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Measuring solar reflectance—Part II: Review of practical methods

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Abstract

A companion article explored how solar reflectance varies with surface orientation and solar position, and found that clear sky air mass 1 global horizontal (AM1GH) solar reflectance is a preferred quantity for estimating solar heat gain. In this study we show that AM1GH solar reflectance $R_{g,0}$ can be accurately measured with a pyranometer, a solar spectrophotometer, or an updated edition of the Solar Spectrum Reflectometer (version 6). Of primary concern are errors that result from variations in the spectral and angular distributions of incident sunlight.

Neglecting shadow, background and instrument errors, the conventional pyranometer technique can measure $R_{g,0}$ to within 0.01 for surface slopes up to 5:12 [23°], and to within 0.02 for surface slopes up to 12:12 [45°]. An alternative pyranometer method minimizes shadow errors and can be used to measure $R_{g,0}$ of a surface as small as 1 m in diameter. The accuracy with which it can measure $R_{g,0}$ is otherwise comparable to that of the conventional pyranometer technique.

A solar spectrophotometer can be used to determine $R^*_{g,0}$, a solar reflectance computed by averaging solar spectral reflectance weighted with AM1GH solar spectral irradiance. Neglecting instrument errors, $R^*_{g,0}$ matches $R_{g,0}$ to within 0.006. The air mass 1.5 solar reflectance measured with version 5 of the Solar Spectrum Reflectometer can differ from $R^*_{g,0}$ by as much as 0.08, but the AM1GH output of version 6 of this instrument matches $R^*_{g,0}$ to within about 0.01.

Keywords: Solar reflectance; Solar heat gain; Pyranometer; Solar spectrophotometer; Solar Spectrum Reflectometer; Spectrally selective "cool colored" surface

1. Introduction

In Part I of this study (Levinson et al., 2010) we defined clear sky air mass 1 global horizontal (AM1GH) solar reflectance $R_{g,0}$, a metric that can be used to accurately estimate the solar heat gain of an opaque surface. Here in Part II we consider the measurement of $R_{g,0}$ with each of three instruments: a pyranometer, a solar spectrophotometer and a Solar Spectrum Reflectometer. Of primary concern are errors that result from variations in the spectral and angular distributions of incident sunlight.

2. Conventional pyranometer technique (method E1918)

Global solar reflectance R_g can be measured with a pyranometer (solar radiation meter) by facing its sensor directly away from the target surface to measure incident global solar irradiance I_i, then directly toward the target surface to measure reflected global solar irradiance I_r. If preferred, I_i and I_r can be measured simultaneously with back-to-back pyranometers. ASTM E1918-06 (Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field) (ASTM, 2006)

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Nomenclature

English symbols

a_j	detector j response multiplier
c_j	detector j reflectance weight
D_j	detector j reflectance
F	view factor
F_j	detector j integrated response
f_j	detector j spectral response
g	solar spectral response
I_i	incident solar irradiance
I_r	reflected solar irradiance
i_g	global spectral irradiance
$i_{g,0}$	AM1GH spectral irradiance
N	near-infrared reflectance
R	solar reflectance
R^2	coefficient of determination
R_g	global solar reflectance
$R_{g,0}$	AM1GH solar reflectance
$R^*_{g,0}$	E903_AM1GH solar reflectance
R_{E1918}	solar reflectance measured with conventional pyranometer method ASTM E1918
R_{E1918A}	solar reflectance measured with alternative pyranometer method E1918A
$r_{b,n}$	normal-incidence beam-hemispherical spectral reflectance
$r_{b,nn}$	near-normal beam-hemispherical spectral reflectance
S	solar reflectance
V	visible reflectance
Y_j	detector j signal
z	solar zenith angle

Greek symbols

γ	surface solar azimuth angle
ΔS	difference in solar reflectance
ΔI_r	white-black difference in reflected solar irradiance
θ	incidence angle
λ	wavelength
Σ	surface tilt angle
ϕ	target diameter

Initialisms

AM	air mass
AM0BN	air mass 0 beam normal
AM1BN	(clear sky) air mass 1 beam normal
AM1DH	(clear sky) air mass 1 diffuse horizontal
AM1GH	(clear sky) air mass 1 global horizontal
AM1.5GT-	(clear sky) air mass 1.5 global tilt opposing sun
B*n*	(spectral) band *n*
E1918	(ASTM Standard) E1918
E1918A	(alternative pyranometer method) E1918A
E891BN	(ASTM Standard) E891 beam normal
E903	(ASTM Standard) E903
E903_*n*	average of solar spectral reflectance weighted with solar spectral irradiance *n*
G173BN	(ASTM Standard) G173 beam normal
G173GT	(ASTM Standard) G173 global tilt
LST	local standard time
NIR	near infrared
SSR	Solar Spectrum Reflectometer
SSRv5	Solar Spectrum Reflectometer version 5
SSRv5_*n*	SSRv5 solar reflectance output corresponding to solar spectral irradiance *n*
SSRv6	Solar Spectrum Reflectometer version 6
SSRv6_*n*	SSRv6 solar reflectance output corresponding to solar spectral irradiance *n*
SSRv6_V5*n*	SSRv6 solar reflectance output emulating SSRv5 solar reflectance output *n*

(hereafter, E1918) details the application of this technique to a surface whose pitch does not exceed 2:12 [9.5°]. The E1918 solar reflectance $R_{E1918} \equiv I_r/I_i$ will equal R_g if (a) the surface reflects diffusely; (b) the pyranometer casts no shadow on the surface; and (c) the pyranometer sees only the target surface when measuring I_r. Simulations performed in Part I of this study indicate that for a horizontal surface or sun-facing low-slope surface, $|R_g - R_{g,0}| \leqslant 0.01$ when the solar zenith angle $z \leqslant 45°$ (Fig. 1). Therefore, under these ideal conditions $|R_{E1918} - R_{g,0}| \leqslant 0.01$.

This simple technique requires only a portable, relatively inexpensive instrument and applies equally well to flat and curved surfaces. However, there are some restrictions. First, the sky must be clear, particularly around the sun. Haze or cloudiness can change the spectral power distribution of sunlight, and the passage of a cloud across the sun can lead to serious error.

Second, the spectral distribution of I_i and the incidence angle θ of the solar beam both vary with hour of day and day of year. This can limit the daily time window during which $R_{E1918} \approx R_{g,0}$. For example, method E1918 requires that $z < 45°$. At the mainland US mean latitude of 37°N, this condition would be met from about 08:45 to 15:20 local standard time (LST) on June 21 (the summer solstice); about 10:00 to 14:00 LST on March 21 (the spring equinox) and September 21 (the autumn equinox); and not at all on December 21 (the winter solstice).

Third, the target must be large to ensure that nearly all reflected radiation collected by the downward-facing sensor comes from the target, rather than its surroundings. If a 3 cm diameter sensor is placed 50 cm above the center of a circular target, the target's diameter ϕ must be 3 m to yield a sensor-to-surface view factor F of 0.90; 4.4 m, for $F = 0.95$; or 10 m, for $F = 0.99$ (Siegel and Howell, 2002).