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Characterizing Solar Mirror Materials Using Portable Reflectometers

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CHARACTERIZING SOLAR MIRROR MATERIALS USING PORTABLE REFLECTOMETERS

ABSTRACT

Currently available portable instrumentation for hemispherical and specular reflectance measurements of solar mirror materials is discussed. Particular attention is given to the wavelength dependence of the measurement spectrum, which in most cases does not approximate a solar spectral distribution, and to other limitations of each instrument. Because a portable instrument is not available that can determine the solar averaged specular reflectance from a single measurement, two procedures are recommended for obtaining a reasonable estimate for this quantity using the existing portable equipment. Finally, future developments in this area are briefly discussed.

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1.0 Introduction

Characterization of the reflectance properties of solar mirror materials requires the measurement of both the hemispherical and specular reflectance characteristics. The need to measure both of these quantities and their relationship to each other have been described in published reports.¹ While these two reflectance properties can be adequately measured in the laboratory on moderately sized samples (up to approximately 25 cm x 25 cm), measurements in the field on large samples using currently available portable instrumentation are limited. The purpose of this report is to discuss the measurement characteristics of these portable instruments and how these characteristics limit the determination of a solar averaged specular reflectance value. Two procedures are recommended for estimating the solar averaged specular reflectance value based on measurements obtained using the available instruments. Since one objective of field measurements is to characterize the specular reflectance changes that occur with outdoor exposure, a distinction is drawn between measuring changes in the intrinsic reflectance properties of the mirror and changes caused by accumulated dust particles. The usefulness of present instrumentation in these areas is outlined.

2.0 Hemispherical Reflectance

Hemispherical reflectance is defined as the ratio of the radiation reflected from a surface into a hemisphere to the radiation incident on that surface.² Although the hemispherical reflectance contains no information concerning the angular distribution of the reflected radiation, it does represent the upper limit for the specular reflectance for a material.

While the hemispherical reflectance is a function of the incident angle, for typical solar materials, this dependence is small for angles up to 60

degrees from normal.³ Therefore, measurements limited to incident angles less than 30 degrees from normal should all provide equivalent values.

All portable instruments designed to measure the solar averaged hemispherical reflectance, $R_s(2\pi)$, contain their own light source. Typically, these sources do not provide a good match to a solar spectral distribution. Therefore, it is important to understand the spectral characteristics of each instrument and how the measurement spectrum differs from a typical solar spectral distribution. These differences can lead to appreciable errors in the measured solar averaged hemispherical reflectance value, depending upon the reflectance characteristic of the mirror being measured. The measurement characteristics of two currently available portable instruments designed to measure $R_s(2\pi)$ are discussed below.

2.1 Devices and Services SSR Reflectometer: The Devices and Services (D&S) Solar Spectrum Reflectometer (SSR) hemispherically illuminates a sample placed over the measurement port and measures the amount of radiation reflected from the sample at a 20 degree angle using four separate detector/filter combinations. The four detector/filters cover distinct wavelength regions across the solar spectrum as shown in Fig. 1a. The output of each detector is weighted according to the portion of the solar spectral distribution to be matched. By summing these weighted outputs, an approximation to the solar averaged hemispherical reflectance is obtained.

While the overall wavelength response of the instrument provides a good match to a solar spectral distribution (see Fig. 1b), other problems have been found when measuring second surface solar mirror materials; modification of the measurement head of this instrument has improved the measurement accuracy for such mirrors.⁴ Without this modification, the instrument significantly underestimates the actual solar averaged hemispherical reflectance for second surface mirrors. The problem arises from the fact that, for second surface

Figure 1. (a) Wavelength response of the four detector/filter combinations used in the Devices and Services SSR reflectometer.

(b) The effective measurement spectrum of the SSR reflectometer as compared to an air mass one solar spectral distribution.

mirrors, the reflecting surface (metal layer) is displaced away from the plane of the measurement port in the instrument. The greater the thickness of the transparent protective layer (typically glass or plastic), the greater this displacement and the larger the measurement error. After modifying the instrument as described in Ref. 4, the measured solar reflectance is only 5% below the true value for a second surface glass mirror 6 mm thick. This value is compared to a reflectance decrease of over 20% before the modifications. This smaller reduction in the measured reflectance value can be corrected using an easily generated correction curve (see Ref. 4). Using this curve, the solar averaged hemispherical reflectance of mirrors varying in thickness from 0 to 6 mm can be determined (after correction) to an accuracy of ± 0.008 reflectance units (100% reflectance = 1.000 reflectance units).

Finally, it should be pointed out that the reflectance properties of a sample can also be measured with each individual detector/filter in order to obtain an indication of the wavelength dependence of the reflectance properties. This measurement technique will be discussed later as one of the recommended procedures for determining the solar averaged specular reflectance properties.

2.2 Gier Dunkle MS-251 Solar Reflectometer: Gier Dunkle Instruments, Santa Monica, California (now part of Dynatech) manufactures a solar spectrum reflectometer, Model MS-251. The operating characteristics of this instrument have previously been described.⁵ In this instrument, the output of a xenon lamp is directed onto a sample and the amount of reflected energy measured using an integrating sphere. By comparing the intensity of radiation reflected from the sample to the intensity of the incident radiation, the hemispherical reflectance of the sample is obtained. The measurement spectrum, shown in Fig. 2, is approximately equal to the spectral output of the xenon lamp that contains many large intensity peaks from 800 to 1100 nanometers. The differences between

Figure 2. Measurement spectrum of a Gier-Dunkle Solar Reflectometer, Model MS-251. Also shown is an air mass one solar spectral distribution.

this measurement spectrum and the solar spectral distribution can lead to errors in the measured solar averaged hemispherical reflectance value. The magnitude of these errors has not been quantified for typical solar mirror materials.

In addition, the MS-251 also underestimates the reflectance values measured for second surface mirrors. This occurs because some of the radiation reflected at the metal layer of a second surface mirror does not enter the measurement cavity (sphere) but is clipped by the measurement port. Correction of this problem would parallel the modifications performed on the D&S SSR instrument, but no correction has been attempted for this instrument. Correction curves as a function of mirror thickness could also be obtained for the MS-251 in a manner similar to the techniques used for the D&S SSR instrument (see Ref. 4).

3.0 Specular Reflectance Measurements

It has been found that the specularly reflected beam profile of solar mirror materials can be adequately described by a normal distribution of the form

$$R(\Delta\theta) = \frac{R_0}{2\pi\sigma_0^2} \exp\left[\frac{-\Delta\theta^2}{2\sigma_0^2}\right] \quad (1)$$

where σ_0 is the dispersion of the distribution, $\Delta\theta$ is the angle measured from the specular direction and R_0 is the integrated reflectance value at the wavelength of interest.¹ Typically, R_0 is equal to the hemispherical reflectance. A determination of the dispersion (σ_0) requires reflectance measurements using a bidirectional reflectometer over a range of angular apertures, typically from 1 mrad to 15 or 30 mrad, and computer analysis of the resulting data.⁶ Presently available portable instruments are not capable of this type of detailed data acquisition.

In a solar concentrator, the reflectance quantity of interest is the amount of reflected sunlight that is incident on the receiver surface. A detailed discussion of how the specular reflectance properties are utilized in calculating the solar collector performance is presented in Ref. 7. Briefly, the quantity of interest is the integral of equation (1) out to an angular size, θ , which represents the angular size of the receiver surface. This quantity, which is termed the cumulative reflectance $R'(\theta)$, is given by⁸

$$\begin{aligned} R'(\theta) &= \int_0^\theta 2\pi\Delta\theta R(\Delta\theta) d\Delta\theta \\ &= R_0 \left[1 - \exp\left(\frac{-\theta^2}{2\sigma_0^2}\right) \right] \end{aligned} \quad (2)$$

Note that when $\theta \gg \sigma_0$, $R'(\theta)$ is equal to R_0 , as expected.

While the parameters in equations (1) and (2) are valid at specific wavelengths, the equations themselves can be used to describe the solar averaged specular reflectance properties. In this case, R_0 is replaced by its solar averaged value, R_s , and σ_0 is replaced by a solar averaged dispersion, σ_s .

As discussed below, currently available portable specular reflectometers cannot measure $R'_S(\theta)$.

In the special case of silvered glass mirrors, the dispersion σ_0 has been found to be always less than or equal to 0.5 mrad, which is the resolution of the laboratory measurement. Thus for collection angles $\theta \geq 2$ mrad, the cumulative reflectance is equal to the hemispherical reflectance and is independent of the size of the collection aperture θ used in the measurement.

Measurements have shown⁹ that accumulated dust on the surface of a mirror does not significantly change the dispersion σ_0 , but only reduces the intensity R_0 of the specular beam (see Eq. (1)). This means that the fractional decrease in the cumulative reflectance due to dust accumulation is the same at all angular apertures, θ . Thus, if a measurement is designed to determine the decrease in the cumulative reflectance due to dust accumulation, the size of the measurement angular aperture used in the portable specular reflectometer is not important. However, other changes in $R'(\theta)$ due to outdoor exposure may be a function of the measurement angular aperture (i.e., σ_0 may change).

The reduction in the specular reflectance due to soiling is a function of wavelength. Measurements have shown that the specular reflectance loss (which is defined as the difference between R_0 measured before and after soiling) increases with decreasing wavelength over the solar spectral region. In addition, the wavelength dependence changes considerably with the exposure conditions.⁹ Typical variations in the wavelength dependent behavior for silvered glass mirrors after various lengths of exposure in Albuquerque, NM, are shown in Fig. 3. For the data shown, the wavelength dependence of the specular reflectance loss caused by the spectral reflectance characteristics of the silvered glass mirrors has been removed, as discussed in Ref. 9, in order to emphasize the wavelength dependence resulting only from the soiling. In addition, all curves

Figure 3. Wavelength dependence of the specular reflectance loss caused by dust accumulation during outdoor exposure. All curves have been normalized to pass through 1.00 at 500 nm (see Ref. 9). The time of outdoor exposure is listed next to each curve.

have been normalized to pass through the value 1.00 at 500 nm in order to highlight their different wavelength behavior. Clearly, a reflectance measurement over the complete solar spectrum is required in order to obtain an accurate indication of the solar averaged specular reflectance loss because of these wavelength and exposure time variations. Errors in the specular reflectance loss as a result of this wavelength dependence are discussed below for the available portable specular reflectometers.

3.1 Sandia Portable Specular Reflectometer: In early 1978, J. M. Freese developed a portable specular reflectometer whose optical design was based on

the laboratory bidirectional reflectometer discussed earlier.¹⁰ A schematic of the optical arrangement is shown in Fig. 4. Cumulative reflectance values obtained with the portable instrument agreed with data obtained using the laboratory bidirectional reflectometer to within ± 0.005 reflectance units.¹⁰

Figure 4. Schematic optical diagram of a portable specular reflectometer showing the location of the collimation and collection lenses, filters, the light source and the detector.

Because of the success of this first prototype, a second generation instrument¹¹ was built as shown in Fig. 5. This instrument incorporated several improvements over the first prototype including: (1) A larger diameter measurement beam (10 mm vs 5 mm); (2) Reduced weight from 6.5 lbs to 3.5 lbs; (3) The addition of adjustable apertures for ease of alignment; (4) Ability to

measure specular transmittance properties as well as specular reflectance properties; (5) Improved X-Y beam tilting adjustments that are used for alignment. A complete set of drawings for this instrument was also prepared.

Figure 5. Photograph showing the Sandia-designed second generation portable specular reflectometer and power supply (right) and the new Devices and Services portable specular reflectometer (left).

The measurement spectrum of this instrument was defined primarily by the spectral characteristics of several internally mounted filters, as well as the optical characteristics of the light source (tungsten lamp) and detector (silicon photocell). The wavelength dependence of the measurement spectrum was measured and is shown in Fig. 6. Note that the spectrum extends from 450 nm to 750 nm and peaks near the maximum of the solar spectral distribution (compare with Fig. 1b). Since this measurement spectrum does not correspond to a solar spectral distribution, the instrument cannot determine the solar averaged cumulative reflectance properties. The limited measurement spectrum also affects the accuracy of changes measured in the specular reflectance due to dust accumulation. From

the data shown in Fig. 3, the sample represented by the 10-month curve would cause the largest error in measured cumulative reflectance loss using the Sandia reflectometer as compared to the actual solar averaged cumulative reflectance loss. For this curve, the Sandia instrument will measure a cumulative reflectance loss that is 20% higher than the actual solar averaged loss. For example, if the solar averaged cumulative reflectance loss were 0.100 reflectance units, the Sandia instrument would measure a loss of 0.120. Note that the potentially large percent error (20%) in the Sandia instrument does not translate into substantial reflectance errors for small to moderate cumulative reflectance losses. For this reason, this limitation is considered only a minor problem.

Figure 6. The wavelength dependence of the measurement spectrum of the Sandia second generation portable specular reflectometer (see Ref. 11).

3.2 Devices and Services Portable Specular Reflectometer: D&S, under contract to Sandia, has developed a portable specular reflectometer based on the previously discussed Sandia instrument. A picture of the instrument is shown on the left in Fig. 5. While this new instrument uses the same optical design as the Sandia reflectometer, it incorporates several improvements: (1) The electronics are entirely contained within the measurement head and are battery operated; thus the instrument is completely portable. (2) Three different collection apertures can be easily selected ranging in size from $\theta = 7.5$ mrad to $\theta = 23$ mrad. (3) The light source is chopped so that the instrument is not sensitive to direct background light. Thus, the instrument can be used outdoors in direct sunlight without affecting the reflectance readings. (4) A viewing eyepiece is installed in the instrument so that an image of the reflected beam can be viewed directly.

This reflectometer uses a light emitting diode (LED) as the light source. The measurement spectrum is thus limited to a narrow 50 nm wide band centered at 660 nm. While this obviously precludes measurement of the solar averaged cumulative reflectance, it does reduce the errors associated with the wavelength dependent scattering caused by dust accumulation. For the 10 month sample data shown in Fig. 3, the D&S reflectometer will measure a cumulative reflectance loss only 5% higher than the true solar averaged loss. Thus a solar average cumulative reflectance loss of 0.100 reflectance units will be measured as 0.105 with this instrument.

After a 15-minute warmup period, this reflectometer performs as well as the Sandia instrument. However, because the measurement optics are completely enclosed, the instrument is not capable of the direct specular transmittance measurements that are possible with the Sandia portable reflectometer.

4.0 Recommended Measurement Procedure

The currently available portable specular reflectometers cannot directly provide a value for the solar averaged cumulative reflectance, $R'_S(\theta)$. Therefore, two procedures are recommended for obtaining a reasonable estimate for $R'_S(\theta)$ using the existing portable instrumentation described above.

It should be reemphasized that, for clean silvered glass mirrors, the solar averaged hemispherical reflectance, $R_S(2\pi)$, is always equal to the solar averaged cumulative reflectance, $R'_S(\theta)$, for $\theta \geq 2$ mrad. Therefore, a portable hemispherical solar reflectometer can be used to determine the solar averaged cumulative reflectance properties of a silvered glass mirror before any outdoor exposure. After outdoor exposure, a portable specular reflectometer can be used to determine the effect of dust accumulation following one of the procedures outlined below.

4.1 Procedure I

The easiest and most straightforward procedure for determining the solar averaged cumulative reflectance involves first measuring the solar averaged cumulative reflectance using laboratory instrumentation on a small sample of the mirror material of interest. Details for obtaining a value of $R'_S(\theta)$ in the laboratory are outlined in the Appendix. Next, the cumulative reflectance value, $R(\text{port})$, is measured for the same small sample using a portable specular reflectometer. These two values are used to generate a correction factor, C , given by

$$C = \frac{R'_S(\theta)}{R(\text{port})} \quad (3)$$

Multiplication of $R(\text{port})$ by C results in the value $R'_S(\theta)$. Thus, subsequent measurements of the same material using the portable specular reflectometer can be converted to a solar averaged values by multiplication using the constant C .

For this calculational procedure to remain valid as the sample ages, the assumption is made that any changes in the cumulative reflectance properties over the wavelength band of the portable reflectometer, occur equally across the entire solar spectrum. For dust accumulation, this is not usually the case, as shown in Fig. 3. However, for the D&S specular reflectometer, the above procedure leads to errors less than +0.01 reflectance units for losses up to 0.20. For the Sandia portable specular reflectometer, the maximum error is +0.04 reflectance units for losses up to 0.20. For other changes in the cumulative reflectance properties, the resulting measurement errors may be unknown.

4.2 Procedure II

The alternate procedure utilizes hemispherical reflectance measurements obtained using the D&S portable hemispherical reflectometer (SSR). This procedure can be used when a laboratory measurement of $R'_S(\theta)$ for the same material is not available. In this procedure, a value of $R_S(2\pi)$ is first obtained using the D&S SSR. Next the hemispherical reflectance is measured using only the RED detector/filter combination of the SSR (see Fig. 1) to obtain a value $R_{RED}(2\pi)$. Note that the wavelength response of this detector/filter peaks at 660 nm, which is the same as the peak wavelength of the D&S portable specular reflectometer. By comparing $R_{RED}(2\pi)$ with the reflectance value measured with the D&S portable specular reflectometer, $R_{port}(\theta)$, the relative amount of scattered radiation, ΔR , in the wavelength region near 660 nm can be calculated as

$$\Delta R = \frac{R_{RED}(2\pi) - R_{port}(\theta)}{R_{RED}(2\pi)} \quad (4)$$

By reducing $R_S(2\pi)$ by the same fractional amount ΔR , a reasonable estimate of the solar average cumulative reflectance can be obtained. Thus,

$$\begin{aligned}
 R'_S(\theta) &= R_S(2\pi) - \Delta R \cdot R_S(2\pi) \\
 &= R_S(2\pi)(1 - \Delta R) \\
 &= R_S(2\pi) \cdot \frac{R_{\text{port}}(\theta)}{R_{\text{RED}}(2\pi)} \quad (5)
 \end{aligned}$$

Again, this value is subject to similar assumptions as in the first procedure.

6.0 Future Developments

Clearly, a portable specular reflectometer is needed which can provide a solar averaged cumulative reflectance value from a single measurement. The development of such an instrument must overcome several potential problems. First, the instrument measurement spectrum must match a solar spectral distribution. While xenon lamps filtered to remove the large intensity peaks near 1000 nm may approximate this distribution, they are usually large, require substantial electrical power, and their output is not stable with time. Secondly, the focal characteristics of currently used glass lenses change with wavelength. This leads to variations in the effective size of the measurement angular aperture with wavelength that may not be acceptable. Therefore, more expensive reflecting optics may have to be utilized in the future. Finally, there are very few detectors available that are sensitive across the entire solar spectrum (roughly 300 to 2000 nm). Acceptable detectors would include thermopiles and pyroelectric devices. The use of several detector/filter combinations, as in the D&S SSR instrument, is complicated by the fact that each detector must view the same measurement angular aperture. Several detector/filter combinations may also substantially increase the size, weight and power requirements of the instrument. Therefore, before an improved reflectometer is considered, the

needs of the solar program and the limitations imposed by the presently available portable instrumentation and approximate measurement procedures should be carefully weighed.

7.0 Conclusions

Portable reflectometers are available for obtaining either hemispherical or specular reflectance information. In the case of hemispherical reflectometers, the instrumentation can provide accurate values for the solar averaged hemispherical reflectance, $R_s(2\pi)$, if properly corrected. However, portable instrumentation is currently not available that can measure the solar averaged cumulative reflectance directly. A realistic estimation of this quantity can be obtained using one of two proposed measurement procedures. One procedure relies on previous measurements of the solar averaged cumulative reflectance using laboratory equipment. Alternatively, a measurement of both the hemispherical and specular reflectance values over the same wavelength region using the available portable instrumentation can be combined to estimate the solar averaged cumulative reflectance as described in the text.

For monitoring the effect of dust accumulation on the cumulative reflectance of solar mirror materials, the Devices and Services portable specular reflectometer introduces less error in determining the solar averaged cumulative reflectance loss than the Sandia designed portable instrument. This results from the different wavelength measurement regions of the two instruments. Clearly, an understanding of the operational characteristics and limitations of the available portable specular reflectometers is essential to using and interpreting their measured reflectance values correctly.

8.0 Appendix

The purpose of this appendix is to discuss the determination of the solar averaged cumulative reflectance using laboratory instrumentation. The solar averaged cumulative reflectance properties can be adequately described by the equation

$$R'_S(\theta) = R_S \left[1 - \exp\left(\frac{-\theta^2}{2\sigma_S^2}\right) \right] \quad (1a)$$

This is identical to equation (2) except that R_0 and σ_0 have been replaced by their solar averaged values.

Currently, laboratory instruments that can measure the specular reflectance characteristics of solar mirrors are limited to measurements at a single wavelength (usually because they use a laser source^{11,12}) or are limited to providing measurements at only discrete wavelengths. Therefore these data must be "averaged" in order to determine suitable values for R_S and σ_S in equation (1a). Instead of obtaining cumulative reflectance data at a variety of wavelengths, the following procedure has been used.

First the cumulative reflectance $R'(\theta)$ is measured at one wavelength, typically near 500 nm (the peak of the solar spectrum) as a function of θ . The resulting curve is fit with the expression in equation (2) to determine R_0 and σ_0 . The value of R_0 is not set equal to the hemispherical reflectance value, $R_\lambda(2\pi)$, measured at the same wavelength. The value determined for R_0 should be less than or equal to $R_\lambda(2\pi)$. Note that the cumulative reflectance results are fit with a single normal distribution. This is done here even though earlier work has shown that, for some materials, a better fit can be obtained using the sum of two normal distributions.⁶ The use of two distributions results in determining two sets of values (R_1, σ_1) and (R_2, σ_2). If the cumulative reflectance data do not closely match a single

distribution, then an alternative procedure must be used. However, if the reflectance data approximate a single distribution, the assumption is then made that σ_0 does not change appreciably with wavelength so that $\sigma_s \approx \sigma_0$.

This assumption can be easily checked by measuring $R'(\theta)$ at another wavelength, calculating R'_0 and σ'_0 , and comparing σ_0 to σ'_0 . Significant differences between the σ values mean that alternative averaging procedures need to be considered on an individual material-by-material basis.

If $\sigma_0 \approx \sigma'_0$ (which is usually the case⁶), then the value R_0 should be compared to the hemispherical reflectance value, $R_\lambda(2\pi)$, at the same wavelength. If $R_0 \approx R_\lambda(2\pi)$, the specular and hemispherical reflectance values are equivalent, and $R'_s(\theta)$ is given by setting $R_s = R_s(2\pi)$ and $\sigma_s = \sigma_0$ in equation (1a).

If $R_0 < R_\lambda(2\pi)$, the amount of scattering $\Delta R_\lambda = R_\lambda(2\pi) - R_0$ is calculated. The wavelength dependence of ΔR_λ has been found to be the same as the wavelength dependence of the diffuse reflectance.¹ (The diffuse reflectance is defined as the amount of reflected radiation that is outside a specified cone angle that is centered in the specular direction. The diffuse reflectance is measured using an integrating sphere as discussed in Ref. 9.) Thus a solar averaged value for ΔR can be calculated using the solar averaged diffuse reflectance, $R_s(\text{diffuse})$, and the diffuse reflectance value, $R_\lambda(\text{diffuse})$, measured at the same wavelength as ΔR_λ using the following equation:

$$\Delta R_s = \Delta R_\lambda \cdot \frac{R_s(\text{diffuse})}{R_\lambda(\text{diffuse})} \quad (2a)$$

Finally, $R'_s(\theta)$ is determined by setting

$$\begin{aligned} R_s &= R_s(2\pi) - \Delta R_s \\ \sigma_s &= \sigma_0 \end{aligned} \quad (3a)$$

in equation (1a).

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