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Quantifying Spectral Error in Thermopile Radiometers

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Acknowledgment:

- **Emiel Hall and Chuck Long – NOAA: For lending us radiometers for the study.**
- **Marc Korevaar – Kipp and Zonen: for providing us data for the study.**

Motivation:

- **The accuracy of solar radiation measured by radiometers depends on the specifications of the instrument, calibration procedure, measurement conditions, maintenance, location, and environmental conditions.**
  - Some of the pyranometer specifications include;
    - **Spectral Mismatch/Error**
    - Thermal Offset
    - Directional Response
    - Etc.

Motivation

- **ISO/WMO term "spectral selectivity" is the only specification that does NOT translate directly in a measurement error**

Non-linearity (100 to 1000 W/m^2)	± 0.5 %
Directional response	± 10 W/m^2
Spectral selectivity (350 to 1500 x 10^{-9} m)	± 3 %
Temperature response (interval of 50 K)*	2 %

- **That is a problem in uncertainty evaluation**

Spectral Error Equation:

$$spectral\ error\% = \left[\frac{\int_{350}^{2400} \tau_{dome_{(new,aged)}}(\lambda) \cdot \alpha_{coating_{(new,aged)}}(\lambda) \cdot E_{AM_i}(\lambda)\, d\lambda}{\int_{350}^{2400} E_{AM_i}(\lambda)\, d\lambda} \cdot \frac{\int_{350}^{2400} E_{AM_{1.41}}(\lambda)\, d\lambda}{\int_{350}^{2400} \tau_{dome_{(new,aged)}}(\lambda) \cdot \alpha_{coating_{(new,aged)}}(\lambda) \cdot E_{AM_{1.41}}(\lambda)\, d\lambda} - 1 \right] * 100$$

- τ_{dome}= Dome transmittance
- $\alpha_{(coating)}$= Absorptance of coating
- E_{AM_i}= Spectral irradiance under various Airmass (obtained using SMARTS Model)
- $E_{AM_{1.41}}$= Reference Spectral Data (ASTM G173) at AM 1.41 (SZA 45)

Radiometers included in the study:

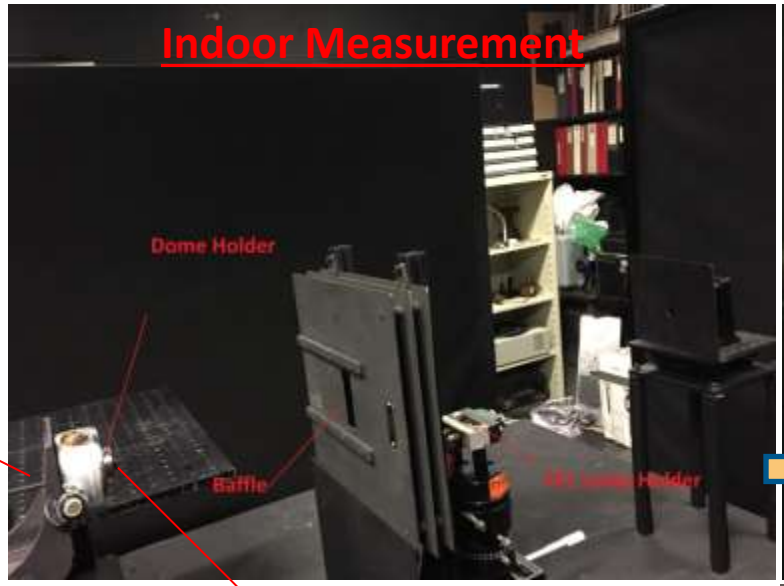
Inst#	Model	Type	Comment
1	PSP	Double Dome and aged coating	
2	PSP	Double Dome and aged coating	
3	PSP	Double Dome and aged coating	
4	PSP	Double Dome and aged coating	
5	TSP-1	Double Dome and aged coating	
6	---	Transmission 2mm and new coating data (HukseFlux)	Provided by Manufacturer
7	---	Transmission 4mm(Kipp and Zonen)	Provided by Manufacturer
8	---	Transmission 4mm +Fresnel (Kipp and Zonen)	Provided by Manufacturer
9	---	SCHOTT-N-WG295	Data Sheet

6. HukseFlux
(Data from manufacturer)

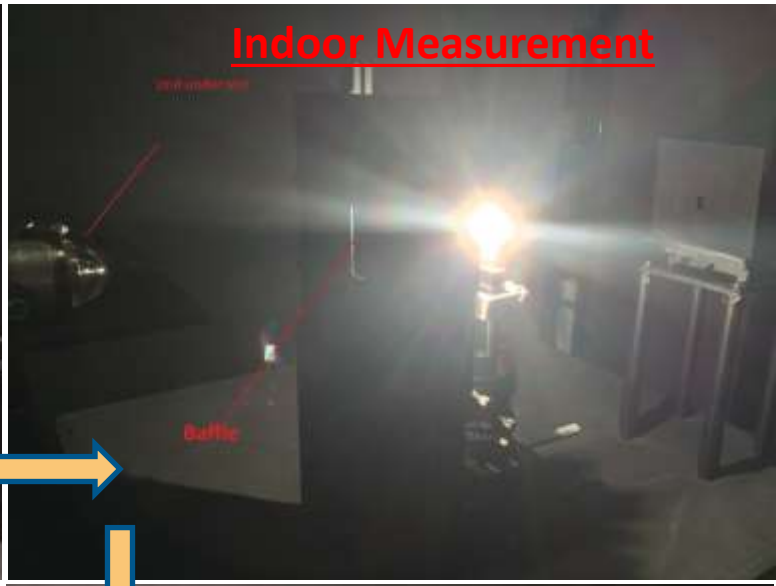
7&8. Kipp and Zonen
(Data from manufacturer)

9. **N-WG295**

Indoor and Outdoor Glass Transmittance Measurement:



Fiber optic going through the dome holder



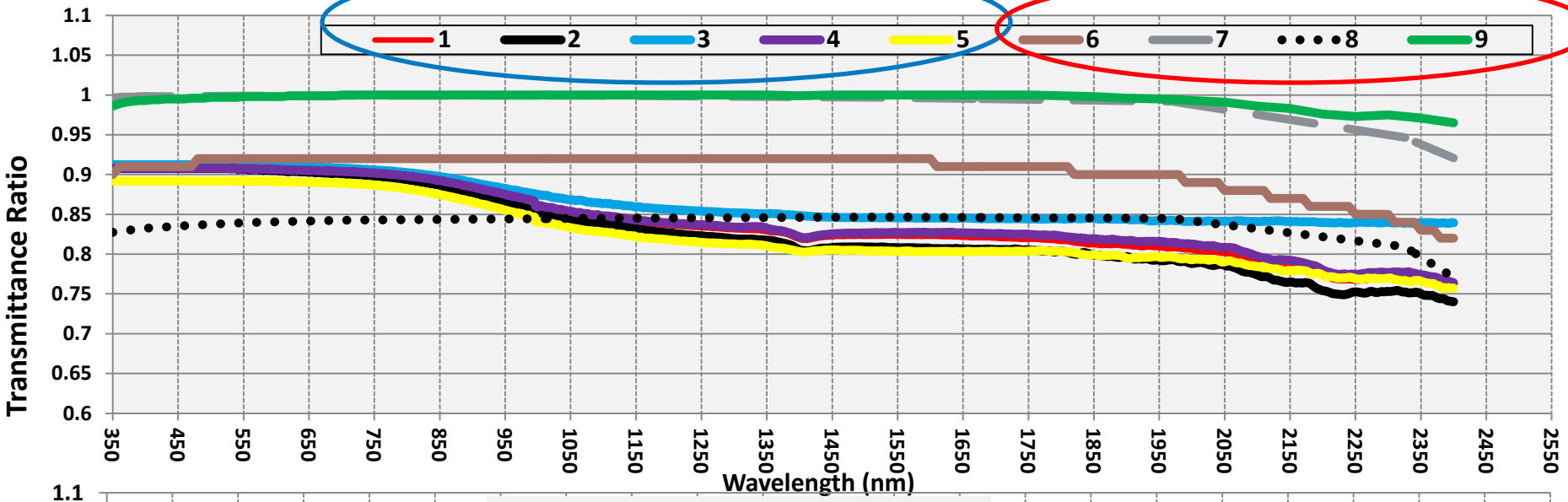
- Care was taken to minimize Stray Light by putting baffle and diaphragm in between the light source (FEL lamp) and the unit under test
- ASD spectroradiometer was used to measure the transmittance (350 to 2400 nm)

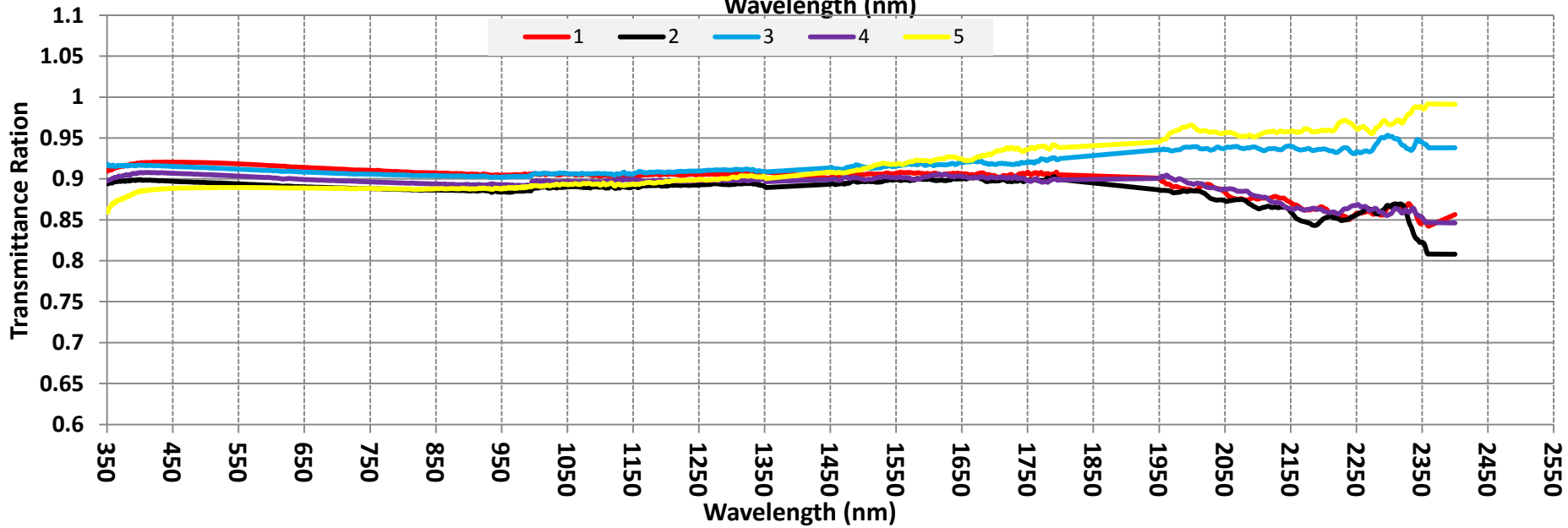
Diffuser

Domes Transmittance Measurement:

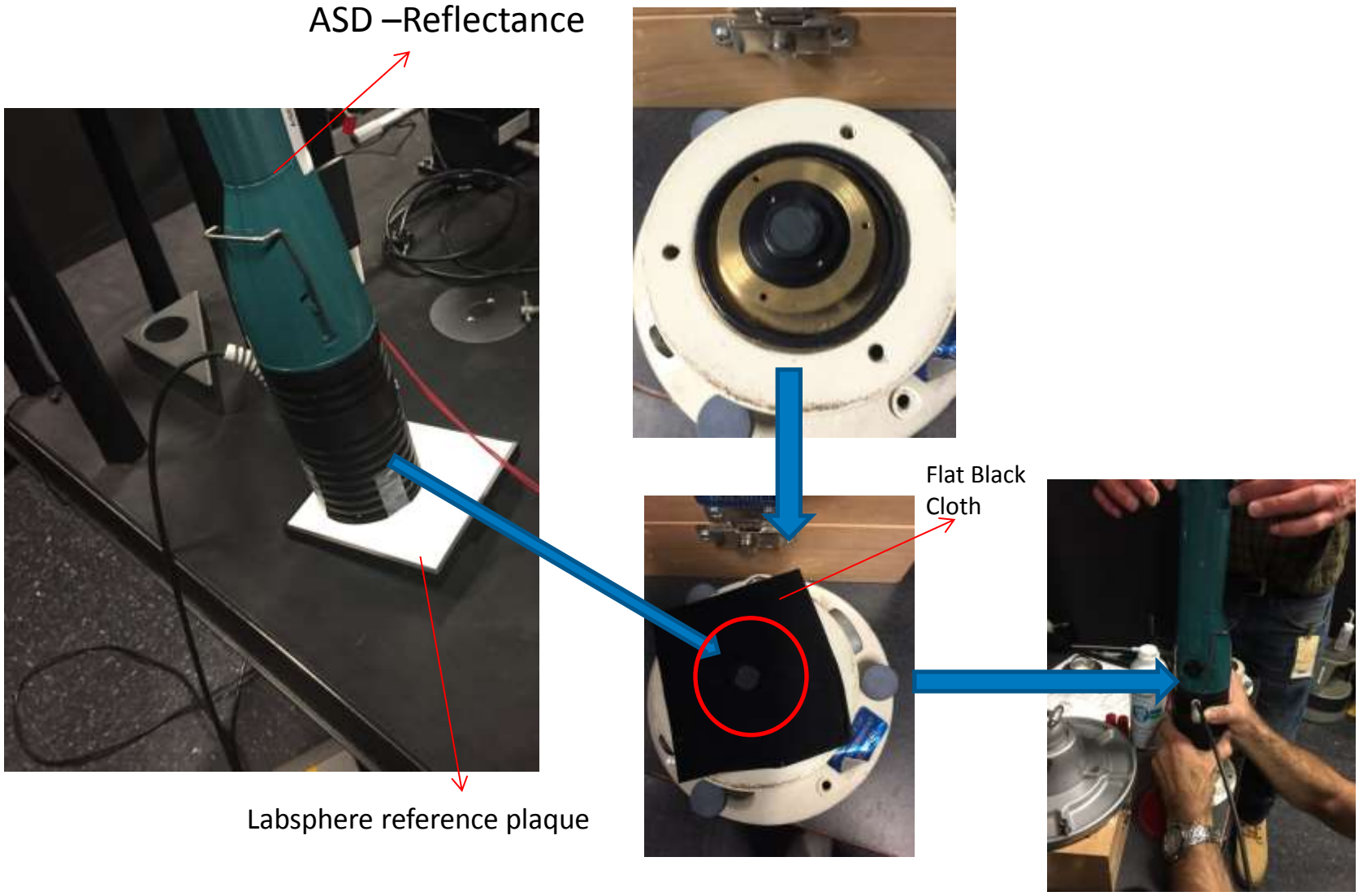
MEASURED, AGED

DATASHEET, NEW

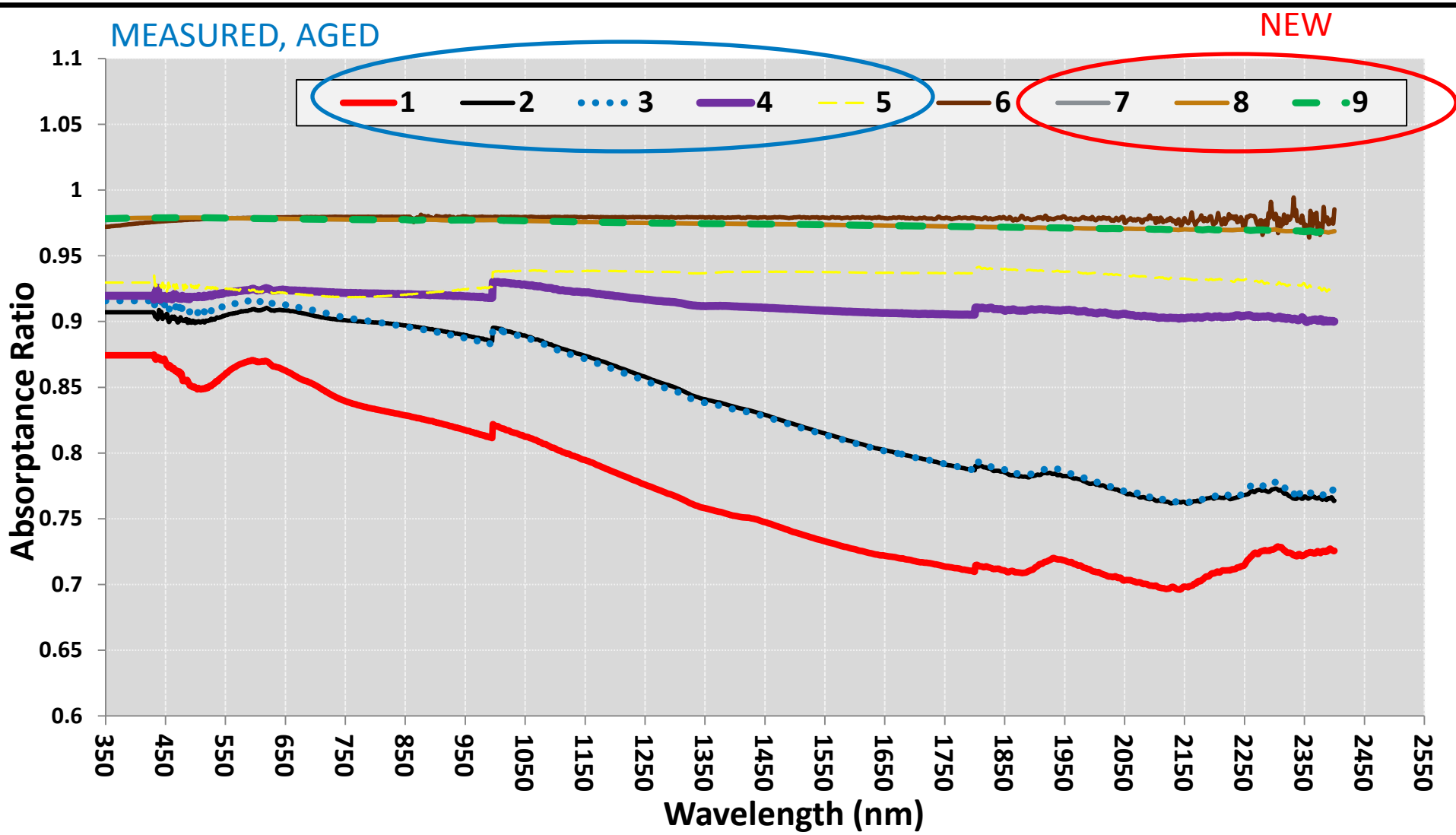




Coating Absoptance Measurement:



Coating Absorptance Measurement:

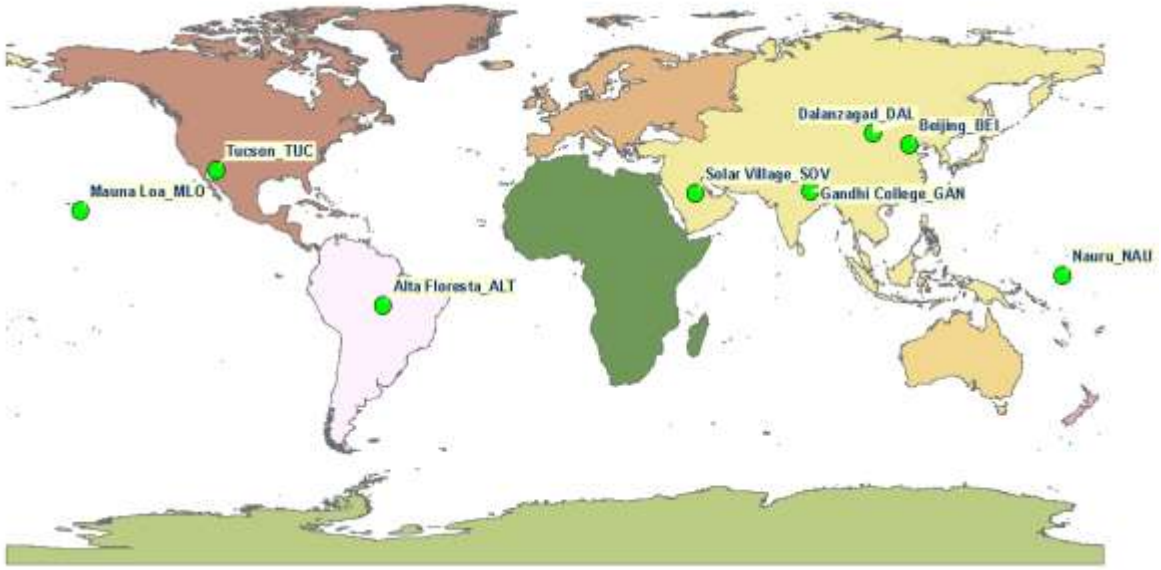


SMARTS Model Input:

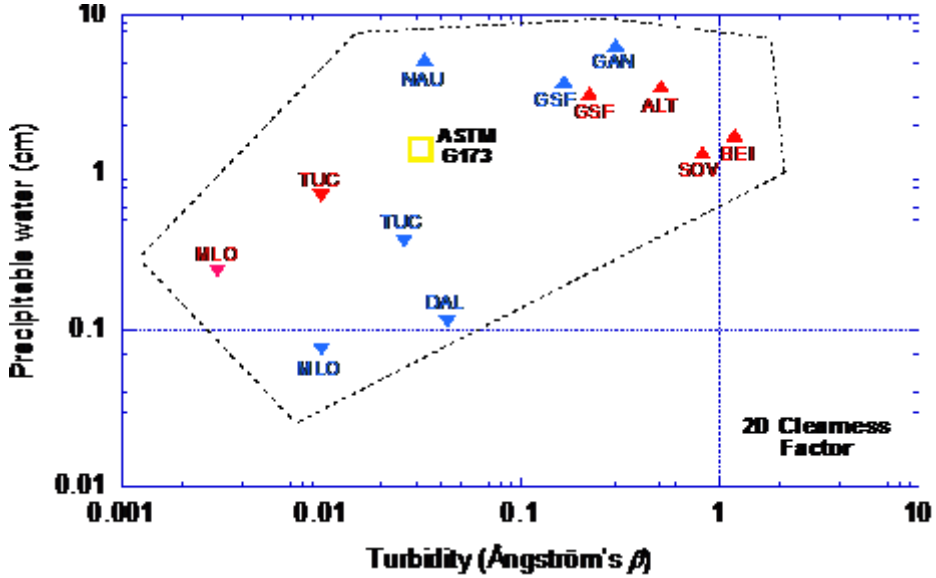
- **Data for various climatic regions**
  - For Solar Zenith Angles: 0, 45, 60, 65, 70, 75, 80, and 85 degrees corresponding to AM1, AM1.41, AM2, AM2.3, AM2.92, AM3.86, AM5.76, and AM11.47
- **ASTM G173 spectral data at 45 degree was used as a reference data**

Site	Lat.	Long.	Elev. (m)	Alpha	Beta	PW (cm)	Ozone (DU)	NO2 (DU)	Pressure (mb)	SSA (assumed)	ASY (assumed)	Surface (assumed)
Mauna Loa (MLO)	19.539	-155.578	3397	1.498	0.003	0.235	266	0.072	680.1	0.98	0.68	Basalt rock
				0.867	0.010	0.075	270	0.076	680.0	0.98	0.68	Basalt rock
Tucson (TUC)	32.233	-110.953	779	1.572	0.010	0.707	281	0.154	929.0	0.96	0.65	Light soil
				1.067	0.026	0.364	293	0.158	929.1	0.96	0.65	Light soil
Nauru (NAU)	-0.521	166.916	7	0.670	0.033	5.280	251	0.047	1007.5	0.95	0.66	Water
Dalanzagad (DAL)	43.577	104.419	1470	0.827	0.043	0.113	356	0.075	857.6	0.96	0.65	Light soil
Alta Floresta (ALT)	-9.871	-56.104	277	1.553	0.508	3.567	272	0.157	980.2	0.96	0.65	Trees
Beijing (BEI)	39.977	116.381	92	0.902	1.190	1.746	344	0.654	1000.4	0.80	0.65	Asphalt
Solar Village (SOV)	24.907	46.397	764	0.131	0.821	1.354	280	0.331	924.3	0.96	0.70	Sand
Gandhi College (GAN)	25.871	84.128	60	1.071	0.301	6.516	279	0.147	994.8	0.87	0.65	Dry soil
ASTM G173	—	—	0	1.198	0.033	1.416	344	0.200	1013.3	0.95	0.70	Light soil

SMARTS Model Input:

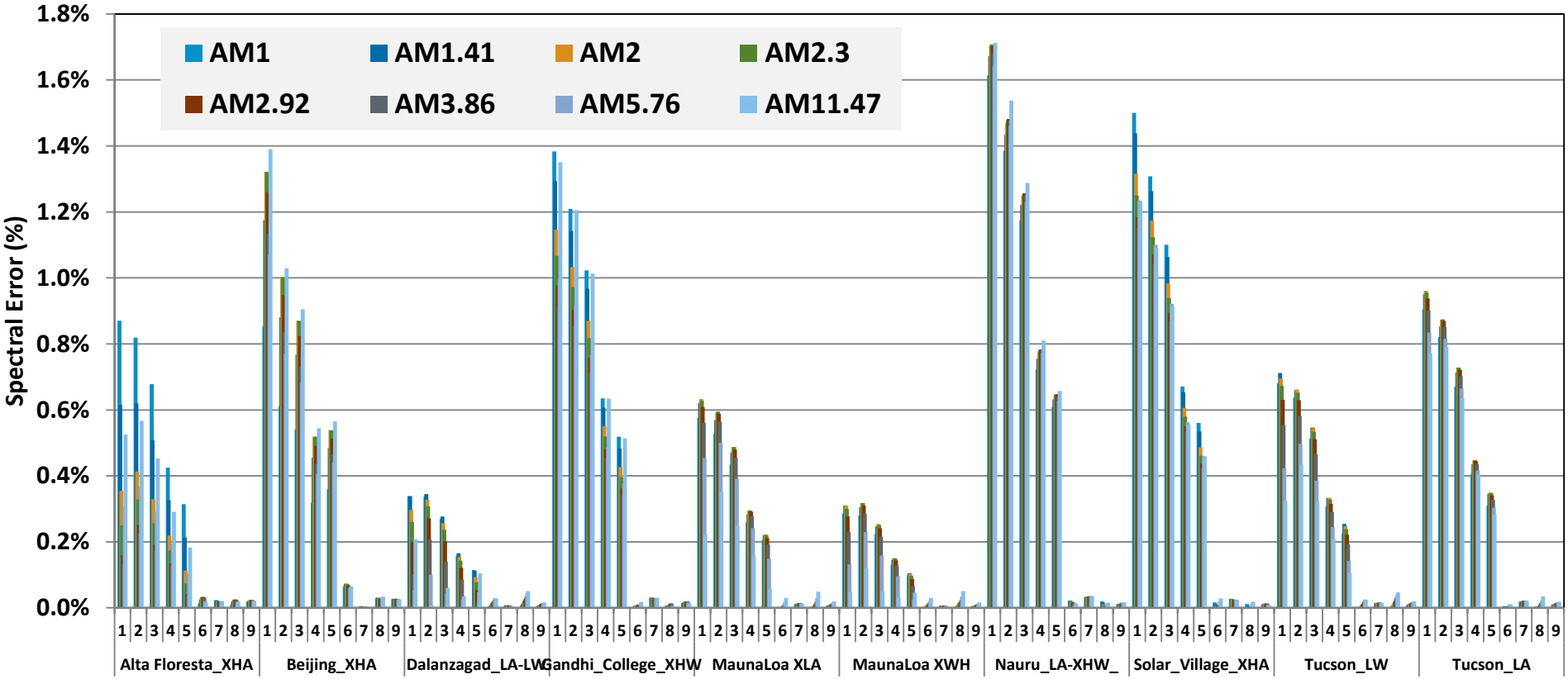


- 8 locations were selected representing various climatic conditions



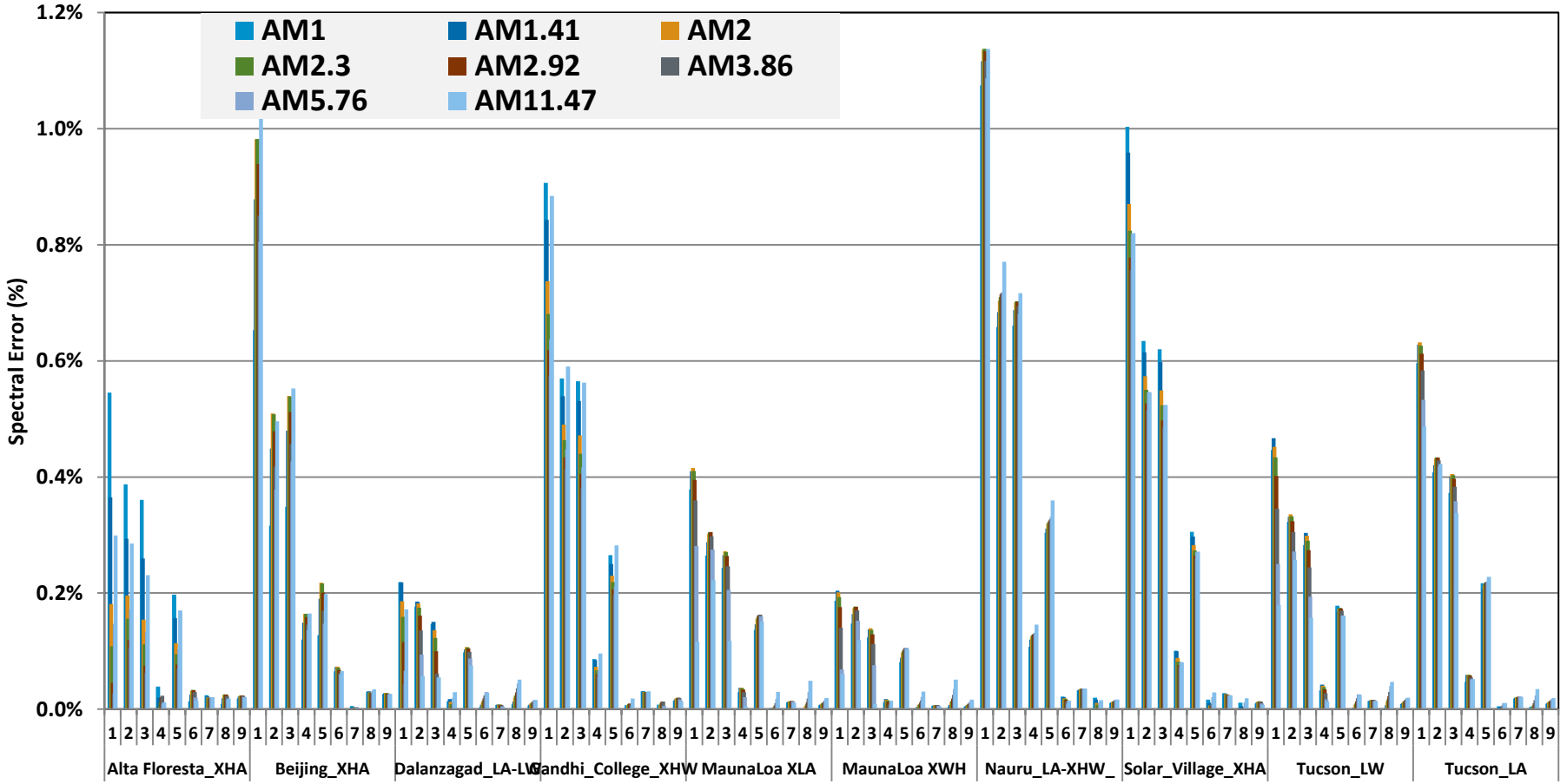
- The plot below shows the distribution of the climatic locations based on PWV and Turbidity

Result Using Indoor Transmittance Measurement (400 to 2400 nm):



- Results are based on combined transmittance measurement of the inner and outer dome for Inst# 1-5
- 1 to 9 are instrument numbers and 10 location conditions
- 6 to 9 are new radiometer with new glass transmittance and coating absorptance – Data Obtained from the manufacturer

Result Using Outdoor Transmittance Measurement (400 to 2400 nm):



- Outdoor: Result is based on combined transmittance measurement of the inner and outer dome

Result (400 to 2400 nm):

INDOOR Result

	Error	Inst.# 1	2	3	4	5	6	7	8	9
Alta Floresta_XHA	Max (%)	0.87%	0.82%	0.68%	0.43%	0.31%	0.03%	0.02%	0.03%	0.02%
	Max (W/m²)	3.03	2.59	1.83	5.03	3.47	1.75	7.72	6.43	3.74
Beijing_XHA	Max (%)	1.39%	1.03%	0.90%	0.54%	0.57%	0.07%	0.01%	0.03%	0.03%
	Max (W/m²)	4.96	2.85	1.92	1.86	4.40	3.26	1.79	6.93	5.60
Dalanzagad_LA-LW	Max (%)	0.34%	0.34%	0.28%	0.17%	0.12%	0.03%	0.01%	0.05%	0.02%
	Max (W/m²)	3.48	4.51	2.36	1.69	1.50	3.72	2.67	1.43	5.80
Gandhi_College_XHW	Max (%)	1.38%	1.21%	1.02%	0.64%	0.52%	0.02%	0.03%	0.01%	0.02%
	Max (W/m²)	4.71	2.88	3.76	1.48	1.02	0.89	2.31	1.62	0.85
MaunaLoa XLA	Max (%)	0.63%	0.59%	0.49%	0.30%	0.22%	0.03%	0.01%	0.05%	0.02%
	Max (W/m²)	3.65	2.88	1.75	2.31	1.09	1.05	0.62	1.89	1.22
MaunaLoa XWH	Max (%)	0.31%	0.32%	0.25%	0.15%	0.10%	0.03%	0.01%	0.05%	0.02%
	Max (W/m²)	0.59	2.96	2.40	1.34	1.80	0.10	0.11	0.14	0.06
Nauru_LA-XHW_	Max (%)	1.71%	1.54%	1.29%	0.81%	0.66%	0.02%	0.04%	0.02%	0.02%
	Max (W/m²)	0.14	0.15	0.09	0.11	0.12	0.05	0.07	0.01	0.04
Solar_Village_XHA	Max (%)	1.50%	1.31%	1.10%	0.67%	0.56%	0.03%	0.03%	0.02%	0.01%
	Max (W/m²)	0.10	0.07	0.03	0.14	0.10	0.07	0.10	0.09	0.06
Tucson_LW	Max (%)	0.71%	0.66%	0.55%	0.33%	0.25%	0.03%	0.02%	0.05%	0.02%
	Max (W/m²)	0.27	0.05	0.27	0.28	0.09	0.08	0.25	0.18	0.07
Tucson_LA	Max (%)	0.96%	0.87%	0.73%	0.45%	0.35%	0.01%	0.02%	0.03%	0.02%
	Max (W/m²)	0.04	0.08	0.06	0.09	0.08	0.06	0.05	0.09	0.09

OUTDOOR Result

		Inst.# 1	2	3	4	5
Alta Floresta_XHA	Max %	0.55%	0.39%	0.36%	0.04%	0.20%
	Max (W/m²)	1.90	1.91	1.18	3.30	2.28
Beijing_XHA	Max (%)	1.03%	0.51%	0.55%	0.16%	0.22%
	Max (W/m²)	3.26	1.35	0.95	1.00	2.15
Dalanzagad_LA-LW	Max (%)	0.22%	0.19%	0.15%	0.03%	0.11%
	Max (W/m²)	1.77	2.24	1.25	1.03	0.81
Gandhi_College_XHW	Max (%)	0.91%	0.59%	0.56%	0.10%	0.28%
	Max (W/m²)	2.66	1.60	2.09	0.13	0.31
MaunaLoa XLA	Max (%)	0.42%	0.31%	0.27%	0.04%	0.16%
	Max (W/m²)	0.66	0.43	0.22	0.31	0.69
MaunaLoa XWH	Max (%)	0.20%	0.18%	0.14%	0.02%	0.11%
	Max (W/m²)	0.60	1.62	1.31	0.94	1.17
Nauru_LA-XHW_	Max (%)	1.14%	0.77%	0.72%	0.15%	0.36%
	Max (W/m²)	0.14	0.15	0.09	0.11	0.12
Solar_Village_XHA	Max (%)	1.00%	0.63%	0.62%	0.10%	0.31%
	Max (W/m²)	0.10	0.07	0.03	0.14	0.10
Tucson_LW	Max (%)	0.47%	0.34%	0.30%	0.04%	0.18%
	Max (W/m²)	0.27	0.05	0.27	0.28	0.09
Tucson_LA	Max (%)	0.63%	0.43%	0.41%	0.06%	0.23%
	Max (W/m²)	0.04	0.08	0.06	0.09	0.08

Summary

- Spectral Error was calculated under clear sky spectral condition for various climate locations and differing Airmass.
- ASTM G173 spectra - AM1.41 (45 SZA) was used as a reference.
- The result shows non-flat transmittance of the glass dome and non-flat absorptance of the black coating due to aging contribute to spectral error up to 1.6% for indoor transmittance measurement and up to 1.2% for outdoor transmittance measurement.
- Performing a round-robin by multiple labs to measure the transmittance and absorptance of glass dome and coating would assist in confirming the result obtained in this study.
- The intent of the study is to quantify the spectral error of thermopile radiometers and thus promote the update and development of uncertainty and classification standards of radiometers.

Thank You!

Questions?