The Light Scattering Properties of Clouds
Volume I: Analysis of Experimental Results

Prepared by R. T. HALL and R. D. RAWCLIFFE
Space Physics Laboratory
Laboratory Operations

71 NOV 30

Prepared for SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

NATIONAL TECHNICAL
INFORMATION SERVICE
Arlington, Virginia

APPROVED FOR PUBLIC RELEASE:
DISTRIBUTION UNLIMITED
A series of experimental measurements of the visible light angular scattering profiles of clouds is described. The results for single layer overcast clouds were found to correlate well with standard hemispheric and narrow-angle pyrheliometric transmittances. The resulting expression for the angular scattering profile of an overcast cloud layer is:

\[ T(\theta) = A + B \sin^2 \theta \]

where

\[ A = -0.0056 + 0.89 \times T_n \]
\[ B = -0.028 + 1.09 \times T_w \]

and \( \theta \) is the half angle of the field of view, \( T_n \) the transmittance measured with a narrow-angle pyrheliometer, and \( T_w \) the transmittance measured with a hemispheric pyrheliometer.
KEY WORDS

Clouds
Transmission
Meteorology
Scattering

Distribution Statement (Continued)

Abstract (Continued)
THE LIGHT SCATTERING PROPERTIES OF CLOUDS
VOLUME I: ANALYSIS OF EXPERIMENTAL RESULTS

Prepared by
R. T. Hall and R. D. Ravencliffe
Space Physics Laboratory
Laboratory Operations

71 NOV 30

Systems Engineering Operations
THE AEROSPACE CORPORATION

Prepared for
SPACE AND MISSILE SYSTEMS ORGANIZATION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

Approved for Public Release;
Distribution Unlimited
FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract No. F04701-71-C-0172.

This report, which documents research carried out from January 1967 through July 1971, was submitted 3 November 1971 to Lieutenant Colonel Roy C. Robinette, SZD, for review and approval.

The authors would like to thank T. Mott for his assistance in setting up and running the experiment; R. Williams for his help in designing the electronics and data recording systems; Lieutenant Colonel J. Coblenz, B. Walker, and the staff of Detachment 10, 6th Weather Wing, for their assistance and hospitality during the course of the experiment; and Mrs. Gwen Boyd and her staff for their efforts in the transcription of the data onto computer coding sheets.

Approved

J. C. Creswell, Director
Mission Support Office
Group II Programs Directorate
Satellite Systems Division
Systems Engineering Operations

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Roy C. Robinette, Lt. Col., USAF
Director of Test
Defense Support Program

-ii-
ABSTRACT

A series of experimental measurements of the visible light angular scattering profiles of clouds is described. The results for single layer overcast clouds were found to correlate well with standard hemispheric and narrow-angle pyrheliometric transmittances. The resulting expression for the angular scattering profile of an overcast cloud layer is:

$$T(\theta) = A + B \sin^2 \theta$$

where

$$A = -0.0056 + 0.89 \times T_n$$
$$B = -0.028 + 1.09 \times T_w$$

and $\theta$ is the half angle of the field of view, $T_n$ the transmittance measured with a narrow-angle pyrheliometer, and $T_w$ the transmittance measured with a hemispheric pyrheliometer.
FIGURES

1. Optical Diagram ........................................... 9
2. Photograph of Instrument as Seen From the Ground ....... 11
3. Photograph of Instrument as Seen From the Roof ......... 12
4. Sample Output Data Sheet .................................. 26
5. Relative Irradiance Plot for 1205 Hours, 1 March 1968 ... 31
6. Sample Plot Showing Example of Quality of Fit .......... 33
7. Plot of $T_n$ vs $A$ ........................................ 39
8. Plot of $T_w$ vs $B$ ......................................... 40
9. Plot of $T_n$ vs $B$ ......................................... 41
10. Plot of $T_w$ vs $A$ ....................................... 42
11. Plot of $T_n$ vs $A$ Showing Linear Least-Squares Fitted Line .................................................................. 44
12. Plot of $T_w$ vs $A$ Showing Linear Least-Squares Fitted Line .................................................................. 45
13. Plot of $T_w$ vs $B$ ......................................... 46
14. Plot of $T_w$ vs $T_n$ ........................................ 48
15. Sample Plot Showing Accuracy of Model .................. 49
TABLES

1. Aperture Normalization Factors............................................. 15
2. Effective Fields of View ...................................................... 16
3. Solid Angle Factors ........................................................... 17
4. Number of Measurements Made by Amount of Cloud Cover ............. 21
5. Number of Measurements of 10/10's Cloud Cover by Number of Cloud Layers Reported. 22
6. Number of Complete Measurements of Single-Layer 10/10's Cloud Cover by Cloud Type. 23
7. Relative Irradiance and Least-Squares Values for Clear Sky Case ........ 32
8. Least-Squares Fitted Relationships Between $T_n$, $T_w$, $A$, and $B$ ..................................................... 47
I. INTRODUCTION AND SUMMARY

The light scattering properties of clouds are of great interest for a variety of reasons. In particular, they have a major impact on the performance of several classes of optical systems for which clouds may serve as a background or foreground. It is important in the understanding of the performance of these systems that the cloud scattering characteristics be known. Many experimental and theoretical studies of cloud scattering have been and are being carried out. However, one important aspect, the angular distribution of the scattered sunlight that penetrates the cloud, has been neglected. In this paper the results of an experimental measurement of this distribution are presented. An analysis of these measurements resulted in an empirical equation that permits prediction of this angular distribution for a variety of clouds from standard pyrheliometric measurements made at most major weather stations.

In an earlier study (Ref. 1) a large body of actinometric data was analyzed. Probability distributions of the transmittance of clouds were developed. These actinometric data were measured with two types of pyrheliometers: a wide-angle instrument that accepts radiation from the entire celestial hemisphere, and a narrow-angle instrument that tracks the sun and accepts radiation from a \( \frac{1}{5.10} \) full-angle heliocentric cone. The wide-angle and narrow-angle transmittances were calculated from these two measurements and from the known incident solar irradiance. The value obtained from the wide-angle pyrheliometer is the effective transmittance for a system that accepts radiation from a wide range of angles. This transmittance is also useful in estimating the light available for ordinary photography. On the other hand, the transmittance value obtained from the narrow-angle pyrheliometer applies to a system that has a suitable narrow acceptance angle. The suitability of the angle depends, unfortunately, on a number of parameters, including the cloud height and the position of the source of light being measured. If the effective narrow-angle transmittance is needed for a range of conditions, it must
be measured as a function of the scattering angle. The experiment described in this paper was designed to perform these measurements.

An instrument was developed to measure the total irradiance from the sun and the circumsolar sky for a series of angular fields of view from $1^\circ$ to $32^\circ$ half angle. These measurements were made and recorded automatically every ten minutes from sunrise to sunset over a six month period.

Eglin Air Force Base was selected as the site for the experiment for two reasons. The first was that this geographical area experiences the frequent occurrence of suitable cloud formations. The second was that the well-equipped Air Force weather station at the site could provide concurrent standard meteorological observational data including radar cloud height measurements.

A total of 3296 sets of measurements were made during the course of the experiment. Of these, 334 sets were obtained when there was a single overcast layer of clouds. Because of the difficulty in modeling mathematically all but this single-layer overcast data, the analysis presented here is based on these 334 data sets.

A model equation that gives reasonable agreement to the measured data is:

$$T = A + B \sin^2 \theta$$

where $T$ is the transmittance, $\theta$ the half angle of the field of view, and $A$ and $B$ parameters. These parameters were found to correlate well with the standard wide- and narrow-angle pyrheliometric transmittance measurements. These parameters, expressed in terms of $T_w$ and $T_n$, which are the transmittances measured with the wide-angle and narrow-angle pyrheliometers, respectively, are:
This model represents an angular scattering distribution consisting of an undeviated component plus a component which has been diffusely scattered. This should serve as an adequate model for cloud scattering profiles.
II. BACKGROUND AND PREVIOUS WORK

The optical engineer needs a fairly detailed knowledge of the transmission and scattering properties of clouds when designing a visible optical system to operate in the presence of clouds. While this subject has been treated extensively from a theoretical viewpoint (Ref. 2), surprisingly few experimental measurements have been made by which the theories can be checked.

Haurwitz (Ref. 3) has correlated measurements of the total radiation from the sun and sky with cloud type and solar elevation angle. Unfortunately, these measurements give no information about the angular scattering distributions produced by the clouds since the measurements were made with a $2\pi$ field of view detector. Gibbons and coworkers (Refs. 4-6) have made studies of the effect of field of view on horizontal atmospheric transmission measurements. These measurements give the scattering properties of the atmosphere plus aerosols, haze, etc., but tell nothing about clouds. Arnulf and coworkers (Ref. 7) have made transmission measurements of haze and fog but unfortunately only with a detector with a narrow angle field of view. The aircraft-based measurements of Neiburger (Ref. 8) and Griggs and Marggraf (Refs. 9 and 10) of the transmission of solar radiation through clouds were again, unfortunately, made only with $2\pi$ field of view detectors.
III. INSTRUMENTATION AND EXPERIMENTAL DESIGN

A. EXPERIMENTAL DESIGN

In designing the experiment, several requirements were laid down. The first was that the experiment should run automatically with a minimum of maintenance and adjustment. This was necessary because a large number of measurements would need to be made in order to accumulate a good statistical sample.

The second requirement was that the experimental site be subject to a wide variety of cloud conditions. The panhandle region of Florida experiences the tail ends of the winter storms that sweep down across the United States from Canada and the Arctic. In the summer, cumulus clouds are prevalent due to the moisture-laden Gulf air.

The third requirement was that the experimental site be located near a well-equipped weather station. This would facilitate concurrent observations of meteorological conditions on a routine basis.

The fourth requirement was for simultaneous narrow- and wide-angle pyrheliometric measurements. This would allow for testing possible correlations of the experimental measurements with standard solar radiation measurements that are made on a routine basis at many stations around the world.

The first requirement was met in the actual design of the instrument. The second and third were met in the experimental site selection. Eglin Air Force Base near Pensacola in northwestern Florida (latitude 30°29'N, longitude 86°31'W) has a well-equipped weather station staffed by personnel of Detachment 10 of the 6th Weather Wing, United States Air Force. In addition to the standard meteorological instrumentation, this station also has a cloud
height radar, AN/TPQ-11, operating routinely. The fourth requirement was met by the inclusion of standard narrow- and wide-angle pyrheliometers in the experimental setup.

B. INSTRUMENTATION

The basic components of the instrument designed to measure the angular scattering profiles of clouds, hereafter called the cloud scattering instrument, are a lens, a series of field stops, an integrating sphere, and a detector. The arrangement is shown in Figure 1. The lens is a Nikkor 21mm focal length, f/4 35mm camera lens. The field stops are thirteen holes drilled in a rotating disc plus an opaque position. The hole sizes correspond to field of view ranging from 0.95° to 32.2° half angle. The integrating sphere is made from two 9-inch diameter plastic hemispheres with holes drilled at their "poles" for the entering and exiting light. The sphere is painted on the inside with 3M "White Velvet Coating", which is a 50-50 mixture of titanium dioxide and silicon dioxide. The detector is prevented from seeing direct radiation by a spider-mounted baffle on the optic axis 1.5 inches from the face of the detector. The detector is an RCA 7764 multiplier phototube with an S-11 response. This tube has its maximum response between 3900Å and 4900Å, and 50% sensitivity points at 3500 and 5700Å (Ref. 11).

The instrument is enclosed in a weather-tight box with an outer window of glass with a thin layer of evaporated chromium to act as a neutral density filter and heat reflector. Mounted on the same base plate and bore sighted

---

These instruments were loaned to The Aerospace Corporation by the Army Electronics Proving Ground at Fort Huachuca, Arizona, through the efforts of Capt. L. Johnson of Detachment 50, 6th Weather Wing, Space and Missile Systems Organization, Air Force Systems Command, Los Angeles, California
Figure 1. Optical Diagram
with the cloud scattering instrument is an Epply narrow-angle (2.85° half angle field of view), normal incidence pyrheliometer. The pyrheliometer has a visual indicator of correct solar pointing that can be used when the sun is shining to adjust the alignment of the two instruments during operation.

The instrument and the narrow-angle pyrheliometer are mounted on a conventional astronomical telescope clock drive whose polar axis was carefully aligned to true north. An appropriate declination adjustment of the instruments permitted correct tracking of the sun with the sun centered in the fields of view of the apertures. Electrical and signal connections are made through a set of slip rings mounted on the polar axle to prevent wind up of the cabling by the rotation of the drive.

The instrument was placed on a wooden platform on the roof of a hangar at Eglin Air Force Base approximately 50 feet above the ground. Figures 2 and 3 show the instrument in place. An Eppley wide-angle (2π field of view), horizontal incidence pyrheliometer was placed in an unshaded location on the roof of a small penthouse near the instrument.

The power and signal cabling was run approximately 200 feet to the Weather Operations room on the floor of the hangar where the recording electronics were housed. Because of the long cable run, preamplifiers were included in the weather-proof box.

The recording electronics consisted of a Hewlett-Packard Model 3440A Digital Voltmeter with a Model 3443A High Gain/Auto Range plug-in unit, a Hewlett-Packard Model 562AR-J74 Digital Recorder, a Parabam Digital Clock/Calendar, and additional automatic sequencing electronics built at The Aerospace Corporation.

The operation of the experiment was as follows. A 24-hour timer turned the electronics on before sunrise and off after sunset. A set of data was taken automatically every 10 min during this time. The instrument
Figure 2. Photograph of the Instrument as Seen From the Ground
Figure 3. Photograph of Instrument as Seen From the Roof
sequenced through the thirteen apertures from smallest to largest, stopping 1-2 seconds at each aperture to allow recording of the signal. After sequencing through the thirteen apertures, the instrument turned itself off at the opaque position. A zero (opaque) reading was taken at the start and end of each sequence. After cycling through the apertures, the instrument recorded the signals from the two pyrheliometers. Thermistors located in the cloud instrument and each of the pyrheliometers were also sampled. Finally, the minute, hour, and day number were recorded from the digital clock/calendar. The entire cycle took about a minute, after which the electronics went into standby until ten minutes elapsed.

The pyrheliometric measurements were made with two standard Eppley pyrheliometers, a 50-junction hemispheric pyrheliometer, and a Model 15 normal-incidence pyrheliometer (Ref. 12). The cloud height radar in operation at Eglin Air Force Base was a Model AN/TPQ-11 Radar Cloud Detecting Set operating in the K_A frequency band (33-36 GHz) (Ref. 13). The facsimile chart recordings from this instrument were provided to The Aerospace Corporation personnel who made the interpretations. These interpretations were made by combining the standard observations of the clouds and the indicated clouds on the charts. This was necessitated by the inability of the AN/TPQ-11 to detect all clouds. Kankor (Ref. 14) has analyzed the detection capabilities of the AN/TPQ-11 radar and found that only 62% of visually-observed overcast clouds were detected by the radar.

Standard meteorological observational data were supplied by the personnel at Eglin Air Force Base on WBAN Form 10 "Surface Weather Observations." The WBAN Form 10 includes the following data used in this experiment: time, sky condition, horizontal visibility, temperature and dew point, total sky cover, remarks, and supplemental coded data. Observations were made hourly except when rapidly changing conditions warranted more frequent observations. The supplemental coded data
included the synoptic code observations of low, middle, and high clouds (ICLCMCH) (Ref. 15). These were recorded every three hours. These synoptic measurements were used to identify the clouds present during our measurements. Identifications between the synoptic observations were made by interpolating between the bracketing observations using the remarks recorded by the observer as to advancing or receding clouds.

C. CALIBRATION

The calibration of the cloud scattering instrument entailed several steps. All the measurements were made in a darkroom using a small but very bright tungsten coil lamp mounted in the same horizontal plane as the cloud scattering instrument and about twenty feet away. A slight adjustment in the focus of the lens of the instrument was made to correct for the non parallelism of the light from twenty feet.

The normalization factors between the apertures were determined by measuring the on-axis signal for each aperture and normalizing to the smallest aperture \(10^6\). These normalization factors are listed in Table 1. The effective angular field of view of each aperture was determined as follows. With no limiting aperture, the intensity is given by a \(\cos^4\theta\) angular distribution.\(^2\) The signal was measured at a number of angles on both sides of the optic axis (in a horizontal plane only). The two points at which the signal dropped to 50% of the above-mentioned \(\cos^4\theta\) value were averaged to give the effective field of view of a given aperture. The results of these measurements are given in Table 2. The areas under these curves of angular response were measured with a planimeter to determine the solid angle factor for each aperture. These solid angle factors are given in Table 3.

\(^2\)The \(\cos^4\theta\) represents the fall off of intensity of off-axis rays due to geometric factors. See, for example: Jenkins and White, *Fundamentals of Optics*, Chapter 7.
Table 1. Aperture Normalization Factors

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Normalization Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(≈1.0000)</td>
</tr>
<tr>
<td>2.5</td>
<td>0.9882</td>
</tr>
<tr>
<td>5</td>
<td>0.9824</td>
</tr>
<tr>
<td>7</td>
<td>0.9824</td>
</tr>
<tr>
<td>10</td>
<td>0.9719</td>
</tr>
<tr>
<td>12</td>
<td>0.9644</td>
</tr>
<tr>
<td>14</td>
<td>0.9516</td>
</tr>
<tr>
<td>16</td>
<td>0.9143</td>
</tr>
<tr>
<td>18</td>
<td>0.8947</td>
</tr>
<tr>
<td>22</td>
<td>0.8330</td>
</tr>
<tr>
<td>26</td>
<td>0.8029</td>
</tr>
<tr>
<td>30</td>
<td>0.7928</td>
</tr>
<tr>
<td>32</td>
<td>0.7966</td>
</tr>
</tbody>
</table>
Table 2. Effective Fields of View

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Effective Field of View (Half Angle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0.9583^\circ$</td>
</tr>
<tr>
<td>2.5</td>
<td>$2.400^\circ$</td>
</tr>
<tr>
<td>5</td>
<td>$4.858^\circ$</td>
</tr>
<tr>
<td>7</td>
<td>$7.171^\circ$</td>
</tr>
<tr>
<td>10</td>
<td>$9.753^\circ$</td>
</tr>
<tr>
<td>12</td>
<td>$12.076^\circ$</td>
</tr>
<tr>
<td>14</td>
<td>$14.290^\circ$</td>
</tr>
<tr>
<td>16</td>
<td>$16.198^\circ$</td>
</tr>
<tr>
<td>18</td>
<td>$18.156^\circ$</td>
</tr>
<tr>
<td>22</td>
<td>$21.882^\circ$</td>
</tr>
<tr>
<td>26</td>
<td>$25.882^\circ$</td>
</tr>
<tr>
<td>30</td>
<td>$30.042^\circ$</td>
</tr>
<tr>
<td>32</td>
<td>$32.170^\circ$</td>
</tr>
</tbody>
</table>
Table 3. Solid Angle Factors

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Solid Angle Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0002688</td>
</tr>
<tr>
<td>2.5</td>
<td>0.0017617</td>
</tr>
<tr>
<td>5</td>
<td>0.0071867</td>
</tr>
<tr>
<td>7</td>
<td>0.015631</td>
</tr>
<tr>
<td>10</td>
<td>0.028955</td>
</tr>
<tr>
<td>12</td>
<td>0.044267</td>
</tr>
<tr>
<td>14</td>
<td>0.061882</td>
</tr>
<tr>
<td>16</td>
<td>0.079400</td>
</tr>
<tr>
<td>18</td>
<td>0.099587</td>
</tr>
<tr>
<td>22</td>
<td>0.14410</td>
</tr>
<tr>
<td>26</td>
<td>0.20062</td>
</tr>
<tr>
<td>30</td>
<td>0.26868</td>
</tr>
<tr>
<td>32</td>
<td>0.30705</td>
</tr>
</tbody>
</table>
The conversion factor in langley/volt for each of the pyrheliometers is given by the Eppley Company with their instruments. An additional calibration factor required is the gain of the preamplifiers that take the low-level pyrheliometer output and amplify it prior to its being transmitted down the long signal cable. It was impossible to calibrate the entire pyrheliometer-preamplifier-signal cable assembly as installed in Florida. An indirect method of calibration had to be applied.

Several crystal-clear days with very high reported horizontal visibility occurred in the early period of the experiment. The calculated transmittance of a Rayleigh atmosphere in the spectral region passed by the glass bulb of the pyrheliometers is 0.904 and the calculated transmittance of a turbid atmosphere is 0.718. Since the atmospheric conditions on these crystal-clear days seemed to be clearer than those described by Elterman for his "turbid" atmosphere, the simple Rayleigh atmospheric transmittance of 0.90 was adopted for the pyrheliometric readings on these days. With the use of this value of the transmittance, the calibration factors of the pyrheliometers were calculated. The absolute accuracy of the pyrheliometric measurements does not affect the shapes of the angular scattering profiles that are more significant to this study than the absolute magnitudes.

3 A langley is 1.0 cal/cm².

4 The calculated transmissions are based on Elterman's atmospheric attenuation model as given in Handbook of Geophysics and Space Environments, U.S. Air Force Cambridge Research Laboratories. New York: McGraw-Hill Book Co, Inc., 1965, Chapter 7. The spectral range was considered to be that passed by the glass window or envelope of the pyrheliometers; namely 0.35 to 2.5 microns. The sun with a spectral distribution as given in Chapter 16 of the Handbook was used for the radiation source.
IV. EXPERIMENTAL OPERATION AND DATA SAMPLE

A. PERIOD OF EXPERIMENT

The experiment was operated between 9 February and 18 October 1968. Because of equipment malfunctions, data were obtained only for the periods 9 February through 3 April, 5 April through 9 April, 17 April through 22 May, 12 June through 21 July, 28 August through 4 October, and 16 October through 18 October. The data for 15 May through 22 May were lost in the mails. The narrow-angle pyrheliometer was inoperative for the period 12 June through 21 July. The data for the period 28 August to the end of the experiment are considered unreliable because of a belatedly discovered possible misfocus and f/stop change. Reliable, complete data are available, therefore, only for 88 days between 9 February and 14 May. In addition, incomplete data (narrow-angle pyrheliometer inoperative) are available for the 40-day period between 12 June and 21 July.

B. DATA SAMPLE

During the 88-day period for which complete data are available, a total of 3296 measurements were made during times when the sun was higher than 35° above the horizon. Of these 3296 measurements, 530 were made during completely clear skies (0/10's cloud cover) and 1200 during completely overcast skies (10/10's cloud cover). The 1566 measurements made during periods of broken or scattered clouds were not used for further analysis because of the uncertain location of holes in the clouds with respect to the sun's position. In addition, measurements of overcast clouds made when more than one layer of clouds was reported were also not used for further analysis. This was because of uncertainties about breaks in the individual layers. This left a sample of 530 measurements during completely clear skies and 398 measurements made during single-layer, completely overcast skies. Of the 398 overcast measurements, 64 were discarded because of various problems with the data.
Table 4 gives a breakdown of the 3296 measurements by the amount of cloud cover. Table 5 gives a breakdown of the 1200 overcast measurements by the number of cloud layers reported. Table 6 further breaks down the single-layer overcast measurements into reported cloud types. This table gives the breakdown of the measurements upon which the analysis was based.
Table 4. Number of Measurements Made by Amount of Cloud Cover  
(Solar Elevation Angle $\geq 35^\circ$)

<table>
<thead>
<tr>
<th>Cloud Cover</th>
<th>Number of Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/10</td>
<td>530</td>
</tr>
<tr>
<td>1/10</td>
<td>236</td>
</tr>
<tr>
<td>2/10</td>
<td>152</td>
</tr>
<tr>
<td>3/10</td>
<td>142</td>
</tr>
<tr>
<td>4/10</td>
<td>189</td>
</tr>
<tr>
<td>5/10</td>
<td>109</td>
</tr>
<tr>
<td>6/10</td>
<td>112</td>
</tr>
<tr>
<td>7/10</td>
<td>215</td>
</tr>
<tr>
<td>8/10</td>
<td>214</td>
</tr>
<tr>
<td>9/10</td>
<td>168</td>
</tr>
<tr>
<td>10/10</td>
<td>1200</td>
</tr>
<tr>
<td>Broken (6/10 to 9/10)</td>
<td>7</td>
</tr>
<tr>
<td>Scattered (1/10 to 5/10)</td>
<td>16</td>
</tr>
<tr>
<td>Unknown</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>3296</td>
</tr>
</tbody>
</table>
Table 5. Number of Measurements of 10/10's Cloud Cover by Number of Cloud Layers Reported

<table>
<thead>
<tr>
<th>Number of Cloud Layers</th>
<th>Number of Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>398</td>
</tr>
<tr>
<td>2</td>
<td>486</td>
</tr>
<tr>
<td>3</td>
<td>249</td>
</tr>
<tr>
<td>≥4</td>
<td>67</td>
</tr>
<tr>
<td>Total</td>
<td>1200</td>
</tr>
</tbody>
</table>
Table 6. Number of Complete Measurements of Single-Layer 10/10's Cloud Cover by Cloud Type

<table>
<thead>
<tr>
<th>Cloud Type</th>
<th>Name</th>
<th>No. of Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low clouds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_L = 3$</td>
<td>Cumulonimbus</td>
<td>3</td>
</tr>
<tr>
<td>$C_L = 4$</td>
<td>Stratocumulus cumulogenitus</td>
<td>5</td>
</tr>
<tr>
<td>$C_L = 5$</td>
<td>Stratocumulus</td>
<td>34</td>
</tr>
<tr>
<td>$C_L = 6$</td>
<td>Stratus</td>
<td>127</td>
</tr>
<tr>
<td>Middle clouds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_M = 1$</td>
<td>Altostratus</td>
<td>5</td>
</tr>
<tr>
<td>$C_M = 3$</td>
<td>Altocumulus translucidus</td>
<td>5</td>
</tr>
<tr>
<td>$C_M = 7$</td>
<td>Altocumulus opacus</td>
<td>17</td>
</tr>
<tr>
<td>High clouds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_H = 1$</td>
<td>Cirrus fibratus</td>
<td>5</td>
</tr>
<tr>
<td>$C_H = 7$</td>
<td>Cirrostratus</td>
<td>133</td>
</tr>
<tr>
<td>Incomplete data or unknown cloud type</td>
<td></td>
<td>64</td>
</tr>
</tbody>
</table>
V. DATA REDUCTION

The first stage in the data reduction scheme was the laborious manual transcription of the data from the digital printer tapes to computer coding sheets. This was done by the computress staff in the Space Physics Laboratory at The Aerospace Corporation.

Three cards were used to encode all the data for each observation. The data included for each observation were the following: day, time, wide-angle pyrheliometer reading, narrow-angle pyrheliometer reading, phototube initial and final zero readings, the thirteen aperture readings, the thermistor readings of the two pyrheliometers and the phototube, an abbreviated description of the weather and obscurations to vision, the total cloud cover, the horizontal visibility, the air temperature and dew point, and a description of up to four layers of clouds. This description included the coverage of the individual layer, the type of cloud, and the base and top of the layer.

A computer program was written (by R. T. H.) which took these three cards for each observation and computed the mean relative radiance and irradiance, the wide- and narrow-angle transmittances, the relative humidity, and the solar elevation angle. All these data were printed by the computer on one page together with verbal descriptions of the weather and clouds. Plots were made on 35-mm film of the mean relative radiance and irradiance as a function of the field of view. An example of a page of computed data is given in Figure 4.
DAY 99  TIME 850  SOLAR ELEVATION ANGLE 42.70 DEGREES  TOTAL CLOUD COVER 10
TEMPERATURE  68 DEGREES F.,  RELATIVE HUMIDITY 90 %,  HORIZONTAL VISIBILITY 2.5 MILES
PPT (WITHOUT ANGULAR FACTOR)  12.85%,  PPI  20.12%,  PPN,  .24%,  ZERO  2.800E-04,  ZERO VARIANCE 4.000E-05
WEATHER AND OBSTRUCTIONS TO VISION
PARTIALLY OBCUDED SKY

OBSTRUCTION TO VISION = FOG

CLOUD LAYER 1
10 TENTHS COVER OF LOW  CLOUD TYPE 6
WITH ITS BASE AT  400 FEET AND ITS TOP AT  2000 FEET.
NO OTHER LAYERS

<table>
<thead>
<tr>
<th>THETA, DEGREES</th>
<th>RELATIVE AIRHADRANCE</th>
<th>RELATIVE RADIANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.170</td>
<td>.07552</td>
<td>2.4596E-01</td>
</tr>
<tr>
<td>30.0420</td>
<td>.06705</td>
<td>2.4955E-01</td>
</tr>
<tr>
<td>25.8820</td>
<td>.05066</td>
<td>2.5254E-01</td>
</tr>
<tr>
<td>21.8820</td>
<td>.03593</td>
<td>2.4934E-01</td>
</tr>
<tr>
<td>18.1560</td>
<td>.02417</td>
<td>2.4268E-01</td>
</tr>
<tr>
<td>16.1980</td>
<td>.01900</td>
<td>2.3930E-01</td>
</tr>
<tr>
<td>14.2900</td>
<td>.01471</td>
<td>2.3771E-01</td>
</tr>
<tr>
<td>12.0760</td>
<td>.01042</td>
<td>2.3529E-01</td>
</tr>
<tr>
<td>9.7630</td>
<td>.00733</td>
<td>2.5300E-01</td>
</tr>
<tr>
<td>7.1710</td>
<td>.00432</td>
<td>2.7619E-01</td>
</tr>
<tr>
<td>4.8580</td>
<td>.00196</td>
<td>2.7265E-01</td>
</tr>
<tr>
<td>2.4000</td>
<td>.00047</td>
<td>2.6678E-01</td>
</tr>
<tr>
<td>.9583</td>
<td>.00007</td>
<td>2.6042E-01</td>
</tr>
</tbody>
</table>

Figure 4. Sample Output Data Sheet
The relationships used to compute the various output quantities are the following:

\[
\text{IRRAD}(I) = [\text{READING}(I) - \text{ZERO}] \times \text{NFAC}(I) \tag{1}
\]

\[
\text{RAD}(I) = \frac{\text{IRRAD}(I)}{\text{SAF}(I)} \tag{2}
\]

\[
\text{RELHUM} = \left[\frac{\text{VP(DEWPT)}}{\text{VP(TEMP)}}\right] \times 100 \tag{3}
\]

\[
\sin \gamma = \sin \delta \sin \phi + \cos \delta \cos \Omega \cos \phi \text{ (Ref. 16)} \tag{4}
\]

\[
\Omega = \text{TIME} - 11.76722 \tag{5}
\]

\[
\cos \beta = \sin \gamma \left[\cos \epsilon + \sin \epsilon \cos A \tan \phi\right] \text{ (Ref. 16)} \tag{6}
\]

\[
I_0 = \frac{2.000}{R_v^2} \text{ (Ref. 16)} \tag{7}
\]

\[
T_{\text{ww}} = \left[\frac{\text{WA}}{I_0}\right] \tag{8}
\]

\[
T_W = \frac{T_{\text{ww}}}{\cos \beta} \text{ (Ref. 16)} \tag{9}
\]

\[
T_n = \left[\frac{\text{NA}}{I_0}\right] \tag{10}
\]

The definitions of the quantities in these equations are:

- \text{IRRAD}(I) = \text{mean relative irradiance for aperture I}
- \text{ZERO} = \text{average of initial and final zero readings}
- \text{READING}(I) = \text{reading for aperture I}
- \text{NFAC}(I) = \text{normalization factor for aperture I}
- \text{RAD}(I) = \text{mean relative radiance for aperture I}
- \text{SAF}(I) = \text{solid angle factor for aperture I}
- \text{RELHUM} = \text{relative humidity}
- \text{VP}(I) = \text{vapor pressure of water at temperature I}
- \text{DEWPT} = \text{dew point temperature}

5Not all these quantities were actually used in the final analysis. Printouts of the complete output data are available from the author.

6It should be noted that \(\cos \beta = \sin \gamma\) for a horizontal plane, and Equation 9 would take its usual form \(T_W = T_{\text{ww}}/\sin \gamma\).
TEMP = air temperature

γ = solar elevation angle

δ = solar declination angle

ϕ - latitude (30°29'N for Eglin AFB)

Ω = hour angle (11.76722 is the local Central Standard Time of true solar noon at Eglin AFB)

β = angle between the solar elevation angle, γ, and the normal to an arbitrarily inclined plane

ε = angle between a horizontal plane and an arbitrarily inclined plane

A = azimuth of the vertical plane containing the normal to an arbitrarily inclined plane

I₀ = amount of solar radiation incident at the top of the atmosphere

(2,000 langleyas per minute is the solar constant used)

Rᵥ = radius vector of the sun (earth-sun distance)

TᵥW = wide-angle transmittance of the sun's radiation not taking into account the solar elevation angle

Tᵥ = narrow-angle transmittance

WA = wide-angle pyrheliometer calibrated reading

NA = narrow-angle pyrheliometer calibrated reading

The quantities β and ε above were necessitated by a small tilt (~3°WNW) of the wide-angle, horizontal incidence pyrheliometer which occurred shortly after its installation. The correction resulted in approximately a 5% change in the wide-angle pyrheliometer readings.
VI. ANALYSIS AND RESULTS

A. ANALYSIS

The goal of the experiment was the development of a realistic model of the angular scattering profiles of clouds for use in designing visible-light optical systems. It was hoped that the observed scattering profiles could be correlated with some routinely observed meteorological quantity or quantities so that system performances could be predicted from readily available meteorological data.

Various correlations and relationships were tried. The most obvious is a correlation between the irradiance measurements and the cloud type. This correlation was tried and failed. This failure is probably due to the great variability in cloud characteristics within a cloud type. The same cloud can exist over a wide range of thicknesses and opacities.

The failure of this obvious correlation prompted a search for some other way of describing the scattering profiles, such as a combination of the measures of the direct and diffuse solar radiation. This description should be reasonable in light of the observation that on a clear day the sun's radiation is virtually entirely direct and that on a heavily overcast day the sun's radiation which penetrates to the earth is entirely diffuse. All other cases should be some combination of these two extremes. The intermediate cases can be described by a bright spot at the position of the sun surrounded by a diffusely scattering region.

The results as derived by the computer analysis are in terms of relative irradiances. A more useful quantity is the transmittance. Since there was no way to derive absolute transmittances from the relative irradiances an alternative was to derive the transmittances relative to a clear sky. The transmittances could be determined from the relative
Figure 5. Relative Irradiance Plot for 1205 Hours, 1 March 1968
### Table 7. Relative Irradiance and Least-Squares Values for Clear Sky Case

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>Relative Irradiance</th>
<th>Least-Squares Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9583</td>
<td>---</td>
<td>2.06447</td>
</tr>
<tr>
<td>2.400</td>
<td>2.06147</td>
<td>2.06509</td>
</tr>
<tr>
<td>4.858</td>
<td>2.06995</td>
<td>2.06613</td>
</tr>
<tr>
<td>7.171</td>
<td>2.06613</td>
<td>2.06712</td>
</tr>
<tr>
<td>9.763</td>
<td>2.06845</td>
<td>2.06822</td>
</tr>
<tr>
<td>12.076</td>
<td>2.06969</td>
<td>2.06920</td>
</tr>
<tr>
<td>14.290</td>
<td>2.07364</td>
<td>2.07014</td>
</tr>
<tr>
<td>16.198</td>
<td>2.07244</td>
<td>2.07096</td>
</tr>
<tr>
<td>18.156</td>
<td>2.06909</td>
<td>2.07179</td>
</tr>
<tr>
<td>21.882</td>
<td>2.07186</td>
<td>2.07337</td>
</tr>
<tr>
<td>25.882</td>
<td>2.07277</td>
<td>2.07508</td>
</tr>
<tr>
<td>30.042</td>
<td>2.07434</td>
<td>2.07685</td>
</tr>
<tr>
<td>32.170</td>
<td>2.08186</td>
<td>2.07775</td>
</tr>
</tbody>
</table>

(Relative Irradiance)\text{clear sky} = 2.064064 + 0.0004255\theta
Figure 6a. Sample Plot Showing Example of Quality of Fit
0921 hr 2 MARCH 1968
10/10's ALTOCUMULUS OPACUS CLOUDS
BASE 13,000 ft
TOP 18,000 ft
13 MILE HORIZONTAL VISIBILITY
\( T_n = 0.012 \)
\( T_w = 0.547 \)
\( A = 0.016 \)
\( B = 0.4996 \)
"GOOD" FIT

Figure 6b. Sample Plot Showing Example of Quality of Fit
Figure 6c. Sample Plot Showing Example of Quality of Fit
Figure 6d. Sample Plot Showing Example of Quality of Fit
Figure 6e. Sample Plot Showing Example of Quality of Fit
With the coefficients A and B available as descriptors of the transmittance profiles, correlations of these coefficients with routinely measured actinometric quantities could be tested. The four combinations of A and B with $T_w$ and $T_n$ were tested for possible correlations. Separate tests were made for "good", "fair", "poor", "good + fair", and all data. Some of these plots are shown in Figures 7-10.

Looking at Figure 7 there appears to be a linear correlation with an origin intercept between $T_n$ and A. This is reasonable in view of the fact that both are measures of the direct sunlight. A linear correlation with origin intercept between $T_w$ and B is again indicated in Figure 8 although the scatter is fairly great at large values of $T_w$. This correlation is also reasonable in view of the fact that both quantities are measures of the diffuse radiation.

Figure 9 shows no simple correlation between $T_n$ and B as would be expected. Figure 10 illustrates a more complex situation. A linear correlation seems to exist between $T_w$ and A but with a non-zero intercept. It would seem that a threshold value of $T_w$ must be exceeded before A has a nonzero value. This is reasonable from the observation that the sun can be seen through the clouds only for a range of transparency of the clouds. For more opaque clouds no direct sunlight can be seen.

Linear least-squares fits of these data and their correlation coefficients were calculated to quantify these visual correlations. The "poor" data were omitted from these calculations. The calculations for $T_w$ versus B and $T_n$ versus A are straightforward. The calculation of $T_w$ versus A requires that the threshold point be determined first. The threshold point was found by using only those points in the least-squares
Figure 9. Plot of $T_n$ vs $B$
calculations whose \( T_w \) coordinate was above some arbitrary value. The threshold point was defined when the \( T_w \) cutoff most nearly equalled the \( T_w \)-axis intercept. The threshold determined by this method was 0.54. The results of the linear least-squares calculations are plotted in Figures 11-13 and tabulated in Table 8.

An additional correlation between \( T_w \) and \( T_n \) was tested. These data are shown in Figure 14. The results are qualitatively similar to those for the correlation between \( T_w \) and \( A \). The least-squares fit with a \( T_w \) threshold of 0.54 gave the straight line shown in Figure 14 and the results tabulated in Table 8.

B. RESULTS

In light of the good correlation between \( T_n \) and \( A \) and between \( T_w \) and \( B \), it would appear that a reasonable model of the angular scattering characteristics of clouds has been found which can be quantitatively calculated from two routine meteorological observations. Combining the results tabulated in Table 8 with Equation 11 results in the following formula for the visible light angular transmittance of a cloud relative to that of the clear sky as a function of the narrow- and wide-angle pyrheliometric transmittance:

\[
T = -0.0056 + 0.89 \times T_n + \left[ -0.028 + 1.09 \times T_w \right] \times \sin^2 \theta \quad (12)
\]

The formula is valid at least for \( \theta \leq 35^\circ \). For larger values of \( \theta \) an extrapolation of unknown accuracy is assumed.

How well this model will predict the angular transmittance profiles is shown in Figures 15a-e. The data are the same as used in Figures 6a-e. The lines in the figures are calculated from Equation 12; the points are the observed data. The agreement of the calculated lines
Figure 13. Plot of $T_w$ vs $B$ Showing Linear Least-Squares Fitted Line
Table 8. Least-Squares Fitted Relationships Between $T_n$, $T_r$, $A$, and $B$

$T_n$ vs $A$: $A = -0.0056 + 0.89 \times T_n$
[correlation coefficient = 0.98]

$T_w$ vs $A$: $A = -0.0026 + 0.0126 \times T_w$ ($T_w < 0.54$)
[correlation coefficient = 0.24]

$A = -1.0427 + 1.92 \times T_w$ ($T_w \geq 0.54$)
[correlation coefficient = 0.76]

$T_w$ vs $B$: $B = -0.0281 + 1.09 \times T_w$
[correlation coefficient = 0.77]

$T_w$ vs $T_n$: $T_n = -0.00417 + 0.029 \times T_w$ ($T_w < 0.54$)
[correlation coefficient = 0.45]

$T_n = -1.190 + 2.19 \times T_w$ ($T_w \geq 0.54$)
[correlation coefficient = 0.84]
Figure 15a. Sample Plot Showing Accuracy of Model
Figure 15b. Sample Plot Showing Accuracy of Model
Figure 15c. Sample Plot Showing Accuracy of Model

1438 hr 18 APRIL 1968
10/10's CIRROSTRATUS CLOUDS
BASE 30,000 ft
TOP 37,000 ft
13 MILE HORIZONTAL VISIBILITY

T_n = 0.708
T_w = 0.798
Figure 15d. Sample Plot Showing Accuracy of Model
Figure 15e. Sample Plot Showing Accuracy of Model
with the observed points is quite satisfactory. An estimate of the accuracy of a calculated transmittance is ±0.02 or ±10%, whichever is greater.
VII. INTERPRETATION AND APPLICATION

A. INTERPRETATION

The success of the angular scattering model developed here is really a validation of the idea that the transmission of light through the atmosphere has two components: a direct component and a scattered component, and that these two components are separable. The relative magnitudes of the two components varies with the characteristics of the scattering media in the light beam. The direct component is important only when the wide-angle transmittance of the scattering media is greater than roughly 0.50.

Diffuse radiation is usually taken to mean an intensity decrease with the cosine of the angle to the normal of the surface from which the radiation emerges. Such a surface appears equally bright from all directions because this cosine dependence just compensates for the foreshortening of the surface as seen by the observer. The diffuse component of $T_w \sin^2 \theta$, which was calculated from this experiment would have been simpler to explain if the measurements could have been made by observing at the zenith so that the vector to the sun would have been perpendicular to the cloud layer. Then $\theta$ would have been the ray angle from the cloud normal. However, the minimum solar zenith angle during the experiment was about $12^\circ$ and measurements were necessary at still larger zenith angles (to $55^\circ$) to obtain a reasonable data sample. Because a diffuse surface appears equally bright in all directions, the readings obtained for the diffuse components are still properly made. Note, however, that for nonzero solar zenith angles, the path length of the radiation through the cloud increases and the transmittance decreases. This is borne out qualitatively by the diurnal plots of $T_w$ (denoted PPT) in Ref. 1.
It should be possible to relate $T_w$ and $T_n$ directly to $A$ and $B$. Indeed $T = T_w$ for $\theta = 90^\circ$ and $T = T_n$ for $\theta = 2.85^\circ$. If we use these relations to evaluate $A$ and $B$ we find that:

$$T \approx T_n + (T_w - T_n) \times \sin^2 \theta$$

These values of $A$ and $B$ do not correlate with the experimental data as well as those deduced above. Possible partial explanations for this discrepancy include:

1. The cloud scattering instrument measures in the spectral band from about 0.35 to 0.57 microns with an S-11 photomultiplier response. The pyrheliometers are thermal detectors which respond to all wavelengths transmitted by the atmosphere and by their glass envelopes or windows, i.e. from about 0.35 to 2.5 microns. The scattering properties of the cloud droplets are wavelength dependent.

2. The corrections for atmospheric absorption used in the normalizations are not the same for the two types of instruments.

3. The model was derived only for $\theta \leq 35^\circ$. An extrapolation of the model to $\theta = 90^\circ$ is of unknown accuracy.

B. APPLICATION

The model derived for the angular scattering profile of visible solar radiation through clouds has several possible limitations on its validity and applicability. The primary limitation is that the model is valid only for single, overcast cloud layers. Multiple cloud layers cannot be treated for the simple reason that the light impinging on the second layer after emerging from the first layer no longer can be considered to be collimated. Rather it has a scattered component that will diffusely illuminate the second layer, thereby grossly deviating from the conditions of the model.
Likewise the model is inapplicable for broken clouds even with the source behind one of the clouds. The direct component is affected by the presence of broken clouds to the same extent as it was for an overcast layer. However, the scattered component will be grossly changed because of the non-uniform scattering medium. The change can be either to increase or decrease the apparent scattered component. The increase could result from strong reflections off the sides of the clouds into the field of view of the sensor. A decrease might result from a fortuitous arrangement of the clouds so as to preferentially scatter the beam away from the sensor with little or no scattering back into the beam. Such a case might be a single small cloud directly in front of the source with no other clouds in the sky.

A further limitation is that the model is applicable only to collimated light. Diverging or converging light might deviate wildly from the results predicted by the model. This aspect of the model is subject to experimental verification albeit with considerable difficulty.

What has been developed here is a model which describes the angular scattering characteristics of collimated visible light through a single, overcast layer of clouds. The model gives satisfactory agreement with experimental observations. The model should be of great use in the evaluation and prediction of the performance of visible light optical systems in the presence of clouds. It should also serve as a useful stepping off point for the development of models of more complex situations such as broken clouds or multiple cloud layers. It should also serve as a useful test for the theoretical models of collimated light incident on an infinite scattering layer.
REFERENCES


2. For example see:

3. B. Haurwitz, J. Meteor. 2, 154 (1945); 3, 123 (1946); 5, 110 (1948).


APPENDIX

EGLIN DATA FOR 10/10's COVER SORTED BY CLOUD TYPE

A listing of all 334 data samples is shown on the following pages.
<table>
<thead>
<tr>
<th>CLOUD TYPE</th>
<th>DAY</th>
<th>TIME</th>
<th>BASE</th>
<th>TOP</th>
<th>WEATHER</th>
<th>MOP, T x 100</th>
<th>T x 100</th>
<th>NO. OF APERTURES</th>
<th>SOLAR ELEV.</th>
<th>ANGLE</th>
<th>C(1)</th>
<th>C(2)</th>
<th>FIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>L4</td>
<td>1754</td>
<td>300</td>
<td>1000</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>67.12</td>
<td>0.000</td>
<td>.3046</td>
<td>GOOD</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>1744</td>
<td>500</td>
<td>3000</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>68.62</td>
<td>0.000</td>
<td>.0121</td>
<td>FAIR</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>1734</td>
<td>400</td>
<td>2000</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>69.98</td>
<td>0.000</td>
<td>.0150</td>
<td>GOOD</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>1724</td>
<td>400</td>
<td>2000</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>54.91</td>
<td>0.000</td>
<td>.1579</td>
<td>GOOD</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>1156</td>
<td>4000</td>
<td>6000</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>27.29</td>
<td>0.000</td>
<td>.2638</td>
<td>GOOD</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>1156</td>
<td>4000</td>
<td>7500</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>56.11</td>
<td>0.000</td>
<td>.5977</td>
<td>FAIR</td>
<td></td>
</tr>
<tr>
<td>L4</td>
<td>1156</td>
<td>4000</td>
<td>7500</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>60.10</td>
<td>0.000</td>
<td>.4941</td>
<td>FAIR</td>
<td></td>
</tr>
<tr>
<td>L5</td>
<td>1126</td>
<td>4000</td>
<td>9000</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>53.57</td>
<td>0.000</td>
<td>.7699</td>
<td>GOOD</td>
<td></td>
</tr>
<tr>
<td>L5</td>
<td>1036</td>
<td>4000</td>
<td>9000</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>54.52</td>
<td>0.000</td>
<td>.2097</td>
<td>GOOD</td>
<td></td>
</tr>
<tr>
<td>L5</td>
<td>956</td>
<td>4000</td>
<td>9000</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>50.12</td>
<td>0.000</td>
<td>.2166</td>
<td>GOOD</td>
<td></td>
</tr>
<tr>
<td>L5</td>
<td>949</td>
<td>5000</td>
<td>2000</td>
<td>XTRMF</td>
<td>.6</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>50.60</td>
<td>0.000</td>
<td>.1902</td>
<td>GOOD</td>
<td></td>
</tr>
</tbody>
</table>

-A-2-