Devices & Services Company
10290 Monroe Drive, Suite 202 - Dallas, Texas 75229 USA - Tel. 214-902-8337 - Fax 214-902-8303
Web: www.devicesandservices.com – Email: sales@devicesandservices.com

D&S Technical Note 09-2

A Proposed Correction to Reflectance Measurements of Profiled Surfaces

Introduction

For a profiled surface such as clay roofing tiles or metal roofing, measurement of solar reflectance with the D&S Solar Spectrum Reflectometer (SSR) is limited to obtaining the property of the surface, as if it were flat, as opposed to the actual solar reflectance accounting for the surface geometry. Typically the actual or aggregate solar reflectance will be lower than the surface reflectance because some of the reflected energy will strike the surface a second (third, etc.) time. In practice, profiled surfaces for roofs do not have severe geometries and therefore the difference between the surface reflectance and the aggregate reflectance is expected to be small. If the difference is small and a correction can be estimated based on the geometry of the surface, the SSR surface reflectance measurement can be used to estimate the aggregate reflectance of a profiled surface.

Discussion

The original proposal to estimate a reflectance correction for profiled surfaces was to create miniature versions with features small enough that the aggregate reflectance could be measured with the SSR. Since the port size of the instrument is about 1 inch in diameter this means that the depth of the profiled surface should be "small" in comparison. Some recent work on reflectance of irregular surfaces (ref (1) D&S Technical Note 08-1) provides some guidance on the required scale of the miniature profiled surface. Figure 2 in the technical note is a graph of reflectance ratio versus surface displacement from the port. Even at 0.050 inches uniformly displaced from the port a diffusely reflecting surface will read at least 96% of its reflectance value as measured at the port. Therefore for a profiled surface that is around 0.050 inches in depth, the correction for displacement from the port is relatively small. Note that the intent of the correction described in the technical note is to obtain the aggregate reflectance of an irregular surface as opposed to the surface reflectance. The correction accounts only for the reduction in illumination of the surface due to displacement.

In order to create a profiled surface with a depth near this size, a paper crimping (corrugating) tool was obtained. The tool creates a corrugated pattern on paper or card stock that is similar to the typical extruded shapes for practical roofing materials. The first measurements were made with white and gray card stock both before and after running through the crimper. The card stock does not support a very deep profile however it was expected that the reflectance would be decreased slightly. The result however was that there was no decrease or even a slight increase in reflectance with the crimped card. Both the surface geometry and the displacement of portions of the surface from the port should result in a lower reflectance reading however no decrease was observed. It was determined that this odd behavior is due to the fact that the card stock is somewhat transparent. The reflectance of two thicknesses is slightly higher than one so that the reflectance of the material depends on thickness. When corrugated, the card stock appears thicker (i.e. more material present to reflect) and therefore the reflectance is increased just enough to offset the decrease due to geometry and displacement from the port. In a real application of a thin non-opaque reflective coating on a flat dark substrate it would make sense that the reflectance would initially increase slightly with increasing angle of incidence because the coating appears slightly thicker to beam incident radiation at off normal angles.

To avoid this problem, a sample of white painted aluminum foil was prepared for testing. The foil is similar in reflectance properties to the white paint so that although a thin coat of white paint is not opaque, the reflective backing of the aluminum foil produces nearly the same net reflectance as if the white coating were thick enough to be opaque. The foil also holds a deeper corrugated shape when run through the crimper and thus the change in reflectance should be larger.

It was also decided that it would not be practical to try to reproduce various miniature profile shapes for measurements. Therefore a “finite element” computer model was created to calculate reflectance for a profiled surface.

Finite Element Reflectance Model

The model is based on a net-radiation method described in reference (1) page 250 and basically breaks the surface into N pieces for analysis. Since the profile shapes in question are always extruded there is a simple relationship for the diffuse view factor from one strip element on the profile to another. By making an energy balance at each element it is possible to generate N equations in N unknowns. Upon solving the N equations the net energy absorbed in all N elements can be calculated and compared to the incident energy. Ideally the model will accurately predict the change in reflectance for the corrugated aluminum foil sample and therefore could be used to estimate a correction for other profile shapes.

For the kth element an energy balance gives this relationship for the energy absorbed by the element:

$$Q_k = A_k * (q_{i,k} – q_{o,k})$$

$$q_{o,k} = \rho_k * q_{i,k}$$

$$q_{i,k} = \Sigma_{j=1,N} F_{k-j} * q_{o,j} + i_k * \cos \theta_k$$

Q_k – energy absorbed by element k
$q_{i,k}$ – incoming energy at element k
$q_{o,k}$ – outgoing energy at element k
i_k – source energy incident on element k
ρ - reflectance
θ - angle of incidence

Eliminating Q_k and $q_{i,k}$ terms produces N equations that can be solved for the N values of $q_{o,k}$.

$$i_k \cos \theta_k = q_{o,k} /\rho_k - \Sigma_{j=1,N} F_{k-j} * q_{o,j}$$

Then the total (in this case aggregate) reflectance for the surface is the ratio of the sum of Q_k’s divided by the sum of the incident energy.

$$(1 - \rho_a) = \left(\Sigma_{k=1,N} A_k * q_{o,k} * (1 - \rho_k) / \rho_k\right) / \Sigma_{k=1,N} A_k * i_k * \cos \theta_k$$

Diffuse view factors between elements are determined using two expressions taken from Appendix C of reference (1). For any two parallel strip elements the view factor from one to the other can be estimated from a relationship for differential elements.

$$dF_{d1\text{-}d2} = (\cos\varphi / \pi)\ d\varphi\ \tan^{-1}(b/r)$$

where,
b/r – ratio of length to distance between the elements
φ - is the angle of incidence of a ray from element 2 to element 1

The profile shape is assumed to be very long compared to its width so b/r is large and the $\tan^{-1}(b/r)$ term is estimated to be $\pi/2$.

For adjacent elements a more accurate expression is available for infinitely long finite plane areas attached on one edge.

$$F_{1\text{-}2} = (A1 + A2 - A3) / (2 * A1)$$

where,
A1, A2 – are the widths of the attached adjacent elements
A3 – is the length of a line completing a triangle with A1 and A2

Several test cases were run to check for errors in the coding of the reflectance model .

1. For a flat profile, the model returns an aggregate reflectance equal to the surface reflectance.
2. A 90 degree V profile was created to test the view factor calculations. At the bottom of the V the total view factor from one element to all others should approach 0.50 and this is observed by stepping through the code.
3. The V profile was also used to test the affect of the number of elements used. For a surface reflectance of 0.80 the aggregate reflectance is 0.733, 0.735 and 0.736 for 6, 24 and 96 elements respectively.
4. Estimation of the reflectance a simple three element rectangular profile by hand calculation agrees closely with the result of the model.

Measurements

For the first measurements, a piece of flat white painted aluminum foil was prepared. The paint was applied to a thickness of approximately 0.0022 inches. The sample was first measured for reflectance before crimping to ensure that it was uniform over the central area and then it was crimped into the corrugated shape shown in Figure 1. Three measurements of the crimped shape were made at different azimuth angles. The reflectance was only slightly dependent on azimuth angle and therefore only the average values are reported. Finally, each reading was corrected for the displacement error as described above based on the average depth (0.030”) of the profiled surface. From D&S Technical Note 08-1 the correct reflectance was estimated to be about 1.02 times the indicated reflectance.

To create a comparable shape for the computer reflectance model the foil length was measured before and after crimping. In the computer model a cosine shape was used to estimate the shape of the crimped foil. The height of the cosine shape was adjusted to match the measured ratio of surface length to final length for the crimped foil. For this sample, the ratio of surface length to final width was 1.2. The measured flat reflectance values were used as the surface reflectance in the model. Reflectance values are calculated for an incidence angle of 20 degrees to the plane of the profiled surface matching the incidence angle for the SSR.

White enamel, 0.0022” thickness, on Al foil:

	IR	Red	Blue	UV	AM2	AM1.5
measured R flat	0.685	0.753	0.783	0.223	0.724	0.719
crimped R x 1.02	0.645	0.723	0.755	0.197	0.690	0.686
model predicted R	0.645	0.718	0.751	0.194	0.687	0.682

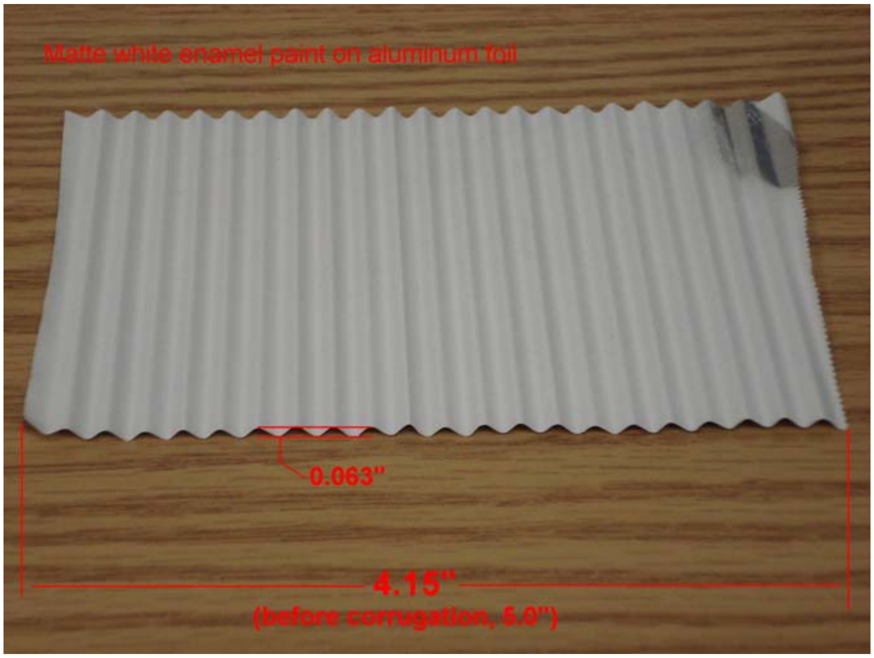


Figure 1. Corrugated matte white painted aluminum foil sample

A second series of measurements were made with the crimped foil in its initial shape and then stretched back out to simulate a more shallow profile. The estimated port displacement correction (1.02 for the “as crimped” sample) was also adjusted for the more shallow profiles.

surface L / L	reflectance	IR	Red	Blue	UV	AM2	AM1.5
1.0	measured flat	0.673	0.749	0.783	0.236	0.719	0.714
1.19	meas. x 1.02	0.637	0.713	0.762	0.209	0.686	0.682
	model predicted	0.635	0.716	0.753	0.208	0.684	0.679
1.11	meas. x 1.012	0.658	0.733	0.774	0.225	0.704	0.699
	model predicted	0.652	0.730	0.766	0.219	0.699	0.694

1.19	meas. x 1.007	0.673	0.745	0.782	0.236	0.716	0.712
	model predicted	0.666	0.743	0.778	0.230	0.713	0.708

To determine if coating thickness is an issue with the painted foil as it was with the card stock, a second coating was added to a thickness of about 0.0074 inches. The crimped foil with thick paint is stiffer and therefore holds a more shallow profile with the ratio of surface length to final width being 1.136 vs. 1.2.

White enamel, 0.0074" thickness, on Al foil:

	IR	Red	Blue	UV	AM2	AM1.5
measured R flat	0.655	0.762	0.788	0.237	0.720	0.715
crimped R x 1.014	0.633	0.738	0.771	0.218	0.698	0.693
model predicted R	0.626	0.738	0.766	0.215	0.693	0.688

This result is comparable to the measurements for the foil with the thinner coating of white pant verifying that there is little dependence on coating thickness.

Aggregate Reflectance Correction for Real Profiled Surfaces

Three typical shapes have been input into the computer model. The shapes are taken from actual examples and then scaled to different heights to create a family of profile shapes.

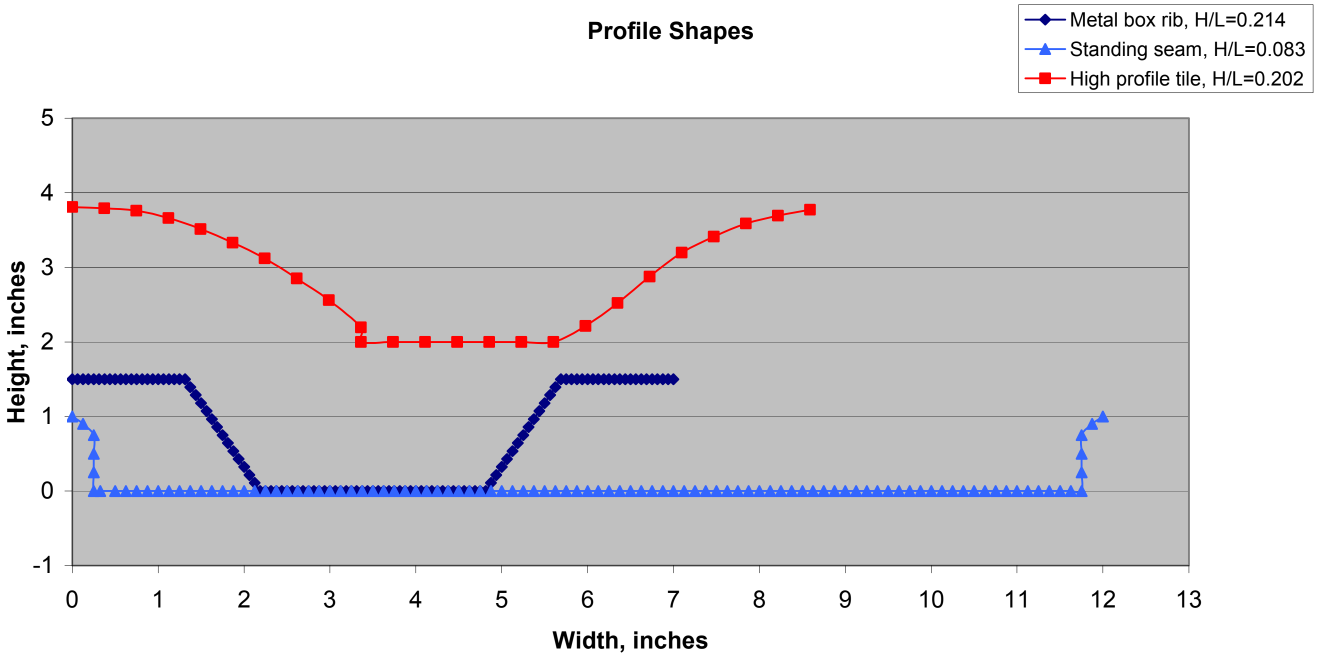


Figure 2. Profile Shapes divided into finite elements for reflectance modeling.

Figure 2 shows the actual profile shapes roughly to scale along with the endpoints of the finite elements. The parameter H/L is the height (measured from the top surfaces) divided by the length of one full cycle of the profile. The plots in Figure 3 were created by scaling the profiles to different values of H/L and calculating the aggregate reflectance for different surface reflectance values using the reflectance model.

The cosine profile is included for comparison. Note that the H/L values range to at least twice that of a typical profiled shape.

Figure 3a. Metal Box - Aggregate Reflectance Correction

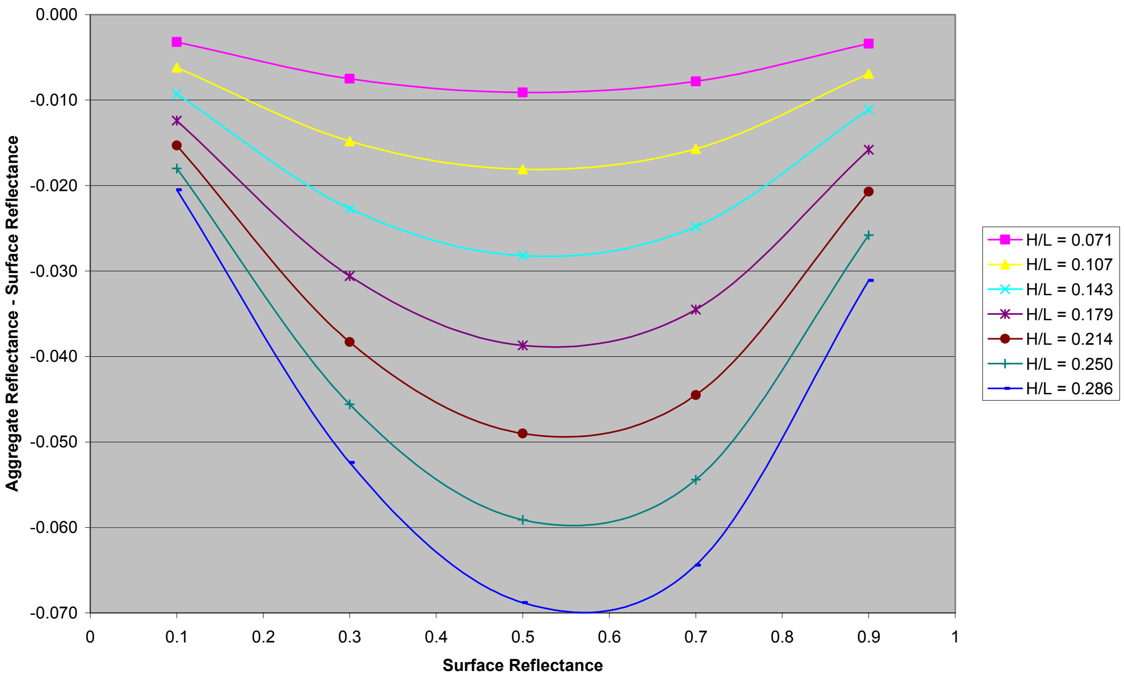


Figure 3b. Standing Seam - Aggregate Reflectance Correction

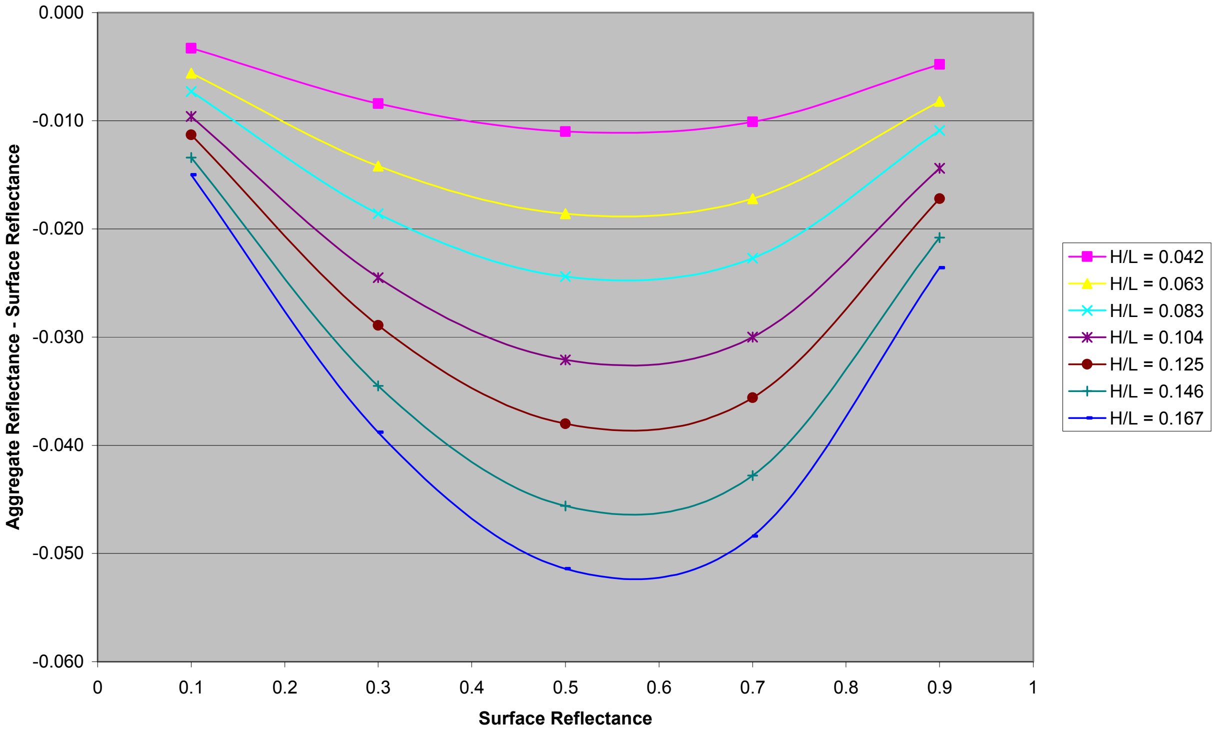


Figure 3c. High Profile Tile - Aggregate Reflectance Correction

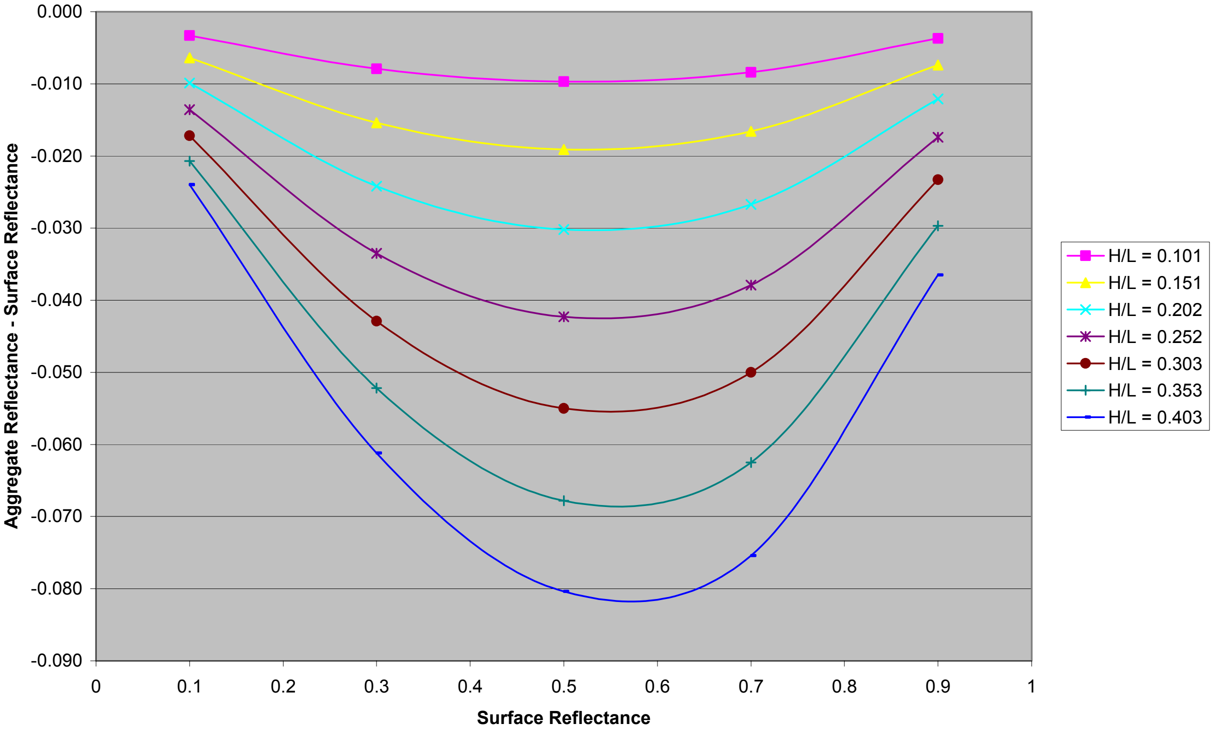
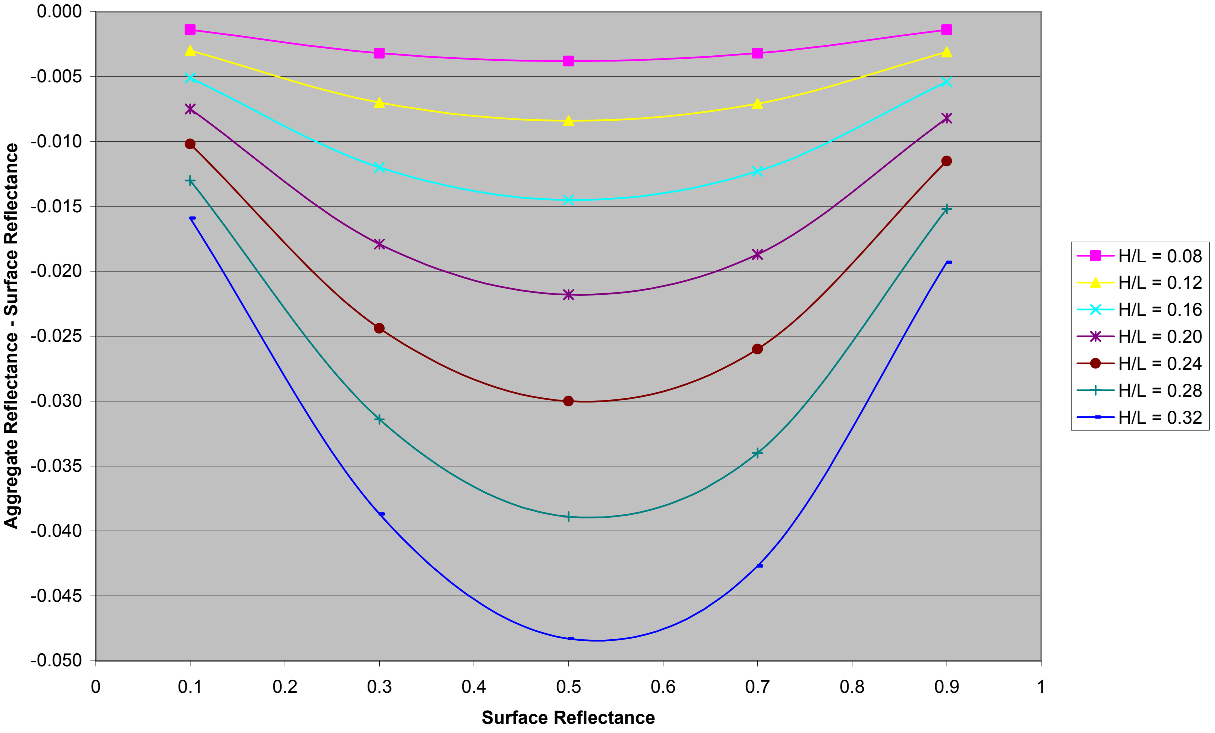


Figure 3d. Cosine Profile - Aggregate Reflectance Correction



The correction for aggregate reflectance is a strong function of surface reflectance and is largest in magnitude at a reflectance of about 0.50. This is explained by the fact that most of the additional energy absorbed occurs due to radiation from the first reflection striking the surface a second time. The amount absorbed should be roughly proportional to the surface reflectance multiplied by the absorptance (1 – reflectance).

$$R_{aggregate} - R_{surface} \sim= k * R_{surface} * (1-R_{surface})$$

The term R * (1-R) is a maximum when R is 0.5.

Note that if there were only two reflections the corrections for surface reflectances of 0.9 and 0.1 would be the same since the R * (1-R) term is the same. The predicted corrections however are larger in magnitude for higher surface reflectance values because of the additional reflections. For low surface reflectance values the influence of the third and subsequent reflections is very small. The influence of subsequent reflections is greater for the profile shapes with "corners" and thus the plots of the correction versus surface reflectance are more asymmetric. For the selected shapes, the correction can be closely estimated with the following equations:

Metal Box Rib ($0.036 \leq H/L \leq 0.286$):

$$R_{aggregate} - R_{surface} \sim= -1.834 * (H/L)^{1.396} * R_{surface}{}^{1.164} * (1-R_{surface})$$

Standing Seam ($0.021 \leq H/L \leq 0.167$):

$$R_{aggregate} - R_{surface} \sim= -1.609 * (H/L)^{1.059} * R_{surface}{}^{1.200} * (1-R_{surface})$$

High Profile Tile ($0.050 \leq H/L \leq 0.403$):

$$R_{aggregate} - R_{surface} \sim= -1.442 * (H/L)^{1.495} * R_{surface}{}^{1.164} * (1-R_{surface})$$

Cosine ($0.039 \leq H/L \leq 0.320$):

$$R_{aggregate} - R_{surface} \sim= -1.653 * (H/L)^{1.810} * R_{surface}{}^{1.071} * (1-R_{surface})$$

Variation in Reflectance with Wavelength

If there is a variation in surface reflectance with wavelength the correction for aggregate reflectance will also vary and thus a single correction applied to the measured solar reflectance of the surface may be in error. With the SSR, even correcting the individual detector readings and applying the weightings may be in error because each detector measures a broad wavelength band.

To test the sensitivity of the correction to variation in wavelength a set of 155 reference reflectance tiles were measured with the SSR and the reflectance data for each detector recorded. Spectrophotometer data is available for the tile set and therefore it is possible to estimate what the aggregate reflectance correction should be at each wavelength. The overall aggregate correction was then determined by integration of the surface reflectance and the aggregate corrected reflectance at each wavelength, weighted by the nominal response curves for different Air Mass selections on the SSR. These calculations were done for the Metal Box Rib profile with H/L = .214 (the actual measured ratio for the example profile). Details are found in reference (3) which is a spreadsheet file that implements the calculations. The calculations based on the spectrophotometer data are assumed to be the "correct" values and the comparison is made to the correction for the AMn solar reflectance value or correcting each individual detector and then calculating the AMn solar reflectance correction based on the detector weightings. For the 155 samples the results are summarized below for AM1.5 readings and are about the same for the other air mass selections.

Average AM1.5 aggregate reflectance correction based on spectrophotometer data = -0.033
Average correction of AM1.5 based on AM1.5 reflectance = -0.039, std dev = 0.004, max dev = -0.019
Average correction of AM1.5 based on detector reflectance = -0.035, std dev = 0.002, max dev = -0.010

This result shows that the correction to aggregate reflectance is likely to be overestimated slightly if it is applied to the total reflectance value and as expected, more accurately estimated if applied to the individual detector readings.

Comments

The computer reflectance model for profiled surfaces agrees reasonably well with measured reflectance values that are corrected for displacement from the port, for the white painted aluminum foil. On average the measured and corrected reflectance values are slightly higher than predicted by the model. Most practical profiled materials are not as deep as the test surface and therefore the correction from a measured surface reflectance to an aggregate reflectance will be smaller. This approach is subject to odd results if the coating / substrate combination has reflectance properties that vary significantly with coating thickness. For example if a reflective surface coating is not opaque, the aggregate reflectance of a profiled shape at near normal incidence may be higher than expected due to the beam incident radiation encountering a greater thickness of the coating.

Included in the programming of the reflectance model is a simple ray tracing approach that handles the first two reflections for a specular surface. The results running a few cases show a lower reflectance than for the diffuse case at near normal incidence because of increased multiple reflections but a higher reflectance at angles not too far from normal because of the absence of multiple reflections. For most practical surfaces there is only a small fraction of energy that is reflected specularly and the net difference between the surface being diffuse or specular is probably small. The case of a specular or partially specular profiled surface was not investigated further.

There is potential for confusion when discussing surface reflectance versus aggregate reflectance, profiled versus rough or textured surfaces and to what value a reading is being corrected. For the purpose of solar reflectance measurements with the SSR there are two size ranges of surface features that matter. Since the measurement port is about an inch in diameter, typical surface roughness features can be ignored until they reach a size on the order of say 0.02 inches. The terms "textured" and "irregular" are used in reference (1), D&S Technical Note 08-1, to describe basically flat surfaces that have surface features large enough to require that a correction be made to the reading but the measured and then corrected value includes the affect of the surface geometry.

For the typical profiled surface, the scale of the surface geometry is much larger and therefore a direct reading of the reflectance including the surface geometry cannot be made with the SSR. Therefore, if it is not possible to measure a flat spot on a profiled surface it is first necessary to determine the surface reflectance and then as proposed here, apply a correction for the profiled shape. The surface reflectance for such curved shapes has typically been measured with the SSR by creating a working reflectance standard that matches the curved portion of the profiled shape that will be measured. For example, an opaque white vinyl tape can be applied to a sample of the curved surface and used as a reflectance standard. The reflectance values of the white tape as measured flat are programmed into the SSR as one of the five programmable working standards. Then the SSR is calibrated to read the surface reflectance value of the tape when positioned on the curved surface of the tape. To measure an unknown sample, the port is positioned at the same orientation on the identically shaped sample. Errors with this approach are related to the amount of surface curvature and the difference between the directional reflectance properties of the sample and the standard.

References:

(1) D&S Technical Note 08-1, SSR Reflectance Measurements of Irregular Surfaces
(2) “Thermal Radiation Heat Transfer”, Siegel and Howell, McGraw-Hill Book Company, 1972.
(3) D&S document “S:\DOC\CSM\Aggregate Reflectance correction comparison.xls”
(4) D&S document “S:\SOLAR\SSR\Profile Aggregate Reflectance Correction.xls”
(5) D&S source code “\qbasic\profile.bas”