J_0} e^{\sigma_2 R} + \frac{H_3}{J_0} e^{\sigma_3 R} \quad (9)$$

Substituting Eq. (9) into Eq. (7) allows us to write the total transmission of the medium as

$$\tau = e^{-\sigma R} + R^2 \left(\frac{H_1}{J_0} e^{\sigma_1 R} + \frac{H_2}{J_0} e^{\sigma_2 R} + \frac{H_3}{J_0} e^{\sigma_3 R} \right) \quad (10)$$

The problem now reduces to analyzing a sufficient number of experiments so that the quantities H_1/J_0 , H_2/J_0 , H_3/J_0 , and σ_1 , σ_2 , σ_3 can be determined.

3.1 Long-Range Slope and Intercept (σ_3 and H_3)

Only Gibbons and Lane provide useful data for ranges between 10 and 30 km. By plotting $\ln(H_S/J_0)$ vs R for these data, a straight line can invariably be fit to the data points beyond 8 to 10 km (see Figure 1a). Figures 1a, 1b, and 2 are presented to demonstrate the method used in determining the unknowns mentioned above. The slope of this straight line is equal to the value of σ_3 in Eq. (10). From 23 sets of

data obtained under various meteorological conditions, it was noted that σ_3 is always negative and that a functional relationship exists between the direct beam extinction coefficient, σ , and $|\sigma_3|$. A different function exists for overcast and non-overcast conditions (see Figure 3). The straight lines are least-square fits to the plots of $|\sigma_3|$ as a function of σ .

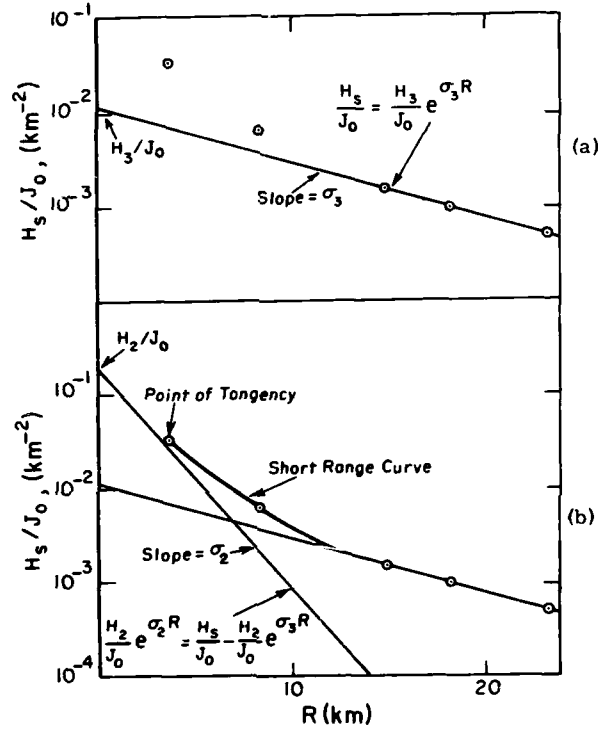


Figure 1. (a) Long-Range Slope and Intercept; (b) Intermediate Slope and Intercept

The analytic expressions obtained for this function are:

$$\sigma_3 \text{ (km}^{-1}\text{)} = \begin{cases} -0.14 \sigma^{0.045} & \text{for non-overcast conditions} \\ -0.22 \sigma^{0.12} & \text{for overcast conditions.} \end{cases}$$

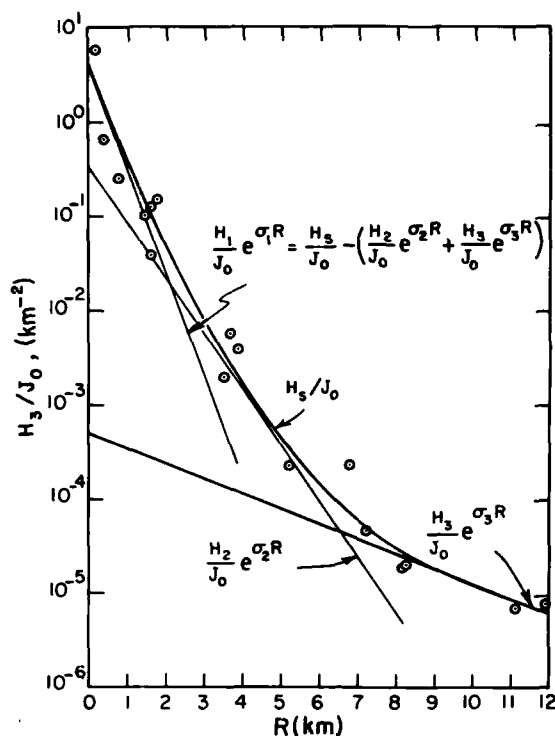


Figure 2. Short-Range Slope and Intercept

The value of H_3/J_0 is determined from the ordinate intercept of the straight-line approximation to the long-range data described above (see Figure 1a). Twelve sets of Eldridge-Johnson and Cantor-Petriw data were available which had transmissions in the neighborhood of 8 km. It was assumed that the H_3/J_0 decay versus R for this data at the longer ranges would follow the σ_3 slope determined above, hence $R = 0$ intercepts could be determined for these sets even though long-range data were not acquired. Two sets of Lane's data also fell into this category. This yielded 37 sets of transmission data for which H_3/J_0 could be determined.

Correlation was found to exist between the value of H_3/J_0 and the overcast conditions present during the measurements. The intercepts are grouped as follows:

- (I) Complete overcast between 1000 and 5000 ft.
- (II) Complete overcast below 1000 ft (clear below) or partial overcast between 1000 and 5000 ft.
- (III) Clear sky or high overcast.
- (IV) Complete overcast below 1000 ft (fog below) or partial overcast below 1000 ft.

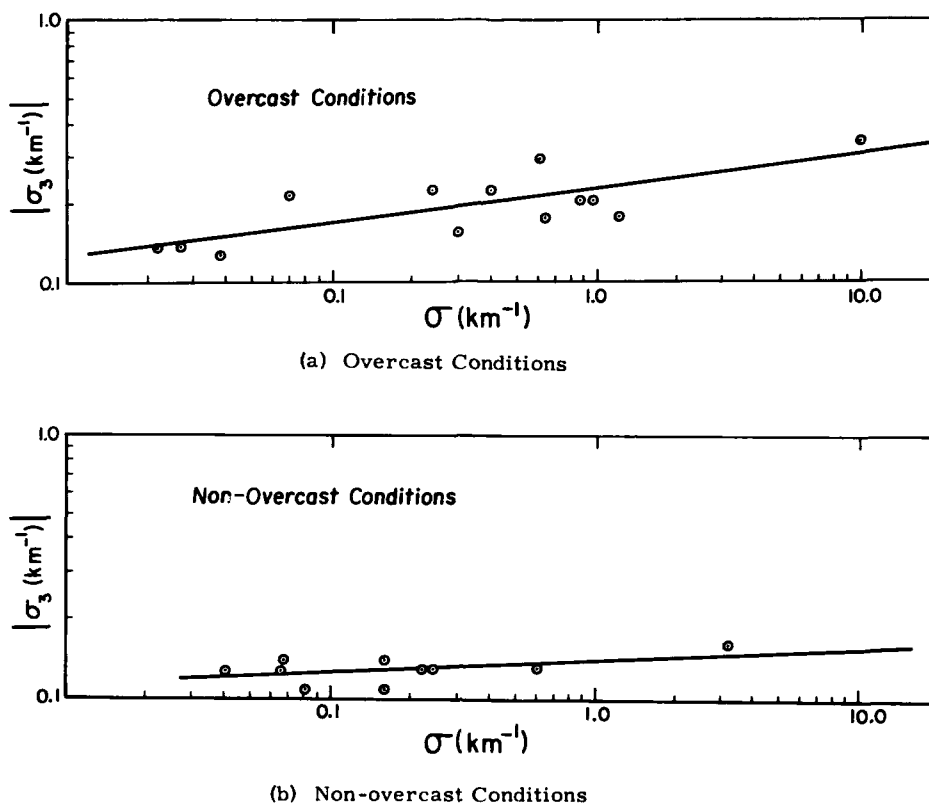


Figure 3. Absolute Value of Long-Range Slope

There were 8 transmissions on days in Group I, 10 transmissions on days in Group II, 14 transmissions on days in Group III, and 5 transmissions on days in Group IV. Only one of these was disregarded as an anomaly (more will be said about this one value later), and the values in each group were averaged and statistically analyzed. The results are:

| | | |
|--|------------|--|
| $\frac{H_3}{J_0} \text{ (km}^{-2}\text{)}$ | Group I, | 0.033 with a standard deviation of 0.009 |
| | Group II, | 0.0102 with a standard deviation of 0.0016 |
| | Group III, | 0.0032 with a standard deviation of 0.0009 |
| | Group IV, | 0.0006 with a standard deviation of 0.0001 |

3.2 Intermediate Range Slope and Intercept (σ_2 and H_2)

For each of the 37 transmissions where a long-range slope was evident or

inserted, a smooth curve was drawn through the short-range values of H_S/J_0 . This curve was faired into the straight-line approximation discussed above (see Figure 1b). The value of the function $H_3 e^{\sigma_3 R}$ was then subtracted point by point from the short-range curve until the resulting curve $\frac{H_S}{J_0} - \frac{H_3}{J_0} e^{\sigma_3 R}$ approached tangency with $\frac{H_S}{J_0}$. This curve could invariably be approximated by a straight line and, hence, denoted by $\frac{H_2}{J_0} e^{\sigma_2 R}$, where H_2/J_0 and σ_2 are the $R = 0$ intercept and the slope respectively. Thirty-two values of H_2/J_0 and σ_2 were subsequently determined and analyzed.

The remaining five transmissions yielded no values for H_2/J_0 and σ_2 for the following reasons: four of these transmissions contained no data for ranges less than 8 km (all data lay on long-range asymptote); one of these transmissions contained short-range data which rose sharply from the long-range asymptote (σ_2 was anomalous). The consequences of the latter transmission will be discussed along with the anomaly mentioned previously, which happens to be in the same set of data.

The 32 values of σ_2 were negative and had magnitudes between 0.50 km^{-1} and 1.73 km^{-1} . The values seemed to fall naturally into three groups centered at 0.61, 1.08, and 1.49 km^{-1} . There were no obvious connections between the characteristics of the days in each group, with the exception that all of the data from Greenland yielded values of σ_2 in the 1.49 km^{-1} group.

Because of the inability to reasonably explain this natural grouping, all 32 values of σ_2 were averaged and statistically analyzed, yielding:

$$\sigma_2 (\text{km}^{-1}) = -1.12 \text{ with a standard deviation of } 0.25.$$

The values of H_2/J_0 obtained from the $R = 0$ intercept of the medium-range function $\frac{H_2}{J_0} e^{\sigma_2 R}$ were divided into six groups according to the overcast condition prevalent during the data acquisition. The characteristics of these days are as follows:

- (I) Complete overcast less than 5000 ft (clear below).
- (II) Complete overcast less than 5000 ft in Arctic.
- (III) Partial overcast.
- (IV) Clear sky or high overcast (clear below).
- (V) Clear sky or high overcast (fog below).
- (VI) Low overcast with fog below.

There were 5 transmissions in Group I, 2 transmissions in Group II, 4 transmissions in Group III, 10 transmissions in Group IV, 5 transmissions in Group V, and 5 transmissions in Group VI. The values of H_2/J_0 for each group were averaged and the results were:

| | | |
|--|------------|--|
| | Group I, | 1.29 with a standard deviation of 0.17 |
| | Group II, | 3.55 with a standard deviation of 0.30 |
| $\frac{H_2}{J_0} \text{ (km}^{-2}\text{)}$ | Group III, | 0.063 with a standard deviation of 0.014 |
| | Group IV, | 0.151 with a standard deviation of 0.031 |
| | Group V, | 0.83 with a standard deviation of 0.16 |
| | Group VI, | 0.38 with a standard deviation of 0.04 |

3.3 Short-Range Slope and Intercept (σ_1 and H_1)

The sum of the two functions $\frac{H_2}{J_0} e^{\sigma_2 R} + \frac{H_3}{J_0} e^{\sigma_3 R}$ was subtracted point by point from the curve H_S/J_0 for the remaining range of R values less than the value of R where the medium-range, straight line approached tangency with the H_S/J_0 curve. The resulting function $\frac{H_S}{J_0} - \left(\frac{H_2}{J_0} e^{\sigma_2 R} + \frac{H_3}{J_0} e^{\sigma_3 R} \right)$ could be approximated by a straight line and, hence, denoted by $\frac{H_1}{J_0} e^{\sigma_1 R}$, where H_1/J_0 and σ_1 are the R = 0 intercept and slope respectively (see Figure 2). There were only 11 sets of data where these values could be determined by the above method, due to the lack of short-range data for 21 of the 32 transmissions already analyzed. However, five pairs of values of H_1/J_0 and σ_1 were obtained in the following manner. There were four transmissions for which data was available for ranges less than 4 km. The value of $\ln(H_S/J_0)$ was plotted against R for these transmissions and a straight line fitted to all the data yielding values of R = 0 intercept and slope which agreed with values of H_1/J_0 and σ_1 as obtained by the previously described method. The one remaining pair of H_1/J_0 and σ_1 values was obtained from the anomaly mentioned twice before, where the short-range values of H_S/J_0 rose sharply from the long-range asymptote and the value of H_2/J_0 was anomalous. The long-range asymptote was subtracted from the short-range data, and a straight line of slope comparable to the value of σ_1 already determined was obtained; the R = 0 intercept agreed with values of H_1/J_0 .

The 16 values of σ_1 obtained from the slopes of the short-range asymptote were all negative and had a magnitude in the range from 2.5 km^{-1} to 4.6 km^{-1} . No functional dependence could be determined. The values were averaged and analyzed statistically; the result is:

$$\sigma_1 \text{ (km}^{-1}\text{)} = -3.10 \text{ with a standard deviation of } 0.05.$$

The 16 values of H_1/J_0 were a function of σ , and it was noted that the function was different for different environments (see Figure 4). A least-squares fit to the plot of H_1/J_0 vs σ yielded the following relationships:

$$\frac{H_1}{J_0} \text{ (km}^{-2}\text{)} = \begin{matrix} 9 \sigma^{2/3} & \text{for an Arctic environment} \\ 2 \sigma^{1/3} & \text{for a Temperate environment.} \end{matrix}$$

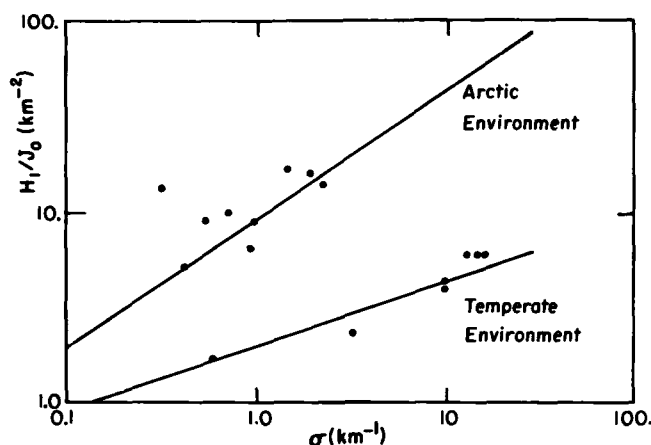


Figure 4. Short-Range Intercept Versus the Direct-Beam-Extinction Coefficient

The scattered-in irradiance can be thought to arise from three virtual sources that radiate as parallel beams: $H_S = H_1 e^{\sigma_1 R} + H_2 e^{\sigma_2 R} + H_3 e^{\sigma_3 R}$, where σ_1 , σ_2 , σ_3 are the negative of the extinction coefficients for these three virtual sources. In the case of the one anomaly, the long-range source (H_3) is very intense and masks the medium-range source (H_2). The origin of these three virtual sources is unknown at the present, but further investigation should verify their existence.

The preceding paragraphs indicated how the values of the unknowns in Eq. (10) are determined from available data, and they also indicated the variance to be expected. Since all parameters in Eq. (10) are now known or can be determined from their dependence on particular meteorological conditions, the problem of calculating the transmissivity of the lower atmosphere for a particular σ and R reduces to substituting the proper values into Eq. (10) and solving for τ .

4. DISCUSSION

All of the data used in this analysis, with the exception of eight transmissions from Gibbons, were for white light; hence, σ is the white light extinction coefficient. Two each of Gibbons' 0.70 μ and 0.83 μ transmissions respectively, and the value of σ associated with each transmission, were determined from the slope of the direct-beam irradiance vs range curve. Consequently, the transmissivity was determined as a function of σ , and any functional dependence on wavelength would appear from the fact that σ is a function of wavelength.

Another factor which should be mentioned is the possible effect of the surface albedo between source and receiver. For all of the experiments quoted in this report, it is believed that light reflected from the surface toward the receiver was occulted, intentionally or accidentally, or else it was a minimum due to the angle of elevation of the receiver, as in the case of Eldridge-Johnson and Lane where they were using sources well above ground level. It would, therefore, be necessary in computing the total irradiance at a receiver that could see the ground, to use the atmospheric transmissivity as determined here and an enhancement factor that requires finding the distribution of energy in space from a point source illuminating a reflecting surface. Solutions of this problem exist only for the case of a non-absorbing, non-scattering half space and are treated in detail by Guess (1957). It has been shown by Cahill, Gauvin, and Johnson (1962) that uncertainties in the earth's surface albedo make it possible to use Guess' theory in a real atmosphere. They published curves of this enhancement factor for two surface albedos, $\rho = 0.2$ and 1.0 (see Figures 13 and 14 of Cahill et al, 1962).

The extinction of the scattered flux intensity at the longer ranges seems to be quite adequately described by a slope of the form $A \sigma^B$. The coefficients (A, B) were derived from 23 sets of data over a large range of the direct-beam-extinction coefficient, $0.022 < \sigma < 3.0 \text{ km}^{-1}$ (see Figure 3).

It is quite obvious that in this type of analysis the confidence placed in the results is directly proportional to the amount of data analyzed. While the data analyzed herein were all that were available, it should be pointed out that a large quantity of this type data has recently been acquired by the United States Army Electronics Command (Cantor and Petriw) and should be published soon. The United States Naval Radiological Defense Laboratory has also some unpublished atmospheric transmission data of this type. For this reason the empirical relationship developed herein should be considered interim and a re-examination made when new data becomes available.

Eldridge (1968) recently compared the formulae derived herein with other empirical determinations of optical energy transport and with Monte Carlo calculations.

The main conclusions of this report are:

1. An interim empirical model of the total visible transmissions as a function of meteorological observables has been developed.
2. The extinction of scattered flux at long ranges has been formalized.

5. SUMMARY

The final form of the transmissivity equation for a path in the lower atmosphere is as follows:

$$\tau = e^{-\sigma R} + R^2 \left(A e^{-3.1 R} + B e^{-1.12 R} + C e^{-\alpha R} \right) \quad (11)$$

where

- $A = 9\sigma^{2/3}$ for an Arctic environment
 $2\sigma^{1/3}$ for a Temperate environment
 1.29 for an overcast less than 5000 ft (clear below)
 3.55 for overcast less than 5000 ft in Arctic environment
 $B = 0.063$ for partial overcast
 0.151 for clear sky or high overcast
 0.83 for clear sky or high overcast with snow and/or fog
 0.38 for low overcast and fog below
 0.033 for complete overcast between 1000 and 5000 ft
 $C = 0.0102$ for complete overcast below 1000 ft or partial overcast between 1000 or 5000 ft
 0.0033 for clear sky or high overcast
 0.0006 for overcast (complete or partial) below 1000 ft and fog below
 $|\alpha| = 0.14 \sigma^{0.045}$ for non-overcast conditions
 $0.22 \sigma^{0.12}$ for overcast conditions
 $\sigma = \frac{3.91}{V}$ where V is the visual range in kilometers.

- Note:
1. The units of A, B, and C are km^{-2} and the units for α are km^{-1} .
Consequently the units for R must be km.
 2. Eq. (11) is considered valid under the following conditions:

 $0.02 < \sigma < 3.0 \text{ km}^{-1}$
 $0.2 < R < 30 \text{ km}.$

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