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Comparison of Techniques for In-Situ, Non-Damaging Measurement of Solar Reflectances of Low-Slope Roof Membranes

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Abstract

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, accuracy 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. The 95% confidence interval about the average is ±t·s.d., where t is the Student's t-statistic for the number of measurements and s.d. is the measurement standard deviation. Scatter can be as little as ±0.001. 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 expected 95% confidence intervals of ±0.02 to ±0.06.

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 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. 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[1,2].

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, for example, if its initial solar reflectance exceeds 0.65 on a scale from 0 to 1 and its solar reflectance is greater than 0.50 after three years[3]. The latter creates a challenging expectation: certification that large areas of roofs are meeting the prescribed performance criterion despite being subjected to various weathering conditions for three years. A mature Energy Star Roof Products Program, with many participants in many locations, argues strongly for non-damaging 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, non-damaging reflectance measurements. Both instruments are commercially available. The accuracy and typical scatter in measurements is 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 instruments are presented over the range of solar reflectance encountered on real roofs.

Accuracy of Portable Solar Spectrum Reflectometer

To document the accuracy of a commercially available portable solar spectrum reflectometer (SSR), two U.S. national laboratories undertook a collaborative effort. Five samples, approximately 5.1 cm (2 in.) square, were prepared from 22.9 cm (9 in.) 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 (1 in.) 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 nanometers with a scanning spectrophotometer. The reflectance at each wavelength and the average over the spectrum were determined by comparison to 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[4]. The measurement and analysis techniques meet the criteria set forth in ASTM E903-96[5].

The other laboratory measured the AM2 solar spectrum reflectance with the portable instrument before and after the samples were evaluated with the scanning spectrophotometer. The portable instrument has four individual detectors that cover the spectrum from 250 to 2500 nanometers with considerable overlap. Figure 1, from the instrument's operation manual, shows the relative response of the detectors over their respective parts of the solar spectrum. Firmware in the instrument weights the signals from the four detectors to produce the solar spectrum reflectance. AM2, AM1.5, AM1 and AM0 integrated reflectances are selectable for output and display by the instrument. The reflectances from the individual detectors are also available for output and display.

The portable solar spectrum reflectometer is designed expressly to give the integrated solar spectrum reflectance for the four different air masses. To display some comparative spectral information, the reflectance from each of the four detectors for each of the five samples can be assigned to the wavelength at which each detector is most sensitive. These 20 values are superimposed on the spectral reflectances from the scanning spectrophotometer in Figure 2. The figure shows that the individual detectors 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 detect the decreasing reflectances of the aluminized asphalt emulsion and the white latex surfaces as wavelength increases. For the average reflectance over the solar spectrum, behavior beyond 2000 nanometers is not very important. As Figure 3 illustrates, there is relatively little incoming solar radiation in this part of the spectrum. Table 1 proves this assertion by presenting the AM2 solar spectrum reflectance values for all the samples in the collaborative effort. The average was taken of the AM2 values with the portable solar spectrum reflectometer before and after the solar 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[5]. Bias is not able to be specified because it depends on the individual apparatus and care with which the measurement is done. For this collaborative effort, the scanning spectro-photometer 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 of the table. The average difference for the five samples is +0.003, which is within the expected drift of the SSR during 30 minutes of operation after warm-up. 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 of Table 1, the difference of +0.02 for the white latex and -0.02 for the aluminum emulsion is 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.

Techniques for In-Situ, Non-Damaging Reflectance Measurement

Two techniques are available for in-situ, non-damaging measurement of solar reflectance. One involves the portable solar spectrum reflectometer used in the collaborative effort described above. The SSR is taken onto the roof and an extension cord or battery-powered inverter is used to bring 110 volt AC to it. The instrument needs to warm up for about 30 minutes. It then can be automatically calibrated in about 30 seconds for zero reflectance with a blackbody cover and, in another 30 seconds, for high reflectance with a ceramic-surfaced reference sample.

Figure 4 shows a photograph of the SSR on a standing seam metal roof. The instrument has been taken out of its carrying case and power has been provided to the console, which contains the digital output meter and a keypad for selection of instrument functions. A high reflectance reference is in place on top of the measurement head in front of the console. The blackbody cover is between the measurement head and the console. The console and measurement head are connected by an electrical cable, 7.6 m (25 ft) long to permit measurements over a large area without moving the console.

The measurement head of the SSR contains a tungsten-filament halogen light source. 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 early morning shadows apparent in Figure 4 are no problem.

The opening on the measurement head is 2.5 cm (1 in.) in diameter. Reflectance can be obtained for this area on a sample within 30 seconds by placing the measurement head over the area and allowing at least three 10 second cycles to ensure that a stable reading has been obtained. Several areas can be sampled to obtain data from which an average over a large area is calculated. The values for each area are recorded manually on a data sheet with notes about the location and appearance of the sampling area.

The other technique for in-situ, non-damaging 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 by ASTM E1918-97[6]. Detailed discussion of the technique is in a research report by Lapujade[7].

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. The Sun must be low enough in order that the pyranometer does not see too much of its own shadow in the inverted position. The Sun must be high enough to get good response in both positions. Full sun is needed to ensure that the solar radiation is the same in both the normal and 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 two minutes[6]. 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.

The incident solar radiation causes a thermoelectric voltage to be generated without external power. A voltmeter is required to read the output. 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[6]. 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. Figure 5 is a photograph of its application on a dirty, white PVC, low-slope roof. The single-dome pyranometer is also in place on this roof and is unattended.

In Figure 5, solar altitude is low enough that the shadow cast by each pyranometer will be in the fringe of the field of its view when it is inverted. The ASTM procedure recommends a solar altitude of less than 45° for application of the technique on horizontal or low-slope roofs[6]. Lapujade[7] recommends 45°±3°. Both recommendations seem too restrictive in light of Lapujade's data for measured reflectance with a double-dome pyranometer 0.50 m (19.5 in.) 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 solar altitude from 35° to 85° allows measured reflectance between 0.155 and 0.16.

Lapujade[7] presents and discusses estimates of error for many of the parameters affecting the accuracy and precision of the inverted pyranometer technique. He used the prototype double-dome apparatus in Figure 5 for his work. He did not investigate the effect of reducing the height between the detector and roof surface. The effect of reducing the height between the detector and roof surface was of special interest to us in an ongoing outdoor laboratory project with 1.2 m (4 ft) wide strips of different roof membranes.

To extend Lapujade's work, Table 2 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 m by 1.2 m (4 ft by 4 ft) pieces of single-ply roof membrane were cut from rolls of material and cleaned with detergent and a brush. Sixteen equally spaced locations on each specimen were surveyed with the SSR and the results shown in the first column of data in Table 2. The measurement standard deviations are given along with the averages of the respective sixteen reflectances. The standard deviations indicate that the test specimens had very uniform reflectances.

Five reflectances are then given for each specimen from 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 tripod of the single-dome instrument and the stand of the prototype double-dome instrument are shown in Figure 5. They hold their respective pyranometers 0.50 m (19.5 in.) above the surface. To achieve the lower heights in Table 2, 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 m (10 in.) to 0.50 m (19.5 in.). A value 0.03 lower is obtained when the pyranometer is only 0.20 m (8 in.) above the surface. No reason is apparent but the claim of ±0.01 precision with this method[6] 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 m (8 in.) to 0.41 m (16 in.). Values of 0.31 and 0.74, respectively, are obtained when the pyranometer is held 0.50 m (19.5 in.) above the surface. These values are significantly lower than the 0.36 and 0.85 averages with the SSR and are attributed to the effect of the black asphalt surroundings. They are not as low as Lapujade's estimate for this situation. Corrections in his report yield a 0.65 ratio between apparent and actual reflectance because of the 1.2 m by 1.2 m (4 ft by 4 ft) sample size or an apparent reflectance of 0.23 for the gray surface and 0.54 for the white surface.

As the pyranometer is lowered toward the surface with 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 2. A similar documentation of the effect of height is recommended for other narrow test sections when use of the standard 0.50 m (19.5 in.) height yields unacceptable error.

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 near noon during clear time periods on scattered cloudy days. The solar altitude was 37° to 39°. One set of measurements was done in early December 1998 in Cape Canaveral, Florida near 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 (19.5 in.) above the roof surfaces. The surfaces were large enough for no edge effects.

Figure 6 compares the average solar reflectances determined by each technique. Nine different surfaces are included for which the portable solar spectrum reflectometer yielded from nine to eighteen different values for the reflectance over the approximately 1.2 m (4 ft) radius circle in the field of view of the inverted pyranometers. The height of each bar for the portable SSR corresponds to the SSR=s average reflectance for each surface. A 95% confidence interval is given above each SSR bar. For a normal distribution about the average of nine measurements, the 95% confidence interval is ∀2.26·s.d., where 2.26 is the 95% confidence Student=s t-statistic for nine measurements and s.d. is the measurement standard deviation. For eighteen measurements, the t-statistic is 2.10.

Before Figure 6 is discussed in detail, Figure 7 is presented to show how well the 95% confidence interval is given by ∀t·s.d for two weathered roof surfaces. Distributions are given of solar reflectances measured with the SSR at sixty-four locations equally spaced over two 1.2 by 1.2 m (4 by 4 ft) pieces of coated APP-modified bitumen. The 95% confidence Student=s t-statistic for sixty-four measurements is 2.00. One piece was coated with an elastomeric white coating and the other with a ceramic white coating. Both were weathered 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 of Figure 7. The limits of the intervals are also shown by two vertical lines for each distribution. The deviations from the average of each distribution were grouped in ±0.005 bins. The number in each bin was assigned to the mid-point of the bin and was plotted against the deviation. For example, for the ceramic coating, thirteen out of sixty-four reflectances were between 0.00 and 0.01 above the average. Zeroes were filled in for unpopulated bins in the range of deviations.

For sixty-four measurements, 95% confidence means 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 of the sixty-four reflectances for the elastomeric and thirty-five of sixty-four for the ceramic lie above the average. The values that fall outside the confidence intervals do so mostly on the low side of the average. Regardless, the estimate of confidence interval is accurate: only three measurements lie outside the confidence interval for each distribution.

In Figure 6, for five of the nine cases, both the SD and DD pyranometers were applied to generate values that compare to the average of reflectances with the portable SSR at nine to eighteen locations within the pyranometers' field of view. 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 only be used 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 in Arizona. 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 in

Arizona had seams that cast shadows in the field 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 in Florida were oriented so 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 Figure 6, 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 with the dirty white PVC showing an exceptionally high ±0.14. To these levels of confidence, there does not appear to be any bias in the SSR relative to the pyranometers nor 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 were generally dirty as a result of wind-blown soil fines. No attempt was made to clean the roofs prior to the measurements in Figure 6. 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 signficant change was noted in reflectance relative to the SSR average in Figure 6. 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 white PVC, cleaning increased 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.

Conclusions

As a result of the effort we have made to compare the solar reflectances obtained with two methods for in-situ, non-damaging measurements, we make the following conclusions:

- $ A portable solar spectrum reflectometer, suitable for in-situ, non-damaging field measurements of reflectance on about 2.5 cm (1 in.) diameter spots on a roof, 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.
- $ Confidence intervals about the average of multiple reflectance measurements on a roof surface with the portable solar spectrum reflectometer can be expressed by the product of the Student=s t-statistic for 95% confidence in the particular number of measurements and the measurement standard deviation about the average.
- $ Within the 95% confidence intervals about the averages of nine to eighteen 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 an average over non-cleaned 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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Tables

Table 1. Solar reflectances: results with scanning spectrophotometer for Air Mass 2 integrated solar spectrum (E903) vs. portable solar spectrum reflectometer (SSR). Difference = SSR_{avg} – E903

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

Table 2. Solar reflectances: average ± standard deviation with portable solar spectrum reflectometer (SSR) and average at various heights above 1.2 by 1.2 m test surface with single-dome pyranometer (SD)

Sample description	SSR avg ± s.d.	SD 0.50 m	SD 0.41 m	SD 0.36 m	SD 0.25 m	SD 0.20 m
Black EPDM	0.078 ± 0.009	0.10	0.12	0.10	0.09	0.06
Gray PVC	0.359 ± 0.002	0.31	0.33	0.34	0.35	0.35
White PVC	0.852 ± 0.001	0.74	0.77	0.78	0.81	0.80

Figure Captions

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

Figure 2. Comparison of results from individual detectors in the portable solar spectrum reflectometer and the scanning spectrophotometer.

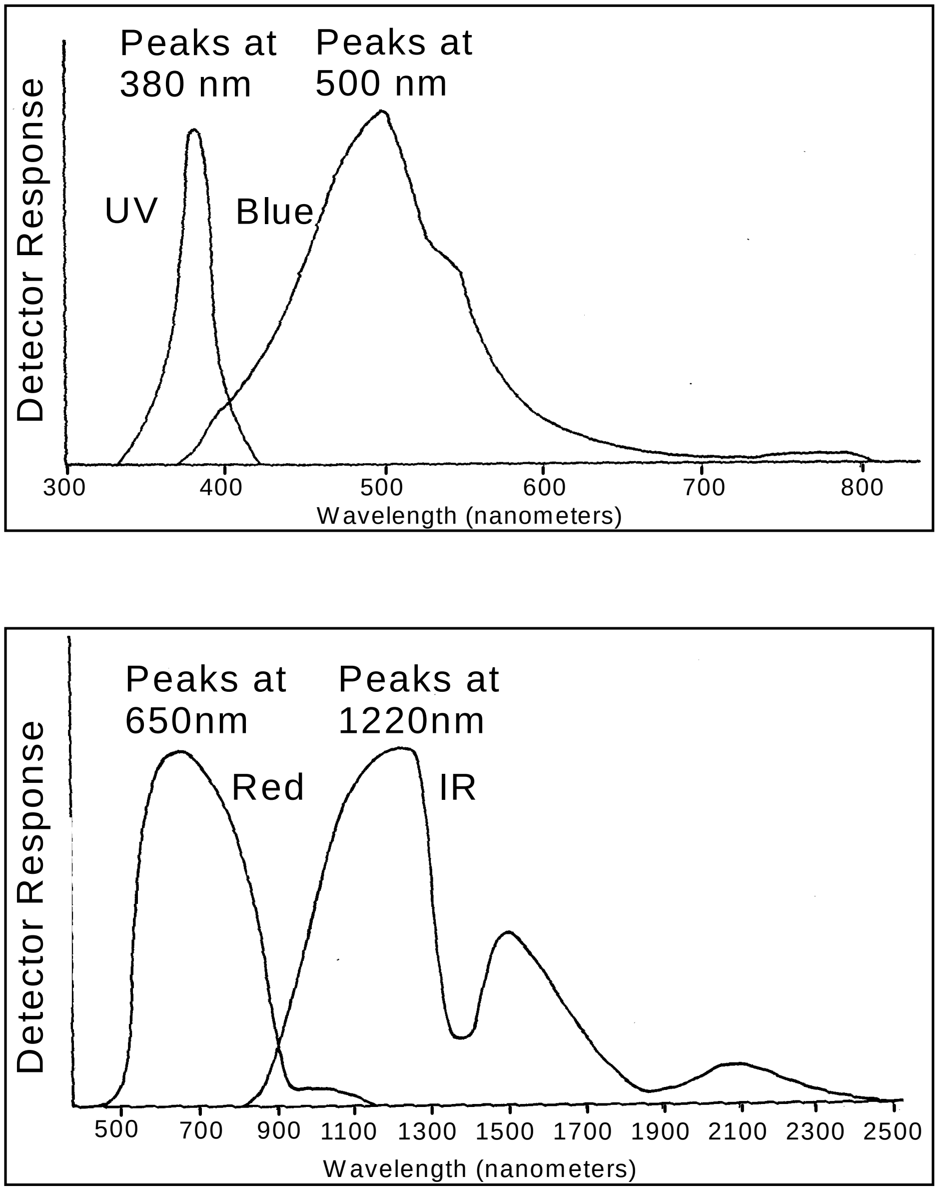
Figure 3. Relative amount of incoming solar radiation over the wavelength range from 200 to 2600 nanometers.

Figure 4. Portable solar spectrum reflectometer being prepared for in-situ, non-damaging measurement of solar reflectance for a standing seam metal roof.

Figure 5. Use of single-dome pyranometer and prototype double-dome pyranometer (with operator) for in-situ, non-damaging measurement of solar reflectance for a dirty, white PVC, low-slope roof.

Figure 6. Solar reflectances for various roof surfaces with a portable solar spectrum reflectometer (SSR), a single-dome (SD) pyranometer and a double-dome (DD) pyranometer.

Figure 7. Example distributions of reflectances about averages for weathered, white-coated, low-slope roof membranes to show accuracy of 95% confidence interval estimated by ∀t·s.d.



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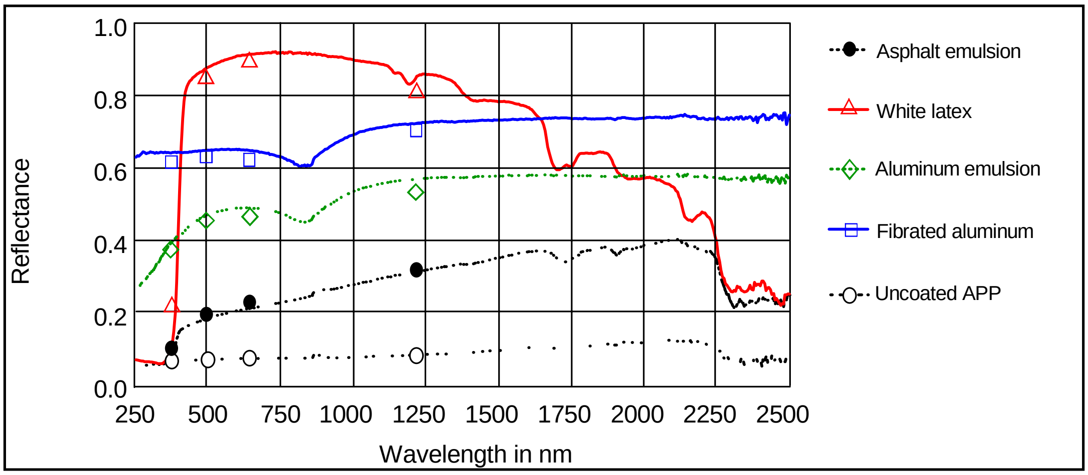
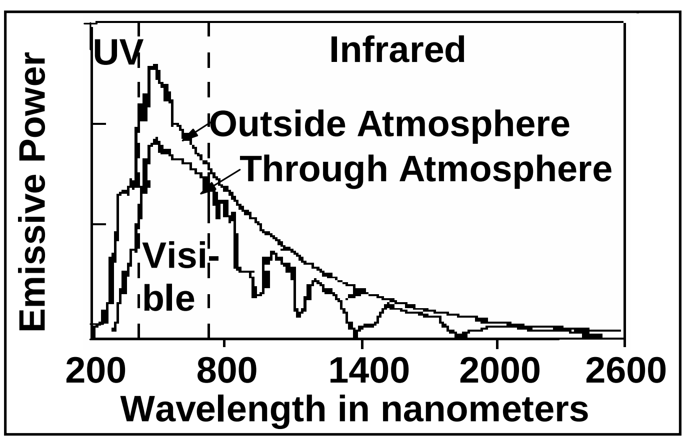


Figure 2. Comparison of results from individual detectors in the portable solar spectrum reflectometer and the scanning spectrophotometer.



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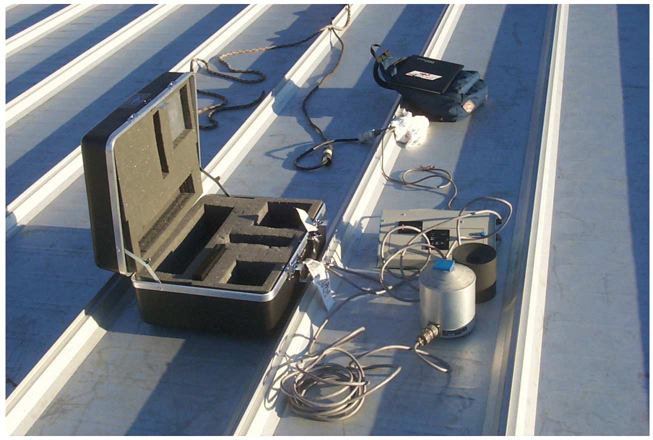

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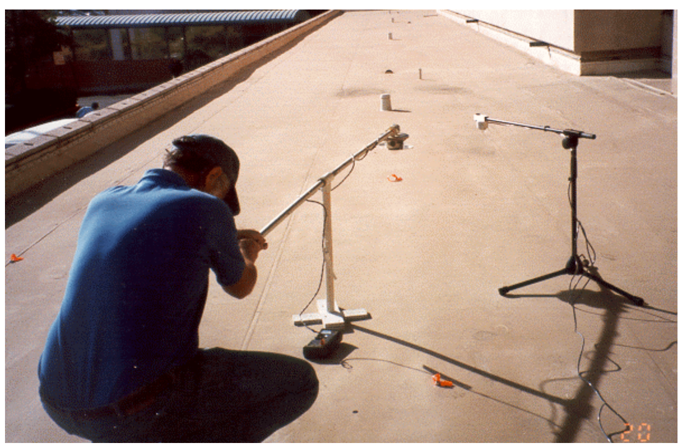

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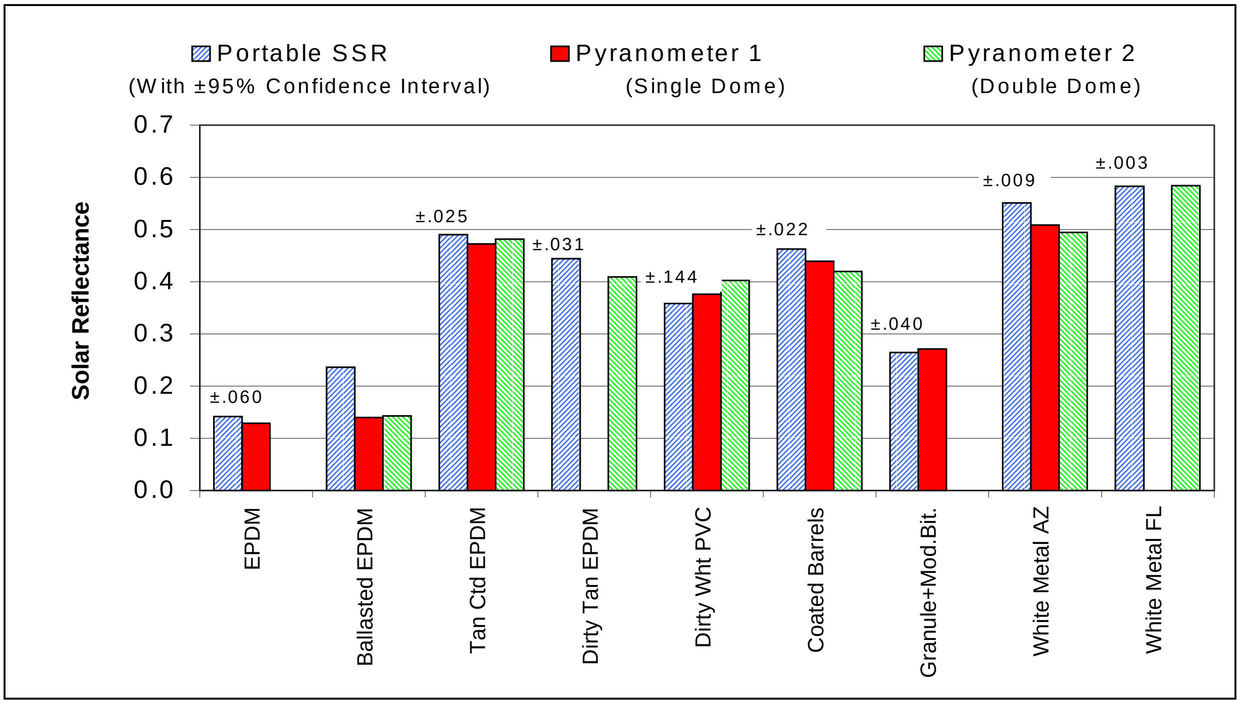

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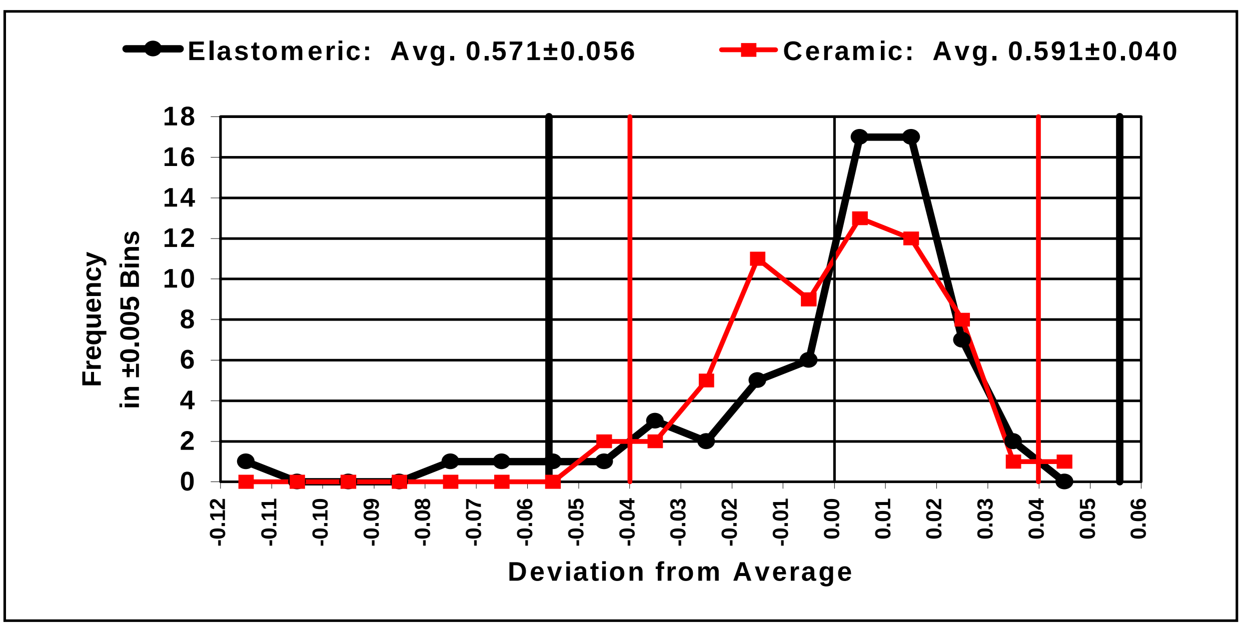

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