U.S. Department of Energy
HelioCon
Heliostat Consortium for
Concentrating Solar-Thermal Power

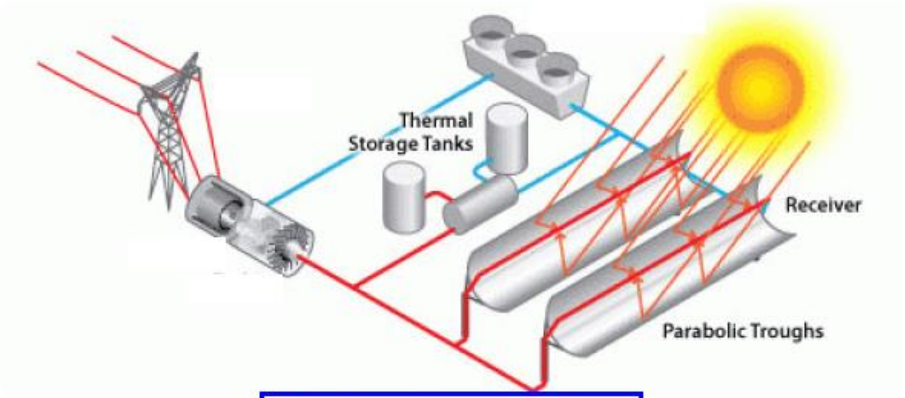
Solar Mirror Reflectance and Standardized Reporting

Stephanie Meyen and Tucker Farrell

conceptional design • components • integration • mass production • heliostat field

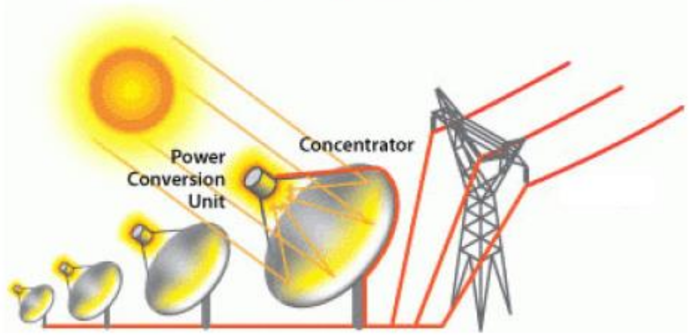
Solar Collectors Overview

Parabolic Trough[1]



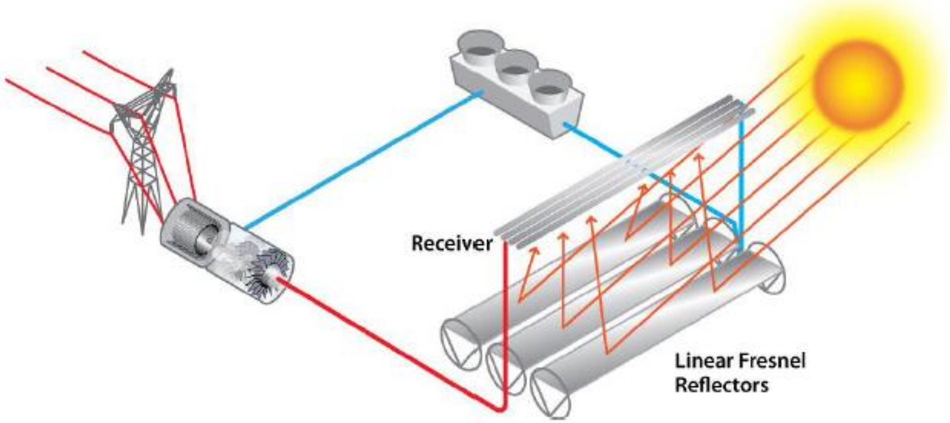
Medium Concentration

Parabolic Dish[2]



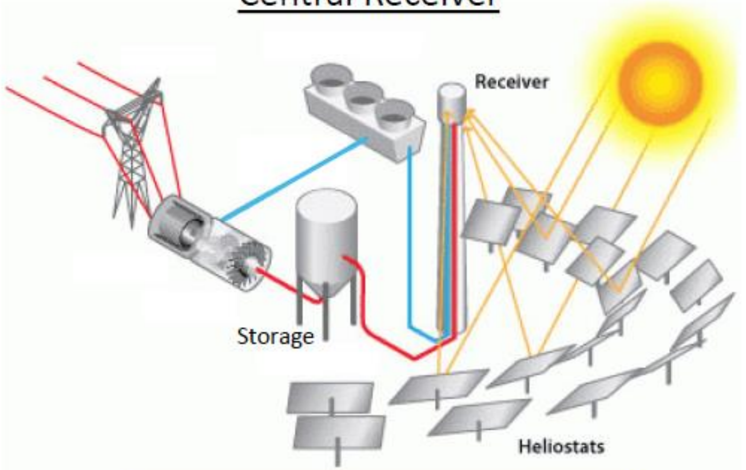
High Concentration, Limited Power

Linear Fresnel[3]



Medium Concentration

Central Receiver[4]



High Concentration, High Power

Only heliostats combine high concentration and high power.

Source: energy.org/CSP basics;
HelioCon Seminar: R. Brost, Heliostat Optical Metrology

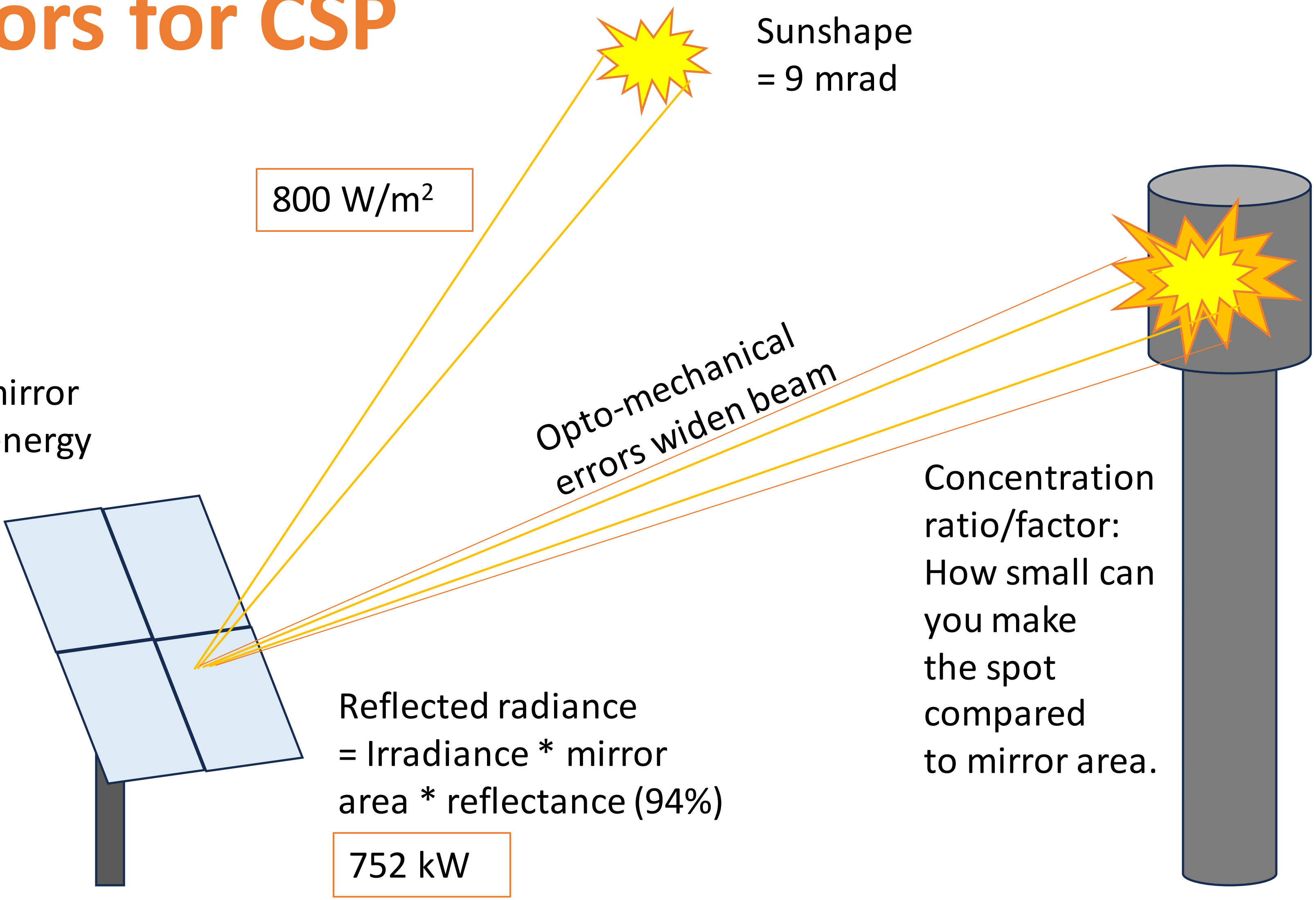
Today's focus is on Reflectance

- Important characteristics of solar reflectors
- Reflectance properties
- The importance of standardization
- How NREL can help
- A tool for standardized reporting
- Measurement procedure
- Standardized report
- Why does it matter

Reflectors for CSP

Sunshape
= 9 mrad

800 W/m²



The bigger the mirror area, the more energy will be focused.

1000 m²

Reflected radiance = Irradiance * mirror area * reflectance (94%)

752 kW

Concentration ratio/factor: How small can you make the spot compared to mirror area.

Useful thermal energy = Reflected radiance * concentration factor * receiver absorptance (90%)

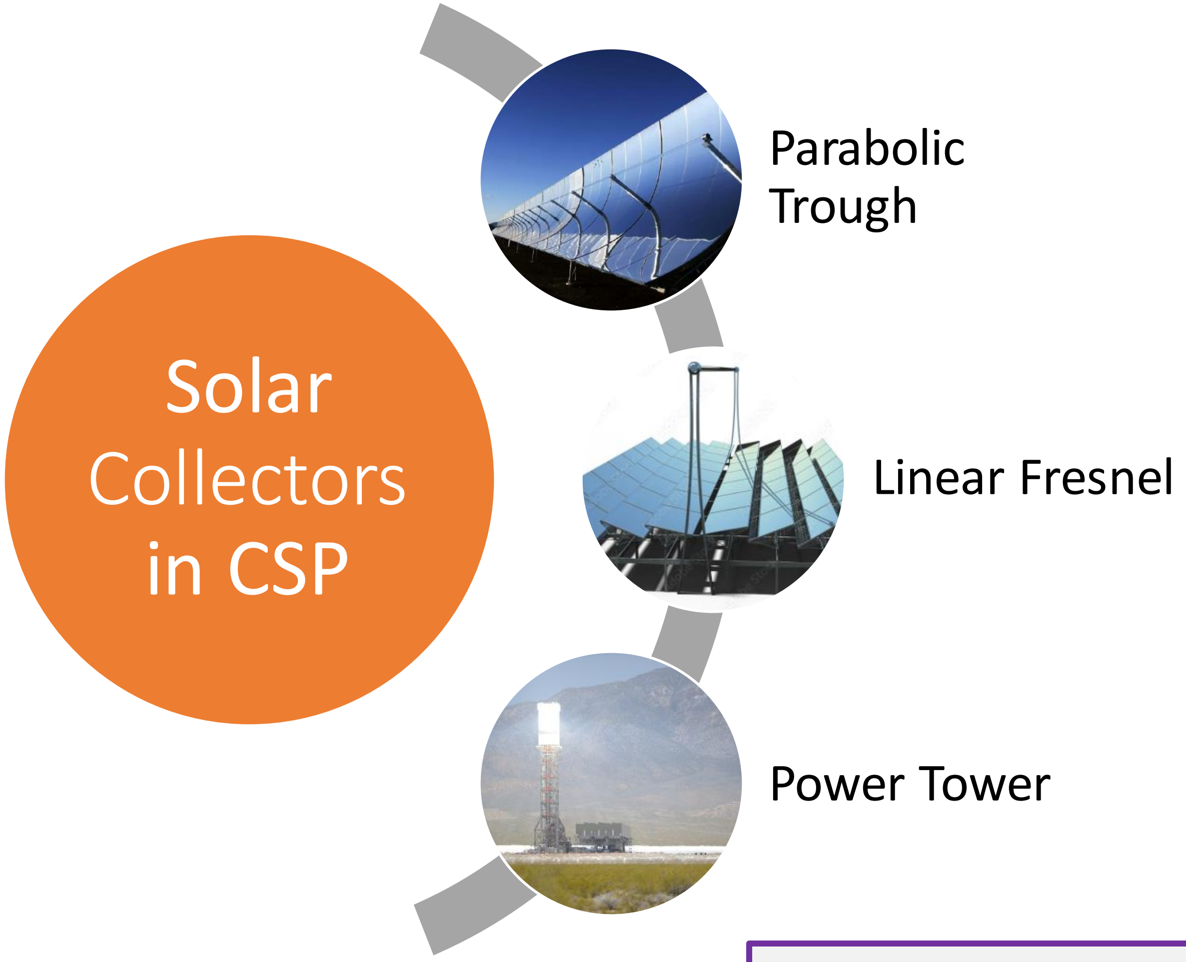
$E_{th,1}$ = 5.35 MW
$E_{th,2}$ = 3.52 MW

$E_{th,3}$ = 5.18 MW
@ 91% reflectance
= 170kW loss
per 1000m²

Reflectance and absorptance are material properties.
All other losses are due to geometrical errors.

C_1 = 7.9 @ 9mrad
C_2 = 5.2 @ 11mrad
Distance = 1000m

Reflectors for CSP



Reflector requirements:

- *High reflectance of the whole solar spectrum*
- *Highly specular*
- *Durability under extreme conditions*
  - *Vibrations and flexing of collector shape*
  - *Heat/cold cycles*
  - *Humidity & air pollution*
  - *UV radiation*
  - *Abrasion*
- *Low cost*

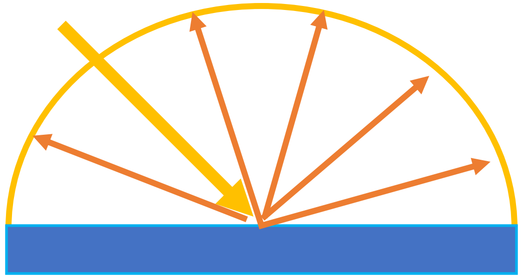
Soiling & degradation change reflectance and specularity.

The two properties of reflectance

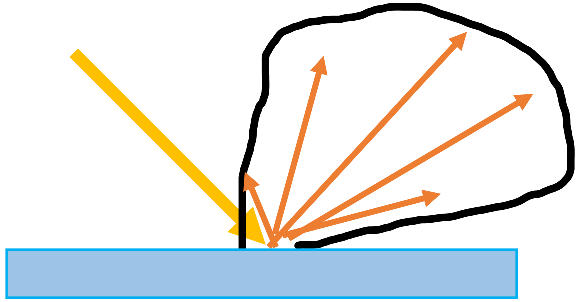
1. ***Reflectance*** *= How much of incidence light is reflected.*
   - *Material absorbs, transmits and reflects portions of the electromagnetic spectrum.*
   - *The portion of reflected light depends on wavelength and incidence angle of incident light.*
2. ***Specularity*** *= Surface finish determines where the reflected light goes.*

$$\rho = \frac{I_r}{I_i}$$

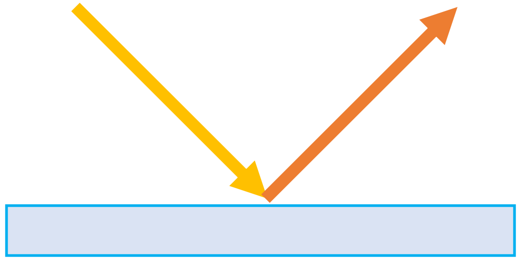
Reflectance is measured as a function of wavelength, incidence angle and detector acceptance aperture.



Perfectly hemispherical:
Isotropic rough surface



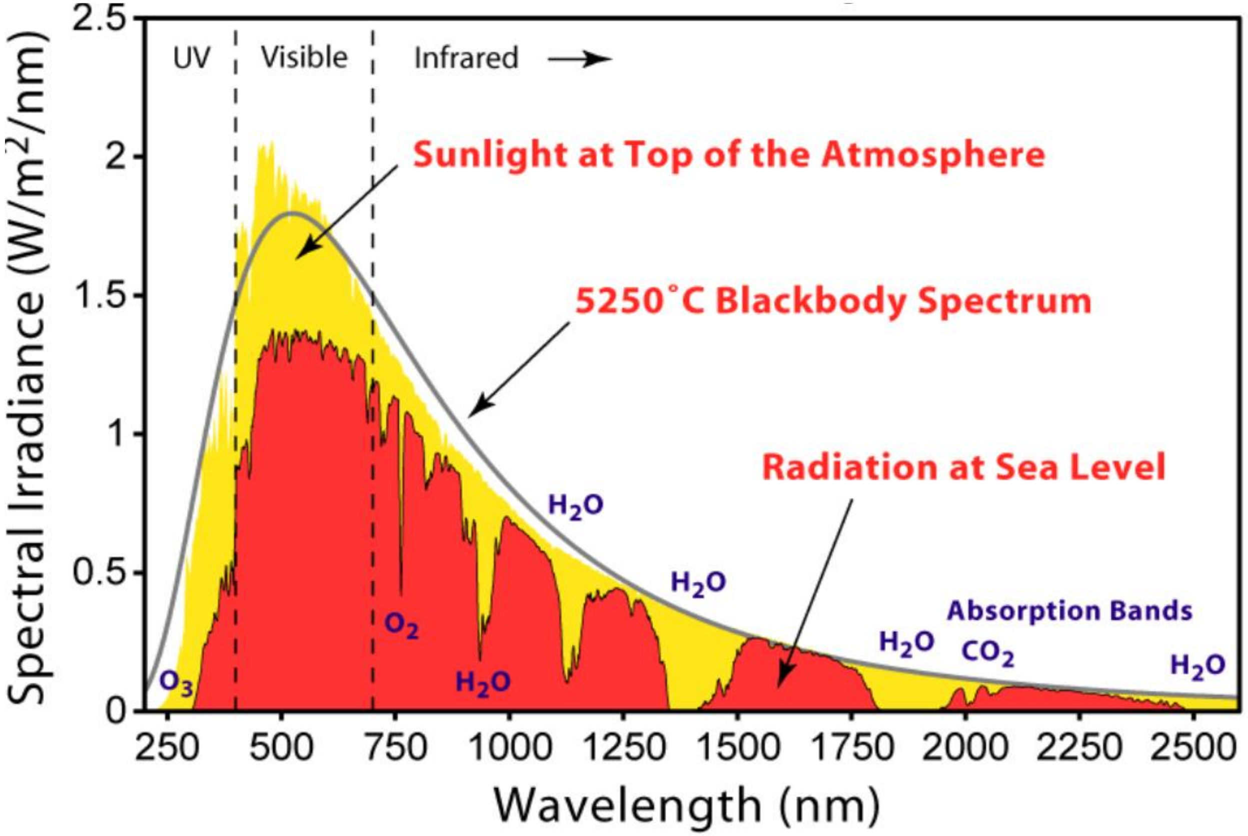
Directional scatter:
Most surfaces



Perfectly specular:
Extremely smooth mirror surface

Why solar weighted reflectance

- *Most solar energy is within visible spectrum.*
- *Atmosphere absorbs some solar radiation depending on path length (air mass AM).*
- *AM 1.5 is most common in CSP. Represents yearly average conditions at mid-latitudes (Europe, China, USA, Japan, northern India, South Africa and Australia) .*



Mirror reflectance spectrum convoluted with solar spectrum = actual reflected light

Source: Wikipedia

The discussion on specularity

- *Since 2010, a body of work has shown that modeling and measuring the specular reflected distribution is not that simple[1,2,3,4,5,6,7].*
- *Different materials require different models. Simple Gauss does not work in most cases other than highly specular glass mirrors.*

No "one-size-fits-all" solution is commercially available, yet.
Scattering reduces the reflectance directed towards the receiver.

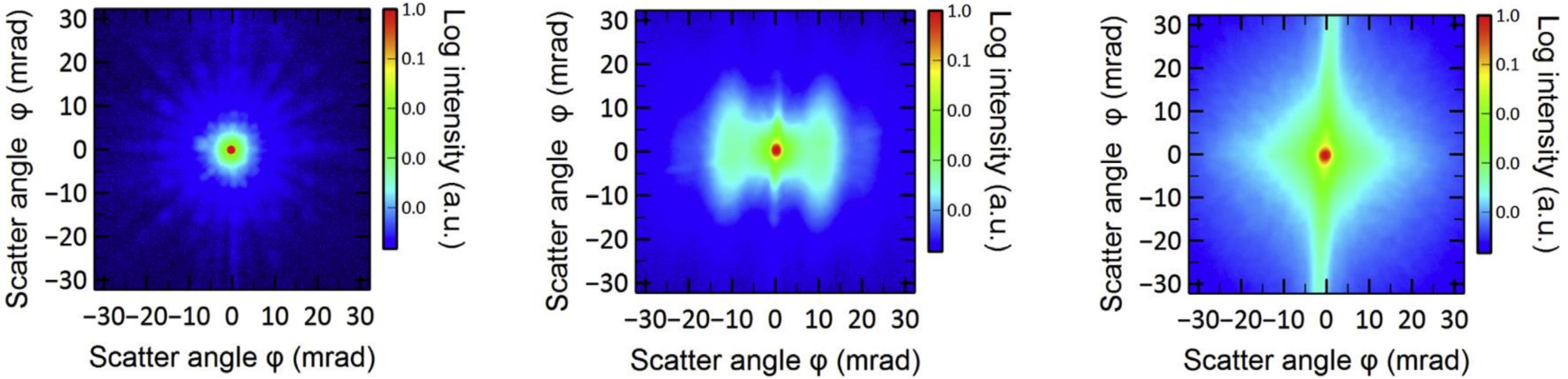
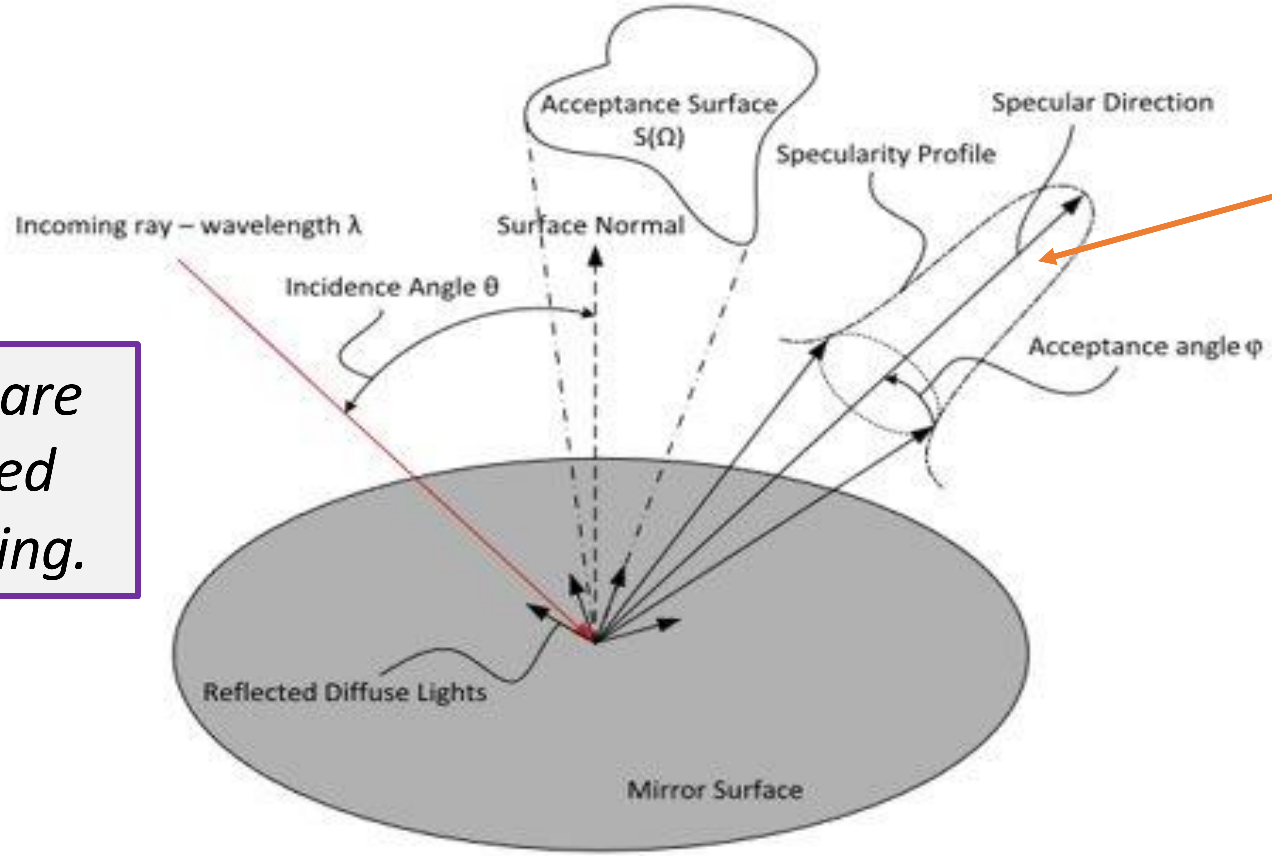


Image source: (Heimsath and Nitz, 2019[2])

The discussion on specularity

- *Measure specular reflectance within a defined acceptance angle.*
- *Relevant acceptance (half) angle φ ranges from 7.5 mrad (solar tower heliostats) to 12.5 mrad (parabolic trough collectors) (Heimsath).*



Most important: How much light is in this beam cone.

Reflectance nuances are largely being neglected in commercial reporting.

Image source: (Zhu et al., 2014[3])

Relevant metrics for reflectance

$\rho_{s,h}([\lambda_a, \lambda_b], \theta_i, h)$

- *Solar weighted hemispherical reflectance at near normal incidence θ over the solar spectrum $[\lambda_a,\lambda_b]$.*

$\rho_{\lambda,h}(\lambda, \theta_i, h)$

- *Hemispherical reflectance at near normal incidence θ the same wavelength λ as specular reflectance, plus hemispherical reflectance spectrum.*

$\rho_{\lambda,\varphi}(\lambda, \theta_i, \varphi)$

- *Specular reflectance at near normal incidence θ, at specific wavelength λ and several specified acceptance angles φ, at least at one acceptance angle between 7 and 12.5 mrad.*

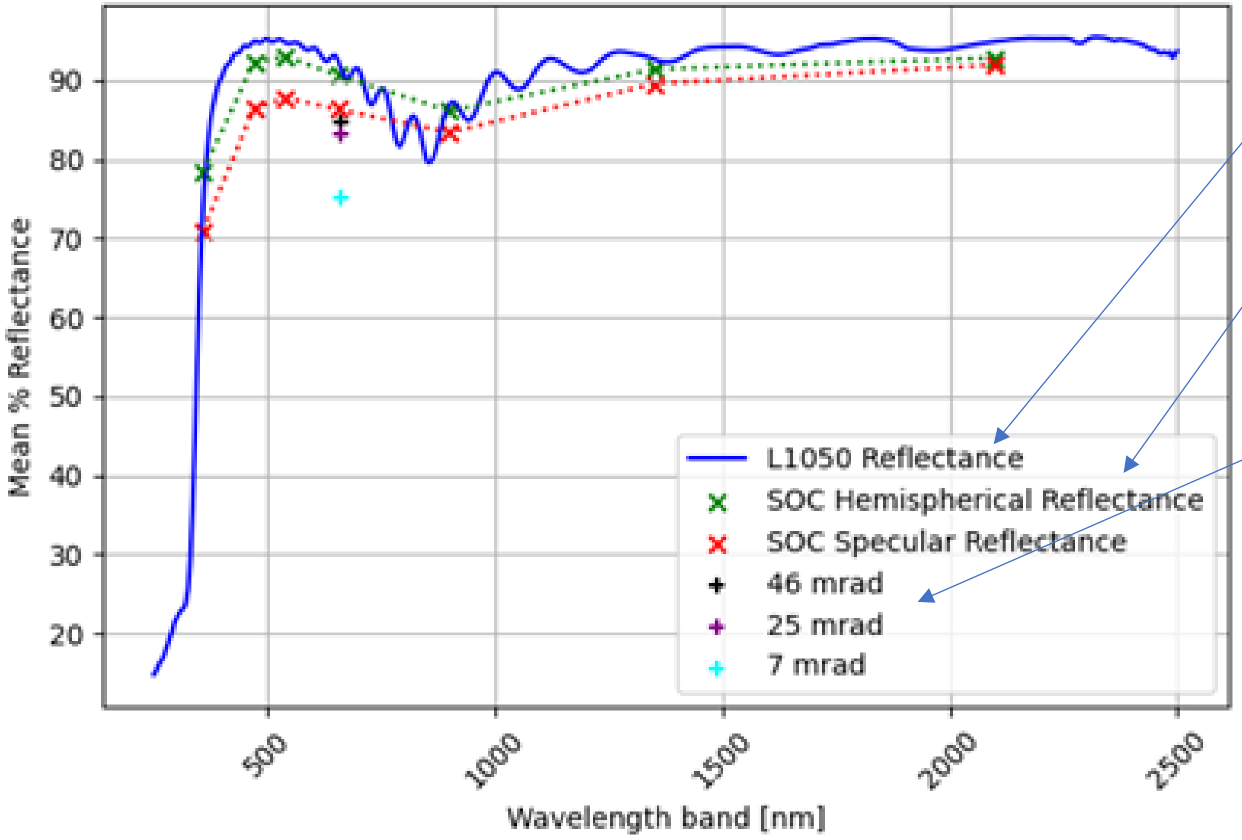
$\varphi_{s,\varphi}([\lambda_A, \lambda_B], \theta, \varphi)$

- *Solar weighted specular reflectance estimate at $\varphi = 12.5$ mrad.*

Currently main reference document:
SolarPACES Official Reflectance Guideline Version 3.1 (2020)[7]

What does it mean

- *Challenges in measurement and instrumentation*



- *Spectrophotometer – whole spectrum but only hemispherical.*
- *SOC Solar410 – sections of spectrum, derives specular from hemispherical – diffuse.*
- *Devices & Services – specular with a range of acceptance angles, only at limited, discreet wavelengths.*
- *All at near normal incidence angles*

What metrics do vendors report?

- *All provide hemispherical reflectance or "average" reflectivity.*
- *Some provide "reflectivity up to"- value according to ISO 9050 (Glass in buildings).*
- *Many provide durability test results as pass/fail and standards used (most commonly ISO 9227 & ISO 6720-2). Pass/fail might look different for CSP.*
- *3M film provides specific "specularity".*
- *Rarely the means of measurement, instrument used, solar weighting airmass or weighting factors, or specularity details are provided.*

- *Everybody reports what they see fit. Not comparable.*
- *Manufacturers are limited to published ISO/IEC standards, some of which do not currently cover CSP specific needs.*

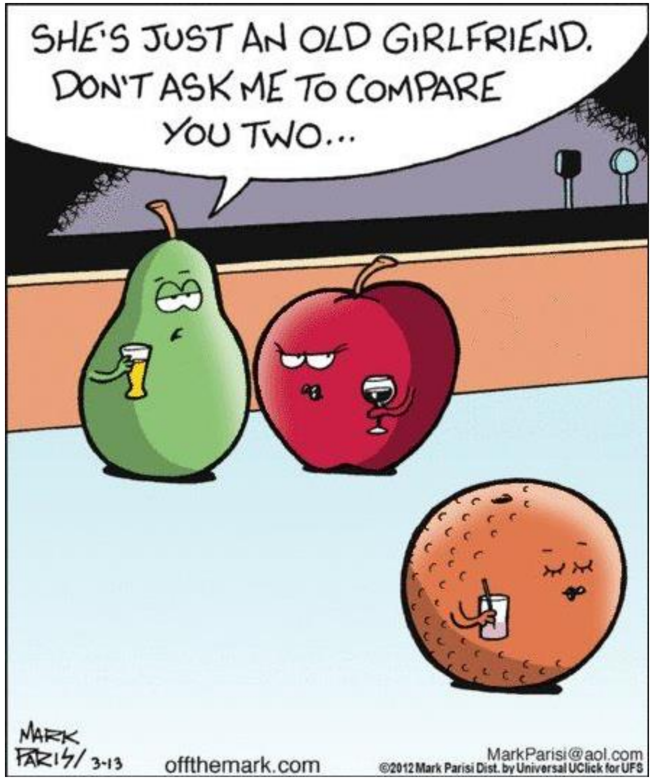
The importance of standardization

IEC – International Electrotechnical Commission definition of a standard:

- *A standard is an agreed, repeatable way of doing something. It is a published document containing a technical specification or other precise criteria designed to be used consistently as a rule, guideline or definitions.*
- *International standards are technical rules that help reduce technical barriers to trade.*

Why is it important?

- *So that we are sure to be comparing apples to apples.*
- *So that manufacturers, vendors, customers and investors have a common language to communicate what they need and what they get.*



IEC TC 117 Solar Thermal Electric Plants published

IEC Standards	SCOPE
IEC 62862-5-2:2022 General requirements and test methods for large-size linear Fresnel collectors	This document covers the determination of optical and thermal performance of linear Fresnel collectors, and the tracking accuracy of the collector one-axis tracking system. This test method is for outdoor testing only. This document applies to linear Fresnel collectors according to Annex A equipped with the manufacturer-supplied sun tracking mechanism.
IEC 62862-3-2:2018 General requirements and test methods for large-size parabolic-trough collectors	This document covers the determination of optical and thermal performance of parabolic-trough collectors, and the tracking accuracy of the collector one-axis tracking system. This test method is for outdoor testing only. This document applies to parabolic-trough collectors equipped with the manufacturer-supplied sun tracking mechanism.
IEC 62862-4-1:2022 General requirements for the design of solar power tower plants	specifies the general requirements for the design of solar power tower plants and covers the electric power system requirements, the solar resource assessment, the site selection, the overall planning, the layout of the heliostat field and the receiver tower, the layout of the power block, the collector system, the heat transfer, the thermal energy storage and steam generation system, the steam turbine system, the water treatment system, the information system, instrumentation and control, the electrical equipment and system, occupational safety and occupational health.

IEC TC 117 Solar Thermal Electric Plants drafted

Based on SolarPACES Official Reflectance Guideline Version 3.1 (2020)7

IEC Standards	Leader	Status	Publication date
PT 62862-1-5 Performance test code for solar thermal electric plants	Francisco Javier Gonzalez CIEMAT - ES	Being published	Publ. 03/24
PT 62862-3-4 Code of solar field performance test for parabolic trough solar thermal power plant	Lupig Liu China	Approved for CD	Draft to be circulated 04/24 Publ. 06/25
PT 62862-3-5 Laboratory reflectance measurement of concentrating solar thermal reflectors	Aranzazu Fernandez CIEMAT - ES	Approved for CD	Draft to be circulated 03/24 Publ. 03/25
PT 62862-3-6 Durability of silvered glass reflectors – Laboratory test methods and assessment	Florian Sutter DLR - DE	Approved for CD	Draft to be circulated 03/24 Publ. 03/25
PT 62862-4-3 Technical requirements and design qualification of heliostats for solar power tower plants	Daniel Tsvankin / Stephanie Meyen / Jianxiang Jin NREL - US	Approved for CD	Draft to be circulated 07/24 Publ. 12/25

What is NREL doing

- *NREL's Optical Materials laboratory is ISO-9001 certified*
  - *Quality management system standing behind the reflectance measurements taken at NREL*

- *State-of-the-art, industry-accepted instrumentation*
  - *Lambda 1050+ Spectrophotometer*
  - *Devices and Services 15-RGB specular reflectometer*
  - *Surface Optics Corporation 410 Solar portable reflectometer*

- *Established procedure meets or exceeds SolarPACES reflectance guideline*

Instrument	Measurements	Method	Metric
Reflectometer SOC Solar 410	16 readings on 10x10 cm sample	Evenly distributed across the sample reflective surface	Hemispherical and diffuse reflectance, specular derived – 7 discrete bands, 20-degree incidence
Reflectometer D&S 15R	5 readings at each of 4 apertures – 46, 25, 15 and 7 milliradians	5 locations using an alignment jig. Center, and 4 corners. Use each aperture at each location.	Specular reflectance at varying apertures, up to 4 monochromatic wavelengths.
Spectrometer L1050	3 readings	Sample is rotated approximately 90 degrees between each reading, with the incident beam aimed approximately at the same location.	Hemispherical reflectance at 5 nm resolution

What is NREL doing

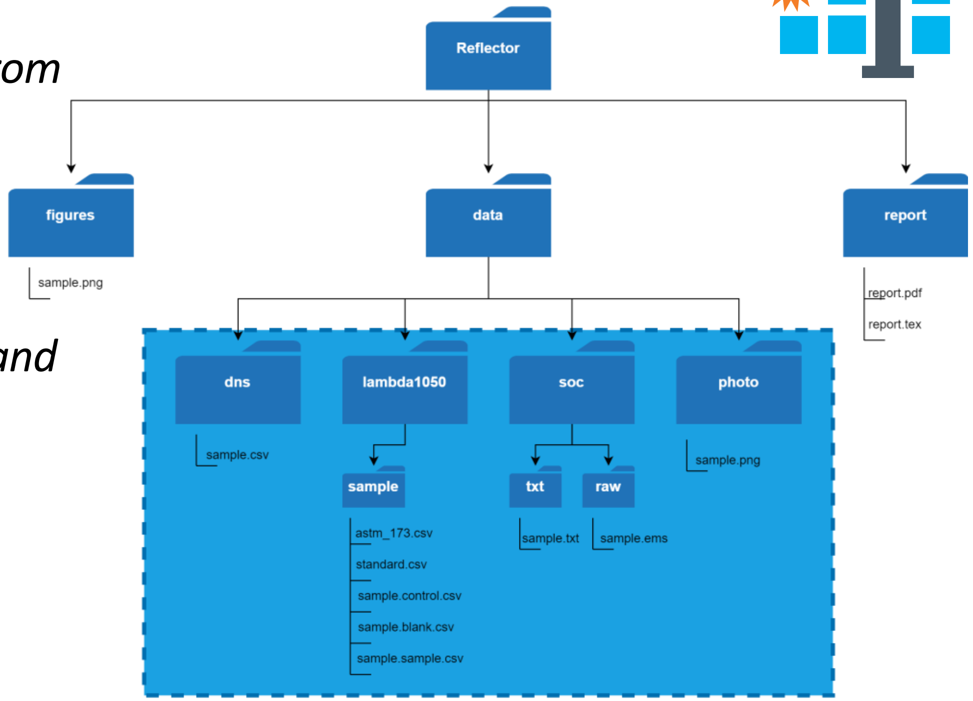
- *An open-source codebase and procedure for measuring and reporting reflectance metrics including*
  - *Hemispherical reflectance*
  - *Specular reflectance*
  - *Specularity (under construction)*
  - *Absolute spectral reflectance*
    - *Report the same values collected the same way for every sample*

- *Reporting may be used on new or weathered mirrors to monitor and report on degradation*

- *Can be added to OpenCSP if suitable*

A tool for standard report generation

- *A Python codebase integrated with LaTex to generate a standard report from a standard set of measurements.*
- *To use:*
  - *User measures each sample in accordance with the procedure*
  - *User saves files in accordance with the template*
  - *Script takes raw data and outputs a standard reflectance report pdf and .tex.*
    - *Hemispherical solar-weighted value*
    - *Specular reflectance value at collected wavelength*
    - *Spectral reflectance*
    - *Measurement uncertainty values*
    - *Photos and sample descriptions*
    - *Means and methods for sample preparation and calculation*
- *Open-source software to be released this year*



User puts data here – that's it

A standardized report

- *Report generated by script*
- *Pulls raw data from SOC, D&S, and L1050, handles processing, figure generation, uncertainty, report formatting, and report output.*
- *Includes .tex file to edit directly in LaTex if desired.*

Generated by NREL

Solar Mirror Reflectance Measurement Report
2024-06-11_test_test

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National Renewable Energy Laboratory
Email: Tucker.Farrell@nrel.gov
2024-06-11

1 Mirror Sources

Mirror sources are outlined in Table 1 and the tested mirror samples are illustrated in Figure 1.

Manufacturer	Sample ID	No. Received	No. Sampled	Sample Size [cm]	Description
test	test	3	2	10x10 cm	test
Sample discussion box.					

2 Measurement Procedure

The standard initial characterization of a mirror sample consists of the following measurements at NREL:

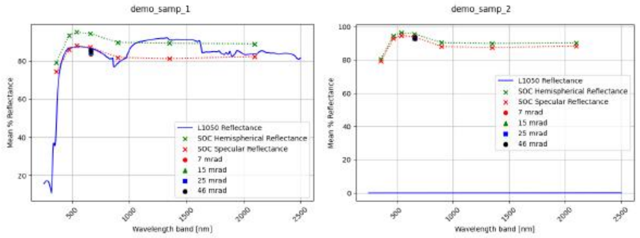
Instruments	Measurements	Method
Reflectometer SOC 410 Solar	16 readings	4 by 4 evenly distributed grid across reflector surface.
Reflectometer D&S 15RGB	5 readings at each of 4 apertures: 46, 25, 15, and 7 milliradians	5 locations, each corner and center. Use each aperture at each location.
Spectrometer Lambda 1050+	3 readings at approximate center of sample	Sample is rotated approximately 90 degrees between each reading, with the incident beam aimed approximately at the same location.

3 Measurement Results

Measurement Data for individual samples are given in Table 3. Graphical representations of these data are displayed in Figure 2.

Measurement	demo_samp_1	demo_samp_2
Solar-Weighted Reflectance, Specular, (410-Solar)	%R +/- sigma	%R +/- sigma
Solar-Weighted Reflectance, Hemispherical, (SOC)	%R +/- sigma	%R +/- sigma
Solar-Weighted Reflectance, Hemispherical, (Lambda 1050)	%R +/- sigma	%R +/- sigma
Specularity RMS at 660nm, (D&S)	%R +/- sigma	%R +/- sigma
Specular Reflectance at 25mrad, 660nm (D&S)	%R +/- sigma	%R +/- sigma

Generated by NREL



(a) Demo sample 1 (b) Demo sample 2

Figure 1: Sample reflectance

4 Appendix A: Instruments

The instruments used include a PerkinElmer Lambda 1050 Spectrophotometer (L1050), a Device and Services 15R USB Portable Specular Reflectometer (D&S), and a Solar Optics Corporation 410 Series Portable Reflectometer (SOC). General characteristics of each measurement are provided in Table 4 and are fully detailed in the proceeding sections.

Instrument	Measurement Type	Wavelength Ranges	Incidence Angle	Measured Spot Size	Acceptance Aperture
Lambda 1050+	Hemispherical	250-2500nm, 5nm increments	8/deg	0.5cm^2	hemispherical
D&S 15 RGB	Specular	660 nm peak irradiance	15/deg	5.07E-4 cm^2	7, 15, 26, and 46 mrad
SOC 410 Solar	Hemispherical Diffuse Specular	Bands from 335-2500nm, 5nm increments	Near normal	0.18cm^2	106 mrad and hemispherical

5 Appendix B: Measurement and Analysis Procedure

5.1 Sample Preparation

Mirror washing

5.2 Instrument Setup and Calibration

5.2.1 Surface Optics Portable Reflectometer: 410-Solar

soc

Conclusion: What does this report do? Why should these be available?

- *Third-party reporting of product performance is a fundamental aspect of a mature industry. Third-party testing exists for every subsystem in automotive, for PV, for oil/gas, etc.*
- *Using the reporting tool allows for normalized spec sheets and visibility about how results have been generated.*
- *Don't build your heliostat with spectralon! Using a normalized reporting tool helps in avoiding decisions based on misleading information .*

- *While ISO standards are in the works, this tool can help along the way to promote consistent reporting practices*

References (not comprehensive)

[1] Meyen, S., Lupfert, E., Center, D.G.A., and Fernandez-Garcia, A., "Standardization of Solar Mirror Reflectance Measurements - Round Robin Test: Preprint"11 (2010).

[2] Heimsath, A., and Nitz, P., "Scattering and specular reflection of solar reflector materials – Measurements and method to determine solar weighted specular reflectance," Solar Energy Materials and Solar Cells 203, 110191 (2019).

[3] Zhu, G., Kearney, D., and Mehos, M., "On characterization and measurement of average solar field mirror reflectance in utility-scale concentrating solar power plants," Solar Energy 99, 185–202 (2014).

[4] Montecchi, M., "Proposal of a new parameter for the comprehensive qualification of solar mirrors for CSP applications," presented at SOLARPACES 2015: International Conference on Concentrating Solar Power and Chemical Energy Systems, 2016, Cape Town, South Africa, 130014.

[5] Meyen, Stephanie and Sutter, Florian and Heller, Peter (2014) Near specular scatter analysis method with a new goniophotometer. SPIE Optics & Photonics, 2014-08-18 - 2014-08-21, San Diego, USA. doi: 10.1117/12.2061036.

[6] Sutter, F., Fernández-García, A., Heimsath, A., Montecchi, M., and Pelayo, C., "Advanced measurement techniques to characterize the near-specular reflectance of solar mirrors," presented at SOLARPACES 2018: International Conference on Concentrating Solar Power and Chemical Energy Systems, 2019, Casablanca, Morocco, 110003.

[7] Aránzazu Fernández-García, Florian Sutter, Marco Montecchi, Fabienne Sallaberry, Anna Heimsath, Carlos Heras, Estelle Le Baron, and Audrey Soum-Glaude, "Official Reflectance Guideline Version 3.1: PARAMETERS AND METHOD TO EVALUATE THE REFLECTANCE PROPERTIES OF REFLECTOR MATERIALS FOR CONCENTRATING SOLAR POWER TECHNOLOGY UNDER LABORATORY CONDITIONS," SolarPACES (2020).

Thank You

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