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Solar Hemispherical Reflectometer Modification for Second Surface Mirror Measurements

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SOLAR HEMISPHERICAL REFLECTOMETER MODIFICATION FOR SECOND SURFACE MIRROR MEASUREMENTS

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Abstract

A commercial reflectometer has been modified for improved measurement of the solar hemispherical reflectance of second surface mirrors. The Solar Spectrum Reflectometer (SSR), manufactured by Devices and Services Co., Dallas, TX is designed to measure the solar hemispherical reflectance of flat, diffusely reflecting and first surface specular samples. Initial investigation of the device revealed that the SSR yielded significant deviations from the actual solar reflectance of second surface mirrors. The low reflectance values were determined to be caused by the displacement of the reflective surface away from the measurement port caused by the mirror protective layer. In this report, instrument modifications are described which reduce the sensitivity of the instrument to second surface mirror thickness. The modifications involve enlarging both the sample port opening and the specular disk (target) located inside the measurement cavity, adjusting the lamp assembly height, and installing a diffuser over the lamp. The modified SSR demonstrated only a small linear reflectance variation with mirror displacement. It was shown that any mirror of known solar hemispherical reflectance having a thickness within the range, 0 mm (first surface) to 3.2 mm, could be used as the reflectance standard. A variety of mirror samples, ranging from first surface to 6 mm thick, were measured using the modified SSR. All corrected measured SSR solar reflectance values were within ±0.008 reflectance units (1.000 reflectance units = 100% reflectance) of the actual solar reflectance, as determined from laboratory hemispherical reflectance measurements.

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1.0 Introduction

The optical properties of solar reflector materials are important in predicting collector performance. Two properties of mirrors are important: specular and hemispherical reflectance.[1] Portable instrumentation designed to measure the reflectance can be used to evaluate localized effects of soiling and weathering conditions and serve as a quality control parameter during the manufacture of solar reflector materials. Portable instrumentation for the measurement of the solar averaged hemispherical reflectance of mirror materials is available from several commercial manufacturers. In this paper the measurement characteristics of the Solar Spectrum Reflectometer (SSR) manufactured by Devices and Services Co., Dallas, TX, are evaluated. As previously published,[2] the solar hemispherical reflectance measured by the SSR for second surface mirrors was systematically lower than the actual reflectance values. The low values were found to be a result of the displacement of the reflective surface away from the measurement port. A modification to the SSR is described which reduces the sensitivity of the instrument to the thickness of second surface mirrors.

2.0 Theory of Operation

The Devices & Services Solar Spectrum Reflectometer (SSR) is designed to measure the solar reflectance (or absorptance) of flat, opaque samples for an air mass two (AM2) solar spectral distribution.[3] This measurement is accomplished by hemispherical illumination of a sample placed over the measurement port and determination of the intensity of radiation reflected at an angle of 20° from the normal. A schematic of the SSR measurement head, shown in Fig. 1, illustrates the position of the optical components within the cylindrical measurement cavity. Hemispherical illumination of the measurement port is achieved by a diffusely reflecting coating applied to all surfaces within the measurement cavity. A direct illumination shield is positioned between the

lamp and the measurement port so that the lamp does not directly illuminate the sample. A photograph of the measurement head interior with the cylindrical cavity removed (before modification) is shown in Fig. 2. The radiation reflected from the sample is measured using four different detector/filter combinations positioned inside and at the base of a collimating tube shown in Fig. 2. The individual detector outputs are electronically summed to approximate the solar spectral distribution.

Although the instrument is primarily designed for the measurement of diffusely reflecting materials, special provisions have been provided for the measurement of front surface mirrors. For a mirror sample, the detectors primarily view a small area of the interior cavity wall (without a specular disk installed), as shown in Fig. 1. Because the cavity interior is not uniformly illuminated, the reflectance reading for a mirror sample will not be correct unless the instrument GAIN is adjusted. In order for the instrument to measure both specularly reflecting and diffusely reflecting materials with no adjustment in the instrument GAIN, a diffusely reflecting disk, referred to as the specular disk, is positioned 20° from normal opposite the collimating tube as shown in Fig. 2. For mirror samples, the detectors view the front surface of the specular disk. During initial assembly and checkout by the manufacturer, the position of the disk relative to the sample port is adjusted so that specular and diffuse samples are correctly measured. This adjustment also insures the proper hemispherical reflectance reading is obtained for samples that have partially specular and partially diffuse reflectance characteristics. Although this calibration procedure is adequate for first surface materials, problems arise for second surface mirrors. For a completely specular sample, the detectors primarily view the specular disk as shown in Fig. 1. The precise detector field of view is dependent upon several variables including: the aperture diameter of the

collimating tube, the detector location relative to the collimating tube aperture, the diameter of the sample measurement port, and the thickness of any protective layer (substrate) for second surface mirrors.

As previously shown,[2] the SSR displays low reflectance values for second surface mirrors. Large reflectance losses, plotted in Fig. 3, were observed with increasing displacements away from the sample measurement port. The schematic of the SSR optics in Fig. 1 illustrates the effect of a thick protective layer upon the detector field of view. The four detector/filter combinations are assumed to be a single point for this example. With increasing mirror thickness the detector field of view is shifted to the right due to refraction in the transparent protective layer. The specular disk originally provided with the instrument was not large enough to intercept the entire detector viewing field. Thus the detectors were viewing both the surface of the specular disk as well as an area of the cylindrical cavity wall. In addition Fig. 1 also illustrates the possibility of partial clipping of the detector viewing field by the measurement port for displacements away from the plane of the port. These two effects were thought to be the major contributing factors resulting in reduced reflectance values measured for second surface samples and were used as the basis for the design modifications. Before discussing these modifications, the instrument calibration procedure will be described.

3.0 Standard Calibration Procedure

Two diffuse reflectance standards, a $BaSO_4$ and an Al_2O_3 field standard, are supplied by Devices & Services (D&S). In order to check the calibration values supplied with these standards, pressed halon (teflon) powder was used as our primary reflectance standard.[4] Halon was selected as the absolute diffuse reflectance standard because published NBS data are available and fresh standards

can easily be prepared.[5] The halon was packed in a 6 mm deep optical reflectance plate to meet NBS specifications.

The solar averaged hemispherical reflectance (AM2) for 6 mm thick halon is calculated to be 0.991. Even though the SSR can be set to display a reading of 0.991 by the simple adjustment of the instrument GAIN, this procedure is not sufficient for a complete calibration of the instrument. Since the reflectance measured by the SSR is obtained by summing the response of the four detectors, the individual detector gains must be adjusted so that the instrument spectral response matches the AM2 solar spectral distribution.

The individual detector weighting factors, D_n, for an AM2 solar spectral distribution have been determined by the manufacturer[3] to be

$$\begin{aligned} D_1 &= 0.027 \text{ (UV, } n = 1) \\ D_2 &= 0.211 \text{ (Blue, } n = 2) \\ D_3 &= 0.449 \text{ (Red, } n = 3) \\ D_4 &= 0.313 \text{ (IR, } n = 4) \end{aligned} \tag{1}$$

Note that $\sum_{n=1}^{4} D_n = 1.000$. If a perfectly reflecting material was available, the instrument reflectance reading for each detector could be set equal to the detector weighting factor, D_n, thereby calibrating the instrument. (Note that the individual detector readings are displayed by switching all detectors off except the one of interest.)

Because a perfectly reflecting material is not available, the instrument reflectance reading that is set for each detector, I_n, must include the reflectance properties of the material used for the calibration. Thus I_n is equal to the detector weighting factor, D_n, times the average reflectance of the calibration material within the detector response region, $\overline{R}_n$, so that

$$I_n = D_n \cdot \overline{R}_n \tag{2}$$

The $\overline{R}_n$ values for 6 mm thick halon were calculated using the reflectance properties for halon[5] and the individual detector response curves.[3] The detector response curves are shown in Figures 4A and 4B. Each detector response curve was divided into several ($3 < m < 5$) narrow wavelength intervals (see Fig. 4) and the fractional area, $A_{n,i}$, within each detector response region was determined using a planimeter. Again note that $\sum_{i=1}^{m} A_{n,i} = 1.000$. The average halon reflectance value, $\overline{R}_n$, was obtained from the sum

$$\overline{R}_n = \sum_{i=1}^{m} A_{n,i} \cdot R_i \qquad (3)$$

where R_i = the reflectance of halon within the ith wavelength interval. The individual values of $A_{n,i}$ and R_i for halon for the four detectors are listed in Table 1. Finally, with the halon standard positioned over the measurement port, the individual detector electronics were adjusted to obtain the reflectance value, I_n, for each detector. After this procedure, all detectors were switched on, the 6 mm thick halon standard was placed on the instrument, and the measured reflectance was 0.991 ± 0.001, as expected.

The $BaSO_4$ and Al_2O_3 standards were then measured to check the calibration values supplied by D&S. The SSR measured reflectance values, listed in Table 2, were within ±0.013 reflectance units from the manufacturer supplied values. The 6 mm thick halon standard was used as the diffuse reflectance standard for the SSR during the modification and alignment procedures detailed below.

4.0 Modification and Adjustment Procedure

The first modification consisted of enlarging the measurement port diameter using a replacement top for the SSR. The normal 19.7 mm diameter measurement port was enlarged to a diameter of 29.5 mm.

The second change involved modifing the specular disk. The original specular disk (16.5 mm diameter) was mounted on a threaded rod using a hex nut on the front surface, as shown in Fig. 2. Because the position of the nut resulted in a nonuniform front surface on the disk, the mounting was changed to the back to insure a uniform surface facing the sample port. In addition a larger specular disk, 41.3 mm diameter, was fabricated and mounted on the threaded rod. The new specular disk assembly was then coated with Eastman white reflectance paint, ~2 mm thick.[6]

A third modification involved lowering the lamp assembly to allow for the increased diameter and lower position of the new specular disk. In addition, a thin plastic diffuser was positioned over the direct illumination shield to eliminate nonuniform illumination on the specular disk (see Fig. 1). The detector calibration procedure was repeated after the lamp assembly movement. This was done because the detector responses are dependent upon the efficiency of the measurement cavity and must be recalibrated after any change, e.g., measurement top removal/modification, lamp replacement, lamp assembly movement, collimating tube removal, specular disk removal, etc.

As previously discussed, the function of the specular disk is to provide a uniform response for samples that have both specular and diffuse reflectance characteristics. The alignment of the disk is very critical for this balance. The procedure used to align the disk was:

a) The instrument was allowed to warm up in OPERATE mode for 30 minutes.

b) The individual detectors were calibrated following the manufacturers calibration procedure[3] using the calculated detector readings, I_n, for halon, see Table 1.

c) A hohlraum (black cylindrical cavity) was placed over the sample port to obtain a zero offset value [δ].

A zero reading (0.000) could not be obtained by adjusting the zero potentiometer due to the increased size of the measurement port. Therefore, a zero offset reading was obtained by adjusting the potentiometer to a convenient value, typically -0.010. (The zero offset reading after the 30 minute warmup was within ±0.001 reflectance units). This value was then added to the raw measured value to obtain the corrected hemispherical solar reflectance. As an example: the halon reflectance standard has a calculated solar averaged hemispherical reflectance (AM2) of 0.991. If the zero offset [δ] is -0.010, the SSR should be set to display 0.981.

d) The halon reflectance standard was placed over the sample port and the instrument GAIN was adjusted to obtain the zero offset corrected value R_s(D&S) Halon = 0.991 + [δ].

e) A thin silvered glass mirror, measured on a Beckman 5270 spectrophotometer with an integrating sphere accessory, was used as the specular standard. All measurements on the Beckman 5270 were referenced to a NBS calibrated mirror and have an uncertainty of ±0.005 reflectance units. (1.000 reflectance units = 100% reflectance.)

NOTE: Any mirror of known solar averaged hemispherical reflectance, having a thickness within the range 0-3.2 mm, could be used as the specular standard. The selection of the thin silvered glass mirror is explained in the performance section (section 5.0).

The standard mirror was placed over the sample port and the specular disk was positioned to obtain the calculated solar averaged hemispherical reflectance (AM2), i.e., the gain was <u>not</u> changed. The position of the new specular disk was very critical and the SSR readings were very

sensitive to the vertical height (relative to the base plate) of the disk. The mounting block holding the disk was drilled out to permit the threaded rod to slip freely up and down. These steps allowed easier adjustment of the vertical height. The position of the vertical height adjustment affected the SSR measured reflectance as follows: lowering the disk, relative to the measurement cavity base plate and also to the sample port, increased the reading, raising the disk lowered the reading.

f) The specular disk assembly was secured by two locking nuts, one inside and the other outside of the measurement cavity. Glyptal paint was applied to the external nut, under the base plate, to eliminate movement due to jarring and/or vibration during transport.

5.0 Measurement Characteristics After Modification

The solar reflectance as a function of mirror displacement both before and after the modifications is shown in Figure 3. In order to measure the effect of mirror displacement, a first surface (F.S.) aluminum mirror and various thicknesses of quartz shims were used. The quartz shims were placed between the F.S. mirror and the sample port to simulate second surface mirror displacements. The simple displacement of a F.S. mirror away from the measurement port is not adequate for checking this effect, since radiation incident on a second surface mirror is refracted by the transparent protective layer. Thus a different behavior would be exhibited if the displacement was done without the use of quartz shims. Before modification the SSR demonstrated a reflectance loss of 5% for a displacement of only 1.2 mm as shown in Fig. 3. After modification the same displacement resulted in a reflectance loss of only 1%. A reflectance loss after modification of 5% was observed for a displacement of 6 mm, the before modification reflectance loss was 35%.

As previously stated, any mirror of known solar averaged hemispherical reflectance within the thickness range, 0 to 3.18 mm, could have been used as the specular standard for the specular disk alignment. The validity of using mirrors in this displacement range after modification was verified by measuring the solar reflectance as a function of mirror displacement for three mirrors; one F.S., the second 1.52 mm thick, and the third 3.18 mm thick. The effect of the mirror displacement was measured using quartz shims as described above. The SSR (GAIN) was adjusted to display the calculated solar averaged hemispherical reflectance, $R_s(0)$, for each mirror without quartz shims. The solar reflectance values as a function of mirror displacement are shown in Fig. 5. They were normalized by dividing the SSR measured solar reflectance with shims $R_s(X)$, by the solar reflectance $R_s(0)$ calculated using a Beckman 5270 spectrophotometer. The R_s vs x functions were approximately linear and parallel for the mirrors measured. Therefore, any mirror of known solar reflectance and within the displacement range measured, could have been used as the specular standard and would exhibit linear reflectance changes with displacement. (It should be noted, however, that the slopes of the straight lines may be different for other instruments.)

Notice that if the second surface mirror R_s vs x curves were extended back to a displacement of zero, see Fig. 5, the normalized solar reflectance as a function of mirror displacement is greater than 1.00. This overestimation characteristic will be inherent for samples having a thickness less than the thickness of the selected specular standard used for the specular disk alignment. The higher reflectance reading occurs because, relative to the thinner sample, the vertical position of the specular disk is too low (see Theory of Operation section 2.0).

A thin (1.52 mm) second surface silvered glass mirror was selected as the specular standard for the specular disk alignment for the following reasons. Ideally, a specular standard corresponding to the thickness of the unknown mirror samples to be measured should be used. Since this is not always practical, the thin second surface mirror was selected because it lies near the center of the expected displacement range (0 to 3.18 mm) that is likely to be encountered for solar reflector materials. Also, a thin protective layer offered a distinct advantage in handling and cleaning over an unprotected mirror surface.

Although a significant decrease was made in the measured solar reflectance loss as a function of mirror displacement by the modifications described above, the loss was not completely eliminated. As a result, there is a need for small corrections to the SSR measured solar reflectance, $R_{SSR}(2\pi)$. The correction value is the inverse of the normalized solar reflectance value. The correction factor as a function of mirror displacement (using quartz shims) for the thin second surface specular standard is shown in Figure 6. As an example: the normalized solar reflectance for a 3 mm displacement is 0.987 (middle curve, Fig. 5). The correction factor is the inverse or 1.013. Therefore, for a 3 mm displacement, the SSR corrected solar reflectance = 1.013 times the SSR measured solar reflectance. Note that correction factors less than 1.000 are necessary for displacements less than the thin second surface specular standard.

The correction curve will be unique to the specular standard selected and must be redetermined if another standard of different thickness is used and/or the specular disk is readjusted.

As a check on the utility of the modification, numerous mirror samples of various thickness were measured using the modified SSR. The actual solar averaged hemispherical reflectance (AM2), $R_S(2\pi)$, for each mirror was determined using a Beckman 5270 spectrophotometer with an integrating sphere accessory.

All calculated solar reflectance data, obtained with the 5270, were referenced to a NBS calibrated mirror and have an uncertainty of ±0.005 reflectance units. The solar averaged hemispherical reflectance values, $R(2\pi)$, for all the mirrors are listed in Table 3.

The corrected SSR solar reflectance values, $R_c(2\pi)$, were determined using correction factors (CF) obtained from the correction curve, Fig. 6, which was fit to a straight line. The resulting equation was

$$CF(1.52\ \text{mm}) = 0.986 + 0.009\ (x) \tag{4}$$

where x is the thickness of the mirror sample in mm. A majority of the corrected solar reflectance values were within measurement uncertainty (±0.005 reflectance units). A maximum difference of +0.008 reflectance units was exhibited by the 6 mm silvered glass sample.

6.0 Conclusion

A significant decrease in the measured solar reflectance error caused by mirror displacement was achieved by modifying the Solar Spectrum Reflectometer. It was shown that any mirror of known solar averaged hemispherical reflectance within the thickness range, 0 to 3.18 mm, could be used as a specular standard on the modified instrument. A correction curve was generated for the selected specular standard which enabled the SSR corrected solar reflectance values, over a wide thickness range (0 to 6 mm), to within ±0.008 reflectance units of the actual solar reflectance. It should be noted that other instruments may have a slightly different correction curve that would need to be determined in each case.

Acknowledgement

The author would like to thank R. B. Pettit for his helpful discussions concerning the instrument modifications.

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2. R. B. Pettit and A. R. Mahoney, "Portable Instrumentation for Solar Absorptance and Emittance Measurements," Proceedings Line-Focus Solar Thermal Energy Tech. Dev. Conf., Sept. 9-11, 1980, Albuq., NM (Sandia Nat. Labs Report SAND 80-1666).*
3. Solar Spectrum Reflectometer Operating Instructions and D&S Technical Note 79-16, Devices & Services Co., Dallas, TX.
4. Halon consists of polytetrafluoroethylene (PTFE) powder manufactured by Allied Chemical Co.
5. V. R. Weidner and J. J. Hsia, "Reflection Properties of Pressed Polytetrafluoroethylene Powder," J. Opt. Soc. Am. 71, 856 (1981).
6. See F. Grum and T. E. Wrightman, Applied Optics 16, 2775 (1977).

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Table 1. Detector Calibration Values for Halon Diffuse Reflectance Standard

Detector	i^{th} Interval/$\Delta\lambda$(μm)	$A_{n,i}$	R_i(Halon)	$A_{n,i} \cdot R_i$	D_n	$I_n = D_n \cdot R_n$
UV(n=1)	1/0.33-0.36	0.142	0.990	0.141		
	2/0.36-0.38	0.338	0.990	0.335		
	3/0.38-0.40	0.459	0.990	0.454		
	4/0.40-0.42	0.061	0.990	0.060		
				$\bar{R}_n$ = 0.990	0.027	0.027
Blue(n=2)	1/0.37-0.45	0.164	0.990	0.162		
	2/0.45-0.50	0.349	0.991	0.346		
	3/0.50-0.55	0.311	0.991	0.308		
	4/0.55-0.60	0.112	0.991	0.111		
	5/0.60-0.81	0.064	0.991	0.063		
				$\bar{R}_n$ = 0.990	0.211	0.209
Red (n=3)	1/0.46-0.60	0.198	0.991	0.196		
	2/0.60-0.80	0.610	0.991	0.605		
	3/0.80-1.15	0.192	0.991	0.190		
				$\bar{R}_n$ = 0.991	0.449	0.445
IR (n=4)	1/0.80-1.1	0.233	0.991	0.231		
	2/1.1-1.3	0.393	0.990	0.389		
	3/1.3-1.5	0.131	0.989	0.130		
	4/1.5-1.9	0.174	0.986	0.172		
	5/1.9-2.5	0.069	0.972	0.067		
				$\bar{R}_n$ = 0.989	0.313	0.310

Note that $\sum_{n=1}^{4} I_n = (0.027 + 0.209 + 0.445 + 0.310) = 0.991$, the solar averaged reflectance of halon powder.

Table 2. Diffuse Standards Solar Averated Hemispherical Reflectance

Standard	Calculated Reflectance	*Measured Reflectance	Δ
Halon (6 mm thick)	0.991 (Ref. 5)	0.991	0.000**
$BaSO_4$ (D&S)	0.974 (Ref. 3)	0.978	+0.004
Al_2O_3 (D&S)	0.844 (Ref. 3)	0.857	+0.013

*All four detectors switched on.
**Adjusted to be 0.000 as discussed in text.

Table 3. Solar Averaged Hemispherical Reflectance of Mirror Samples

Mirror Sample	Material	Thickness (mm)	$R_s(2\pi)$ Calculated (5270)	$R_{SSR}(2\pi)$ Modified SSR	Correction Factor (1.52 mm STD)	$R_c(2\pi)$ Corrected SSR	Δ $(R_c - R_s)$
1	1st Surface Aluminum	none	0.910	0.916	0.986	0.903	-0.007
2	Silvered polyester film	none	0.962	0.970	0.986	0.956	-0.006
3	YS-91A (3M)	0.002	0.846	0.856	0.986	0.844	-0.002
4	FEK-244 (3M)	0.002	0.860	0.870	0.986	0.858	+0.002
5	Roll polished aluminum; protective coating	0.002	0.840	0.857	0.986	0.845	+0.005
6	Roll polished aluminum; protective coating	0.002	0.866	0.878	0.986	0.866	0.000
7	Silvered drawn glass	0.71	0.939	0.940	0.992	0.932	-0.007
8	Silvered drawn glass	0.76	0.955	0.955	0.993	0.948	-0.007
9	Silvered drawn glass	1.02	0.948	0.946	0.995	0.941	-0.007
10	Aluminized Quartz	1.52	0.883	0.880	1.0	0.880	-0.003
11	Silvered float glass	1.63	0.881	0.875	1.001	0.876	-0.005

Table 3 (cont.)

12	Silvered float glass	1.63	0.883	0.879	1.001	0.880	-0.003
13	Silvered float glass	2.54	0.851	0.840	1.009	0.848	-0.003
14	Silvered float glass	2.54	0.849	0.836	1.009	0.844	-0.005
15	Silvered float glass	3.05	0.833	0.819	1.013	0.830	-0.003
16	Silvered float glass	3.05	0.913	0.899	1.013	0.912	-0.001
17	Silvered B270 glass	3.18	0.958	0.946	1.015	0.960	+0.002
18	Aluminized acrylic	3.18	0.755	0.749	1.015	0.760	+0.005
19	Silvered float glass	5.0	0.906	0.884	1.031	0.911	+0.005
20	Silvered B270 glass	6.0	0.935	0.907	1.040	0.943	+0.008

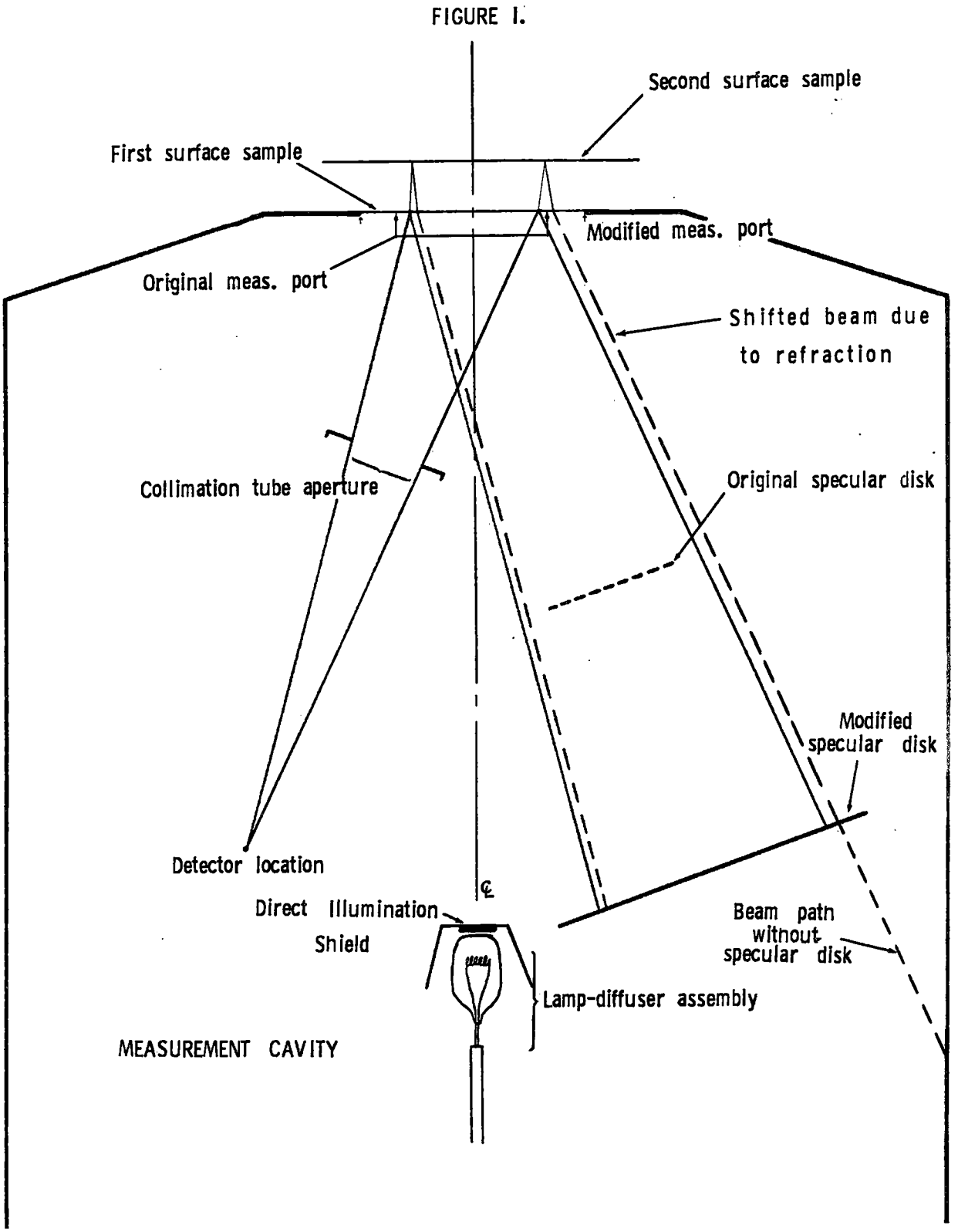

FIGURE 1. Sketch of SSR optics, before and after modifications, using a first surface and second surface mirror sample.

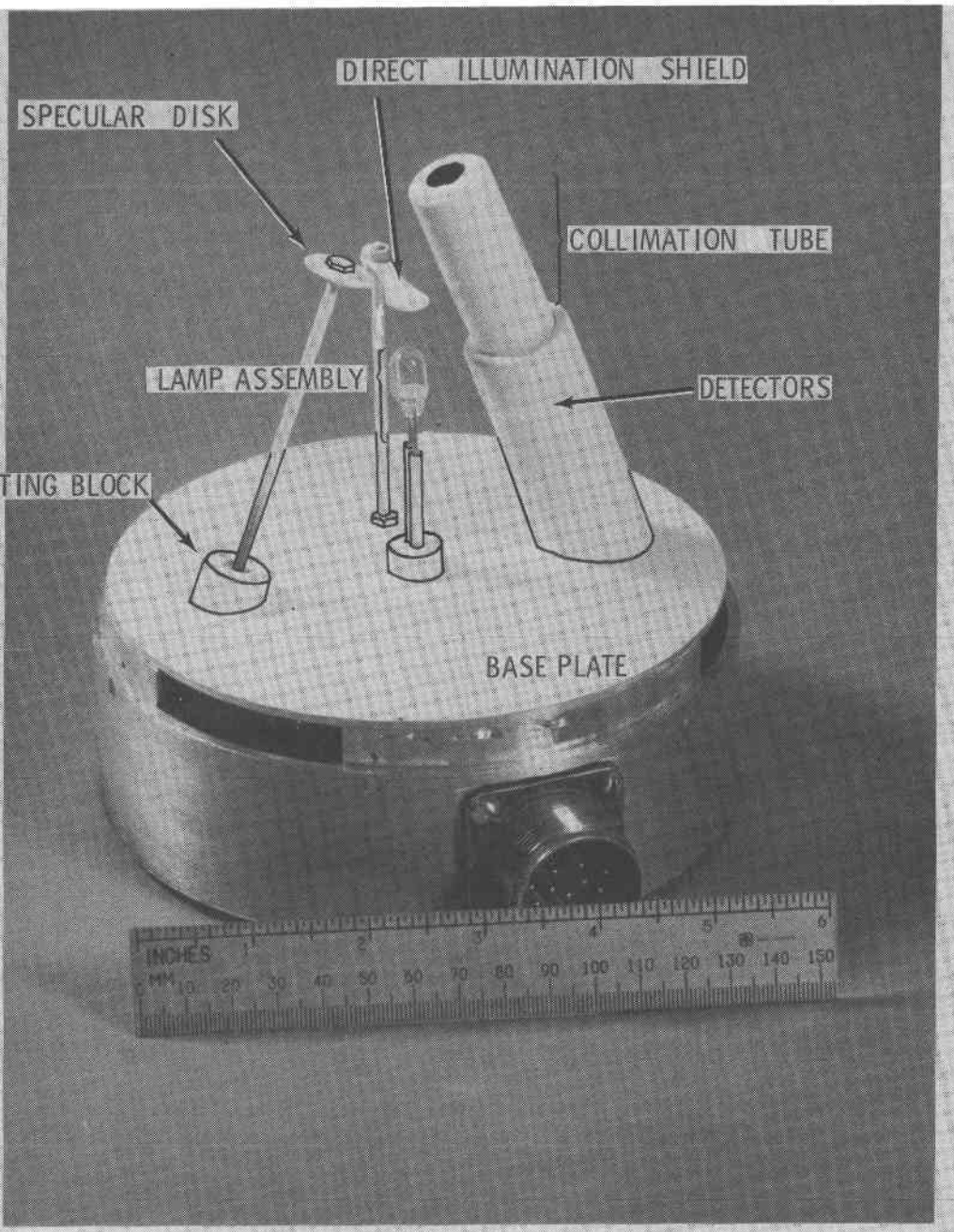

FIGURE 2.

FIGURE 2. D&S Solar Spectrum Reflectometer measurement cavity with cylindrical housing removed. Components shown before modifications. Note: The detectors are located inside the collimating tube assembly.

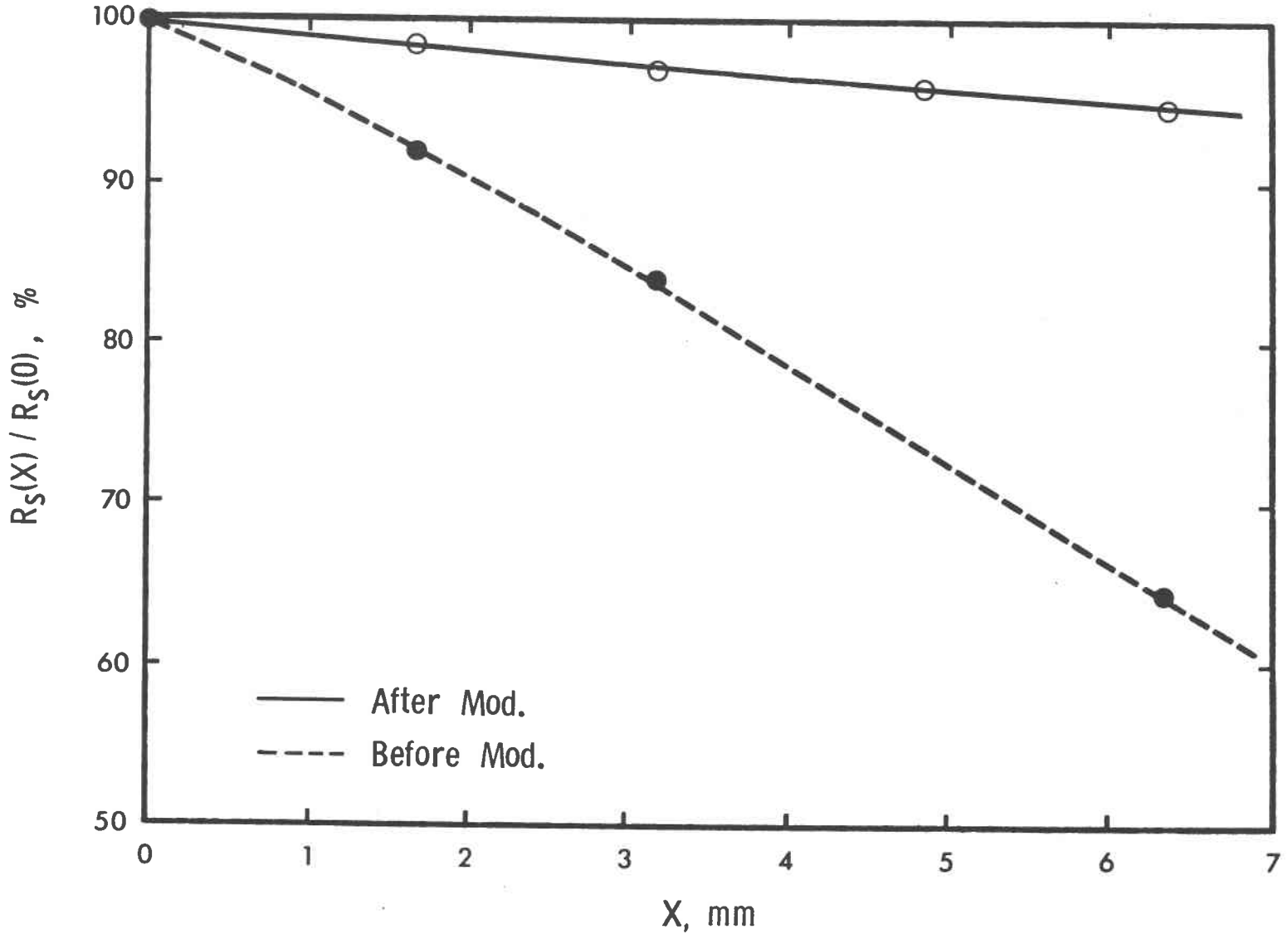

FIGURE 3. Normalized solar reflectance values, $R_S(x)/R_S(0)$, measured for a first surface mirror as a function of its displacement, x, away from the measurement port of the D&S Solar Spectrum Reflectometer, before and after modification. Displacement accomplished using quartz shims as discussed in the text.

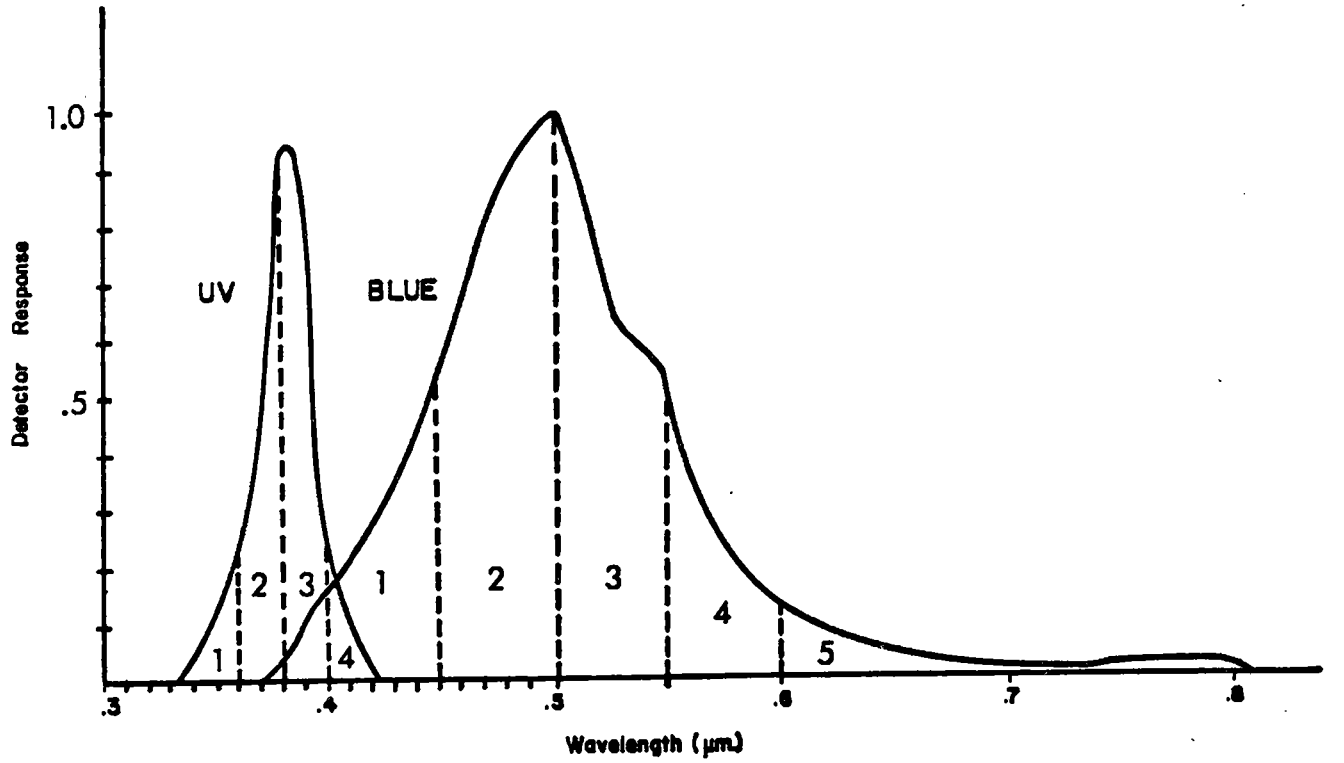

FIGURE 4A.

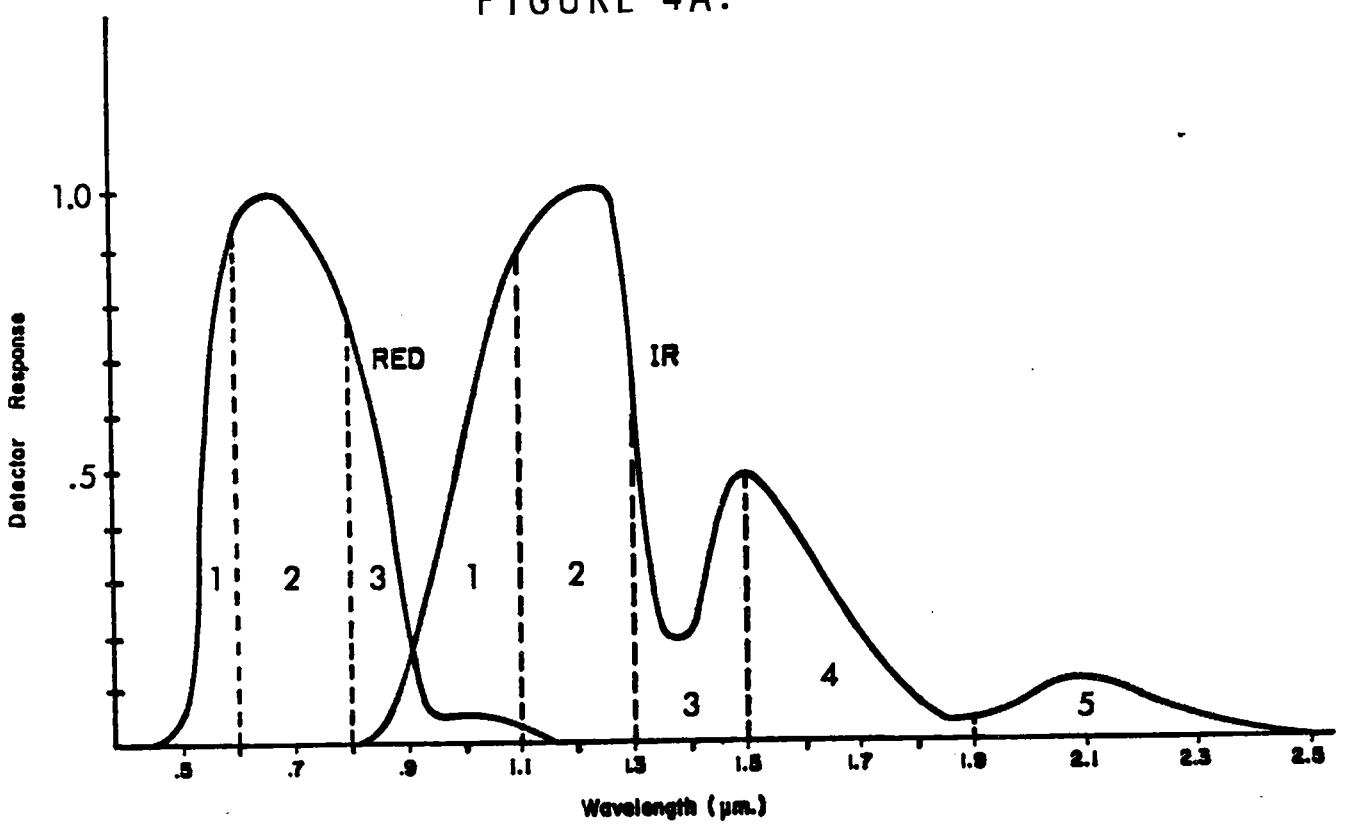

FIGURE 4B.

FIGURE 4. Normalized detector response vs wavelength for the four detector/filter combinations in the D&S Solar Spectrum Reflectometer (Ref. 3).

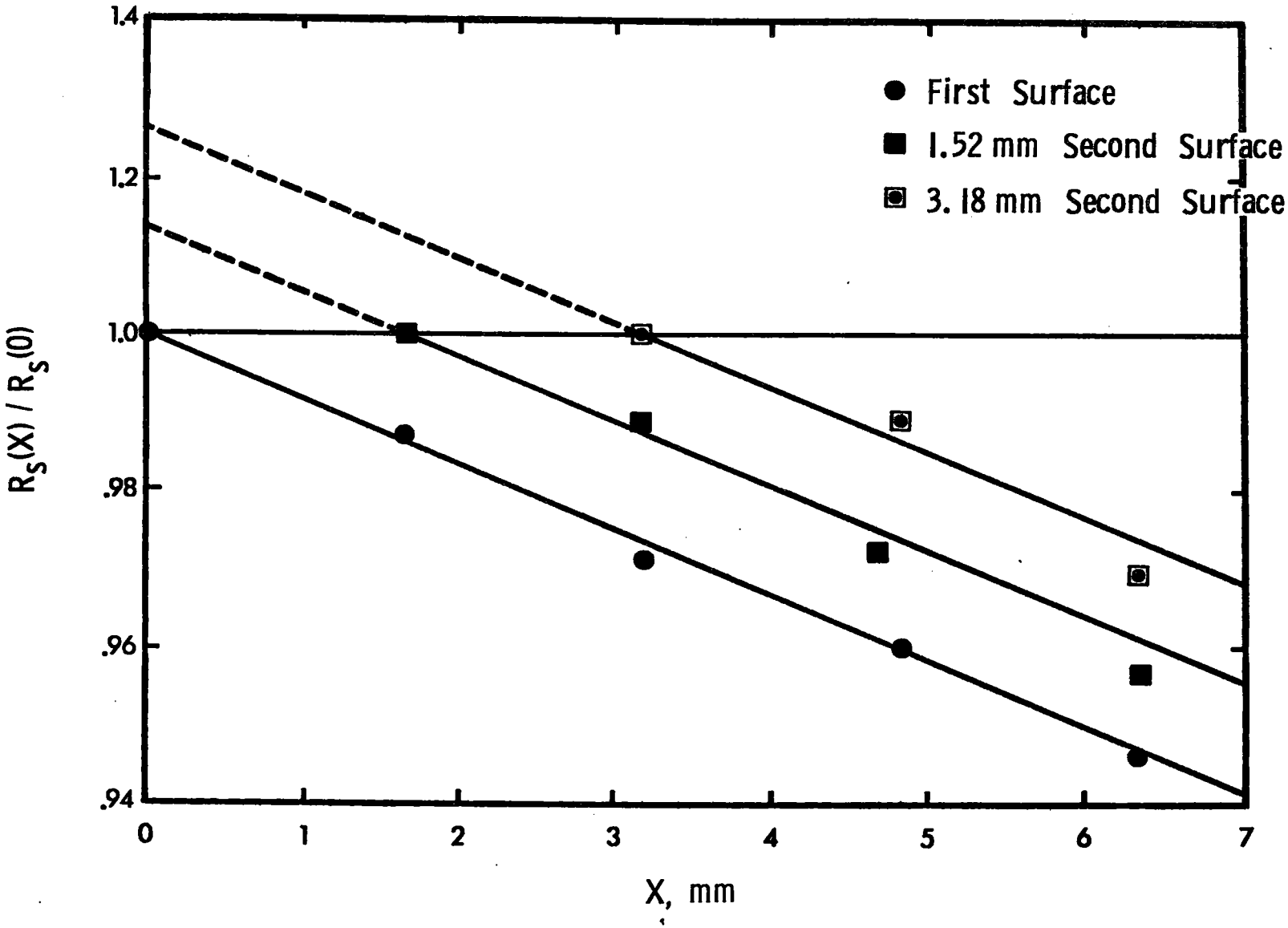

FIGURE 5. Normalized solar reflectance values $R_S(x)/R_S(0)$ for a first surface, a 1.52 mm second surface, and a 3.18 mm second surface mirror as a function of displacement, x, away from the measurement port of the modified D&S Solar Spectrum Reflectometer.

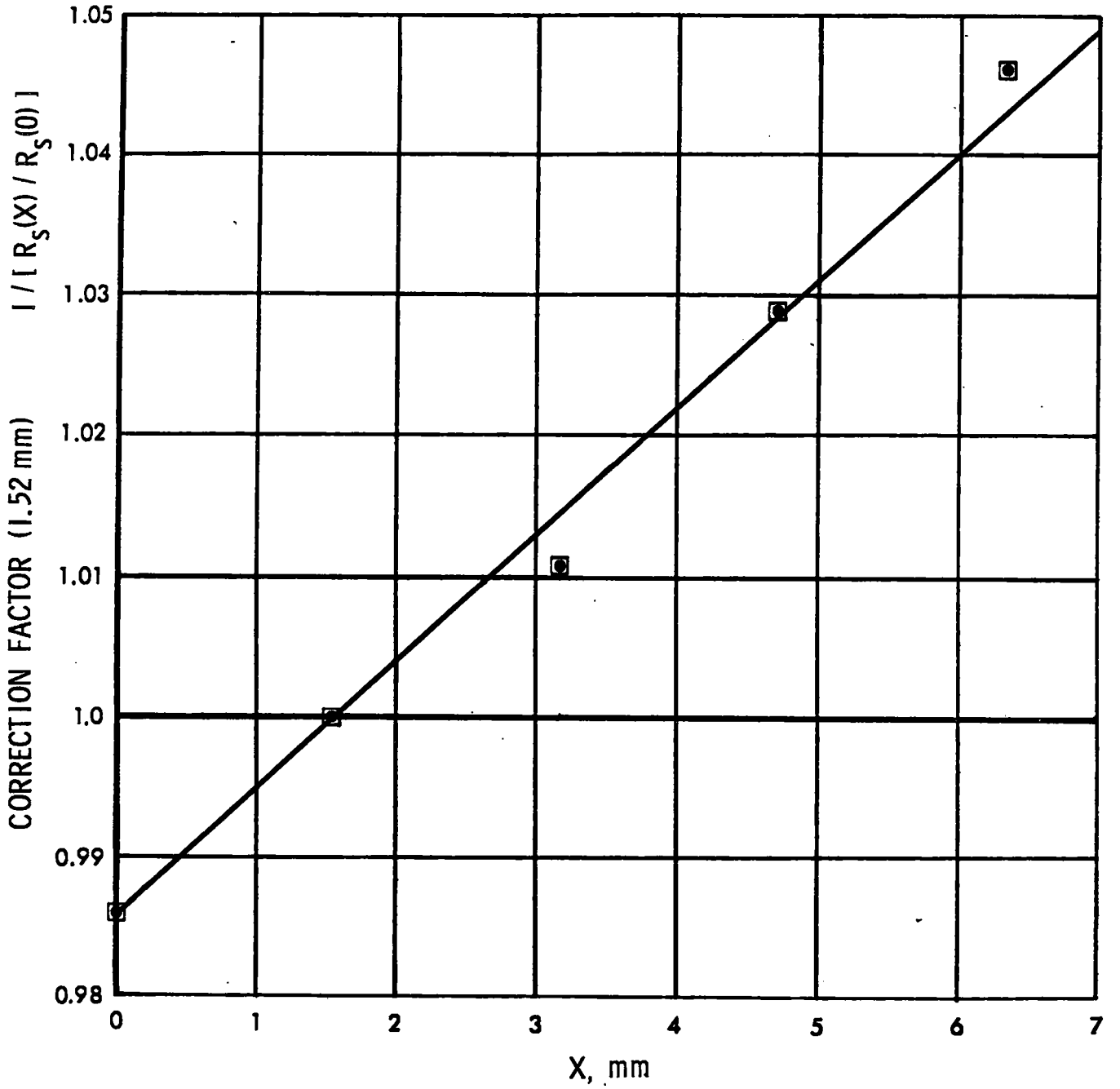

FIGURE 6. Correction factor, $1/[R_s(x)/R_s(0)]$ for a 1.52 mm specular reference mirror as a function of its displacement, x, away from the measurement port of the modified D&S Solar Spectrum Reflectometer.

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