Optical Characterization of PV Glass Coupons and PV Modules Related to Soiling Losses

Session 5: Characterization (Chair: Xiaohong Gu, NIST)
December 6th, 2017, 11:35 AM - 12:00 PM

Greg P. Smestad, Ph.D.
Sol Ideas Technology Development

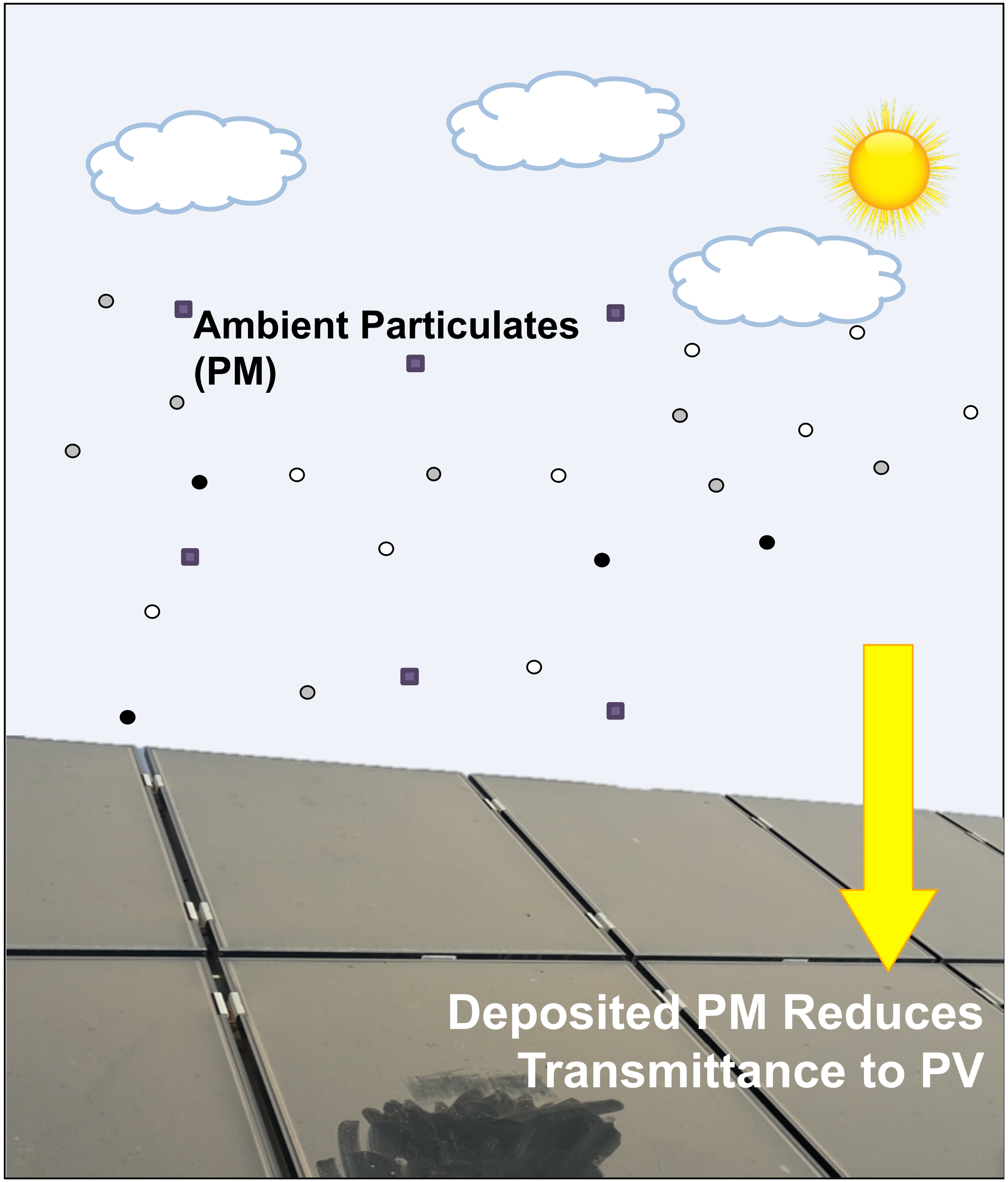
Leonardo Micheli, Ph.D.,
National Renewable Energy Laboratory (NREL)

Thomas A. Germer, Ph.D.,
National Institute of Standards and Technology (NIST)

Eduardo F. Fernández, Ph.D.
University of Jáen, Spain

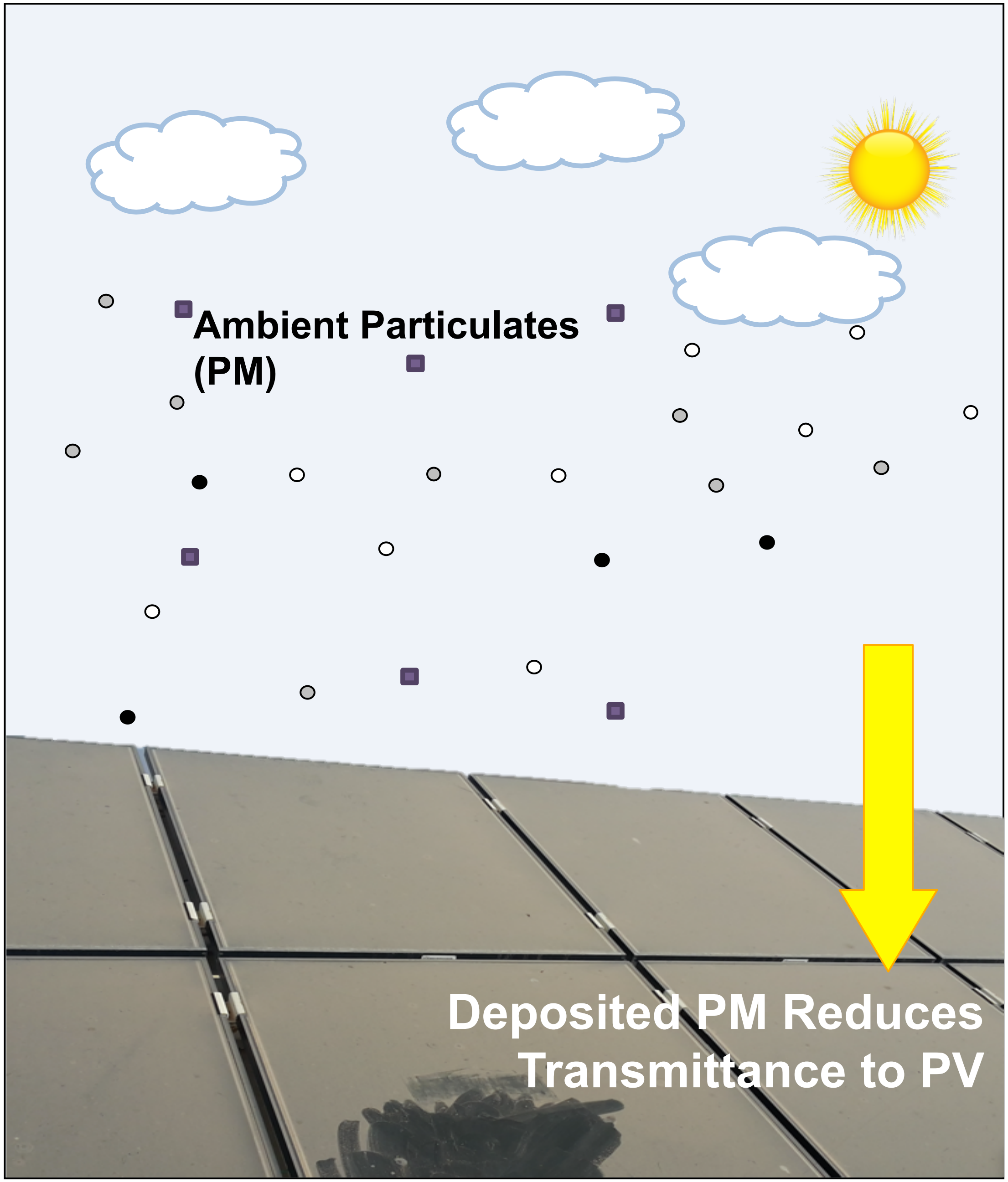
Outline

- Soiling Overview
- Ångström formula
- Experimental Procedure
- Transmission Results
- Coupon vs. PV Module
- Angle of Incidence effects
  - Model vs. Experiments
- Conclusions



Graphic: M.H. Bergin et al, Duke University, Durham, NC

"Large Reductions in Solar Energy Production Due to Dust and Particulate Air Pollution", Mike H. Bergin, Chinmay Ghoroi, Deepa Dixit, James J. Schauer, and Drew T. Shindell, Environ. Sci. Technol. Lett., 2017.



Graphic: M.H. Bergin et al, Duke University, Durham, NC

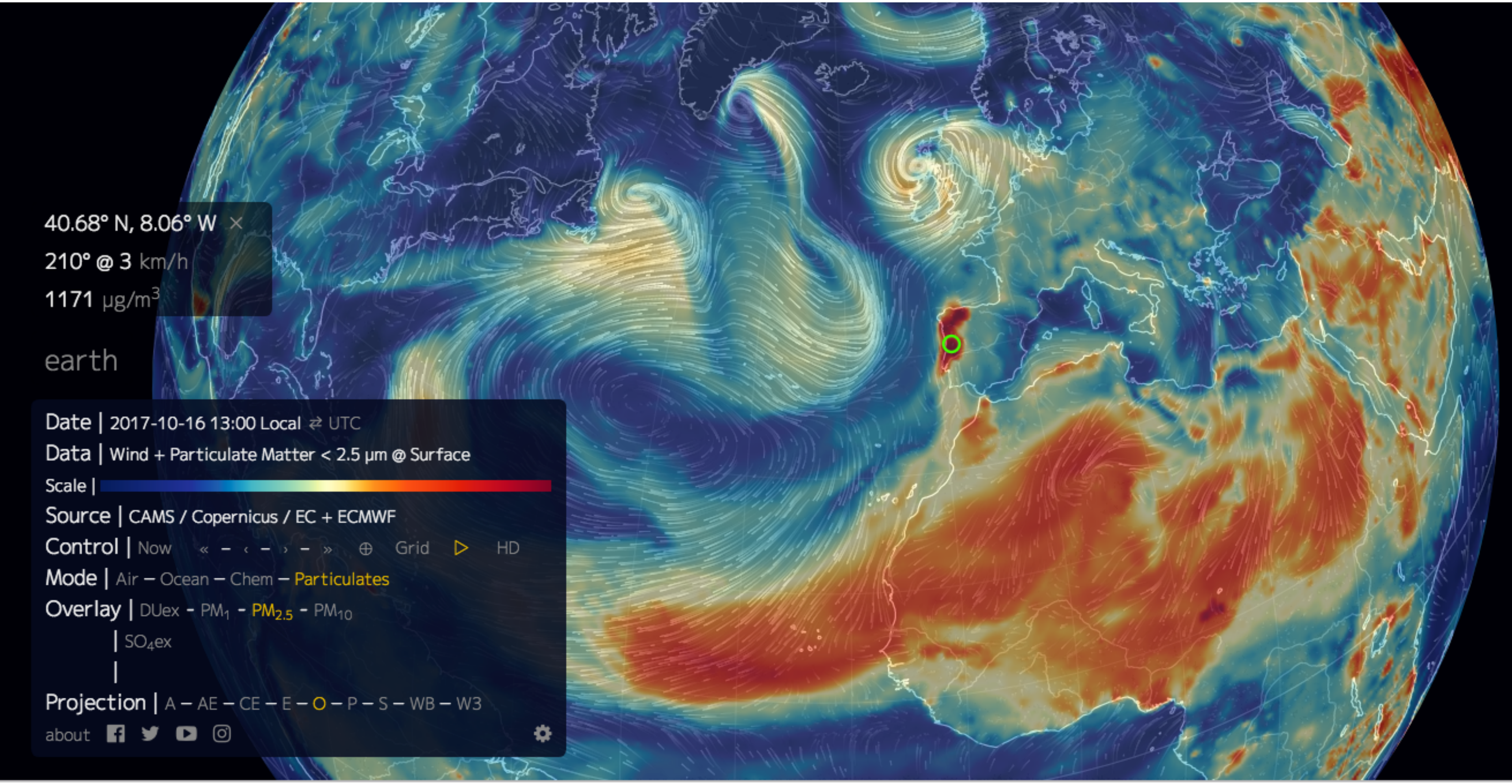
Soiling: Definition

Accumulation of dust, dirt and particles on the surface of PV modules.

Drop in power output: can be > 50%.

Drop in energy yield: 0 to 6% in the U.S.

Real time visualization of PM2.5



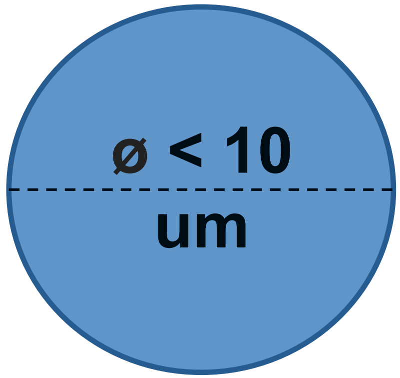
https://earth.nullschool.net/#current/particulates/surface/level/overlay=pm2.5/

Definition of Particulate Matter

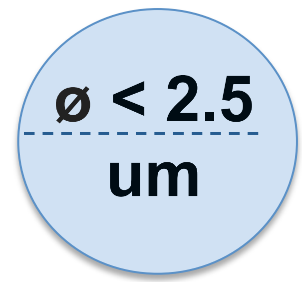
Particulate matter (PM): concentration ($\mu g/m^3$) of solid particles and liquid droplets suspended in 1 m^3 of air.

PM_{10} Sources:

Crushing or grinding operations
Dust stirred up by vehicles on roads



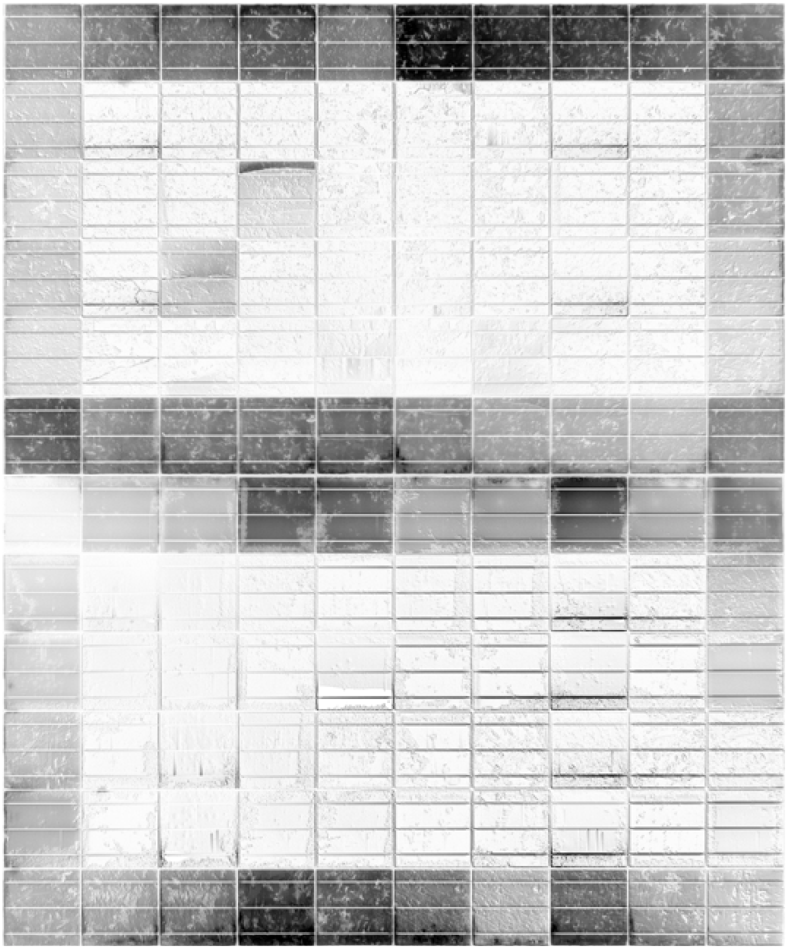
$PM_{2.5}$ Sources:
Motor vehicles, power plants, residential wood burning, forest fires, agricultural burning, industrial processes.



Source: https://www.airnow.gov/index.cfm?action=aqibasics.particle

PV EL and Soiling

a



b

Fig. 4. Subtractive electroluminescence images taken at 4.1-A forward-bias current on module type A with salt; (a), 73.3% power remaining; (b) without salt, 84.7% power remaining. Degraded areas appear dark.

Peter Hacke, et al, Effects of Photovoltaic Module Soiling on Glass Surface Resistance and Potential-Induced Degradation, Conference Paper, NREL/ CP-5J00-64492 December 2015

The Optical Path of the Light (clean vs. soiled)

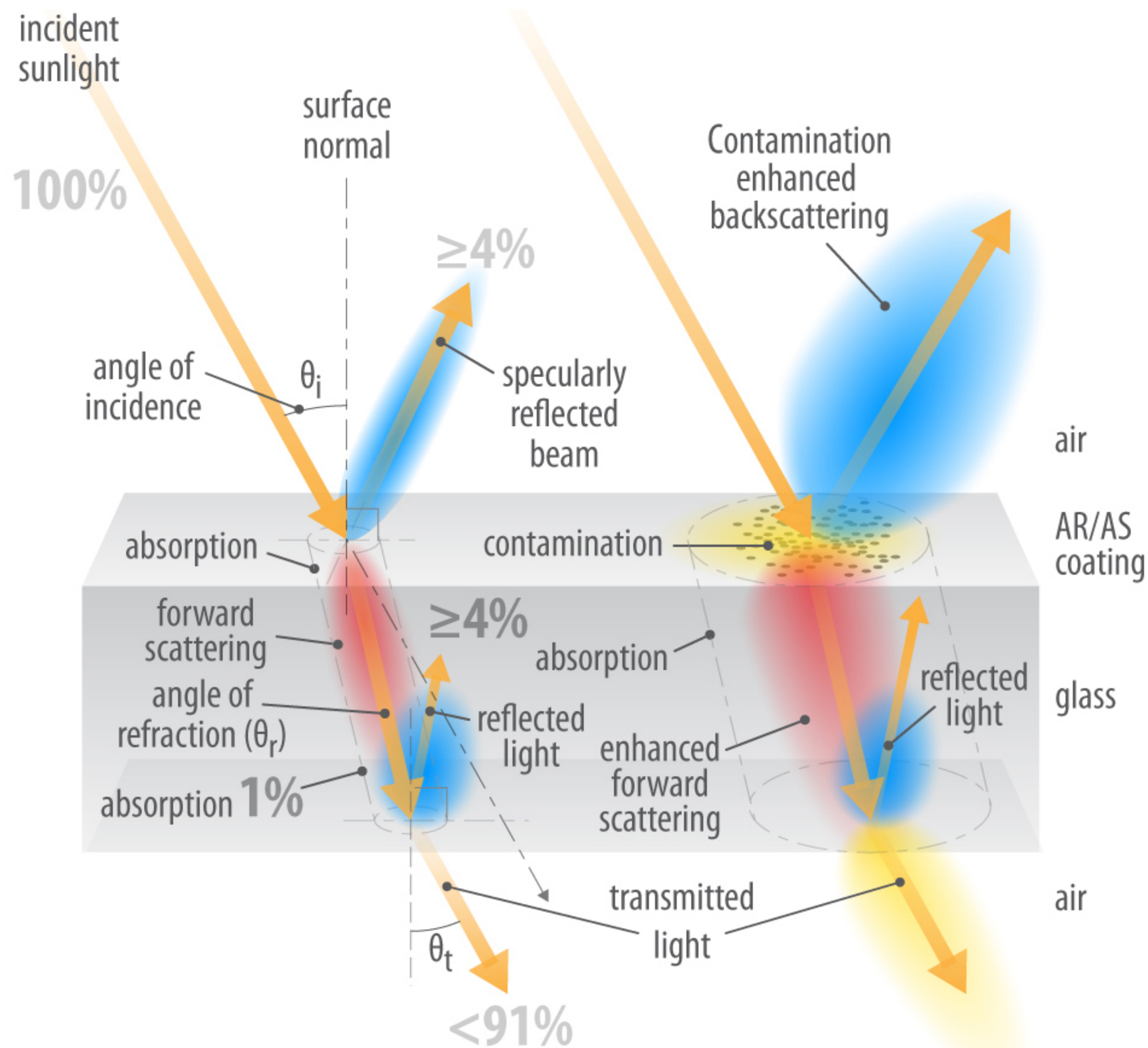
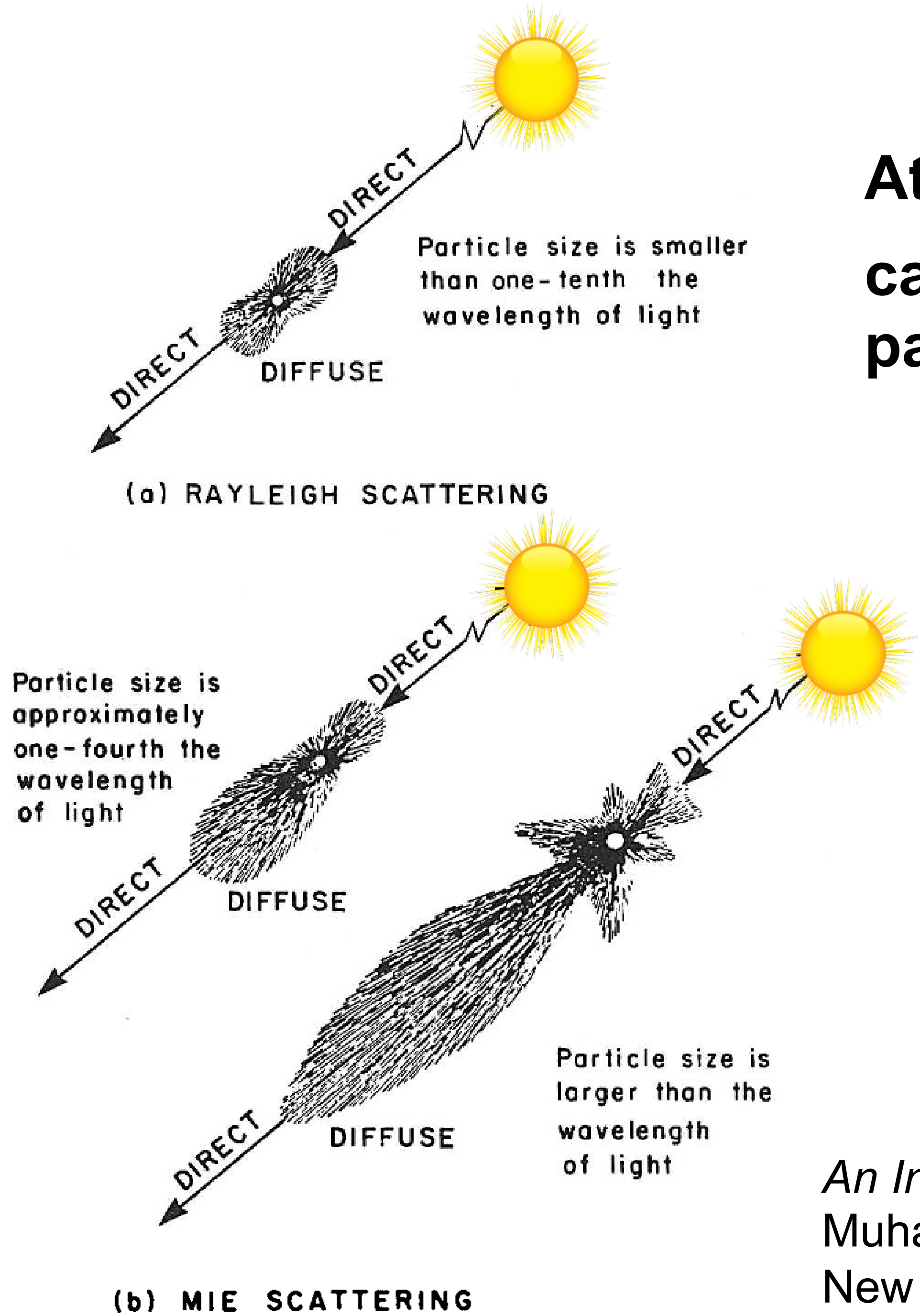


Diagram Courtesy of Al Hicks, NREL

Atmospheric Scattering

can be applied to particles on the glass



An Introduction to Solar Radiation, Muhammad Iqbal, Academic Press, New York, 1983, Chapter 6.

Ångström turbidity formula

$$\tau_{a\lambda} = \exp(-\beta\lambda^{-\alpha} m_a)$$

$\beta \rightarrow 0.0$ to 0.5 or even higher

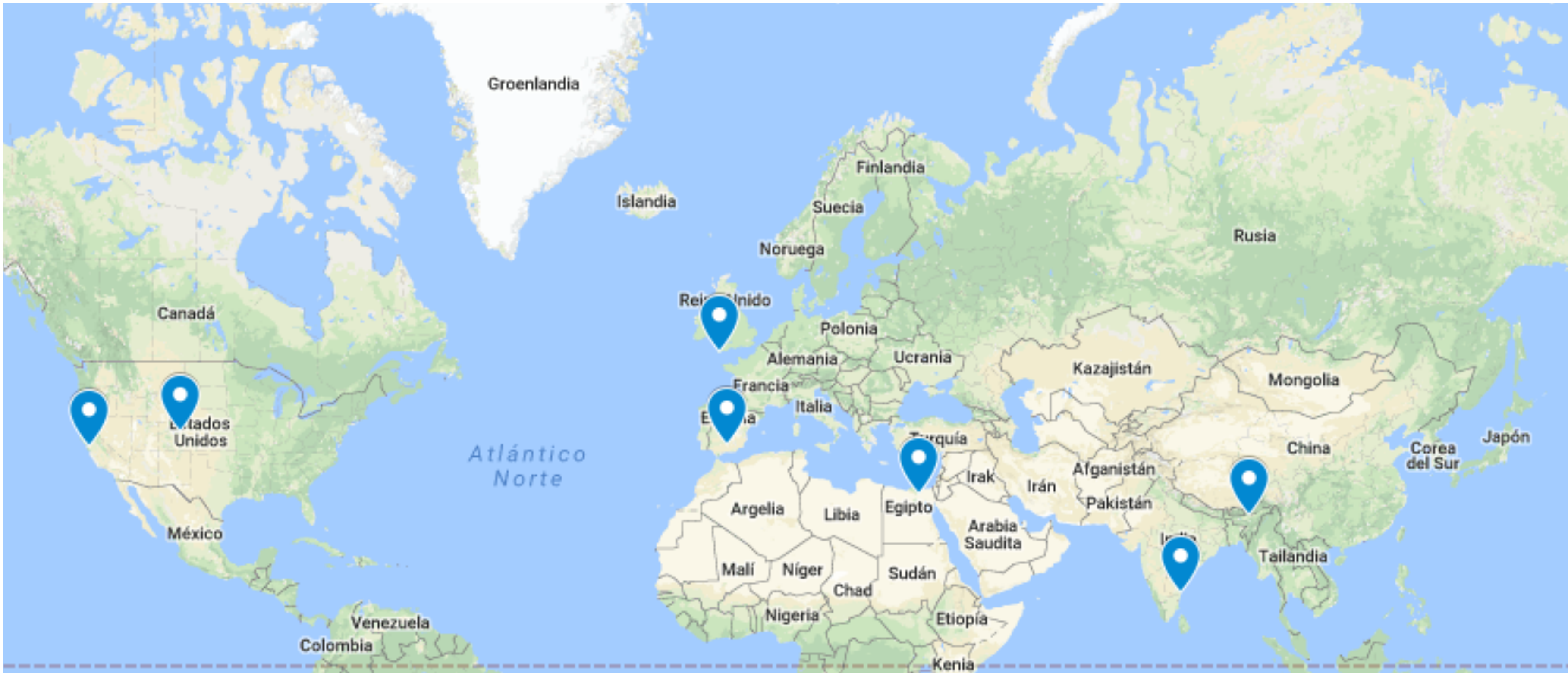
- An index representing the amount of aerosols (particles) present

$\alpha = 4$ for small non-absorbing particles
$\alpha = 1$ for small absorbing particles
$\alpha = 0$ for large particles

- Wavelength (λ) exponent
- Generally 0.5 to 2.5 (Ångström suggested 1.3)

m_a is the optical path length

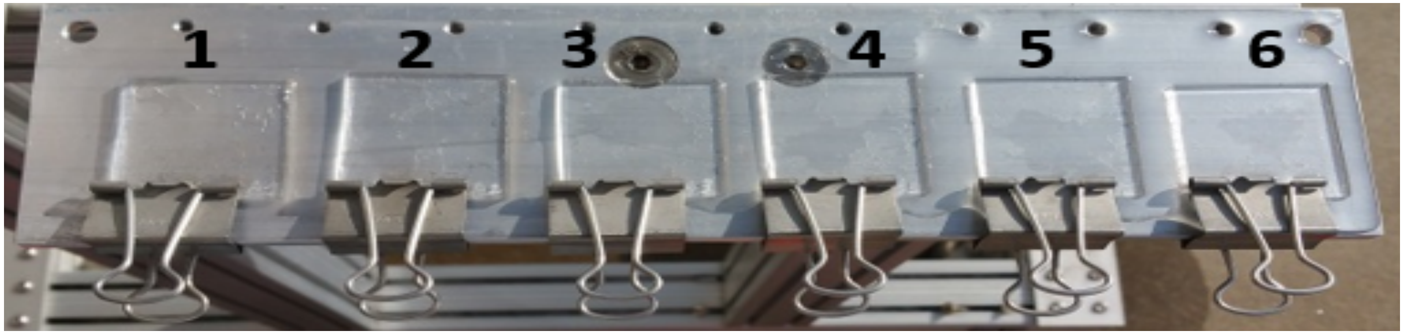
Spectral impact of soiling: Experiments



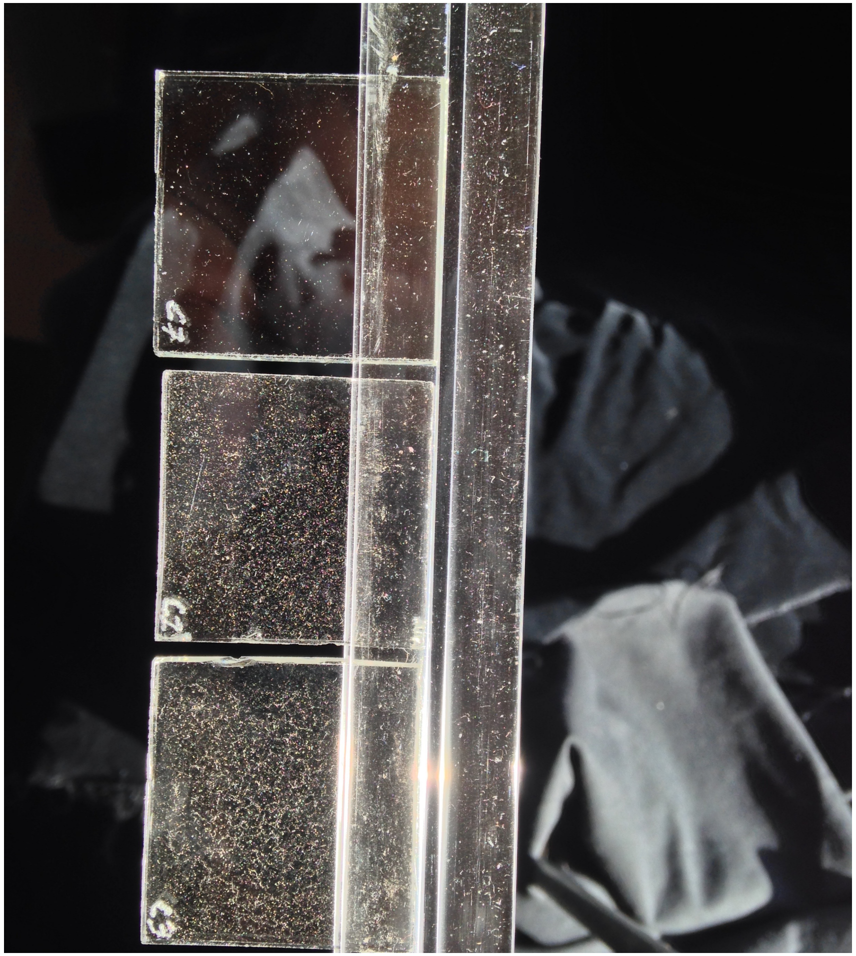
City, Country	*Coordinates*	*Climate classification*
Chennai, India	13.08, 80.27	Equatorial savannah with dry winter (Aw)
El Shorouk City, Egypt	30.12, 31.61	Desert climate (Bwh)
Golden (CO), USA	39.74, -105.18	Snow climate, fully humid (Dfb)
Jaén, Spain	37.79, -3.78	Warm temperate climate with dry summer (Csa)
Penryn, UK	50.17,-5.13	Warm temperate climate, fully humid (Cfb)
San José (CA), USA	37.29, -121.91	Warm temperate climate with dry summer (Csb)
Tezpur, India	26.70, 92.83	Warm temperate climate with dry winter (Cwa)

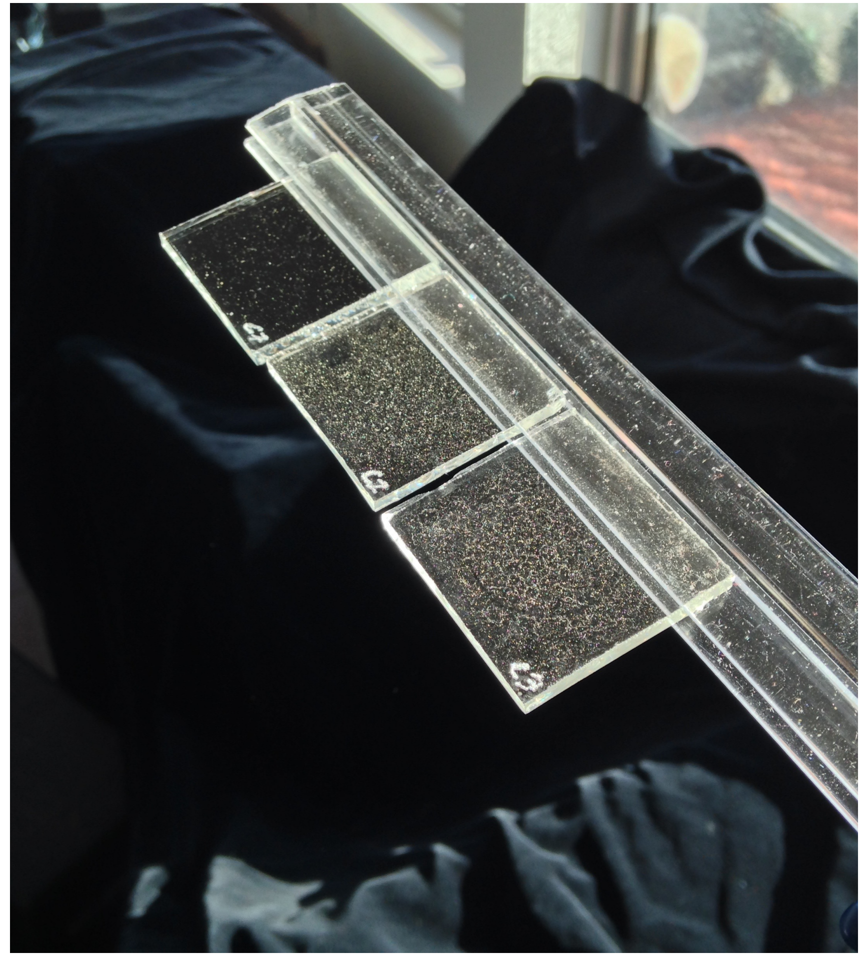
Experimental procedure

- **Seven 4 cm x 4 cm x 3 mm-thick low iron glass coupons shipped to each location.**
- **Coupon 1 to 6 installed outdoors at zero tilt angle for eight weeks.**
- **Coupon 0 kept in a dust free container and used to calibrate each spectrophotometer.**
- **Weekly transmission measurements for coupons 1, 2, 3.**
- **Daily weather and particulate matter (PM) concentration recorded.**
- **A dry cleaning is performed by using a microfiber cleaning cloth.**
    - **Coupon 1 cleaned every week, Coupon 2 every four weeks.**

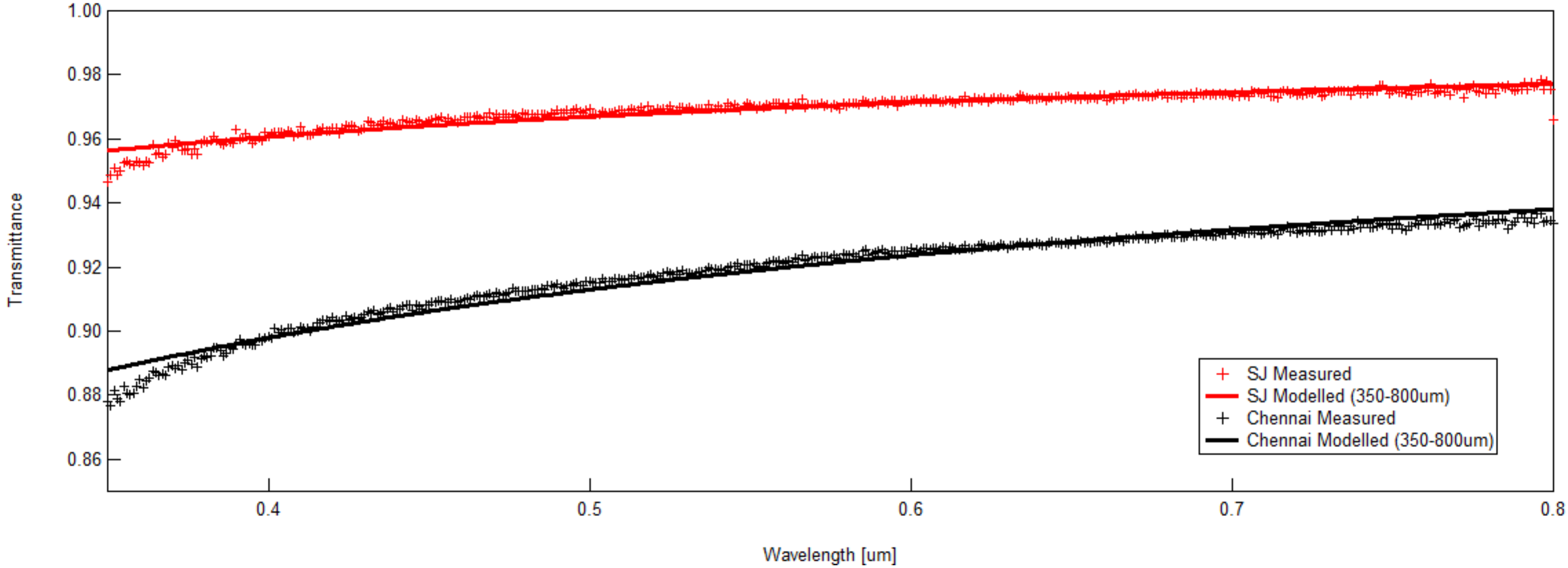


After 8 weeks (San José, CA)





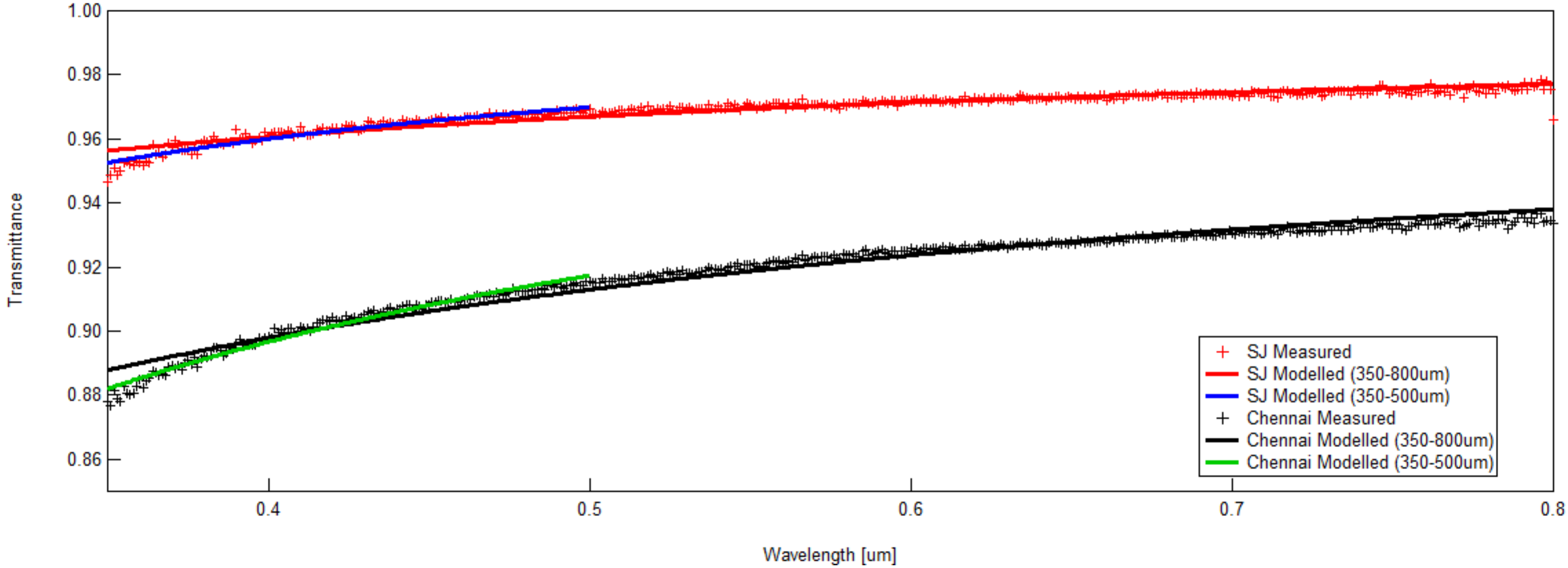
Fitting San José and Chennai Data
(after 8 weeks)



Ångström equation returns in both cases high R^2 (≥90%), and low RMSE (<0.3%).

Fitting San José and Chennai Data

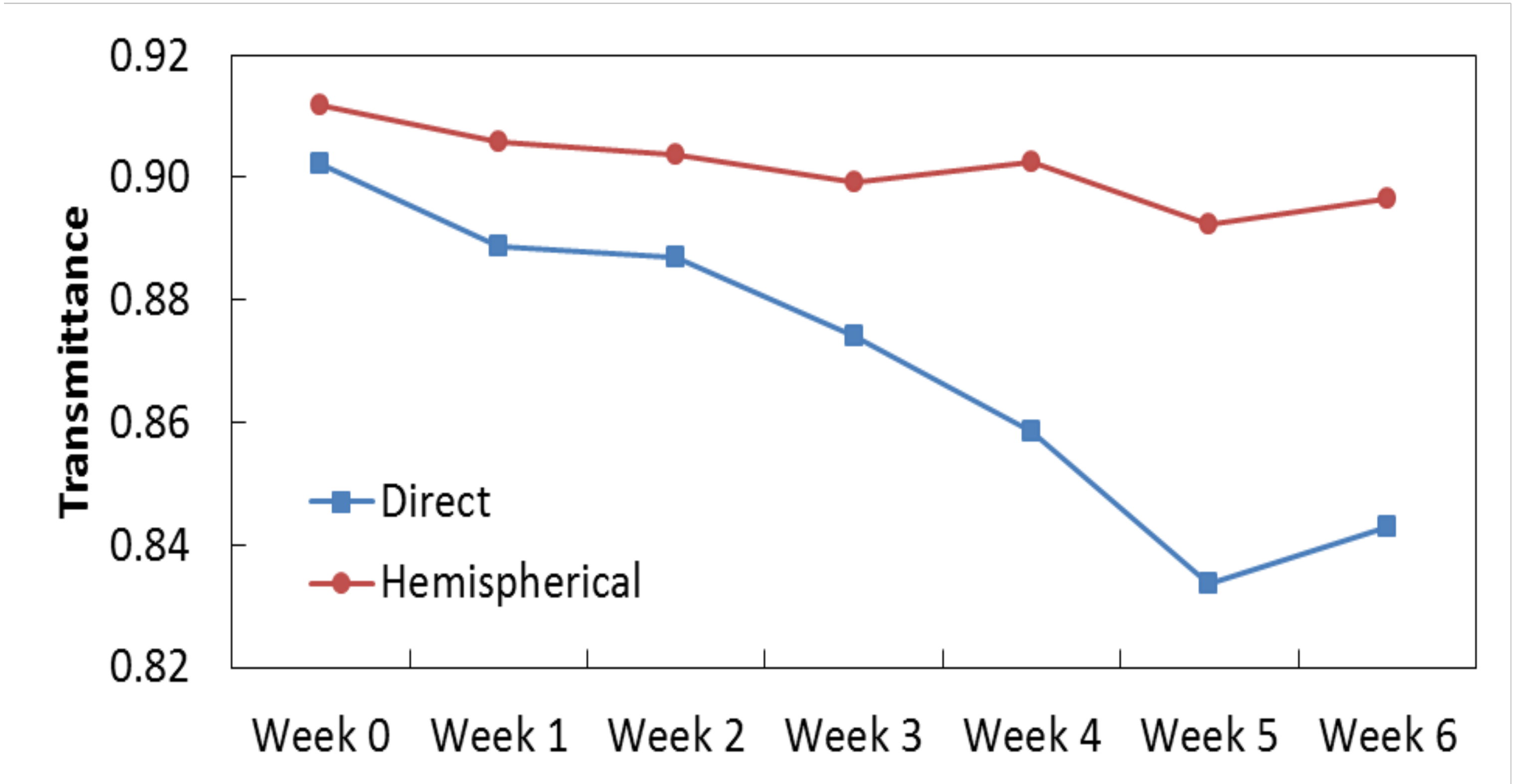
(after 8 weeks)



Ångström equation returns in both cases high R^2 (≥90%), and low RMSE (<0.3%).

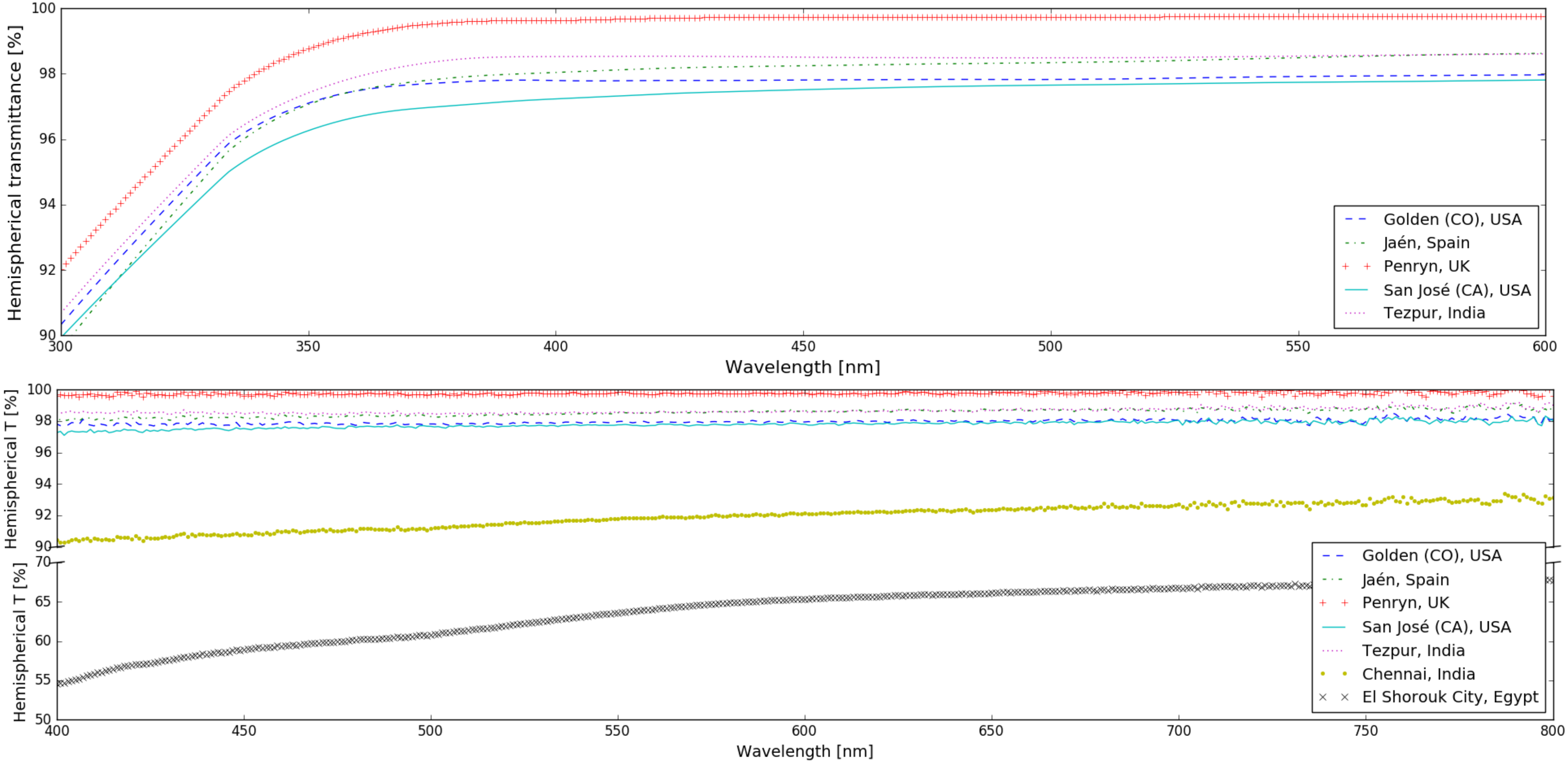
<u>…but fitting at low wavelengths can still be improved.</u>

First results



Absolute direct and hemispherical transmittance of coupon 3 in Golden, CO. Wavelengths between 500 and 1100 nm have been averaged.

Hemispherical transmittance (8 weeks)



Hemispherical transmittance in the visible and NIR range of coupon 5 for all the sites (above) and for the low soiling sites (below), referenced to the transmittance of coupon 0. The spectra were measured using a PerkinElmer Lambda 1050 UV/Vis spectrophotometer with a 150 mm integrating sphere at NREL and processed using a local regression technique to remove noise.

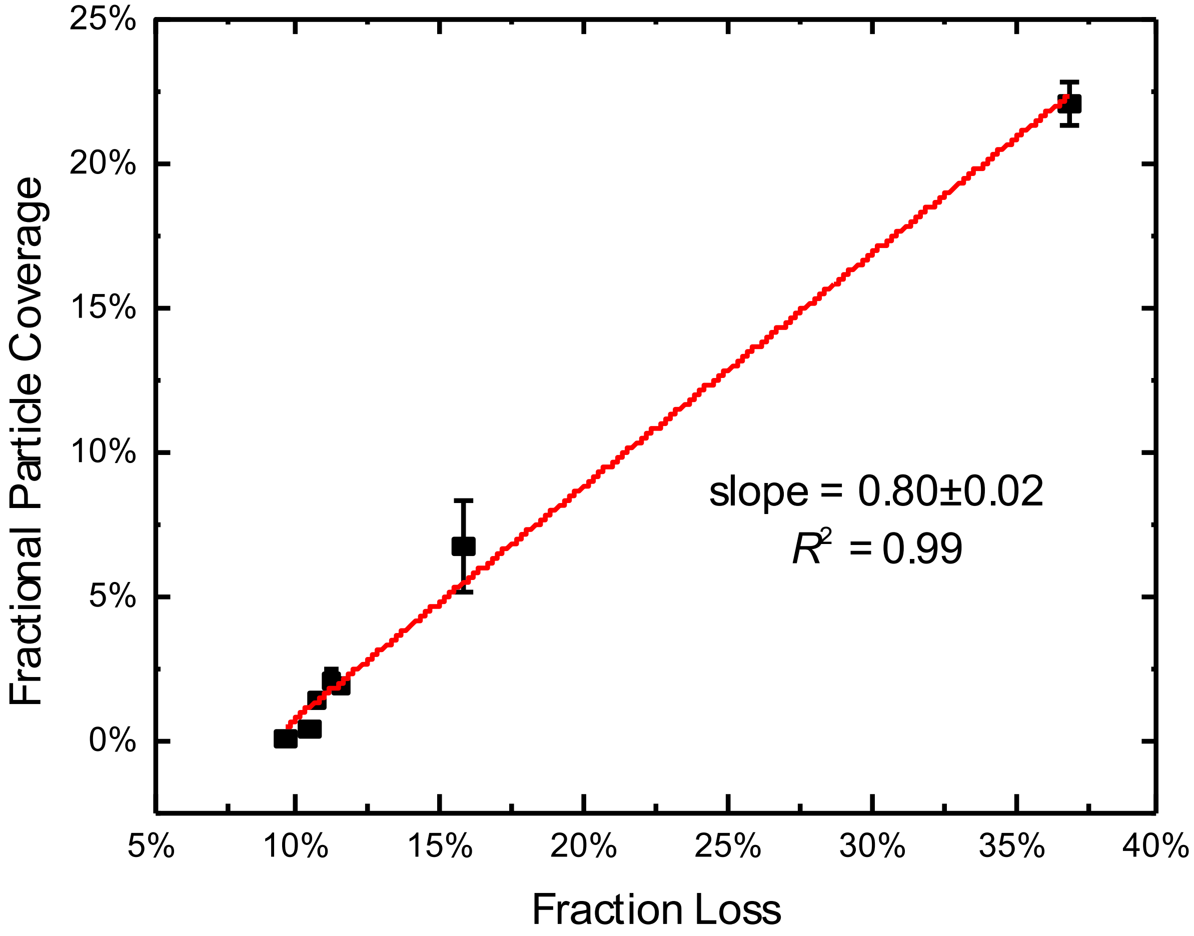
Particle Area and Hemispherical Transmittance

- Average particle area was determined by high resolution optical microscopy.
- Percentage of the surface covered by particles was estimated.

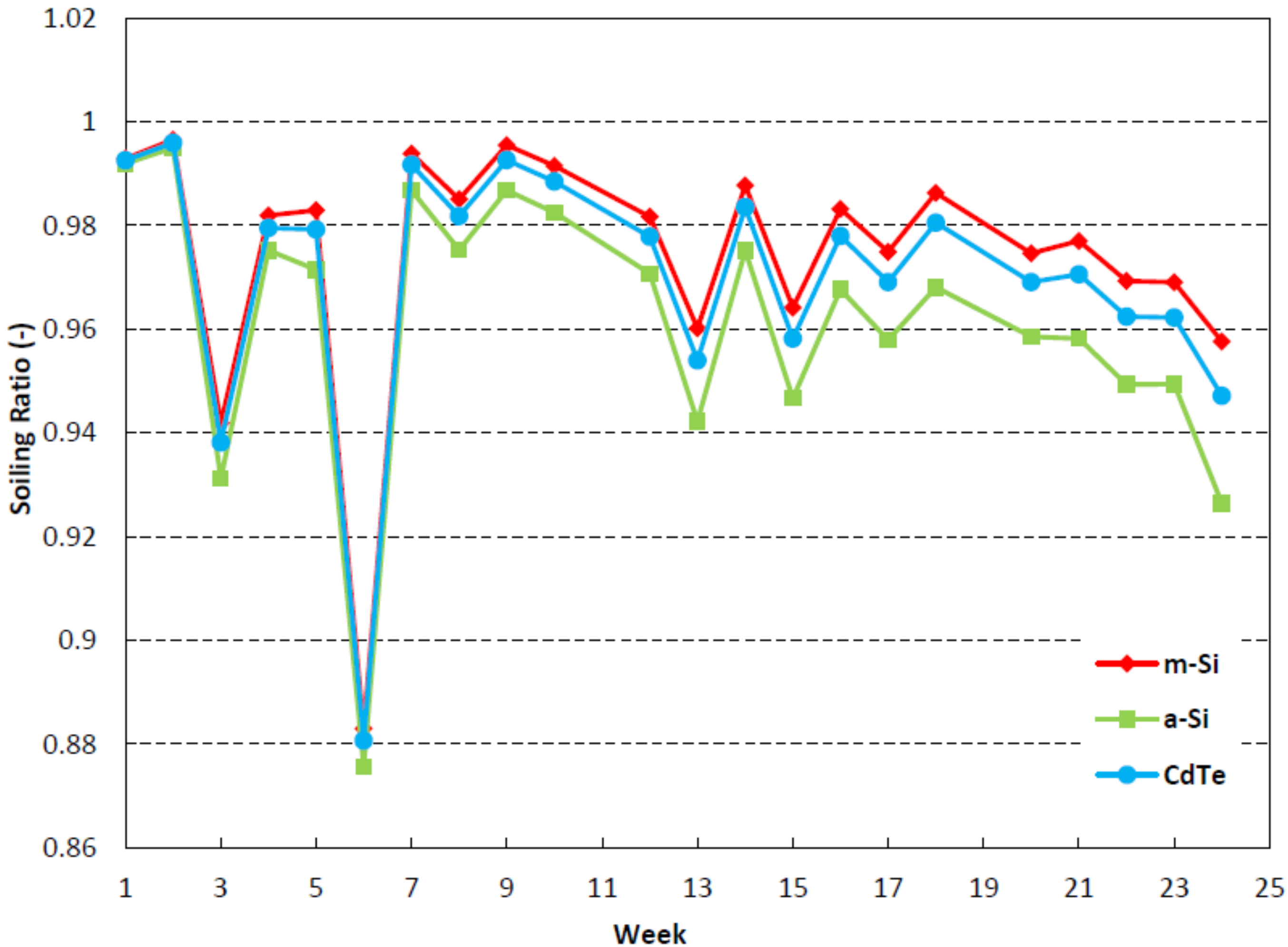
- Broadband hemispherical transmittance (300-2500 nm) was measured.

- A linear correlation, with R^2 higher than 0.99, is found by comparing the percentage area covered by particles to the hemispherical transmission.
- The broadband hemispherical transmission could be directly obtained from the coverage area, independently of location, dust type and composition.
- See the subsequent plot (slide).

Fractional Loss versus Particle Coverage



The Dust & Rain in Spain falls mainly…



Predication: 6-months of outdoor exposure at Jáen, Spain.
Estimated weekly evolution of Soiling Ratio index estimated for three PV materials.

From the transmission of glass coupons times the solar spectrum times the PV spectral response or QE. There was a Saharan dust storm at week 6 and then rain.

Optics of a PV Module (right) does not match that of the coupons (left)

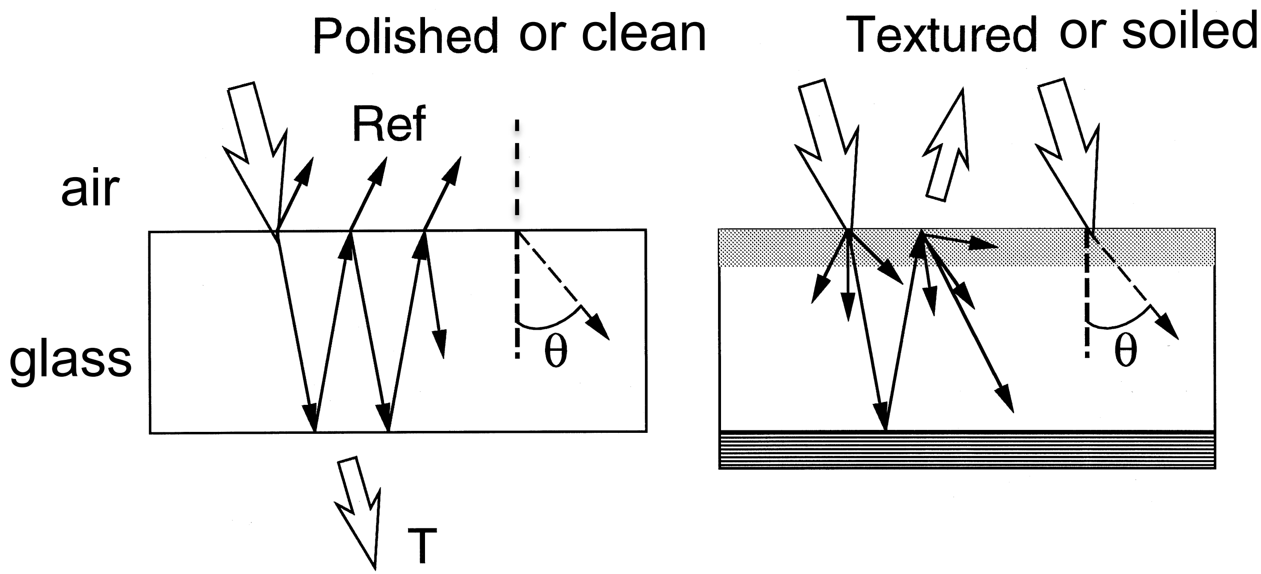
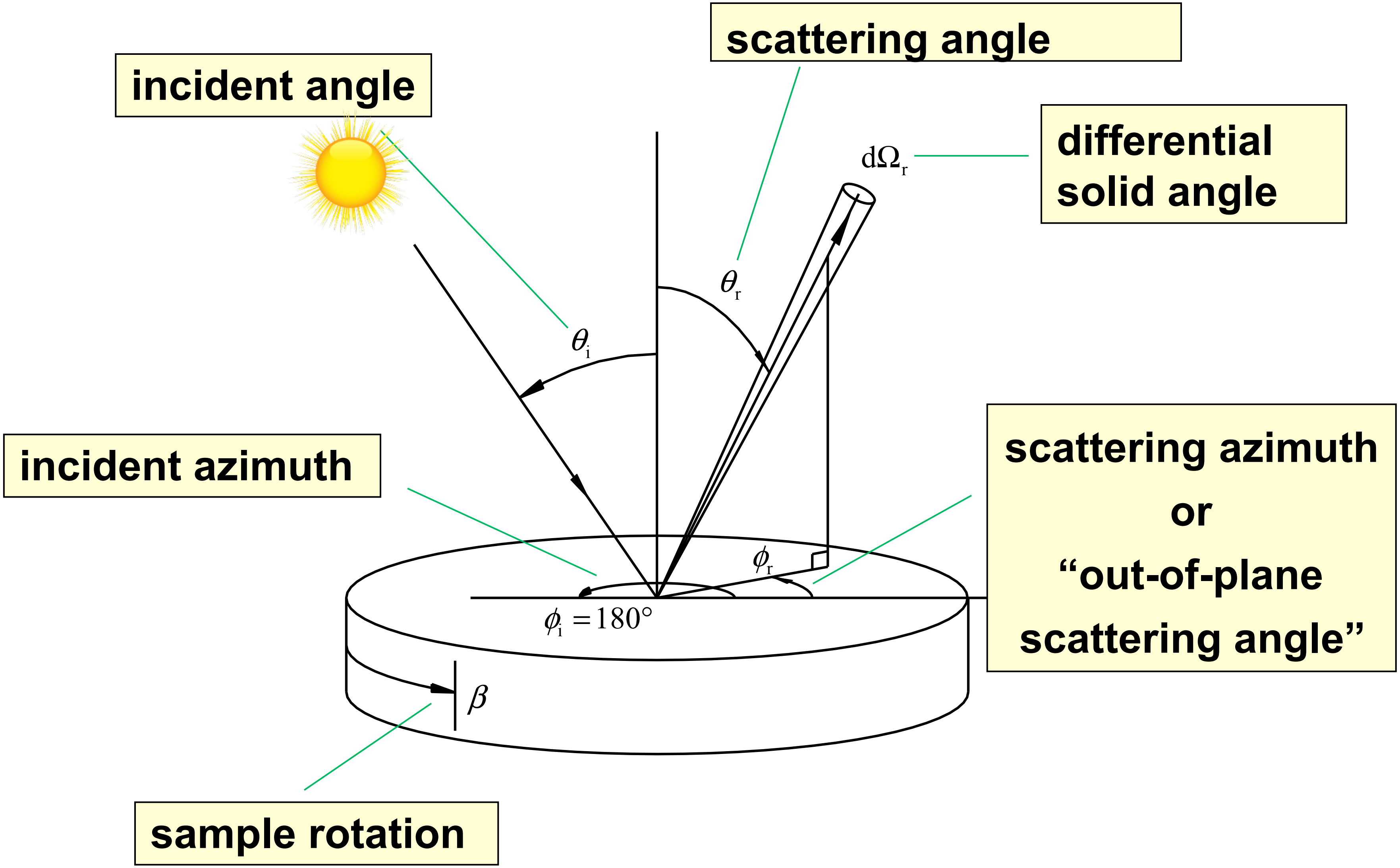


Fig. 2.10 Geometry for calculation of the absorptivity from a polished (left side) and textured (right side) light absorber. In each case, a summation of multiple reflections must be made in order to calculate the absorptivity. The angle θ is measured from the surface normal.

Smestad, Greg P.
Optoelectronics of solar cells / by Greg P. Smestad.
p. cm.-- (SPIE Press monograph ; PM115)
Includes bibliographical references and index.
ISBN 0-8194-4440-5 (softcover)
1. Solar cells. 2. Optics. I. Title. II. Series.

Angular Measurements and Model



Thomas A. Germer, Sensor Science Division, NIST

Describing the scatter from a delocalized scatterer

The <u>Bidirectional Scattering Distribution Function</u> (BSDF) is the fraction of power scattered per unit projected solid angle.

$$f_\mathrm{r} = \lim_{\Omega \to 0} \frac{P_\mathrm{r}}{\Omega \, P_\mathrm{i} \cos\theta_\mathrm{r}} \qquad [\mathrm{sr}^{-1}]$$

Scattered power [W]

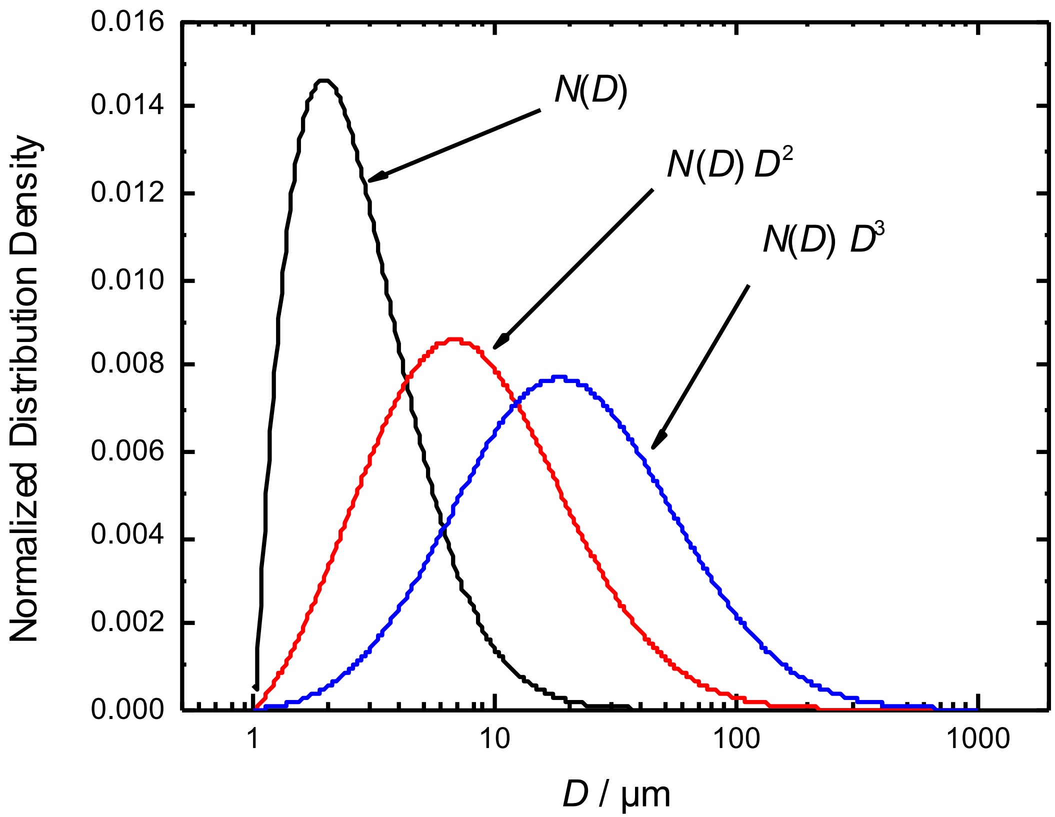
Solid angle [sr]

Incident power [W]

Polar scattering angle

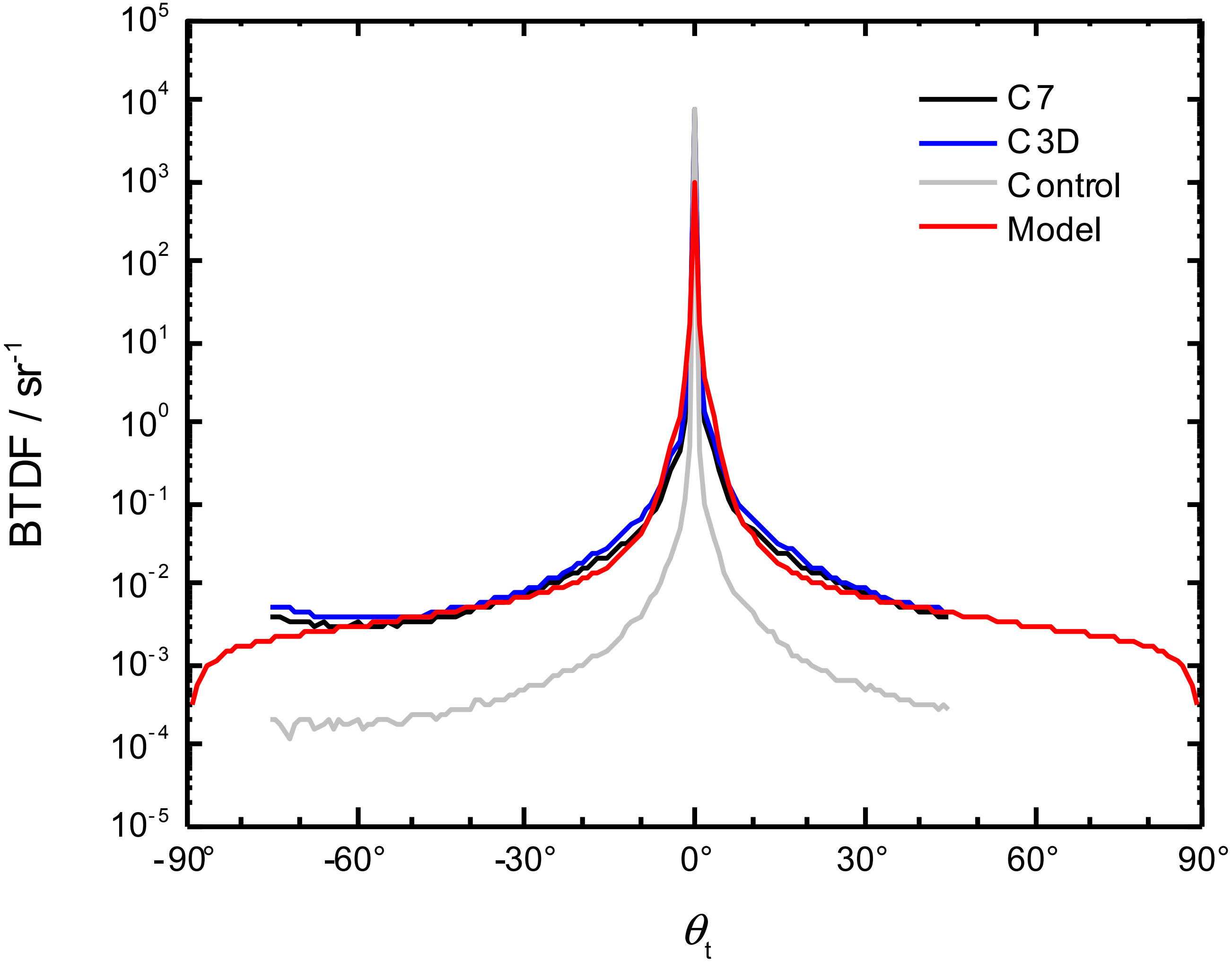
Thomas A. Germer, Sensor Science Division, NIST

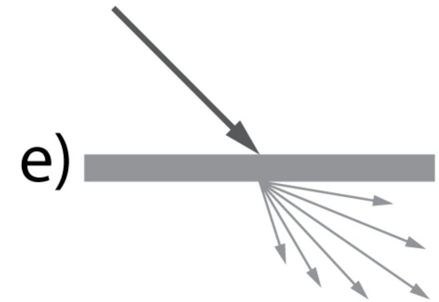
IEST-STD-CC 1246E Distribution



The cumulative distribution is the number of particles between 1 µm and D. Shown here are the distribution density, dN(D)/dD, and the distribution density weighted by area and volume. Notice how much the peak appears to change. It is hard to eyeball a peak size in a distribution from an image.

The Transmission Data (San José)





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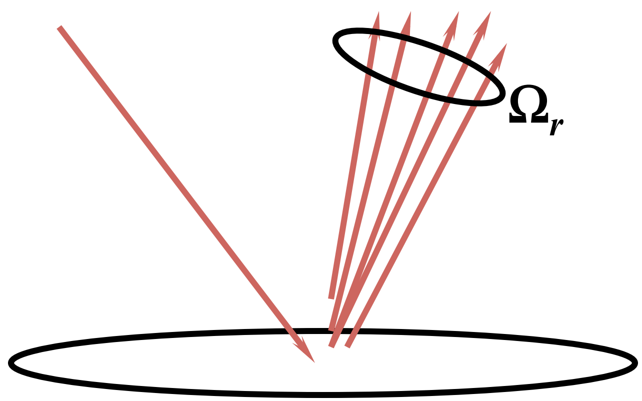
Reflectance for collimated incident light

With a lot of experimental geometries, the incident light is close to collimated. Then, the reflectance is

$$\rho(\theta_{\mathrm{i}},\phi_{\mathrm{i}};\Omega_{\mathrm{r}}) = \int_{\Omega_{\mathrm{r}}} f_{\mathrm{r}}(\theta_{\mathrm{i}},\phi_{\mathrm{i}};\theta_{\mathrm{r}},\phi_{\mathrm{r}}) \cos\theta_{\mathrm{r}} \, \mathrm{d}\Omega_{\mathrm{r}}$$

$$= \int_{\Omega_{\mathrm{r}}} \mathrm{d}\theta_{\mathrm{r}} \, \mathrm{d}\phi_{\mathrm{r}} \sin\theta_{\mathrm{r}} \cos\theta_{\mathrm{r}} \, f_{\mathrm{r}}(\theta_{\mathrm{i}},\phi_{\mathrm{i}};\theta_{\mathrm{r}},\phi_{\mathrm{r}})$$



Program **INTEGRATED.MIST** calculates the hemispherical reflectance for any BRDF model.

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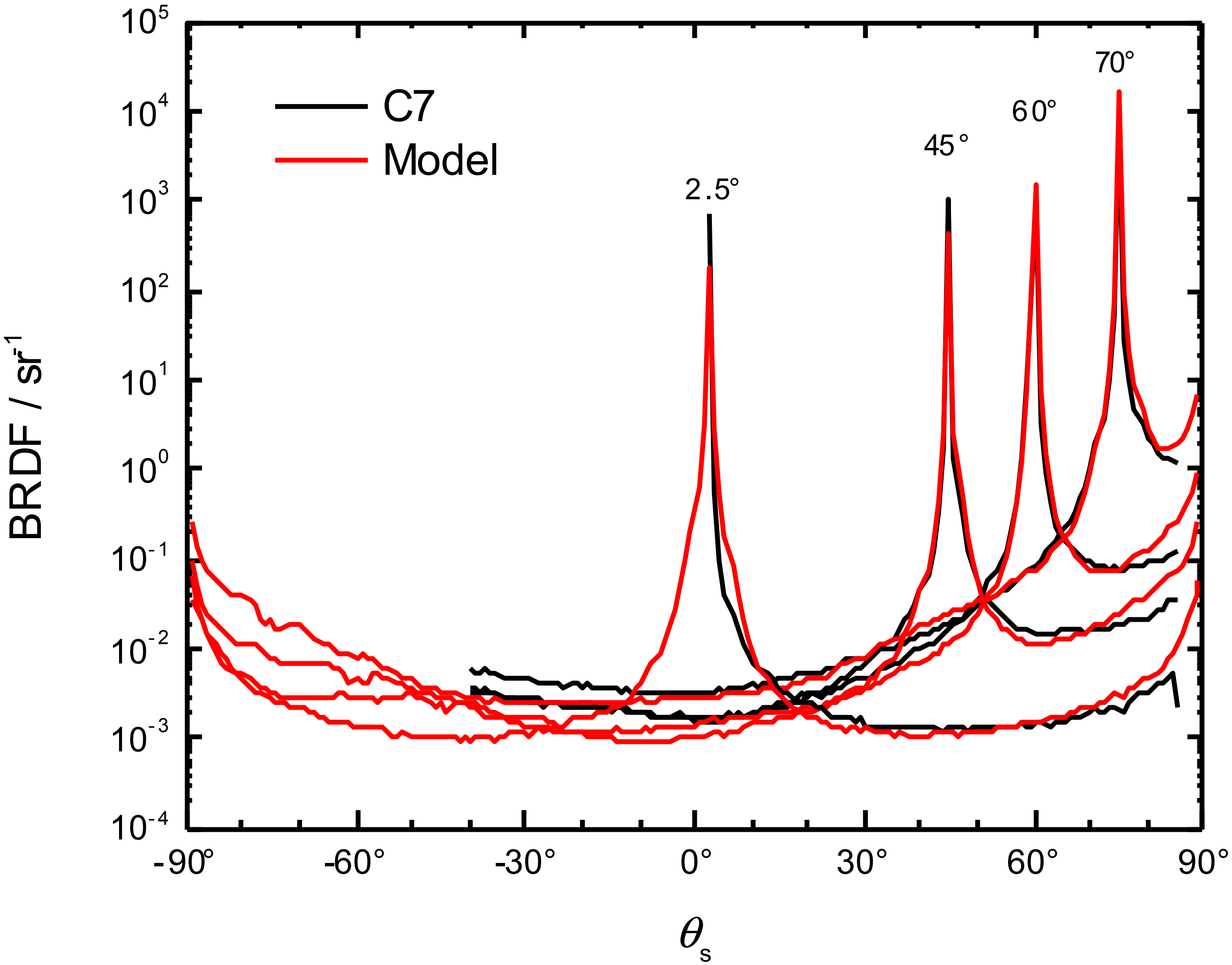
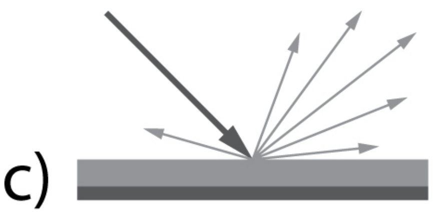
The Reflection data





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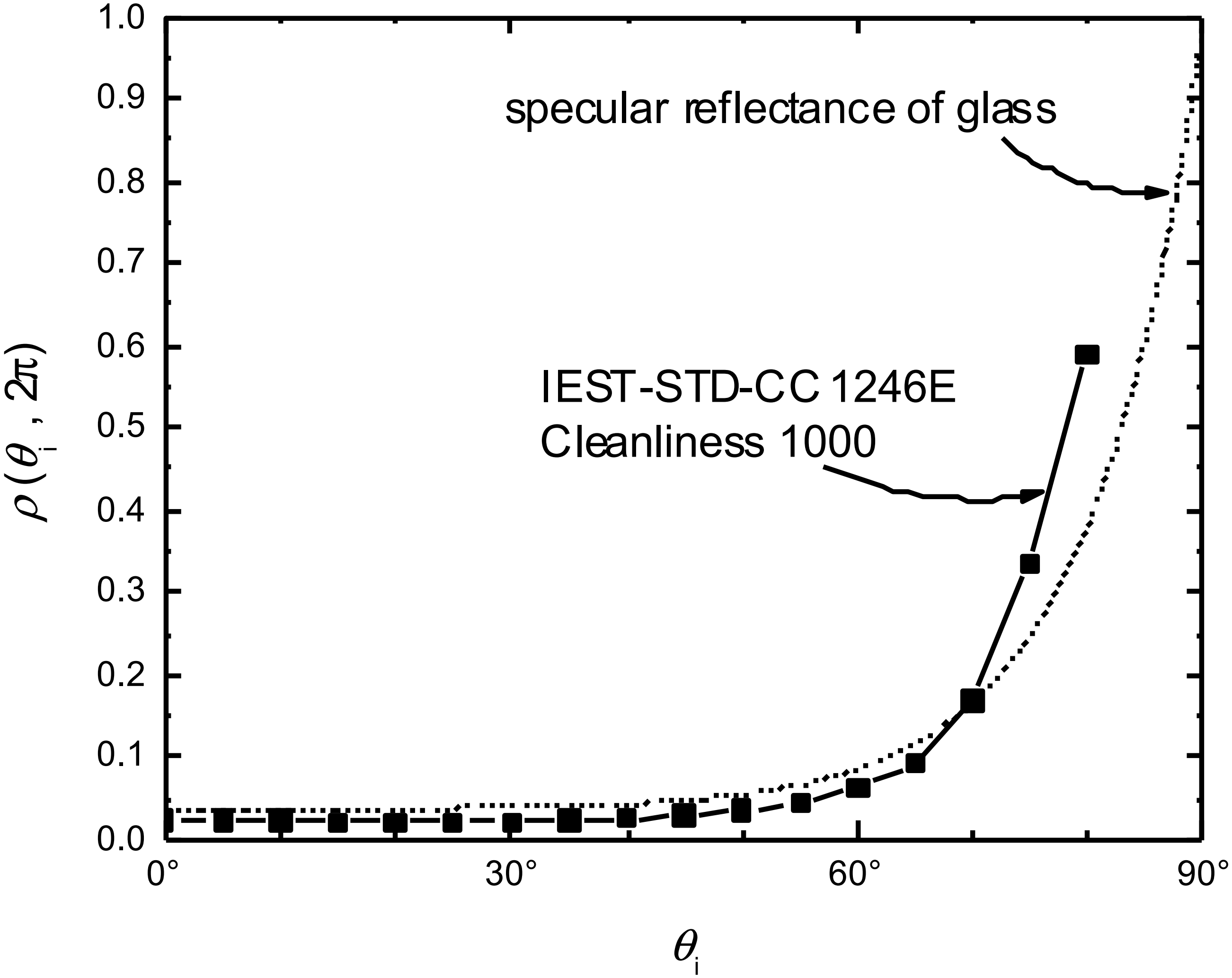
Predicted Reflectivity vs incidence angle



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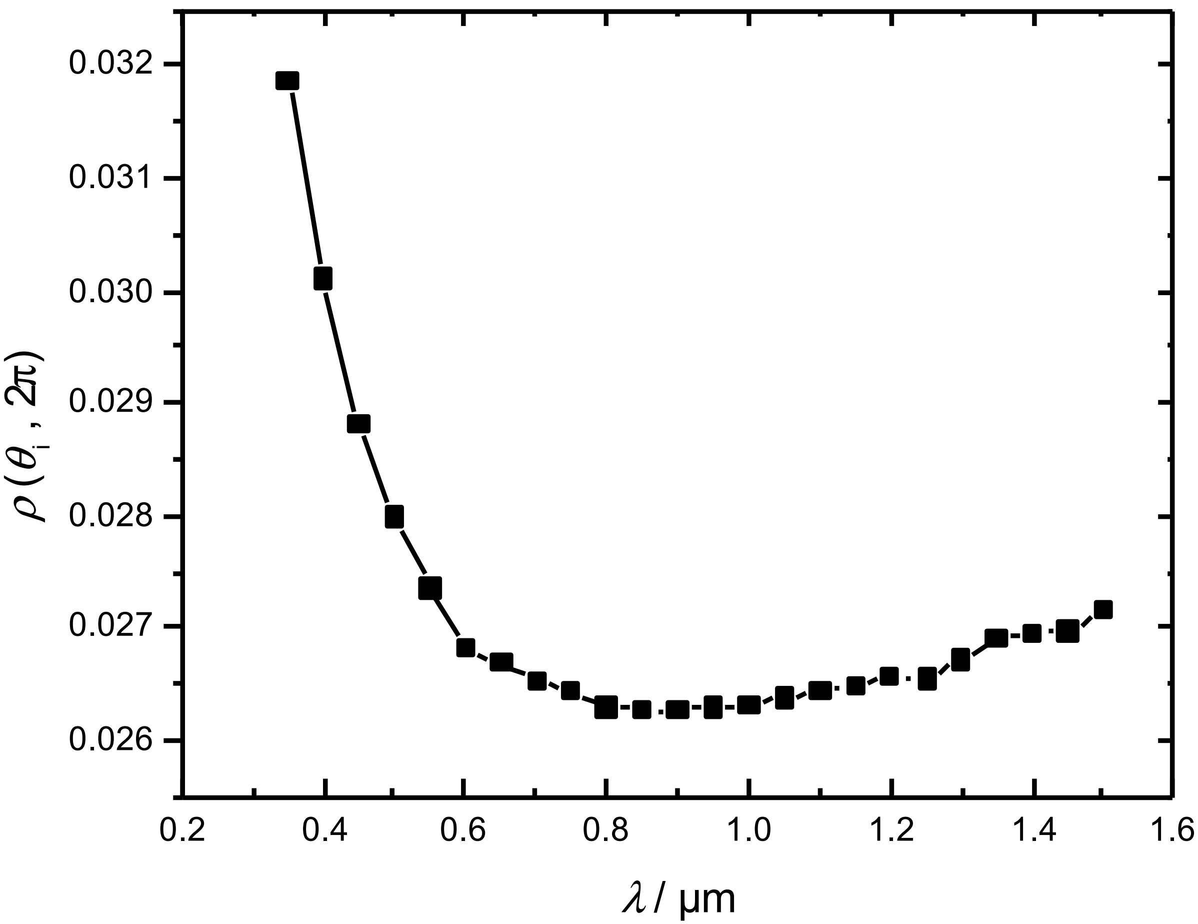
Calculated Hemispherical Reflectance of Soot Particles



Using IEST-STD-CC 1246E Distribution Cleanliness 1000

Thomas Germer, NIST

Conclusions (Optics of PV soiling)

- Estimating soiling losses using the transmission from glass coupons may not easily translate to knowledge about power losses from PV modules.
- The affect on direct transmission is greater than hemispherical.
- There is a linear correlation between the area covered by particles and the broadband hemispherical transmittance.
- Soiling produces a higher attenuation at shorter wavelengths (Ångström turbidity formula) compared to longer wavelengths.
- The impact of soiling is likely higher on PV materials with larger bandgap (a-Si, CdTe).
- Soiling Losses are certainly a function of input angle.

Acknowledgments

- EPSRC SUPERGEN SuperSolar Hub's "International and industrial engagement fund" for the project "Global investigation on the spectral effects of soiling losses"
- University of Exeter, UK; National Renewable Energy Laboratory (NREL), USA; University of Jáen, Spain; Sol Ideas Technology Development, San José (CA), USA; Tezpur University, Tezpur, India; Robert Gordon University, Aberdeen, UK; South Valley University, Qena, Egypt; British University in Egypt, El Sherouk City, Egypt; BITS Pilani, Dubai Campus, Dubai, UAE; Academy of Scientific and Innovative Research, Chennai, India; CSIR-Central Electronics Engineering Research Institute, Chennai, India; Indian Institute of Technology Madras, Chennai, India.

Greg P. Smestad, Sol Ideas Technology Development

smestad@solideas.com — www.solideas.com

PVQAT
International PV Quality Assurance Task Force

The International PV Quality Assurance Task Force (PVQAT, "PV cat") TG-12. Website: http://www.pvqat.org

Soiled Residential PV System of David Bernal in Los Angeles (Photo by Greg Smestad)

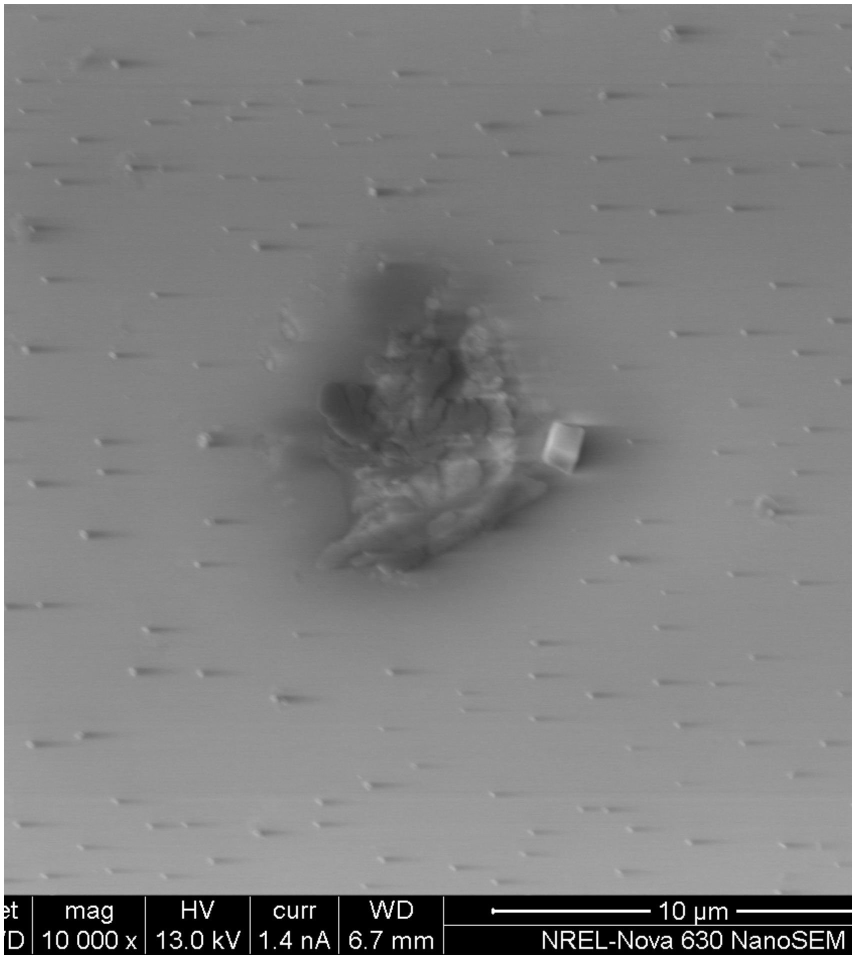
Greg P. Smestad, Sol Ideas Technology Development
smestad@solideas.com — www.solideas.com

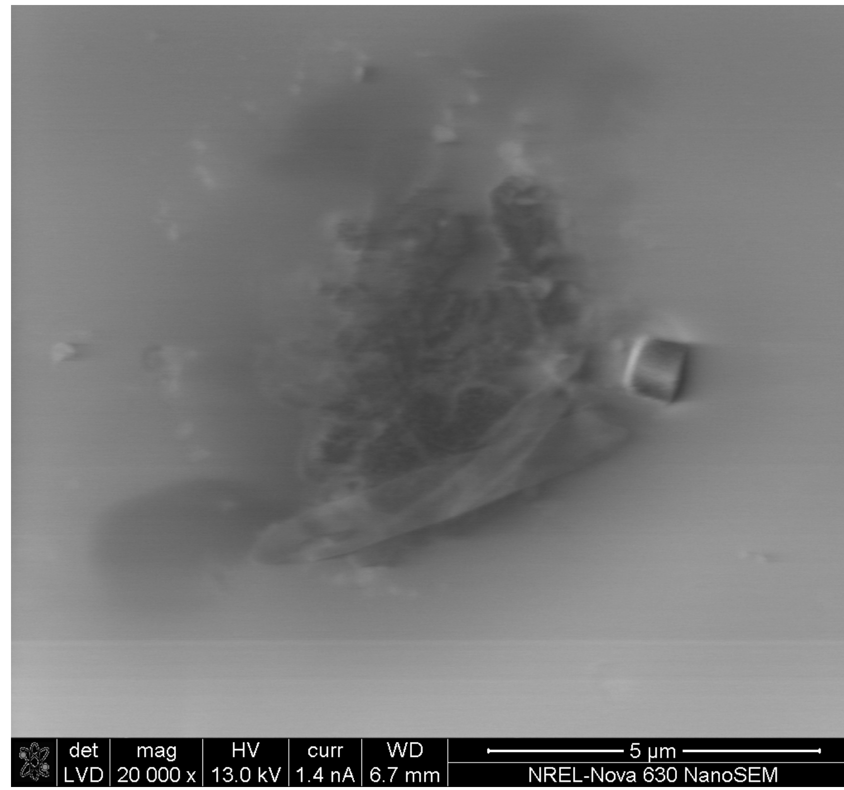
Background, Supporting Information

Leonardo Micheli, Eduardo F. Fernández, Greg P. Smestad, et al, **"A unique global investigation on the spectral effects of soiling losses of PV glass substrates: preliminary results"**.

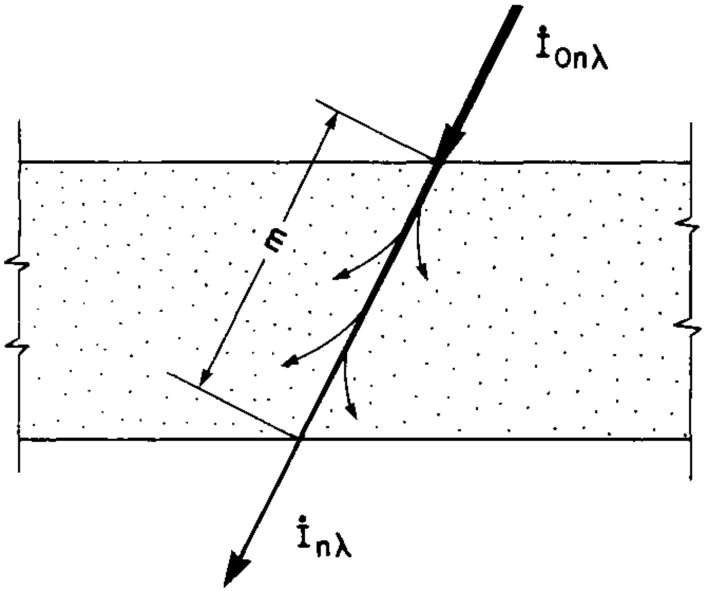
- Paper & Poster available
- Presented at ieee-pvsc.org/PVSC44/
- Download the materials for free here:
  http://www.solideas.com/projects/pvquality/index.html

SEM (soiling site: San José, CA)





SEM image of particles from soiling in San José, CA.
Photo: Greg Smestad/NREL, Helio.Moutinho@nrel.gov



Bouguer's law - the attenuation of light through a medium is proportional to the distance traversed in the medium.

k_λ is the monochromatic extinction or attenuation coefficient

m is the optical path length

$k_\lambda m$ is the monochromatic extinction optical thickness

$$\tau_{i\lambda} = \exp(-k_{i\lambda} m_i).$$

An Introduction to Solar Radiation, Muhammad Iqbal, Academic Press, New York, 1983, Chapter 6.

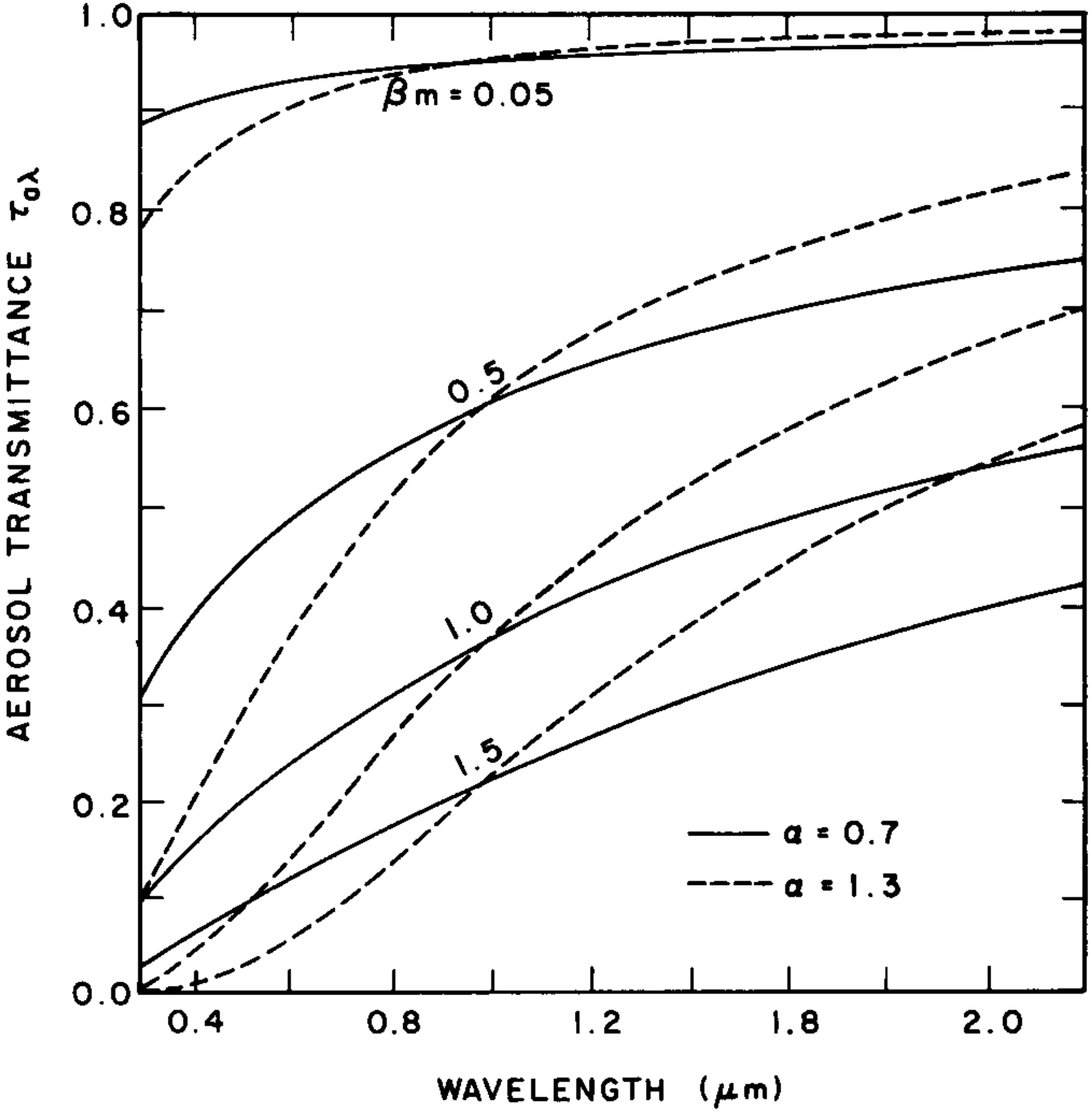


Figure 6.6.2 Aerosol spectral transmittance as a function of α and βm.

An Introduction to Solar Radiation, Muhammad Iqbal, Academic Press, New York, 1983, Chapter 6.

First results: *Coupon 5 (2 months of outdoor exposure)*

City, Country	Hemispherical transmittance [%]	Average particle area [μm²]	Area coverage [%]
Chennai, India	84.2%	132-168	5.1-8.3
El Shorouk City, Egypt	63.1%	110-194	21.3-22.8
Golden (CO), USA	88.8%	55-100	1.7-2.4
Jaén, Spain	89.3%	33-92	1.3-1.4
Penryn, UK	90.1%	N.A.	N.A.
San José (CA), USA	88.5%	206-220	1.9
Tezpur, India	89.6%	47-60	0.3-0.4

Broadband hemispherical transmittance (300-2500 nm), average particle area, and percentage of the surface covered by particles, measured at the end of the data collection. Unsoiled PV glass transmittance is 90.4%

- A linear correlation, with R^2 higher than 0.99, is found by comparing the percentage area covered by particles to the hemispherical transmission
- The broadband hemispherical transmission could be directly obtained from the covered area, independently of dust type and composition.

Quantum Efficiency

(spectral response of PV technologies)