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Optical reflectance of pyrheliometer absorption cavities: progress towards SI-traceable measurements of solar irradiance

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Abstract

We have accurately determined the absorptance of three pyrheliometer cavities at 532 nm by measuring the residual reflectance using an angle-resolved bidirectional reflectometer. Measurements were performed at normal incidence as a function of viewing angle and position on the cavity cone. By numerically integrating the measured angle resolved scatter (ARS) over both direction and position and accounting for an obstructed view of the cavity, we determined that the effective cavity reflectance was between 8×10^{-4} and 9×10^{-4} . Thus, the absorptance of the three cavities ranged from 0.99909 ± 0.00014 to 0.99922 ± 0.00012 ($k = 2$ combined expanded uncertainties). These measurements, when extended over the spectral range of operation of the pyrheliometer, are required to establish SI traceability for absolute solar irradiance measurements.

1. INTRODUCTION

The accurate measurement of terrestrial solar irradiance levels is critical for a broad range of activities in solar energy, agriculture, climate monitoring, and meteorology.[1] In solar energy, solar irradiance data is used in optimizing the location of solar energy installations and projecting their power production. In agriculture, the data can be used to optimize crop production. Climate scientists and meteorologists use solar irradiance in developing models for atmospheric circulation and for monitoring ground irradiance to improve understanding of earth's energy budget.

Pyrheliometers measure direct, normal incidence solar irradiance using the electrical-substitution method, which compares solar heating of a highly absorbing cavity to the electrical power required to hold the cavity at the same temperature, thus giving an electrical signal that is proportional to solar irradiance. This is similar in principal to an absolute cryogenic radiometer (ACR), where the optical radiant power scale is directly traceable to the scale for electrical power in watts.[2] A precision aperture of known area in front of the cavity allows the pyrheliometer to report irradiance.

Measurements of irradiance using the electrical substitution method and a precision aperture can be traceable to the International System of Units (SI). However, for terrestrial solar

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irradiance measurements, a suite of cavity pyrheliometers called the World Standard Group (WSG) provides a scale that is used to define the World Radiometric Reference (WRR).[3] Solar irradiance measurements worldwide are tied back to the response of this reference group through periodic World Meteorological Organization (WMO) International Pyrheliometer Comparisons (IPC's) conducted at the Physikalisch Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC).[4] Comparisons between the WRR and the SI are technically challenging because while ACR's are operated in an underfilled mode with modest power levels of a few milliwatts, pyrheliometers are operated in an overfilled mode with total powers in the 10's of milliwatts.[5] Nonetheless, comparisons have been made periodically, and in the most recent comparison the WRR was found to be 0.34 % higher than the SI.[5] Because of this, and also because of attrition of the number of instruments in the WSG over time, we are investigating ways to establish direct SI traceability of pyrheliometers for solar irradiance measurements. An important step in establishing SI traceability is measurement of the absorptance of the pyrheliometer cavities.

In this work, we determined the absorptance of the cavities from three Eppley model AHF Pyrheliometers.[6] A schematic of a cavity is shown in Fig. 1. The cavities consist of an inverted cone, and the interior of the cavity, including the cone, is coated with black specular paint. Ideally, light that enters the cavity (incident from the left hand side of the drawing in Fig. 1) undergoes one of two processes: absorption or specular reflection. Light that is not absorbed is specularly reflected within the cavity, with each reflection successively lower in intensity until all of the light is absorbed. The absorption of the light causes a rise in the temperature of the cavity, which is proportional to the amount of light trapped within the cavity. The pyrheliometer determines the incident radiant power of the light trapped within the cavity from the temperature rise. A precision aperture (shown in the bottom drawings of Fig. 1) in front of the cavity, which is overfilled by the incident sunlight, defines a measurement area so that the solar irradiance can be computed from incident radiant power.

For perfect electrical substitution, all the incident radiant power goes towards optical heating of the cavity; that is, zero cavity reflectance. In fact, there is a small cavity reflectance that is primarily due to the diffuse component of reflection in the nominally specular paint.[2] The cavity reflectance is estimated by the manufacturer to be on the order of 1×10^{-3} . Measuring low levels of diffuse reflectance is challenging. There are no standards available for relative measurement, so absolute reflectance must be performed. A laser source is usually needed in order to produce sufficient scattered light for detection. However, a laser underfills the cavity; whereas in pyrheliometer operation, the cavity is uniformly illuminated. Past measurements of low reflectance cavities at infrared wavelengths have used a laser source and integrating sphere to collect all the diffuse reflectance, spatially mapped the cavity reflectance as a function of the position of the incident laser spot on the cavity, and then used the reflectance map to calculate reflectance for uniform illumination. However, these measurements required a specially designed integrating sphere to enable spatial scanning and numerous corrections to accurately measure low reflectance.[7] An alternative to integrating sphere measurements of diffuse reflectance is to make angle-resolved (goniometric) measurements of scattered light in the hemisphere above the sample, and integrate the measurement to hemispherical reflectance. This method for measuring diffuse reflectance has been performed in the past on high- and low-reflectance uniform samples.

[8-11] In this work, we extend the goniometric technique to cavity reflectance. We used a 532 nm laser source and a gonireflectometer,[12] which allows both spatial scanning of the cavity and angle-resolved measurement of reflectance, to measure the cavity reflectance as a function of viewing angle and illumination position on the cavity. We used these measurements to obtain values for directional hemispherical reflectance (DHR), ρ , as a function of radial position in the cavity, and present a model to calculate the effective cavity absorptance during pyrliometer operation from the DHR values. These measurements will be used as part of the validation of end-to-end efficiency of the pyrliometers, with the ultimate goal of SI-traceability of the instruments for solar irradiance.

2. MEASUREMENT APPARATUS

Reflectance measurements of the cavity were made using NIST's Goniometric Optical Scatter Instrument (GOSI). The instrument is capable of measuring reflectance and scattering at select laser wavelengths for nearly any angle of incidence θ_i and polar and azimuthal viewing angles (θ_r and ϕ_r) in the hemisphere above the sample.[13] These measurements included measurements of cavity reflectance at a fixed incident angle as a function of viewing angle and as a function of location within the cavity itself, allowing us to map the cavity reflectance radially. The set of results were then integrated to obtain a value for total cavity reflectance.

The pyrliometers were partially disassembled to allow access to the cavities and to mount them at the sample location at the center of the goniometer. The pyrliometers are illuminated at normal incidence when making solar irradiance measurements; thus, we chose $\theta_i = 0^\circ$. Additionally, the housing around the pyrliometers was quite large even when partially disassembled, restricting the safe motion of the goniometer. Consequently, we limited the goniometer motion to in-plane scanning of the viewing angle θ_r and small cavity translations (x, y) to map the cavity reflectance. A schematic of the geometry used is shown in Fig. 2.

The light source for the reflectance measurements was a chopped, linearly polarized 532 nm laser. The direction of the laser was fixed and propagated through the center of the goniometer, and the size of the incident laser spot at the cavity was measured to be approximately 0.25 mm wide by 0.5 mm high using a beam profiling camera. Scattered light from the cavity was collected by the receiver, which is mounted on a detector arm that orbits the center of the goniometer and allows the scattered light to be collected as a function of viewing angle θ_r . The receiver includes an aperture (A_r) of area $A_r = 38.375 \text{ mm}^2$ located a distance $D = 587 \text{ mm}$ from the center of the goniometer and a lens that focuses the scattered light to the opening of an integrating sphere (IS) fitted with two detectors: a silicon photodiode (PD) and a photomultiplier (PMT). When viewing the cavity, the receiver collects all of the scattered power P_r in the solid angle defined by $\Omega = A_r/D^2$. The receiver can also be positioned opposite the laser with the cavity removed, in order to measure the incident power P_i . The PD was used for the incident power measurements, while the PMT was used for the scatter measurements due to its higher sensitivity and lower noise floor. In both cases lock-in detection was used. The light scattered into a particular viewing angle θ_r is presented as angle resolved scatter (ARS) which is calculated from:

$$ARS(x, y, \theta_r) = \frac{P_r(x, y, \theta_r)}{P_i \Omega} \quad (1)$$

The ARS is the fraction of the incident light scattered per solid angle.[14] The variables x and y refer to the translation of the cavity. As shown in Fig. 2, we also translated the cavity by small distances x and y , in the plane perpendicular to the incident beam using the goniometer. This allowed us to measure ARS spatially, with the laser hitting different spots within the cavity. Measurements at each angle and position were also performed with both horizontally polarized light and vertically polarized light; the scattering results were averaged to obtain an unpolarized result for ARS.

As a final note, the distance D was measured from the center of the goniometer to the receiver aperture. Because the cavity has depth, D is not exactly the same as the distance from the illuminated area of the cavity to the aperture. The effect of this on the integrated results is minimal, however, and is discussed in Section 6.

3. DATA COLLECTION

Representative measurements of angle resolved scatter (ARS) are shown in Figs. 3(a) and 3(b). The measurements shown were made with the laser hitting either at the center of the cavity (approximately on the tip as shown in Fig 3(a)) or at a small translation of the cavity from the center (for example, when the laser entered the cavity 2 mm to the right of center as shown in Fig 3(b)). At each laser position, the viewing angle θ_r was varied from $\theta_r = -77^\circ$ to $\theta_r = +77^\circ$ in 2° steps. Negative values of θ_r correspond to geometries where the receiver is in the lower left of Fig. 2, and positive values where the receiver is in the upper left. $\theta_r = 0^\circ$ corresponds to viewing in the normal direction, in which case the receiver blocks the incident light, leading to the unmeasurable data around $\theta_r = 0^\circ$ seen in Fig. 3. The instrument noise floor in ARS was $< 10^{-7}$.

When the pyrheliometer precision aperture is in front of the cavity, it blocks the view for large viewing angles. Thus, measurements were made with and without the precision aperture on the cavity. In all cases, we restricted the locations inside of the cavity illuminated by the laser to be within the 8 mm diameter area that would be illuminated by sunlight during pyrheliometer operation when the precision aperture is in place. Fig. 3 shows collected angle-resolved scatter data with the cavity precision aperture on (open blue circles) and with the aperture off (red solid diamonds). While the ARS in Fig. 3(a) is relatively symmetric, when the laser is hitting 2 mm away from the tip of the cone, as in Fig. 3(b), the ARS pattern is asymmetric. Furthermore, since the laser hits the cone deep in the cavity, the cutoff from the aperture occurs at different angles. The feature near $\theta_r = 45^\circ$ in Fig. 3(b) is a reflection off the inside of the cavity's cylindrical wall that occurs on the same side of the cone that is illuminated by the laser.

The point-to-point variation in the data (for example, looking near $\theta_r = -20^\circ$ in Fig. 3(a)) is primarily due to laser speckle, which is quite large in these measurements due to the small size of the focused beam on the cavity surface.[14] We have observed that measurements

with a larger laser spot show significantly less point-to-point variation, but at the expense of spatial resolution in the reflectance measurements; also, the laser spot needs to be kept small so that light in the wings of the Gaussian laser spot does not significantly illuminate areas outside the cavity. The effect of the precision aperture on the effective cavity reflectance and efficiency will be further discussed in Section 5.

We took ARS data with the laser incident on multiple locations within the cavity in addition to the locations represented in Fig. 3. Fig. 4 shows a map of all the locations measured, each shown as an ellipse representing the incident laser position. In the figure, the dark grey area represents the inside of the cavity, and the lighter annulus surrounding it shows the size of the precision aperture and the size of the outside of the cavity cylinder. The figure is to scale, with the size of the ellipses approximately the size of the laser spot. The incident laser locations for the data shown in Fig. 3(a) and Fig. 3(b) are also indicated on the figure. The measurement locations formed three circles at radii of 1 mm, 2 mm, and 3 mm from the center, with 8 measurement points located around the circle at each radius. Additionally, one point at the cavity center was measured. Sets of ARS data were taken for both the aperture on and aperture off conditions.

4. DATA ANALYSIS

In this section, we discuss the method used to transform the ARS data, collected using laser light that underfills the cavity, into the total reflectance that is seen when the cavity is uniformly illuminated during operation as a pyrheliometer. We do this in two steps. First, we show that, for each radius, the 8 ARS measurements can be integrated to give the cavity reflectance for light incident at that radius. Second, we spatially average the radial dependence, including the single ARS measurement at the cavity center, to obtain the reflectance for a uniformly illuminated cavity.

In general, in order to calculate the fraction of incident light reflected by a surface into the full hemisphere above the surface, called the directional-hemispherical reflectance, or DHR, ρ , we need to measure all the light scattered into the hemisphere and integrate. Following [14] and [15], this integration is expressed by

$$\rho = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} f_r(\theta_r, \phi_r) \cos \theta_r \sin \theta_r d\theta_r d\phi_r \quad (2)$$

where f_r is the bidirectional reflectance distribution function (BRDF). The quantity we have measured, ARS, is equal to $f_r(\theta_r, \phi_r) \cos \theta_r$, giving

$$\rho = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} ARS(\theta_r, \phi_r) \sin \theta_r d\theta_r d\phi_r \quad (3)$$

The data for ARS shown in Fig. 3 is measured only in the horizontal plane, scanning only θ_r , with the ϕ_r dependence left unspecified. When the laser spot is incident at the center of the cavity as in Fig. 3(a), we assume that the circular symmetry of the cavity leads to an ARS

that is independent of ϕ_r . In this case, the DHR for light that hits the center of the cavity, $\rho_r=0$, can be approximated by

$$\rho_{r=0} = \pi \cdot \Delta\theta_r \sum_j \text{ARS}(\theta_{r,j}) |\sin \theta_{r,j}| \quad (4)$$

where $\theta_{r,j}$ are the sampled angles, $\Delta\theta_r$ is the spacing between the sampled angles, and we use the absolute value of $\sin \theta_{r,j}$ and a factor of π (as opposed to 2π) because we are including data for both positive and negative $\theta_{r,j}$. For the values of $\theta_{r,j}$ around 0° , the goniometer receiver blocks the incident beam. In preliminary observations, we did not observe any evidence for a specular peak or coherent backscattering from the pyrheliometer. In addition, as a multiple scattering phenomenon, coherent backscattering would not be expected to contribute significantly to the reflectance from a highly absorbing medium. [16] Thus, in integrating the ARS, we simply interpolated the data where the detector blocked the incident radiation. For $|\theta_{r,j}| > 77^\circ$, outside the measured angles, we assumed $\text{ARS}(\theta_{r,j})$ to be zero.

When the laser is incident on other areas of the cavity, such as shown in Fig. 3(b), the circular symmetry in the data is broken. Without circular symmetry, Eq. 4 measured in a single azimuthal plane is not sufficient to calculate DHR for that area of the cavity; we need to measure ARS in other azimuthal planes. The 8 positions measured at each radius from the center achieve this. Using the circular symmetry of the cavity, each set of 8 measurements at fixed radius from the center is equivalent to scanning $\text{ARS}(\theta_r)$ at different values of ϕ_r . The reflectance at a given radial position around the cavity center (equivalent to being able to illuminate with an annulus of light at 1 mm, 2 mm or 3 mm) is then given by

$$\rho_{r=x} = \frac{1}{8} \sum_{i=1}^8 \rho_{i,x} \quad (5)$$

where each $\rho_{i,x}$ is calculated from the $\text{ARS}(\theta_r)$ scan at the i th position around the circle at that radius (see Fig. 4) using Eq. 4.

Table 1 shows, the values of DHR when light was incident on the center of the cavity, $\rho_r=0$, and the DHR for light hitting the cavity at different radii, $\rho_r=x$. The DHR decreases as incident light moves radially outward from the cavity center; as the radius increases, the light beam strikes the cone deeper into the cavity and, presumably, undergoes more attenuating reflections before any light can escape the cavity opening. Furthermore, blemishes in the cavity coating scatter, and the deeper into the cavity that the initial beam strikes, the less scatter from these blemishes escape the cavity. The uniformly illuminated DHR value, ρ_{uniform} , shown in the last column of Table 1, is calculated using the area-weighted average of the center and radial values:

$$\rho_{\text{uniform}} = \frac{\sum_{i=0}^3 \rho_{r=i} \cdot w_i}{\sum_{i=0}^3 w_i} \quad (6)$$

where w_i is the area of each region. We took w_0 to be the area of the center circle of radius 0.5 mm, w_1 to be the area of the annulus between 0.5 mm and 1.5 mm radii, w_2 to be the area of the annulus between 1.5 mm and 2.5 mm radii, and w_3 to be the area of the annulus between 2.5 mm and 4.0 mm radii. The values of ρ_{uniform} represent the calculated reflectance of the cavity when uniformly illuminated by a circular beam with radius equal to the radius of the cavity's precision aperture. The values of ρ_{uniform} are lower when the precision aperture is on because the presence of the aperture blocks the view of a significant portion of the cavity interior. Calculation of the uncertainties shown in Table 1 will be discussed in Section 6.

5. CALCULATING CAVITY ABSORPTANCE FROM DHR

We now discuss the evaluation of the effective cavity absorptance during operation based on the values of ρ_{uniform} in Table 1. During pyrheliometer operation, the aperture is in front of the cavity, as shown in the bottom right of Fig. 1, and the cavity is uniformly illuminated by an 8 mm diameter beam defined by the size of the aperture. We wish to calculate the effective absorptance α_e , the fraction of the incident illumination that is absorbed by the cavity. The effective absorptance is related to the effective DHR by

$$\alpha_e = 1 - \rho_e \quad (7)$$

The effective DHR, ρ_e , represents all of the light that escapes the cavity. It is between the values of ρ_{uniform} with the aperture on and ρ_{uniform} with the aperture off, depending on how much of the light that escapes the cavity and hits the back of the aperture does not return to the cavity to be reabsorbed. Thus ρ_e has three components: reflected light that escapes through the front of the aperture, reflected light that impinges on the aperture and is absorbed by it, and reflected light that is scattered away from the cavity upon reflection from the aperture. We assume the light that is scattered or reflected by the aperture and returns into the cavity is fully absorbed.

We first consider the light that escapes through the front of the aperture, which is equal to ρ_{uniform} measured with the aperture on for each cavity and will be referred to as ρ_{on} . Although some return of this light into the cavity is possible (for example, if the light were to reflect or scatter off of baffles in the forward tube of the pyrheliometer), this effect is expected to be very small and will not be considered here.

The next source of escaped light is light that exits the cavity, but is absorbed by the back of the aperture. Light that is incident on the back of the aperture is the light that is seen in the goniometric measurement at large viewing angles with the aperture off, but is then blocked by the aperture when measuring with the aperture on. We assume that this light does not contribute to cavity heating; the aperture is not physically part of the cavity, and as the

amount of light impinging on the back of the aperture is very small, thermal re-emission due to a resulting change in aperture temperature[5] should be negligible. The fraction of incident light that impinges upon the back of the aperture is given by $\rho_{off} - \rho_{on}$, where ρ_{off} is equal to $\rho_{uniform}$ measured with the aperture off. In order to determine the aperture absorption, we measured the reflectance of one of the apertures using a commercial spectrophotometer in an 8°:di-configuration (that is, 8° angle of incidence, hemispherical collection with both specular and diffuse components included.)[17] The results of this reflectance measurement are shown in Fig. 5. At 532 nm, the reflectance was measured to be $\rho_{app} = 0.26$. This means that the aperture absorbs 74 % of the light incident upon it, giving an additional contribution of $\rho_{e,a} = 0.74(\rho_{off} - \rho_{on})$ to ρ_e . The remaining $0.26(\rho_{off} - \rho_{on})$ is reflected by the aperture.

The final loss mechanism considered is the small amount of light that is reflected by the aperture, but does not return to the cavity. From the measurements of Fig. 5, the aperture reflects 26 % of the light incident upon it. Referring to Fig. 1, the bevel of the rear surface of the aperture is such that light reflected by the aperture will tend to return to the cavity simply due to geometrical considerations. If the light returns to the cavity, we consider it to be absorbed and not contributing to ρ_e . However, depending upon incident angle and the aperture surface properties, some light can be scattered behind the cavity, contributing to ρ_e . We used a ZEMAX[6] ray tracing model to estimate this contribution. Fig. 6 shows the configuration of the model. An incident beam with a top-hat profile that just filled the area of the precision aperture illuminated the cavity. Two polar detectors, front and back, collect the flux that reaches them. For the front detector, dividing the reflected flux by the incident flux in the top hat beam gives the modeled DHR. Note that in the figure, the number of rays shown is pseudo-random and is not proportional to flux in that direction. The painted cavity surface was modeled to have 0.9 $\rho_{surface}$ specular reflectance and 0.1 $\rho_{surface}$ diffuse Lambertian reflectance, and the total reflectance of the coating $\rho_{surface}$ was adjusted until the modeled DHR seen on the front detector with aperture off and aperture on was approximately equal to the values of ρ_{off} and ρ_{on} that we determined from the measurements of the cavities. For the model, this occurred when we set $\rho_{surface} = 0.072$. For comparison, we also measured separate coupons coated with the same type of paint (Chemglaze Z-302) [6] using the commercial spectrophotometer in an 8°:di-configuration, and obtained directional-hemispherical reflectance of 0.05 to 0.055 with approximately 0.06 to 0.07 diffuse component at 532 nm. Differences between the model and measured values may arise because light is incident on the cavity cone at an angle of incidence greater than 8°, and the reflectance of Z-302 has been measured to increase with angle of incidence,[18] and/or because of differences in the cavity and coupon surface roughnesses. Since the purpose of the model was to reproduce the flux hitting the aperture as well as possible, we used $\rho_{surface} = 0.072$. We then looked at the flux seen at the back detector, which represents light that scatters away behind the cavity, with the aperture on using our measured aperture reflectance of 26 % and an assumption of this reflectance being distributed as 50 % specular, and 50 % Lambertian. From the model, the total fraction of light reflected from the cavity, which reflects from the aperture but does not get reabsorbed by the cavity, was $\rho_{e,b} = 5 \times 10^{-5}$. That same fraction was assumed to be scattered behind the cavity in the pyrheliometers, adding to ρ_e .

The total effective DHR of each cavity is $\rho_e = \rho_{on} + \rho_{e,a} + \rho_{e,b}$. Table 2 summarizes the contributions to ρ_e . For each cavity, the first two columns show ρ_{off} and ρ_{on} , which were taken from the values of $\rho_{uniform}$ of Table 1. All the cavities were found to have greater than 0.999 absorptance α_e , which was calculated from ρ_e using Eq. 7. Uncertainty will be discussed in the next section.

6. UNCERTAINTY CONSIDERATIONS

In this section we first consider the uncertainty in integrating $ARS(\theta_{r,j})$ to an individual value $\rho_i=0$ or $\rho_{i,x}$ from the uncertainties inherent in the goniometric measurements. We then propagate this uncertainty to the uncertainty in $\rho_{uniform}$ following Eqs. 4-6. We will show that while the relative standard uncertainty $u(\rho_{uniform})/\rho_{uniform}$ that arises from the goniometer measurement uncertainties is at the 1 % level, the final combined uncertainty in $\rho_{uniform}$ is considerably larger and is dominated by factors that are more difficult to estimate, such as pyrheliometer cavity nonuniformity and errors due to the relative sparseness of the data points in the spatial cavity scans. We attempt to estimate these uncertainties using several methods, present the resulting uncertainty in $\rho_{uniform}$, and finally discuss the resulting uncertainties in effective cavity DHR, ρ_e , and cavity absorptance, α_e .

We start with Eq. 1. The uncertainty in $ARS(\theta_{r,j})$ at each viewing angle follows previous uncertainty estimates for GOSI; [8] note that a standard uncertainty $u(y)$ in a general measurand y means that the value with its standard uncertainty (coverage factor $k = 1$) is $y \pm u(y)$. [19] We also often use the relative standard uncertainty $u(y)/y$. For this work, the dominant uncertainty terms in an individual point $ARS(\theta_{r,j})$ are the uncertainty in the incident power, P_i , at $u(P_i)/P_i = 0.3$ %; the uncertainty in the detector linearity, $u(P_r/P_i)/(P_r/P_i) = 1$ %; and uncertainty in the scattered power, P_r , at $u(P_r)/P_r = 9.8$ %. The relative uncertainty contributions from the geometrical factors D and A_r are each less than 0.1%. [8] Detector linearity uncertainty arises from the electronics used to measure P_r/P_i ; there are many orders of magnitude of signal level between incident power and reflected power, and we must also transfer the calibration from a photodiode (used for measuring P_i) to a PMT (used for measuring P_r). The uncertainty in P_r is dominated by laser speckle produced by the interaction of the focused, coherent laser source with the surface roughness. As discussed in [8], we estimated $u(P_r)/P_r$ based on the standard deviation of a flat area of a typical ARS plot with viewing angle.

In order to calculate the uncertainty in $\rho_i=0$ or an individual $\rho_{i,x}$ of Eq. 4 from integration of a scan of $ARS(\theta_{r,j})$ we must treat the random, uncorrelated components of uncertainty in each point of $ARS(\theta_{r,j})$ separately from the systematic uncertainty components. [8] The random uncertainty component is the laser speckle. While the relative uncertainty component in a single value of $ARS(\theta_{r,j})$ due to speckle is 9.8%, the relative uncertainty in $\rho_i=0$ or $\rho_{i,x}$ due to speckle is considerably lower because random errors integrate out. On the other hand, systematic errors that cause correlated changes in all the $ARS(\theta_{r,j})$ points (for example, if the incident power measurement is low for all points in an $ARS(\theta_{r,j})$ scan) are not reduced upon integration, so that a given relative uncertainty in a systematic error like P_i leads to the same relative uncertainty in $\rho_i=0$ or $\rho_{i,x}$. We treat the incident power and detector linearity uncertainties as systematic and correlated. We also considered two more

subtle potential uncertainty contributions: the depth of the pyrheliometer cavity, and the uncertainty $u(\theta_r) = 0.2^\circ$, which is primarily an angular alignment uncertainty that would shift all values of θ_r in the same direction. First, we use the aperture distance D in the calculation of ARS. One might initially consider that the roughly 10 mm depth of the cavity would directly lead to errors in $\rho_r=0$ and $\rho_{i,x}$ because this distance changes as the light is incident at different spots down the cone of the cavity. This error, however, cancels out when summing $ARS(\theta_{r,j})$ in Eq. 4, because the position of the sample back from the goniometer center systematically shifts both D and θ_r , leading to calculation over the same fraction of the hemispherical surface above the sample as if the sample were at the goniometer center. For the angular alignment, we simulated a shift in θ_r of 0.2° and found that the typical relative change in a $\rho_r=0$ or $\rho_{i,x}$ result was $< 0.05\%$, an insignificant source of error. Continuing the uncertainty analysis through Eqs. 5 and 6 to compute $u(\rho_{uniform})/\rho_{uniform}$, the multiple values of $\rho_{i,x}$ in Eq. 5 and $\rho_r=x$ in Eq. 6 reduce the random component of relative uncertainty in $u(\rho_{uniform})/\rho_{uniform}$ to 0.4% ; the systematic component of relative uncertainty in $u(\rho_{uniform})/\rho_{uniform}$ is 1.0% from adding the relative uncertainties from incident power and linearity in quadrature. Finally, assuming no uncertainty in the areas w_i of Eq. 6 and combining the systematic and random uncertainty components gives a total relative uncertainty $u(\rho_{uniform})/\rho_{uniform} = 1.1\%$.

The above calculated value for $u(\rho_{uniform})/\rho_{uniform}$ is quite low. However, we stress that this value indicates the uncertainties assuming there are no sample-dependent uncertainty contributions or uncertainties arising from the coarseness of the numerical integration represented by Eq. 6. We now attempt to evaluate these uncertainties.

We identified two uncertainty contributions related to cavity uniformity. The first is the centering of the tip of the cone at the $(x,y) = (0,0)$ measurement point, which was defined by the center of the pyrheliometer precision aperture. The tip of the cone may not be at exactly $(0,0)$, as a result of which our measurements could miss the tip. While the effect of the tip reflectance on $\rho_{uniform}$ is fairly small due to the small area of the tip, the tip also tends to be the most reflective part of the cavity. For one cavity, the tip appeared to be slightly off of center, so we translated that cavity to look for the position with the largest reflected signal and re-scanned ARS at that position. From this process we estimate a relative uncertainty contribution of 3% to $\rho_{uniform}$ due to tip centering. There is also the question of the uniformity of response over the rest of the cavity, which would have to be perfectly circularly symmetric with no areas of anomalously high or low reflectivity that we might inadvertently sample. We attempted to quantify this by looking at the values of $\rho_{i,x}$ calculated from symmetric positions on the cone; for example, at $x=2$ mm, $y=0$ mm compared to $x=-2$ mm, $y=0$ mm, which we would expect to be equal. We used a cavity where the cone appeared to be well-centered on the precision aperture and found typical variation of 4.5% . Assuming the uniformity is a random error source, after the averaging and area weighting of Eqs. 5 and 6, we estimate this gives a relative standard uncertainty contribution of 1% to $\rho_{uniform}$. Combining the uniformity uncertainties, we assigned a total relative standard uncertainty of 3% for cavity uniformity.

Finally, there is the potential for error due to the coarseness of the spatial resolution in our measurements of the cavity reflectance. While we are estimating the reflectance for light

incident upon a 50 mm² area, we have only measured this reflectance sampled over a limited area of 9.8 mm², and we integrated in a very coarse manner, assuming, for example, that $\rho_r=2$ is the fixed DHR value for light incident at any radius between 1.5 mm and 2.5 mm from the center. If, instead, we fit the $\rho_r=x$ values ad hoc to a second order polynomial and integrate with a much finer step, we find different values for $\rho_{uniform}$. Following this procedure we estimate the relative standard uncertainty in $\rho_{uniform}$ from numerical integration to be 7 %.

Adding all the relative uncertainty terms in quadrature, we estimate the $k = 1$ combined relative uncertainty in $\rho_{uniform}$, $u_c(\rho_{uniform})/\rho_{uniform}$, to be 7.5 %. Most of this uncertainty comes from the coarseness of the spatial sampling and the cavity uniformity, not from the intrinsic uncertainty of the goniometer measurements, leaving room for future improvement. The resulting $k = 2$ expanded uncertainties $U(\rho_{uniform}) = 2 u_c(\rho_{uniform})$ are shown with the values of $\rho_{uniform}$ in Table 1.

Having calculated the uncertainty in $\rho_{uniform}$, it is straightforward to propagate uncertainty to the effective reflectance, ρ_e , and absorptance, α_e following the equations of Section 5. We estimate the value and standard uncertainty of the aperture absorption to be 0.74 ± 0.02 . For the value and standard uncertainty in the light scattered outside of the cavity by the aperture, we estimate $(5.0 \pm 0.6) \times 10^{-5}$ from variations in the amount of scattering calculated in the model when the scattering fraction was changed. The final values of ρ_e and α_e with $k = 2$ expanded uncertainties $U(\rho_e)$ and $U(\alpha_e)$ are shown in Table 2.

7. SUMMARY AND FUTURE WORK

In this paper, we demonstrate that spatial- and angle-resolved goniometric reflectance measurements of a pyrheliometer cavity can be used to spatially map the DHR of the cavity, and we present a model that uses the measured DHR, with and without the cavity precision aperture in place, and information about the absorption and scattering of the precision aperture to predict the effective DHR, ρ_e , and absorptance α_e of the cavity during pyrheliometer operation. The values of α_e in Table 2 are in good agreement with the manufacturer's estimates for these cavities. While it is not known if α_e is a source of the discrepancy between the cavities of the WSG and the SI, measurements of α_e will be used in support of establishing SI traceability for future solar irradiance measurements made with pyrheliometers.

A typical value and expanded uncertainty of ρ_e is $(8.1 \pm 1.3) \times 10^{-4}$ which is roughly 16 % relative expanded uncertainty. This uncertainty is dominated by the coarseness of the spatial scan and cavity uniformity, with smaller contributions from instrument linearity and uncertainty in the properties of the precision aperture surface. Because $\alpha_e = 1 - \rho_e$, this DHR accuracy translates to a typical $\alpha_e = 0.99919 \pm 0.00013$ which is sufficient accuracy to support our initial goal of validating the end-to-end efficiency of the pyrheliometers. It should be noted that these uncertainties assume the validity of the model presented in Section 5 for the way the presence of the precision aperture affects ρ_e and the completeness of our estimate of cavity-dependent uncertainties in $\rho_{uniform}$. We also note that cavity absorptance is only one of the components that can contribute to uncertainty in solar

irradiance measurements. Other factors, such as diffraction, lead heating, scattered light, electronics, and aperture-related uncertainties must be considered when establishing a full uncertainty budget for the pyrheliometers.[1,5]

Going forward, we will need to consider how the single wavelength measurements presented here translate to the cavity when used with broadband solar irradiance. These effects will include the wavelength dependence of both cavity DHR (ρ_{on} and ρ_{off}) and of the precision aperture optical properties. Of these, the aperture absorption and scattering will be more significant. The cavity itself gets its low DHR value from the exponential decrease in flux after multiple specular reflections, and the DHR is typically only weakly dependent upon the exact reflectance value of the interior coating reflectance, $\rho_{surface}$. [2] Our model for ρ_e , on the other hand, directly depends the absorptance (which is $1 - \rho_{app}$) of the precision aperture, which has significant wavelength dependence as seen in Fig. 5. Measurements of ρ_{on} and ρ_{off} at multiple wavelengths throughout the solar spectrum as well as an exploration of the relative pyrheliometer efficiency at different wavelengths, while time-consuming, would be useful in confirming our model. In the near term, the 3 pyrheliometers have been re-assembled and are being tested. It may be possible to operate each cavity in pyrheliometer mode using a laser source of suitable power, scanning the cavity to compare the spatial map of the absorptance/reflectance to relative pyrheliometer efficiency when light hits different spots in the cavity. It may also be possible to generate effectively uniform laser illumination using a scanning mirror – an approach that has been used in calibrating space-bound pyrheliometers[20] – and measure ARS for a fully illuminated cavity. This would allow determination of $\rho_{uniform}$ without the step of spatially averaging multiple measurements, and comparisons of pyrheliometer efficiency with a fully illuminated cavity to that with an under-illuminated cavity. Future work could also include reflectance characterization of other cavity designs. Finally, goniometric measurements of angle-resolved scatter and integration to DHR for other low-reflectance samples, such as carbon nanotube absorbers and novel low-reflectance solar cell materials, are planned.

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Fig. 1.

Schematic of a pyr heliometer cavity. On the top, a cross section view of the cavity alone is shown. While appearing grey in the diagram, the inside of the actual cavity is coated with a specular black paint. During operation, light is incident from the left side of the drawing. On the bottom, the cavity is shown as it would be used during pyr heliometer operation, with an 8 mm diameter precision aperture installed in front of the cavity to define the area for irradiance measurements. The aperture has a beveled rear surface that can be seen in the rear view.

Fig. 2. GOSI configuration for cavity reflectance measurements (not to scale). In the inset photo, the cavity is shown illuminated at its center with the precision aperture removed.

Fig. 3.

Typical angle resolved scatter (ARS) data taken (a) with the laser incident at approximately the center (tip) of the cavity, and (b) with the laser incident 2 mm away from the tip.

Fig. 4. Map of laser incident spots that were measured within the cavity, as viewed looking into the front of the cavity. The detector plane was horizontal.

Fig. 5.
8°:di reflectance of one of the precision apertures versus wavelength. Inset: image of the rear surface of the aperture.

Fig. 6. Configuration of ray trace model for estimating light scattered away behind the cavity, as described in the text.

Table 1

Directional-hemispherical reflectance versus radial position from center of the cavity, $\rho_r = x$, or with uniform illumination, $\rho_{uniform}$, and as a function of whether its precision aperture is on, or off during the measurement, for the three cavities measured. The numbers in parentheses under the $\rho_{uniform}$ values are the $k = 2$ combined expanded uncertainties, whose calculations are described in Section 6.

Cavity	Aperture	$\rho_r=0$	$\rho_r=1$	$\rho_r=2$	$\rho_r=3$	$\rho_{uniform}$ [$U(\rho_{uniform})$]
1	off	3.68×10^{-3}	1.9×10^{-3}	9.3×10^{-4}	5.8×10^{-4}	8.8×10^{-4} [1.3×10^{-4}]
	on	1.48×10^{-3}	6.2×10^{-4}	3.8×10^{-4}	3.5×10^{-4}	4.1×10^{-4} [0.6×10^{-4}]
2	off	2.79×10^{-3}	1.58×10^{-3}	9.3×10^{-4}	6.0×10^{-4}	8.4×10^{-4} [1.3×10^{-4}]
	on	9.2×10^{-4}	5.5×10^{-4}	3.7×10^{-4}	4.0×10^{-4}	4.2×10^{-4} [0.6×10^{-4}]
3	off	3.63×10^{-3}	2.36×10^{-3}	1.01×10^{-3}	6.5×10^{-4}	1.00×10^{-3} [0.15×10^{-3}]
	on	1.62×10^{-3}	7.5×10^{-4}	4.1×10^{-4}	3.9×10^{-4}	4.6×10^{-4} [0.7×10^{-4}]

Table 2

Contributions used calculate the final effective DHR for the cavity, ρ_e , and the effective absorptance α_e as described in the text. The numbers in parentheses under the ρ_e and α_e values are the $k = 2$ combined expanded uncertainties, whose calculations are described in the text.

Cavity	ρ_{off}	ρ_{on}	$\rho_{e,a}$	$\rho_{e,b}$	ρ_e [$U(\rho_e)$]	α_e [$U(\alpha_e)$]
1	8.8×10^{-4}	4.1×10^{-4}	3.5×10^{-4}	5×10^{-5}	8.1×10^{-4} [1.3×10^{-4}]	0.99919 [0.00013]
2	8.4×10^{-4}	4.2×10^{-4}	3.1×10^{-4}	5×10^{-5}	7.8×10^{-4} [1.2×10^{-4}]	0.99922 [0.00012]
3	1.00×10^{-3}	4.6×10^{-4}	4.0×10^{-4}	5×10^{-5}	9.1×10^{-4} [1.4×10^{-4}]	0.99909 [0.00014]