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THE ATMOSPHERIC TRANSMISSION OF INFRARED RADIATION FROM 2 - 5 MICRONS FOR SLANT PATHS FROM 35,000 FEET TO THE UPPER LIMIT OF THE ATMOSPHERE, A SURVEY

Compiled by Herbert L. Richard

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Greenbelt, Md.

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ABSTRACT

Data on the atmospheric transmission of infrared radiation along slant paths in the region from 35,000 feet up to the upper limit of the atmosphere are presented. Solar spectra are examined in regions within the various transmission bands. Research conducted at The University of Denver, The Canadian Armament Research and Development Establishment and other locations is discussed and illustrated.

This investigation was conducted on NASA contract NAS5-9585 with the University of Michigan as part of the program for investigating the applicability of infrared detection and tracking on the Apollo Spacecraft during re-entry.

CONTENTS

Abstract ii

INTRODUCTION 1

ATMOSPHERIC CONSTITUENTS 1

APPLICATION OF SOLAR SPECTRA DATA 2

RESULTS OF MEASUREMENTS. 2

CONCLUSIONS. 8

ACKNOWLEDGMENTS 9

References 10

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INTRODUCTION

Infrared systems, among other techniques, have been considered by Goddard Space Flight Center for detecting and tracking the Apollo spacecraft during re-entry into the earth's atmosphere (Reference 1). Although no present plans exist for utilizing this method of tracking, investigations have shown that infrared tracking on the heated spacecraft (6000°R - 7000°R surface temperatures) would be possible during the communications blackout period and for most of the re-entry trajectory, nominally 2000 nautical miles.

A paramount consideration in defining the acquisition and tracking capability, given the source radiation and detector characteristics, is the transmission of the atmosphere through which the infrared radiation must pass.

ATMOSPHERIC CONSTITUENTS

The atmosphere is a mixture of gases in which are suspended a variety of particles distributed over a great range of sizes and differing in chemical composition. The gases absorb radiation, and the suspended particles scatter it.

The most abundant gases in the earth's atmosphere (Reference 2) are nitrogen, oxygen, water vapor, carbon dioxide, methane, nitrous oxide, carbon monoxide, and ozone. Fortunately, the two gases present in the highest concentrations, N_2 and O_2, are homonuclear and therefore possess neither a permanent nor an induced electric moment; hence they do not exhibit molecular absorption bands.

Over the range of altitudes extending from sea level to approximately 40,000 feet, water vapor and carbon dioxide are by far the most important absorbing molecules. The concentration of H_2O varies between 10^{-3} percent and 1 percent (by volume), depending on geographical location, altitude, time of year, and local meteorological conditions. Carbon dioxide, CO_2, is much more uniformly distributed, varying between 0.03 and 0.04 percent, and is more abundant in an air mass which has been over heavy vegetation than in the atmosphere over the ocean. The distribution is more uniform at higher altitudes where the mixing is more complete. Methane, CH_4, is present at a concentration between 1×10^{-4} and 2×10^{-4} percent and is very uniformly distributed in altitude. Nitrous oxide, N_2O, at concentrations of 3×10^{-5} to 4×10^{-5} percent, and carbon monoxide, CO, with a typical concentration of 2×10^{-5} percent, have bands which show up if long paths are utilized. Ozone, O_3, is present at concentrations as large as 10^{-3} percent at altitudes near 100,000 feet, but it is present at much lower concentrations at other altitudes.

APPLICATION OF SOLAR SPECTRA DATA

The infrared system was designed for placement aboard jet aircraft flying at 35,000 feet or above. Therefore, slant paths above this altitude to 350,000 feet, the altitude at which appreciable spacecraft heating is encountered, are of interest. Since 350,000 feet for all practical purposes can be considered to constitute the limit of the atmosphere, solar spectra data measured from aircraft should provide a valuable source for establishing the infrared transmission of the atmosphere at the desired altitude and look angles.

Accordingly, the University of Michigan's Institute of Science and Technology was asked to investigate the solar spectra for the wavelength region from 2.0 to 5.0 microns and for slant paths from 35,000 feet to the limit of the atmosphere so that predictions of atmospheric absorption could be made with particular emphasis on the window regions. From system design and source radiation characteristics, the wavelength region from 2.0 to 5.0 microns had previously been found to be the most desirable region to investigate. The following chapters are a summary of their findings as reported by David Anding of the University of Michigan:

RESULTS OF MEASUREMENTS

The available data, unfortunately, indicated that the absorption bands have been of primary concern to the high-altitude investigators rather than regions of low absorption. Therefore, the data available for analysis are very sparse. Nevertheless, something can be said concerning the absorption spectra for certain slant paths. Five researchers have reduced solar spectra to absolute transmission spectra for this spectral region, and their data are presented in this summary.

The measurement of the solar spectrum to determine the nature of the absorption due to the various atmospheric constituents has been done by various researchers (References 3 and 4). The first work was done with ground-based instruments with only partial success. In the stronger absorbing bands the absorption was complete, so quantitative data could not be obtained. Houghton et al., carried out a broad program of high-altitude studies of the near-infrared atmospheric transmission, chiefly to determine the mixing ratio of water vapor in the stratosphere. The principal results of their study is an atlas of the infrared solar spectrum from 1 to 6.5 microns observed from a Canberra aircraft at altitudes from 20,000 to 40,000 feet, which was published in 1961 (Reference 5). A sample of the spectra is shown in Figure 1. Unfortunately, the data were such that quantitative data on absorption could not be determined.

One of the first attempts to obtain absolute transmission data from solar spectra was carried out by Templin at the Naval Ordnance Laboratory, White Oak, Maryland. Special attention was given to the 2.7 and 4.3 micron atmospheric absorption bands in an effort to determine the altitude at which the sun begins to appear in the center of the absorption band. In an aircraft flight in June 1955, spectra were obtained for altitudes up to 21,000 feet. The spectra for the 2.7 micron region are shown in Figure 2. Absolute absorption can be obtained by examining the difference between the spectrum and the solar envelope. Transmission values obtained from these curves agree with other data, but their usefulness is limited by the fact that the highest altitude was only 21,000 feet and the wavelength region extends only partially into the window regions.

Templin also made solar spectra measurements from Mt. Chacaltaya, Bolivia (Reference 6) at an altitude of 17,000 feet. For the conditions of measurement, he obtained transmission values greater than 90 percent for 2.3, 3.6, and 4.7 micron window regions.

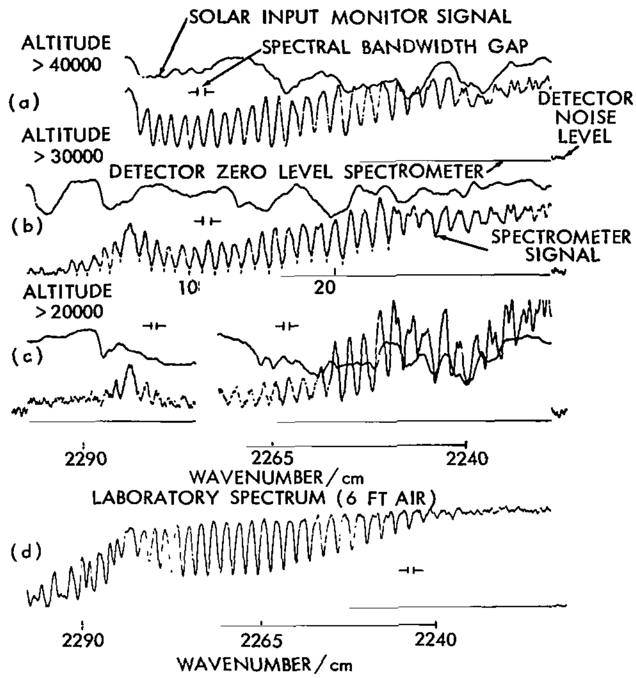

Figure 1—A section of the solar spectrum as observed from a Canberra aircraft (Houghton). Intensity is in arbitrary units.

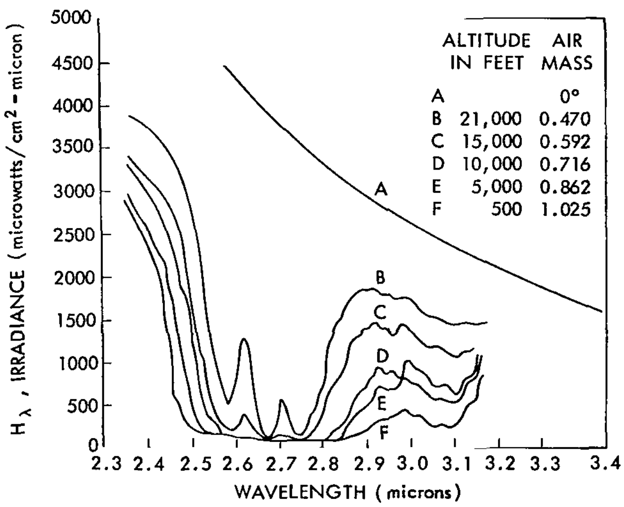

Figure 2—Solar spectral irradiance in the 2.8 micron region at various altitudes (Templin).

John Strong of Johns Hopkins University performed some high-altitude transmission studies from a U-2 aircraft at 35,000 and 65,000 feet (Reference 7). The data obtained were useful for determining water vapor content and predicting the solar envelope at high altitudes, but absolute transmission values were not determined from the data.

The most recent and extensive measurement program is being conducted by Cumming and Markle, et al. (References 8-13) of the Canadian Armament Research and Development Establishment (CARDE). They are involved in a continuing investigation of the infrared solar spectrum observed from an aircraft platform. The solar spectra have been reduced to atmospheric transmission data in the 2.5 to 3.35 micron region for slant paths from space down to altitudes in the 35,000 to 45,000 foot region. They have also made measurements in the 3.0 to 5.0 micron region, but these data will not be reduced to transmission spectra.

A Perkin-Elmer Model 108 spectrometer utilizing a lead-telluride detector and a lithium-fluoride prism was flown in a CF-100 aircraft to obtain their initial data. Later the spectrometer was replaced with a model 99-G, and resolution of approximately 1 cm^{-1} was obtained. An example of their high-resolution transmission spectra is shown in Figure 3. These data are presently in the form of an atlas of transmission spectra from 2.5 to 3.35 microns which is to be published. There are 41 curves of transmission versus wavelength in this atlas which were reduced from solar spectra taken at 35,000 feet, for zenith angles ranging from 6 to 91.3 degrees. The spectra were taken over a period of approximately one year from January 1, 1963 to February 12, 1964. Since the amount of water vapor within the slant path varied from day to day, it is difficult to determine the variation of transmission with zenith over the absorption band without further data reduction. In order to generate a composite plot to demonstrate this variation, each of the 41 curves were smoothed to a resolution of approximately 0.05 micron. The value of transmission versus zenith angle was then plotted for each inflection point on the smoothed curves. These curves were used to generate the curves in Figure 4, which represent yearly averages of transmission for various zenith angles. The spectra obtained on any given day may vary from the average by ±10 percent. Since most of the work by CARDE was confined to the absorption band rather than the window regions, it is presented here for completeness. They did obtain some measurements for the region from 2.85 to 3.35 microns (Figures 5-8).

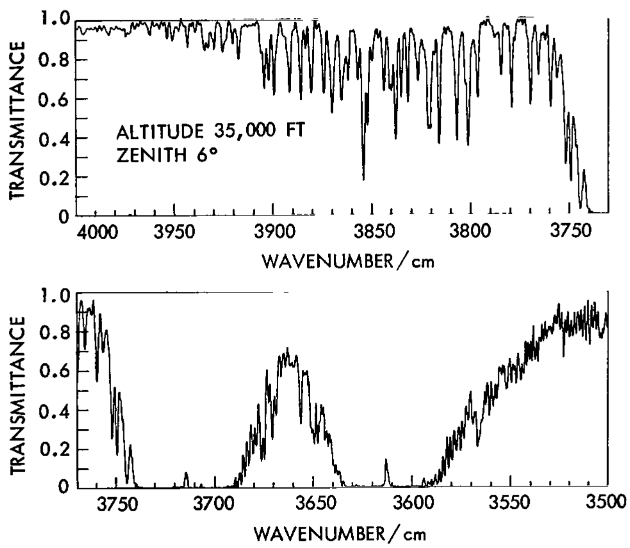

Figure 3—Transmittance determined from solar radiation measurements (CARDE).

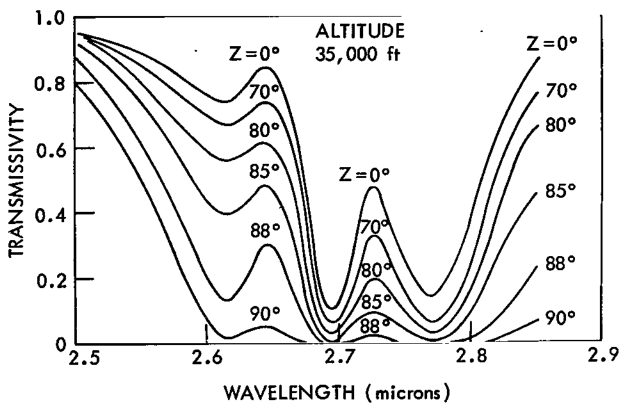

Figure 4—Yearly averages of transmission versus wavelength (CARDE).

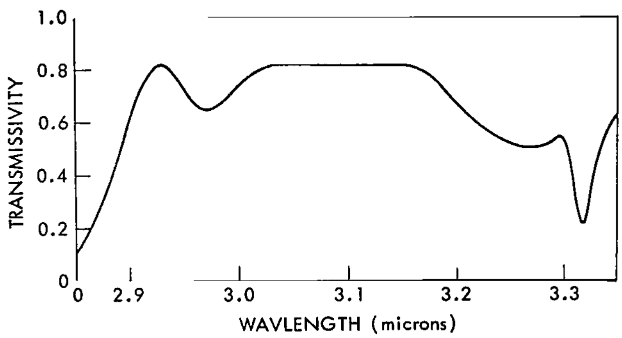

Figure 5—Transmission versus wavelength for 89.9° zenith and 35,000 ft altitude (CARDE).

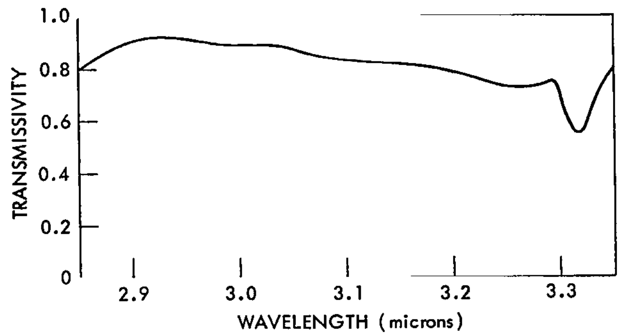

Figure 6—Transmission versus wavelength for 53° zenith and 30,000 ft altitude (CARDE).

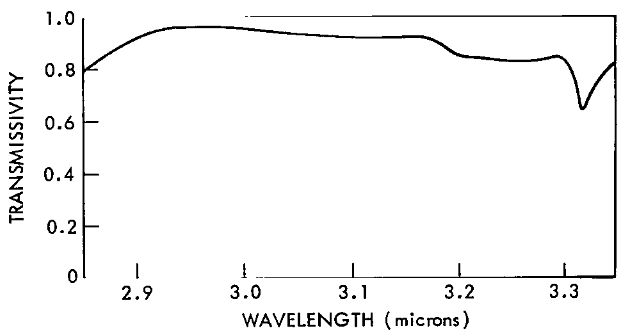

Figure 7—Transmission versus wavelength for 69° zenith and 40,000 ft altitude (CARDE).

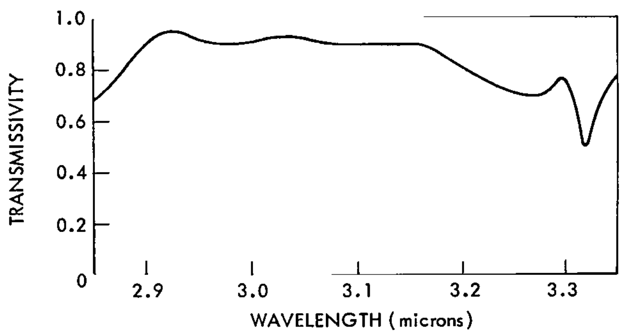

Figure 8—Transmission versus wavelength for 80° zenith and 45,000 ft altitude (CARDE).

Each curve represents a single measurement so variations in transmission with zenith, altitude, and water vapor content cannot be determined.

Murcray, Murcray, and Williams, et al. (References 14-20) of the University of Denver have also been involved in high-altitude solar spectra measurements for determining absolute transmission. A prism spectrometer capable of scanning the region from 1.96 to 3.57 microns was flown on a balloon launched from Holloman AFB, New Mexico in January 1963. Solar spectra were obtained at various altitudes from the ground through 23 km. The spectrometer used was a single-pass Littrow prism spectrometer equipped with a LiF prism and a thermistor bolometer detector. The zenith was measured with a biaxial pointing control. The solar spectra obtained were reduced to transmission data which are shown in Figures 9 through 11. These three figures and Table 1 represent all of the reduced data for this balloon flight. Figure 12 is a reproduced curve for an altitude of 35,433 feet at 61.1 degrees zenith.

The University of Denver made further balloon flights in 1963 and 1964, but the complete set of data have not been reduced. Spectra were obtained for the 2.7, 4.3, and 6.3 micron absorption bands. Figures 13, 14, and 15 are representative samples of the data taken at 4.3 microns. They are each compared with the spectra predicted by Plass who considered only CO_2 absorption,

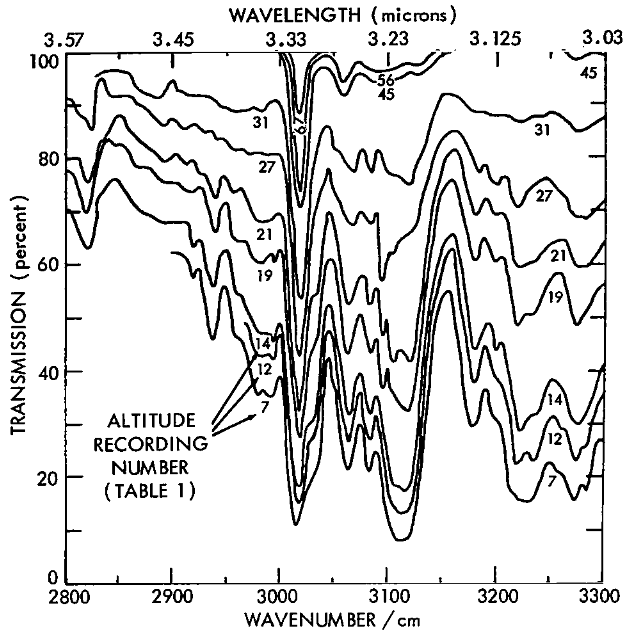

Figure 9—Observed spectral transmission of the atmosphere at various altitude for the region 2800 cm^{-1} to 3300 cm^{-1} (Murcray).

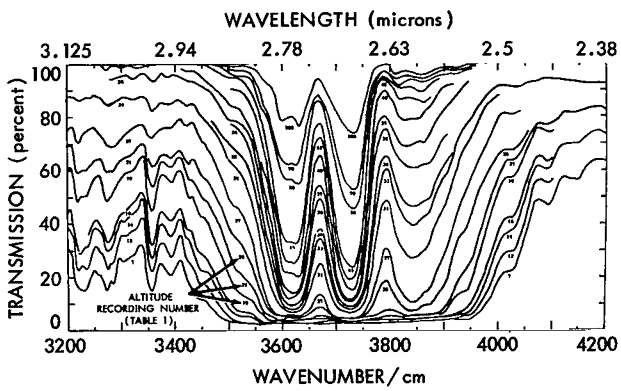

Figure 10—Observed spectral transmission of the atmosphere at various altitude for the region 3200 cm^{-1} to 4200 cm^{-1} (Murcray).

neglecting absorption by N_2O which is a noticeable contributor in this region. Experimentalists at Denver stated that the uncertainty in the scale was sufficient to account for the spectral shift between the predicted and experimental curves. Data taken at altitudes near 35,000 feet were not

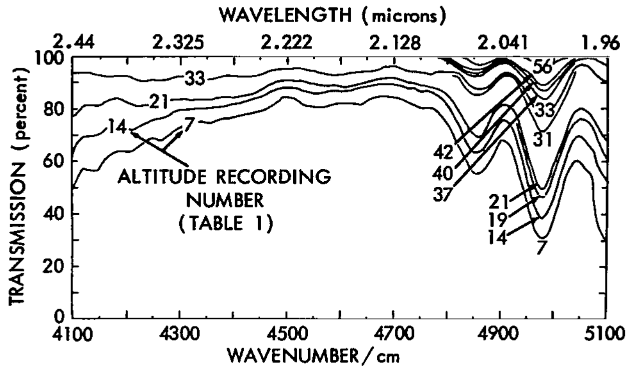

Figure 11—Observed spectral transmission of the atmosphere at various altitude recordings for the region 4100 cm^{-1} to 5100 cm^{-1} (Murcray).

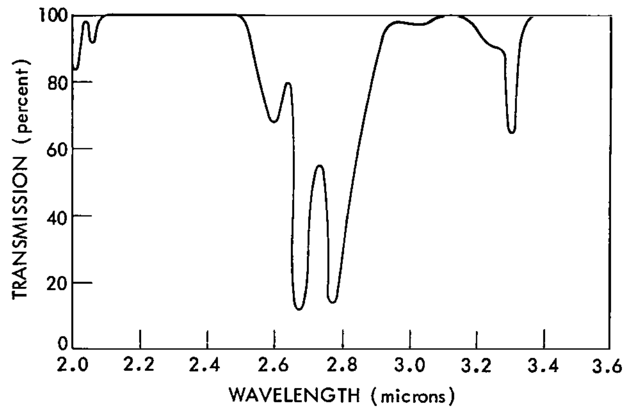

Figure 12—Transmission versus wavelength for 61.1° zenith and 35,433 ft altitude (Murcray).

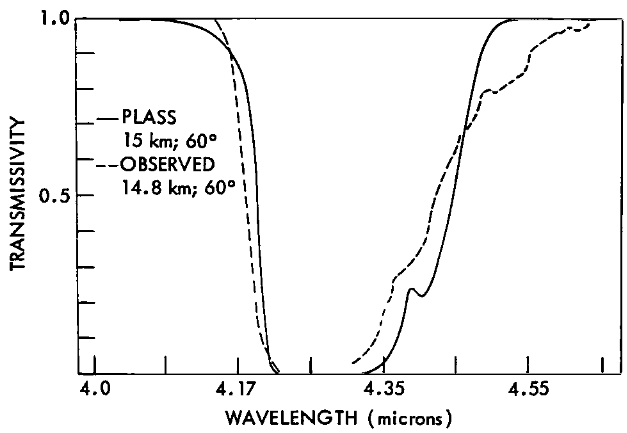

Figure 13—Theoretical and observed spectral transmission of the atmosphere at 15 km. Altitude for the region from 4.0 to 4.65 microns (Murcray).

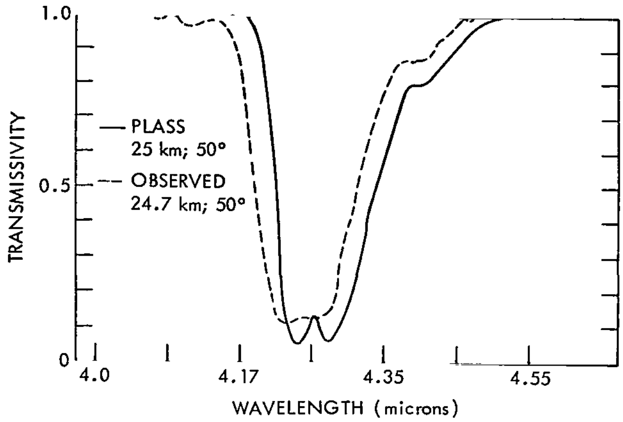

Figure 14—Theoretical and observed spectral transmission of the atmosphere at 25 km. Altitude for the region from 4.0 to 4.65 microns (Murcray).

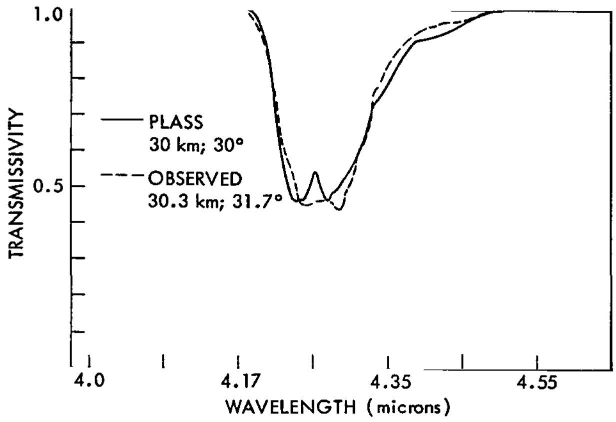

Figure 15—Theoretical and observed spectral transmission of the atmosphere at 30 km. Altitude for the region from 4.0 to 4.65 microns (Murcray).

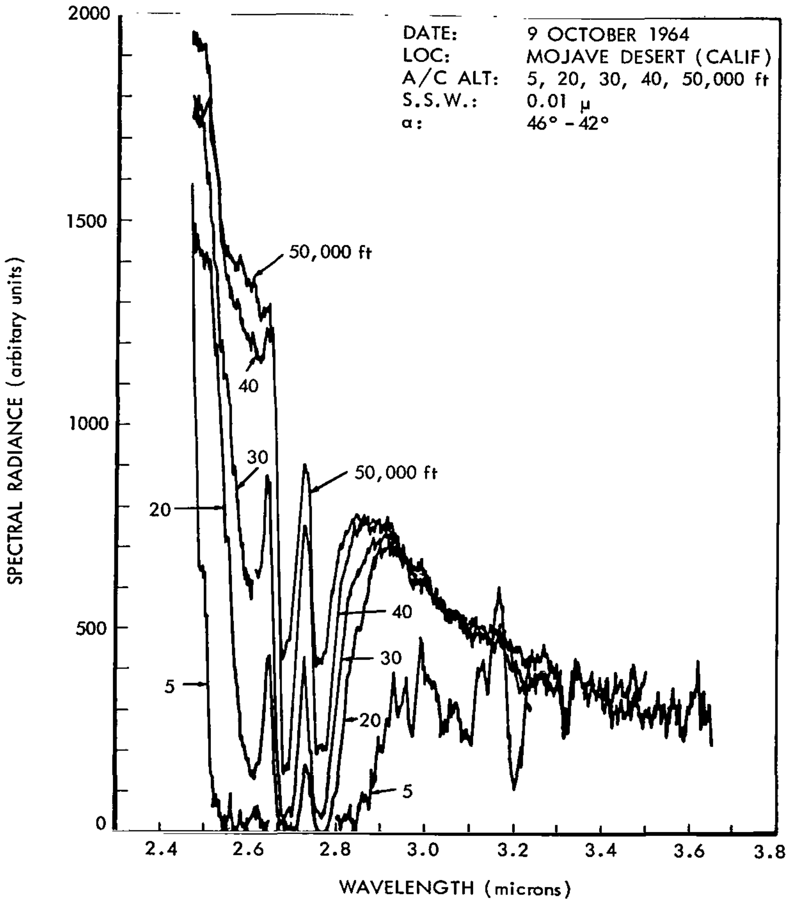

Figure 16—Solar spectra: 2.4 - 3.6 microns (Blau).

Table 1

Balloon Flight, 17 January 1963.

Record	Altitude (ft)	Zenith (deg)
7	3987	69.9
12	5906	68.1
14	6890	67.6
16	8202	67.0
19	11155	66.1
21	13451	65.4
25	17388	64.2
27	20013	63.9
31	24934	62.8
33	28871	62.1
34	30184	61.9
36	34121	61.3
37	35433	61.1
40	40026	60.5
42	42323	60.0
45	45604	59.2
56	57087	57.2
67	60367	55.5
70	62008	55.1
106	74803	55.1

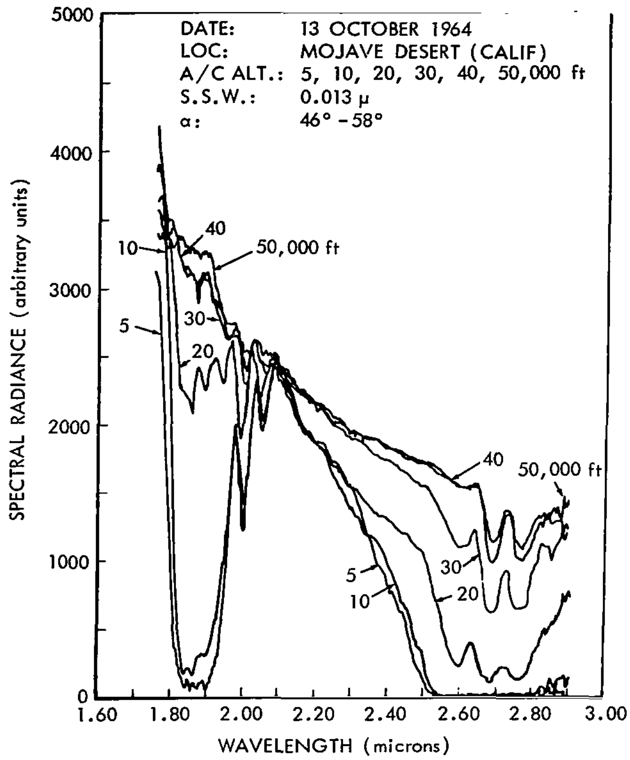

Figure 17—Solar spectra: 1.7 - 2.9 microns (Blau).

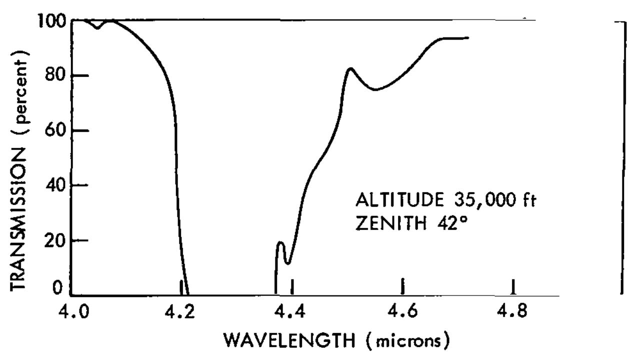

Figure 18—Transmission versus wavelength determined from reduced solar spectra (Farmer).

published but the figures indicate that absorption is complete at the center of the band to approximately 60,000 feet for a 50 degree zenith angle.

Bradley and Hampson of the Royal Radar Establishment measured the solar spectra from a Canberra aircraft up to altitudes of 60,000 feet for the 4.3 micron absorption band. Their data were not reduced to absolute transmission spectra. However, their results indicated complete absorption up to 60,000 feet for zero zenith.

Henry Blau (Reference 21) of the Arthur D. Little Corporation has been involved in a program for measuring the spectral scattering properties of high-altitude sunlit clouds in the 1.2 to 3.6 micron region. During this program, the spectrum of the sun was measured and the results are shown in Figures 16 and 17. Since the radiance values were not calibrated, only qualitative information can be determined from the spectra. An effort is being made by a group at the University of Michigan to reduce the data but at present no results are available.

Farmer, of EMI (References 22 and 23), made a survey of all available solar spectra for the wavelength region from 3.5 to 5.5 microns and reduced selected data to absolute intensity with uniform resolution of approximately 0.015 micron. His survey included spectra taken at altitudes ranging from sea level to 49,000 feet. Absolute transmission for 35,000 feet (curve E, Figure 2) was determined by taking the difference between the spectra and the solar envelope, and the results are shown in Figure 18. Farmer (Reference 24) also determined the absolute solar spectra for slant paths above 50,000 feet by applying theoretical transmission functions and appropriate model atmospheres to the solar envelope used by Templin. Two other EMI reports of interest are also given (References 25 and 26).

CONCLUSIONS

In an effort to present the composite of this survey, a single curve was drawn which is an average value of the five contributors for a zenith angle of approximately 60 degrees and an altitude of 35,000 feet. This curve is shown in Figure 19. Some groups did not make measurements over the entire region from 2.0 to 5.0 microns, so the wavelength interval was divided into five regions and the groups are noted in the region where their data were used. No data were available much beyond 4.5 microns but Templin indicated in his work that the transmission was greater than 90 percent (to 4.9 microns) for an altitude of 17,000 feet. So for an altitude of 35,000 feet it would be reasonable to assume that the transmission is nearly 100 percent to 4.9 microns. Changes in atmospheric conditions cause changes in the spectrum presented but it can be assumed on the basis of the data reviewed that such fluctuations will be less than 10 percentage points with the greatest effect being observed in the absorption bands rather than the window regions.

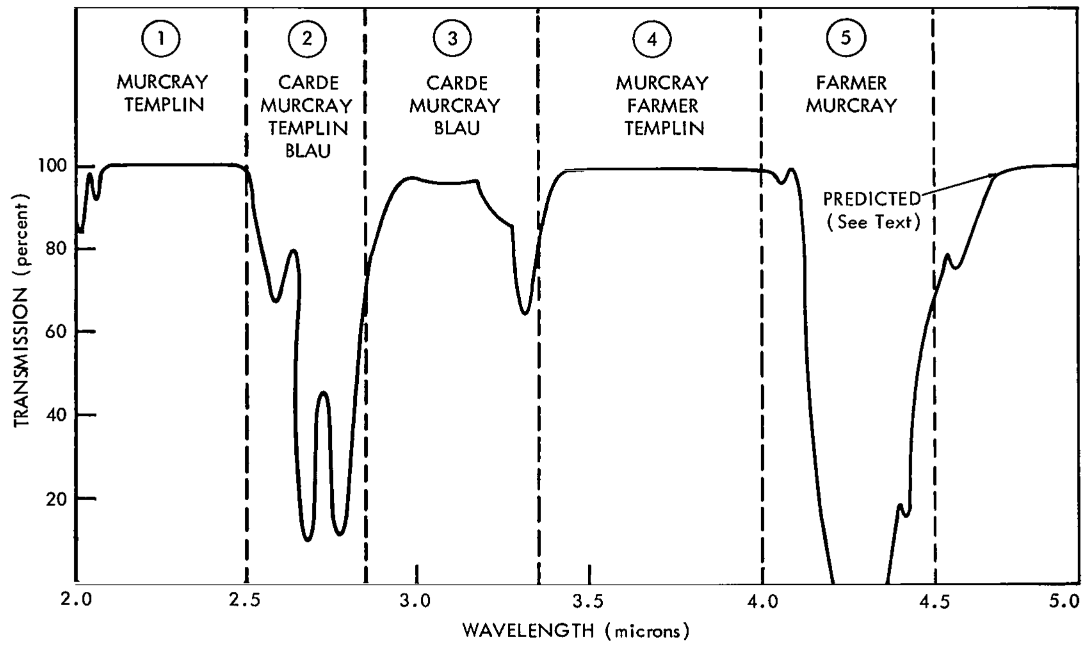

Figure 19—Composite transmission spectra; altitude 35,000 feet; zenith angle 60°.

In summary, the data indicate that the absorption is indeed very low in the various window regions and hence the probable reason for the existence of limited solar spectra for regions outside the absorption bands.

ACKNOWLEDGMENTS

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National Aeronautics and Space Administration
Greenbelt, Maryland, August 22, 1966
125-22-02-00-51

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