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D&S Technical Note 09-1

Solar Spectrum Reflectometer Version 6.0

Version 5.0 of the Solar Spectrum Reflectometer measures reflectance for beam radiation at 20 degrees incidence. A Tungsten Halogen source provides diffuse illumination and reflected energy is measured with four broadband filtered detectors roughly covering the UV, Blue, Red and near IR. A solar reflectance value is estimated by adding best fit weighted fractions of the four detector outputs. Solar reflectance values are calculated for air mass 0, 1, 1.5 and 2 direct irradiance. The version 5.0 instrument is documented in references (1) and (2).

An updated version 6.0 instrument was proposed based on the following issues:

1. A potential problem with the SSR Red detector readings was brought to our attention by Berkley labs (4). By comparing spectrophotometer readings of a number of samples to reflectance readings for the red detector it was determined that the detector was more responsive to the NIR than expected based on the published nominal response curve. Round robin testing was also reported showing variation in readings from one instrument to another which appeared to be of a similar origin.
2. During investigation of the red detector issue it was determined that several changes could be made to significantly improve both the statistical match between SSR solar reflectance values and values based on spectrophotometer measurements, and the variation in readings from one instrument to another.
3. The version 5.0 instrument provides reflectance readings matched to direct irradiance only. Global irradiance, which includes the diffuse component, is more heavily weighted to shorter wavelengths and better represents the average irradiance experienced by most outdoor surfaces. With the ability to better match solar irradiances, selections for standard global irradiance models can be added and later altered to match future irradiance standards if necessary.

The new version 6 instrument has the following updated functions and features.

1. Each version 6 instrument is spectrally calibrated against a set of 155 reflectance tiles measured with a spectrophotometer. The spectrophotometer reference readings for the tiles have been verified with measurements on four different spectrophotometers. Rather than having fixed detector weightings as with version 5, a custom set of weightings for each instrument is generated to best fit each irradiance model to be matched. This results in a much tighter match between the SSR reflectance value reported and the spectrophotometer readings as well as greatly reducing unit to unit variations.
2. To better match various solar irradiance reflectance values, two “virtual” detectors were added to the four actual detectors. The four actual detectors cover broad wavelength bands roughly centered

on the UV, Blue, Red and IR. The two virtual detectors are added by resampling the Red and IR detectors at a much lower lamp color temperature. With effectively six detectors rather than four it is possible to generate a good match to a variety of solar irradiances. For typical global and direct irradiances, the SSR reflectance readings of the calibration set of 155 color tiles match the calculated reflectance based on spectrophotometer readings with a bias of less than 0.002 and a standard deviation of about 0.005.

3. The instrument is programmed to display reflectance for 10 different selections of irradiance along with the individual detectors as listed below.

Selection	**Description**
G173	ASTM G173 air mass 1.5 global irradiance
b173	ASTM G173 air mass 1.5 beam normal component
G1	Air mass 1 global irradiance on a horizontal surface*
b1	Air mass 1 beam normal component*
d1	Air mass 1 diffuse component*
b0	Air mass 0 beam normal
b891	ASTM E891-87 air mass 1.5 beam normal**
2E	Emulation of version 5 air mass 2 beam normal***
1.5E	Emulation of version 5 air mass 1.5 beam normal***
0E	Emulation of version 5 air mass 0 beam normal***
L1-L4	IR, Red, Blue and UV detector readings at ~3125K lamp
L5-L6	IR and Red detector readings at ~ 2300K lamp

* Air mass 1 selections are matched to a solar irradiance proposed to closely predict the total solar load for a range of surfaces and conditions. See reference (3) – "Measuring solar reflectance – Part I: defining a metric that accurately predicts solar heat gain", Ronnen Levinson, Hashem Akbari, Paul Berdahl, submitted to <u>Solar Energy</u>, Feb. 2009.

** b891 should be used for new measurements as specified by ASTM C1549. For version 5 instruments C1549 specifies the air mass 1.5 setting however the version 6 fit to the E891-87 air mass 1.5 irradiance is more accurate.

*** Emulation of version 5 beam normal reflectance is provided primarily for backward compatibility with existing instruments and instruments that are upgraded to version 6. Note that the emulation of version 5 is currently a best match to reflectance values for the calibration tile set with the instrument configured in native version 5 mode. At a later date an average or nominal version 5 response may be used in place of the match to the one particular instrument.

4. If it is required at a later date, one or more different solar irradiance models can be substituted for the listed selections. These can be generated from the original calibration data for the instrument and supplied in a replacement EPROM or alternatively uploaded to battery backed up RAM.
5. Along with the three calibration standards supplied with the instrument (two diffuse white tiles and one second surface specular mirror), four additional tile standards are supplied to track the spectral calibration of the instrument. These tiles are selected to have monotonically increasing or decreasing reflectance over the wavelength range of one or more of the detectors. This will allow a shift in the spectral response to be detected. A lamp color temperature calibration is implemented using one of the reference color tiles but it is not known if it will be necessary. If spectral drift occurs in the detector responses and the nature of the drift is similar to a shift in color temperature, this calibration can approximately correct for the drift.

6. Smaller tile sample sets have been created for field calibration of instruments if that becomes necessary.
7. A number of other changes are implemented including: software to report additional error conditions, set the lamp current on each power up if required, monitoring the lamp for replacement, improved control of the lamp to match the intended color temperature and operation in a sample and hold mode rather than continuous sampling.
8. Included in version 6 firmware is the option to operate in a fully version 5 hardware and software compatible mode. All that is required is to change out a single optical filter element and spacer and switch to version 5 mode from the keypad. It is not anticipated that this feature will be needed because the version 5 emulated reflectance values are available.
9. Other hardware modifications for version 6 include a new switching power supply that allows the instrument to be operated for 5 hours continuous use with an optional small battery pack, a more flexible signal cable and an optional handle. All version 5 instruments that are operating properly are fully upgradeable to version 6 (including the battery and handle options).

Note that the air mass 1.5 selection (based on E891-82) on the version 5 instrument has become the defacto standard for SSR reflectance measurements. For measurements of solar reflectance previously specifying the air mass 1.5 selection with version 5 instruments, it is recommended that the "b891" selection be used on version 6 instruments (based on E891-87). E891-87 and E891-82 are very similar and the version 5 air mass 1.5 reflectance values are close to the version 6 b891 readings. For four instruments tested to date (5) the average deviation between version 6 b891 and version 5 AM 1.5 reflectance values for the 155 reference tiles ranges from -.0066 to +.0039 and the standard deviation ranges from .0086 to .013. The variation in the average deviation for the different instruments is due to differences in the version 5 AM 1.5 measurements whereas the version 6 b891 measurements are nearly identical for the four instruments (standard dev of 0.002 or less). The version 6 measurement of E891-87 reflectance will be more accurate compared to spectrophotometer measurements and will be more repeatable from one instrument to another.

Detector Response Characterization

In the original design of the SSR, nominal detector response curves (a combination of the source and detector response) were calculated from transmittance measurements of a number of color glass, photographic color filters and other filter elements for which the spectral transmittance was measured independently. Transmittance measurements are made with an SSR-T transmittance attachment. The response curve is then calculated starting with an estimate of the response that is iteratively corrected to minimize error. For the development of version 6 we have subsequently recharacterized all of the version 5 responses of the detectors using a new set of color glass and band pass filters. It was verified that the red detector response was shifted toward longer wavelengths as reported (4). The difference between the apparent response and the original nominal response of the detectors is due to error in the original characterizations and unintended changes in the filter and detector elements used in the instrument over a period of time. An error of 50 mA in setting the lamp current was discovered in the version 5.0 software but this was determined to be a minor issue. There has not yet been enough data obtained from early units to track unintended variations due to changes in detector elements. Figure 3 shows the original nominal and updated red detector response curve for version 5 of the SSR.

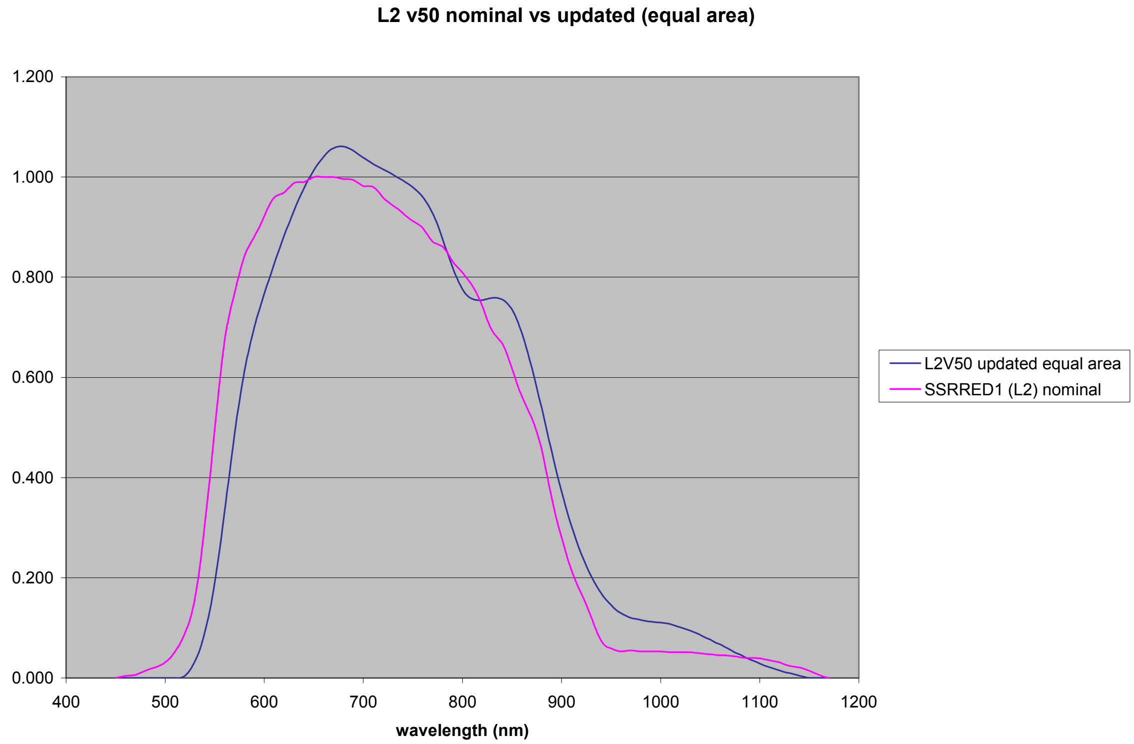


Figure 3. Original nominal vs. updated RED (L2) detector response

Based on the new response curves a large number of trial measurement spectra were generated to match terrestrial global, direct and diffuse irradiances. For the updated characterizations of the detectors it was found that a change in response of the IR detector (L1) was needed to better fit both the existing and newly proposed irradiance distributions. This change was implemented by changing the thickness of an IR attenuating filter element. The filter can be changed out in the instrument so that a new or upgraded instrument is fully backward compatible with version 5.

Matching Irradiances for Version 6

The original matching of SSR measurement spectra to direct irradiances was based on designing the four detector responses to be approximately the correct shape and then calculating weightings of the four detectors to best power match the particular irradiance in five wavelength bands, .3-.4, .4-.6, .6-.9, .9-1.4 and 1.4-2.5 microns. While generating the updated measurement spectra it was found that the selection of the wavelength boundaries had a significant effect on the calculated weightings. This can be explained by observing that in each band the total power is matched but the energy in the measurement spectrum may be wavelength shifted in the same direction compared to the irradiance. The entire spectrum is therefore shifted in one direction which is unlikely to be the best fit for the calculation of reflectance. Because of the sensitivity to the arbitrary selection of wavelength boundaries an integral approach was developed that eliminates the boundaries. Also, recognizing that there is at least some variation in detector responses from one instrument to another, a second method was developed using a large set of reflectance samples to directly calculate the weightings, bypassing the calculation of the detector response curves altogether. This method uses the measured reflectance values of the samples for the four detectors to produce weightings that best fit the solar reflectance values calculated from the spectral reflectance of the samples. These two methods use different measurements and are essentially independent except that reflectance values for each detector for a reference standard must be known for the reflectance method. These values are obtained by integration of the spectral reflectance of the reference standard over the detector response curves. Since the reflectance standard is a white tile and relatively spectrally flat, the reflectance values for each of the four detectors are not sensitive to errors in the detector response curves. The detector weightings for the D&S test unit, s/n 137, were calculated using the reflectance method and were found to be comparable to the weightings obtained using the detector response curves and the integral power matching method.

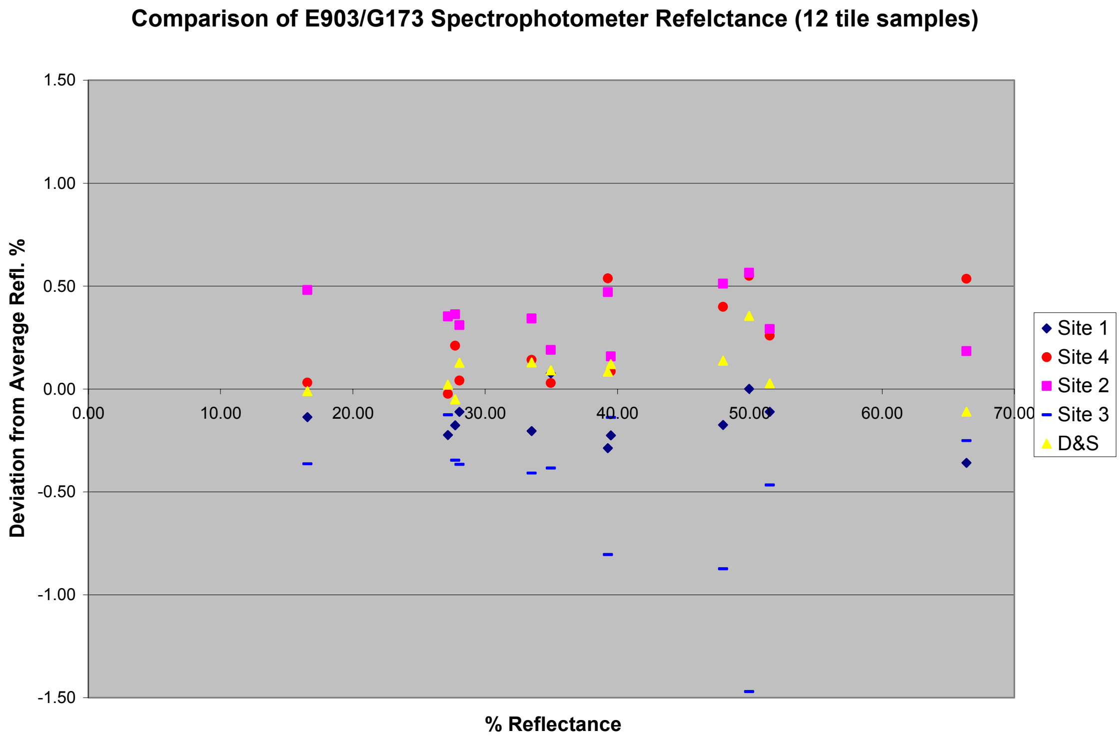
For version 6 instruments the reflectance method is used to directly calculate a custom set of weightings for each instrument. This approach significantly reduces bias and scatter in the SSR reflectance measurements.

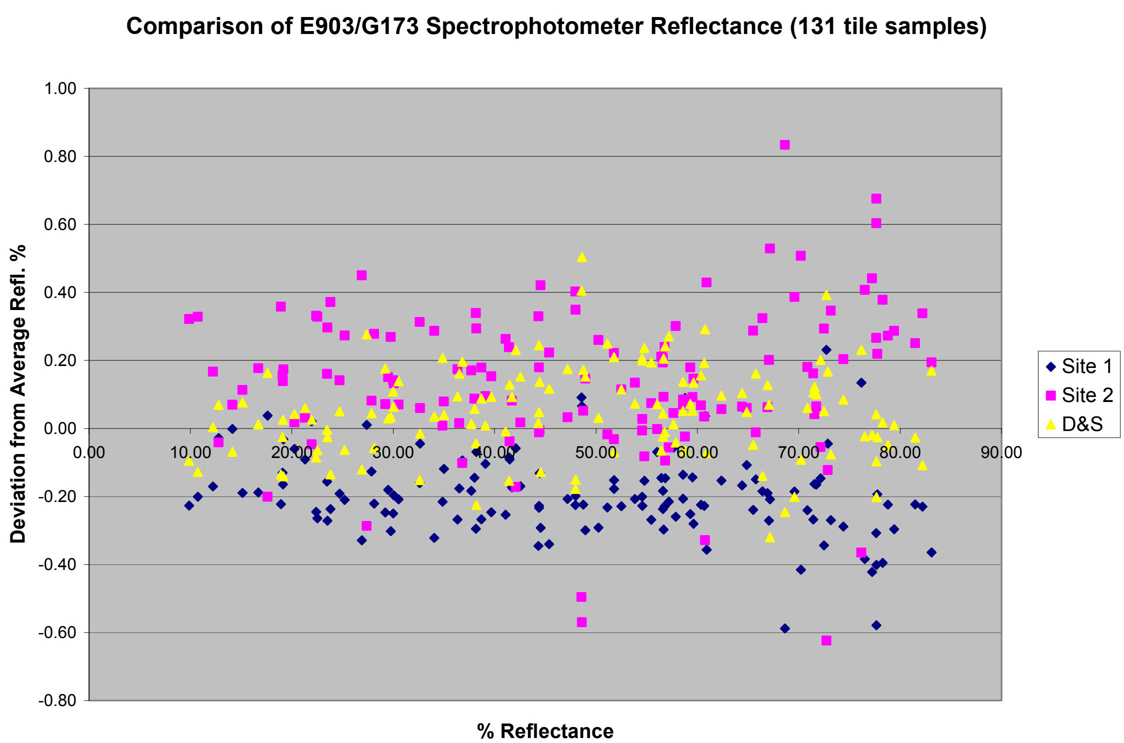
Verification of Reference Tile Set Measurements

To verify the spectral reflectance measurements for the reference tile set a series of independent measurements were made with different spectrophotometers. The instruments and standards used are summarized below.

Site	Spectrophotometer	Standard
Site 1	L900	NBS2019 sn 92
Site 2	L900	NBS2019 sn ??
Site 3	L9	NBS2019 sn ??
Site 4	L900	SRS-99 Spectralon
D&S	L9 upgraded to L19	NBS2019 sn 92

The following charts show the variation in readings for a set of 12 tiles measured at all four sites and a subset of 131 tiles out of the 155 reference tiles measured at two sites.





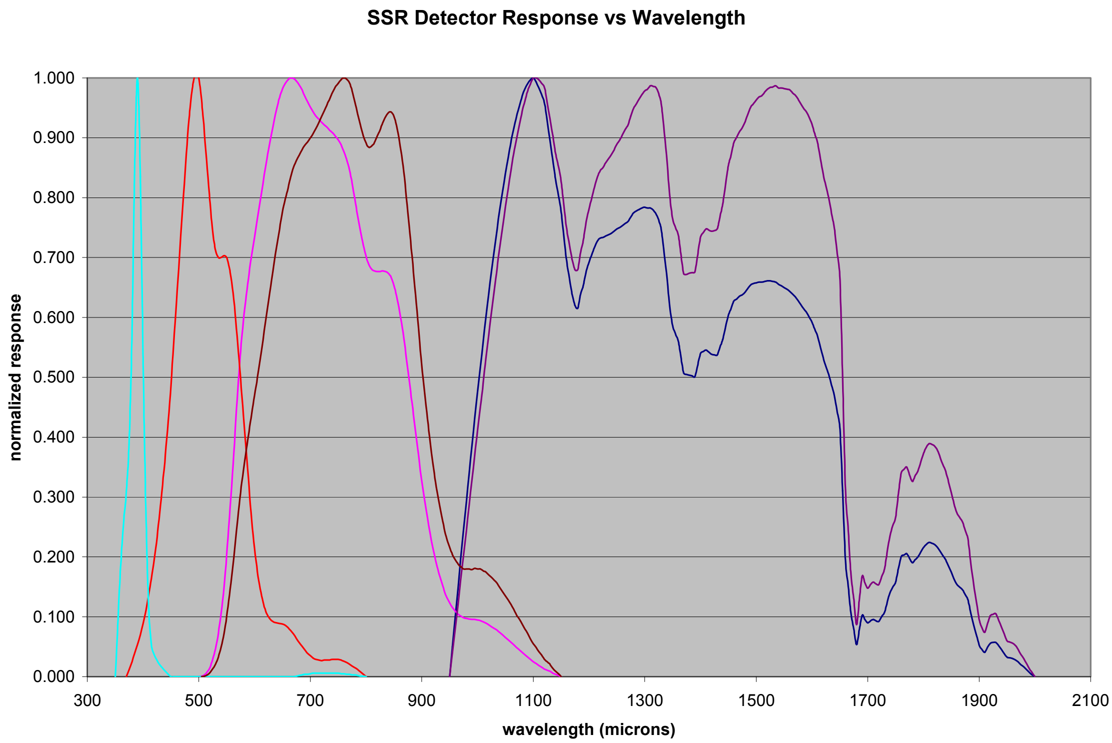
Based on good agreement between the measurements at different sites, the D&S spectrophotometer measurements are used as the reference values for the set of 155 reference tiles.

Smaller Tile Sets for Field Calibration

Five sets of 24 tiles have been created for possible field spectral calibration of instruments. The use of the smaller tile set for calibration results in slightly different weightings for the detectors however the statistical match over the full 155 tile reference set is comparable. For the typical solar irradiance matches, the values are on average 0.001 or 0.002 higher and the standard deviation is increased by about 10 percent.

Addition of Virtual Detectors

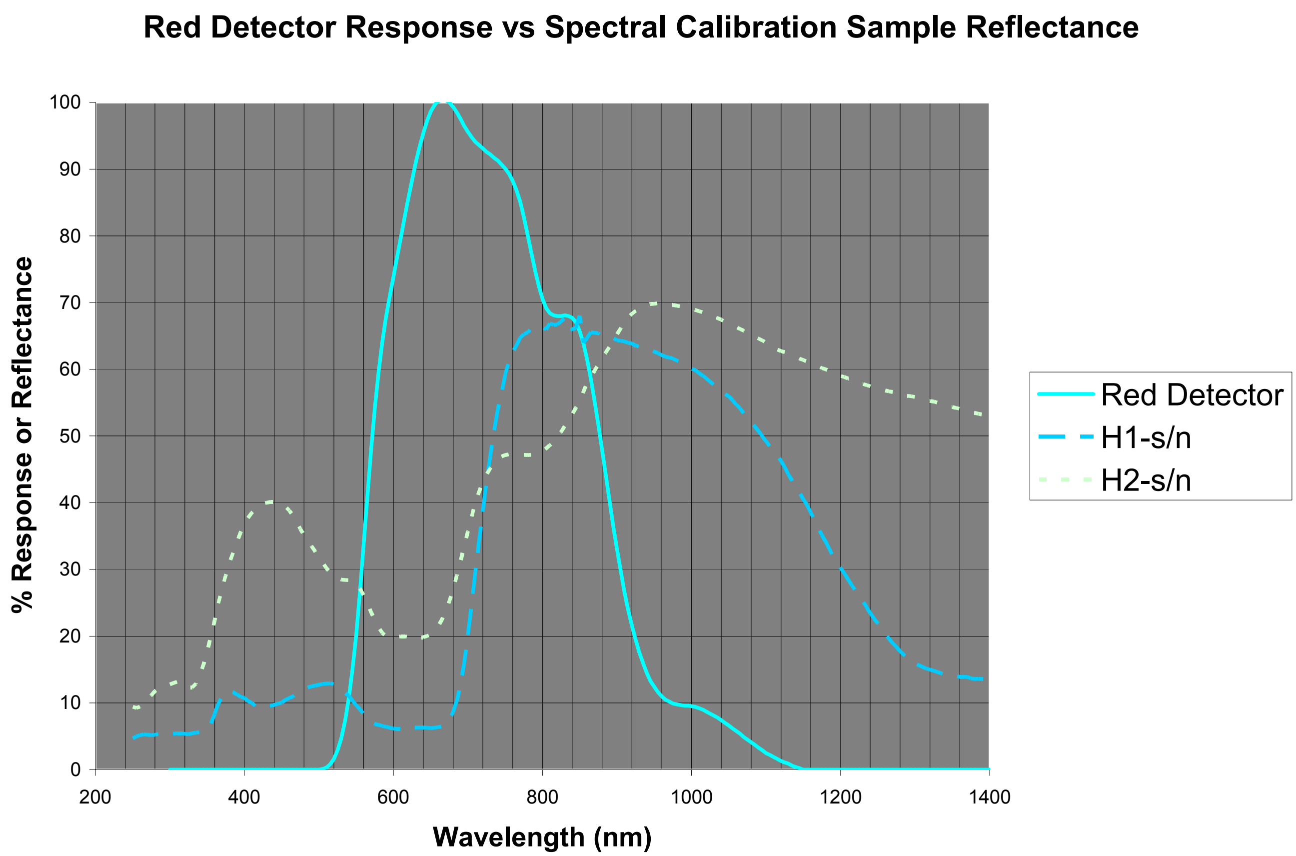
For version 6, two additional virtual detectors were added by sampling the Red and IR detectors at a lower color temperature, ~2300K versus ~3125K. A plot of all of the version 6 detector response curves is shown below. The two additional curves for the Red and IR detectors show the degree to which the Red and IR detectors are shifted to longer wavelengths at the lower color temperature.



Color Temperature Calibration

The plot below shows typical spectral reflectance for two of the samples supplied for tracking spectral response of the SSR version 6 detector responses. The tiles are labeled H1 and H2 along with the three digit serial number of the instrument to create a unique designation. These two tiles both have sharply increasing reflectance over the wavelength range of the Red detector and therefore are very sensitive to any change in the Red detector response. With aging of the lamp and other possible drift in instrument performance the reflectance of these selected samples for the red detector may change over time.

Assuming that drift in the spectral response of the Red detector will be mostly due to lamp color temperature or will at least roughly mimic a shift in color temperature, a color temperature calibration procedure was developed that attempts to correct for the drift.



The color temperature calibration is similar to the gain calibration that uses the supplied white tile or mirror standards. In this case the ALT key on the keypad is used to select the color temperature calibration. The ALT plus STANDARD key allows the user to select either the H1 or H2 tile to use for color temperature calibration. Currently H1 is the recommended selection. Pressing ALT plus CALIBRATE/ZERO initiates a measurement cycle during which the acquired reflectance of the selected standard is compared with the initially calibrated value. A new lamp setting is then calculated for both the high and low color temperature to attempt to correct the readings. With the new settings calculated a "restart" is initiated that requires the usual zero offset and calibrate functions to be executed. During the zero offset sequence, the new lamp current is set. After color temperature calibration the L2 (red) and L6 (red at the lower color temperature) detector readings for the selected standard should be closer to the initially calibrated values. Upon restarting and on subsequent power ups the usual blinking version number display will include a "-" at the end indicating that instrument has been spectrally calibrated. The "-" is used if any calibration or operating parameter is RAM resident, for example a custom or updated irradiance fit. The operation of the instrument is largely "data driven" meaning that many functions can be altered by loading custom tables into RAM over the serial port. If the unit is cold started or looses battery backed up RAM for any reason the spectral calibration must be repeated and RAM would have to be reloaded with the custom tables. No other RAM loaded custom features are currently implemented.

As a test of spectral performance, the D&S SSR test unit, serial number 137 was updated to version 6 and then run continuously for three months. This is equivalent to about one year of heavy use with the same lamp. The reflectance values for the H1-137 tile are given below.

	L1	L2	L3	L4	L5	L6	G173
H1-137, 03/19/09, init. calibration	0.278	0.380	0.110	0.108	0.270	0.454	0.288
H1-137, 06/16/09	0.281	0.388	0.111	0.109	0.272	0.459	0.292
H1-137, 06/16/09, spectral cal'd	0.281	0.379	0.112	0.113	0.272	0.452	0.289

The H1 and H2 standard tiles were specifically chosen to be sensitive to a change in color temperature and thus most other materials will show a smaller change in total solar reflectance due to drift in spectral response.

Acknowledgements

Thanks to Ronnen Levinson of LBNL for providing many valuable comments and suggestions during the evaluation of the version 5 SSR and development of the version 6 instrument.

References:

(1) Devices & Services Co. TN 79-16 The Solar Spectrum Reflectometer

(2) Devices & Services Co. TN 86-1 Solar Spectrum Reflectometer Version 5.0

(3) "Measuring solar reflectance – Part I: defining a metric that accurately predicts solar heat gain", Ronnen Levinson, Hashem Akbari, Paul Berdahl, submitted to Solar Energy, Feb. 2009.

(4) "Measuring solar reflectance – Part II: review of practical methods", Ronnen Levinson, Hashem Akbari, Paul Berdahl, submitted to Solar Energy, Feb. 2009.

(5) Devices & Services Co., SSR version 6 Calibration records 081, 137, 155, 156

D&S reference documents:

ds155 vs ds24 version 6 fit.xls
D&S Tiles – Confidential 1.xls
Calibration Record PLUS Color Temp Calculation.xls
SSR version 5 nominal vs actual vs E891.xls
SSR version 6 Measurement Spectra vs SMARTS irradiance-RL4-CM2.xls