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ANALYSIS OF SOLAR TRANSMISSION DATA FROM SABLE 89

D.R. Longtin

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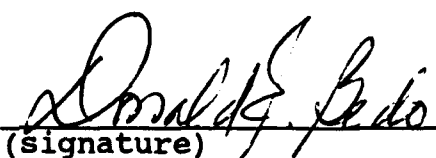
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13. ABSTRACT (Maximum 200 words) This report analyzes solar transmissometer data that was taken during the South Atlantic Backscatter Lidar Experiment (SABLE). The instrument operated on six days between 25 June and 7 July 1989. The instrument was located on Ascension Island, and it measured solar transmission at 532 nm versus time and transmission across the solar spectrum. Time series of solar transmissions at 532 nm are used to study the properties of cirrus and boundary layer stratocumulus that passed in front of the sun while the instrument was working. For 25 June 1989, a qualitative assessment shows the transmissions through cirrus to be between 0.4 and 0.8, and the cirrus thicknesses are estimated to be between 1.0 and 2.2 km. These estimates are consistent with cirrus observations and from aircraft. The analysis also focuses on the properties of the stratocumulus cloud edges and thin spots. Stratocumulus are shown to have very similar edge characteristics from day-to-day: there is a uniform distribution of cloud transmission values between about 0.1 and 0.7, and the percentages increase significantly as cloud transmissions increase from 0.7 to 0.9. The number of occurrences of stratocumulus thin spots and edges are then compared against the total number of stratocumulus occurrences. The comparisons clearly show that the stratocumulus over Ascension Island often are not optically thick and they frequently transmit partial direct solar radiation.				
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ANALYSIS OF SOLAR TRANSMISSION DATA FROM SABLE 89

1 INTRODUCTION

The Geophysics Directorate of Phillips Laboratory (PL/GP), in collaboration with the Royal Signal and Radar Establishment (RSRE), has performed an extensive series of aerosol laser backscatter measurements at Ascension Island as part of the South Atlantic Backscatter Lidar Experiment (SABLE)¹. A series of experiments took place in the fall of 1988 (SABLE 88) and a second in the summer of 1989 (SABLE 89) as a part of a continuing effort to study the aerosol backscatter characteristics of the atmosphere. Catalogs of information and available data from SABLE 88 and SABLE 89 have been assembled^{2,3}.

During SABLE 89, an EK/EG&G solar transmissometer was operated on Ascension Island. Details about the instrumentation are given elsewhere³. As the transmissometer tracked the sun, the system was operated alternately in one of the following modes: at 532 nm as a function of time, and scans of solar spectrum from 400 to 1200 nm. (Note that due to instrument problems, the useable spectral region was from 450 to 1000 nm.) For reference, Table 1 gives the dates and times when the solar transmissometer was operated. Clearly, the series of measurements form an extensive data base with which one can explore the properties of aerosols and clouds over Ascension Island.

¹ Alejandro, S.B., Koenig, G.G., Vaughn, J.M., and Davies, P.H. (1990) "SABLE: A South Atlantic Aerosol Backscatter Measurement Program," *Bul. Am. Meteor. Soc.*, 71:281-287.

² Hummel, J.R., and Longtin, D.R. (1992) "Catalog of Data and Information from the 1988 SABLE Mission," in progress.

³ Hummel, J.R., and Longtin, D.R. (1992) "Catalog of Data and Information from the 1989 SABLE Mission," in progress.

Table 1. Dates and Times When the EK/EG&G Solar Transmissometer Was Used During SABLE 89. All listed times are local time which is the same as GMT for Ascension Island

DATE	532 nm SCAN TIMES	SOLAR SCAN TIMES
25 June 1989	11:43-12:01	12:04-12:16
	12:19-12:36	12:38-12:50
	12:54-13:11	13:14-13:26
	13:29-13:46	13:49-14:01
	14:05-14:22	14:27-14:31 (partial scan)
28 June 1989	13:31-14:14	14:16-14:23
	14:27-15:09	15:12-15:24
	15:27-15:55	
	16:23-17:06	17:09-17:22
	17:24-17:38	
1 July 1989	11:41-12:54	12:57-13:13
	13:16-14:03	14:05-14:18
	14:22-15:07	15:09-15:24
	15:31-16:13	
2 July 1989	10:21-11:07	11:18-11:35
	11:39-12:29	12:31-12:45
	12:48-13:35	13:37-13:51
	13:54-14:44	14:47-15:01
	15:04-15:56	15:59-16:14
	17:21-18:01	
6 July 1989	09:33-10:18	10:21-10:32
	10:39-11:25	11:28-11:40
	11:43-12:27	12:30-12:43
	12:52-13:44	13:47-13:51 (partial scan)
	14:03-14:53	14:56-15:09
	15:12-15:58	16:01-16:14
	16:17-17:01	17:03-17:15
	17:18-18:02	18:04-18:19
	18:23-18:37 (poor quality)	
7 July 1989	10:31-11:19	11:22-11:35
	11:38-12:23	12:25-12:39
	12:43-13:28	13:30-13:42
	13:46-14:29	14:32-14:50
	14:53-15:42	15:47-16:01
	16:07-17:06	17:10-17:22
	17:26-18:12	18:15-18:28
	18:30-18:54	

1.1 Purpose and Organization of Report

The purpose of this report is to analyze measurements from the EK/EG&G solar transmissometer. The focus of this report will be the transmission data at 532 nm versus time partly because the solar scans suffered from instrumentation problems. Chapter 2 validates the calibration procedure for the transmission data using the Langley method. Chapter 3 investigates the properties of aerosols and clouds at Ascension Island using the data base of solar transmissometer measurements. Specifically, solar transmissions at 532 nm will be used to study the properties of cirrus and stratocumulus clouds near Ascension Island. Finally, Chapter 4 presents a summary of the results in this report. For reference, Appendix A describes the standard procedure for calibrating the solar transmissometer. Finally, Appendix B gives brief descriptions of computer programs that were developed to analyze the solar transmissometer data, as well as details about how the transmission data files are formatted.

2 VALIDATION OF SOLAR TRANSMISSION MEASUREMENTS

2.1 Concerns About Instrument Calibration

As the solar transmissometer tracked the sun, it measured an electrical current (in nanoamperes) which was then converted to a solar transmission using calibration factors that were based on the current from a filament lamp of known spectral intensity. Unfortunately, the system was very old and there was some question about the quality of the filament lamp. Additionally, the integrating sphere was damaged and there was a re-entrant spectrum problem. An attempt was made to compensate for these problems during SABLE 89, however it is recognized that these corrections are no more than stopgap measures.

2.2 Recalibration Using the Langley Method

As an independent check, the solar transmission at 532 nm has been derived directly from the measured solar signal using the Langley calibration method. The Langley method is an application of Beer's law which can be expressed as

$$\tau_{\lambda} = \exp \left[- \int_0^L k_{\lambda}(l) dl \right] \quad (1)$$

where τ_{λ} is the monochromatic transmittance, $k_{\lambda}(l)$ is the extinction coefficient including molecular and aerosol effects, and $dl = \sec \phi dz$. Clearly, Eq. 1 assumes that atmospheric emission is small, which is reasonable at solar wavelengths, and multiple scattering is insignificant. In the Langley method, the calibration factor is defined as $K_{\lambda} \equiv \tau_{\lambda}/i_{\lambda_s}$ where i_{λ_s} is the measured solar signal at the wavelength of interest. Thus, Eq. 1 can be rewritten as

$$\ln i_{\lambda_s} = - \ln K_{\lambda} - \sec \phi \int_0^{\infty} k_{\lambda}(z) dz \quad (2)$$

where ϕ is the solar zenith angle and z is altitude. Assuming the integral in Eq. 2 is relatively constant over the course of a day (i.e., a range of $\sec \phi$), the expression is linear in $\ln i_{\lambda_s}$ and $\sec \phi$ to a good approximation. (For Ascension Island, this is especially true given the high degree of horizontal homogeneity in that area.) Due to the earth's curvature, however, the approximation is only good for solar zenith angles less than 70 degrees. The calibration factor then is found by plotting measured values of $\ln i_{\lambda_s}$ versus $\sec \phi$ and extending a "best fit" line back to $\sec \phi = 0$. In the Langley method, note that a calibration factor is extremely sensitive to the best fit line drawn because it is defined as the exponential of the axis intercept.

Scatter plots of $\ln i_{\lambda_s}$ versus $\sec \phi$ were constructed for each day of solar transmission data in SABLE 89. For reference, these plots are shown in Figures 1 through 6. The Figures also show the best fit lines that were drawn for calibration factors. Note that deviant points below the linear envelope are due to clouds blocking the sun, and they are not used in the Langley method. Also when drawing the best fit lines, only data for $\sec \phi$ less than 3.0 (i.e., solar zenith angles less than 70°) were considered, because Eq. 2 breaks down when the sun is low in the sky. Calibration factors could have been obtained with a least squares approach as opposed to a

graphical approach, but a least squares approach would remain somewhat subjective because it would be based on an arbitrary selection of data points that make up the linear envelope. Table 2 lists the daily calibration factors that were derived from Figures 1 through 6.

Figures 7 through 12 compare daily solar transmissions at 532 nm as derived with the filament lamp calibration and Langley calibration. Generally speaking, there is reasonable agreement between the two calibration methods. In Figures 11 and 12, which represent 6 and 7 July 1989, respectively, there is near perfect agreement between the two methods. The extensive data sets on 6 July and 7 July may account for the exceptional agreement because the calibration factors for the Langley method can be obtained with more reliable best fit lines. For 25 and 28 June 1989, the Langley transmissions are about 5% less than the filament lamp transmissions. The largest differences exist on 1 and 2 July where transmissions derived from the Langley method are about 10% less than those from the filament lamp. It is difficult to say which calibration technique is "correct" because both methods have their limitations. However, the transmissions derived from the Langley method appear to show better agreement with the day-to-day trends in observed surface visibility at Ascension Island (see Section 3.1).

Table 2. Daily Calibration Factors for the Solar Transmissometer Obtained with the Langley Method

DATE	$\ln K_\lambda$	K_λ
25 June 1989	4.3916	80.775
28 June 1989	4.3533	77.737
1 July 1989	4.3800	79.838
2 July 1989	4.3950	81.045
6 July 1989	4.3633	78.518
7 July 1989	4.4166	82.819

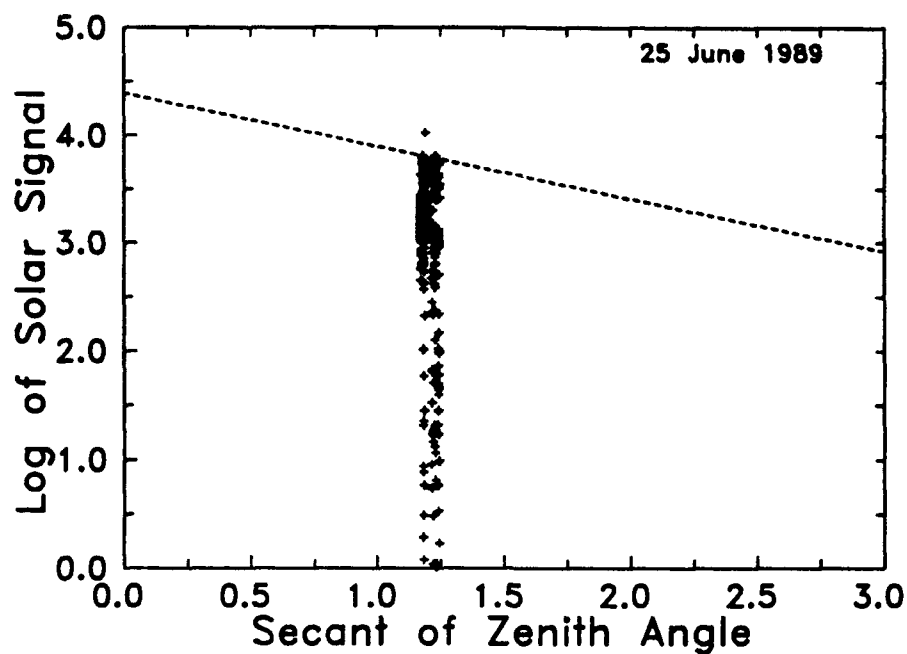


Figure 1. Scatter Plot of $\ln i_{\lambda_s}$ as a Function of $\sec \phi$ for 25 July 1989. The dashed line is the best fit line for the Langley method. Because they represent transmissions through clouds, values of $\ln i_{\lambda_s}$ less than 0.0 are not plotted to reduce clutter

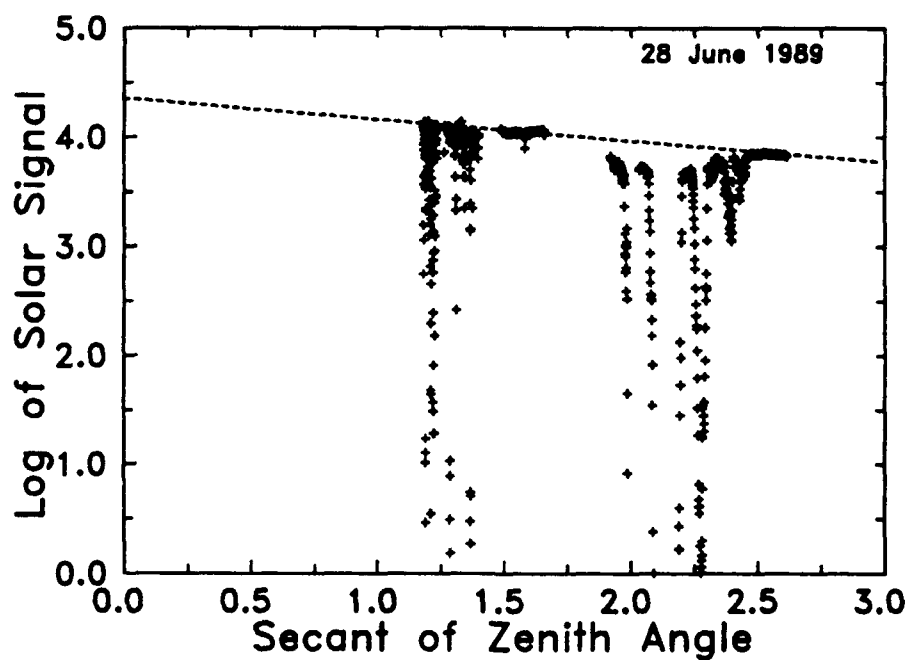


Figure 2. Scatter Plot of $\ln i_{\lambda_s}$ as a Function of $\sec \phi$ for 28 June 1989. The dashed line is the best fit line for the Langley method. Because they represent transmissions through clouds, values of $\ln i_{\lambda_s}$ less than 0.0 are not plotted to reduce clutter

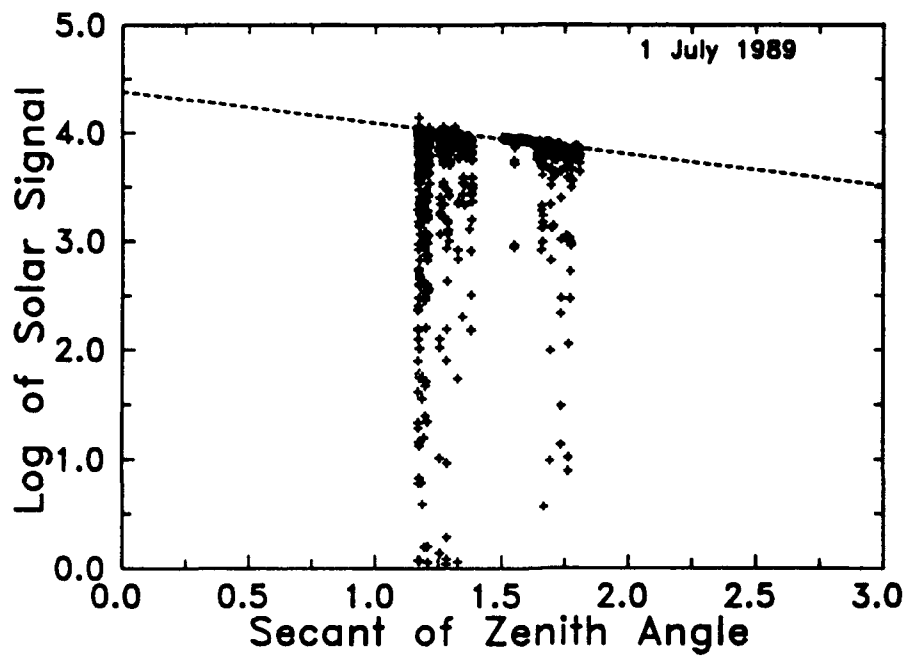


Figure 3. Scatter Plot of $\ln i_{\lambda_s}$ as a Function of $\sec \phi$ for 1 July 1989. The dashed line is the best fit line for the Langley method. Because they represent transmissions through clouds, values of $\ln i_{\lambda_s}$ less than 0.0 are not plotted to reduce clutter

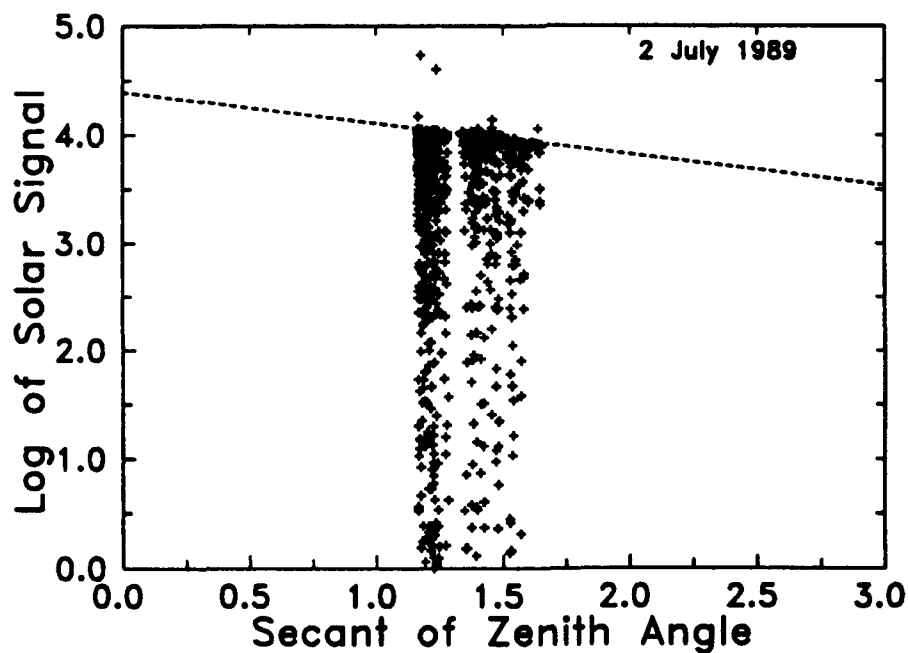


Figure 4. Scatter Plot of $\ln i_{\lambda_s}$ as a Function of $\sec \phi$ for 2 July 1989. The dashed line is the best fit line for the Langley method. Because they represent transmissions through clouds, values of $\ln i_{\lambda_s}$ less than 0.0 are not plotted to reduce clutter

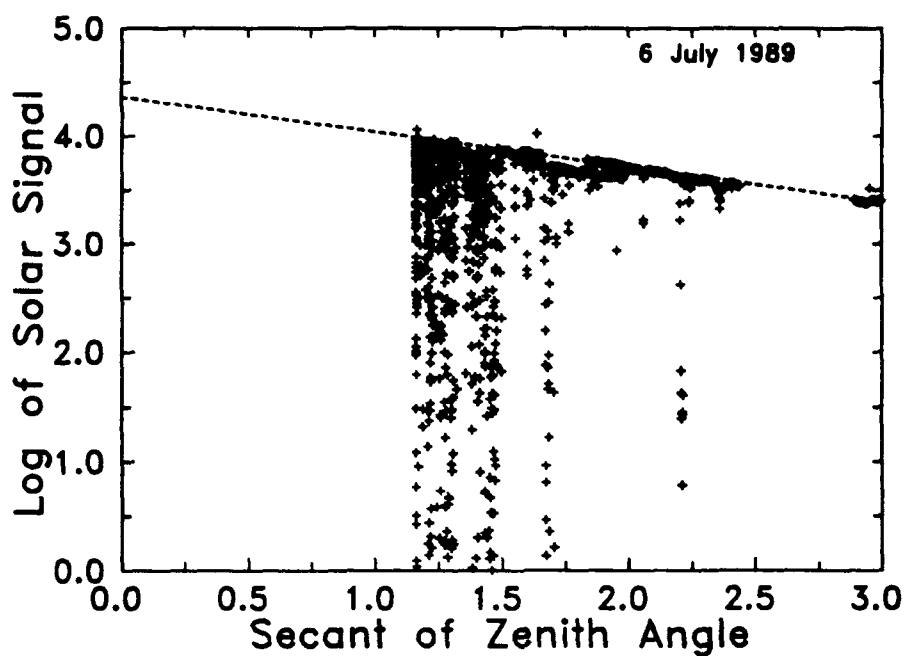


Figure 5. Scatter Plot of $\ln i_{\lambda_s}$ as a Function of $\sec \phi$ for 6 July 1989. The dashed line is the best fit line for the Langley method. Because they represent transmissions through clouds, values of $\ln i_{\lambda_s}$ less than 0.0 are not plotted to reduce clutter

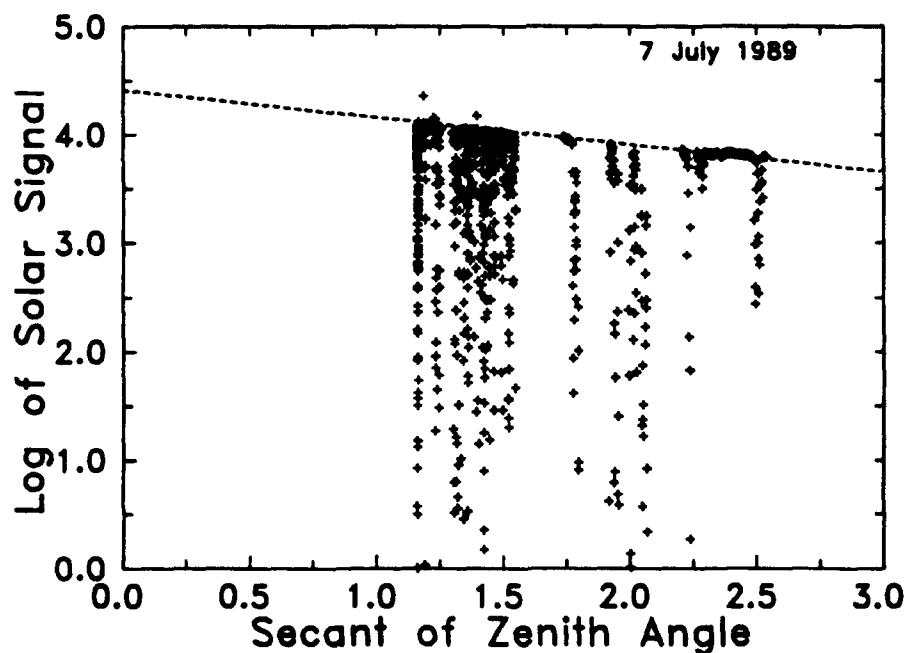


Figure 6. Scatter Plot of $\ln i_{\lambda_s}$ as a Function of $\sec \phi$ for 7 July 1989. The dashed line is the best fit line for the Langley method. Because they represent transmissions through clouds, values of $\ln i_{\lambda_s}$ less than 0.0 are not plotted to reduce clutter

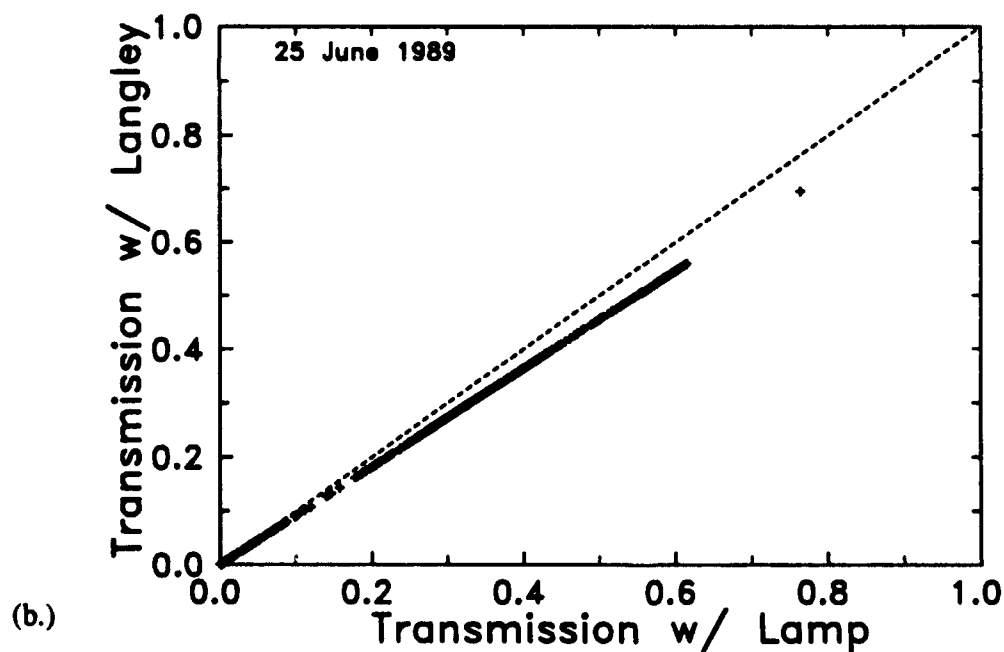
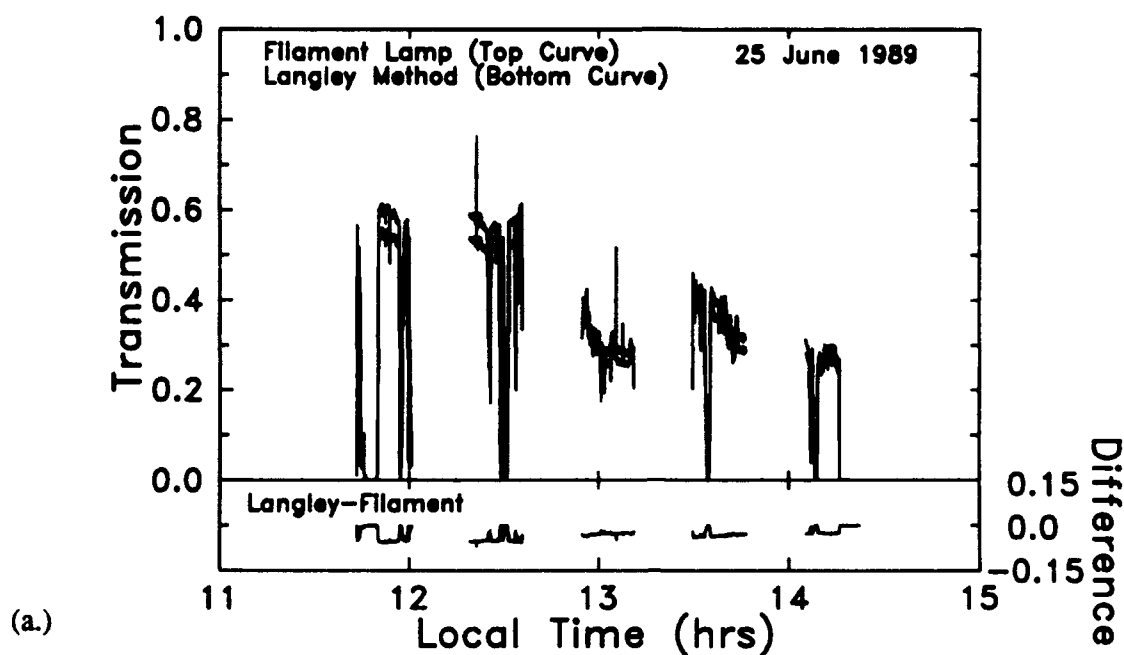


Figure 7. Comparison of Solar Transmissions From the Filament Lamp Calibration Against Those From the Langley Calibration for 25 June 1989. In (a.), transmissions from each calibration and their differences are shown as a function of time. In (b.), corresponding transmission measurements from each calibration are shown in terms of a scatter plot

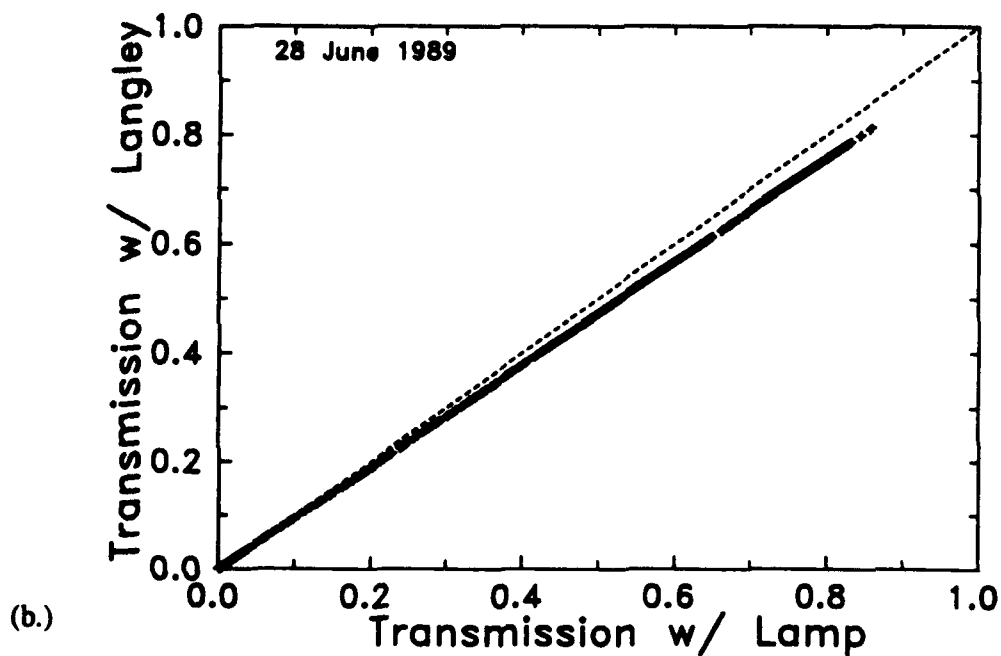
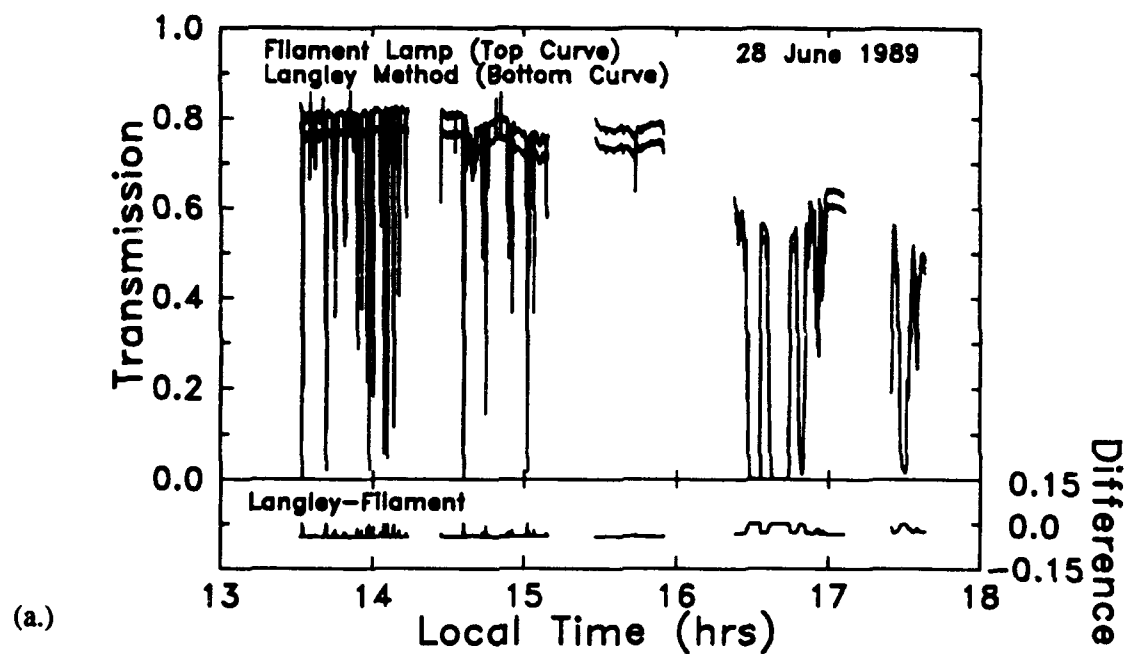


Figure 8. Comparison of Solar Transmissions From the Filament Lamp Calibration Against Those From the Langley Calibration for 28 June 1989. In (a.), transmissions from each calibration and their differences are shown as a function of time. In (b.), corresponding transmission measurements from each calibration are shown in terms of a scatter plot

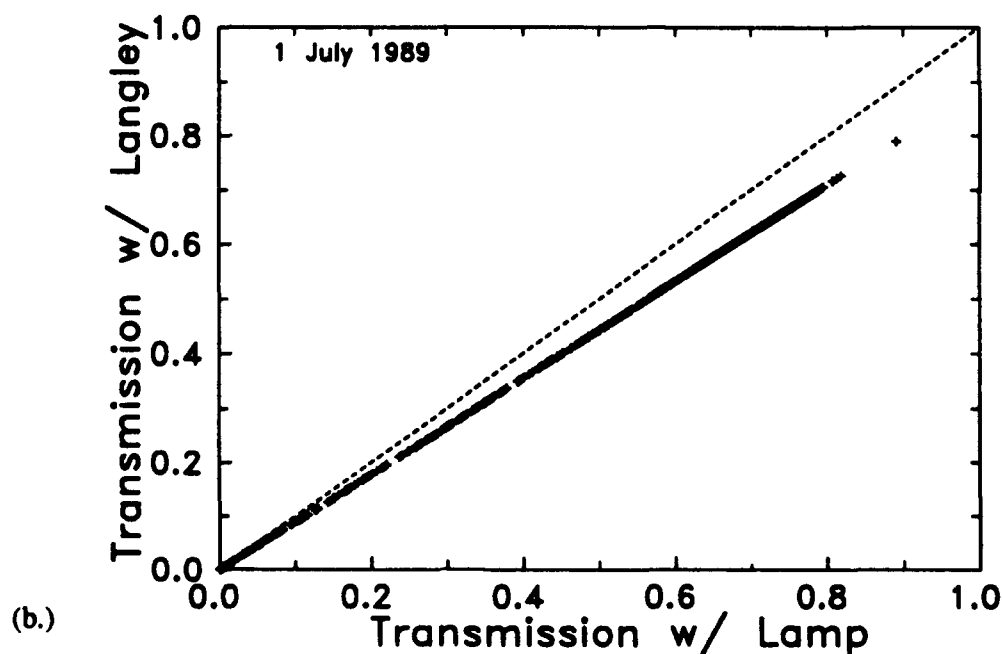
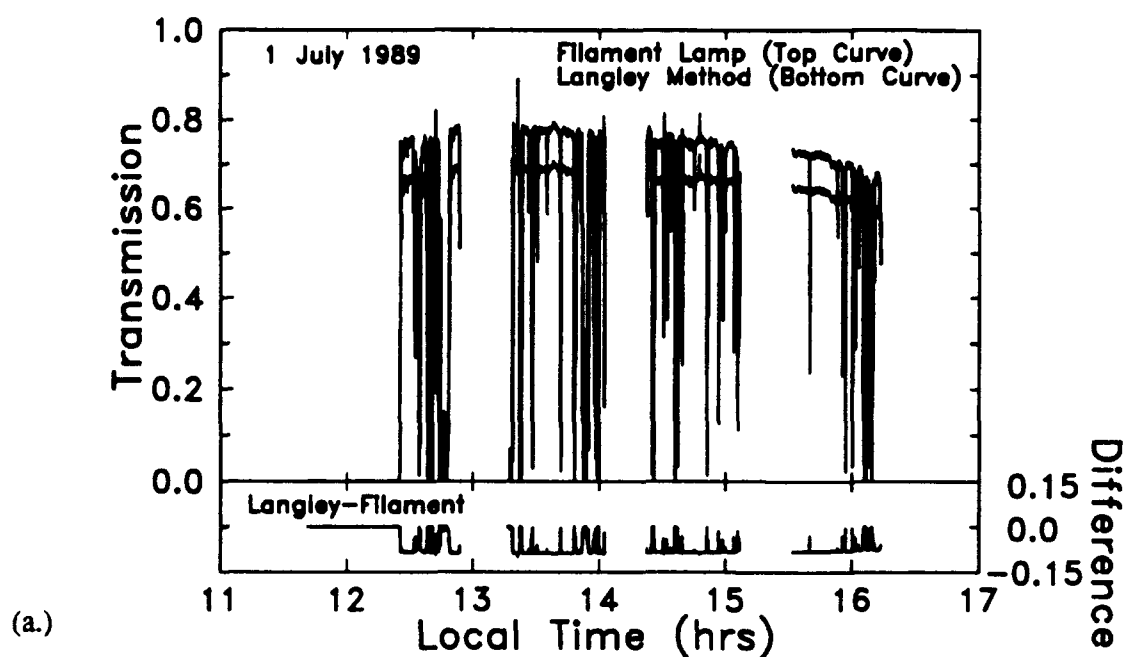


Figure 9. Comparison of Solar Transmissions From the Filament Lamp Calibration Against Those From the Langley Calibration for 1 July 1989. In (a.), transmissions from each calibration and their differences are shown as a function of time. In (b.), corresponding transmission measurements from each calibration are shown in terms of a scatter plot

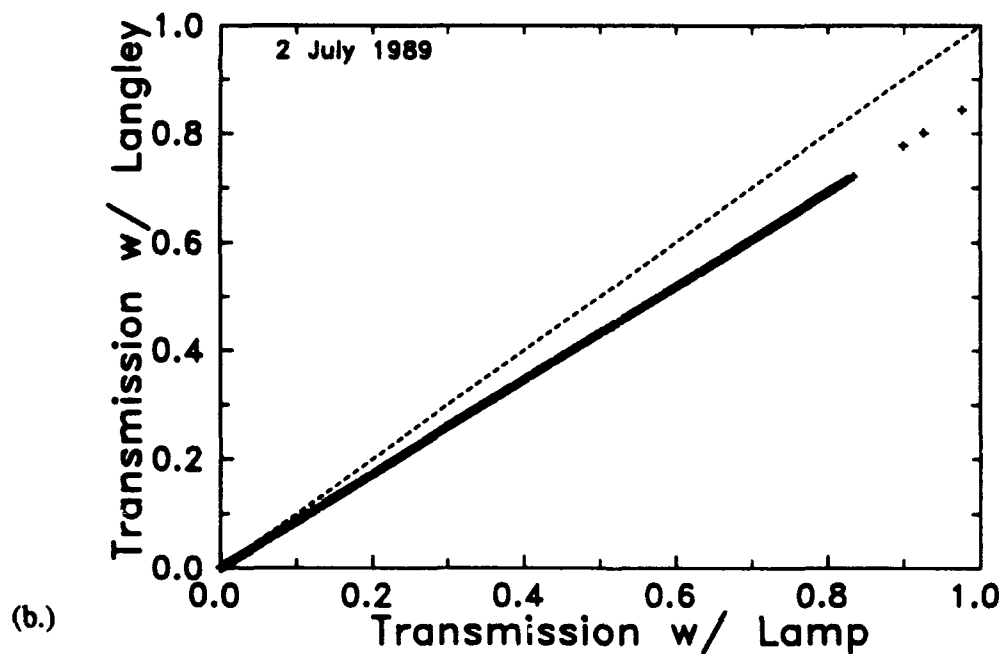
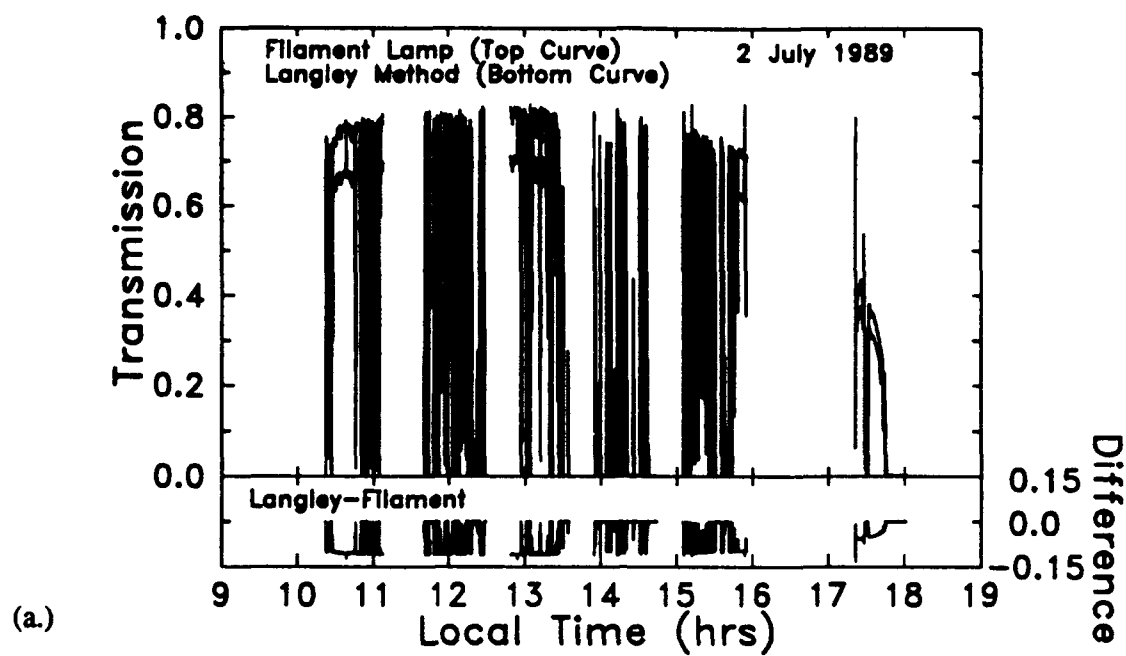


Figure 10. Comparison of Solar Transmissions From the Filament Lamp Calibration Against Those From the Langley Calibration for 2 July 1989. In (a.), transmissions from each calibration and their differences are shown as a function of time. In (b.), corresponding transmission measurements from each calibration are shown in terms of a scatter plot

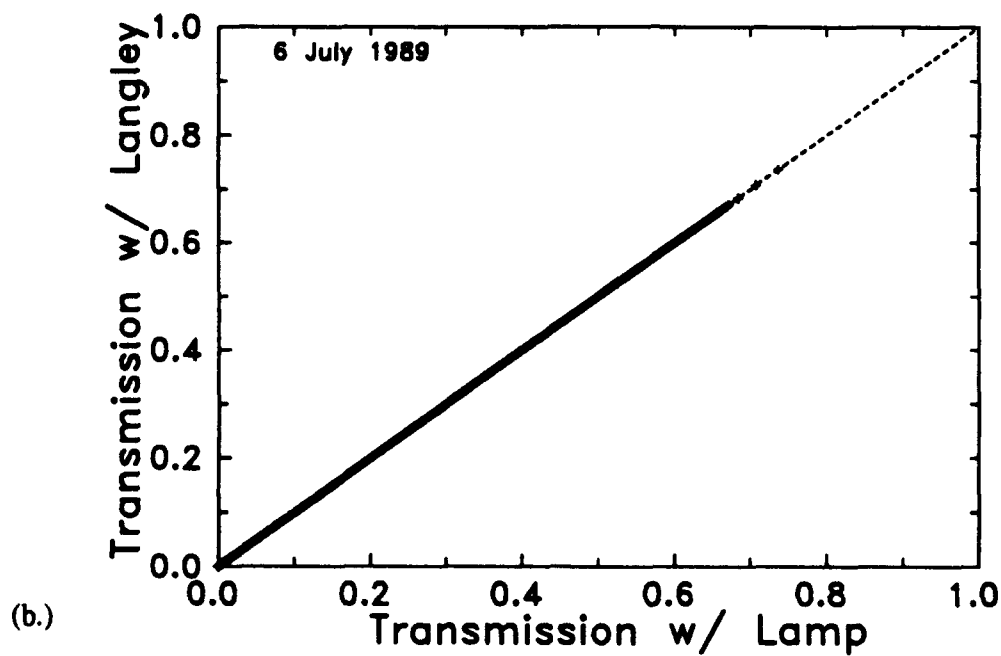
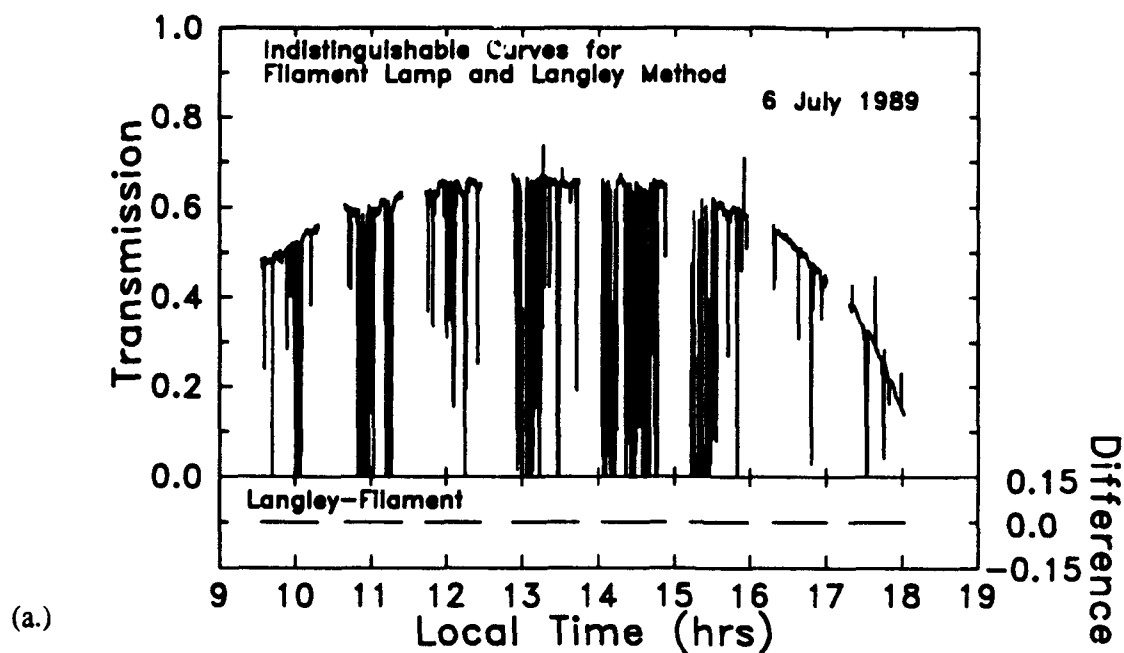


Figure 11. Comparison of Solar Transmissions From the Filament Lamp Calibration Against Those From the Langley Calibration for 6 July 1989. In (a.), transmissions from each calibration and their differences are shown as a function of time. In (b.), corresponding transmission measurements from each calibration are shown in terms of a scatter plot

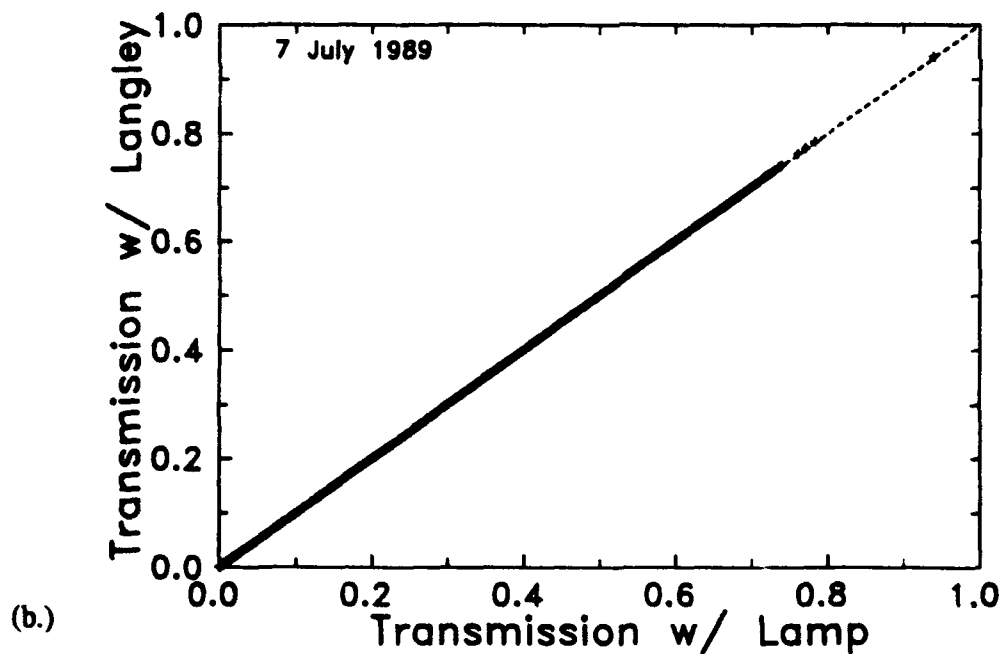
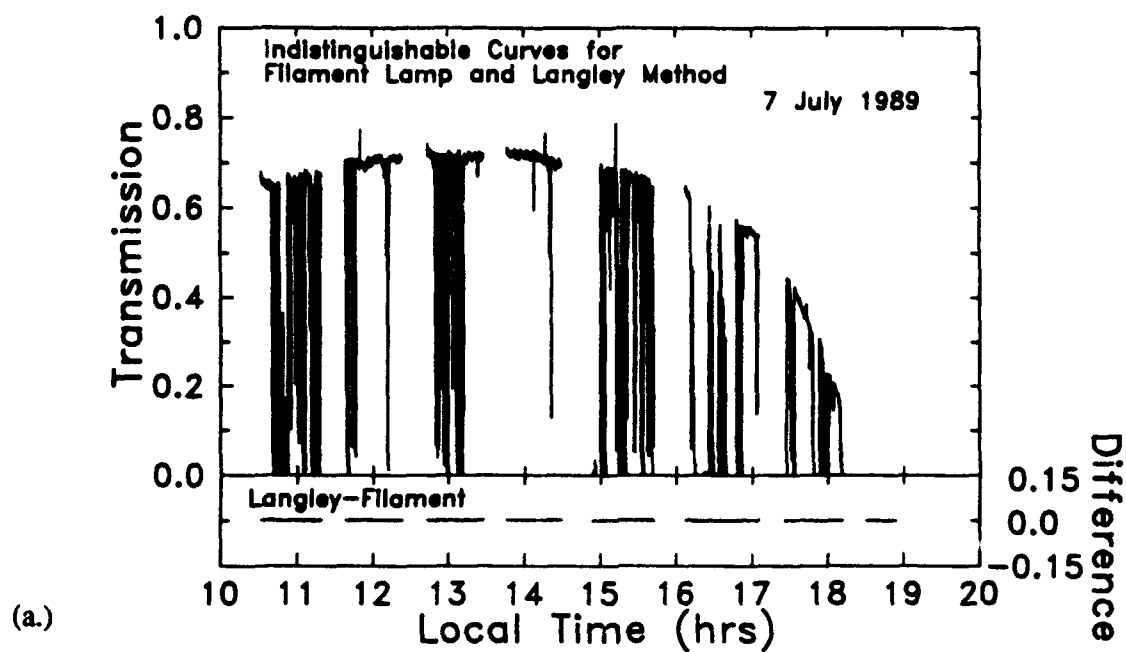


Figure 12. Comparison of Solar Transmissions From the Filament Lamp Calibration Against Those From the Langley Calibration for 7 July 1989. In (a.), transmissions from each calibration and their differences are shown as a function of time. In (b.), corresponding transmission measurements from each calibration are shown in terms of a scatter plot

3 ANALYSIS OF SOLAR TRANSMISSOMETER DATA AT 532 nm

Close examination of solar transmissometer data at 532 nm indicates times when transmissions are greatly reduced, but not zero. An example of this behavior is shown in Figure 13. The reduced transmissions are likely due to the blockage of the sun by boundary layer stratocumulus or cirrus clouds. In the case of boundary layer stratocumulus, reduced transmissions are possible when the cloud is thin or near the cloud edges. Since most radiative and climate models assume cumuloform clouds to be optically thick (*i.e.*, no solar transmission), additional information about cloud transmission properties can be obtained from the solar transmission data from SABLE 89.

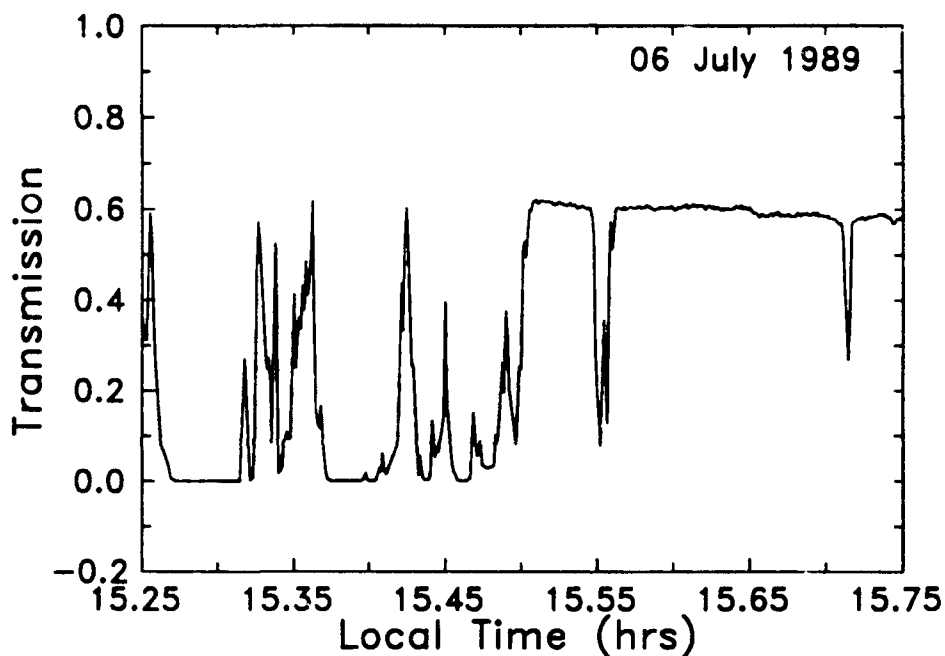


Figure 13. Example of Reduced Solar Transmissions at 532 nm for 6 July 1989.

3.1 Removal Of Aerosol Effects

In order to study the transmission properties of clouds over time, it is first necessary to separate and remove the aerosol and molecular transmissions from the measured solar transmissions to get the cloud transmissions. To do this, the measured solar transmission, τ_{mea} , was expressed as

$$\tau_{mea} = \tau_{clr} \tau_{cld} \quad (3)$$

where τ_{clr} is the atmospheric transmission including aerosol, molecular and zenith angle effects, and τ_{cld} is the transmission due to clouds. Values of τ_{clr} were computed using LOWTRAN7⁴.

⁴ Kneizys, F.X., Shettle, E.P., Abreu, L.W., Chetwynd, J.H., Anderson, G.P., Gallery, W.O.,

The procedure was to calculate τ_{clr} as a function of solar zenith angle assuming steady state aerosol loading in the boundary layer. (With LOWTRAN7, boundary layer aerosol loading is defined by the surface visibility.) Given a knowledge of the solar zenith angle at Ascension Island versus time, the measured transmissions were then divided by zenith angle dependent values of τ_{clr} for an appropriate surface visibility such that the resulting envelope of transmissions was as close to 1.0 as possible. When generating values of τ_{clr} with LOWTRAN7, the default boundary layer height of 2 km was used because it consistently agreed with lidar backscatter and rawinsonde measurements near Ascension Island during SABLE 89.

For each day of transmission data, aerosol effects were removed using iterative guesses on surface visibility until the best results were achieved. Table 3 lists the final surface visibilities that were adopted in LOWTRAN7 to remove aerosol effects. For reference, Figures 14 through 19 compare these "inferred" values against observed surface visibilities at Ascension Island. The comparisons show very good agreement for 1, 2, 6, and 7 July 1989, but large discrepancies exist for 25 and 28 June 1989. The discrepancies for 25 June occur partly because the presence of cirrus clouds on that day cause the envelope to be poorly defined which makes aerosol removal somewhat arbitrary. For 28 June 1989, it is unclear why the inferred visibility is much greater than observed values. However, some of the observed surface visibilities on 28 June 1989 are greater than 70 km, and they may only be estimates because island locations usually lack distant reference points to accurately determine the surface visibility in a very clean atmosphere.

Table 3. Surface Visibilities Used in LOWTRAN7 to Remove Aerosol, Molecular, and Zenith Angle Effects From the Solar Transmission Data Taken During SABLE 89

DATE	LOWTRAN7 SURFACE VISIBILITY
	(km)
25 June 1989	20
28 June 1989	130
1 July 1989	48
2 July 1989	52
6 July 1989	37
7 July 1989	60

Interestingly, the choice of surface visibility in LOWTRAN7 affects the shape of an envelope, besides shifting its absolute value about 1.0. An example of this behavior is shown in Figure 20 which shows initial attempts to remove aerosol and molecular effects for 7 July 1989 using other

Selby, J.E.A., and Clough, S.A. (1988) "Users Guide to LOWTRAN7," Air Force Geophysics Laboratory, Hanscom AFB, MA, AFGL-TR-88-0177, ADA206773.

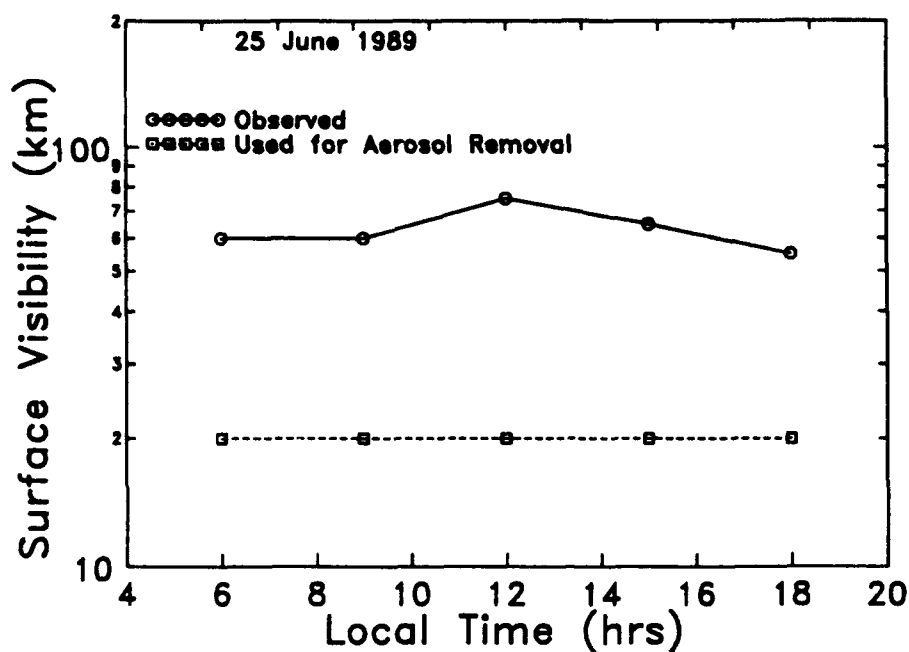


Figure 14. Comparisons Between Observed Surface Visibilities at Ascension Island and Visibilities Used for Aerosol Removal as a Function of Time for 25 June 1989

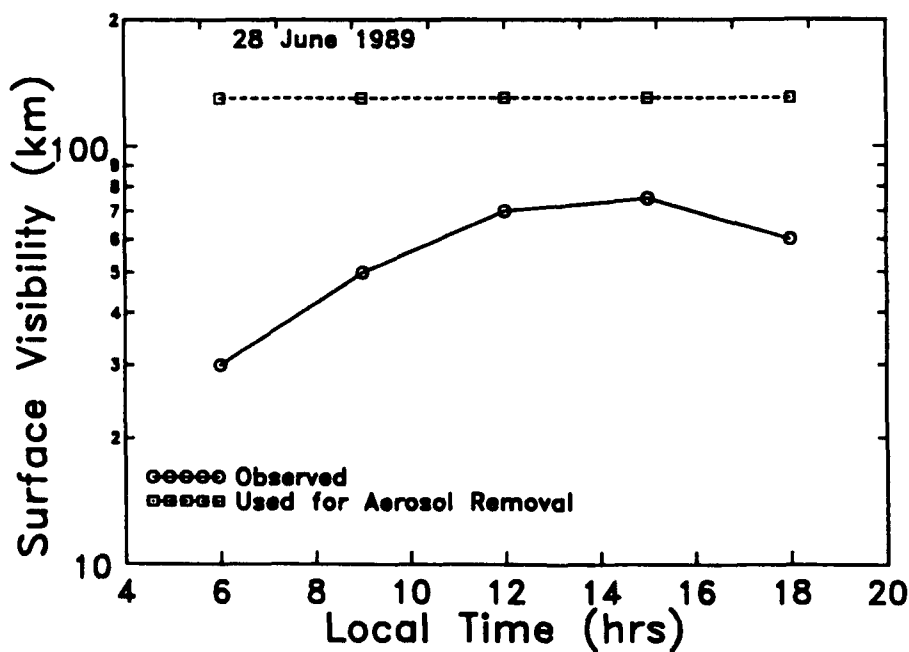


Figure 15. Comparisons Between Observed Surface Visibilities at Ascension Island and Visibilities Used for Aerosol Removal as a Function of Time for 28 June 1989

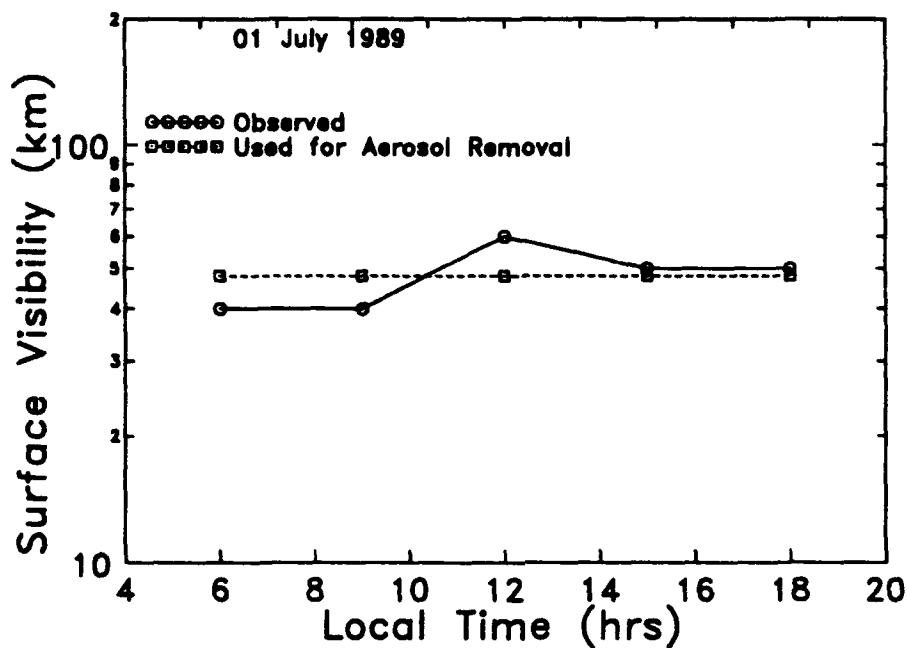


Figure 16. Comparisons Between Observed Surface Visibilities at Ascension Island and Visibilities Used for Aerosol Removal as a Function of Time for 1 July 1989

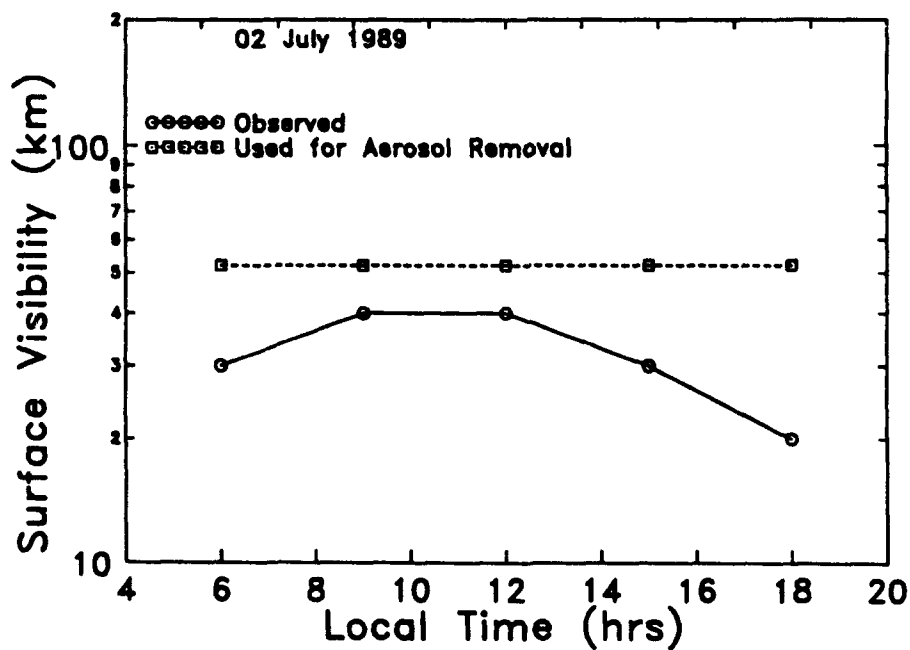


Figure 17. Comparisons Between Observed Surface Visibilities at Ascension Island and Visibilities Used for Aerosol Removal as a Function of Time for 2 July 1989

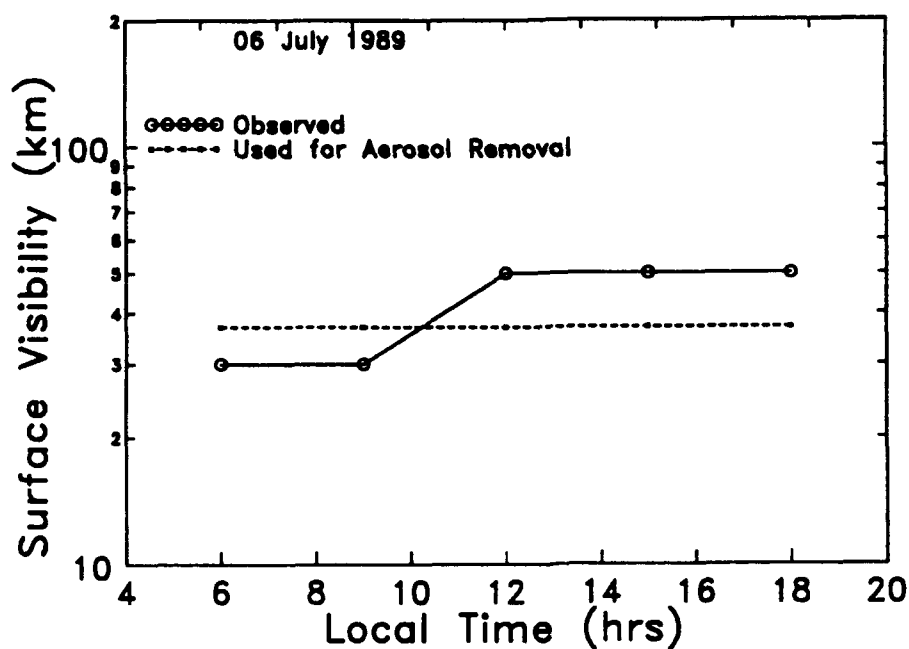


Figure 18. Comparisons Between Observed Surface Visibilities at Ascension Island and Visibilities Used for Aerosol Removal as a Function of Time for 6 July 1989

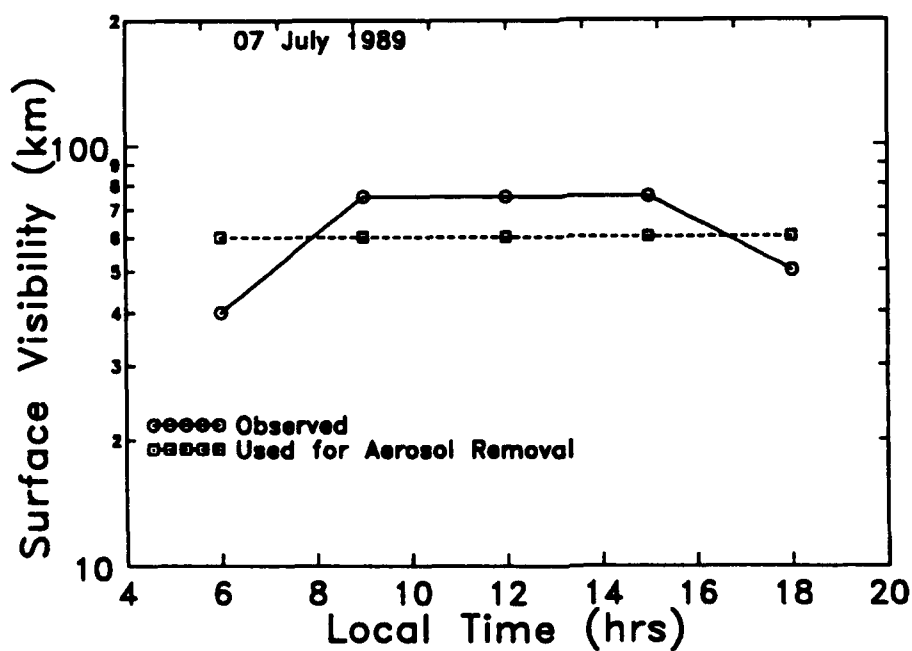


Figure 19. Comparisons Between Observed Surface Visibilities at Ascension Island and Visibilities Used for Aerosol Removal as a Function of Time for 7 July 1989

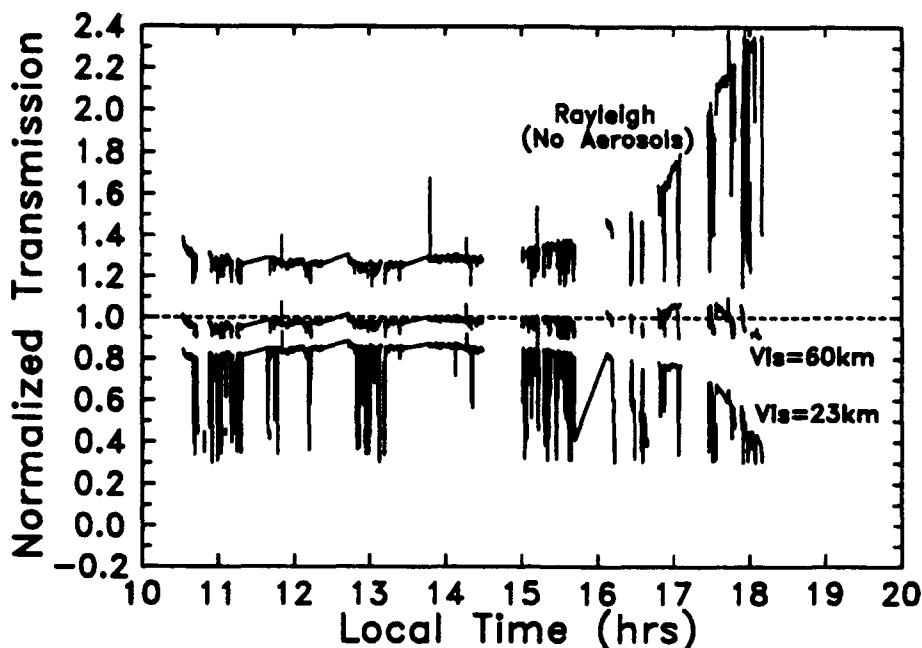


Figure 20. Values of Transmission as a Function of Time After Removing Aerosol, Molecular, and Solar Zenith Effects With Appropriate and Improper Surface Visibilities in LOWTRAN7. For illustrative purposes, only the data depicting the envelopes are shown. Note the distortion of the envelope after 1500 hr when the sun is low in the sky. Measurements for 7 July 1989 were used here

surface visibilities. Clearly, improper surface visibilities cause the envelope to become distorted, especially when the sun is low in the sky.

Figures 21 through 26 show daily transmission values after the aerosol, molecular, and zenith angle effects were removed. Generally, the figures indicate that the technique works well for most days, in that the envelopes are relatively flat and show little diurnal trend. Perhaps the only exception is near sunset (*i.e.*, local times after 1730 hrs) where the envelopes gradually taper below 1.0, as seen on 2 July, 6 July, and 7 July 1989. This behavior may be related to small differences between the actual and modeled values for the height and/or aerosol extinction profile of the boundary layer because their effects on the solar transmissions become more pronounced at low solar zenith angles. Additionally, a time dependent surface visibility may improve the normalization process for a few time periods, although the observed surface visibilities do not suggest too much diurnal variation. On 2 July 1989, for example, the envelope between 1700 and 1800 hrs shows a 10% departure from 1.0 plus a gradually tapering off. This behavior is likely due to "real" changes in the surface visibility as suggested by a marked drop in the observed surface visibility between 1500 and 1800 hrs local time (see Figure 17).

Initially, only a limited series of simple statistics was performed on the data in Figures 21 through 26. For example, Table 4 groups daily values of the inferred τ_{cld} into equally spaced transmission bins. Clearly, values of τ_{cld} greater than 0.9 represent clear skies or extremely thin

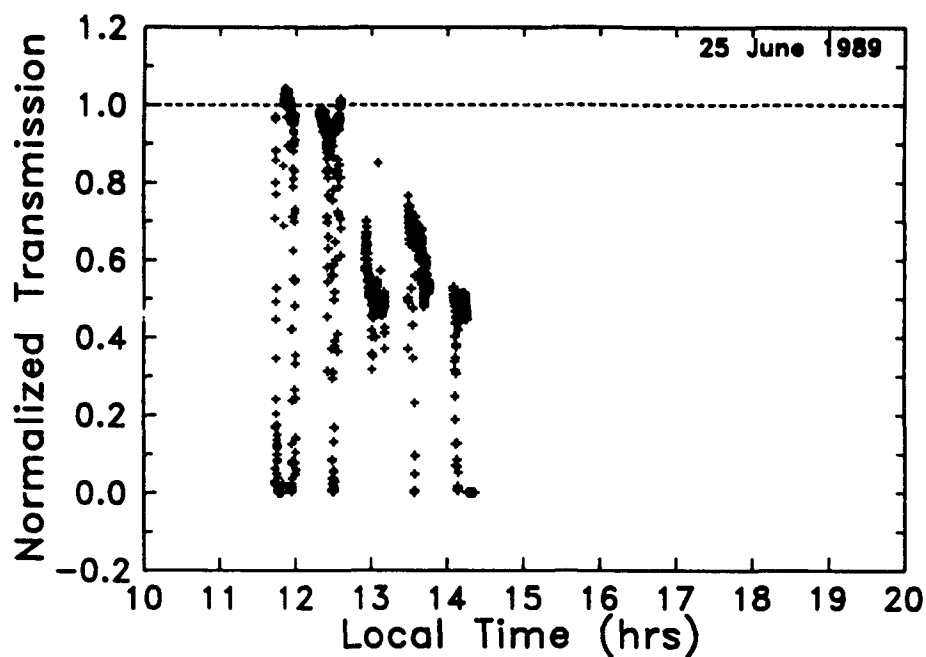


Figure 21. Values of Transmission as a Function of Time for 25 June 1989 After Removing Molecular, Aerosol, and Solar Zenith Effects

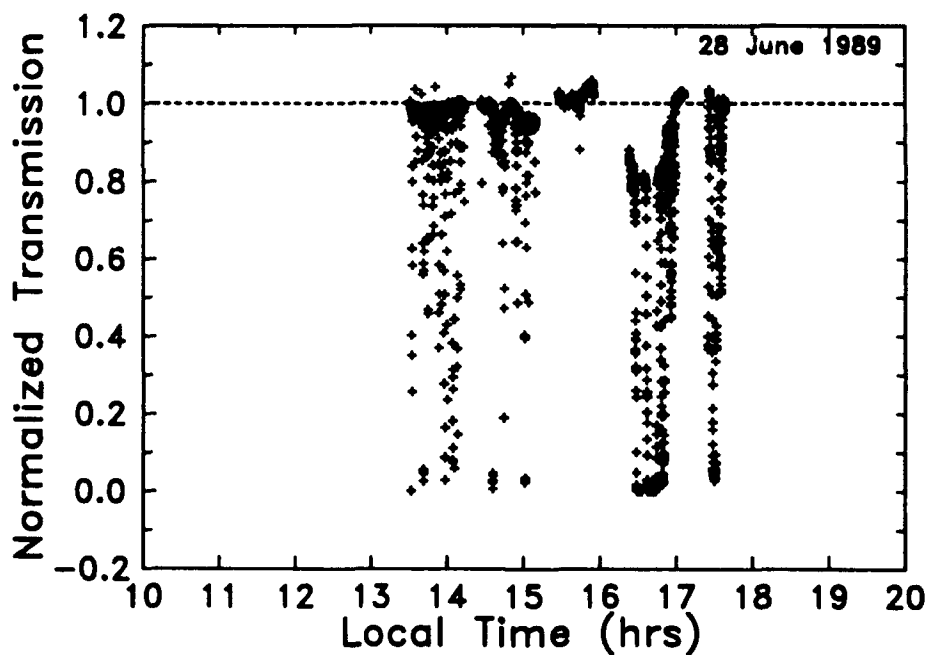


Figure 22. Values of Transmission as a Function of Time for 28 June 1989 After Removing Molecular, Aerosol, and Solar Zenith Effects

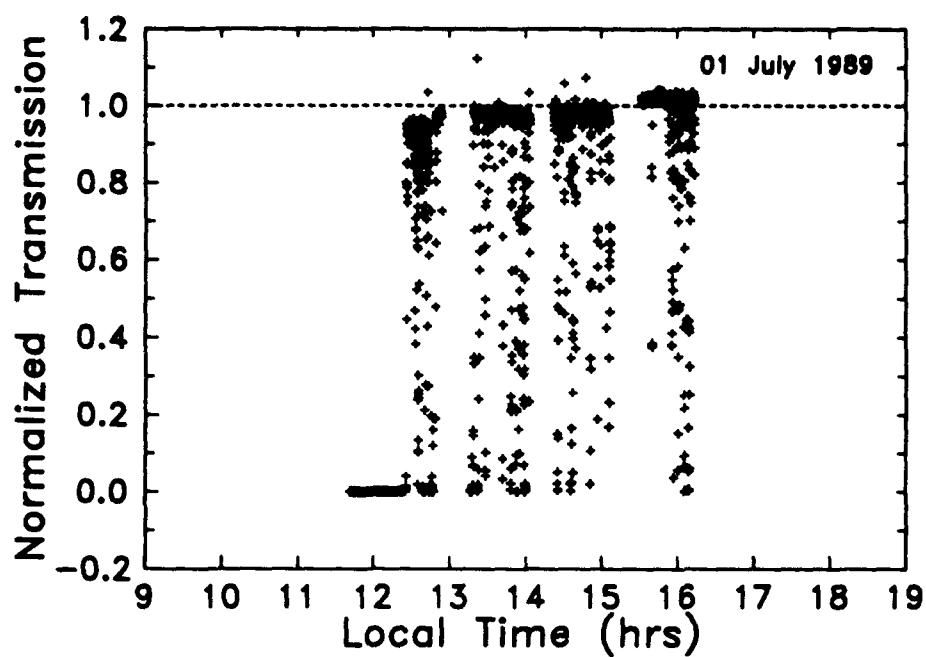


Figure 23. Values of Transmission as a Function of Time for 1 July 1989 After Removing Molecular, Aerosol, and Solar Zenith Effects

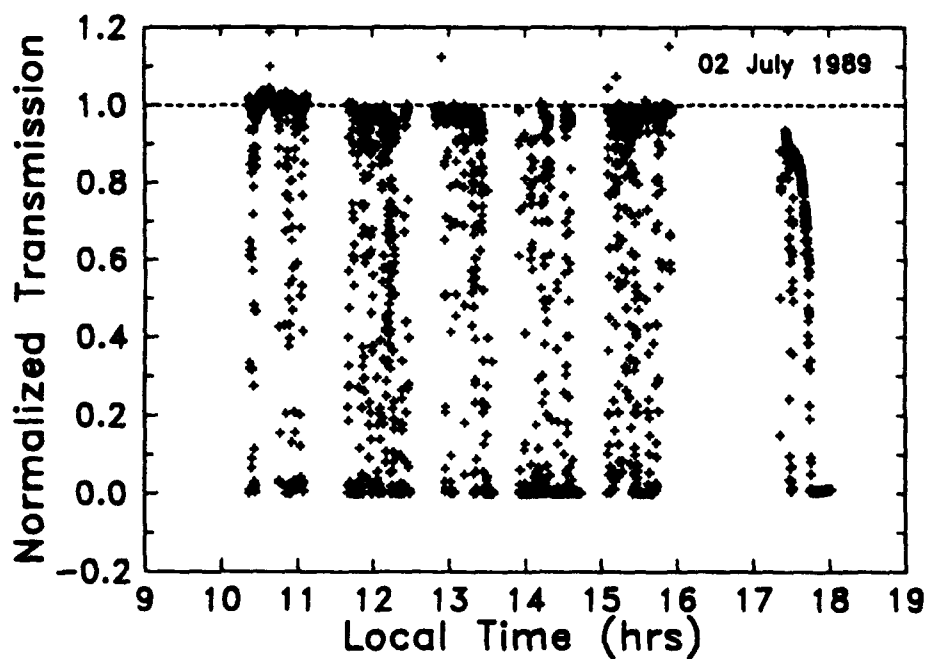


Figure 24. Values of Transmission as a Function of Time for 2 July 1989 After Removing Molecular, Aerosol, and Solar Zenith Effects

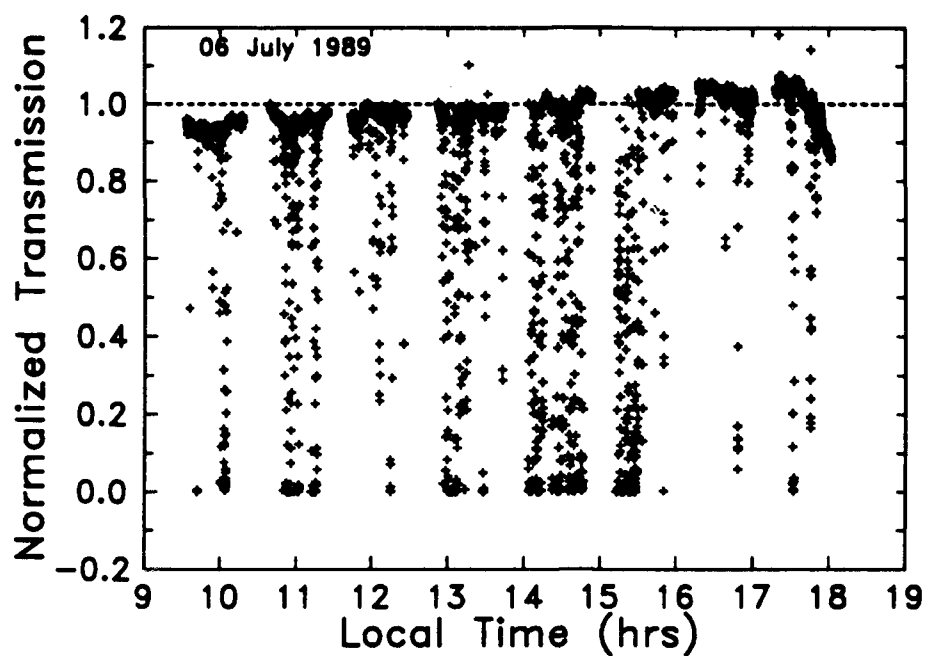


Figure 25. Values of Transmission as a Function of Time for 6 July 1989 After Removing Molecular, Aerosol, and Solar Zenith Effects

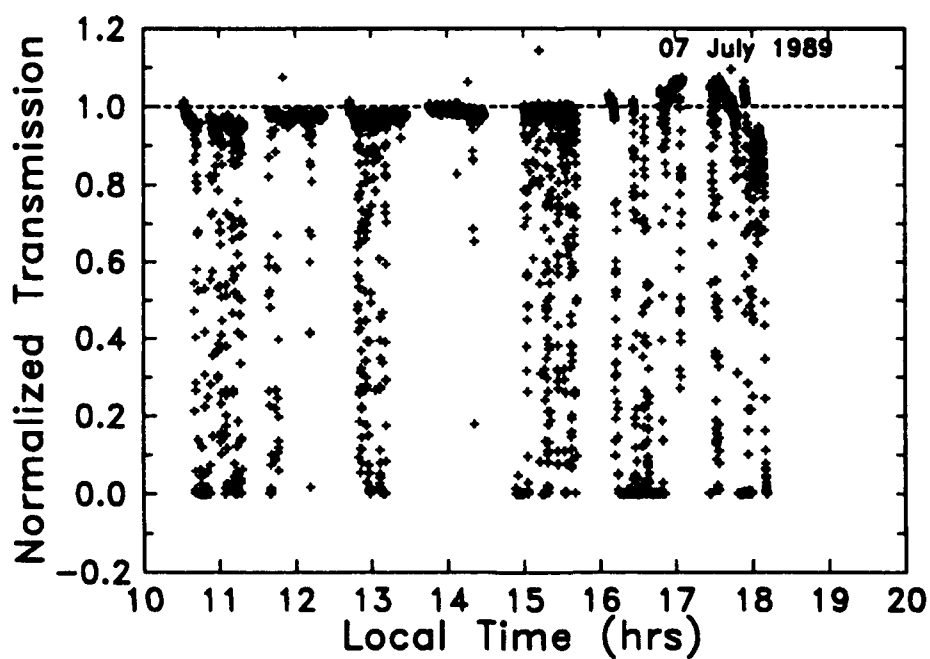


Figure 26. Values of Transmission as a Function of Time for 7 July 1989 After Removing Molecular, Aerosol, and Solar Zenith Effects

Table 4. Daily Occurrences of Inferred τ_{cld} as a Function of Transmission. For example, the first entry means that there were 206 data points of τ_{cld} between 0.0 and 0.1 on 25 June 1989 after aerosol, molecular, and zenith effects were removed

# OF OCCURENCES	25 JUNE	28 JUNE	1 JULY	2 JULY	6 JULY	7 JULY
τ_{cld} 0.0-0.1	206	247	414	1229	407	716
τ_{cld} 0.1-0.2	8	21	21	44	76	69
τ_{cld} 0.2-0.3	8	22	22	62	56	63
τ_{cld} 0.3-0.4	21	29	29	48	51	59
τ_{cld} 0.4-0.5	236	32	35	56	61	57
τ_{cld} 0.5-0.6	213	39	25	73	62	68
τ_{cld} 0.6-0.7	147	54	35	95	70	67
τ_{cld} 0.7-0.8	37	112	44	135	95	91
τ_{cld} 0.8-0.9	30	223	105	251	189	182
τ_{cld} 0.9-1.0	284	1715	1760	1689	3968	3038

cirrus along the solar path, and values of τ_{cld} less than 0.1 represent conditions where the sun is fully obscured by clouds. With the exception of 25 June 1989, the number of occurrences of τ_{cld} as a function of τ_{cld} form a U-shaped distribution.

At this point, it is worth noting that surface observations from Ascension Island indicate the presence of cirrus for 25 June 1989. Additionally, the peak solar transmissions for 25 June 1989 are about 0.6 (see Figure 7), whereas peak solar transmissions on the five other days are closer to 0.8. Since the surface observations of visibility do not suggest any extreme aerosol loading on 25 June 1989, it is quite likely that cirrus are influencing all of the measurements on 25 June 1989. Moreover, the technique to remove aerosol and molecular effects is not adequate for 25 June 1989, so these data will be omitted from many of the analyses in this report. (Note that it is not easy to remove the contributions of cirrus because the thicknesses frequently vary.)

3.2 Discussion of Forward Scattering Effects

Before investigating the transmission properties of cloud gaps and thin spots, it was necessary to estimate how much the values of τ_{cld} were biased by forward scattering. (Note that for particles large compared with the wavelength, the extremely narrow forward lobes due to Fraunhofer diffraction cause additional radiation to be scattered into the instrument field-of-view.) To do this, correction factors for forward scattering were calculated using the model of Mill and Shettle⁵ and Fenn *et al.*⁶

⁵ Mill, J.D. and E.P. Shettle (1983) A Preliminary LOWTRAN Snow Model, AFGL-TR-83-0148, Hanscom AFB, MA, ADA129826.

⁶ Fenn, R.W., Clough, S.A., Gallery, W.O., Good, R.E., Kneizys, F.X., Mill, J.D., Rothman,

Briefly, in the Mill and Shettle model⁵, the relationship between the transmission measured by an instrument, τ_{inst} , and the true radiance transmission, τ_{true} , is given by

$$\tau_{inst} = \tau_{true}(1 + D \ln \tau_{true}). \quad (4)$$

The correction factor, D , is found by integrating the contributions from all of the space common to the beam and the receiver field-of-view. D depends on the half angle of the source, θ_s , the half angle of the receiver field-of-view, θ_o , and the particle size parameter, x , defined as the particle circumference divided by the wavelength of radiation. Fenn *et al.*⁶ have tabulated values of D in terms of the following two parameters:

$$\rho = \frac{\text{Max}(\theta_s, \theta_o)}{\text{Min}(\theta_s, \theta_o)} \quad (5)$$

and

$$v = x \text{Min}(\theta_s, \theta_o) \quad (6)$$

where Max and Min are, respectively, the larger and smaller of the arguments in parentheses.

For the solar transmissometer at Ascension Island, Table 5 lists the values of ρ and v for stratocumulus and cirrus clouds. When these values of ρ and v are used in the lookup table of Fenn *et al.*⁶, it is apparent that correction factors are less than 1% for stratocumulus clouds. Corrections for cirrus clouds are significant, however.

Table 5. Values of Parameters Used to Estimate the Effects of Forward Scattering on the Transmission Measurements at Ascension Island. The size parameters for stratocumulus and cirrus clouds represent typical particle radii of 5 and 100 μm , respectively

PARAMETER	VALUE
θ_o	0.00123 rad
θ_s	0.00465 rad
x (Stratocumulus)	59.8
x (Cirrus)	1196.8
ρ	3.78
v (Stratocumulus)	0.0736
v (Cirrus)	1.472

L.S., Shettle, E.P., and Volz, F.E. (1985) Optical and Infrared Properties of the Atmosphere, Chapter 18 in *Handbook of Geophysics and the Space Environment*, A.S. Jursa Scientific Ed., Air Force Geophysics Laboratory, Hanscom AFB, MA, AFGL-TR-85-0315, ADA167000.

3.3 Cirrus Cloud Analysis

Physically, departures of the transmission values from 1.0 in Figures 21 through 26 represent cloud effects (i.e., values of $\tau_{cld} < 1.0$). Generally, the reduced transmissions are due to boundary layer stratocumulus clouds that frequently occur at Ascension Island. As noted in Section 3.1, however, the transmission data on 25 June 1989 are influenced by cirrus clouds. Although the technique to remove aerosol and molecular effects is not adequate for 25 June 1989, Figure 21 does show extended periods of partial transmission with very few times when it drops to 0.0 or rises to 1.0. Such behavior is characteristic of a fairly uniform cirrus sheet, rather than patchy stratocumulus.

In order to estimate cirrus transmissions, the measured transmissions for 25 June 1989 are compared against those from the other five days. Specifically, the departures from representative transmissions on "non cirrus" days are assumed to be the cirrus transmissions. In this analysis, which uses transmission data before aerosol and molecular effects were removed (see Figures 7 through 12), a detailed quantitative assessment is unwarranted because there are too many uncertainties, such as day-to-day variations of aerosol loading in the boundary layer and forward scattering effects (see Section 3.2). Furthermore, the analysis only considers the transmission envelopes for each day because departures from it are probably due to stratocumulus clouds.

Table 6 gives estimated cirrus transmissions on 25 June 1989 for each period when the solar transmissometer was operated. Note that the estimated cirrus equals the values on 25 June 1989 divided by those on "non cirrus" days. Also, note that transmissions on the "non cirrus" days all equal 0.75 because zenith angle effects are not too prevalent during these times. Table 6 suggests that cirrus transmissions are between about 0.40 and 0.80.

Table 6. Estimated Cirrus Transmissions on 25 June 1989. Values are derived from measured solar measurements on 25 June 1989 and representative transmissions for "non cirrus" days which are also shown

TIME (Local)	Transmission on 25 JUNE 1989	Transmission on Non Cirrus Days	Estimated Cirrus Transmission
11:43-12:01	0.60	0.75	0.80
12:19-12:36	0.55	0.75	0.73
12:54-13:11	0.30	0.75	0.40
13:29-13:46	0.35	0.75	0.47
14:05-14:22	0.30	0.75	0.40

Given cirrus transmissions between 0.40 and 0.80, the corresponding cirrus cloud depths were estimated using the standard LOWTRAN7 cirrus cloud model⁷. To do this, cirrus cloud transmission in the direction of the sun was calculated as a function of solar zenith angle and cloud thickness. The calculations were performed using the default cloud base height of 10 km and the default extinction coefficient of 0.14 km^{-1} for a wavelength $0.55 \text{ }\mu\text{m}$. (Note that the base altitude is not important in these calculations because cirrus transmission does not depend on the base altitude.) For reference, the calculated cirrus transmissions are shown in Figure 27. The data in Figure 27 were then mapped on to the local time grid for Ascension Island (see Figure 28). To estimate cirrus cloud thicknesses over Ascension Island, the values of τ_{cld} for 25 June 1989 (see Figure 21) were then compared against the transmission curves in Figure 28. Specifically, an estimate of cirrus cloud thickness was given by the transmission curve having transmission values that best matched the values of τ_{cld} when cirrus clouds were suspected. For the times between 1300 and 1430 hrs on 25 June 1989, cirrus cloud thicknesses are estimated to be between 1.0 and 2.2 km. These estimates are plausible, and they are consistent with cirrus observations from aircraft for 25 June 1989.

3.4 Stratocumulus Cloud Analysis

The stratocumulus clouds observed over Ascension Island are similar to those generally found in trade wind environments. Individual clouds are often quite small and their distribution is rather regular, so that a group of stratocumulus clouds develops a checkerboard appearance when viewed from above. From the ground, stratocumulus clouds are whitish or grayish with dark spots.

The current analysis focuses on the properties of cloud edges and thin spots in stratocumulus clouds. These properties are of interest to those who model radiative transfer in climate studies. For the solar transmissometer measurements, stratocumulus cloud edges and thin spots are probable whenever values of τ_{cld} are between 0.1 and 0.9.

3.4.1 Thickness Estimates of Cloud Edges and Thin Spots

The depths of thin spots and cloud edges of stratocumulus clouds were estimated using the cloud models in LOWTRAN7. To do this, transmission through a stratocumulus cloud in the direction of the sun was calculated as a function of solar zenith angle and cloud thickness. Here, the standard LOWTRAN7 profile of liquid water content (and hence number density profile) was used in the simulation of stratocumulus clouds of different depths. For reference, the calculated transmissions are shown in Figure 29. The values in Figure 29 were then mapped on to the local time grid for Ascension Island (see Figure 30). Figure 30 was then examined to see what transmission curves produced transmissions between 0.1 and 0.9 for most daylight hours. Figure 30 suggests that cloud depths of 5 to 50 m are required to give values of τ_{cld} between 0.1 and 0.9. However, these depths are probably underestimates because thin spots and cloud edges often result from reduced number density profiles rather than reduced cloud thickness alone.

⁷ Shettle, E.P. (1989) "Models of Aerosols, Clouds, and Precipitation for Atmospheric Propagation Studies", Proceedings of the AGARD 45th Symposium of the Electromagnetic Wave Propagation Panel on *Atmospheric Propagation in the UV, Visible, IR, and mm-Wave Region and Related System Aspects*, Copenhagen, Denmark, 9-13 October 1989.

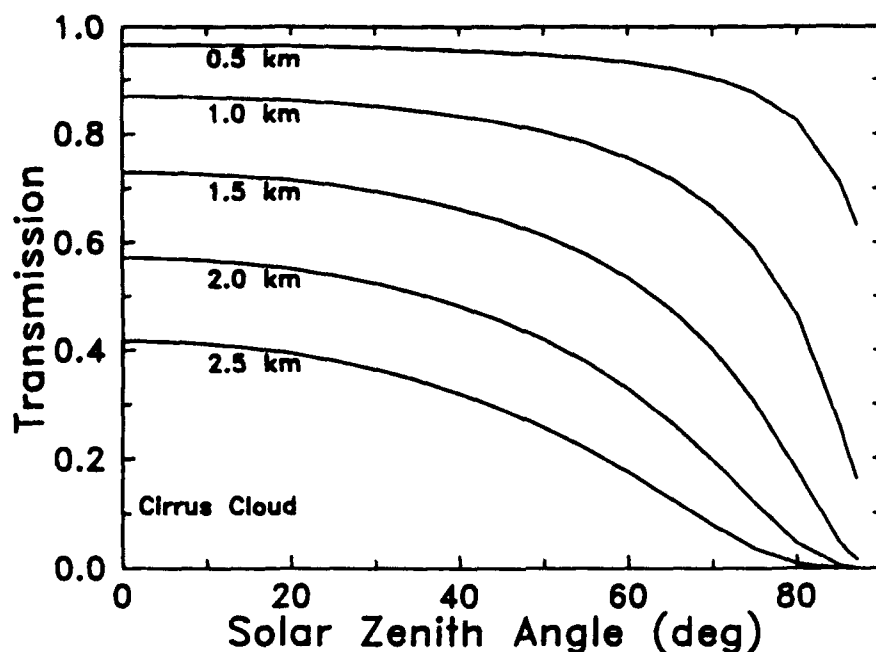


Figure 27. Calculated Transmission Through Cirrus Clouds in the Solar Direction Versus Solar Zenith Angle for Cloud Thicknesses of 0.5, 1.0, 1.5, 2.0, and 2.5 km. Note that these transmissions are for the cirrus alone, and they do not include effects from aerosol and molecules within the cirrus

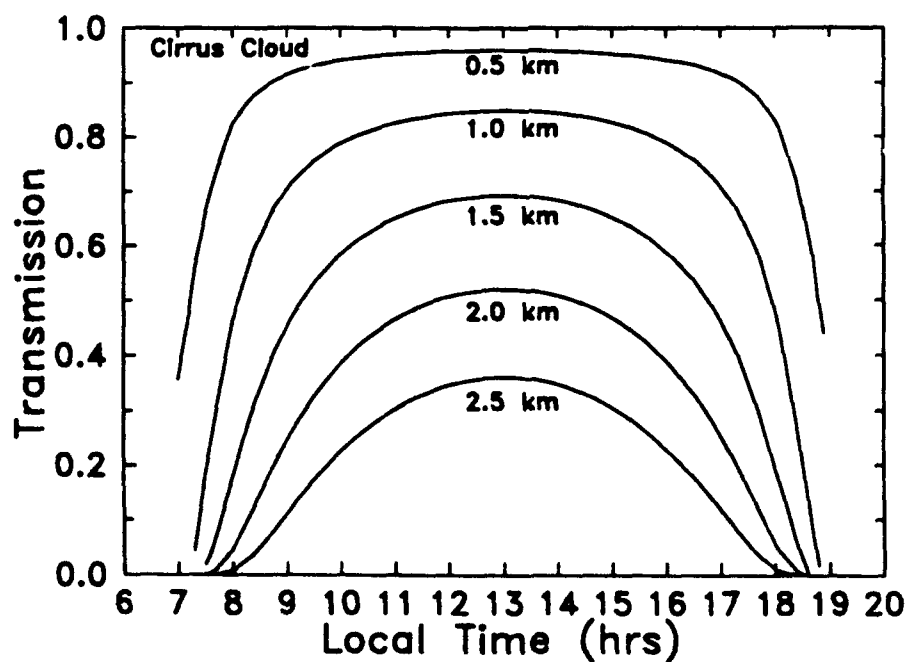


Figure 28. Calculated Transmission Through Cirrus Clouds in the Solar Direction Versus Local Time for Ascension Island for Cloud Thicknesses of 0.5, 1.0, 1.5, 2.0, and 2.5 km. Note that these transmissions are for the cirrus alone, and they do not include effects from aerosol and molecules within the cirrus

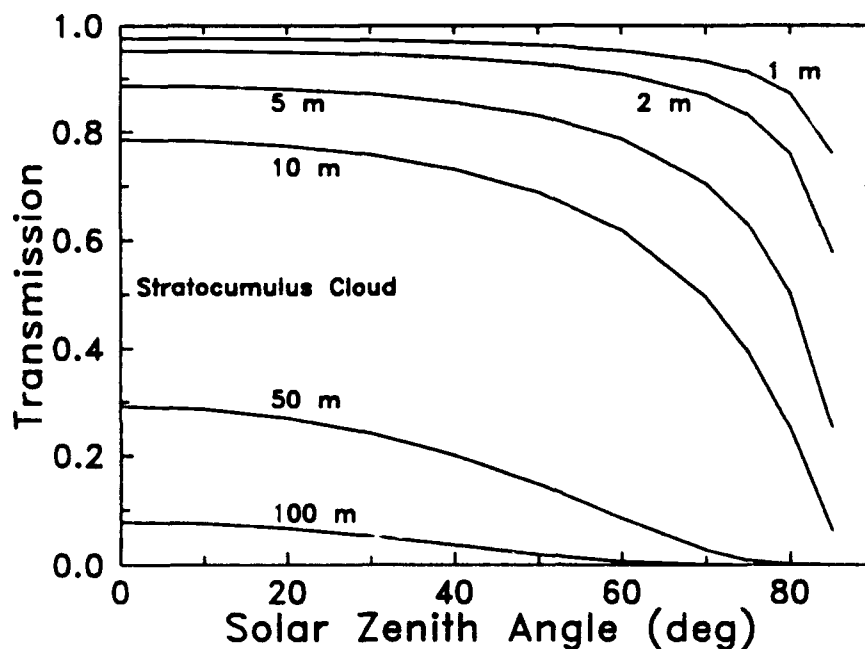


Figure 29. Calculated Transmission Through Stratocumulus Clouds in the Solar Direction Versus Solar Zenith Angle for Cloud Thicknesses of 1, 2, 5, 10, 50, and 100 m. Note that these transmissions are for the stratocumulus alone, and they do not include effects from aerosol and molecules within the stratocumulus

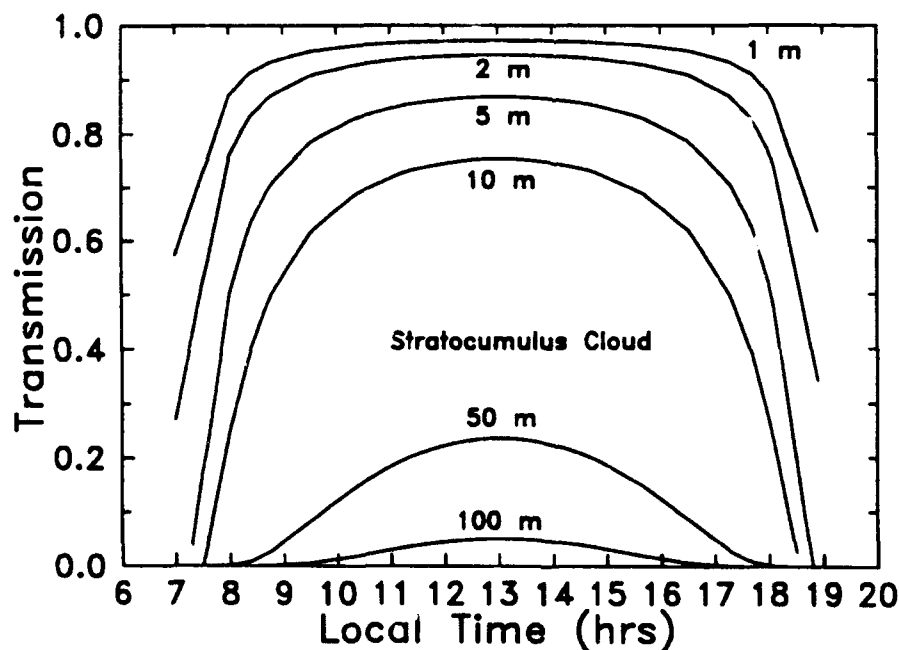


Figure 30. Calculated Transmission Through Stratocumulus Clouds in the Solar Direction Versus Local Time for Ascension Island for Cloud Thicknesses of 1, 2, 5, 10, 50, and 100 m. Note that these transmissions are for the stratocumulus alone, and they do not include effects from aerosol and molecules within the stratocumulus

3.4.2 Occurrence of Cloud Edges and Thin Spots

This section examines the frequency of occurrence of individual transmission measurements in which cloud edges and thin spots are suspected. Initially, the analysis only considered values of τ_{cld} between 0.1 and 0.9. Here, the rationale was that cloud edges and thin spots may exhibit some behavior that was independent of day-to-day fluctuations in average cloud cover. For example, Table 7 shows the daily percent distributions of individual measurements of cloud transmission in which only presumed occurrences of cloud thin spots and edges have been included. These percent distributions were derived from the data in Table 4 so that the first entry in Table 7 represents

$$100 \times \frac{8}{(8 + 8 + 21 + 236 + 213 + 147 + 37 + 30)} = 2.54\%. \quad (7)$$

Except for 25 June 1989, the data seem to show the same trends. That is, there is a uniform distribution of transmission values between about 0.1 and 0.7. Also, the percentages increase significantly as transmissions increase from 0.7 to 0.9. This is interesting because it indicates that the stratocumulus have very similar edge characteristics from day-to-day. However, note that the percent distributions for 25 June 1989 deviate from these generalizations because of cirrus clouds. Figure 31 shows these cloud statistics in pictorial form.

Table 7. Daily Percent Distributions of Individual Transmission Measurements In Which Only Presumed Occurrences of Cloud Edges and Thin Spots Have Been Included. For example, the first entry means that on 25 June 1989, 2.54% of all presumed cloud edge and thin spot measurements were between 0.1 and 0.2

% OF OCCURRENCES	25 JUNE	28 JUNE	1 JULY	2 JULY	6 JULY	7 JULY
τ_{cld} 0.1-0.2	2.54	3.95	6.65	5.76	11.52	10.52
τ_{cld} 0.2-0.3	1.13	4.14	6.96	8.12	8.48	9.60
τ_{cld} 0.3-0.4	2.96	5.45	9.18	6.28	7.73	8.99
τ_{cld} 0.4-0.5	33.24	6.02	11.08	7.33	9.24	8.69
τ_{cld} 0.5-0.6	30.00	7.33	7.91	9.55	9.39	10.37
τ_{cld} 0.6-0.7	20.70	10.15	11.08	12.43	10.61	10.21
τ_{cld} 0.7-0.8	5.21	21.05	13.92	17.67	14.39	13.87
τ_{cld} 0.8-0.9	4.23	41.92	33.23	32.85	28.64	27.74

Table 8 shows daily averages and standard deviations of cloud transmissions in which only presumed occurrences of cloud thin spots and edges have been included. The table suggests that the averages and standard deviations for 1, 2, 6, and 7 July 1989 are remarkably similar, although the average and standard deviation are, respectively, a little higher and lower for 28 June 1989. However, the results for 25 June 1989 clearly differ from the other days because of the presence of cirrus clouds.

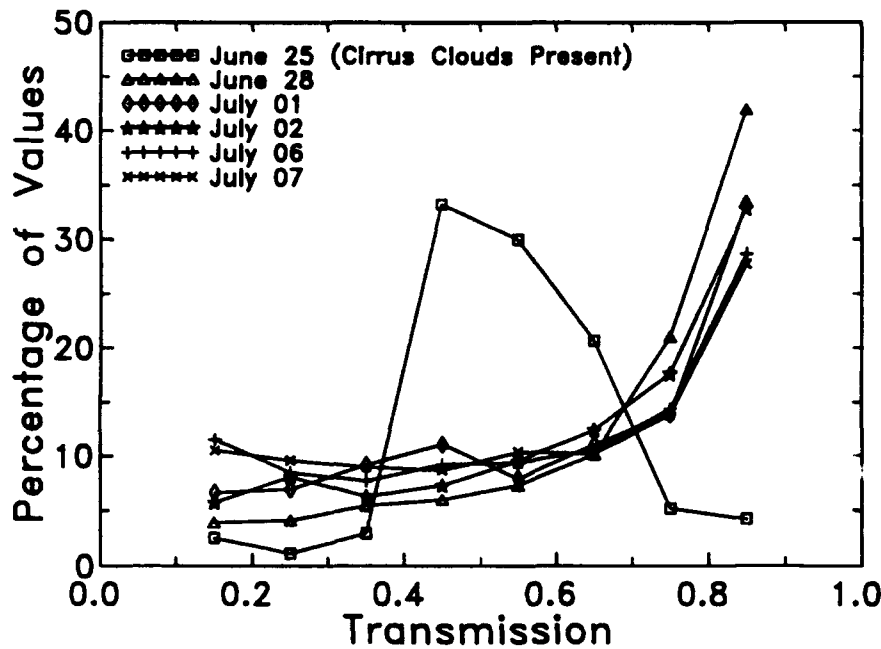


Figure 31. Daily Percent Distributions of Individual Transmission Measurements In Which Only Presumed Occurrences of Cloud Edges and Thin Spots Have Been Included

Table 8. Daily Averages and Standard Deviations of Transmission In Which Only Presumed Occurrences of Cloud Thin Spots and Edges Have Been Included

	25 JUNE	28 JUNE	1 JULY	2 JULY	6 JULY	7 JULY
TOTAL POINTS	1200	2494	2490	3682	5035	4410
EDGE POINTS ($0.1 < \tau_{cld} < 0.9$)	710	532	316	764	660	656
AVERAGE OF EDGE POINTS	0.5439	0.6851	0.6132	0.6309	0.5813	0.5765
ST DEV OF EDGE POINTS	0.1300	0.2061	0.2369	0.2312	0.2567	0.2512

Values of τ_{cld} were then used to estimate the overall opacity of stratocumulus clouds over Ascension Island. To do this, the number of occurrences of cloud thin spots and edges, N_{edge} , were compared against the total number of cloud occurrences which is given by

$$N_{edge} + N_{cld} \quad (8)$$

where N_{cld} equals the number of occurrences in which the clouds were opaque (i.e., values of τ_{cld} less than 0.1). In general terms, the ratio of $N_{edge}/(N_{edge} + N_{cld})$ gives a measure of overall cloud opacity. Values closer to 1.0 suggest that the clouds possess many thin spots and values closer to 0.0 suggest that most of the clouds are opaque. Table 9 gives daily

values of $N_{edge}/(N_{edge} + N_{cld})$ at Ascension Island. (Because of the presence of cirrus clouds, data for 25 June 1989 were not included in these estimates.) In Table 9, the daily values of $N_{edge}/(N_{edge} + N_{cld})$ vary somewhat probably because they are influenced by biases from the daily average cloud cover. However, the fact that daily values of $N_{edge}/(N_{edge} + N_{cld})$ are much greater than 0.0 means stratocumulus clouds over Ascension Island often are not opaque, and they frequently transmit partial solar radiation. Since stratocumulus clouds often cover broad regions of the marine environment, these findings could be of interest to climate modeling studies which often assume stratocumulus clouds to be fully opaque.

Table 9. Daily Values of $N_{edge}/(N_{edge} + N_{cld})$ for Over Ascension Island. Note that this ratio gives an estimate of cloud opacity. A value close to 1.0 means that the clouds possess many thin spots and values closer to 0.0 suggest that most of the clouds are opaque.

	28 JUNE	1 JULY	2 JULY	6 JULY	7 JULY
NO. OF EDGE PTS, N_{edge}	532	316	764	660	656
NO. OF OPAQUE PTS, N_{cld}	247	414	1229	407	716
TOTAL CLOUD PTS	779	730	1993	1067	1372
$N_{edge}/(N_{edge} + N_{cld})$	0.6829	0.4328	0.3833	0.6185	0.4781

3.4.3 Time Duration of Cloud Edges and Thin Spots

This section examines the time duration of cloud edges and thin spots. In the analysis, daily time series of τ_{cld} were subdivided into continuously distinct time periods in which:

1. Skies were clear in the direction of the sun
2. Clouds fully blocked the sun
3. Cloud edges and thin spots dominated.

In order to be classified as a "clear" period, values of τ_{cld} had to be greater than 0.9 for at least 60 seconds. Similarly, a fully "cloudy" period was assigned whenever values of τ_{cld} were less than 0.1 for at least 60 seconds. All remaining time periods in the τ_{cld} time series were classified as being dominated by cloud edges and thin spots. Note in this simple classification scheme that a given cloud edge and thin spot event can contain values of τ_{cld} less than 0.1 or greater than 0.9, provided they are of short duration. Here, the rationale is that cloud edges and thin spots often exhibit a high degree of variability and, therefore, some limiting values would be expected. Also, the 60 second criteria for fully clear and cloudy events was chosen without any true scientific basis; rather, it is based on human experience.

For reference, Tables 10 through 14 show, respectively, the time periods and durations when cloud edges and thin spots occurred on 28 June, 1, 2, 6, and 7 July 1989. (Once again, data for 25 June 1989 were not included in this analysis because of cirrus clouds.) Note that the minimum duration is four seconds which equals the transmission measurement spacing. The

duration of cloud edges and thin spot events were then grouped into evenly spaced time bins and the frequencies of occurrence were tabulated (see Table 15). Figure 32 presents these occurrences in a histogram form. The results suggest that for Ascension Island, time durations of most cloud edges and thin spot events are less than 200 seconds, although some events exceed 250 seconds. The distribution is not gaussian; rather, events of less than 60 seconds occur most frequently and there is a gradual falloff in the number of occurrences as the time durations become longer. However, the results may suggest a local peak around 40 seconds given that the number of events less than 10 seconds may be influenced by spurious measurements with the transmissometer.

Table 10. Times and Durations of Presumed Cloud Edges and Thin Spots for 28 June 1989 at Ascension Island

START TIME (Local)	END TIME (Local)	DURATION (sec)
13.5245	13.5488	92
13.5878	13.5878	4
13.6255	13.6255	4
13.6833	13.6988	60
13.7422	13.7678	96
13.8112	13.8267	60
13.8955	13.9000	20
13.9222	13.9288	28
13.9588	14.0067	176
14.0512	14.1000	180
14.1312	14.1422	44
14.1722	14.1812	36
14.2200	14.2322	48
14.4533	14.4533	4
14.5955	14.6055	40
14.6222	14.6222	4
14.6555	14.6755	76
14.7233	14.7667	160
14.8922	14.9245	120
15.0188	15.0388	76
15.0667	15.0688	12
15.1500	15.1600	40
15.7367	15.7367	4
16.3878	16.4788	332
16.5578	16.6200	228
16.7422	16.8112	252
16.8388	16.9800	512
17.4145	17.4233	36
17.4467	17.4778	116
17.5167	17.5488	120

Table 11. Times and Durations of Presumed Cloud Edges and Thin Spots for 1 July 1989 at Ascension Island

START TIME (Local)	END TIME (Local)	DURATION (sec)
12.4267	12.4355	36
12.5300	12.5955	240
12.6288	12.6367	32
12.6600	12.7455	312
12.7745	12.7933	72
12.8100	12.8255	60
12.8945	12.8955	8
13.3112	13.3212	40
13.3722	13.3933	80
13.4455	13.4455	4
13.4633	13.4767	52
13.5078	13.5112	16
13.5878	13.5878	4
13.6900	13.6978	32
13.7978	13.8245	100
13.8588	13.8712	48
13.8978	13.9200	84
13.9533	13.9833	112
14.0012	14.0022	8
14.0388	14.0467	32
14.3733	14.3767	16
14.4100	14.4388	108
14.5022	14.5067	20
14.5312	14.5312	4
14.5633	14.5633	4
14.5878	14.6278	148
14.6545	14.6600	24
14.7500	14.7500	4
14.8478	14.8645	64
14.9433	14.9488	24
14.9788	14.9812	12
15.0000	15.0012	8
15.0645	15.0645	4
15.0922	15.1122	76
15.6600	15.6645	20
15.8867	15.8867	4
15.9245	15.9500	96
16.0022	16.0300	104
16.0533	16.0545	8
16.0855	16.0900	20
16.1145	16.1755	224

Table 12. Times and Durations of Presumed Cloud Edges and Thin Spots for 2 July 1989 at Ascension Island

START TIME (Local)	END TIME (Local)	DURATION (sec)
10.3622	10.3767	56
10.3945	10.4633	252
10.7555	10.7655	40
10.8345	10.9012	244
10.9233	10.9322	36
10.9567	10.9733	64
10.9933	10.9955	12
11.0345	11.0922	212
11.6655	11.6978	120
11.7322	11.7533	80
11.8000	11.8012	8
11.8212	11.8322	44
11.8555	11.8955	148
11.9455	11.9778	120
11.9945	12.0000	24
12.0522	12.0600	32
12.0967	12.1433	172
12.1612	12.2400	288
12.2622	12.2855	88
12.3022	12.3078	24
12.3778	12.3822	20
12.4133	12.4145	8
12.4345	12.4378	16
12.4612	12.4812	76
12.9412	12.9622	80
12.9800	12.9822	12
13.0145	13.0267	48
13.0945	13.1055	44
13.2012	13.2088	32
13.2955	13.3655	256
13.4200	13.4622	156
13.4945	13.5133	72
13.5733	13.5833	40
13.9122	13.9333	80
13.9912	14.0000	36
14.0745	14.0922	68
14.1288	14.1400	44
14.1778	14.1788	8
14.2133	14.2678	200
14.2878	14.2933	24

Table 12. (cont.)

START TIME (Local)	END TIME (Local)	DURATION (sec)
14.3155	14.3433	104
14.4245	14.4333	36
14.5155	14.5233	32
14.5433	14.5555	48
14.5745	14.6078	124
15.0788	15.0788	4
15.0888	15.1212	120
15.1712	15.2433	264
15.2745	15.2855	44
15.3033	15.3400	136
15.3778	15.4133	132
15.4355	15.5088	268
15.5912	15.5912	4
15.6167	15.6388	84
15.6945	15.6945	4
15.7222	15.7378	60
15.7545	15.7655	44
15.8055	15.8100	20
15.9122	15.9288	64
17.3545	17.3633	36
17.3722	17.3788	28
17.4422	17.4912	180

Table 13. Times and Durations of Presumed Cloud Edges and Thin Spots for 6 July 1989 at Ascension Island

START TIME (Local)	END TIME (Local)	DURATION (sec)
9.5912	9.5912	4
9.7045	9.7055	8
9.8167	9.8278	44
9.8922	9.9088	64
9.9412	9.9412	4
9.9845	10.0588	272
10.0767	10.0867	40
10.2088	10.2088	4
10.7012	10.7022	8
10.7345	10.7388	20
10.8255	10.8633	140
10.8822	10.9022	76
10.9278	10.9888	224
11.0145	11.0422	104
11.1988	11.2000	8
11.2212	11.2867	240
11.7588	11.7633	20
11.8288	11.8300	8
11.8500	11.8500	4
11.9700	11.9733	16
12.0078	12.0112	16
12.0522	12.0600	32
12.0945	12.1212	100
12.2400	12.2700	112
12.4178	12.4200	12
12.9078	12.9422	128
12.9667	13.0112	164
13.0688	13.0878	72
13.1245	13.1700	168
13.1822	13.1845	12
13.2278	13.2500	84
13.2678	13.2800	48
13.3033	13.3033	4
13.3633	13.3633	4
13.4600	13.4600	4
13.4800	13.4912	44
13.7100	13.7178	32
14.0533	14.0622	36

Table 13. (cont.)

START TIME (Local)	END TIME (Local)	DURATION (sec)
14.0912	14.1288	140
14.1467	14.1745	104
14.2078	14.2100	12
14.2188	14.2512	120
14.3645	14.3755	44
14.4300	14.4578	104
14.4855	14.5455	220
14.5633	14.5633	4
14.5800	14.6367	208
14.6578	14.6622	20
14.6800	14.7267	172
14.7455	14.7512	24
14.7745	14.7745	4
14.8755	14.8855	40
15.2078	15.2645	208
15.3178	15.3678	184
15.4088	15.4512	156
15.4688	15.5033	128
15.5488	15.5600	44
15.7122	15.7155	16
15.8288	15.8378	36
15.8888	15.8900	8
16.3167	16.3300	52
16.6367	16.6378	8
16.7967	16.8078	44
16.8322	16.8333	8
16.9433	16.9467	16
17.5122	17.5267	56
17.5445	17.5488	20
17.7388	17.7645	96
17.8222	17.8345	48

Table 14. Times and Durations of Presumed Cloud Edges and Thin Spots for 7 July 1989 at Ascension Island

START TIME (Local)	END TIME (Local)	DURATION (sec)
10.6678	10.7245	208
10.7633	10.7733	40
10.8100	10.8133	16
10.8522	10.8522	4
10.8833	10.8922	36
10.9112	10.9178	28
10.9488	10.9500	8
10.9845	11.0412	208
11.0878	11.1045	64
11.1667	11.2100	160
11.2345	11.2533	72
11.2712	11.3200	180
11.6478	11.6812	124
11.7345	11.7433	36
11.7633	11.7788	60
12.1888	12.2200	116
12.8233	12.8855	228
12.9245	12.9800	204
13.0022	13.0055	16
13.0345	13.0378	16
13.0578	13.0612	16
13.1088	13.1278	72
13.1545	13.1555	8
13.1878	13.2033	60
14.1322	14.1322	4
14.3388	14.3578	72
15.0088	15.0122	16
15.0378	15.0667	108
15.0845	15.0855	8
15.1300	15.1378	32
15.1722	15.1733	8
15.2122	15.2312	72
15.2812	15.3800	360
15.4455	15.4788	124
15.5067	15.5088	12
15.5312	15.5855	200
15.6088	15.6445	132

Table 14. (cont.)

START TIME (Local)	END TIME (Local)	DURATION (sec)
15.6645	15.7033	144
16.1988	16.2255	100
16.2378	16.2388	8
16.4367	16.4822	168
16.5588	16.5688	40
16.5800	16.5978	68
16.6212	16.6478	100
16.8200	16.8345	56
16.8612	16.8812	76
17.0578	17.0945	136
17.4633	17.4912	104
17.5155	17.5655	184
17.7667	17.7688	12
17.7955	17.8078	48
17.8955	17.9455	184
17.9688	17.9833	56
18.0012	18.0733	264

Table 15. Frequency of Occurrence of Cloud Edges and Thin Spots Events of Different Time Durations. The daily averages and standard deviations for the time durations are also listed

# OF EVENTS	28 JUNE	1 JULY	2 JULY	6 JULY	7 JULY
TOTAL	30	41	62	69	54
< 10 sec EVENTS	5	11	6	16	7
10-30 sec EVENTS	3	8	9	12	8
30-50 sec EVENTS	6	6	16	13	6
50-70 sec EVENTS	2	3	5	3	6
70-90 sec EVENTS	2	4	7	3	5
90-110 sec EVENTS	2	4	1	5	4
110-130 sec EVENTS	3	1	4	4	3
130-150 sec EVENTS	0	1	3	2	3
150-170 sec EVENTS	1	0	1	3	2
170-190 sec EVENTS	2	0	2	2	3
190-210 sec EVENTS	0	0	1	2	4
> 210 sec EVENTS	4	3	7	4	3
AVE TIME OF EDGE EVENTS	98.6	56.2	83.5	67.1	89.3
STD DEV OF EDGE EVENTS	106.1	63.7	73.5	64.2	73.8

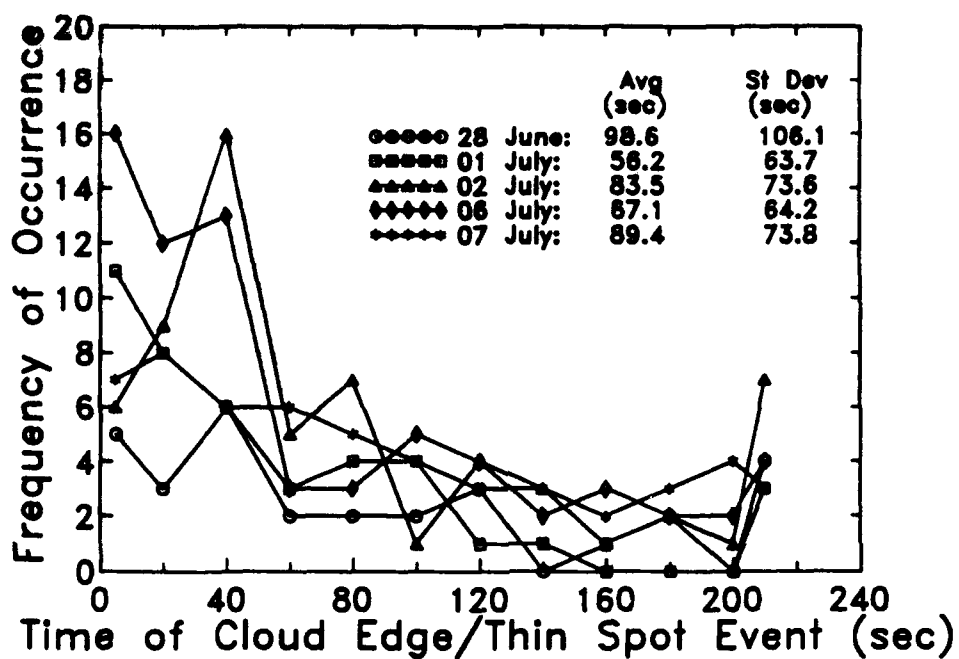


Figure 32. Frequency of Occurrence of Cloud Edges and Thin Spots Events Versus Duration Time. Note that the values for 210 seconds actually represents all occurrences of duration times greater than 210 seconds

4 SUMMARY AND CONCLUSIONS

This report has analyzed solar transmissometer data that were taken during the South Atlantic Backscatter Lidar Experiment (SABLE). There were six days when the instrument was operated: 25 June, 28 June, 1 July, 2 July, 6 July, and 7 July 1989. The instrument was located on Ascension Island, and it measured solar transmission at 532 nm versus time and transmission across the solar spectrum.

Because there were initial concerns about instrument calibration, the first task was to validate the transmission data using the Langley method. Here, the measured solar signals were converted to solar transmissions using calibration factors given by the y intercept on plots of $\sec \phi$ versus $\ln i_{\lambda_s}$ where ϕ and i_{λ_s} are the solar zenith angle and the measured solar signal, respectively. Transmissions derived from the Langley method were 5 to 10% less than those derived from the standard calibration procedure, except for 6 July and 7 July 1989 where there was nearly perfect agreement between the two calibration techniques. The extensive data sets on 6 July and 7 July 1989 may account for the exceptionable agreement because calibration factors for the Langley method can be obtained with more reliable best fit lines.

Next, the time series of solar transmissometer data at 532 nm were used to study the properties of cirrus and boundary layer stratocumulus clouds that passed in front of the sun while the instrument was working. To do this, it was first necessary to separate and remove aerosol and molecular transmissions from the measured solar transmissions to get the cloud transmissions. The removal technique, which made use of "clear sky" values of solar transmission from LOWTRAN7, performed reasonably well.

For the most part, the data taken on 25 June 1989 were analyzed separately because they were influenced by the presence of cirrus and thin cirrus. A qualitative assessment showed the transmissions through cirrus to be between 0.4 and 0.8, and the cirrus thicknesses were estimated to be between 1.0 and 2.2 km. These estimates were consistent with cirrus observations from aircraft for 25 June 1989.

The remainder of the analysis focused on the properties of stratocumulus cloud edges and thin spots. It was shown that stratocumulus had very similar edge characteristics from day-to-day: there was a uniform distribution of cloud transmission values between about 0.1 and 0.7, and the percentages increase significantly as cloud transmissions increase from 0.7 to 0.9. Also, the number of occurrences of cloud thin spots and edges were compared against total of number of cloud occurrences. Although day-to-day variations existed, the comparisons clearly showed that stratocumulus clouds over Ascension Island often are not opaque, and they frequently transmit partial direct solar radiation. Since stratocumulus clouds often cover broad regions of the marine environment, these findings could be of interest to cloud modeling studies that treat stratocumulus clouds as optically thick, developers of ground-to-space systems in the DoD community, and cloud-free-line-of-sight (CFLOS) studies. Finally, the solar transmissometer data were analyzed as a time series in order to estimate the durations of stratocumulus edge and thin spot events. Here, it was shown that time durations of most cloud edges and thin spot events are less than 200 seconds. The distribution is not gaussian; rather, events of less than 60 seconds occur most frequently, and there is a gradual falloff in the number of occurrences as the time durations become longer.

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Appendix A

Calibration and Reduction of Solar Transmissometer Data

This appendix describes the standard procedure for calibrating and reducing the solar transmissometer data taken during SABLE 89. Most of material in this appendix is a compilation of notes from PhotoMetrics, Inc., the group responsible for the collection of the data.

Effectively, calibration of the EK/EG&G solar transmissometer is done in two phases. The first part involves the calculation of a nearly invariant ratio of instrument response to the ribbon filament calibration lamp and to solar input. The second part uses wavelength scans of the lamp taken before and after each data recording session (typically morning and evening) to monitor and correct for variations in instrument response during operation. Instrument dark current is recorded before and after each set of measurements (monitor scans or transmission scans) and used to remove the linear drift in the instrument baseline. Differences in the data reduction procedure for SABLE 89 are given at the end of this appendix.

A.1 Solar Power Input to the Transmissometer

The spectral solar power input to the integrating sphere, P_s , is given by

$$P_s = T_A T_o A \int_0^{2\pi} d\Phi \int_0^{\theta_o} B(\theta, \Phi) \sin \theta d\theta \quad (A-1)$$

where T_A is the atmospheric transmittance, T_o is the transmittance of objective lens, A is the area of objective clear aperture, θ_o is the 1/2-angle of telescope field of view (FOV) including the measurement field stop aperture, and $B(\theta, \Phi)$ is the solar radiance within FOV at (θ, Φ) . In this equation, as in most of the treatment that follows, explicit dependence of physical parameters on wavelength, λ , has been suppressed for notational convenience. Assuming that the sun is centered along the optic axis and noting that $\theta_o \ll 1$, Eq. A-1 can be rewritten as

$$P_s = 2\pi \theta_s^2 T_A T_o A \int_0^{\beta_o} B_s(\beta) \beta d\beta \quad (A-2)$$

where θ_s is the 1/2-angle subtended by the solar disk, β is θ/θ_s , and β_o is θ_o/θ_s . Note that β represents the fraction from the center to the edge at which a ray at angle θ strikes the solar disk. The apparent radiance across the solar disk varies because of emission and reabsorption effects in the solar atmosphere. Usually the variable part of the radiance is separated out such that

$$B_s(\beta) = B_s(0)L(\beta) \quad (A-3)$$

where $B_s(0)$ is the radiance at the center of the solar disk and the function L accounts for the observed darkening toward the edge (limb) of the solar disk. This limb darkening exhibits a

significant wavelength dependence which is taken to be implicit. Allen⁸ has given three alternate forms for L as a function of $\mu \equiv \sqrt{1 - \beta^2}$. In the present calibration procedure, $L(\mu)$ is given by

$$L(\mu) = 1 - u - v + u\mu + v\mu^2 \quad (A - 4)$$

where the parameters u and v , are given at a set of wavelengths, and interpolation is required when calibrating throughout the bandpass of the transmissometer. Defining the parameter

$$F(\alpha) \equiv \int_0^\alpha L(\beta)\beta d\beta = \int_{\sqrt{1-\alpha^2}}^1 L(\mu)\mu d\mu, \quad (A - 5)$$

the mean solar radiance, $\overline{B}_s$, and the solar irradiance, I_s , can be written as

$$\overline{B}_s = 2B_s(0)F(1) \quad (A - 6)$$

$$I_s = \overline{B}_s\Omega_s \quad (A - 7)$$

where $\Omega_s = \pi\theta_s^2$ is the solid angle subtended by the solar disk. Using these definitions, Eq. A-2 can be rewritten as

$$P_s = LDF(\beta_o) \frac{T_A T_o A I_s \Omega_o}{\Omega_s} \quad (A - 8)$$

where Ω_o is the solid acceptance angle of the telescope ($\pi\theta_o^2$) and the limb darkening factor, $LDF(\beta_o)$, is

$$LDF(\beta_o) = \frac{\beta_o^{-2} F(\beta_o)}{F(1)}. \quad (A - 9)$$

Note that LDF equals one if the solar disk were uniformly bright. Physically, the LDF is the ratio of the mean radiance of the imaged fraction of the solar disk to that of the entire disk.

⁸ Allen, C.W. (1973) Astrophysical Quantities, Athlone Press, London.

A.2 Calibration Equation

The power input to the integrating sphere from the calibration lamp is

$$P_c = T_o A \Omega_c R_p B_c \quad (A - 10)$$

where Ω_c is the acceptance solid angle of telescope including the calibration field stop aperture, R_p is the reflectance of parabolic mirror in lamp housing, and B_c is the brightness of ribbon filament calibration lamp. Since the detector current is proportional to input power, the ratio of the solar signal current, i_s , to the calibration current, i_c , can be written as

$$\frac{i_s}{i_c} = \frac{P_s}{P_c} = \frac{I_s \Omega_o LDF}{\Omega_c \Omega_s R_p B_c} T_A. \quad (A - 11)$$

Inverting this expression, the atmospheric transmittance is

$$T_A(\lambda) = \frac{K(\lambda)}{i_c(\lambda)} i_s(\lambda). \quad (A - 12)$$

and the calibration ratio, $K(\lambda)$, is defined as

$$K(\lambda) = \frac{\Omega_c \Omega_s R_p(\lambda) B_c(\lambda)}{I_s(\lambda) \Omega_o LDF(\lambda)}. \quad (A - 13)$$

where for emphasis, the wavelength dependences are explicitly noted in Eqs. A-12 and A-13. In Eq. A-12, the dark current baseline is first subtracted from the signal and calibration currents to yield i_{sb} and i_{cb} respectively. The atmospheric transmission then becomes

$$T_A(\lambda) = \frac{K(\lambda)}{i_{cb}(\lambda)} i_{sb}(\lambda) \quad (A - 14)$$

where the factor $K(\lambda)/i_{cb}$ is the calibration expressed as transmission per nano-amp of signal. The following section discusses the physical parameters used to determine $K(\lambda)$.

A.3 Calibration Constant

A.3.1 Solar Parameters

The solar solid angle is taken to be 6.22×10^{-5} str, corresponding to a full cone angle of 0.51° . The solar irradiance outside the Earth's atmosphere is obtained from PCTRAN6⁹. The annual variation of a few percent, which occurs in both these quantities, should cancel out upon taking the ratio needed in Eq. A-13. Note that I_s/Ω_s is the mean solar radiance which is independent of observation distance. Neither the appropriate Ω_s to use with PCTRAN6 data nor the absolute accuracy of the PCTRAN6 data has been determined for calibration, but PhotoMetrics, Inc. has estimated the uncertainties to be less than 3%.

⁹ ONTAR Corporation (1986) PCTRAN, ONTAR Corporation, Brookline, Massachusetts.

A.3.2 Telescope

The ratio of the calibration to the measurement FOV's can be written entirely in terms of the ratio of the field stop diameters employed:

$$\frac{\Omega_c}{\Omega_o} = \left(\frac{d_c}{d_o}\right)^2. \quad (A - 14)$$

Substituting Eq. A-14 into Eq. A-13, the calibration ratio can be expressed as

$$K(\lambda) = \pi \theta_s^2 \left(\frac{d_c}{d_o}\right)^2 \frac{R_p(\lambda) B_c(\lambda)}{I_s(\lambda) LDF(\lambda)}. \quad (A - 15)$$

Note that due to the ratioing, the result does not depend on the focal length of the objective lens. The instrument specifications for d_c and d_o come from Christiansen¹⁰:

$$d_c = 0.999 \text{ inches}$$

$$d_o = 0.029 \text{ inches}$$

yielding a FOV ratio of $\Omega_c/\Omega_o = 11.65$. Although the number of significant digits in the ratio is specious, the value 11.65 is used to remain compatible with Christiansen². Judging from the number of significant digits quoted for the diameters, the ratio is assumed to have an uncertainty of about 2%.

A.3.3 Calibration Lamp

The spectral radiance of the ribbon filament lamp, B_c , and reflectance of the parabolic mirror, R_p , are taken from Lurie¹¹. For reference, the adopted values for these parameters are shown in Figures A-1 and A-2. The spectral radiance of the lamp was measured by Optronics in September 1974. Although a later recalibration was performed in February 1977, these data are tabulated at fewer wavelengths in Lurie¹¹. The differences between measured spectral radiances from September 1974 and February 1977 are generally less than 2%. For SABLE 89, a larger uncertainty is the use of these calibrations 15 years later. Therefore, without recalibration, the lamp radiance can be trusted to no better than 5%. Also a similar, if not greater, uncertainty is associated with the mirror reflectance which was measured in December 1975.

For calibration throughout the instrument bandpass, mirror reflectances were linearly interpolated from tabulated values in Lurie³ since no model is available. For the lamp radiance, a black body temperature is found by fitting the radiance to the black body spectrum with a linearly varying emissivity. This temperature is then used to interpolate between tabulated values of lamp radiance.

The calibration ratio, $K(\lambda)$, obtained from the above procedure and Eq. A-13 is shown in Figure A-3. Due to the uncertainties mentioned above, a systematic error on the order of 10%

¹⁰ Christiansen, L. (1979) Spectral Radiometric Measurement and Analysis Program, Volume I, E.K.

¹¹ Lurie, N. (1977) Calibration of PAR317S MRV, E.K.

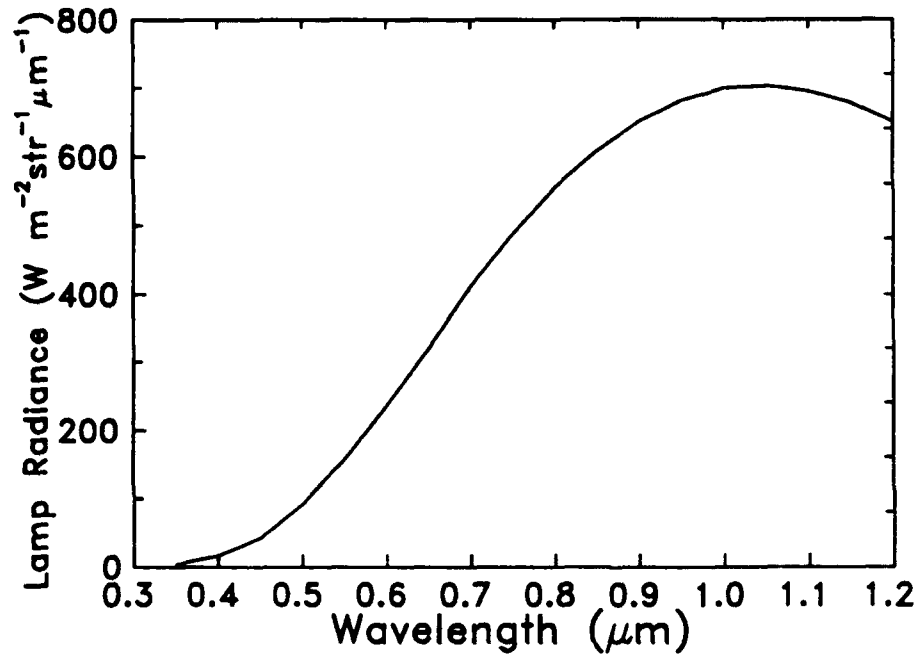


Figure A-1. Spectral Radiance of the Ribbon Filament Lamp, B_c , as a Function of Wavelength

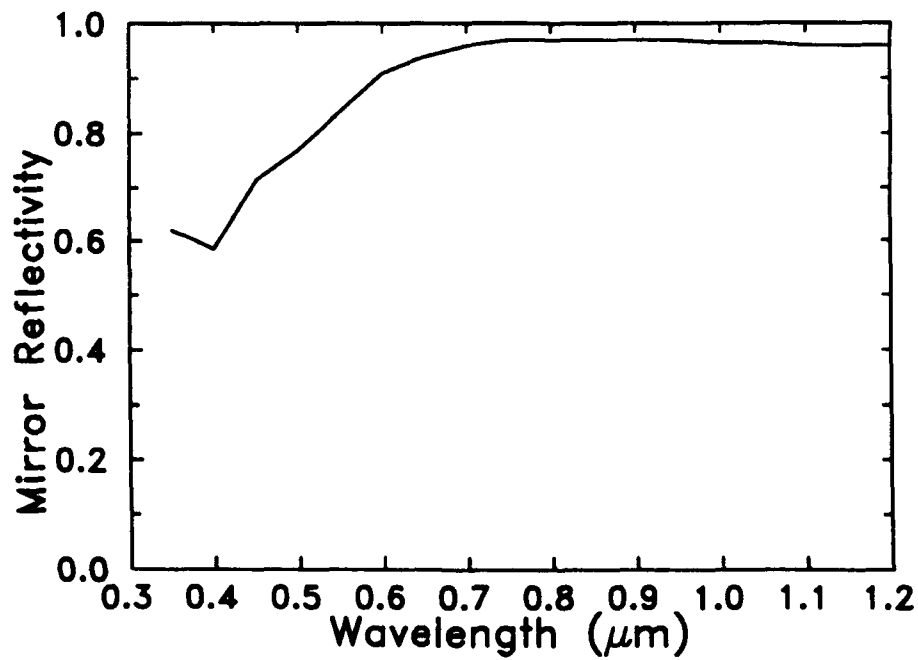


Figure A-2. Spectral Reflectance of the Parabolic Mirror, R_p , as a Function of Wavelength

can be expected in the calculated calibration curve. Most of this error is due to uncertainties in lamp radiance and mirror reflectance. However, the errors involved may be underestimations given the length of time from the last measurement of these quantities.

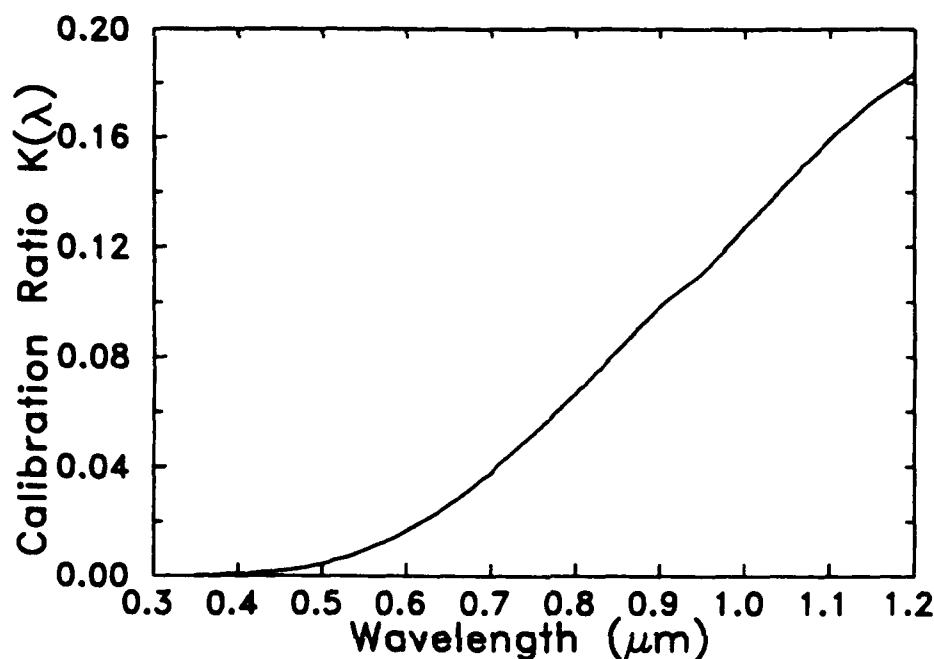


Figure A-3. Calibration Ratio, $K(\lambda)$, for the Solar Transmissometer as a Function of Wavelength

A.4 Measurement Errors of the Signal and Calibration Currents

The two main sources of error in the measurement of the signal, i_s , and calibration currents, i_c , are variations in detector gain and dark current which are discussed below. Also contamination of data below $0.55 \mu\text{m}$ by the reentrant spectrum of longer wavelength radiation is discussed.

A.4.1 Detector Gain

Typically, lamp calibrations (*i.e.*, measurement of i_c) are done before and after all solar data are collected. During this time, gain variations on the order of 10% have been observed. The detector housing has incorporated an LED source and constant current supply so that the gain can be monitored and, if necessary, corrected by trimming the PMT high voltage. This allows for compensation of gain drift to about a 1% level if the internal calibration source is assumed to be repeatable to better than 1%.

A.4.2 Dark Current

Expected signal and calibration currents above about $1\ \mu\text{m}$ and calibration currents below about $0.45\ \mu\text{m}$ are on the order of the detector dark current. Measurement and subtraction of this dark current is necessary in these spectral regions. Due to the age of the detector cooling unit, thermal drifts can cause significant variations in the dark current over a time scale of minutes. Currently, dark currents are measured before and after each series of measurements (*e.g.*, a spectral scan) and dark current values are obtained by means of an interpolation.

A.4.3 Reentrant Spectrum

Recently it was discovered that calibration lamp data, i_c , below about $0.55\ \mu\text{m}$ were significantly contaminated by the reentrant spectrum of light above about $0.7\ \mu\text{m}$. This phenomenon, which is primarily an instrument design problem, occurs when radiation from the calibration lamp enters the Evert-Fastie monochromator with the grating angle set such that light rays less than $0.55\ \mu\text{m}$ reemerge from the exit slit. Allowing for multiple passes, it can be shown that light rays longer than $0.7\ \mu\text{m}$ also arrive at the exit slit. If there is significantly more $0.7\ \mu\text{m}$ light, it can rival that of the primary wavelength even though the reentrant spectrum is not focused on the exit slit.

In the future, reentrant effects will be eliminated or accurately corrected. For the present, it was determined that this spurious component accounts for about half of the detector current, i_c , at $0.45\ \mu\text{m}$. However, this correction should be viewed as no more than a stopgap until more accurate measurements can be made.

A.5 Discussion of Previous EK/EG&G Calibrations

Although calibration data from earlier usages of the transmissometer are not available, Christiansen¹⁰, Lurie¹¹, EG&G¹² and Christiansen¹³ contain discussions of the calibration and other features of the solar transmissometer. The calibration equation is derived in the references^{10,11,13}, for example. Unlike the derivation in this appendix, the other derivations include the effect of limb darkening as an afterthought. Notably and unaccountably, references^{10,11,13} employ the $LDF(\lambda)$ as a multiplying factor in $K(\lambda)$ instead of as a divisor as in Eq. A-13. According to the present values of $LDF(\lambda)$, this would lead to overestimates of 90% in the blue and 20% in the red for the atmospheric transmittance in an otherwise correct analysis.

Concerning the reentrant spectrum, it was recognized in the construction phase of the transmissometer that reentrant effects could be significant.¹² The Jarrel-Ash monochromators were customized to contain a vane at the focal plane of the reentrant rays; however, according to reference¹² "in actual experiments in the laboratory, it became clear that the reentry spectrum is very weak compared to the first order spectrum and can be ignored..." Since the use of the vanes in the reentrant blocking position reduces the instrument throughput by about 50%, it is apparent that they were never employed. If indeed reentrant effects were ignored, and there is no

¹² EG&G MRMS Operation Manual, Vol. IV.

¹³ Christiansen, L. (1976) Memorandum to G. Bouk

indication otherwise, the analysis would underestimate the atmospheric transmission in the blue by a factor of two with little effect at wavelengths above $0.60\ \mu\text{m}$. According to PhotoMetrics, Inc., it is interesting to note that this underestimate of transmission in the blue comes close to compensating for the possible overestimate due to misuse of $LDF(\lambda)$ as discussed above.

A.6 Differences in Data Reduction for SABLE 89

SABLE 89 was the first large data set taken with the solar transmissometer. Calibration was only performed once per day, so lamp monitor scans nearest in time to each data set were utilized. Data taken on 25 June and 28 June used the calibration taken on 29 June. To account for reentrant spectra, an estimated correction was applied to the short wavelength data. The assumption was that one half of the light measured at $0.45\ \mu\text{m}$ from the calibration lamp was due to multiply reflected light from longer wavelengths and that by $0.80\ \mu\text{m}$, there was no reentrance. Values subtracted from the calibration data were as follows:

1. 0.114 between 0.35 and $0.45\ \mu\text{m}$.
2. A linearly decreasing ramp to 0.0 at $0.80\ \mu\text{m}$.
3. 0.0 between 0.80 and $1.2\ \mu\text{m}$.

The value 0.114 was chosen because it was approximately one half of the detector current measured at $0.45\ \mu\text{m}$ for the calibration lamp. Below $0.45\ \mu\text{m}$ however, the signal due to the calibration lamp is on the order of the detector dark current, and correction between 0.35 and $0.45\ \mu\text{m}$ is thus not meaningful (transmissions are also not valid). Also it is noted that from approximately 1.0 to $1.2\ \mu\text{m}$, the signal current derived from the calibration lamp is essentially the detector dark current, invalidating transmission measurements in this region.

Data for the eight individual calibrations of SABLE 89 were averaged to obtain the average calibration, $\overline{K}(\lambda)/i_{cb}$. Next the daily calibrations, $C(\lambda)$, were found by normalizing the average calibration to each individual calibration in the wavelength region from 0.85 to $0.87\ \mu\text{m}$. Values of atmospheric transmission were then determined from the solar currents, i_s , by subtracting dark current background to get i_{sb} and finding $T_A(\lambda) = C(\lambda)i_{sb}$. For reference, Figure A-4 shows daily calibrations, $C(\lambda)$, for SABLE 89.

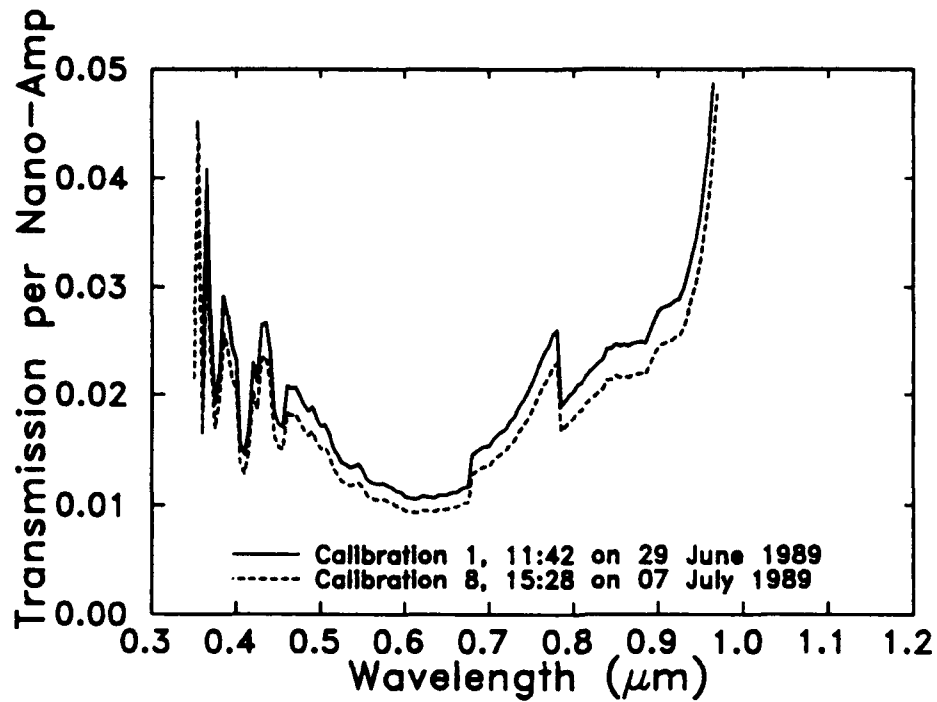


Figure A-4. Daily Calibrations of the Solar Transmissometer as Scaled from the Average for SABLE 89 as a Function of Wavelength. For clarity, only two of the eight calibrations are shown

File Formats and Computer Programs Used in This Analysis

B.1 File Format of the Solar Transmissometer Data

There are 68 files of solar transmission data from SABLE 89, one for each time period when the transmissometer was operated (see Table 1 of the main text). The data are in ASCII format, and the file naming convention consists of a seven digit file name and a *.trn* extension. The first three digits represent the month and day of the measurement, so "628" means 28 June 1989. The second four digits are the start time of the measurement period, so "0631" means the measurement period began at 6:31 Eastern Daylight Time, or 10:31 Local Time for Ascension Island.

Each line of data in a *.trn* file represents an individual solar transmission measurement. Each row of data contains five columns. The meaning of each column is as follows

1. Time in minutes after midnight for Eastern Daylight Time.
2. Wavelength of the measurement in nanometers.
3. Measured solar signal in nanoamperes.
4. Solar tracking parameter.
5. Fractional solar transmission.

For reference, an example of a file containing solar transmission data is shown in Figure B-1.

463.27	531	12.604E-01	28	17.139E-03
463.33	531	92.840E-02	28	12.624E-03
463.47	531	41.690E+00	15	56.689E-02
463.53	531	41.390E+00	11	56.281E-02
463.60	531	30.390E+00	18	41.323E-02
463.67	531	26.901E-01	28	36.579E-03
463.80	531	72.400E-01	8	98.447E-03
463.87	531	73.400E-01	8	99.807E-03
464.07	531	34.390E+00	15	46.762E-02
464.13	531	37.990E+00	13	51.658E-02
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.

Figure B-1. Example of a File Containing Solar Transmission Data

B.2 Computer Programs for Data Analysis

During this effort, a number of computer programs were developed to analyze the solar transmission data. All of the computer programs are written with MicroSoft Fortran 5.0. Generally, the computer programs were written in a research framework, in that users must edit some of the hard-wired parameters to suit their needs, and then recompile the code. Brief descriptions of the computer programs are given below. For the most part, the computer programs execute quickly (under a minute or two) on 80286 computer systems.

B.2.1 Program *SIGNALFOR*

This computer program reads files of solar transmission data and then computes the secant of the solar zenith angle and the logarithm of the measured current. This computer program is very useful for determining Langley calibration factors. The input file names are hard-wired into this computer program, and they assume a *.trn* extension. Output from this computer program includes the secant of the solar zenith angle and the logarithm of the measured current. Output is written to files having a *s* appended to the input file names plus a *.dat* extension.

B.2.2 Program *RECALFOR*

This computer program reads files of solar transmission data and then converts the measured currents to transmissions using the Langley method. The input file names are hard-wired into this computer program, and they assume a *.trn* extension. Output from this computer program includes transmissions from the Langley method and the standard calibration procedure, as well as their difference. Output is written to files having the input files name plus a *.dat* extension. Note that appropriate calibration factors for the Langley method must be predetermined (usually from graphical procedures) and then hard-wired into this computer program before it can be used.

B.2.3 Program *REMOVEFOR*

This computer program removes aerosol, molecular, and zenith angle effects from the solar transmission data. The computer program also computes statistical information about the normalized data, such as frequency of occurrence of normalized transmission versus transmission bin, plus averages and standard deviations of cloud thin spots.

Before *REMOVEFOR* can be run, users must decide on a surface visibility to be used to normalize the data. If the surface visibility is not one of those already in the computer program, users must precalculate (using LOWTRAN7) an array of space-to-ground transmission at 532 nm versus solar zenith angle for the surface visibility of interest, and then hard-wire them into the program. Users must also add a line of code to perform the interpolation for the desired visibility, and then modify the line of code that actually removes the aerosol and molecular effects. If the surface visibility is already in the program, users must still activate the appropriate line of code for the interpolation, and then modify the line that actually removes the aerosol and molecular effects. Also, the computer program currently calibrates the data using the Langley method, so users must supply an appropriate calibration factor on the line that actually removes the aerosol and molecular effects.

It is important to note that *REMOVE.FOR* will need to be run a few times in order to get the best normalized fit. The general procedure is to run the computer program for a certain surface visibility, plot the results, decide on a better surface visibility, and then try again.

Because the normalization scheme is an iterative process, *REMOVE.FOR* only handles one solar transmissometer data file at a time. The input file name must be hard-wired into the program, and it assumes a *.trn* extension. The normalized data is written to a file having a *n* appended to the input file names plus a *.dat* extension. The statistical information is written to a file named *stats.dat*.

B.2.4 Program *CIRRUS.FOR*

This computer program calculates cirrus transmission in the solar direction versus local time at Ascension Island. Note that the cirrus transmission in the solar direction varies according to a secant of the solar zenith angle relationship. Currently, this computer program determines transmissions for cloud thicknesses between 0.1 km and 2.5 km. The reference values for cirrus transmission are computed with LOWTRAN7. There are no input files for this computer program, and the output is written to *cirrus2.dat*.

B.2.5 Program *STRATO.FOR*

This computer program calculates stratocumulus transmission in the solar direction versus local time at Ascension Island. Note that the stratocumulus transmission in the solar direction varies according to a secant of the solar zenith angle relationship. Currently, this computer program determines transmissions for cloud thicknesses between 1 m and 100 m. The reference values for stratocumulus transmission were computed with LOWTRAN7. There are no input files for this program, and the output is written to *strcu2.dat*.

B.2.6 Program *TGAPS.FOR*

This computer program reads a file of normalized transmission data, and then identifies time periods of cloud thin spot events. The computer program also performs statistical study on the duration of thin spot events, including frequency of occurrence of thin spot events versus time bin, plus averages and standard deviations of cloud thin spots events.

TGAPS.FOR identifies individual cloud thin spot events by individually examining each normalized data point to see if it is part of a thin spot event. To do this, the normalized data point to be studied is categorized as being cloudy (*i.e.*, $\tau < 0.1$), thin (*i.e.*, $0.1 \leq \tau \leq 0.9$), or clear (*i.e.*, $\tau > 0.9$). If the normalized point being studied is cloudy, the computer program then searches on each side for the closest thin spot or clear point. If the normalized point being studied is clear, the computer program then searches on each side for the closest thin spot or cloudy point. The resulting time difference is then calculated and if it is less than 60 seconds, the normalized point being studied is part of a cloud thin spot event. Note that thin points are always part of a thin spot event.

Currently, *TGAPS.FOR* only handles one normalized data file at a time. Note that the input file for this computer program is the output file from the *REMOVE.FOR* computer program. The input file name is hard-wired into the computer program with a *n.dat* extension. The output from the computer program lists all times and the corresponding normalized transmissions for all gap

events in sequential order. The output is written to a file in which a *g.dat* extension replaces the *n.dat* extension. The statistical information is written to a file named *gap.dat*.