Advanced Measurement Techniques to Characterize the Near-Specular Reflectance of Solar Mirrors

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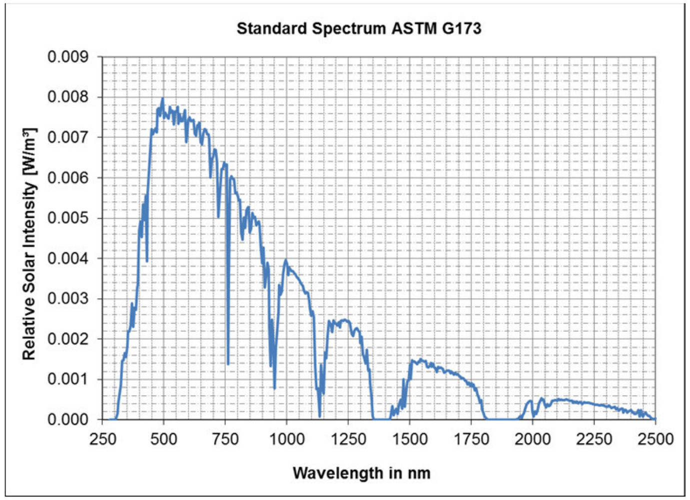
Introduction

$$\rho = \rho(\lambda, \theta_i, \varphi)$$

Solar radiation lies in the range of λ=[280-4000]nm

To facilitate the measurement, the irradiance in the UV [280-320) and far IR (2500-4000] is neglected. Their weight in the total spectrum is 0.09 and 0.87% respectively.

→ **λ=[320-2500]nm is the typical range of interest**



ASTM G173 Air mass 1.5 direct normal irradiance distribution

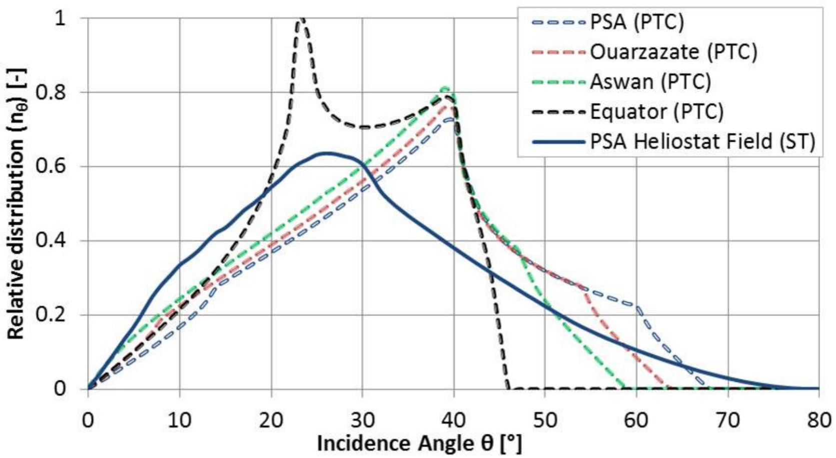
Solar-weighting:

$$\rho_s([\lambda_a, \lambda_b], \theta_i, \varphi) = \frac{\sum_{i=0}^{i_{max}} \rho(\lambda_i, \theta_i, \varphi) \cdot G_b(\lambda_i)}{\sum_{i=0}^{i_{max}} G_b(\lambda_i)}$$

Introduction

$$\rho = \rho(\lambda, \theta_i, \varphi)$$

Annual incidence angle distribution obtained trough simulation (assumption no clouds)



Location	Latitude	$\bar{\theta}_i$ [º]	θ_{max} [º]
Equator (PTC)	0° 0‘	27.8	45
Aswan (PTC)	24° 05‘	30.8	59
Ouarzazate (PTC)	30° 56‘	32.8	64
PSA (PTC)	37° 05‘	34.8	68
PSA (ST)	37° 05‘	29.8	80

Maximum θ_{max} and mean annual incidence angle $\bar{\theta}_i$ according to location and collector type

→ θ_i=[0-70]° is the range of interest

[F. Sutter, M. Montecchi, H. von Dahlen, A. Fernández-García, M. Röger: The effect of incidence angle on the reflectance of solar mirrors. Solar Energy Materials and Solar Cells 176 (2018) 119-133]

Introduction

$$\rho = \rho(\lambda, \theta_i, \varphi)$$

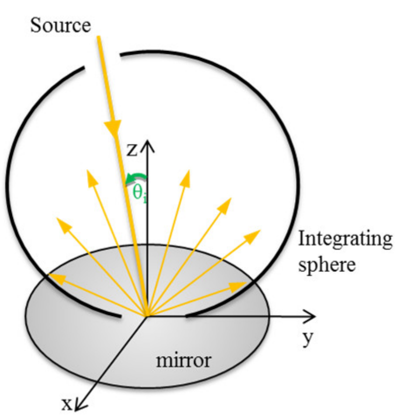
$\varphi = \pi$: hemispherical reflectance

$\varphi = 0$ mrad : specular reflectance

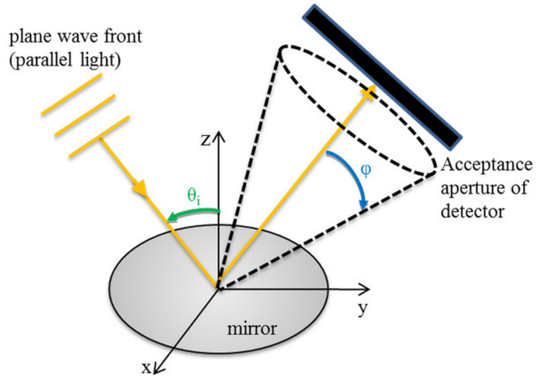
$0 < \varphi < 40$ mrad : near-specular reflectance

Sun-conic reflectance: near-specular reflectance & beam divergence of light source of $\varphi_s = 4.7$mrad to simulate sun disc

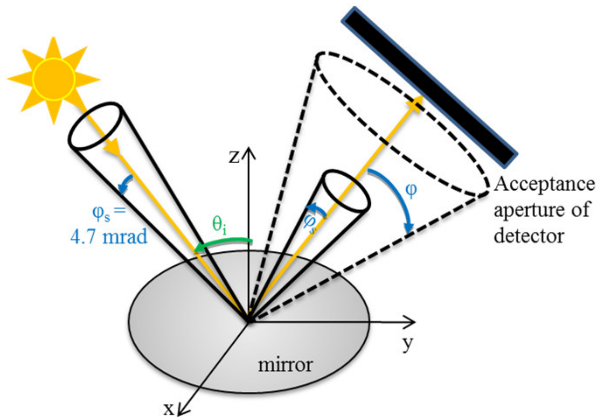
Hemispherical reflectance $\rho_{\lambda,h}$



Specular reflectance $\rho_{\lambda,\varphi}$



Sun-conic reflectance $\rho_{\lambda,\varphi,\varphi s}$

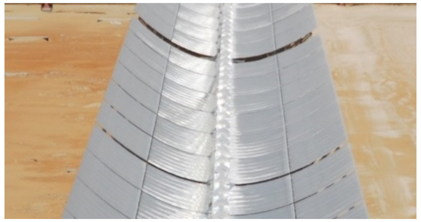


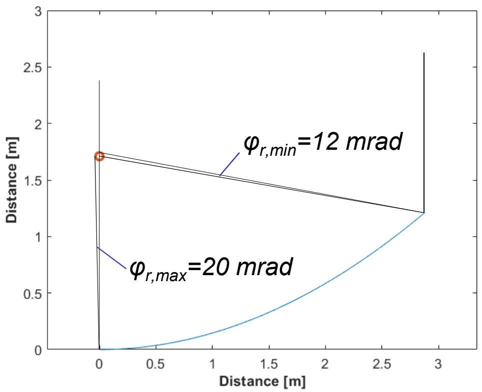
Introduction

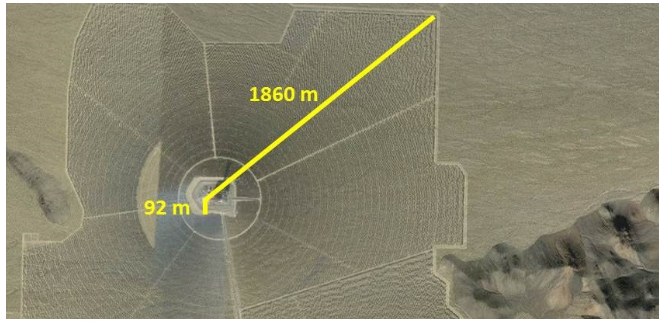
$$\rho = \rho(\lambda, \theta_i, \varphi)$$

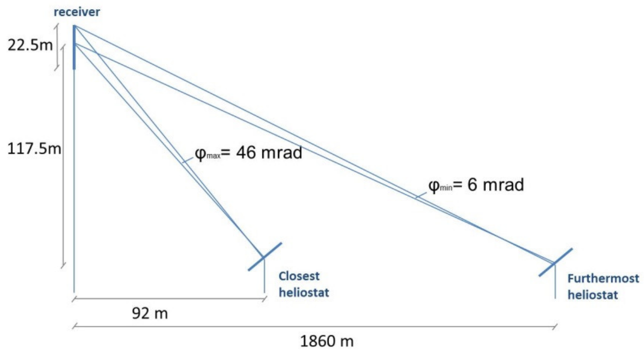
The acceptance half-angle of the receiver φ_r is 1/2 the ratio receiver_size/mirror_distance.

The angular spreading of the reflected beam is driven by angular radius of the sun φ_s=4.7mrad, augmented by an appropriate amount for spreading the beam due mirror scattering, tracking and shape inaccuracies









→ **φ =[7-15]mrad is the range of interest for parabolic troughs of EuroTrough geometry**

→ **φ =[1-41]mrad is the range of interest for solar towers**

Introduction

	Range of interest for CSP	State of the art reflectance measurement
Wavelength λ	[320, 2500] nm	λ = 320 – 2500 nm only near-normal and hemispherical
Incidence angle θ_i	[0, 70]°	Only near normal
Acceptance angle φ	[1, 41] mrad for solar towers [7, 15] mrad for parabolic troughs (EuroTrough geometry)	φ = 7.5, 12.5 or 23 mrad for monochromatic measurement (D&S 15R reflectometer, other commercial devices operate at higher φ)

→ ***Further optimization of reflectance measurement equipment necessary!***

Contents

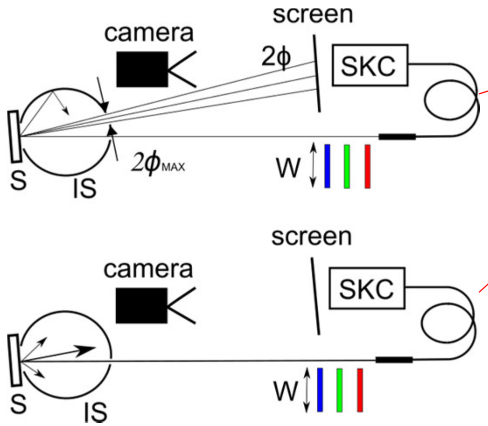
SMQ2: the key instrument in ENEA strategy

ENEA-strategy for evaluating $\rho_{s,\varphi}(\lambda,\theta_i,\varphi)$

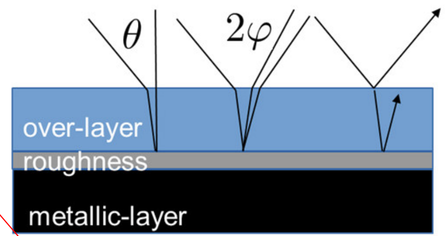
1) Spectrum of hemispherical reflectance in 320-2500 nm at θ ~ 0° → **commercial spectrophotometer**

2) **EMA modeling** to predict off-normal polarized hemispherical spectra

3) Measurement of the ratio near-specular/hemispherical at few λ_i → **SMQ2 instrument**



$$\frac{\rho_{\lambda,\varphi}(\lambda,\theta_i,\varphi)}{\rho_{\lambda,h}(\lambda,\theta_i,\varphi)} \rightarrow \sigma_{\varphi ol} \text{ is evaluated by best fit}$$



4) merged **EMA-TIS modeling**

5) **Prediction** of off-normal near-specular/

sun-conic solar reflectance

$$R = R_1 + \frac{(1-R_1)^2 R_2 \eta}{\exp(2\alpha d) - R_1 R_2 \eta}$$

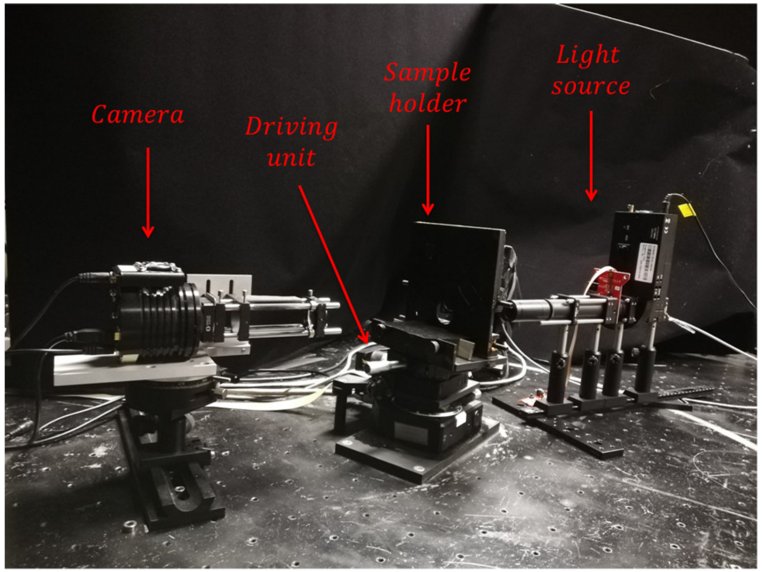
$$\alpha = -\frac{4\pi}{\lambda}\mathrm{Im}\left(\sqrt{n_1^2 - n_0^2\sin(\theta)^2}\right)$$

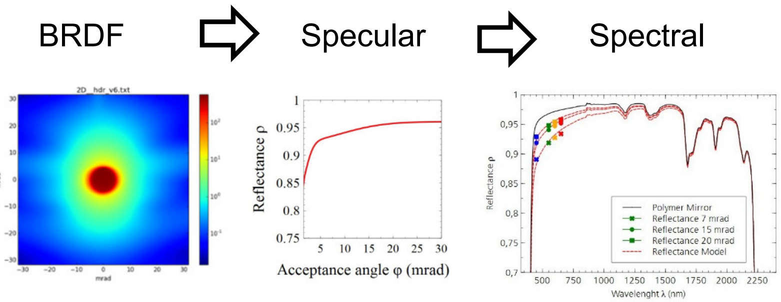
$$\eta = \begin{cases} 1 & \text{for hemispherical} \\ TIS & \text{for near-specular} \end{cases}$$

$$TIS = exp\left[-\left(\frac{4\pi\, n_{ol}\,\sigma_{\varphi ol} cos(\,\theta_{ol})}{\lambda}\right)^2\right]$$

VLABS-II by Fraunhofer ISE – BRDF and specular reflectance

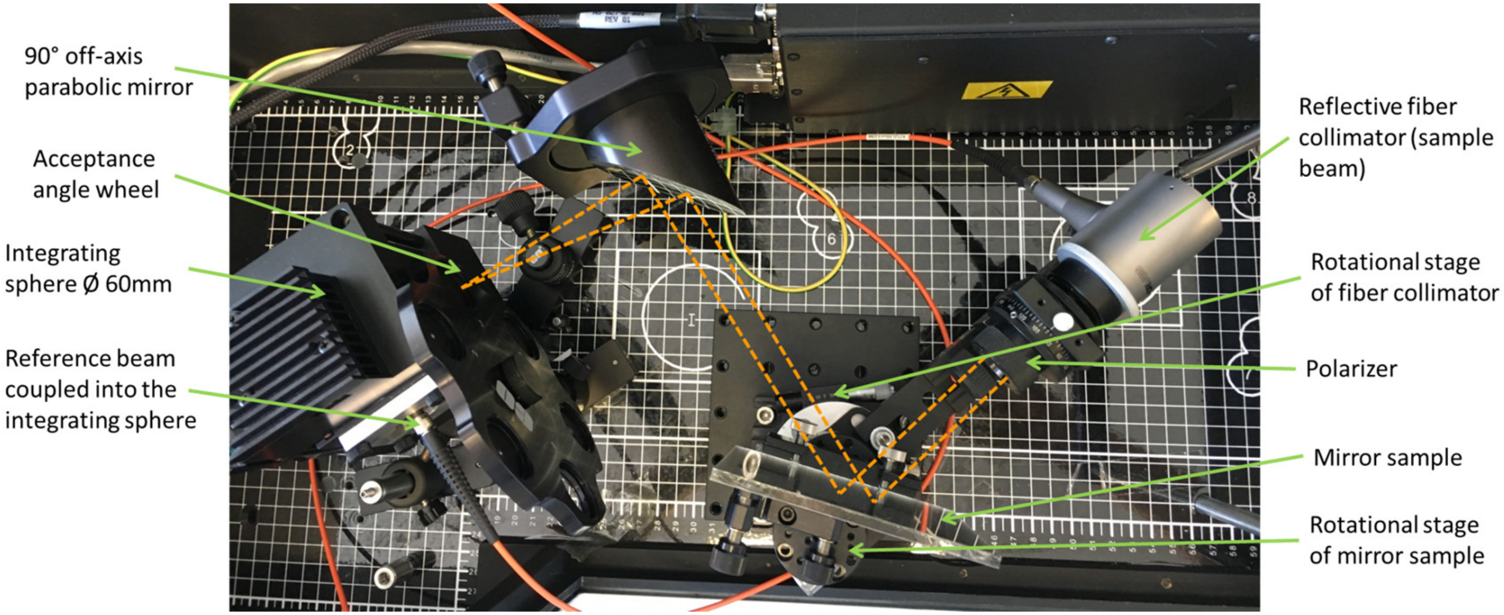
- BRDF & absolute specular reflectance measurement & sunconic reflectance
- λ=[450,550,600,650] nm, flexible; θ_i= [10-70]º, 0.1º res., φ = [1-33] mrad, 0.01mrad res.
- Solar weighted reflectance predicted, TIS-based model
- Update: Lightsource filter wheel, sunconic reflectance, driving unit





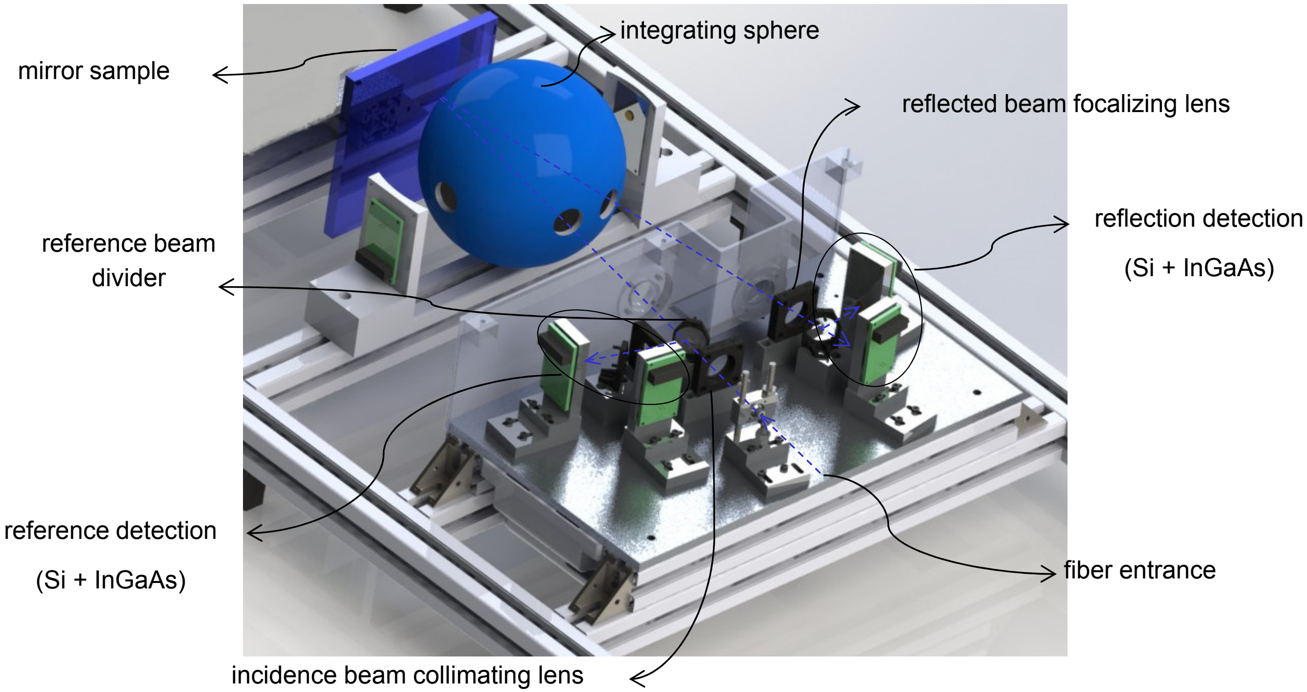
Spectral Specular Reflectometer (*S2R*) by DLR/Ciemat

- Designed as accessory for Perkin Elmer Lambda series spectrophotometers
- Sun-conic reflectance is directly measured in λ=[320-2500]nm, θ_i= [10-70]º, φ = [9.8; 12.3; 14.8; 20.2; 35.9; 107.4] mrad
- Calibration with reference mirror (off-normal behavior predicted by EMA by ENEA)
- Update: Polarizer crystal to measure s- and p- independently and improve off normal accuracy



Custom Spectrophotometer by University of Zaragoza

- Configurable instrument designed *ad-hoc* for the Round Robin measurements
- Sun-conic reflectance is directly measured in λ=[320-2500]nm, θ_i= 10º, φ = 15 mrad
- Calibration with 4mm 2nd surface Ag reference mirror certified by NPL



Summary of reflectometer prototypes

Instruments	Measurand (reflectance)	Modeling	Outputs (solar weighted)
SMQ2 (ENEA)	Near-specular λ = 485; 530; 640 nm ϴ = 3° φ = [3-50] mrad	Merged TIS-EMA	Near-specular / sun-conic ϴ = [0-90] deg φ = [0-50] mrad
VLABS (Fraunhofer ISE)	Near-specular / Sun-conic λ = 450; 550; 600; 650 nm 10° < ϴ < 80° φ = [1-33] mrad	Modified TIS	Near-specular / sun-conic 10° < ϴ < 80° φ = [1-33] mrad
S2R (DLR/CIEMAT)	Sun-conic λ = [320-2500] nm 10° < ϴ < 70° φ = 9.8; 12.3; 14.8; 20.2; 35.9; 107.4 mrad	none	Sun-conic 10° < ϴ < 70° φ = 9.8; 12.3; 14.8; 20.2; 35.9; 107.4 mrad
Custom spectrophotometer (University of Zaragoza)	Sun-conic λ = [320-2500] nm ϴ = 10° φ = 15 mrad	none	Sun-conic ϴ = 10° φ = 15 mrad

Contents

Round Robin Test (RRT): sample types

- 4 samples types were sent around 4 labs
- Hemispherical RRT made use of different commercial spectrophotometers
- Near-specular RRT

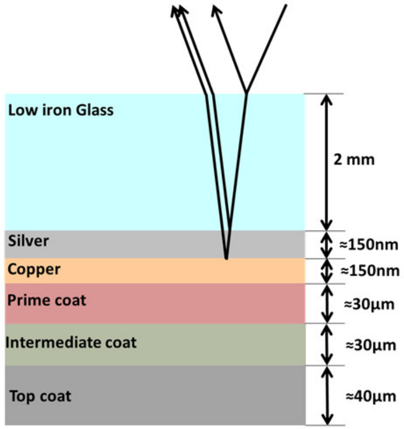
  λ=([320,2500]nm

  Θ_i= 10; 30; 60°

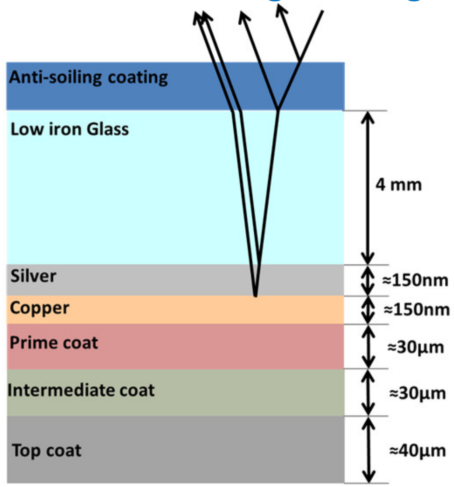
  φ=15 mrad

  φ_S= 4.7mrad

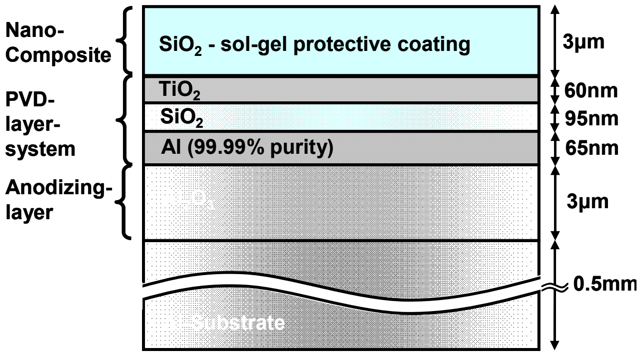
2 mm silvered glass mirror



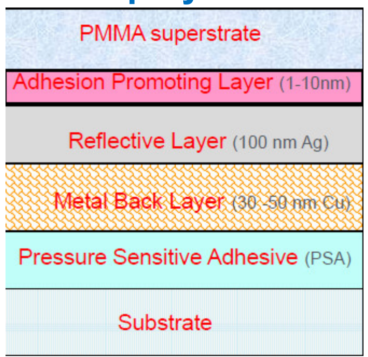
4 mm silvered glass mirror with anti-soiling coating



Enhanced aluminum mirror

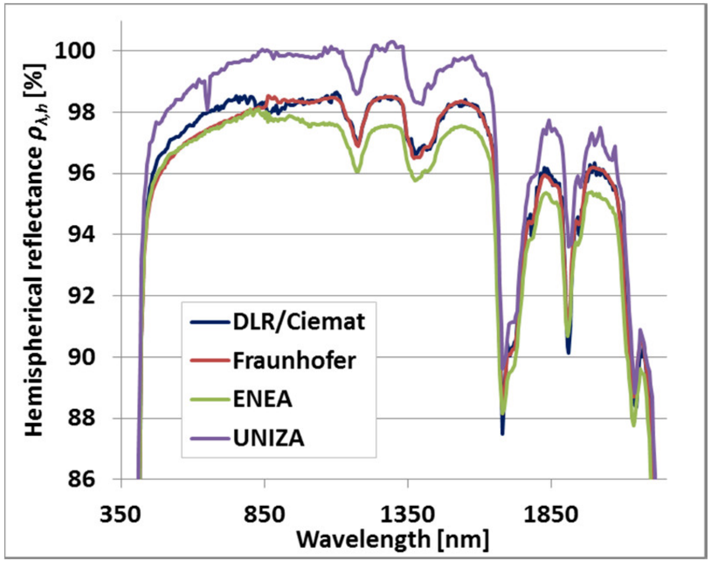


Silvered-polymer mirror

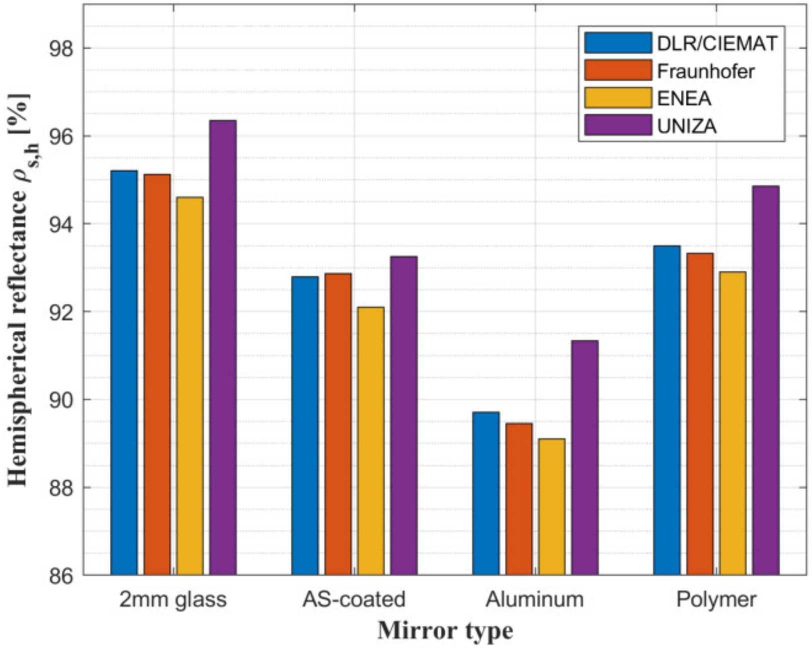


[NREL]

RRT: results of hemispherical measurements



Measured spectra of polymer mirror



Solar weighted reflectance comparison $\rho_{s,h}$

- Good agreement among the labs DLR/CIEMAT, Fraunhofer and ENEA with maximum standard deviation of σ=0.34%-p
- Systematic higher values of UNIZA (in the range of 0.7 to 1.9%-p) is currently being examined

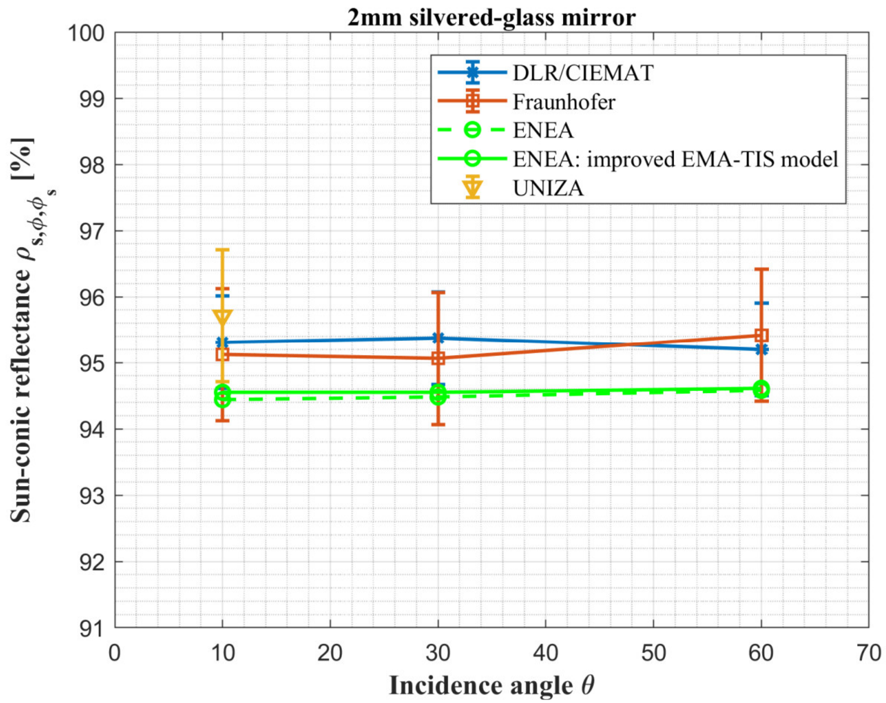
RRT: results of 2mm silvered-glass mirror

- Lowest standard deviations among the laboratories are appreciated (σ=0.38%-p).

→ similar agreement as for the hemispherical RRT is achieved

- The silvered-glass mirror shows constant reflectance values over the range θ_i=[10-60]°

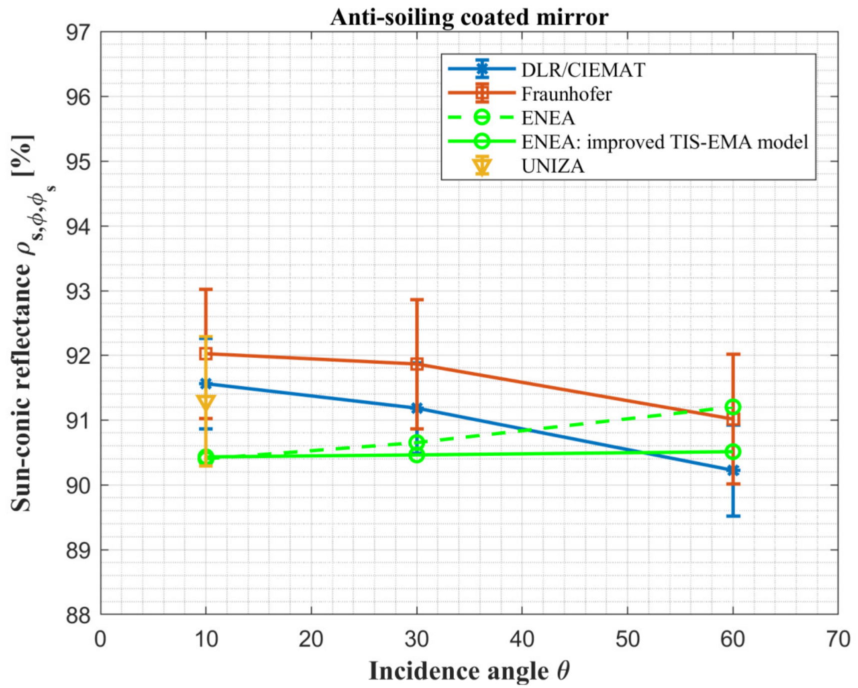
→ **near-normal measurement is sufficient** for silvered-glass mirrors



RRT: results of 4mm silvered-glass mirror with AS coating

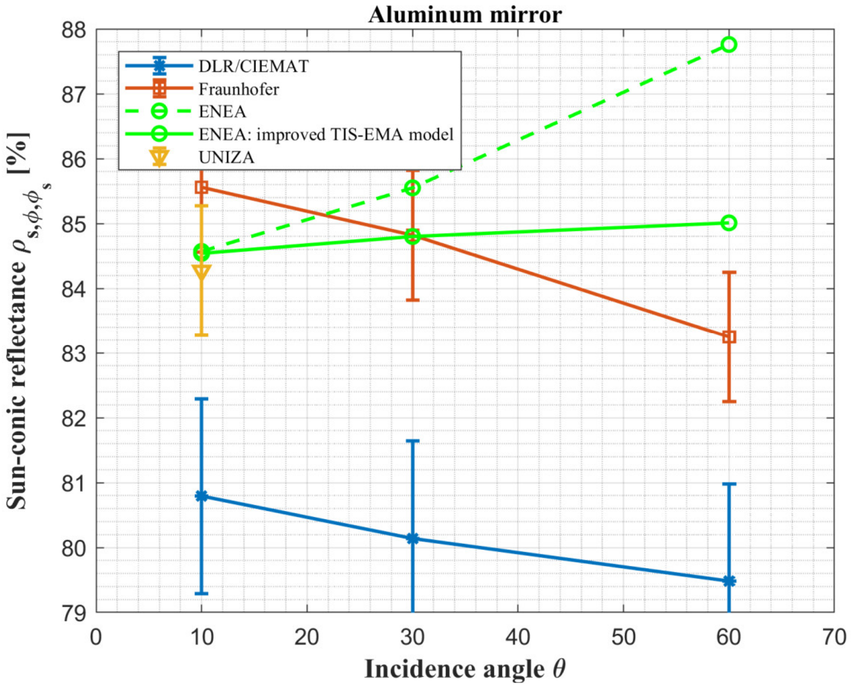
- slightly higher standard deviations among the laboratories of up to σ=0.58%-p
- The results from DLR/CIEMAT and Fraunhofer indicate a decreasing reflectance with growing θ_i, while the ENEA results indicate a slight increase with growing θ_i

→ This is subject of current discussions and model refinement of ENEA



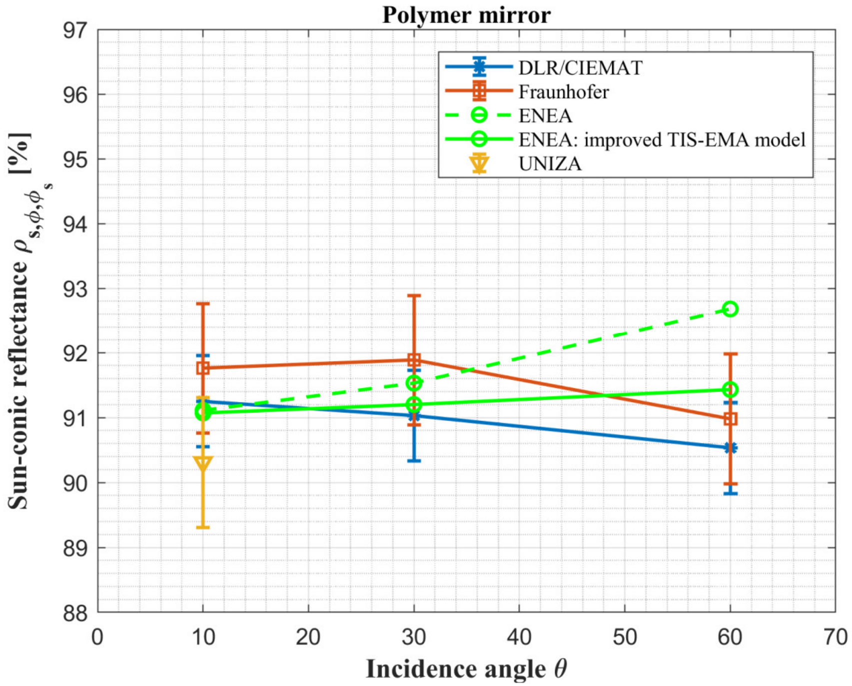
RRT: results of enhanced aluminum mirror

- highest deviations of up to σ=2.31%-p (for θ_i= 60°)
- The results from DLR/CIEMAT and Fraunhofer indicate a decreasing reflectance with growing θ_i, while the ENEA results indicate the opposite
- systemically lower reflectance was measured by DLR/CIEMAT compared to the rest of partners (maybe due to sample curvature)



RRT: results of silvered-polymer mirror

- Intermediate standard deviations up to σ=0.52%-p
- The results from DLR/CIEMAT and Fraunhofer indicate a decreasing reflectance with growing θ_i, while the ENEA results indicate the opposite



Contents

Summary and conclusions

- **Four experimental reflectometers** developed by different research organizations have been improved in order to measure solar-weighted off-normal near-specular reflectance
- Fraunhofer and ENEA's approach is to measure **monochromatically** and to apply different **Total Integrated Scatter models** to compute spectral behavior. DLR/Ciemat and Uni Zaragoza measured directly in the range [320-2500]nm.
- A **Round Robin** test was carried out at θ_i = 10, 30, 60º and φ = 15 mrad. Beam divergence of the reflectometers was set to 4.7 mrad to simulate the sun disc
- Good agreement (σ = 0.38%-p) was obtained for the **silvered-glass mirror**, with constant reflectance up to θ_i = 60º → **near-normal measurement is sufficient** for silvered-glass mirrors
- A decrease with θ_i was measured for the anti-soiling coated glass, polymer and aluminum mirror. ENEA improved its' EMA-TIS model to describe off-normal behavior. Significant deviations among the labs (up to σ = 2.31%-p for the aluminum mirror at θ_i = 60º)
  → **innovative mirrors require deeper analysis than standard silvered-glass mirrors**

Thank you for your attention!

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