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

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

PVQAT
International PV Quality Assurance Task Force

May 08, 2018 Webinar

Objective of the study

- Predict the spectral and total power losses of a Photovoltaic (PV) module due to soiling, given some knowledge of the particles.
  - Optical effects (absorption, scattering)
  - Particle size and obscuration
  - Full form of Mie theory vs. empirical approach

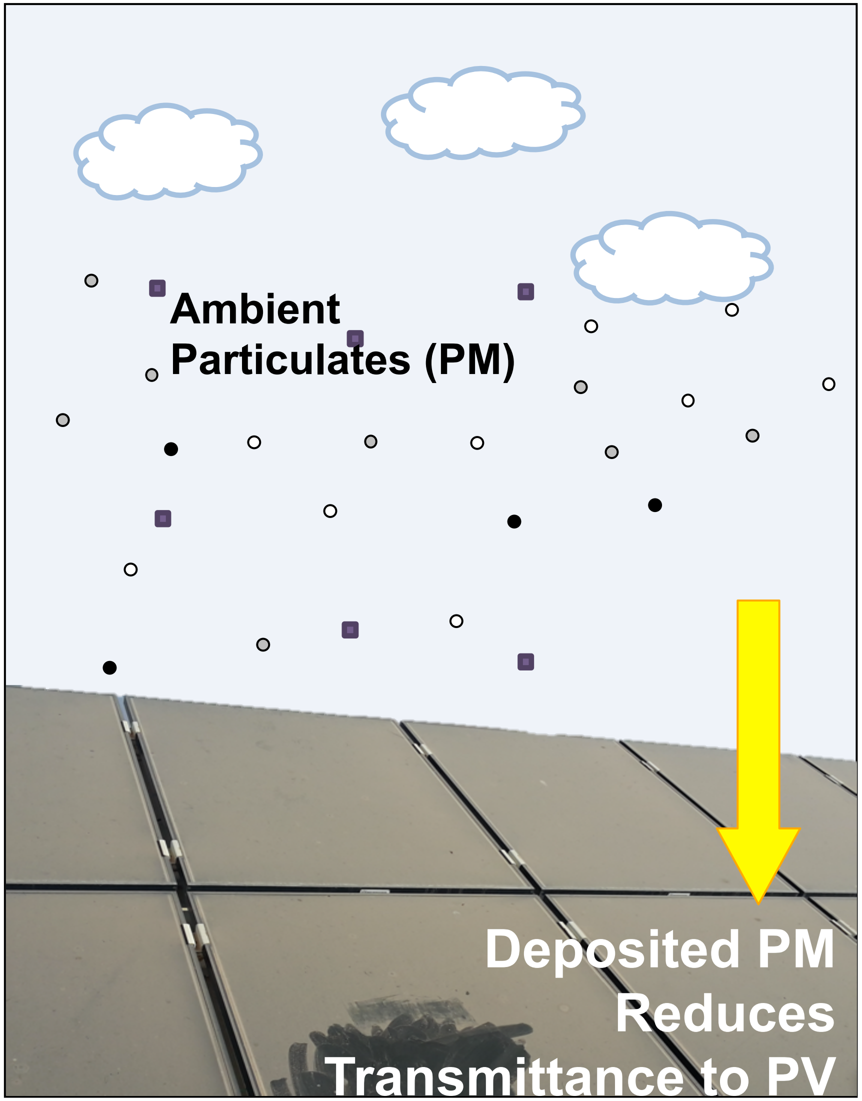
EPSRC SUPERGEN SuperSolar Hub's "International and industrial engagement fund" for the project "Global investigation on the spectral effects of soiling losses"

Some Prior Work

- "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.

- Smestad, G. Micheli, L. Germer, T. A. Fernández, E. F., Optical Characterization of PV Glass Coupons and PV Modules Related to Soiling Losses, Atlas/NIST Workshop on PV Materials Durability (2017).

- P. D. Burton and B. H. King, "Spectral Sensitivity of Simulated Photovoltaic Module Soiling for a Variety of Synthesized Soil Types," in IEEE Journal of Photovoltaics, vol. 4, no. 3, pp. 890-898, May 2014, doi: 10.1109/JPHOTOV.2014.2301895.



Optical Configuration

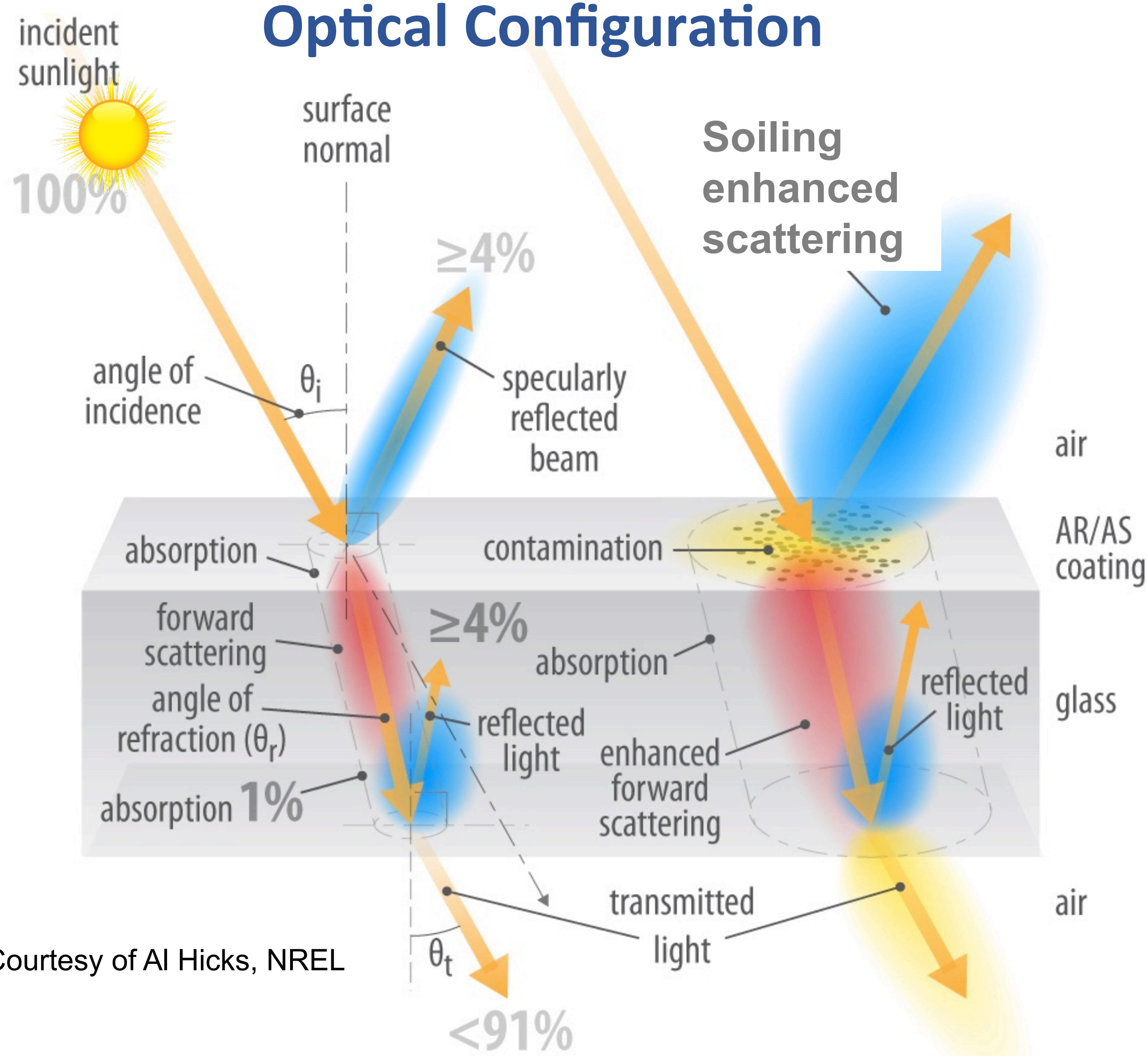
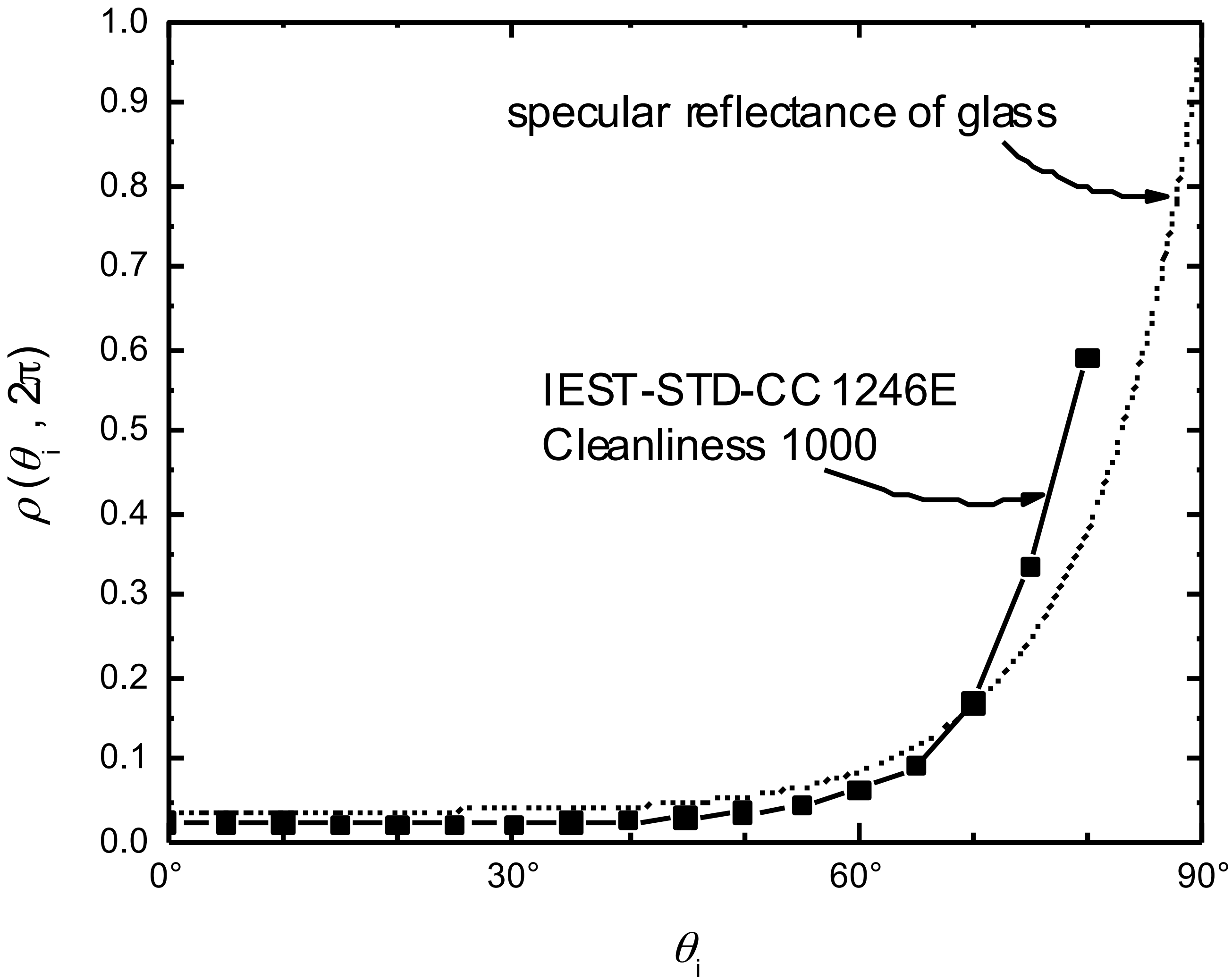


Diagram Courtesy of Al Hicks, NREL

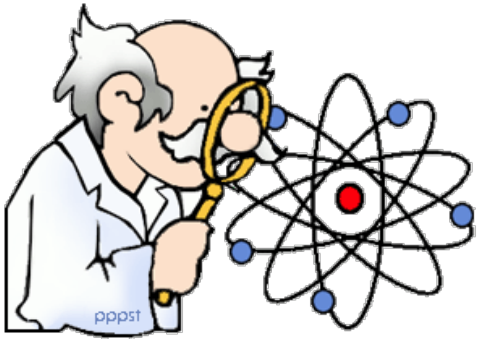
Reflectivity vs. Incidence Angle



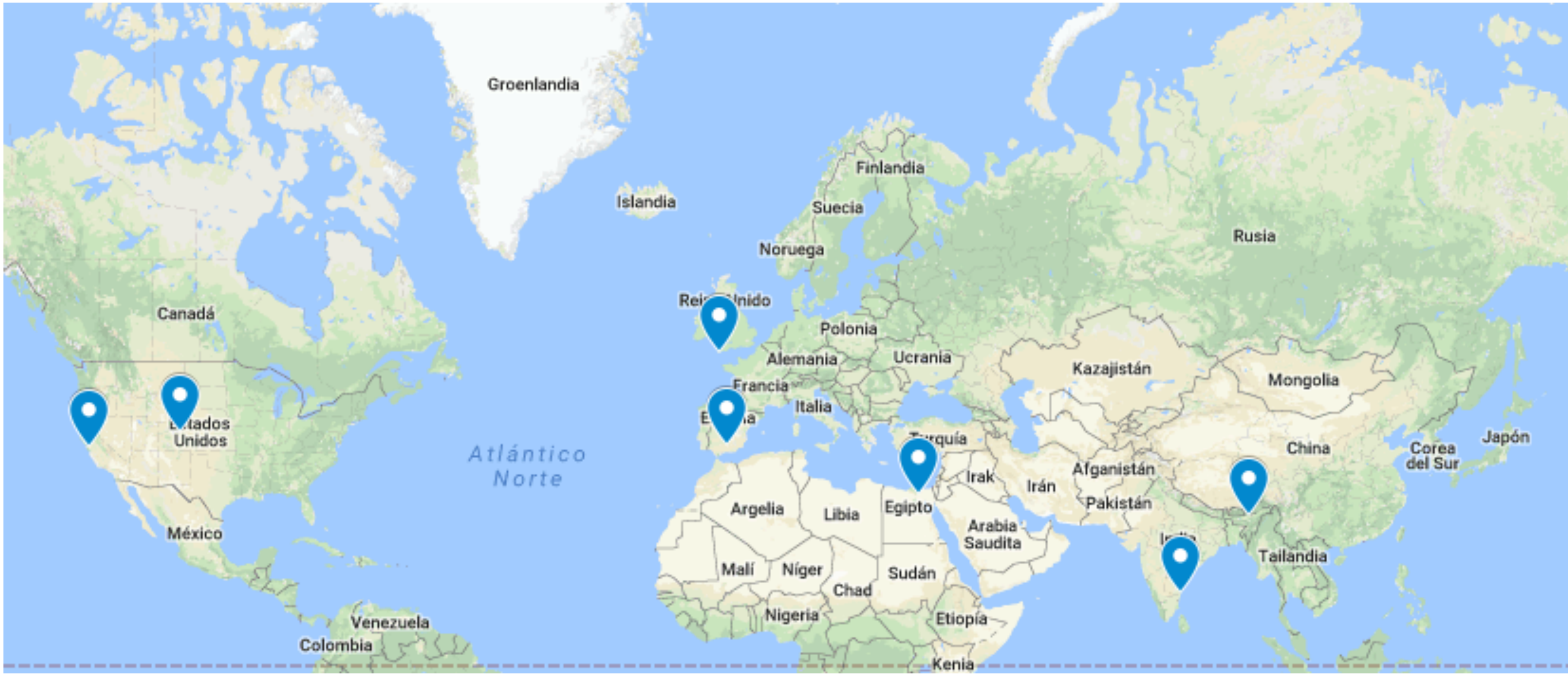
Modeled by: **Thomas A. Germer, NIST**

Spectral Effects of Soiling

- Experimental procedure
- Ångström turbidity formula
- After 8 weeks (e.g., San José, CA)
- Fitting the Transmission data
- Limitations to the measurement
- Caveats and cautions
- EQE (“Call a Quantum Mechanic”)
- Conclusions

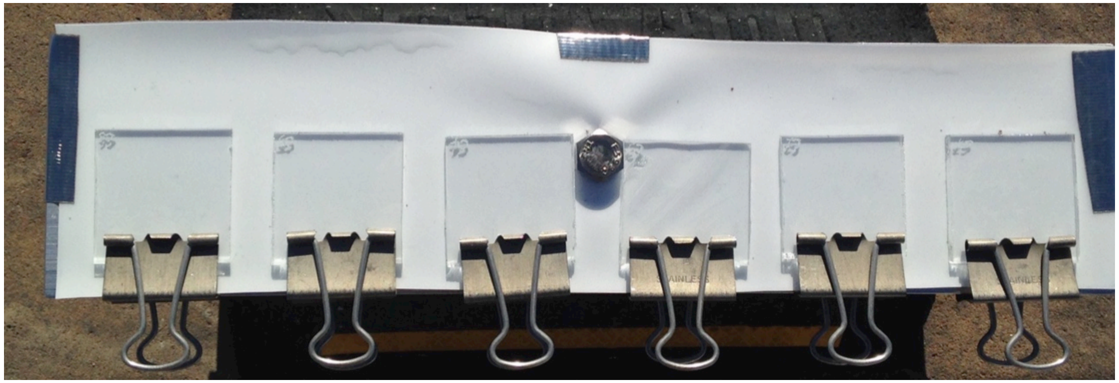


Spectral impact of soiling: Experiments



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



4 cm x 4 cm
x 3 mm-thick

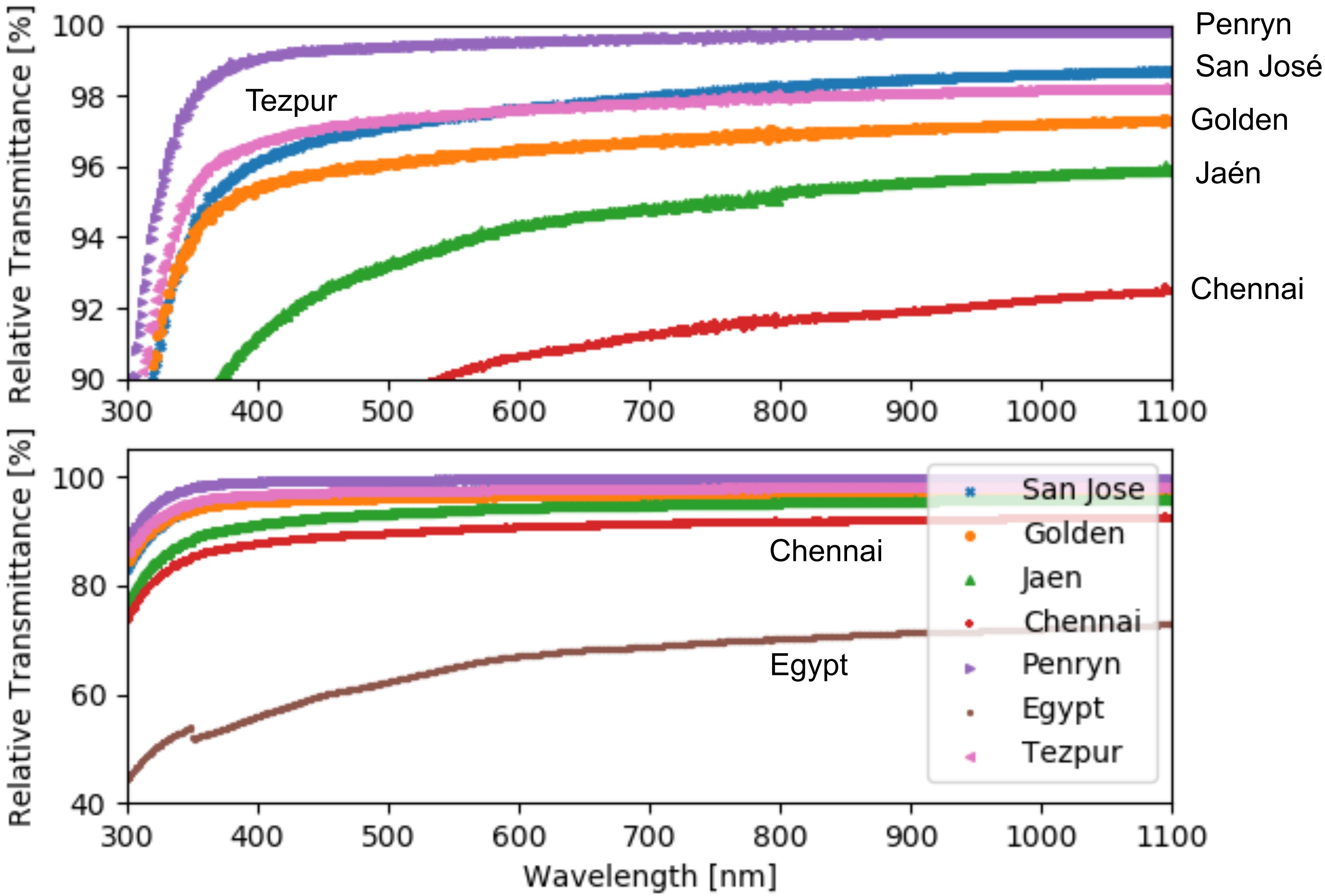
- **Soil Saint-Gobain DIAMANT PV glass coupons outdoors.**

- **Measure spectral transmittance of soiled glass using an Integrating Sphere.**

Photo: Greg Smestad

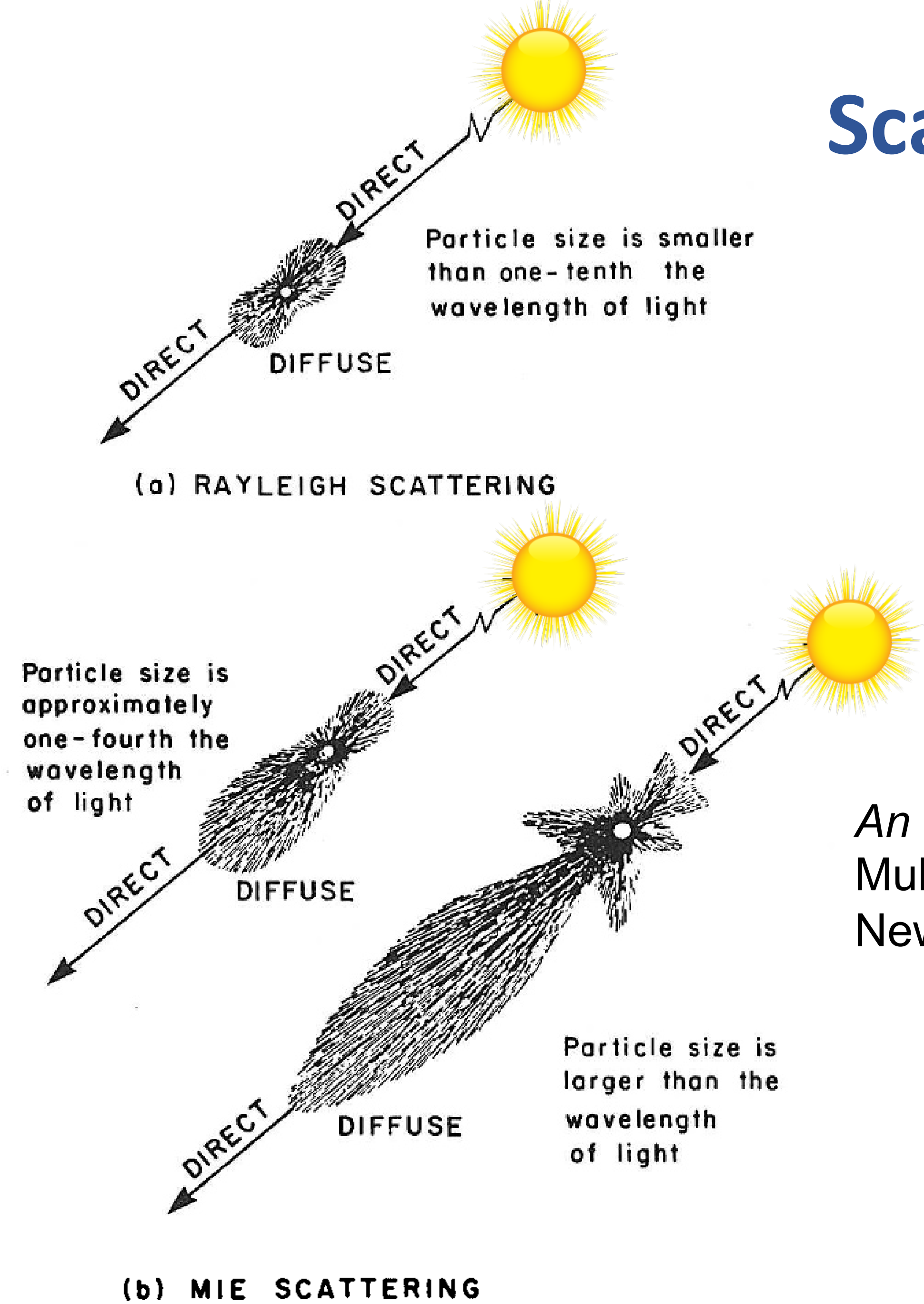
Hemispherical transmittance (8 weeks)

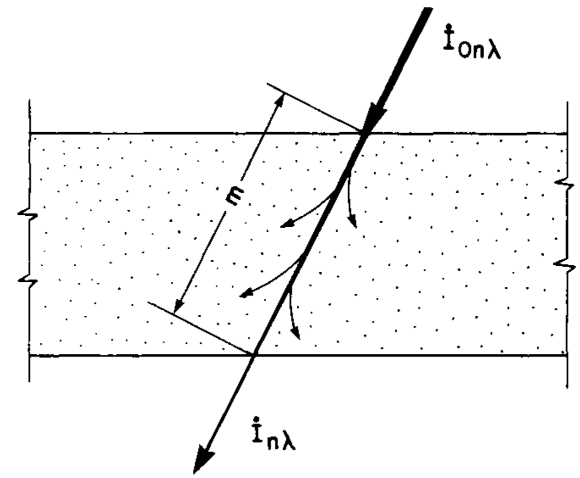
Relative to the transmittance clean glass



Scattering

- ## Atmospheric



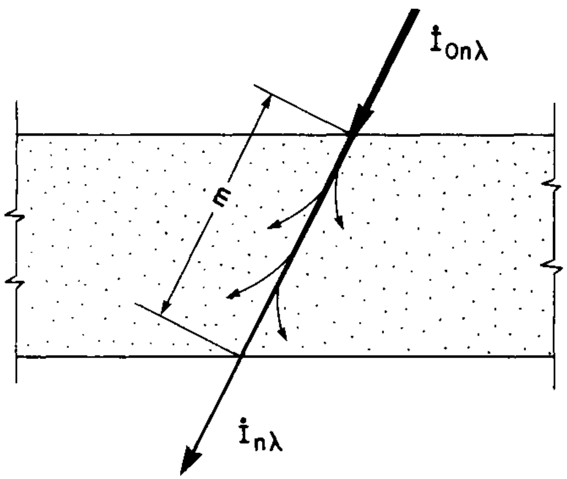


An Introduction to Solar Radiation, Muhammad Iqbal, Academic Press, New York, 1983, Chapter 6.

- ## On the glass

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

α=4 for small non-absorbing particles
α=1 for small absorbing particles
α=0 for large particles

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

m_a is the optical path length

After 8 Weeks (San José, CA)

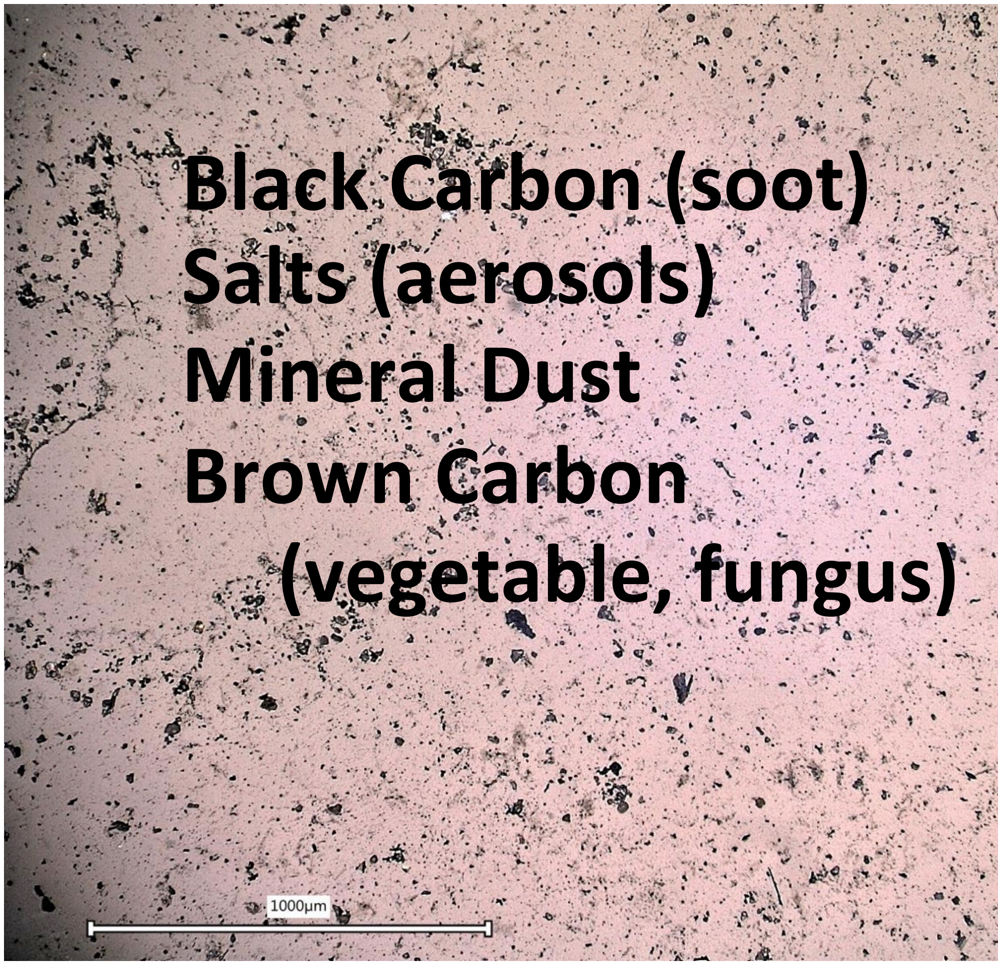


Photo: NREL, optical microscope 100x

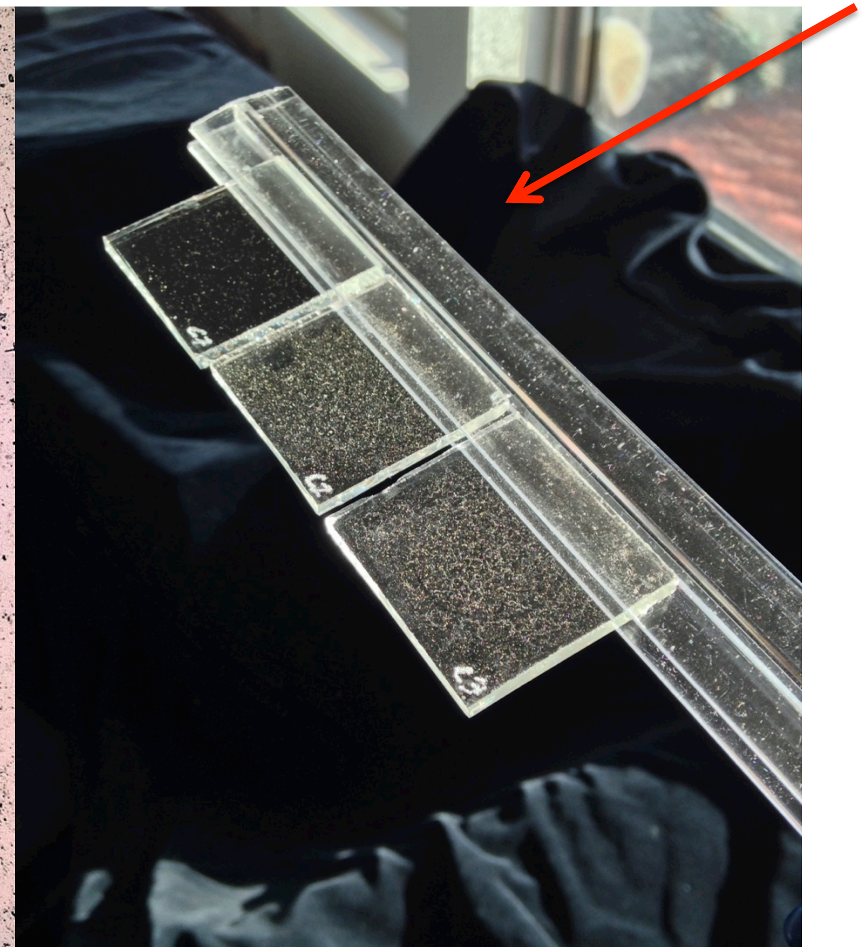
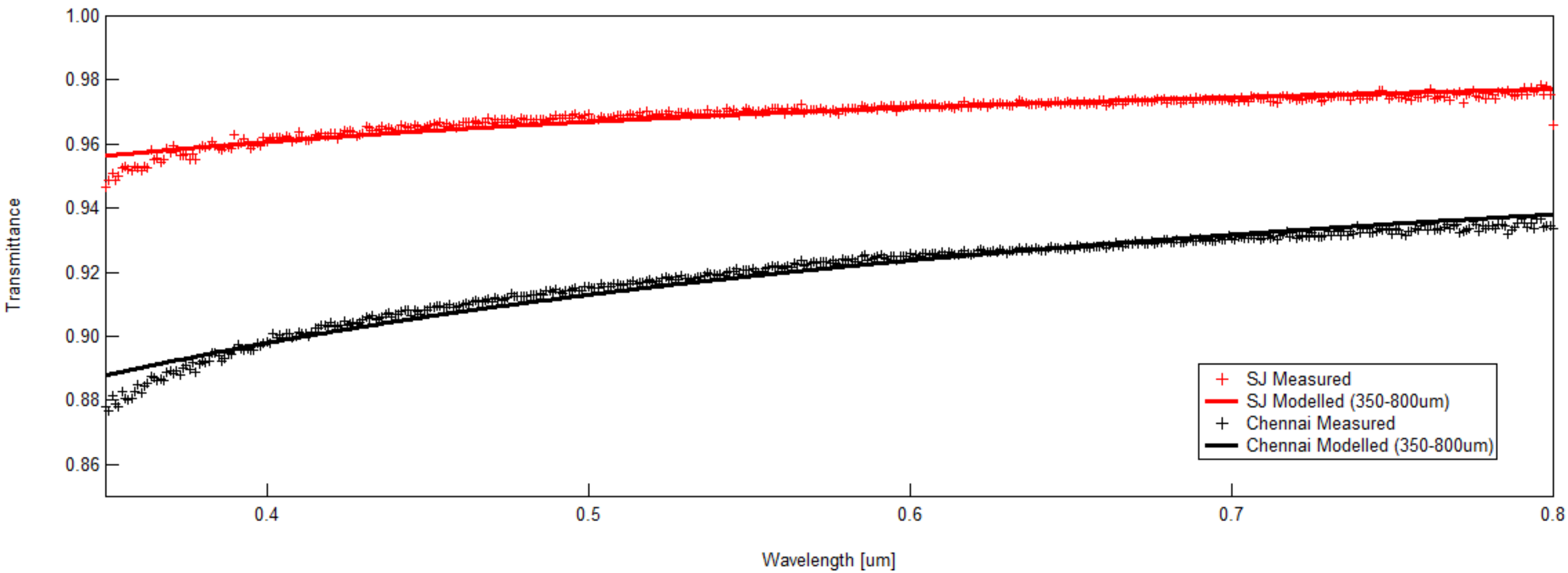


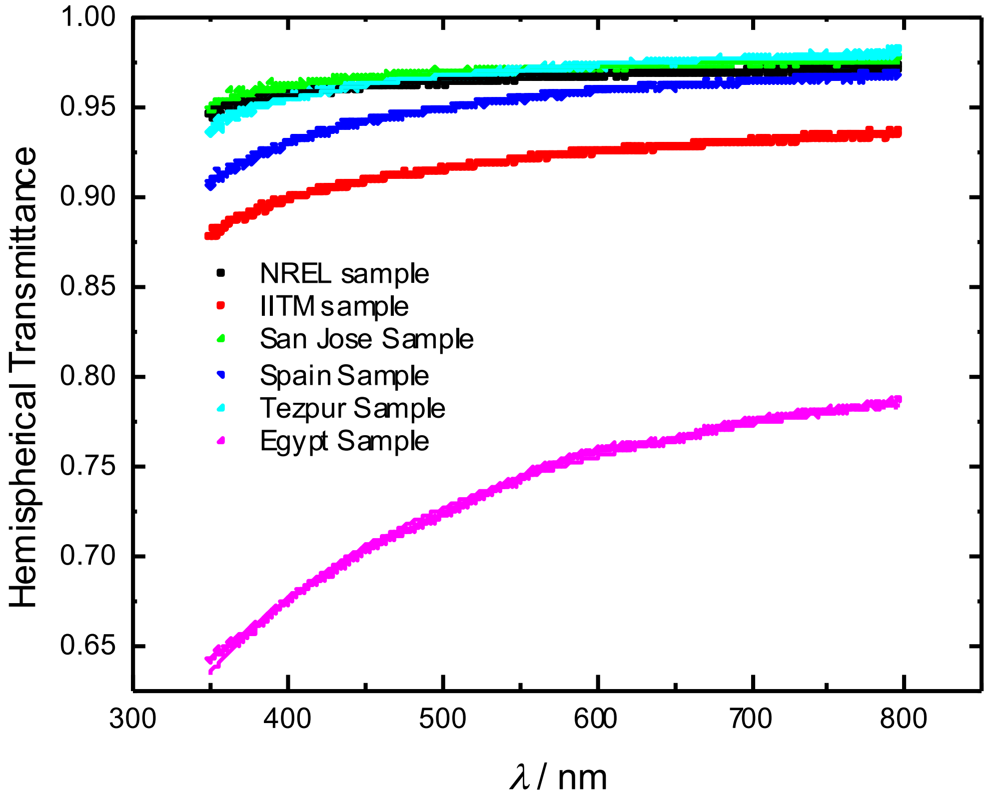
Photo: Greg Smestad

Fitting Hemispherical Transmission Data



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

Fitting the Transmittance Data for All Sites



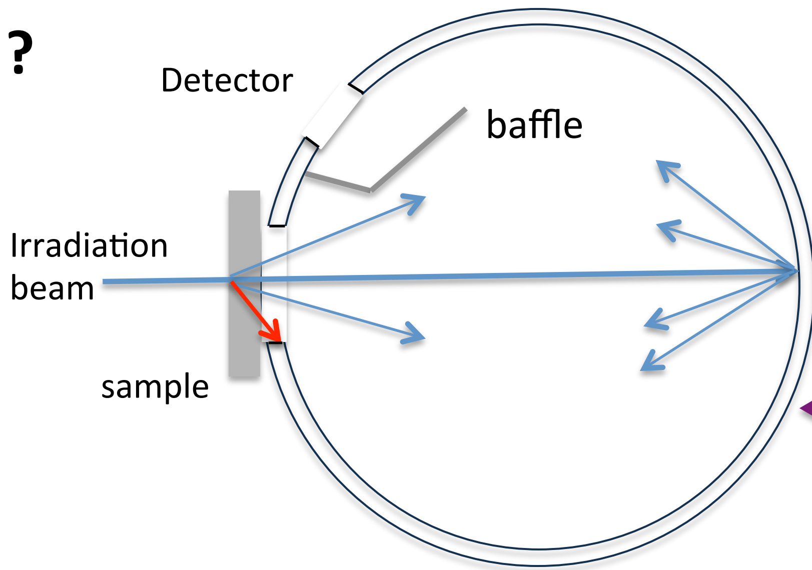
Why?

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

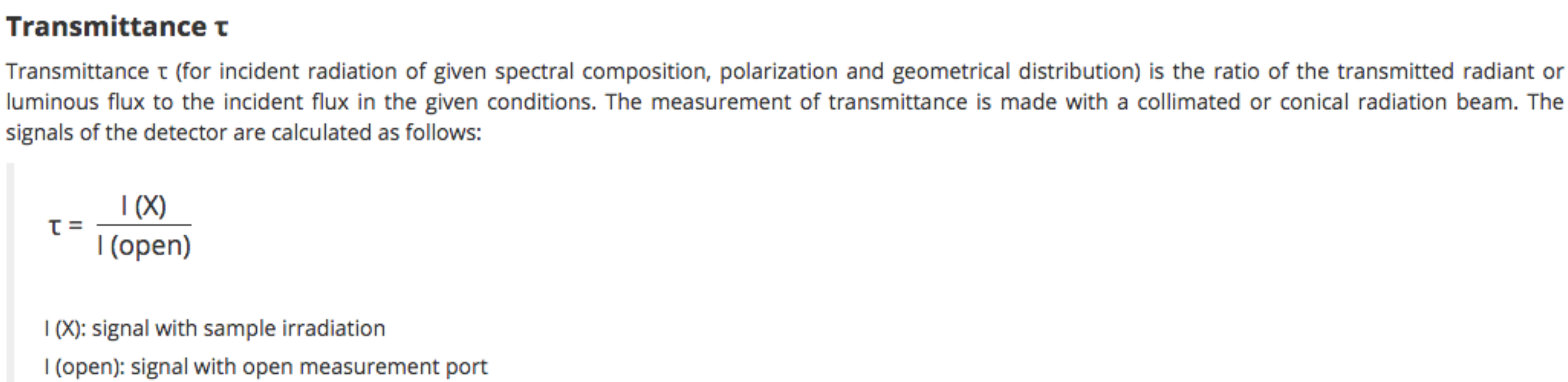
	NREL	IITM	San Jose	Spain	Tezpur	Egypt
beta	0.0015	0.0058	0.0010	0.0035	0.0021	0.0266
alpha	2.7	2.3	3.1	2.8	2.9	2.0
gamma	-0.026	-0.056	-0.023	-0.026	-0.018	-0.175

Does all scattered light make it into the Int. Sphere?

Why a γ ?

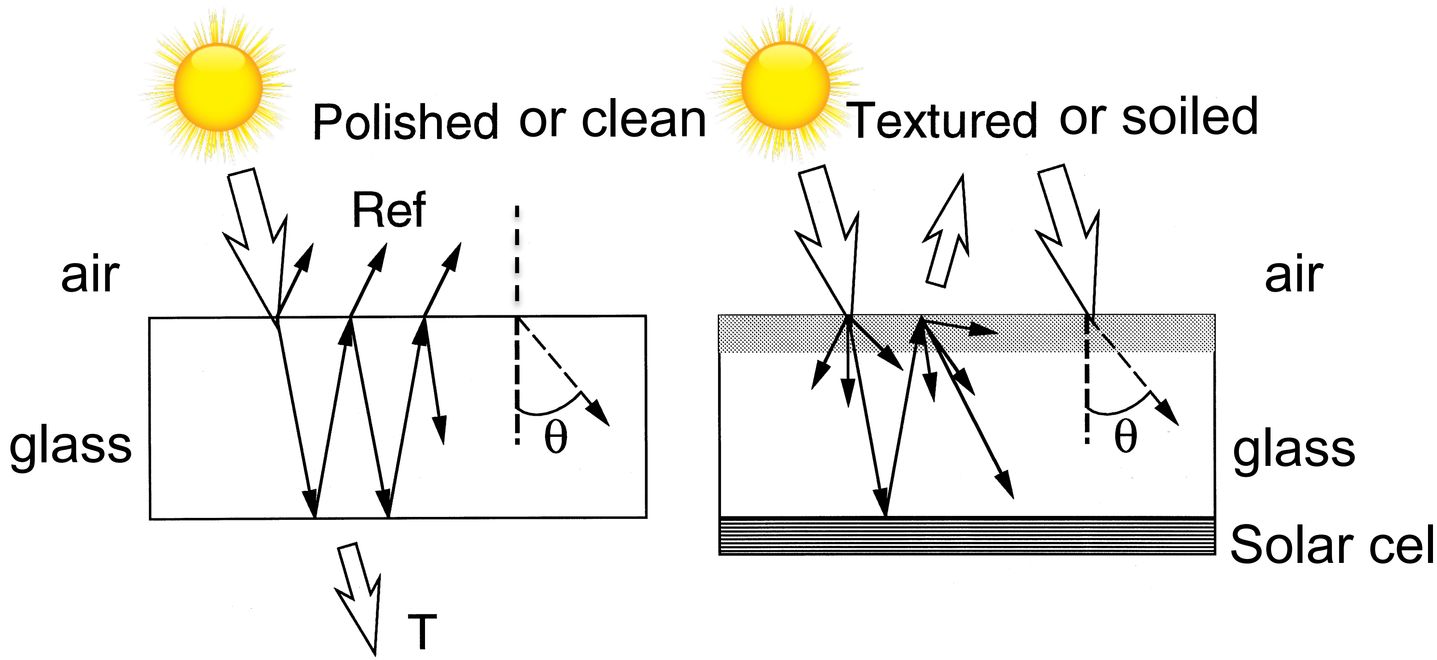


Measure spectral transmittance of soiled glass using an Integrating Sphere.



Graphic: G. Smestad after gigahertz-optik.de

Passage of light through coupon is not equivalent to PV Module



Thom Germer can model this with MIST

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.

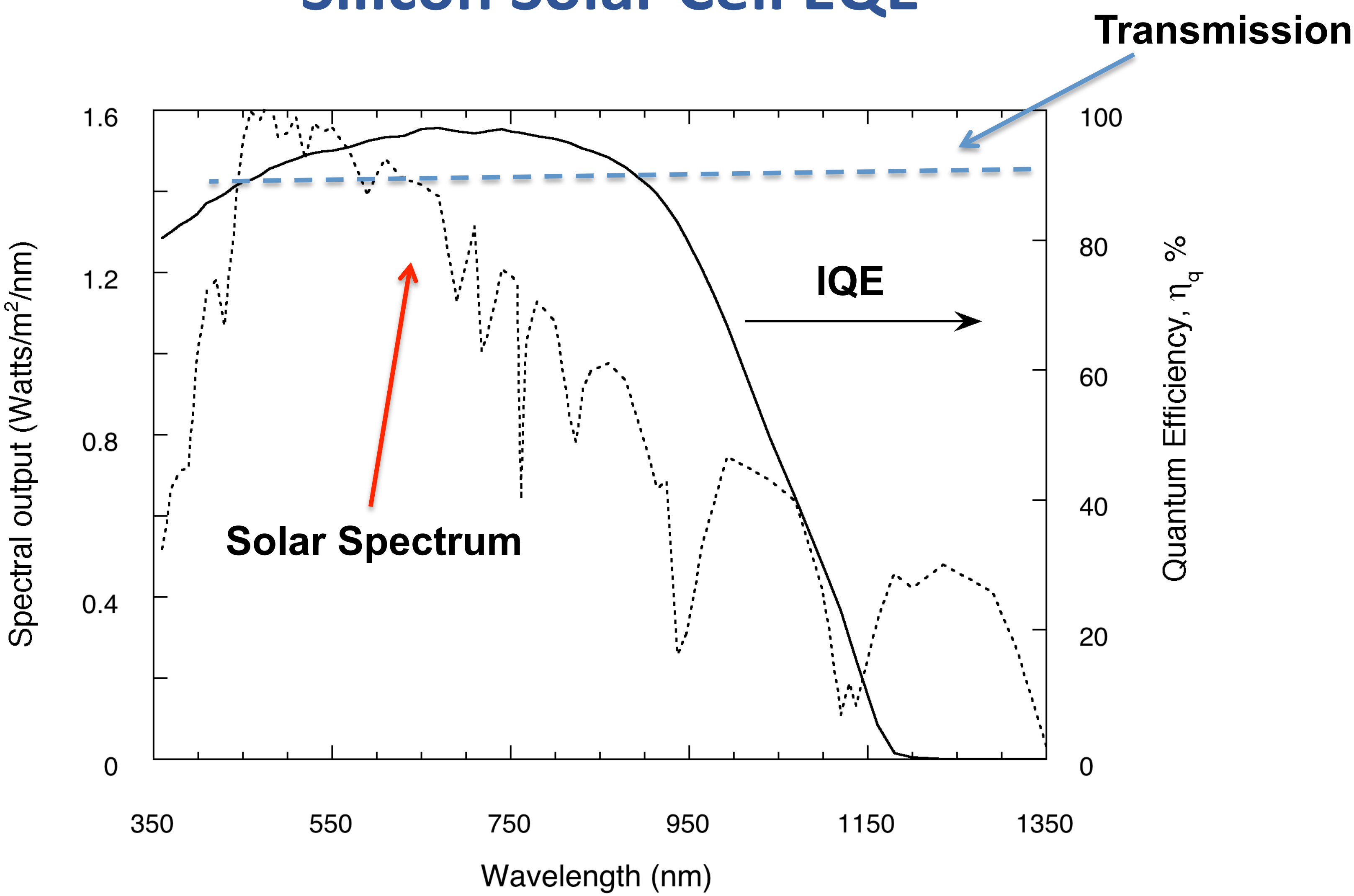
Photo: Greg Smestad

Mini-Modules for EQE (SR) study

Estimating soiling losses using the transmission from glass coupons may not easily translate to exact knowledge about power losses from PV modules (unless EQE and Spectral Response is done to verify).

Fabricated by: Jaewon Oh; Govindasamy Tamizhmani Arizona State University

Silicon Solar Cell EQE



 Graphic: Greg Smestad

Some Conclusions

- We have measured the hemispherical transmission of soiled PV glass coupons.
- Natural soiling yields more or less a *neutral density filter*.
- Soiling produces a higher attenuation at shorter wavelengths compared to longer wavelengths.
  - Analogous to the Ångström turbidity formula
- Estimating soiling losses using the transmission from glass coupons may not easily translate to exact knowledge about power losses from PV modules
  - (EQE is being undertaken to confirm).
  - That work is currently in progress (completed by July).

Acknowledgments (Partners)

- **National Renewable Energy Laboratory, USA (Leonardo Micheli)**
- **University of Exeter, UK**
  (Hameed Alrashidi, Tapas K. Mallick, Aritra Ghosh)
- **University of Jaen, Spain**
  (Eduardo F. Fernández, Florencia Almonacid)
- **IIT Madras and CSIR-Structural Engineering Research Centre, India**
  (Bala Pesala, K.S. Reddy)
- **Tezpur University, India (Nabin Sarmah)**
- **Heriot-Watt and BITS Pilani, UAE (Nazmi Sellami)**
- **South Valley University/University of Bath, Egypt (Ibrahim Hassan)**
- **Sol Ideas Technology Development, USA (Greg P. Smestad - inquiries@solideas.com, www.solideas.com/projects/pvquality/)**

Acknowledgments (Analysis)

- "McMahon, Mark J." <mark.mcmahon@thermofisher.com>, ATR FTIR
- “To, Bobby" <Bobby.To@nrel.gov>, SEM Images, Microscopy and EDS
- "Moutinho, Helio" <Helio.Moutinho@nrel.gov> SEM Images, Microscopy and EDS
- “Panariello, Sam” <custsupport-comment@bwtek.com> BWTEK iSpec Spectrometer
- Oh, Jaewon; Tamizhmani, Govindasamy Arizona State University Mini-Modules
- Optical Configuration diagram Courtesy of Al Hicks, NREL
- Burkhard, George george@sinoviatech.com Optical Haze

Bibliography (Basic Sources)

Ångström turbidity formula from, "An Introduction to Solar Radiation", Muhammad Iqbal, Academic Press, New York, 1983, chapter 6; Available via the web at - www.elsevier.com/books/an-introduction-to-solar-radiation/iqbal/978-0-12-373750-2 and https://books.google.com/

Properties of Aerosols in: Atmospheric Chemistry and Physics: From Air Pollution to Climate Change By John H. Seinfeld (California Institute of Technology) and Spyros N. Pandis (Carnegie Mellon University). Wiley-VCH: New York. 1997. xxvii + 1326 pp. ISBN 0-471-17815-2.

YouTube Video, "Light Scattering by Particles: Theoretical Aspects, Frits F.M. de Mul, M.Sc. courses presented at Universities of Twente and Ancona, Dept. of Appl. Phys. (1981; revised 2017); https://www.youtube.com/watch?v=nlULB_p_l04

Quantum efficiency measurements and theory are described in, "Optoelectronics of Solar Cells", SPIE Monograph PM115, Greg P. Smestad, ISBN 0-8194-4440-5, 118 pages; Pub. July 2002; Softcover; In print from SPIE or via Amazon.

To Be Presented at a Future Talk

- ❑ Light Obscuration by Particles
  - Particle Area and Hemispherical Transmittance
    - Fractional Loss versus Particle Coverage
    - It seems there is a linear correlation between the area covered by particles and hemispherical transmittance.
- ❑ Particle size distribution (Method & Results)
  - IEST-STD-CC 1246E Cleanliness Standard
- ❑ Spectral Characteristics (Spectrophotometer vs. EQE method)