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Comparison of Techniques for *In Situ* Nondamaging Measurement of Solar Reflectances of Low-Slope Roof Membranes[1]

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With the implementation of the Energy Star Roof Products Program by the U.S. Environmental Protection Agency and the U.S. Department of Energy, techniques are especially needed that yield *in situ* measurements of the average solar reflectance of roof surfaces without damage to them. This paper presents results of limited field surveys with two types of instruments that permit such measurements. Solar reflectances on a scale from 0 to 1 were obtained by the established laboratory technique for five samples covering the range exhibited by low-slope roofs and coating systems for them. Based on these results, the average bias for one instrument, a portable solar spectrum reflectometer using a built-in light source, was $+0.003$. The maximum bias for the five samples was ± 0.02. Scatter of readings over a roof area with this instrument depends upon characteristics of the specific surface. Scatter can be as little as ± 0.001 but is typically more than ± 0.02. The other instrument uses a pyranometer and is operated by recording the responses when the pyranometer faces the sun and when it is inverted facing the surface of interest. The reflectance is the ratio of the response when inverted to the response facing the sun. For a variety of roof surfaces, the average of readings with both instruments agreed within 95% confidence intervals of ± 0.02 to ± 0.06, calculated as $\pm t \cdot$s.d., where t is the t-statistic for the number of measurements and s.d. is the measurement standard deviation.

KEY WORDS: field measurements; *in situ*; low-slope roofs; pyranometer; reflectometer; solar reflectance.

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1. INTRODUCTION

The reflectance of the surface of a roof over the spectrum of incident solar radiation is the primary parameter affecting peak roof surface temperatures. Peak roof surface temperatures, in turn, are of special interest in determining peak cooling loads for commercial buildings under low-slope roofs. Limiting peak roof surface temperatures is a practical way to reduce the peak load and overall energy demand by the building. Limiting peak roof surface temperatures could also contribute to extending roof service life.

Our interest in this paper is in comparing techniques for measuring the solar spectrum reflectance of roof surfaces in the field. Reflectance has been proved to be strongly dependent on the nature of the roof surface [1–3]. Uncoated asphalt-based roof surfaces typically reflect less than 10% of incident solar radiation. Roof surfaces freshly coated with white roof coatings or clean white roof membranes reflect up to 85% of incident solar radiation. Other roof surfaces, including white ones in less than clean condition, have reflectance values that lie between these limits.

The solar reflectance of a weathered roof surface is strongly dependent on the condition of the surface. Techniques are needed that yield *in situ* measurements of the average solar reflectance of roof surfaces without damage to them. Our interest in such techniques has been increased by the recent development of the Energy Star Roof Products Program for reflective roofs by the U.S. Environmental Protection Agency and the U.S. Department of Energy. The Energy Star label is to be earned by a low-slope roof surface if its initial solar reflectance exceeds 0.65 on a scale from 0 to 1 and its solar reflectance is higher than 0.50 after 3 years [4]. The 3-year requirement creates a challenging expectation: certification that large areas of roofs are meeting the prescribed performance criterion despite being subjected to weathering conditions in various locations. A mature Energy Star Roof Products Program, with many participants in many locations, argues strongly for nondamaging techniques, that is, ones which do not require cutting samples out of the roofs and sending them to a laboratory for evaluation of solar reflectance.

This paper presents the results of efforts to determine the suitability of two types of instruments for *in situ* nondamaging reflectance measurements. Both instruments are commercially available. The accuracy of and typical scatter in measurements are established for one of the instruments using small coupons to permit comparisons with the established laboratory technique. The field instruments are compared for samples of non-weathered roof membranes in a laboratory situation. Results from limited field surveys with the two types of instruments are presented over the range of solar reflectance encountered on real roofs.

2. THE PORTABLE SOLAR SPECTRUM REFLECTOMETER

The current version of the commercially available portable solar spectrum reflectometer (SSR) has undergone extensive development and testing by its manufacturer [5]. The SSR measures the radiation reflected by a test surface at an angle of 20° from the normal to the surface. A tungsten–halogen lamp inside its measurement head, which is painted with highly reflecting barium sulfate, diffusely illuminates the surface. The surface is placed against a 2.5-cm-diameter opening in the measurement head. By reciprocity relations among reflectances, the instrument yields the total hemispherical reflectance for beam radiation incident at a 20° angle from the normal to the surface.

A solar spectrum measurement is achieved by using four detectors that cover overlapping wavelength intervals in the range from 300 to 2500 nm. Figure 1 shows relative detector responses as a function of wavelength. The detectors are labeled ultraviolet (UV), blue, red, and infrared (IR) to

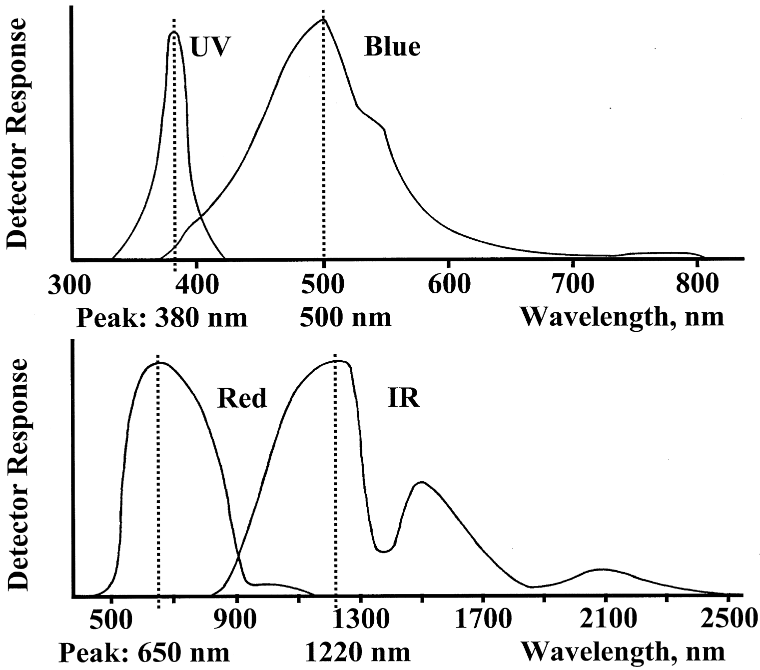

Fig. 1. Relative response of the detectors in the portable solar spectrum reflectometer.

characterize the part of the solar spectrum in which each one's peak response is obtained. The wavelengths at which the peak responses occur are given along the horizontal axis in Fig. 1. Silicon photovoltaic detectors are used for the UV, blue, and red detectors. A lead sulfide cell is used for the IR detector. Filters, numbering 12 in the UV, 56 in the blue, 28 in the red, and 17 in the IR, selectively block light from the tungsten–halogen lamp to approximate the complicated wavelength dependence of solar radiation received at the Earth's surface.

Figure 2 is an example for the incident solar radiation through a path comprising twice the air mass for normal solar radiation at the Earth's equator, the so-called air mass 2 (AM2) solar spectrum. Similar examples could be shown for any air mass value of interest. The air mass 2 solar spectrum is compared to the air mass 2 measurement spectrum in the SSR. For the measurement spectrum, the best linear combination of spectra from the four filtered detectors is determined by matching the solar spectrum in the five wavelength intervals $\Delta\lambda$ shown in Fig. 2. The method of least squares determines the multipliers to use for each detector's response. Firmware in the instrument's microprocessor-based electronics module holds the multipliers for AM2, AM1.5, AM1, and AM0 integrated reflectances.

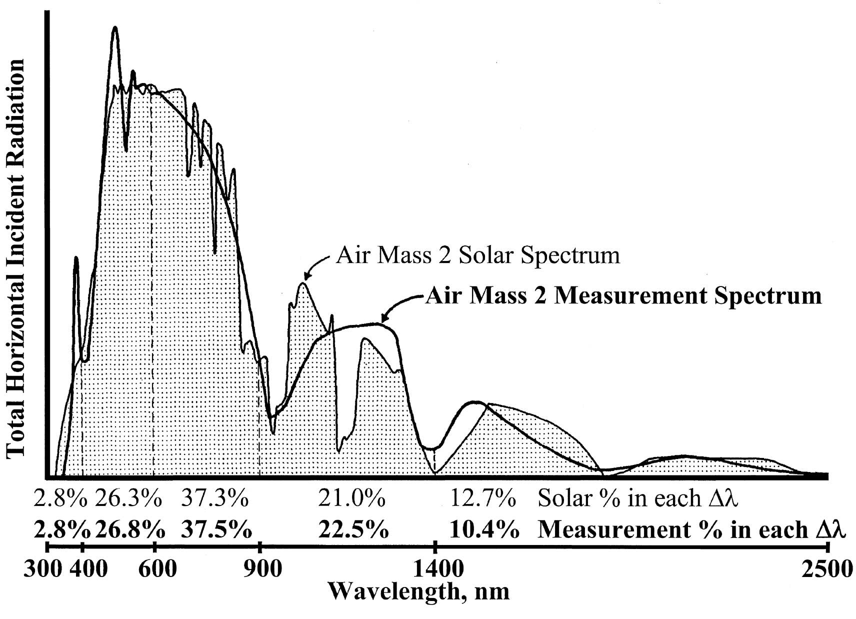

Fig. 2. Comparison of the air mass 2 solar spectrum and the air mass 2 measurement spectrum with the portable solar spectrum reflectometer.

The angular distribution of incident radiation is compensated in the instrument's configuration by minimizing the error electronically for a diffuse surface and for a specular surface. The estimated error for real surfaces, which have both diffuse and specular characteristics, is typically less than 2% of the reflectance value. The worst case of backscatter yielded an error of less than 3%, or a bias error of less than 0.024 for a reflectance of 0.800.

A silicon cell controls the lamp output so as to yield a constant intensity on the internal walls of the measurement head. The effect of reflected light from a sample being reflected back to the sample was measured during instrument development for a highly reflecting surface relative to a zero reflectance surface. If a surface has low reflectance in the range of the silicon cell's sensitivity and high reflectance at short wavelengths, so that the overall reflectance is 0.296, the instrument indicates 0.272 for this worst case. For most surfaces, the actual error is a small fraction of this maximum -0.024 bias error.

As Fig. 1 shows, the IR detector does not respond to infrared radiation at wavelengths greater than 2500 nm. Infrared radiation emitted by a black surface at 80°C, the maximum temperature we have observed for uncoated surfaces in full sunlight, peaks at 8200 nm [6]. Therefore, in this study, effects of radiation emitted by *in situ* test surfaces are negligible in measurements of solar reflectance with the SSR.

To document the accuracy of the SSR on low-slope roof membranes, two U.S. national laboratories undertook a collaborative effort. It was done independently of any effort by the manufacturer during development of the SSR. Five samples, approximately 5.1 cm square, were prepared from 22.9-cm-square specimens. They included uncoated modified bitumen and pieces of the modified bitumen coated with an aluminized asphalt emulsion, an aluminum emulsion, a fibrated aluminum coating, and a white latex coating. These samples cover the range from poorly reflecting to highly reflecting surfaces typical for uncoated and coated low-slope roofs. The size of the samples was sufficient to provide uniform 2.5-cm-diameter circles on each surface for analysis by the instruments used in the collaborative effort.

One laboratory measured reflectance for each sample from 250 to 2500 nm with a scanning spectrophotometer. The reflectance at each wavelength and the average over the spectrum were determined by comparison to the AM2 solar spectrum [7]. The measurement and analysis techniques meet the criteria set forth in ASTM E903-96 [8].

The other laboratory measured AM2 solar spectrum reflectances with the portable instrument before and after the samples were evaluated with the scanning spectrophotometer. The portable solar spectrum reflectometer is designed expressly to give the integrated reflectance over AM2, AM1.5, AM1, or AM0 solar spectra. However, the output reflectance from each detector can be displayed. The reflectance from each of the four detectors for each of the five samples in the interlaboratory collaborative effort was assigned to the wavelength in Fig. 1 at which each detector is most sensitive. These 20 values are superimposed on the spectral reflectances from the scanning spectrophotometer in Fig. 3. The figure shows that the individual detectors in the SSR are able to provide some spectral resolution in very good agreement with the detailed spectra.

Having only four detectors does not give enough resolution, however, to show output for the decreasing reflectances of the aluminized asphalt emulsion and the white latex surfaces as the wavelength increases. As Fig. 2 shows, however, this part of the solar spectrum is included in the integrated reflectance reported by the instrument. Table I proves this assertion by presenting the AM2 solar spectrum reflectance values for all the samples in the collaborative effort. AM2 values were measured with the portable solar spectrum reflectometer before and after the E903 average was determined from the spectra for each sample. ASTM E903 states that the precision of the scanning spectrophotometer method (as indicated by the repeatability of measurements by the method) is typically ± 0.005 [8]. Bias for the scanning spectrophotometer is not able to be specified because it depends on the individual apparatus and care with which the measurement is done. Based on the high quality of the apparatus and the years of experience of

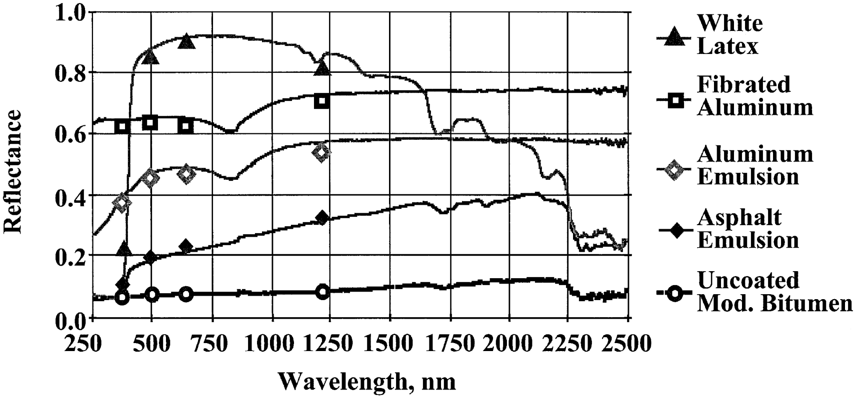

Fig. 3. Comparison of wavelength-dependent results from the scanning spectrophotometer and from individual detectors in the portable solar spectrum reflectometer.

Table I. Solar Reflectances for the Air Mass 2 Integrated Solar Spectrum with the Scanning Spectrophotometer (E903) vs the Portable Solar Spectrum Reflectometer (SSR): Difference $= SSR_{avg} - E903$

Sample description	SSR before	E903	SSR after	Difference
White latex	0.844	0.822	0.842	+0.021
Fibrated aluminum	0.659	0.657	0.650	−0.003
Aluminum emulsion	0.472	0.493	0.478	−0.018
Asphalt emulsion	0.259	0.239	0.246	+0.013
Uncoated modified bitumen	0.077	0.076	0.076	+0.001
Average				+0.003

the personnel operating it for this collaborative effort, the scanning spectrophotometer values are accepted as the true measure of the reflectance of each sample.

The average was taken of the measurements with the SSR before and after the E903 procedure. The difference between this average and the results of the E903 procedure is given for each sample in the last column in Table I. The average difference for the five samples is +0.003, which is within the expected drift of the SSR during 30 min of operation after warmup. The fully warmed-up SSR, when used on a uniform reflectance surface, such as a clean roof membrane or a freshly coated membrane, shows scatter in readings as small as ±0.001. In the last column in Table I, there is a difference of +0.02 for the white latex and -0.02 for the aluminum emulsion. These values are interpreted to mean that ±0.02 is a conservative estimate of the bias in the measurement of the solar reflectance of an individual sample with the portable solar spectrum reflectometer. This estimate is consistent with the worst case uncertainty of 0.024 claimed by the manufacturer.

3. *IN SITU* NONDAMAGING REFLECTANCE MEASUREMENT

Two techniques are available for *in situ* nondamaging measurement of solar reflectances of low-slope roof membranes. One involves the portable solar spectrum reflectometer used in the collaborative effort described above. The instrument needs to warm up for about 30 min. It then can be automatically calibrated in about 30 s for zero reflectance with a blackbody cover and in another 30 s for high reflectance with a ceramic-surfaced reference sample.

The tungsten–halogen light source in the measurement head of the SSR means that it does not need sunlight to illuminate the test surface. The position of the measurement head has no effect on the accuracy of the instrument as long as the opening of the measurement head is firmly against the surface of interest. The measurement head and console are not watertight, so dry conditions are required to use the SSR outdoors. Water or snow on the roof would also affect the value of solar reflectance.

The opening on the measurement head has an area of 4.9 cm^2. Reflectance can be obtained for this area on a sample within 30 s by placing the measurement head over the area and allowing at least three 10-s cycles. This ensures that a stable reading has been obtained. Several spots can be sampled to obtain data from which an average over a large area can be calculated. The values are recorded manually on a data sheet with notes about the location and appearance of the sampling area.

The other technique for *in situ* nondamaging measurement of solar reflectance uses a pyranometer. A pyranometer measures the total solar radiant energy incident upon a surface per unit time and unit surface area. This pyranometer-based technique is addressed in ASTM E1918-97 [9].

The technique consists of taking readings from the pyranometer in its normal orientation, facing the sun, and in an inverted position, facing the surface whose reflectance is to be determined. Full sun is needed to ensure that the incident solar radiation is the same in both the normal and the inverted positions. During partly cloudy conditions, care must be taken to ensure that reflection off clouds does not affect either reading. No fewer than three pairs of measurements should be performed within 2 min [9]. Under proper conditions, the reflectance is simply the ratio of the inverted and normal readings and the three pairs of measurements will agree within a reflectance of ± 0.01 on a scale of 0 to 1. This is taken to be an estimate of the method's precision.

A pyranometer is normally calibrated facing upward with a transparent dome over the receiver. The ASTM standard test method recommends a double-dome design to minimize effects of internal convection resulting from solar heating of the receiver surface [9]. In particular, for a low-slope roof, the pyranometer faces up, then down, which maximizes the internal convection effects. In this paper, we used a commercially available apparatus to apply the inverted pyranometer technique. It had a single-dome pyranometer and is designated SD in the results that follow. We also used a prototype apparatus that had a double-dome pyranometer. It is designated DD in the results that follow.

The SD instrument used a Kipp and Zonen model CM3 pyranometer with an unchanging high sensitivity from 305 to 2800 nm. Response dropped off rapidly to near-zero outside this wavelength range. The DD instrument used an Eppley PSP pyranometer with a pair of precision ground and polished hemispherical domes that transmit over 90% of solar radiation from 340 to 2000 nm and much less outside this range. Note that the sensitivity range of the pyranometers in the SD and DD instruments does not approach 8200 nm. This is the wavelength estimated above as the minimum at which peak radiation is emitted by surfaces heated by the sun. Thus, the inverted pyranometers are not sensitive to effects of radiation emitted by *in situ* test surfaces or surfaces surrounding them. Only reflected sunlight is sensed in the inverted position.

Both pyranometers use a thermopile sensor coated with a black absorbent coating to absorb the global (direct and diffuse) or reflected solar radiation incident upon them. A thermopile generates a voltage in response to the heat absorbed. A pyranometer needs no external power supply. A dc voltmeter is needed to display the voltage output or, after multiplication by the calibration constant, the radiation intensity in $W \cdot m^{-2}$.

When the solar altitude is low enough, the shadow cast by the pyranometer and its support arm will be in the fringe of the field of the pyranometer's view when it is inverted. Conversely, the solar altitude must be high enough to get a good response in both the normal and the inverted positions. The ASTM procedure recommends a solar altitude of less than 45° for application of the technique on horizontal or low-slope roofs [9]. Lapujade [10] recommends $45 \pm 3°$. Both recommendations seem too restrictive in light of Lapujade's data for measured reflectance with a double-dome pyranometer 0.50 m above a horizontal white roof (reflectance of 0.60) as a function of solar altitude. Measured reflectance is 0.60 at 35°, decreasing monotonically to 0.59 at 55°. Data for a horizontal gray gravel roof (reflectance of 0.16) show that a solar altitude from 35 to 85° allows measured reflectances between 0.155 and 0.16.

Lapujade [10] presents and discusses estimates of error for many of the other parameters affecting the accuracy and precision of the inverted pyranometer technique. He used the prototype double-dome apparatus for this work. He did not investigate the effect of reducing the height between the detector and the roof surface. The effect of reducing the height between the detector and the roof surface was of special interest to us in an ongoing outdoor laboratory project with 1.2 m wide strips of different roof membranes.

To extend Lapujade's work, Table II shows the results of our efforts to compare reflectances with the portable solar spectrum reflectometer and a single-dome pyranometer using the inverted pyranometer technique. Three 1.2×1.2-m pieces of single-ply roof membrane were cut from rolls of material and cleaned with detergent and a brush. Sixteen equally spaced

Table II. Average Solar Reflectances ± Standard Deviation with the Portable Solar Spectrum Reflectometer (SSR) and Apparent Solar Reflectances with the Single-Dome Pyranometer (SD) at Various Heights Above a 1.2 × 1.2-m Test Surface

Sample description	SSR (avg ± s.d.)	SD				
		0.50 m	0.41 m	0.36 m	0.25 m	0.20 m
BlackEPDM	0.078 ± 0.009	0.10	0.12	0.10	0.09	0.06
GrayPVC	0.359 ± 0.002	0.31	0.33	0.34	0.35	0.35
WhitePVC	0.852 ± 0.001	0.74	0.77	0.78	0.81	0.80

locations on each specimen were surveyed with the SSR and the results shown in the first column of data in Table II. The measurement standard deviations are given, along with the averages of the respective sets of 16 reflectances. The standard deviations indicate that the test specimens had very uniform reflectances.

Five reflectances are then given for each specimen from the use of the inverted pyranometer technique with the specimens outdoors on an asphalt parking lot on a clear day in early October 1999 in Knoxville, Tennessee. The solar altitude was between 49 and 51° at the time of the measurements, well within the range for which Lapujade shows accurate measurements. The commercially available SD instrument has a tripod and the prototype DD instrument has a stand that hold their respective pyranometers 0.50 m above the surface. To achieve the lower heights in Table II, the single-dome instrument was held manually against its tripod.

For the low-reflectance, black EPDM surface on a surrounding low-reflectance, black asphalt surface, the inverted pyranometer yields constant reflectance for heights from 0.25 to 0.50 m. A value 0.03 lower is obtained when the pyranometer is only 0.20 m above the surface. No reason is apparent but the claim of ±0.01 precision with this method [9] seems optimistic for poor reflection off a black surface.

For the medium reflectance, gray PVC and the high reflectance, white PVC, the reflectances are constant at 0.34 ± 0.01 and 0.79 ± 0.02, respectively, for heights from 0.20 to 0.41 m. Values of 0.31 and 0.74, respectively, are obtained when the pyranometer is held 0.50 m above the surface. These apparent values are significantly lower than the actual 0.36 and 0.85 averages with the SSR and are attributed to the effect of the black asphalt surroundings. Corrections in Lapujade's report [10] yield a 0.65 ratio between apparent and actual reflectance because of the 1.2 × 1.2-m sample size on black surroundings. Using our apparent reflectances at 0.50 m above the surfaces, the actual reflectance would be estimated as 0.48 for the gray surface and over 1.00 for the white surface.

As the pyranometer is lowered toward the surface with the solar altitude fixed, the shadow from the pyranometer and support becomes a larger fraction of the pyranometer's view. It does not appear to affect measurements for the gray and white surfaces in Table II. A similar documentation of the effect of height is recommended for small test sections when apparent reflectances are affected by other surfaces with different reflectances or objects that cast shadows in the field of view of the pyranometer in the inverted position. The manufacturer of the SD instrument recommends an unobstructed view that has an 8-m diameter [11].

4. RESULTS OF FIELD MEASUREMENTS

Limited field measurements were performed on low-slope roofs to compare solar reflectances obtained with the commercially available portable solar spectrum reflectometer (SSR), the commercially available single-dome pyranometer (SD), and the prototype double-dome pyranometer (DD). Most measurements were done in mid-January 1999 in Tucson, Arizona, around noon during clear periods on scattered cloudy days. The solar altitude was 37 to 39°. One set of measurements on a white metal roof without shadows was done in early December 1998 in Cape Canaveral, Florida, around noon on a cloud-free day. The solar altitude was 38°. For all measurements, the tripod of the SD instrument and the stand for the DD instrument were used to hold their respective pyranometers 0.50 m above the roof surfaces. According to the recommendation of the manufacturer of the SD instrument, the surfaces were large enough for no edge effects.

Figure 4 compares the average solar reflectances determined by each technique. Nine surfaces are included, for which the portable solar spectrum reflectometer yielded from 9 to 18 different values for the reflectance over an approximately 1.2-m-radius circle in the center of the field of view of the inverted pyranometers. The height of each bar for the portable SSR corresponds to the average of the nine to eighteen values for each surface. The 95% confidence interval is given above each SSR bar. For a normal distribution about the average of nine measurements, the 95% confidence interval is $\pm 2.26 \cdot$ s.d., where 2.26 is the 95% confidence t-statistic for nine measurements and s.d. is the measurement standard deviation. For 18 measurements, the t-statistic is 2.10.

Before Fig. 4 is discussed in detail, Fig. 5 is presented to show how well the 95% confidence interval is given by $t \cdot$ s.d for two weathered roof

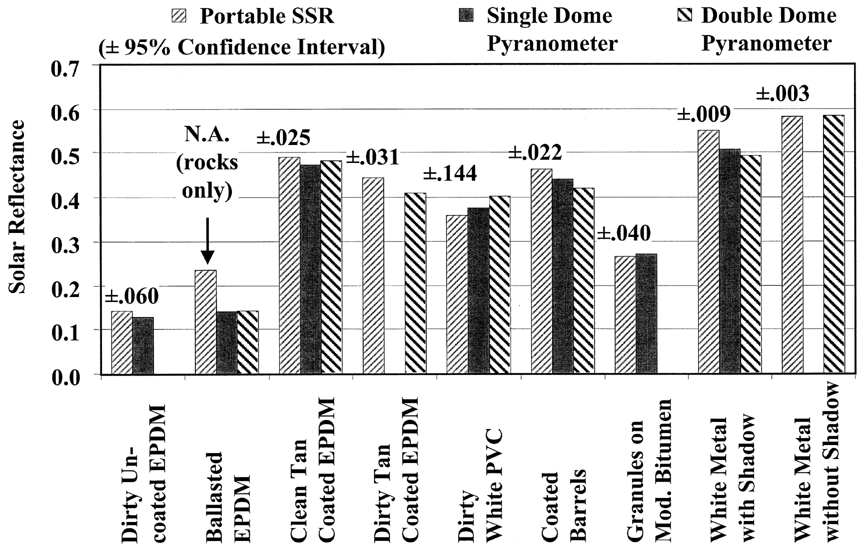

Fig. 4. Solar reflectances for various roof surfaces with a portable solar spectrum reflectometer (SSR), a single-dome pyranometer, and a double-dome pyranometer.

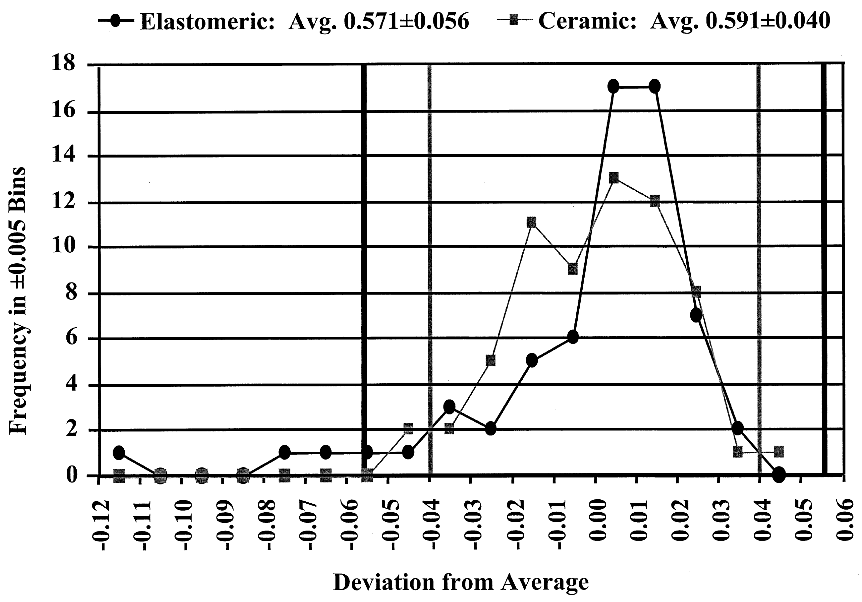

Fig. 5. Example distributions of reflectances about averages for weathered, white-coated, low-slope roof membranes to show the accuracy of 95% confidence intervals estimated by $\pm t \cdot$ s.d.

surfaces. Distributions are given of solar reflectances measured with the SSR at 64 locations equally spaced over two 1.2×1.2-m pieces of coated, modified bitumen, low-slope roof membrane. One piece was coated with an elastomeric white coating and the other with a ceramic white coating. Both were weathered for 2.6 years in the climate of East Tennessee.

The average reflectance and 95% confidence interval about it for each coating are listed in the legend to Fig. 5. The 95% confidence *t*-statistic for 64 measurements is 2.00. The limits of each interval are shown by two vertical lines for each distribution. The deviations of the solar reflectances from the average of each distribution were grouped in ± 0.005 bins. The number in each bin was assigned to the midpoint of the bin and was plotted against the deviation. For example, for the ceramic coating, 13 of 64 reflectances were between 0.00 and 0.01 above the average. Zeroes were filled in for the unpopulated bins for which populated bins existed below them.

For sixty-four measurements, 95% confidence means that three to four (exactly 3.2) measurements are expected to lie outside the confidence interval. Both of these distributions are slightly skewed toward values above the average. Forty-three reflectances for the elastomeric coating and 35 for the ceramic coating lie above the averages of the respective 64 measurements. The values that fall outside the confidence intervals do so mostly on the low side of the average. The distributions are not symmetric, bell-shaped distributions. Regardless, the estimate of confidence interval is accurate: only three measurements lie outside the confidence interval for each distribution.

In Fig. 4, for five of the nine cases, both the SD and the DD pyranometers were applied to generate values that should be the same as the average of reflectances with the portable SSR at 9 to 18 locations within the fields of view of the pyranometers. In the other four cases, one or the other of the pyranometers was not available. Only one of the nine cases shows poor agreement between the SSR and the inverted pyranometer techniques. For the ballasted ethylene propylene diene monomer (EPDM) roof, the SSR could be used only on the different-colored rocks comprising the ballast. Individual readings for the rocks varied from 0.08 to 0.37. There is little correspondence between the arithmetic average of 0.236 for the individual rocks, presented as the SSR bar, and the much lower pyranometer values. Consequently, no 95% confidence interval is claimed for the ballasted EPDM. The rocks were not equally distributed in color, nor does the SSR average take into account shaded crevices between the rocks. These crevices allow multiple reflections, increasing the chances that solar radiation will be absorbed and yielding an effective solar reflectance of the ballast that is lower than that of an "average" rock.

Shading not accounted by the SSR happens to a lesser extent for the coated barrels and the white metal roof with shadows. The coated barrels were curved pieces of concrete laid side by side to give a scalloped appearance to the roof line. They were coated with a tan coating. The pyranometers saw the joints between barrels. The effectively lower reflectance of these joints was not included in the slightly higher SSR average. The white metal roof with shadows had seams that cast shadows in the field of view of the pyranometers at the time of the measurements. Shadows have no effect on measurements with the SSR. Therefore, the average for the SSR is higher than the pyranometer measurements for this roof. The seams on the white metal roof without shadows were oriented so that they did not cast any shadows. Excellent agreement is noted in this case between the SSR average and the value with the DD pyranometer available for the comparison.

In all other cases in Fig. 4, the averages of the SSR reflectances agree with the respective measurements from either or both of the pyranometers within the 95% confidence interval for the SSR average. The 95% confidence interval generally ranges from ± 0.02 to ± 0.06 except for the dirty white PVC. To these levels of confidence, there does not appear to be any bias in the SSR relative to the pyranometers or in the SD pyranometer relative to the DD pyranometer. For the cases where the values yielded by the SSR and SD or DD are not equal, there are examples where the SSR yields higher values and others where the SSR yields lower values.

The roofs surveyed in Arizona (all roofs except the white metal roof without shadows) were generally dirty as a result of wind-blown soil fines. No attempt was made to clean the roofs prior to the measurements in Fig. 4. After completion of the measurements, one spot on three cleanable roofs was sprayed with a commercial cleaner and wiped off with paper toweling. For these three roofs a significant change was noted in reflectance relative to the SSR average in Fig. 4. The general guideline is that both black and white roofs get grayer as a result of weathering. For the EPDM, the cleaning decreased reflectance from 0.14 to 0.06. For the tan EPDM, cleaning increased the reflectance at the cleaned spot from 0.46 to 0.51. For the dirty white PVC, cleaning increased the reflectance from 0.36 to 0.81. Its large 95% confidence interval of ± 0.14 indicates that this surface was not uniformly dirty. To the eye, the dirty tan EPDM and the dirty white PVC roof colors were indistinguishable, but not to the detail seen by the SSR.

5. CONCLUSIONS

As a result of the effort we have made to compare the solar reflectances obtained with two methods for *in situ* nondamaging measurements, we make the following conclusions.

- A portable solar spectrum reflectometer, suitable for *in situ* nondamaging field measurements of reflectance on about 2.5-cm-diameter spots on roofs, gave results that agree within ± 0.02 on a reflectance scale from 0 to 1 with the laboratory ASTM E903 method employing a scanning spectrophotometer.
- Within the 95% confidence intervals about the averages of 9 to 18 measurements of reflectance at spots within the field of view of inverted pyranometers used according to ASTM E1918, the portable solar spectrum reflectometer and the inverted pyranometers give identical results. The confidence intervals are typically ± 0.02 to ± 0.06 on a reflectance scale from 0 to 1.
- Results from a commercially available device to use ASTM E1918 with a single-dome pyranometer and a prototype device with a double-dome pyranometer agreed within the confidence intervals obtained with the portable solar spectrum reflectometer.
- Cleaning a spot on a dirty roof and measuring the local reflectance at that spot with the portable solar spectrum reflectometer alone can give very different reflectances compared to taking an average over noncleaned spots with it or with the pyranometers.
- Unlike the portable solar spectrum reflectometer, the pyranometers are capable of measuring the reflectance of ballasted systems.

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