Goniometric measurements of sub-0.1% reflectance pyrheliometer cavities

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Outline

- Surface solar irradiance measurements using pyrheliometers and the WRR
- Goniometric measurements of pyrheliometer cavities
- Measurement results and integration to directional-hemispherical reflectance (DHR)
- Interpretation: ZEMAX* modeling and treatment of aperture effects
- Additional measurements and modeling
- Conclusions

*Certain commercial products are identified in this talk in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the products identified are necessarily the best available for the purpose.

Surface Solar Irradiance and the WRR

Measuring Solar Irradiance

Cavity Pyrheliometer
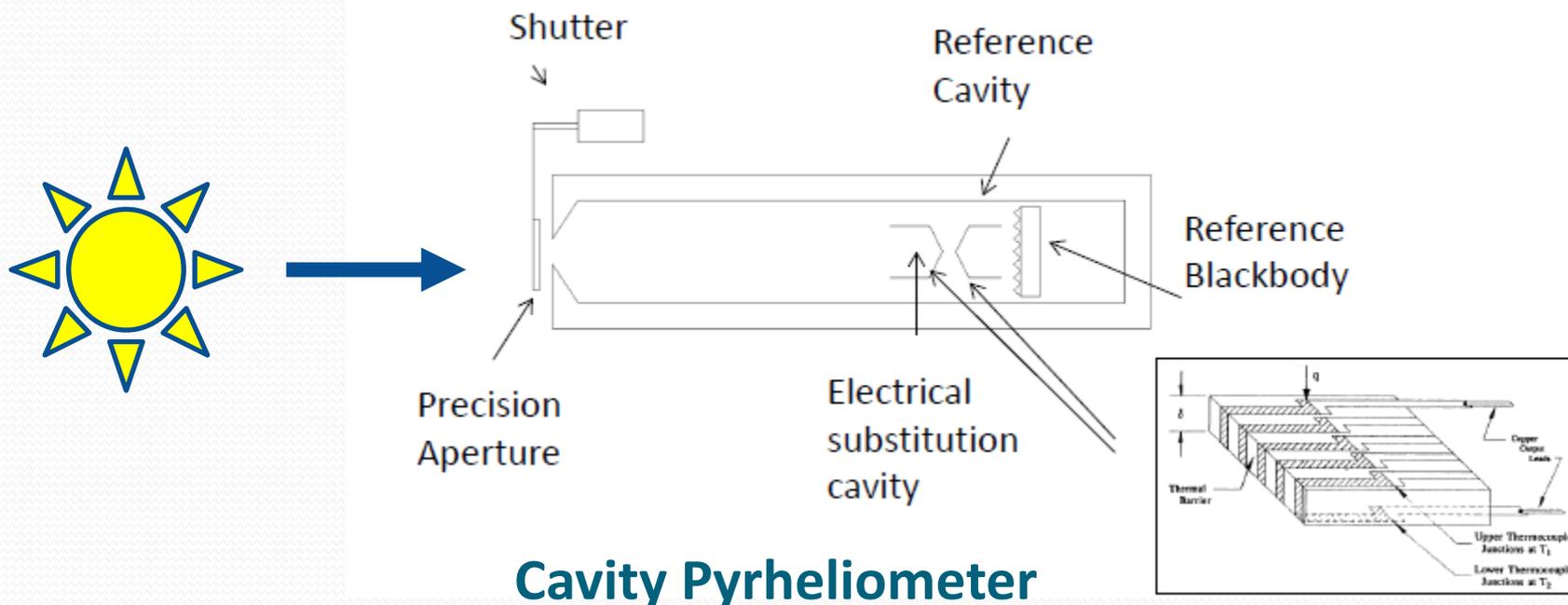
Using calorimetry, the temperature rise using the thermopile in the measuring cavity is determined. The shutter is closed and the electrical power is applied to get the matching rise in temperature.

- Broadband
- Can be absolute
- Traceable to SI through electrical units

WRR (World Radiometric Reference)

An International Pyrheliometer Convention (IPC) being held in Davos, Switzerland.

- Conventional scale for terrestrial solar irradiance
- World Standard Group (WSG) of 6 pyrheliometers (down from 17)
- World Radiometric Reference (WRR) is mean of WSG
- IPC held every 5 years to calibrate other pyrheliometers to WRR
- Not SI traceable, estimated 0.3% offset from SI
- Want to investigate SI traceability for terrestrial solar measurements

NIST Goals
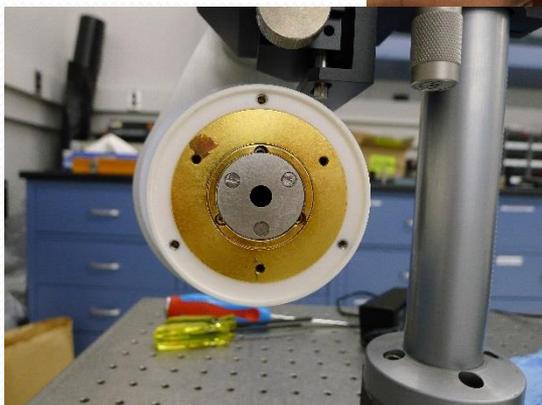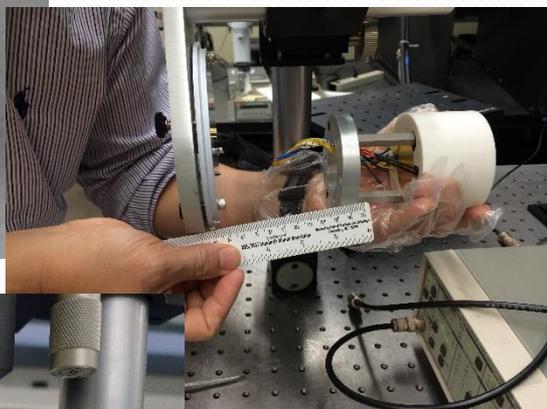
Eppley AHF, assembled (top), disassembled for cavity reflectance measurements (middle), and front view of cavity with aperture (bottom)

- Set of 3 Eppley AHF pyrheliometers purchased

Establish traceability of pyrheliometers to SI

Challenges

- Standard irradiance lamps too low power
- NIST ACR's operate underfilled (power mode) at lower powers; pyrheliometers in irradiance mode

Initial approach

- Characterize pyrheliometer components from the ground up

Goniometric Measurements of Cavities

Measuring Pyrheliometer Cavity Reflectance
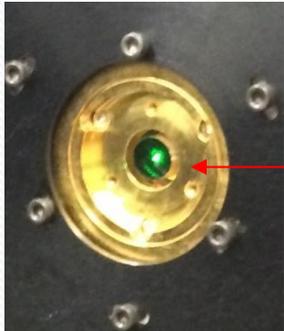
Why measure?

Conversion of light to heat depends directly on cavity absorptance   (absorptance = 1 – reflectance)

Cavity held here

From laser P_i

P_r

Out-of-plane sample rotations (not used)

Sample rotation

Receiver in reflection/scatter position

Receiver arm rotation

Receiver (in incident light position)

GOSI

How to measure?

- **Sphere-based:** fast, spectrally multiplexed, collect directional-hemispherical (DHR) in one step, requires corrections, poor SNR, visible system optimized for white 2" samples and needs reference sample

- **Goniometric (GOSI):** great SNR with laser and PMT, slow, few wavelengths, requires measurement at many points integrated to DHR, flexible sample and beam size, absolute
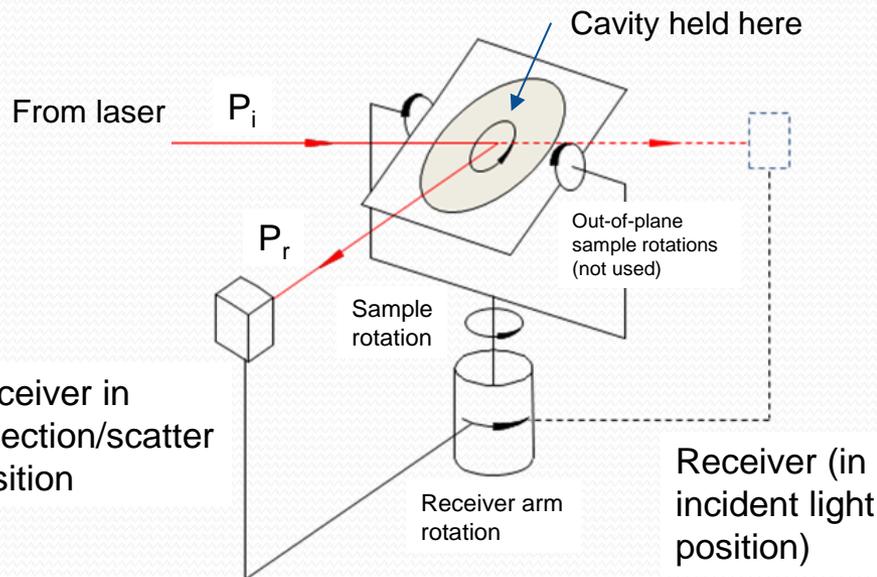
Used Goniometric Optical Scatter Instrument (GOSI) due to its high SNR, scanning capabilities and ability to measure absolute reflectance

Setup

Front View

Translate cavity to sample reflectance over its area

Cavity held at GOSI center

Top View Schematic

Incident beam at 532 nm, polarized, focused, 0.25 mm x 0.5 mm diameter, underfilling cavity

cavity

aperture

θ_s positive

θ_s negative

$\theta_i = 0$
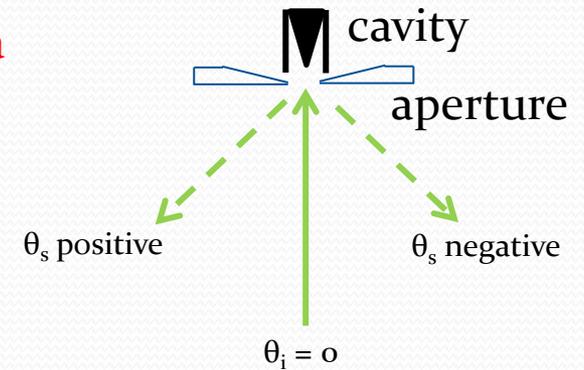
GOSI incident (θ_i) and view (θ_s) angles, from above

- Scan θ_s (receiver arm view position) with $\theta_i = 0°$
- Translate cavity to sample reflectance at different positions
- Reflectance measured aperture on and with aperture off

Example Measurement, BRDF vs. θ_s

Pyrheliometer, centered, unpol

◆ no aperture   ☐ with aperture

BRDF vs Scattering Angle, degrees
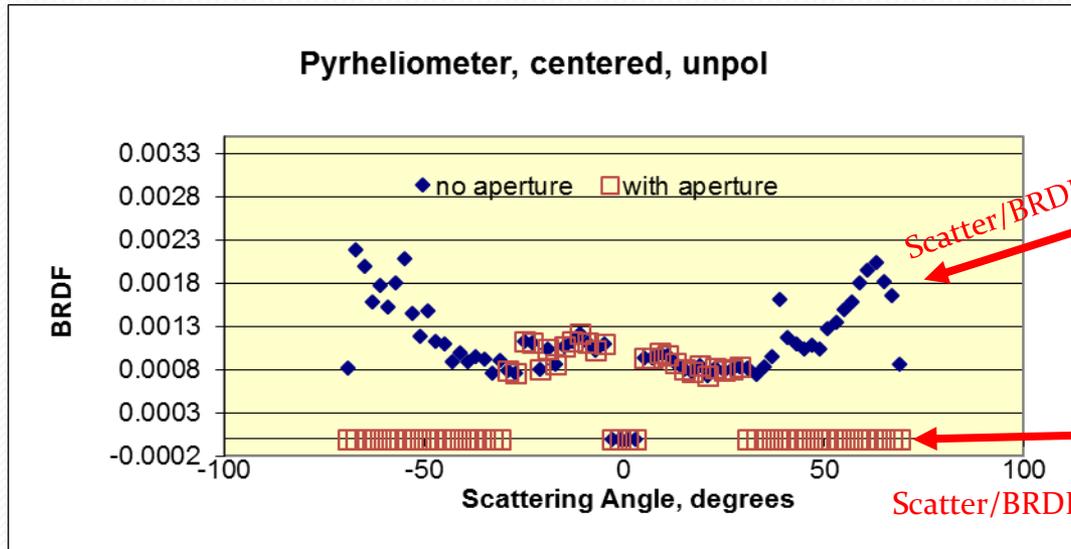
Scatter/BRDF seen without aperture
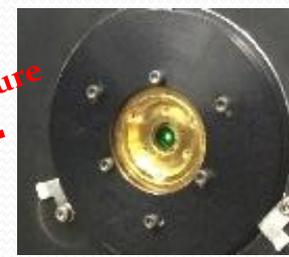
*Scatter/BRDF seen **with aperture***
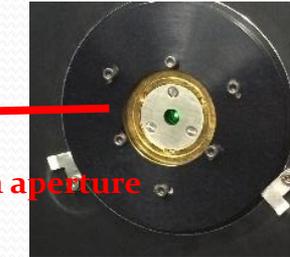
Gonio outputs BRDF: $\text{BRDF} = \dfrac{P_r}{P_i \Omega \cos \theta_s}$ $\Omega = \dfrac{\pi r^2}{R^2}$

- BRDF is reflectance captured in the receiver solid angle Ω
- BRDF vs θ_s integrates to directional-hemispherical reflectance (DHR)

Measured cavity aperture on and aperture off. Will later show model for how to treat when calculating effective cavity absorptance.

Aperture on vs. off

View angles to cavity limited when aperture on
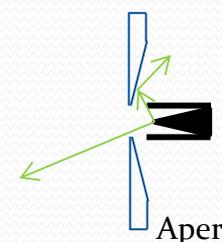
We want to measure this light, too! So also measure aperture off.

Aperture sits in front of cavity

Measurement results and integration of BRDF to DHR

Procedure

- At each cavity position, measure in-plane BRDF at normal incidence
- Raster scan cavity; a circle of 8 positions at radius of 1 mm, 2 mm, and 3 mm from aperture center
- Make the measurements with aperture on, and aperture off
- Integrate each point's BRDF (f_r) to DHR(single)

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

$$= \pi * \Delta\theta_r \sum_j f_j \cos(\theta_j) \sin(abs(\theta_j))$$

- Report average value of the 8 DHR's at each radius from cavity center: DHR(radial)
- Calculate the expected DHR if the beam were uniform and filling the aperture, by using an area-weighted average of the results from each radius: DHR(uniform)

Measurement Positions and Integration to DHR(radial)

Center
Off: 0.368%
On: 0.148%

1 mm radius
Off: 0.190%
On: 0.062%

2 mm radius
Off: 0.093%
On: 0.038%

3 mm radius
Off: 0.058%
On: 0.035%

Aperture (if attached)
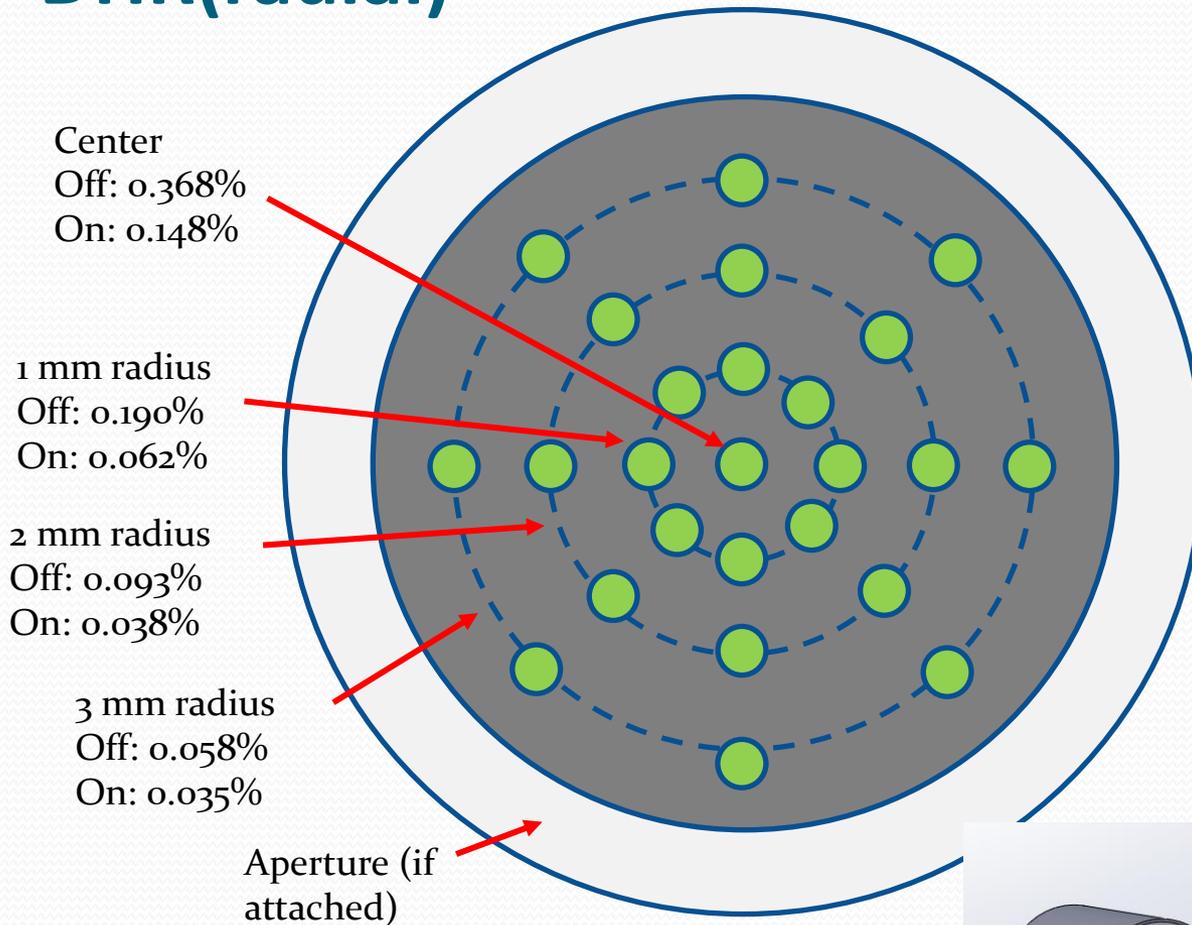
- Green circles show points measured in cavity, also meant to roughly indicate relative size of laser spot to cavity
- Integrate in-plane BRDF from different parts of cavity to DHR(single)
- At each radius, calculate an DHR(radial) from 8 average of DHR(single) points is shown
- Example DHR(radial) values shown for cavity 1 (AHF 36769), aperture off or on

DHR decreases with distance from cavity center, with highest DHR at center; off cone tip
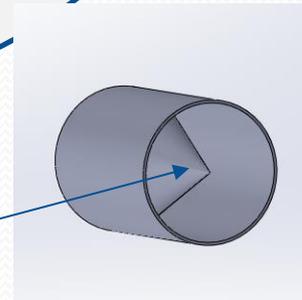
How to calculate DHR(uniform)

ctr

Region 1

Region 2

Region 3

Aperture Edge
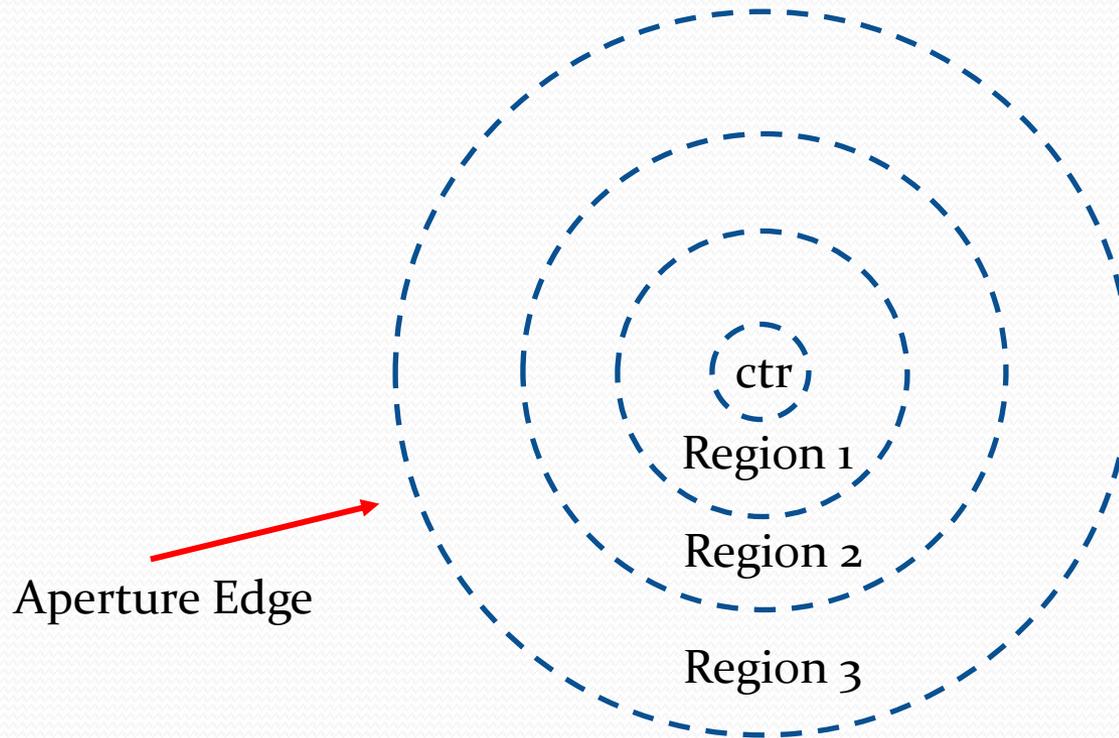
- Take DHR(radial) for each illuminated region
- Compute area-weighted average to give DHR(uniform)

DHR(uniform) for AHF 36769:
Aperture on: 0.041%
Aperture off: 0.090%

DHR(uniform) Summary

	Aperture Off	Aperture On
AHF 36769	0.090%	0.041%
AHF 36770	0.090%	0.043%
AHF 36771	0.103%	0.046%

- Repeatability:
    - DHR(single) from BRDF at center cavity position repeats to +/- 2% k=1.
    - We average many points to get DHR(uniform), so expect it to be better than 1% repeatable
- Believe the difference between 71 and 69, 70 would be reproducible
- Accuracy being evaluated (roughly +/- 5% k=1)
    - Cavity uniformity
    - PMT linearity
    - Coarseness of spatial scan, algorithm used to get DHR(uniform) from DHR(individual)

Recall that: absorptance = 1 – DHR(uniform)

What value of DHR(uniform) is appropriate for calculating cavity effective absorptance?

Zemax Model

Cavity Model
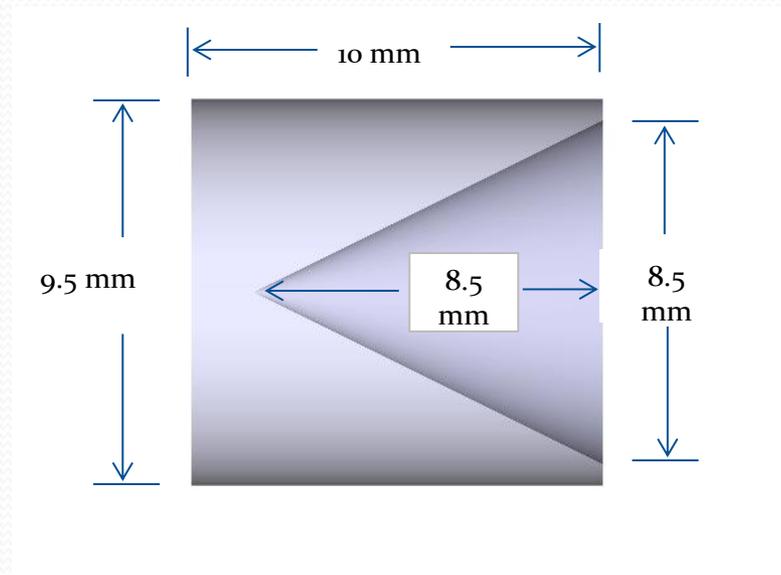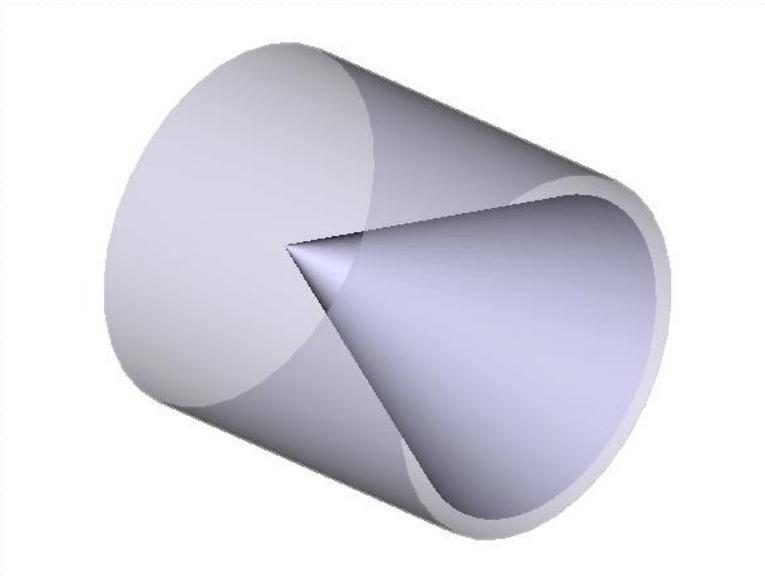
- Measurements good to ~ 0.5 mm
- Cavity coating:
  - 4.5% total reflectance
  - Of the total, 90% specular (independent of incident angle), 10% scattered (ideal Lambertian)
  - We have varied scattered fraction from 5% to 20% and found best in-plane BRDF match around 10%
  - These numbers not quite same as 8:di measured numbers but are a starting point

Introduce a virtual 532 nm laser beam and a Far-Field polar detector…
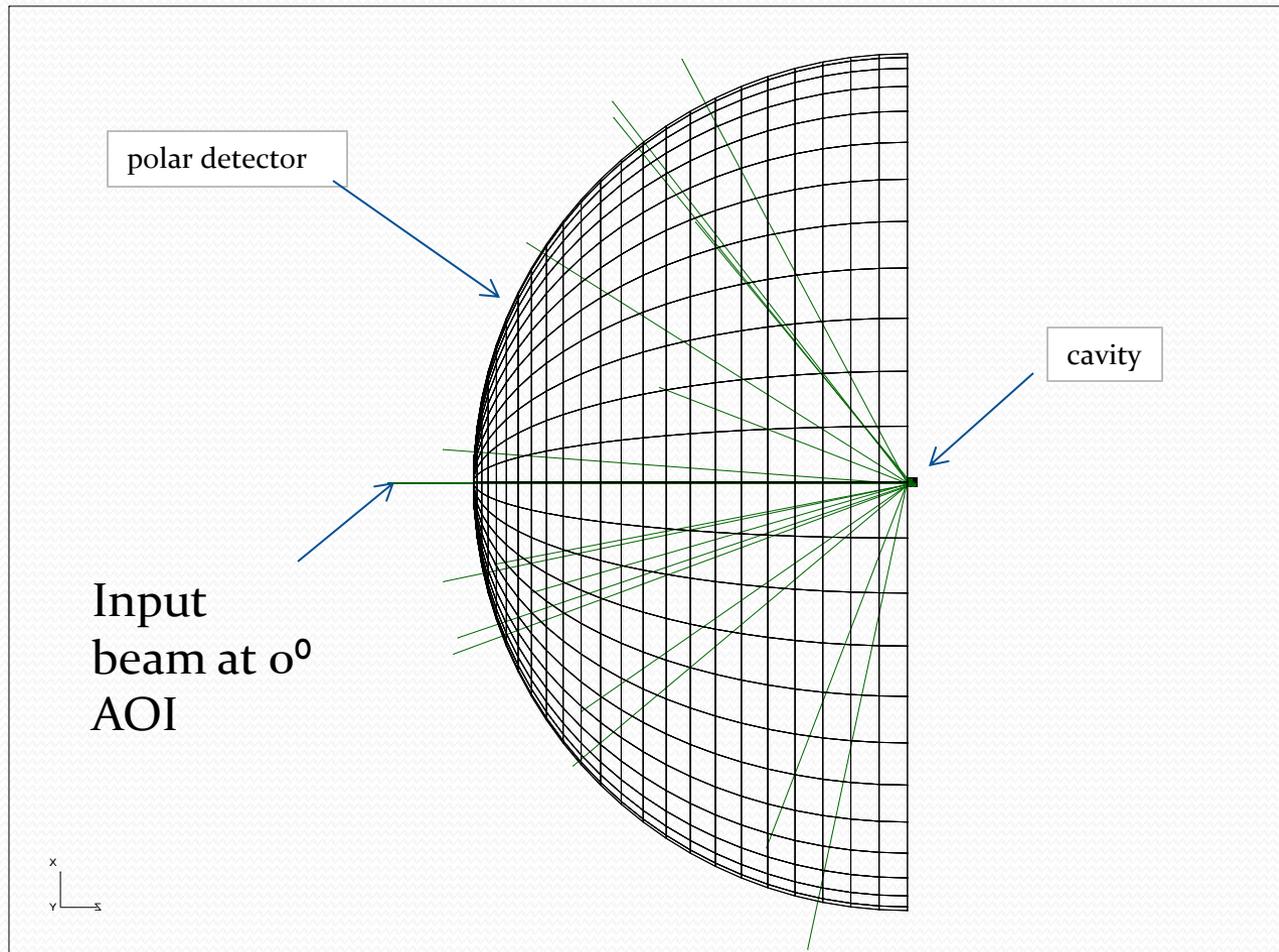
Modeled DHR vs. radial beam position, Aperture OFF
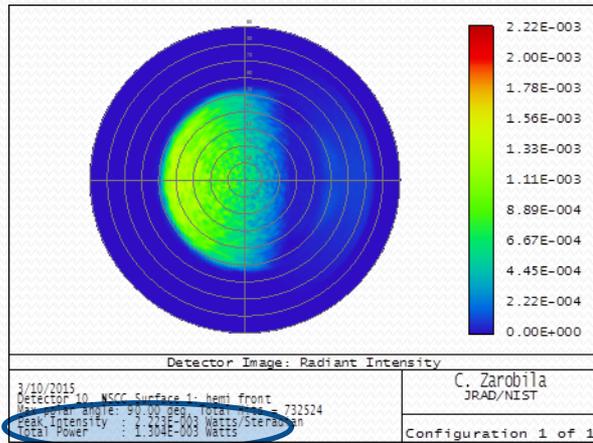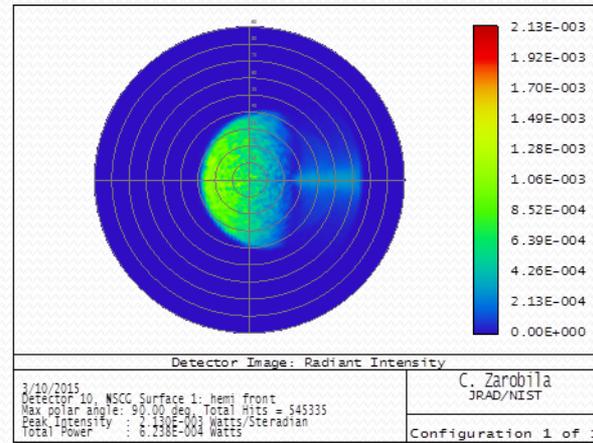
1 mm	2 mm	3 mm
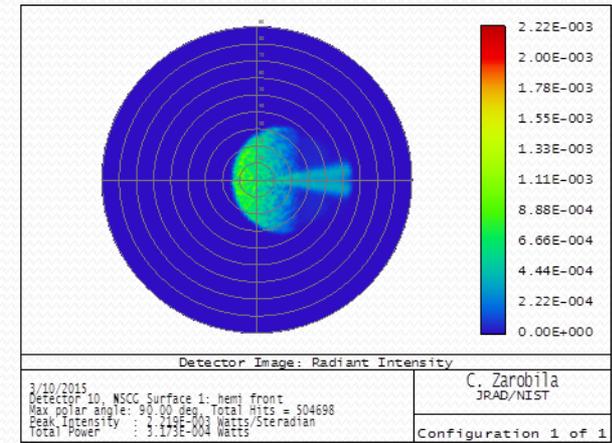
DHR = 0.13 %   DHR = 0.06 %   DHR = 0.03 %

- Incident laser underfilling aperture at 1 mm, 2 mm, 3 mm offset from center, similar to Gaussian beam in experiment
- Zemax integrates power on detector; gives DHR
- These should be compared to the measured DHR(radial) values
- For comparison, AHF 36769 measured for DHR(radial)
  - MEASURED: 1 mm, 0.19%, 2 mm 0.093%, 3 mm 0.058%
  - Similar trend between model/measured, decreasing DHR with radial position

Add Aperture to Cavity

32 mm

19.5 mm

7.6 mm

3.55 mm
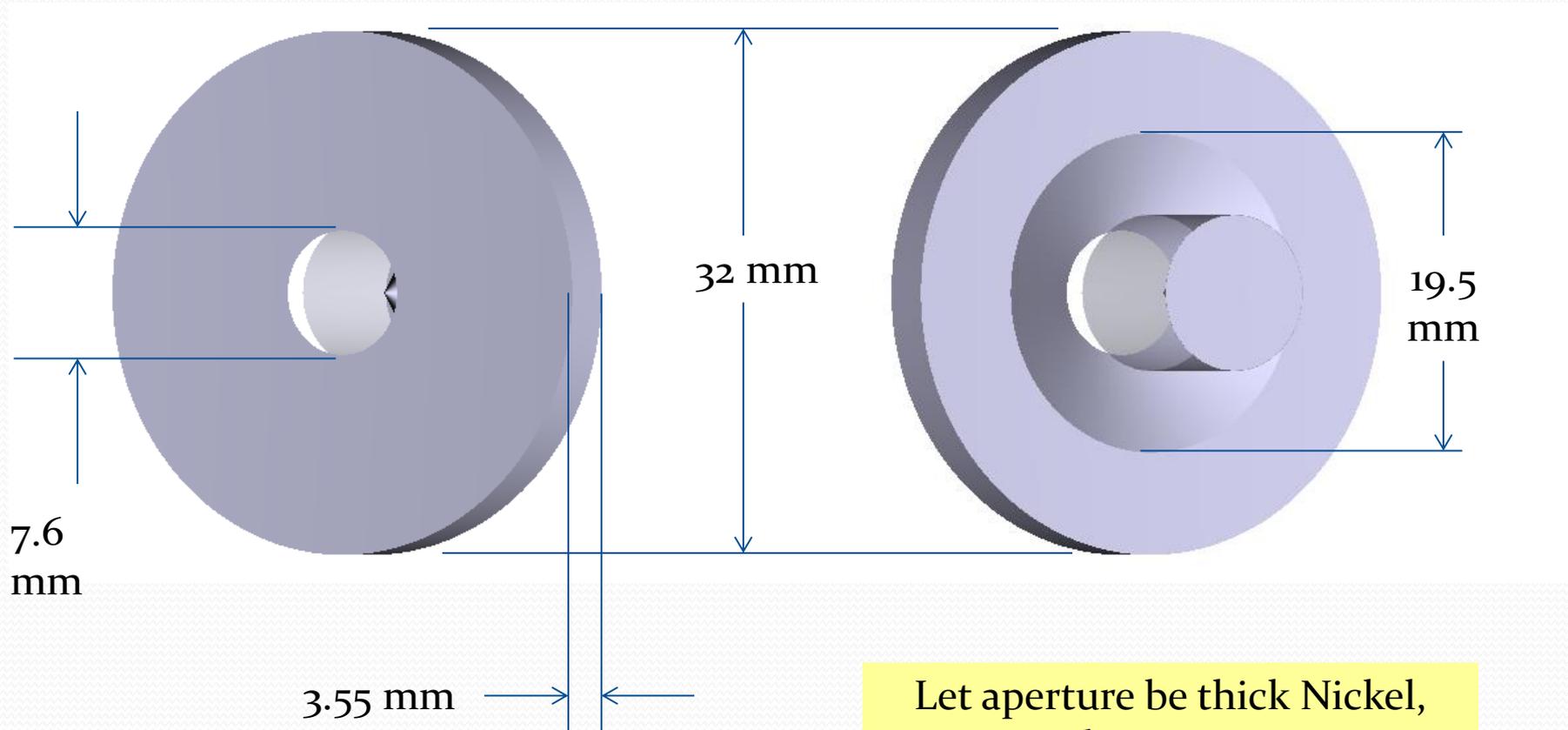
Let aperture be thick Nickel,
n = 1.7764, k = -3.1776 @ 532 nm
Let scatter fraction = 0.20

Modeled DHR vs. radial beam position: Aperture ON
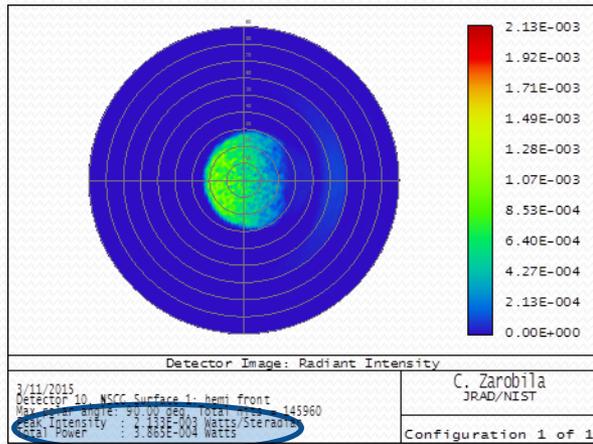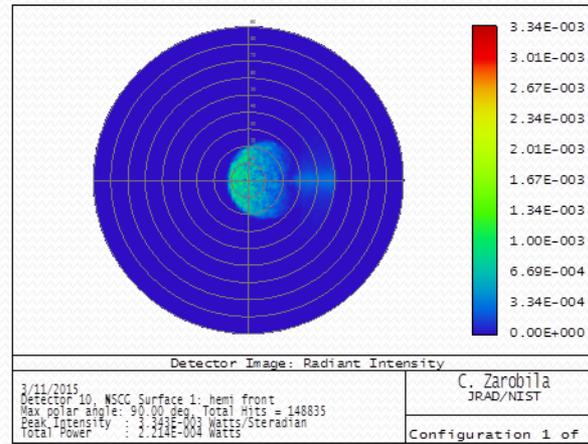
1 mm	2 mm	3 mm
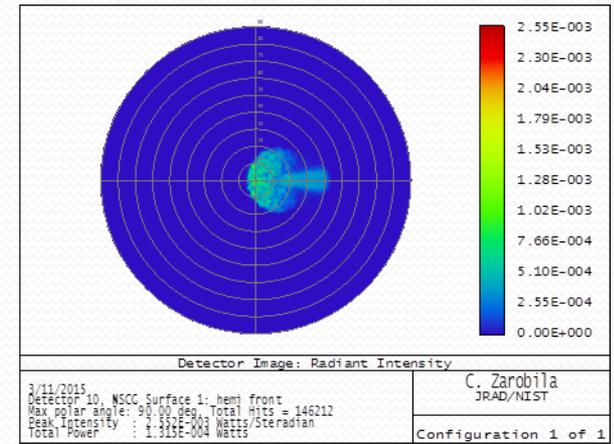
DHR = 0.038 %   DHR = 0.022 %   DHR = 0.013 %

- As expected, aperture cuts off BRDF at high angles as in measured data
- For comparison, AHF 36769 measured DHR(radial)
  - MEASURED: 1 mm, 0.062%, 2 mm 0.038%, 3 mm 0.035%
  - Again, similar radial trend between modeled and measured

Model Uniform Beam DHR: Increase the input Beam Size to 7.6 mm, collimate source rays, flat top
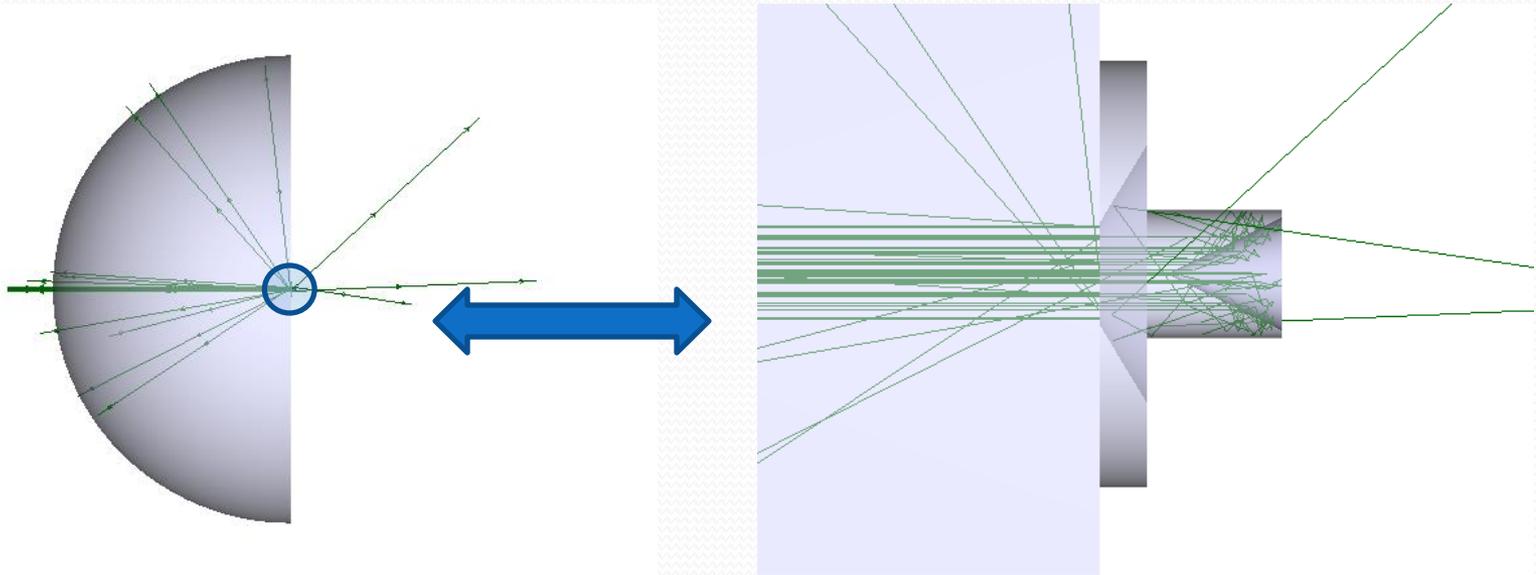
Can do this for both Aperture ON, and Aperture OFF

Model:
DHR(uniform) ON: 0.019%
DHR(uniform) OFF: 0.055%

From Measured AHF 36769
DHR(uniform) ON: 0.041%
DHR(uniform) OFF: 0.090%

Although Model/Measured not perfect match, trends with position and aperture off/on are consistent. Use as guide to how light escapes from cavity, and possibly for future cavity design.

Use Model to Determine Appropriate DHR for Modeling Effective Cavity Absorptance

- Cavity is normally operated with aperture on, uniform illumination
- DHR(uniform) "on" represents all the light that escapes out the aperture
- DHR(uniform) "off" represents all light that escapes from cavity.
- In operation, the high angle light we measure with DHR "off" will hit aperture and go somewhere – either back into cavity (good) or lost (bad)
- The DHR(effective) we want for calculating cavity absorptance is in between DHR off and DHR on; it is DHR "on" plus the light from DHR "off" at high angles that hits aperture, and does not return to cavity

Modeling Lost Light

- Light can leak out behind cavity; this added to ZEMAX model as "BACK" below
- If the only loss mechanism were leaking out back, emissivity DHR for measured cavity would be DHR ON + BACK
- But, aperture will also absorb some of the light that hits it; here use the 60% R nickel aperture model; absorbs 40% of light that hits it
- Suggests that DHR(effective) for measured cavity would be DHR ON + BACK + ABSORBED

What we want?

	DHR(uniform) Aperture OFF	DHR(uniform) Aperture ON	BACK (Leaked)	DHR OFF – DHR ON	Absorbed by Aperture	DHR(effective)
MODEL (nickel)	0.055%	0.019%	0.006%	0.036%	0.014%	0.039%
MEASURED AHF 36769	0.090%	0.041%	0.008%	0.049%	0.020%	0.069%
MEASURED AHF 36770	0.090%	0.043%	0.008%	0.047%	0.019%	0.070%
MEASURED AHF 36771	0.103%	0.046%	0.010%	0.057%	0.023%	0.079%

Modeled or measured

Back detector: assume measured is same fraction of OFF-ON as model

OFF-ON: light that escapes cavity, but hits aperture

Absorbed: aperture absorption * (OFF-ON)

ON + BACK + Absorbed

Model Summary

- Using ZEMAX model as guide, came up with a DHR(effective) in between the "off" and "on" values
  - If back of aperture absorbs 40% of incident light:
    - DHR(effective) = 0.07% to 0.08%
- This is in between the DHR(uniform) for aperture "on" and aperture "off"
  - Absorptance = 1 – DHR(effective)
  - Absorptance = 0.9992 to 0.9993, depending on cavity
  - Compare with Eppley estimate of 0.999
- Biggest uncertainty is understanding aperture effect on DHR(effective).

Additional Measurements and Modeling

Spectral Effects, Cavity Paint

Z3O2 8:di reflectance, 3 samples
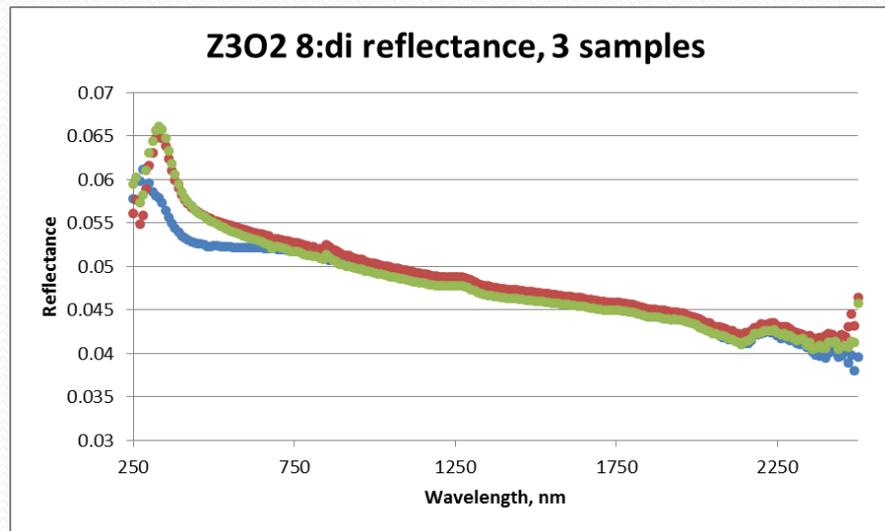
- Samples of Z3O2 specular black paint (as used in Eppley Cavity) measured for reflectance on Lambda 950
- Results can be used to predict cavity spectral dependence from 532 nm GOSI measurements with aid of model
- 8:de also measured in attempt to determine diffuse fraction; difficult due to low signal levels and measurements ongoing

Independent Cavity Absorptivity Model

cavity geometry model

Effective absorptivity of the Eppley AHF pyrheliometer cavity
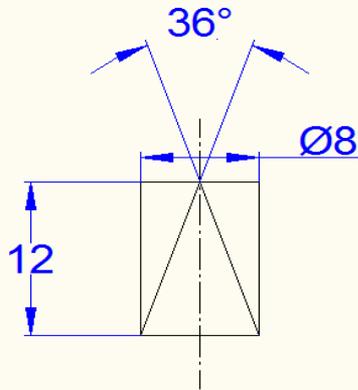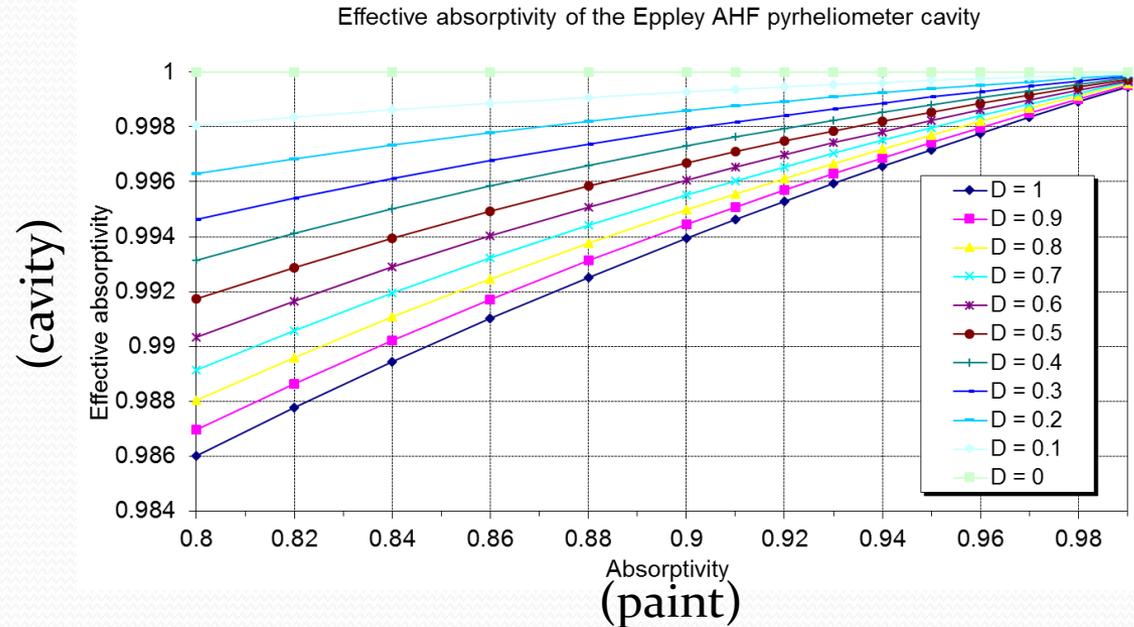
- Using models for blackbody radiation from cavity with certain coating and geometry, the effective cavity absorptivity can be independently predicted
- If Z3O2 coating is 5% reflective with diffuse fraction of 0.1 (i.e., 4.5% specular, 0.5% diffuse)
  - Modeled effective absorptivity: 0.9997
  - Measured aperture OFF
    - Absorptivity = 1 – DHR(OFF) : 0.9990 to 0.9991
- Cavity is not ideal!
  - Model very sensitive to diffuse fraction; which depends on cavity surface finish
  - May not be possible to get perfect match, but can be used to determine limit and guide designs

Improved Estimate of Aperture Absorption/Reflectance
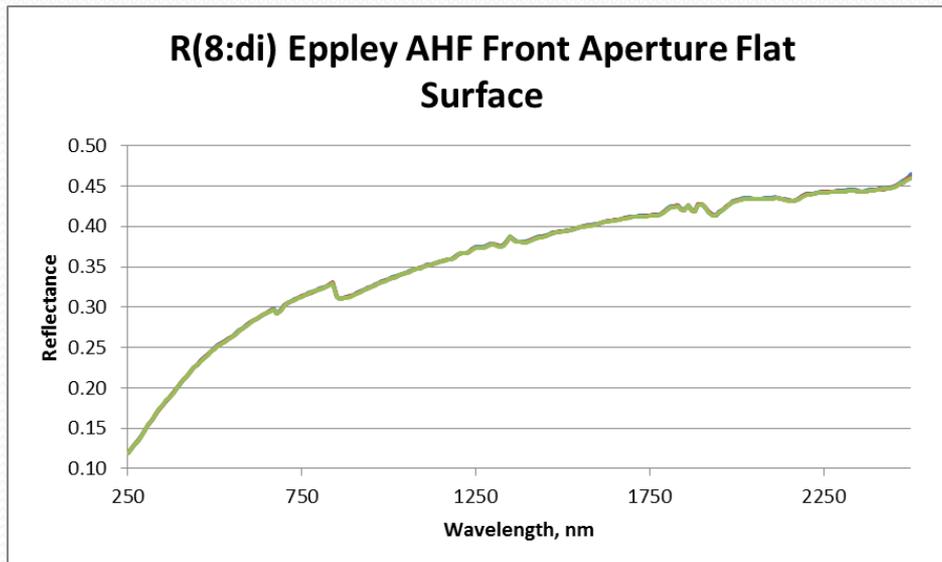
Aperture with 10% and 50% nominal R diffuse reflectors

- Zemax model assumed nickel aperture, 60% R
- Recently, measured flat surface of actual aperture on Lambda 950, using a mask due to small sample size
- Aperture measured about 26% R at 532 nm
- Plan to compare with goniometric measurements
- Likely need to update DHR estimates to account for increased aperture absorptance

Summary

- Goniometric reflectance measurements made on 3 Eppley pyrheliometer cavities
- Measurements suggest cavity 71 is slightly less efficient (higher reflectance, absorbs less light) than the other 2
- DHR(effective) 0.07% to 0.08%, depending on cavity
  - Subject to adjustment as aperture properties better known
- Biggest uncertainty for applying to pyrheliometer model is understanding aperture effect on effective cavity reflectance/absorptance
- Modeling can be used as a guide for future cavity design

Thank you!