Measurements of Shuttle Window Transmission Characteristics with the SPEAM Experiment

W. F. J. Evans,* D. I. Wardle,† J. B. Kerr,† and C. T. McElroy†
Atmospheric Environment Service, Toronto, Ontario, Canada
and
M. Garneau‡
National Research Council of Canada, Ottawa, Ontario, Canada

The Sunphotometer Earth Atmosphere Measurements experiment on Mission 41-G, which measured solar radiation at defined wavelengths through various Orbiter windows using the Atmospheric Environment Service Shuttle sunphotometer, required a knowledge of the transmission characteristics of the Orbiter windows. Consequently, window calibrations were conducted that provide valuable engineering data on Shuttle windows after exposure to space. Three Shuttle window calibrations were conducted: in August 1984, in October 1984, and in April 1985. The window transmissivities during flight were inferred from measurements with the sunphotometer of the solar radiation transmitted through the windows. Measurements of side hatch window transmissivities were 3–16% less than results from a theoretical model. These results require a 5% revision of the sunphotometer 675-nm calibration. The main Shuttle window transmissivities at 380 nm were, as measured at the ground, 4–14% and 13–19% in space. Measurements of the transmissivities in the visible region were between 60 and 85%, with no significant difference between the space- and ground-based measurements. Generally, the values at 675 nm were 10–20% higher than those at 500 and 778 nm. The variable and reduced transmissivities are presumably caused by heat-reduction coatings on these windows. A protective bag and pyrex filter were developed to shield Shuttle crews from harsh solar ultraviolet radiation transmitted through the quartz side hatch window.

Nomenclature

n = index of refraction
r = single surface reflection coefficient

Introduction

THE Sunphotometer Earth Atmosphere Measurements (SPEAM) experiment of the Atmospheric Environment Service (AES), Canada, required data on the transmissivity at 380, 500, 675, and 778 nm of all the Shuttle windows. Calibration sessions were performed using an AES lamp and the flight sunphotometer, and the results are presented here.

The SPEAM[1,2] experiment was flown in October 1984 on Mission 41-G on the Space Shuttle Challenger. Two types of observations were made: under high sun conditions and under sunset conditions through the main Shuttle windows and the side hatch window.

Window transmissivity results are important to the interpretation of the measurements. The side hatch window transmissivity is easy to simulate using the window model described in this paper. The other windows have coatings that are wavelength-dependent and, hence, are more difficult to model.

A protective ultraviolet (uv) filter for the side hatch window on Orbiter vehicle OV-99 is described. The development of a protective bag for the side hatch window is also discussed. This device will allow future experiments access to the direct solar beam while maintaining a safe Orbiter environment for the crew by preventing their exposure to solar uv light.

Presented as Paper 85-6064 at the AIAA Shuttle Environment and Operations II Conference, Houston, TX, Nov. 13–15, 1985; received April 5, 1986; revision received Dec. 22, 1987.

*Chief, Experimental Studies Division.
†Research Scientist, Experimental Division.
‡Canadian Mission Payload Specialist.

Equipment

The AES-SONOTEK Shuttle sunphotometer is a derivative of the commercially available Sonotek sunphotometer used extensively for the measurement of atmospheric turbidity. The standard version of the instrument has a silicon photodiode detector, electrometer amplifier, and digital output display. The instrument may be set to measure at one of six wavelengths (including 380, 500, 675 and 778 nm) by manually setting an internal filter wheel to place one of four interference filters between the detector and the entrance aperture. The bandwidth of the bandpass filter is approximately 5 nm. The instrument has a well-defined field of view of 1.2 deg full width half maximum. This corresponds to approximately 2.5 solar diameters. The electronics allow either continuous readings of the detected intensity or the detection of the peak value measured during a manually selected measurement interval.

A block diagram of the flight version of the sunphotometer is shown in Fig. 1. It is functionally equivalent to the commercial version except that two optical channels are measured simultaneously through filters diametrically opposite on the interference filter wheel. In addition, the detector electronics are interfaced to an output connector to which a hand-held computer may be joined to allow automatic digital recording of the data. The simultaneous operation of two optical channels allows differential intensity measurement, which is an important capability for remote sensing atmospheric constituents during the rapid setting of the sun through the atmosphere below the Shuttle. The two channels in the photometer have parallel optical axes, which are constructed by accurately boring two parallel cylinders from a single block. Identical detectors are mounted at the base of each cylinder. The position of the filter wheel is encoded optically and is recorded by the data logging computer along with housekeeping and intensity data.

Measurements of the Orbiter window transmissivity are made using the flight backup sunphotometer and a 1-kW quartz-iodine lamp.[3] The 1-kW lamp is placed at a distance of approximately 0.5–1.0 m from the photometer, and measurements are made directly on the lamp and on the lamp through

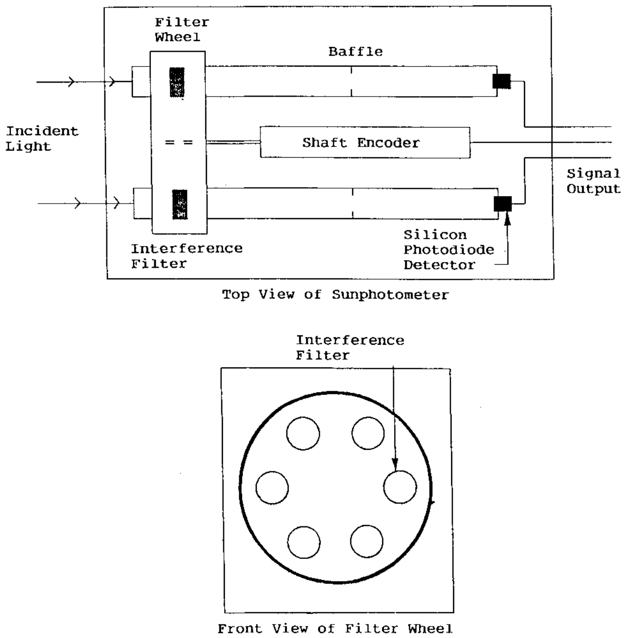

Fig. 1 Optical schematic of sunphotometer.

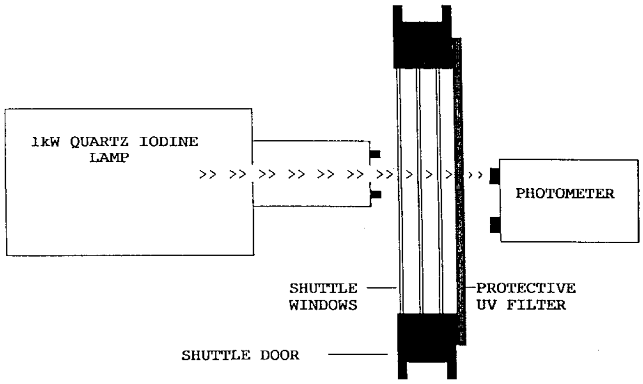

Fig. 2 Apparatus for calibrating the transmissivity of the Shuttle side hatch window.

the window whose transmissivity is to be determined. If the window's "apparent thickness" (i.e., the sum of the physical thickness of each element divided by their respective indices of refraction) is known before the measurement is made, the distance is set so that the readings with and without the window in the light path may be directly compared to determine the transmissivity of the window. Alternatively, the actual distance of the photometer from the window is measured to an accuracy of 0.5 mm, and the light measurement made directly on the lamp is adjusted using the inverse-square law. The properties of the lamp were determined independently to ensure confidence in this procedure.[3]

The light source is a 1-kW quartz-iodine lamp (General Electric no. DXW) operated from 110-V dc provided by a regulated power supply. The lamp itself is mounted inside an aluminum box approximately 10 cm on a side equipped with cooling fins and a quartz window. The box is sealed to prevent cooling air from darkening the envelope of the lamp or causing temporal fluctuations in the lamp output. The box is allowed to reach a rather high temperature (approximately 200°C) and is air-cooled by forced air from fans mounted in an enclosing box, which is 30 cm on a side. This arrangement ensures that the outside temperature of the lamp housing does not exceed 50°C in normal operation. The lamp may be operated safely in any orientation. The filament of the lamp is spaced precisely from the window to be measured by a long "snout" on the lamp housing, which has small nonmarking surfaces 120 cm apart on the surface nearest the window. The lamp is set up by simply touching the window with these surfaces. A small aperture in the front of the snout permits a defined beam to pass through the window. The sunphotometer aperture is centered in this narrow patch of light to ensure that the readings are made at normal incidence to the window and repeatably in the same solid angle of light from the lamp. The instrument and the lamp housing were both mounted on heavy-duty camera tripods to make both the direct lamp measurements and the measurements through the Orbiter windows.

Measurement Procedures

Ground-Based Window Transmissivity Measurements

Ground-based window transmissivity measurements, for the Space Shuttle Challenger, were made on three occasions: August 20, 1984, October 15, 1984, and April 14, 1985. The measurement procedures differed slightly on all three occasions.

Optical transmissivity values for the Orbiter windows were determined by measuring the intensity of light passing through a window (transmitted light) and dividing it by the measured intensity of light from the same source that had not passed through the window (direct light). The lamp beam was normal to the window surface. The SPEAM sunphotometer was used to measure the transmitted and direct light from the well-regulated lamp source described earlier. A diagram of the sunphotometer measuring transmitted light from the lamp is shown in Fig. 2. Measurements were made at four wavelengths: 380, 500, 675, and 778 nm.

On the first occasion, transmissivity measurements were made on Shuttle windows 2, 9, and 10. [Shuttle windows are numbered clockwise from the nose. These measurements were conducted at the NASA Kennedy Space Center (KSC).] At this time, the window thickness and spacing dimensions were not known, therefore, it was important to measure all three distances involved—i.e., the distance between the lamp and the photometer, between the lamp and external window surface, and between the photometer and internal window surface.

Intensity measurements were made directly on the lamp outside the Orbiter before and after the measurements were made through the windows. This was done according to the following procedure. The photometer was aligned in the beam of the lamp, which was on its low-intensity setting. Upon alignment, the photometer was locked by a tripod clamp, the distance between the lamp and the photometer was measured, and the lamp was turned to high intensity while power to the lamp was monitored. After allowing sufficient time for the lamp power to stabilize, intensity measurements were made at the four wavelengths. Following the measurements, the lamp was turned off and allowed to cool before being moved.

Intensity measurements were made through the windows by placing the lamp about 0.6 m from the external surface of the window being measured. The lamp was positioned by gently placing the spacer "snout" against the window. The photometer was located inside the Orbiter about 5 cm from the internal window surface. With the lamp on low intensity, the photometer was aligned with the light source, locked in position, and the distance between the photometer and internal window surface was measured. The lamp was turned to high intensity and, when the lamp power stabilized, intensity measurements were made at the four wavelengths. Power to the lamp was then turned off, the lamp was allowed to cool, and direct intensity measurements of the lamp were repeated outside the Orbiter.

In determining the window transmissivity values, it was necessary to correct for the distance between the lamp and the photometer. When the Orbiter window thickness and spacing dimensions became available, the measured intensity values were adjusted in accordance with the path length of the transmitted light (corrected for the refraction index of the window material) being equal to the path length of the direct light.

On October 15, 1984, transmissivity measurements were made on windows 2 and 5–8. On this occasion, the window thicknesses and spacings were known prior to the measurement. With this information, spacers were made, which were used to set the distance between the lamp and the photometer when direct lamp measurements were made. The lengths of the spacers were made to match the apparent distances through the windows. The direct beam measurements were made with the photometer and lamp pressed gently against the ends of the spacer. The transmitted beam measurements were made with the photometer pressed gently against the internal surface of the Orbiter window and the lamp pressed gently against the external window surface. One of two spacers were used depending on whether measurements were made on forward-looking (windows 2, 5, and 6) or overhead (windows 7 and 8) windows. The use of these spacers eliminated the need to correct the intensity measurements for the distance between the lamp and the photometer when calculating window transmissivity values.

On April 14, 1985, transmissivity measurements were made on the side hatch window (window 11). Again, a spacer was used to simulate the apparent thickness for the direct beam measurements. The measurements were made by setting up the lamp outside the Orbiter and opening the hatch door so that the external surface of the window rested gently against the snout of the lamp. Transmitted light measurements were made with the photometer pressed gently against the inside surface of the hatch window. Direct beam measurements were made with the hatch door closed to clear the lamp, and the spacer was used to position the photometer. Several transmissivity measurements were made on the window in the typical flight-ready condition. Further measurements were taken after the inside and outside window surfaces were cleaned.

In-Flight Window Transmissivity Measurement Procedures

During flight 41-G, several solar occultation measurements were taken during sunset periods through windows 2–11 with the SPEAM sunphotometer. The readings, taken just before the sunlight was attenuated by the Earth's atmosphere, were used to calculate zero-air-mass calibration numbers for the sunphotometer. Shuttle window transmissivities were derived by comparing these in-flight zero-air-mass sunphotometer calibration numbers with previously estimated zero-air-mass numbers obtained from routine ground-based Langley plot[5] sunphotometer calibrations. It was not possible to account for refraction or changing angle of incidence during the space flight.

Table 1 Ground-based transmissivity measurements on main Shuttle windows

Window no.	Transmission coefficient, wavelength, nm 380	500	675	778
	0.118	0.728	0.832	0.698
2	0.131[a]	0.651[a]	0.740[a]	0.640[a]
5	0.113	0.640	0.830	0.684
6	0.144	0.678	0.818	0.624
7	0.117	0.865	0.823	0.590
8	0.081	0.811	0.782	0.532
9	0.099[a]	0.748[a]	0.943[a]	0.741[a]
10	0.040[a]	0.634[a]	0.784[a]	0.666[a]

[a]August 20, 1984; others from October 15, 1984.

Table 2 In-flight transmissivities of main Shuttle windows

Window no.	Transmission coefficient, wavelength, nm 380	500	675	778
2	0.130	0.625	0.741	0.615
5	0.140	0.417	0.801	0.565
	—	—	0.814	0.158
6				0.212
8	0.171	0.714	—	—
10	0.193	0.379	0.793	0.666

Table 3 Lamp side hatch transmissivity measurement

Wavelength nm	Transmission coefficient: Clean (1) ± standard deviation	Before cleaning (2) ± standard deviation	Columns (1)-(2)
380	0.754 ± 0.001	0.746 ± 0.003	0.008
500	0.790 ± 0.006	0.773 ± 0.003	0.017
675	0.795 ± 0.005	0.783 ± 0.004	0.012
778	0.790 ± 0.001	0.785 ± 0.005	0.005
		Average	0.011

Interpretation of Measurements

Results 1: Main Shuttle Windows

Table 1 lists all of the ground-based measurements made on windows 2–10 at KSC. The measurements for August 20, 1984, are flagged with an "a." There was a malfunction in the sunphotometer then, which prevented the lamp-only measurement from being made accurately. This may account for the discrepancy between the August and October measurements on window 2.

Table 2 lists the in-flight Shuttle window transmissivities. They can be compared with those in Table 1. Certain errors in the space values come from the ground-based zero-air-mass calibration errors[5] and, in some cases, because the observations were at considerable slant angles with respect to the windows. A small variation in transmissivity over the window surface would be expected because of the nonuniform appearance of the Shuttle windows.

At the visible wavelengths, there is no evident difference between ground and in-flight measurements. Most values are between 60 and 85%, and those at 675 nm are 10–20% higher than at 500 and 778 nm. At 380 nm, the space-based values are 13–14%, while the ground-based values are 4–14%. The space-based transmissivities at 380 nm for windows 8 and 10 are considerably higher than the ground-based values; the cause of this is not understood. The main Shuttle windows all have heat-reduction coatings, which presumably accounts for the smaller transmissivities at 380 nm as well as much of the variability. By contrast, the side hatch window has much better defined and more uniform optical properties.

Results 2: Side Hatch Window

Table 3 shows the results from the ground-based side hatch window measurement on April 14, 1985, at KSC. The mean change in window transmissivity on cleaning is 0.011.

The first column of Table 4 gives the theoretical transmission coefficient of three plates of Corning 7940 fused quartz. These coefficients were derived from a model that includes multiple reflections[3]; the single surface reflection coefficient, r, is calculated from Corning data on refractive index n according to the well-known Fresnel formula[4] for normal incidence, i.e.,

$$r = [(n-1)/(n+1)]^2$$

Table 4 Side hatch window transmissivities relative to the theoretical clean value for quartz

Wavelength, mm	Theoretical clean coefficient	Clean, %	Before cleaning,%	October 1984 Flight, %
380	0.815	−7.8	−8.8	−16.2
500	0.820	−3.7	−5.9	−10.9
675	0.824	−3.6	−5.1	− 5.3
778	0.825	−4.3	−5.0	−12.5

Table 5 Revisions to zero-air-mass numbers from comparison between April 1985 ground-based window transmissivity measurements and in-flight sunphotometer transmissivity measurements

	Transmissivity, %		
Wavelength, nm	Clean	Before cleaning	Relative to 500 nm
380	−8.4	−7.4	(5.3)[a]
500	−7.2	−5.0	0.0
675	−1.7	−0.2	+5.6
778	−8.2	−7.2	−1.6

[a]No adjustment to the 380-nm extraterrestrial value is proposed at this time because of the remaining uncertainties in the variation with wavelength of the attenuation of light by contaminating films.

The model was also used to calculate the combined transmissivity of a pyrex uv (Corning 7740) shield with the side hatch window. This shield is absolutely necessary in order to protect Shuttle personnel from solar uv-B and uv-C radiation.

Various combinations of plates of quartz (7940) and pyrex were constructed to test the multiple reflection model and the Fresnel reflection prediction against measurements. The preferred measurement method was to use the sun as a source and to take repeated sunphotometer readings alternately through the specimen and directly at the sun. On a clear day and with a series of 20 individual measurements, this method is precise ($+0.2\%$ at 2σ). With three plates of quartz, the measured transmissivity was always slightly less than the theoretical. When the quartz was cleaned just prior to the measurement, the measured 778-nm transmissivity was within 1% of the theoretical value; otherwise, the discrepancies were in the 1–2% range.

Table 4 also shows transmissivity measurements made at KSC in April 1985 on the side hatch window before and after cleaning, referenced to the theoretical clean transmissivities. The "clean" values at 500, 675, and 778 nm are similar—about 4% less than the theoretical state; however, the value at 380 nm is nearly 8% less. The transmissivities prior to cleaning are each approximately an additional 1% smaller. The last column shows the 41-G transmissivity measurements, again referenced to the theoretical clean state and corrected for the effect of the pyrex shield.

The laboratory measurements show significantly larger (by a factor of 1.7) departures at 380 nm from the theoretical clean values than at the other wavelengths. The space measurements of 16.2% of 380 nm and 10.9% at 500 nm indicate a similar factor for the space condition.

The transmissivity values from the space measurements indicate a further contamination to the windows, which might be caused by exhaust from the engine burns of the Orbit Maneuvering System or from the Vernier Thruster burns in the Reaction Control System.

The precision of our space measurements is limited by the uncertainties in the ground-based zero-air-mass calibration numbers which, with the exception of the 500-nm wavelength, are possibly as much as $\pm 5\%$. One of the experiment's objectives, as discussed in the following paragraph, was to obtain better zero-air-mass calibration from an independent knowledge of the window transmissivity.

A straightforward interpretation of these results is provided by assuming that, while in flight, the side hatch window was somewhere between the measured clean and precleaned conditions. The first columns of Table 5 give the range of adjustments that consequently would be required for the ground-based extraterrestrial readings. However, these adjustments are rather large. In particular, it is difficult to believe that the value for 500 nm, at which most ground-based work has been done, is in error by 5–7.2%. A more acceptable hypothesis is that, in flight, the window was actually less transparent than the precleaned state, and, at 500 nm, was 11% less than theoretical clean state. The ground-based window measurements and the model do not show significant spectral behavior between 500, 675, and 778 nm. Therefore, relative to 500 nm, the extraterrestrial values at 675 and 778 nm need adjustments of $+5.6$ and -1.6%, respectively, but the latter is not considered significant. These are shown in the last column of Table 5. These revisions were not used in the previously discussed calculation of the main Shuttle window transmissivity and they do not significantly affect the conclusions.

Ultraviolet Hazards and Protection

The side hatch window transmits radiation at all wavelengths from 200 to 3000 nm. Therefore, it is very attractive to use the side hatch window to carry out a remote sensing optical experiment from space. The optical transmissivity properties of the side hatch window are very well suited for the requirements of the SPEAM experiment.

The original SPEAM proposal was to take intensity measurements of sunlight through the side hatch window with the sunphotometer. It became apparent that the possible exposure of crew members to the solar radiation at all uv wavelengths transmitted through the window would constitute a serious hazard. The uv intensity is strong enough to cause sunburn and eye damage within about 15 s of exposure. As a result, it is not practical to take the photometer measurements of sunlight through the unprotected side hatch window.

The experiment was conducted by taking the measurements through a protective pyrex filter installed on the inside of the window during the measurement periods. The pyrex partially transmits at wavelengths greater than 300 nm and absorbs strongly below 300 nm. The integrated uv dosage that a crew member would receive through the pyrex filter is about one-half that which is received on a summer day at the Earth's surface. Sunburning is still possible but only after exposures of more than an hour. This arrangement allowed the measurement of the soft uv sunlight (a major objective of the SPEAM experiment) without subjecting the operator to a radiation hazard.

Use of the side hatch window to carry out remote sensing experiments from space at wavelengths between 200 and 300 nm would be feasible if the uv radiation could be confined to the experiment. A "bag" has been developed that fastens to the window as well as to the SPEAM experiment. The bag allows adequate flexibility for satisfactory operation of the experiment and does not subject the operator to any uv radiation. A picture of the bag is shown in Fig. 3. Measurements of hard uv light from the sun by using the "bag" technique are being considered for future experiments.

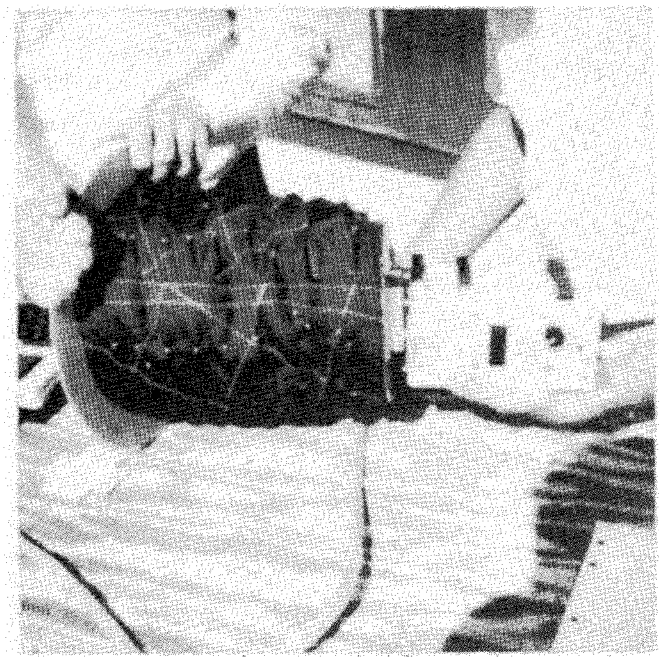

Fig. 3 Cloth bellows used to access uv radiation through the side hatch window. One end of this "bag" or cloth bellows can easily be attached to the side hatch window in the Orbiter. While protecting the operator, it allows experiments within the bag to be exposed to uv radiation. At the other end of the bag, windows allow sunphotometer measurements to be taken safely. Experiments to determine photolysis rates are under discussion.

Conclusions

On three occasions the transmissivities of the Shuttle windows were measured at 380, 500, 675, and 778 nm using the quartz-iodine lamp of the Atmospheric Environment Service and the Shuttle flight sunphotometer. Determinations of the window transmissivities in space were made from in-flight, in-cabin measurements of solar radiation by the sunphotometer.

A model based on the known refractive index of fused silica and incorporating multiple reflection was developed and tested. The model was verified by laboratory measurement of the transmissivity of solar radiation through a simulated side hatch window comprising three slabs of fused silica and by using other combinations.

The side hatch window transmissivity in the flight-ready condition was 5% less than the theoretical model transmissivity at 500, 675, and 778 nm, and 9% less than the theoretical model at 380 nm. The inside and outside surfaces were given a final cleaning, and the transmissivity at all wavelengths increased by about 1.0%.

The in-flight measurements indicated that the window transmissivity was about 10% less than the clean model at visible wavelengths and about 16% less at 380 nm. Deposits on the outside of the windows, as a result of rocket burns during Orbiter maneuvers, may have caused this reduction in transmissivity.

The side hatch window measurements and the known, small-wavelength dependency of transmissivity in the visible suggest that the ground-based zero-air-mass calibration value for the sunphotometer at 675 nm is in error by 5%.

The main Shuttle windows are all treated with a special coating to reduce heat transmissivity from the sun. There is visual evidence of nonuniformity in the coatings. At 380 nm, the ground-based measurements range from 4 to 14%, while the space-based measurements range from 13 to 19%. Measurements in the visible region are mostly between 60 and 85% with no significant difference between space- and ground-based measurements. In general, the values at 675 nm are 10–20% higher than those at 500 and 778 nm.

Care must be seen taken to protect crew members from harmful solar uv radiation. In STS Mission 41-G, a pyrex filter designed to cover the side hatch window was used for this purpose. Future experiments may require access to solar radiation below 300 nm. A special bellows arrangement that protects the operator while exposing an instrument to the direct transmissivity through the side hatch window has been developed.

Acknowledgments

The authors would like to thank the following: NASA for its invitation to fly on the Shuttle and its assistance in flight preparations and window calibrations; Mr. B. Aikenhead of the National Research Council of Canada for invaluable assistance in the SPEAM project; Dr. R. Mercer of ISSR for contributing valuable window data; Dr. S. MacLean, Dr. R. Thirsk, and Dr. B. Tryggvason of the National Research Council for their assistance in preparing and executing the first SPEAM experiment; Mr. C. Midwinter and Mr. W. Clark of AES for their support in the design, assembly, and calibration of the sunphotometers; Mr. R. Hoogerbrug of AES for his assistance in measuring the Shuttle windows; and Mr. L. Poulin of AES for his assistance in compiling this report.

References

[1]Evans, W. F. J., Kerr, J. B., McElroy, C. T., Shah, G., Wardle, D. I., Nicholls, R. W., Cann, M., McConnell, J. C., Davies, J., Garneau, M., and MacLean, S., "The SPEAM Sunphotometer Experiment on Mission 41-G," *Canadian Aeronautics and Space Journal*, Vol. 31, No. 3, Sept. 1985, pp. 240–248.

[2]Doetsch, K. and Aikenhead, B., "Canadian Astronaut Program: From Start to First Flight," *Canadian Aeronautics and Space Journal*, Vol. 31, No. 3, Sept. 1985, pp. 205–209.

[3]McElroy, C. T., "Window Transmissivity Measurements on the Orbiter Challenger Theory, Procedures and Results," Atmospheric Environment Service, Downsview, Ontario, Canada, Internal Rept. 119X42, 1985.

[4]Born, M. and Wolf, E., *Principles of Optics*, 5th ed., Oxford, Pergamon Press, 1975, p. 42.

[5]Slater, P. N., *Remote Sensing Optics and Optical Systems*, Addison-Wesley, Reading, MA, 1980.