DuraMAT
Durable Module Materials Consortium

"A Custom High-Throughput Optical Mapping Instrument (OMI) for Accelerated Stress Testing of PV Module Materials"

Imran S. Khan, Joshua Morse, Robert R. White, and David C. Miller (NREL)*

**David.Miller@nrel.gov*

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Area 9: Module and System Reliability
Session 5B: Characterization of PV Module and System Reliability (Joint 5.8/9.4)
Tuesday, 2021/6/22, 14:15-14:30 (MDT)

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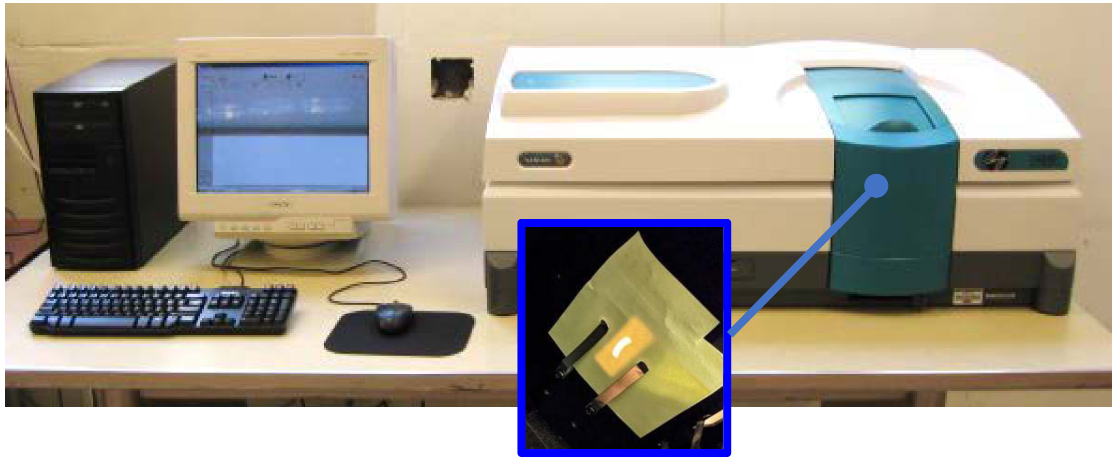
Energy Materials Network U.S. Department of Energy | NREL | Sandia National Laboratories | Berkeley Lab | SLAC National Accelerator Laboratory

Overview: Motivation and Background for the OMI

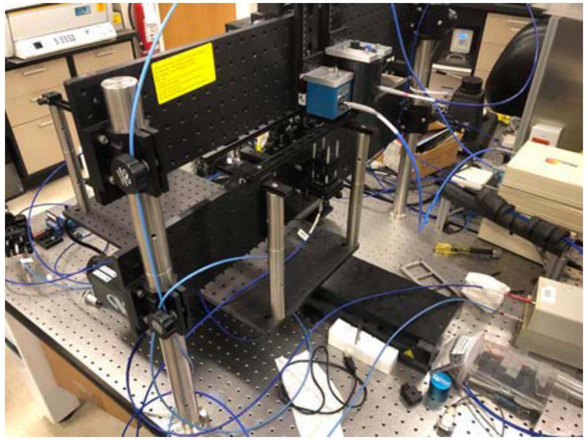
- Optical performance of PV materials, coupons, and modules is examined using commercial benchtop spectrophotometers.
- 5 minute measurement time ($200 \leq \lambda \leq 2500$ nm).
- Single area sampling spot, arc shape, >1 cm^2.



Cary 5000 spectrophotometer and measurement spot.
httcommercialps://images.app.goo.gl/fkfvmXd5FUpvMW2H9

- Can commonly available pixel-array spectrometers be used to decrease measurement time?
- Can an automated mapping capability be developed?

⇒Develop and demonstrate measurement capability, by adding to existing NREL Combi tester.



The custom OMI was added to the Combi tester at NREL.

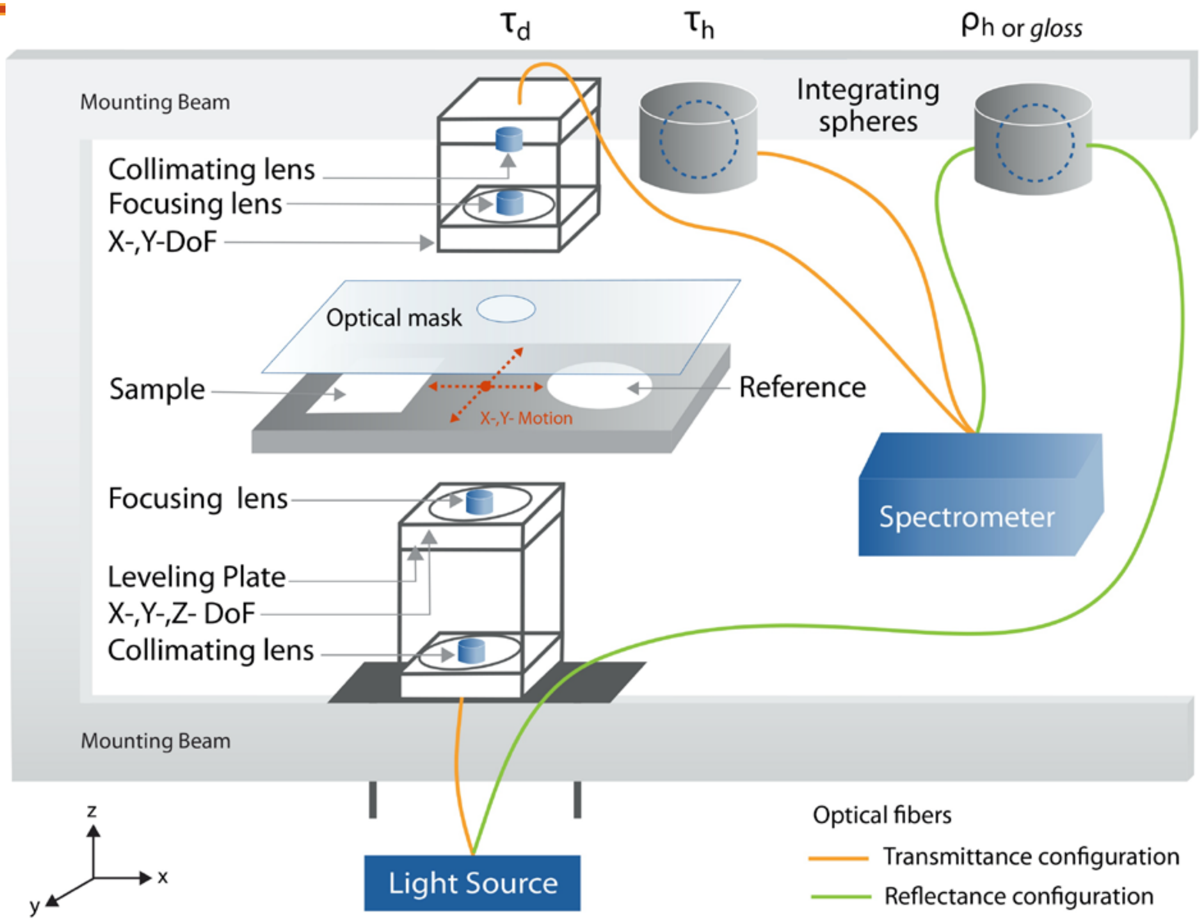
Key Components and Use of the Optical Mapping Instrument

Components:

- **Automated Motion Stages**
  - Newport M/N IMS400PP (linear x-stage)
  - Newport M/N IMS300PP (linear y-stage)
- **UV-VIS-NIR Light Source**
  - OceanOptics DH-2000-BAL (215 - 2500 nm)
- **Integrating spheres**
  - OceanOptics FOIS-1 (transmittance)
  - OceanOptics ISP-50-8-R-GT (reflectance, with gloss trap)
- **Spectrometers (per optical characteristic)**
  - StellarNet EPP2000-UVN-SR (190-1100 nm)
- **Optical Fibers:**
  - Solarization Resistant (200 – 1100 nm), up to 1000 µm core

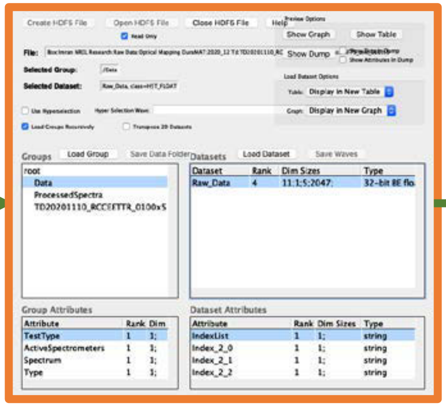
Scope:

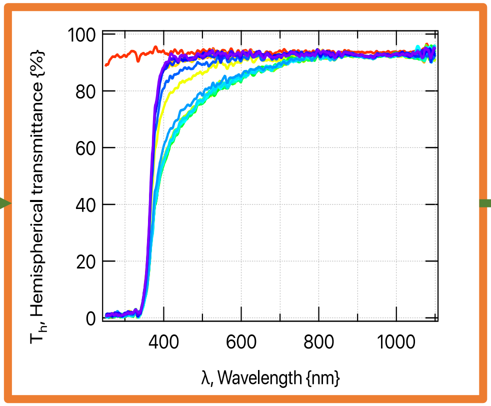
- Use automated stage, measurement, and analysis capabilities of existing NREL Combi tester.
- Add channels: τ_h, τ_d, ρ_h, gloss (ρ_s) for rapid measurement of *thick* specimens.
- Obtain transmittance (y1) and reflectance (y2) maps on samples of interest.
- Develop user interface and pipeline to DuraMAT Data Hub.

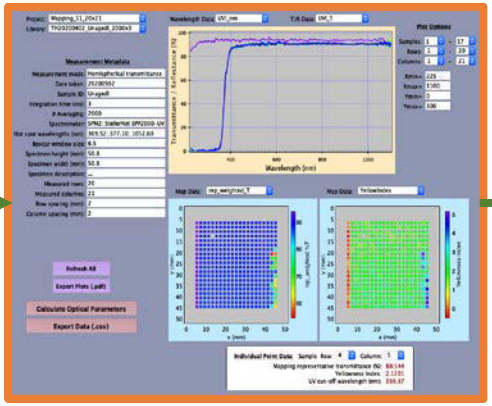


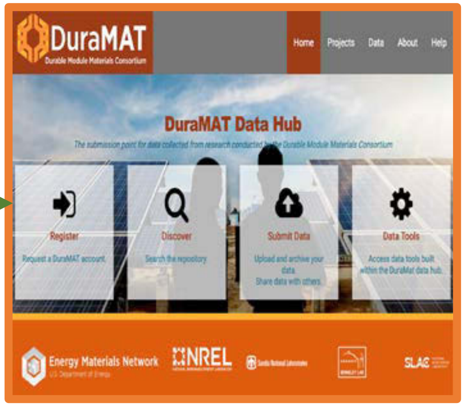
Schematic of key components of the OMI.

The Order of the Measurement, Analysis, and Export Operations









Data collection (instrument):
- Control OMI using LabView
- Perform 0% and 100% baselines
-Measure silica working reference
-Perform sample mapping
-Measure silica working reference

Raw data:
- HFD5 file; 4D matrix
- Contains data and attributes of sample & measurement

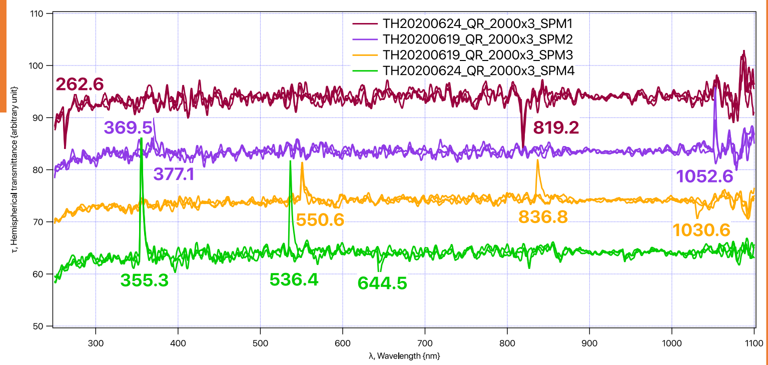
Processing (Igor Pro):
- Import raw data
- Scale relative to baselines
-Verify operation (silica working reference)
- Hotspot removal
- Boxcar averaging
- 1 nm interpolation
- Substrate subtraction (optional)
- Calculate key characteristics ($\tau_{m,rsw}$, YI, λ_{cUV})

Analysis (COMBIgor):
- Visualization: Graphical user interface
- Verify working reference sample data (silica for τ or ρ)

Export
- Re-structure data
- Generate .CSV files for:
  - baseline & reference
  - specimen data
  - specimen metadata
  - map grid coordinates
- Representative images:
  - spectra
  - maps ($\tau_{m,rsw}$, YI, λ_{cUV})
- Export to Data Hub

Measurement Optimization for Hemispherical Transmittance, τ_h

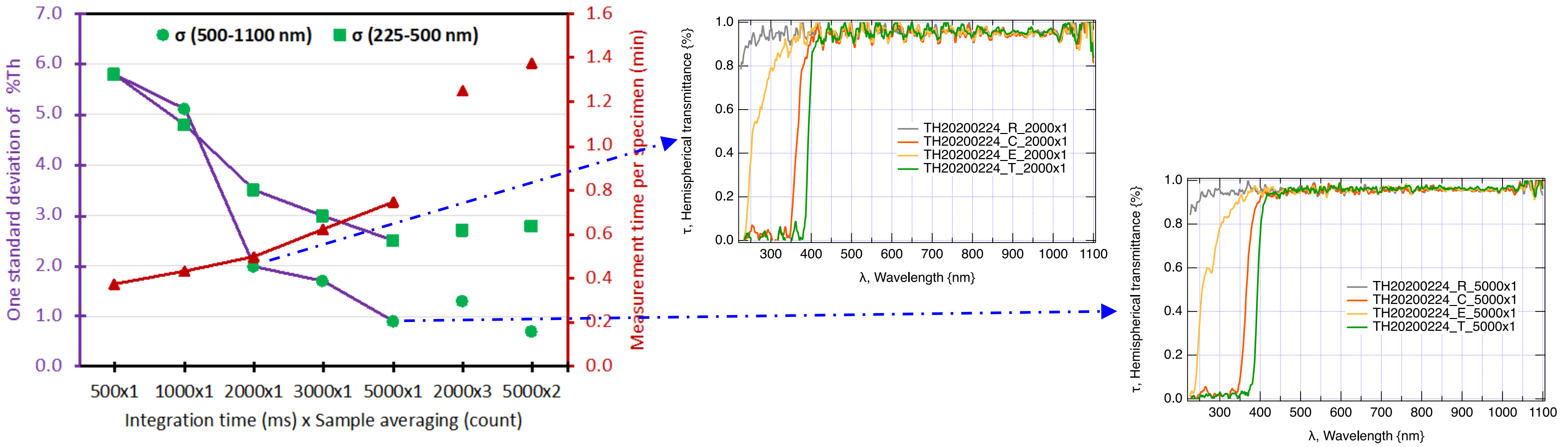
Hotspot Removal



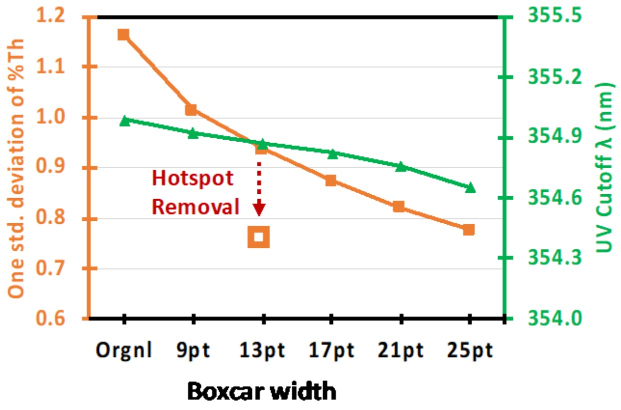
- Each spectrometer has hot spots (bad pixels) at fixed λ's.
- Remove using software processing (Igor).

Noise Reduction

- Noise level quantification: **integration time & measurement averaging.**



Boxcar Averaging

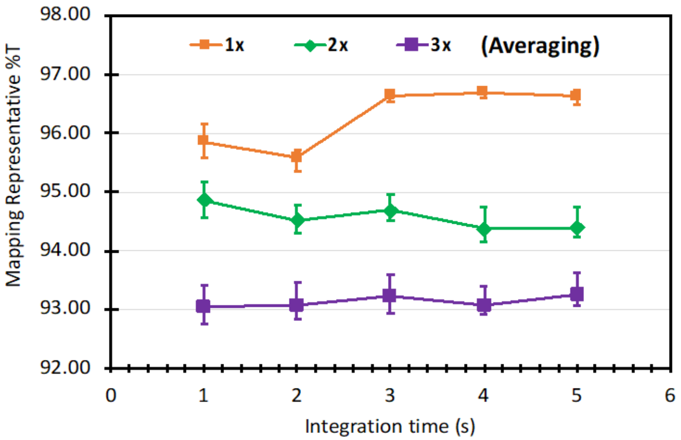


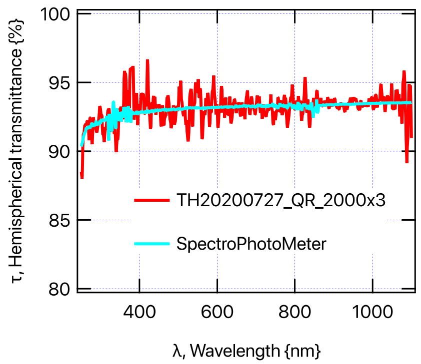
- Local averaging to reduce noise.

- Boxcar smoothing 13 pts (5 nm window) gives a minimal data shift

τ_h

- Overall τ_h depends on **integration time & averaging.**
- 3x minimum averaging required for consistent silica reference measurement.
- 2s & 3x is chosen for a suitable balance of noise level and sampling time.





τ_h: OMI vs. Spectrophotometer.

Benchmarking the OMI Relative to Commercial Spectrophotometers

Compare against the round-robin precision study used to develop IEC 62788-1-4 (optical transmittance).

-Same coupon specimens used (from dark storage).

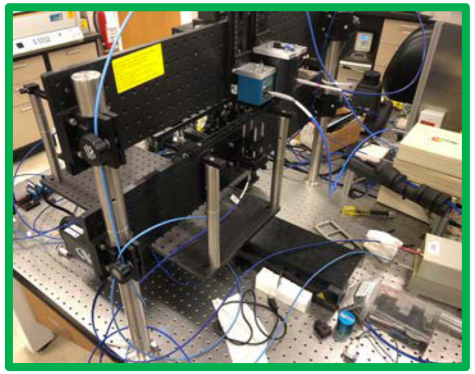
Miller et. al., Proc SPIE, 2013, pp. 8825-8, doi: 10.1117/12.2024372.

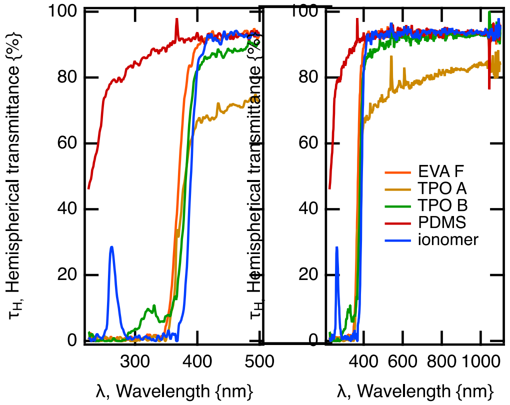
<u>6 materials:</u>

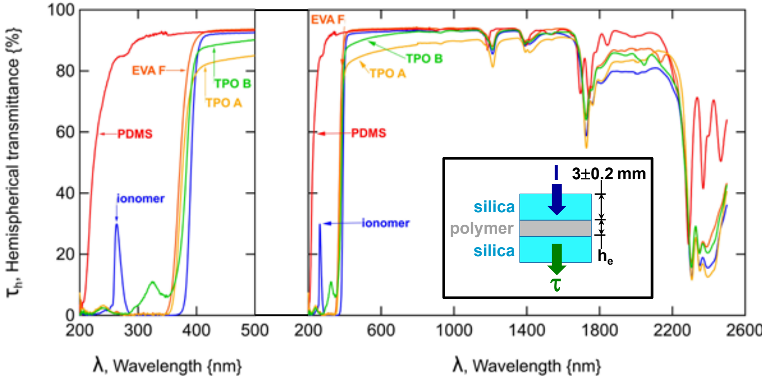
- EVA (representative PV encapsulant)
- TPO-A (greater crystallinity → haze prone)
- TPO-B (lesser crystallinity)
- ionomer (“low PID”)
- PDMS (high performance, durable, $$$)
- glass (silica also separately explored)

<u>Procedure:</u>

- Measure 3 replicate specimens (each material) once at the center.
- Measure τ_h (using integrating sphere).
- Measure $200 \leq \lambda \leq 2500$ nm (ideally).
- Perform r, R analysis for precision study.







Comparison of UV- (inset) and broadband-spectral transmittance for mapping instrument (top) and spectrophotometer (bottom).

The Measurement Threshold Was Typically Comparable (OMI:Spectrophotometer)

- Single silica/EVA/silica coupon measured 10x **without** and with replacement to quantify the measurement threshold.
- Compare *repeatability* and *Reproducibility* from interlab precision study (~95% confidence) to the OMI (2 S.D.).
- Comparison performed using improved measurement & analysis (integration time, # averages, Boxcar averaging, etc).

	R-R only			OMI only	
CHARACTERISTIC	AVG	r	R	AVG	2 S.D.
$\tau_{m,rsw}$ {%}	91.46	0.26	0.76	92.04	0.10
YI {dimensionless}	0.47	0.09	0.14	1.39	0.28
λ_{cUV} {nm}	357.5	0.7	3.3	358.1	0.8

Threshold of measurement (10x, without replacement) for commercial spectrophotometers relative to the OMI.

- Solar weighted transmittance ($\tau_{m,rsw}$) and UV cut-off wavelength (λ_{cUV}) are comparable between instruments.
- Yellowness Index (YI) was greater for the OMI.
  - $YI_{OMI} > YI_{spectrophotometer}$ also for PMMA working reference, but not silica.
  - YI_{OMI} may be limited by the greater UV-VIS noise inherent to OMI.
  - YI is generally more sensitive characteristic than $\tau_{m,rsw}$.

Benchmarking the OMI Against Conventional Spectrophotometers

- λ_{cUV} PDMS < 250 nm, could only be examined for 6/8 labs.
- TPO-A most optical scattering, haze[τ] of 80% at 400 nm.
- EVA gave a 1.5% improvement in τ_{mrsw}. (vs. TPO-B).
- PDMS gave a 1.5% improvement in τ_{mrsw}. (vs. EVA-F).
- The average and repeatability of τ_{mrsw} and λ_{cUV} typically consistent between OMI and spectrophotometers.
- The average value and repeatability of YI remains high for OMI, even with recent improvements (blanket, remove hot spots, boxcar averaging, etc.)
- Haze-prone materials (TPO-A) remain all-instrument-specific. All characteristics subject to scattering of light.

	Round-Robin only, no OMI (~95% C.L.)								
	$\tau_{m,rsw}$ {%}			YI {dimensionless}			λ_{cUV} {nm}		
MATERIAL	AVG[τ]	r	R	AVG[YI]	r	R	AVG[λ_{cUV}]	r	R
EVA-F	91.60	0.20	0.58	0.5	0.06	0.17	357.6	0.3	3.3
TPO-A	85.64	2.00	4.78	2.7	0.68	2.64	354.7	6.1	51.2
TPO-B	89.77	0.31	0.69	2.6	0.22	0.60	361.0	1.7	4.9
ionomer	90.72	0.13	0.47	0.7	0.07	0.19	381.1	0.5	3.8
PDMS	93.17	0.24	0.50	0.5	0.43	0.41	210.9	5.7	5.7

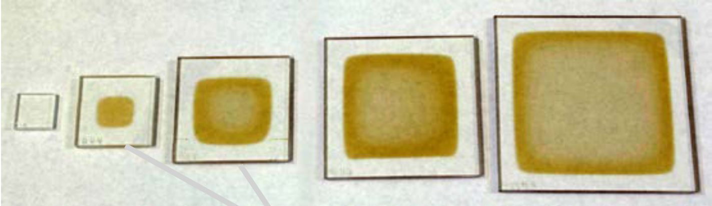
Spectrophotometer measurement precision from the round-robin study.

	OMI only (2 S.D.)					
	$\tau_{m,rsw}$ {%}		YI {dimensionless}		λ_{cUV} {nm}	
MATERIAL	AVG[τ]	2 S.D.	AVG[YI]	2 S.D.	AVG[λ_{cUV}]	2 S.D.
EVA-F	91.48	0.44	1.0	0.32	357.3	0.3
TPO-A	72.91	1.48	9.8	2.16	362.7	4.6
TPO-B	89.19	0.37	4.0	0.34	359.4	1.0
ionomer	90.44	0.17	1.4	0.40	379.2	5.3
PDMS	92.76	0.24	1.0	0.48	N/A	N/A

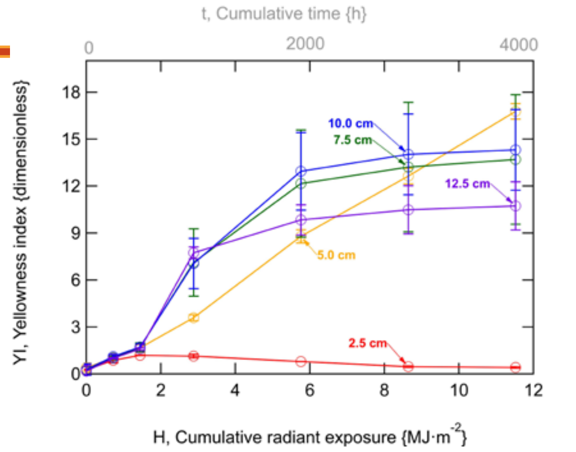
Average measurement values and their variation for the OMI.

Mapping Capability Clarifies Specimen Size Effect

- PVQAT TG5 size effect study gave unexpected result: >5cm glass/encapsulant/glass coupons more rapidly discolored than traditional 5 cm coupons.

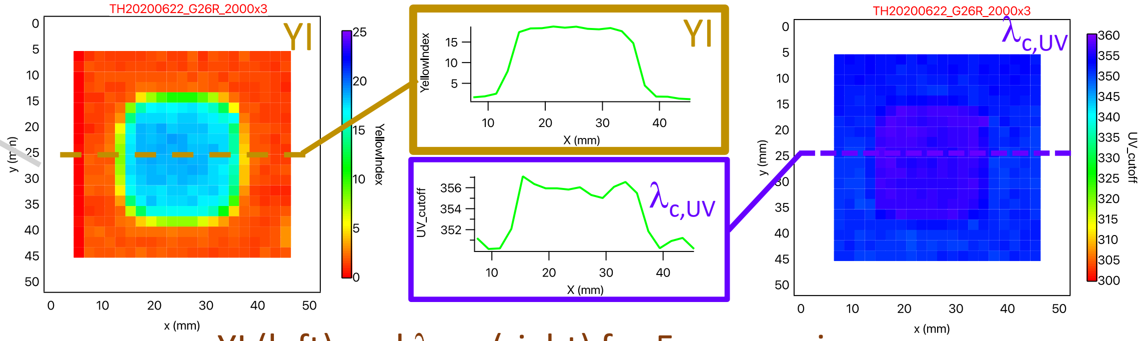


Visual appearance of 2.5, 5, 7.5, 10, 12.5 cm coupons.



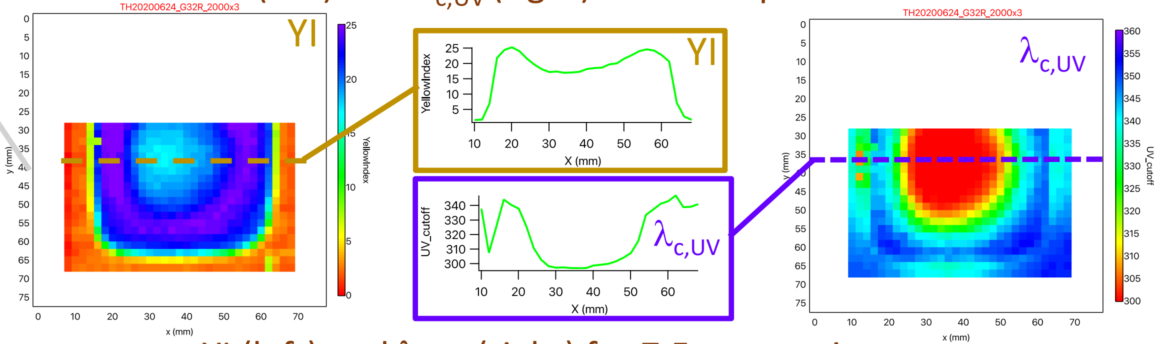
Spectrophotometer:
YI in the discovery experiment (artificial UV weathering).

- After spectrophotometer measurements, OMI identified 5 cm coupons have uniform discoloration (yellowness) & UV cut-off wavelength.



YI (left) and $\lambda_{c,UV}$ (right) for 5 cm specimen.

- OMI identified ≥7.5 cm had spatial-dependent discoloration (yellowness) and UV cut-off wavelength (Δ65 nm). UV absorber lost at center!
- Outcome: recently updated IEC 62788-1-4 (optical transmittance) standard for 7.5 cm size.



YI (left) and $\lambda_{c,UV}$ (right) for 7.5 cm specimen.

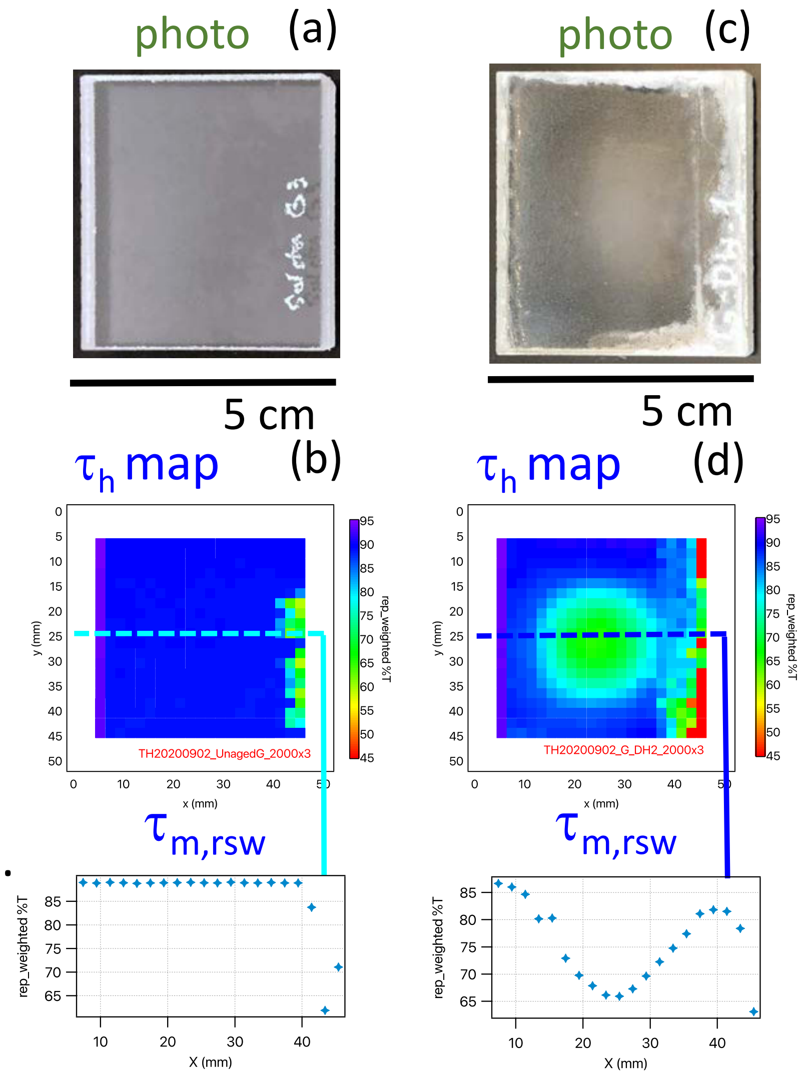
OMI Confirms Internal Haze Formation From Damp Heat

- Optical haze observed in soda-lime-glass/EVA/soda-lime-glass samples after desiccating from Damp Heat (85°C/85% RH).
- Neutral color cast is observed. ΔYI of 6: not EVA discoloration.
- Optical microscopy confirmed external glass corrosion.

- OMI confirms >20% loss in τ_{mrsw} at sample center.
- Failure analysis: adhesion and morphology of EVA/glass interface affected.
- Internal glass corrosion with acid/base (acetic/alkali-OH) chemistry suspected.

$\Rightarrow$Implications and consequences in IEC 61215 and extended testing.

- Validity & implications of DH and extended DH testing remain to be established.
- Internal haze formation has been observed in silica/EVA/silica coupons. Size of affected region reduced, however, with desiccation.



Coupons, unaged (left) and aged for 4000 h (right) in the dark at 85°C/85% relative humidity, including visual appearance in (a) and (c), and transmittance (mapping, representative solar weighted, $\tau_{m,rsw}$) in (b) and (d).

Summary and Conclusions

- Custom optical performance characterization instrument was developed.
- Measurement time is improved, with modest reduction in measurement precision.
- 2 mm spot size enables unique specimen mapping capability. ☺

- To reduce measurement noise:
  cover the OMI, remove hot spots, box car averaging, optimize integration time & # of averages.
- τ_{mrsw}, λ_{cUV} have threshold, repeatability, Reproducibility comparable to spectrophotometers.
- YI remains least precise characteristic (especially for more crystalline materials).

Examples:

- Mapping reveals size-specific encapsulant discoloration $\Rightarrow$ use $\geq$7.5 cm samples.
- Mapping confirms internal haze formation from Damp Heat. Acid/base interaction suspected.

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-NIST: Dr. John Perkins

-Core Objective 4 (Disruptive Acceleration Science) project leaders & teams.

-DuraMAT management team.

If you have interest in UV weathering, see PVQAT TG5, e.g. https://www.pvqat.org/project-status/task-group-5.html
If you have interest in PV soiling, see PVQAT TG12, e.g. https://www.pvqat.org/project-status/task-group-12.html

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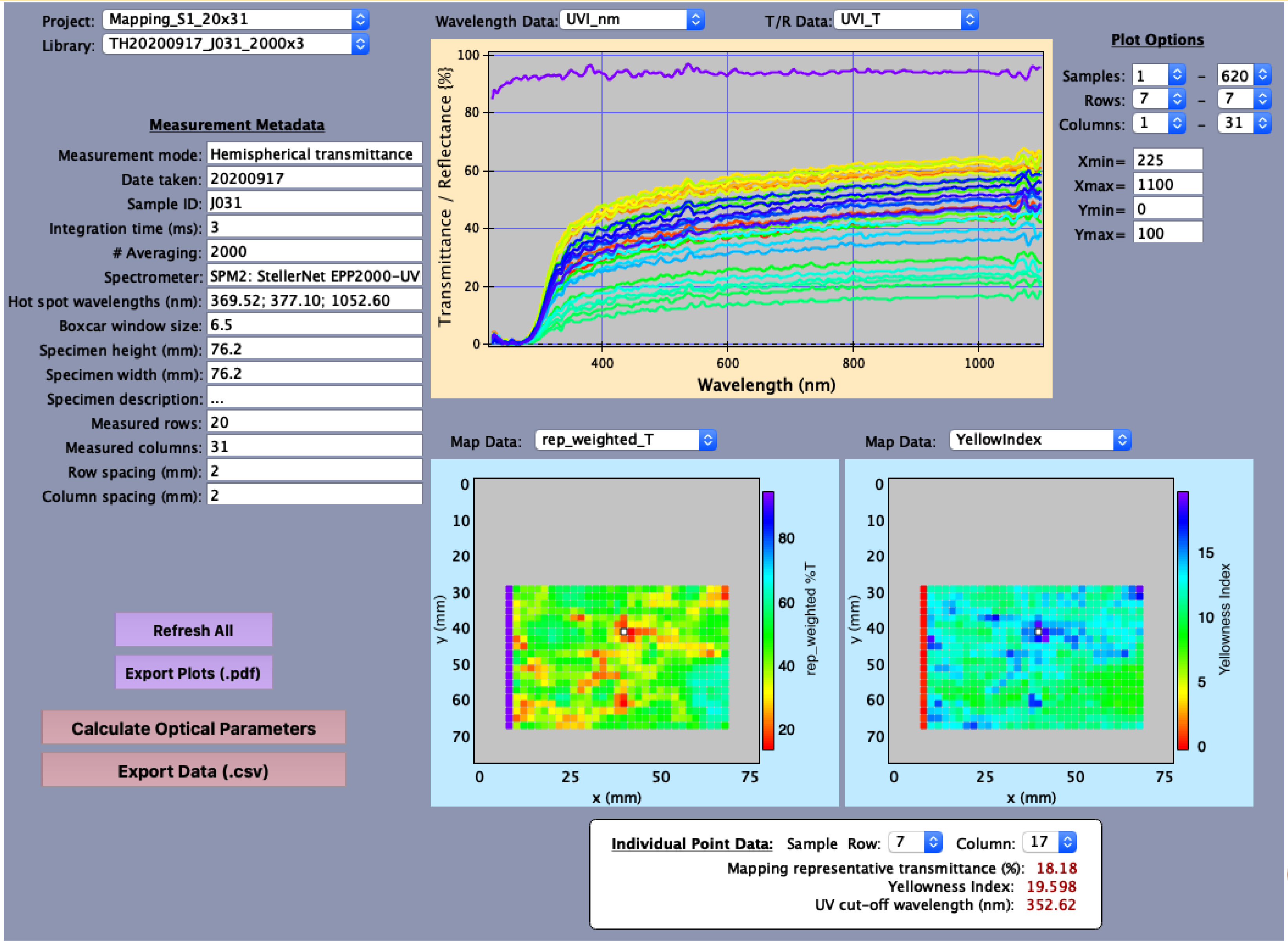
The views expressed in the presentation do not necessarily represent the views of the DOE or the U.S. government. Instruments and materials are identified in this paper to describe the experiments. In no case does such identification imply recommendation or endorsement by LBNL, NREL, SLAC, or SNL.

NREL STM campus (Dennis Schroeder)

The Graphical User Interface



Features:

- Visualization capability of the:
  - τ/ρ data
  - Baseline and reference data
  - Key characteristics
  - Map data and point data
  - Metadata
- Perform export to Data Hub

Let us know suggestions for further improvement! ☺

(Supplemental Material/Reference)

OMI Quantification Readily Distinguishes Falling Sand Abrasion Fixtures

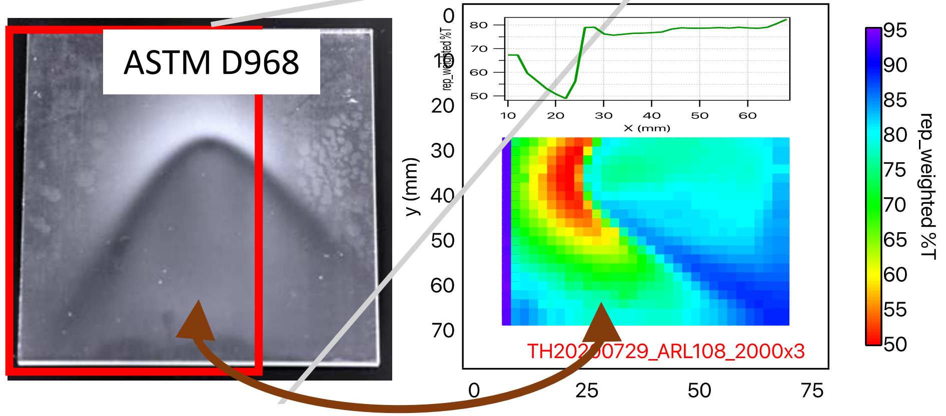
- Industry interest in falling sand test for developing IEC 62788-7-3 (PV abrasion methods) standard.
- Apply ASTM or DIN method (fixture)?

- ASTM fixture gives comet shaped wear pattern, for common test sand!
- OMI allows to quantify ($\Delta\tau_h$ of 42%) what might have been only been qualitative (photo).
- Yes, we still get inquiries about the ASTM D968 test fixture.

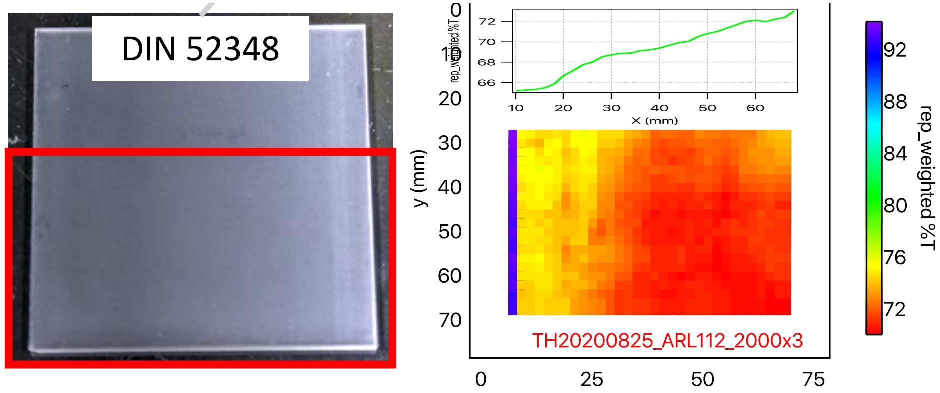
- Also: quantifying uniformity of artificial brush abrasion or soiling of field coupons.

(Supplemental Material/Reference)

Comparison of sand drop fixtures: ASTM (left) and DIN (right) for 6 L ASTM C778 graded sand on solar grade PMMA coupon.



Appearance (left) and measured τ_h (right) for PMMA specimen (ASTM D968 fixture).



Appearance (left) and measured τ_h (right) for PMMA specimen (DIN 52348 fixture).

The Field Coupon Study (Background for Today's Example)

(Supplemental Material/Reference)

Original specimen set deployed at Sacramento.
Einhorn et. al., J PV 2019, 233-239.
Toth et. al., SOLMAT, 185, 2018, 375-384.

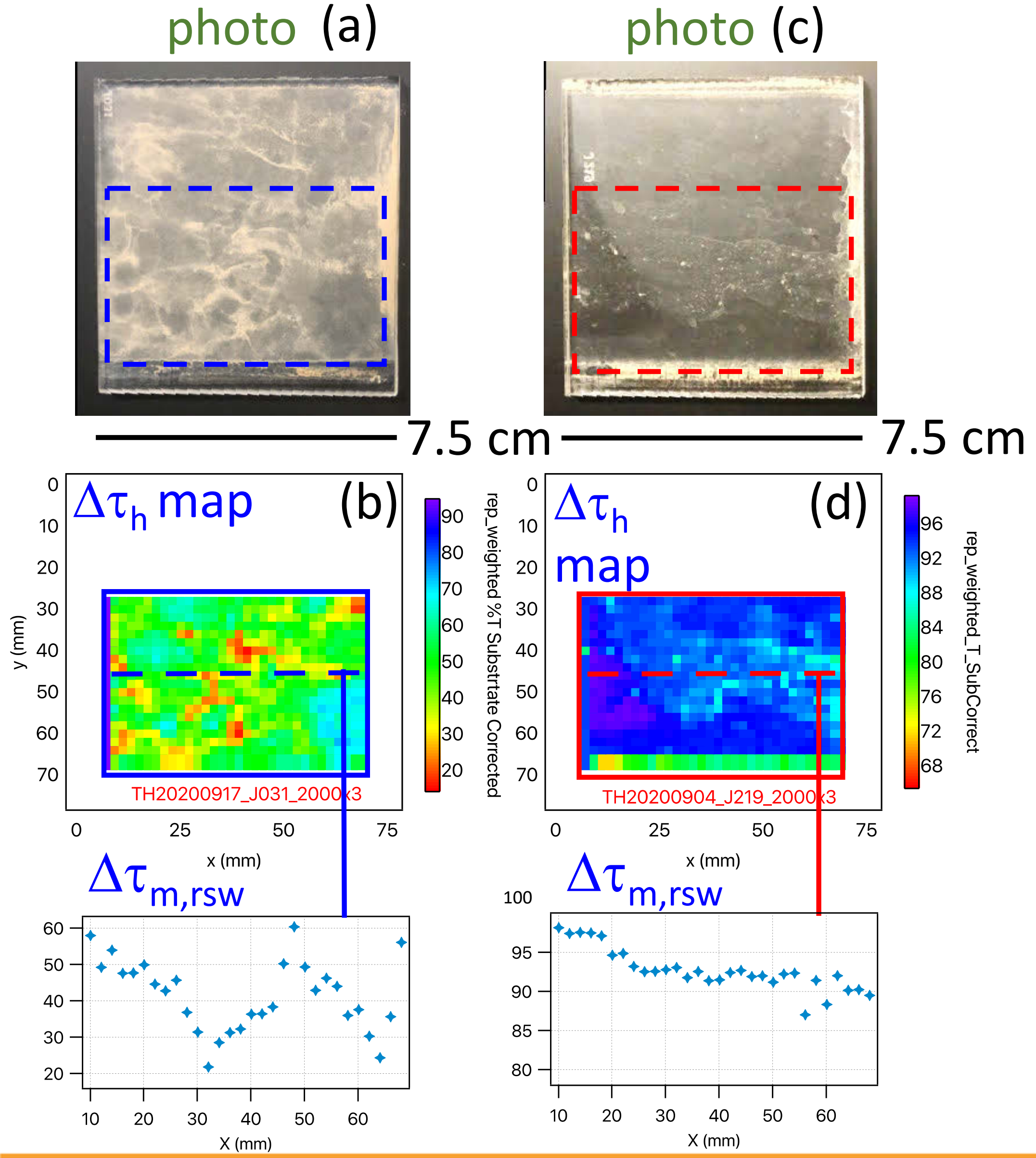
Samples:
- 7.5 cm x 7.5 cm coupons.
- Includes AR, AS (-phobic & -philic), reference glass.
- Black backpane (similar temperature to PV).

Test sites:
- Contamination and abrasion prone locations.
- **Mesa**, Arizona; **Sacramento**, California; **Mumbai**, India; **Kuwait City**, Kuwait; **Dubai**, United Arab Emirates.

Cleaning methods:
- No clean (NC); dry brush (DB); low-pressure water spray (WS); wet sponge and squeegee (WSS).
- Clean 1x/month.
- Examine 1 set of duplicates each year for 5 years.

Characterize:
- Particulate contamination (particle-size distribution, -area coverage, and -mass concentration).
- Optical performance (hemispherical transmittance).
- Damage morphology (scratch-width & -depth).

Example: $\Delta\tau_h$ for Dubai 3y and Kuwait 2y Specimens



- 30 x 20 mapping grid for 60 mm x 40 mm area. (2 mm step size for 2.5 mm τ_h measurement spot.)
- Measurement duration 180 mins (entire map).

- max[$\tau_{m,rsw}$] ~ 60% ... loss of at least 40%!
- $\Delta\tau_{m,rsw}$ 40% (Dubai), 12% (Kuwait).

(Supplemental Material/Reference)

- Millimeter-scale variation can occur in addition to the much larger variation across PV modules and arrays.
- Dubai most, Kuwait next most comminated sites in study.

-Suspect loss of ∅ > 15 μm particulate during shipment.
-Kuwait (21), Dubai (4) average major dust storms y^{-1}.
-Greater number of dew events and possibly site-specific chemistry (calcite) likely contribute to the accumulation and subsequent retention of the contamination in Dubai.

Camera image (top), map of $\tau_{m,rsw}$ (substrate corrected, middle), profile of $\tau_{m,rsw}$ (bottom) for Dubai (left) and Kuwait (right).