AERONET—The Ground-based Aerosol Satellite and the Solar Spectrum Caper

What we didn’t know and does it matter?

Brent Holben

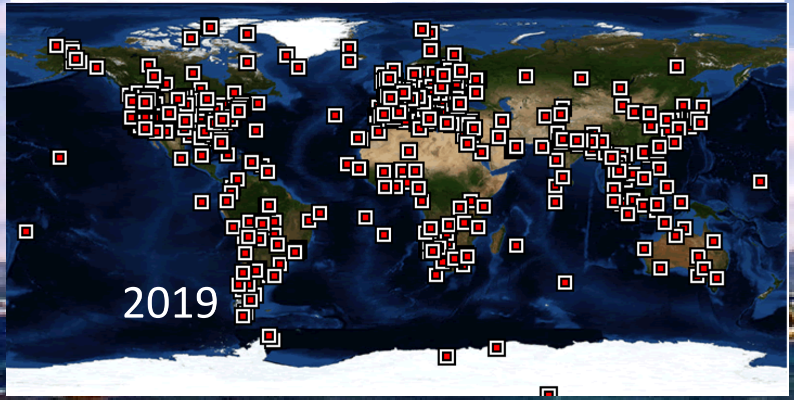
NASA/GSFC

2020 Sun Climate Symposium, Tucson, AZ

The Plan

- What is AERONET?
- AERONET Parameters affected by the Solar Spectrum
- The influence of various spectrums on AERONET Parameters
- The conclusion

AERONET Aerosol Robotic Network- Over 26 Years of Observations and Research



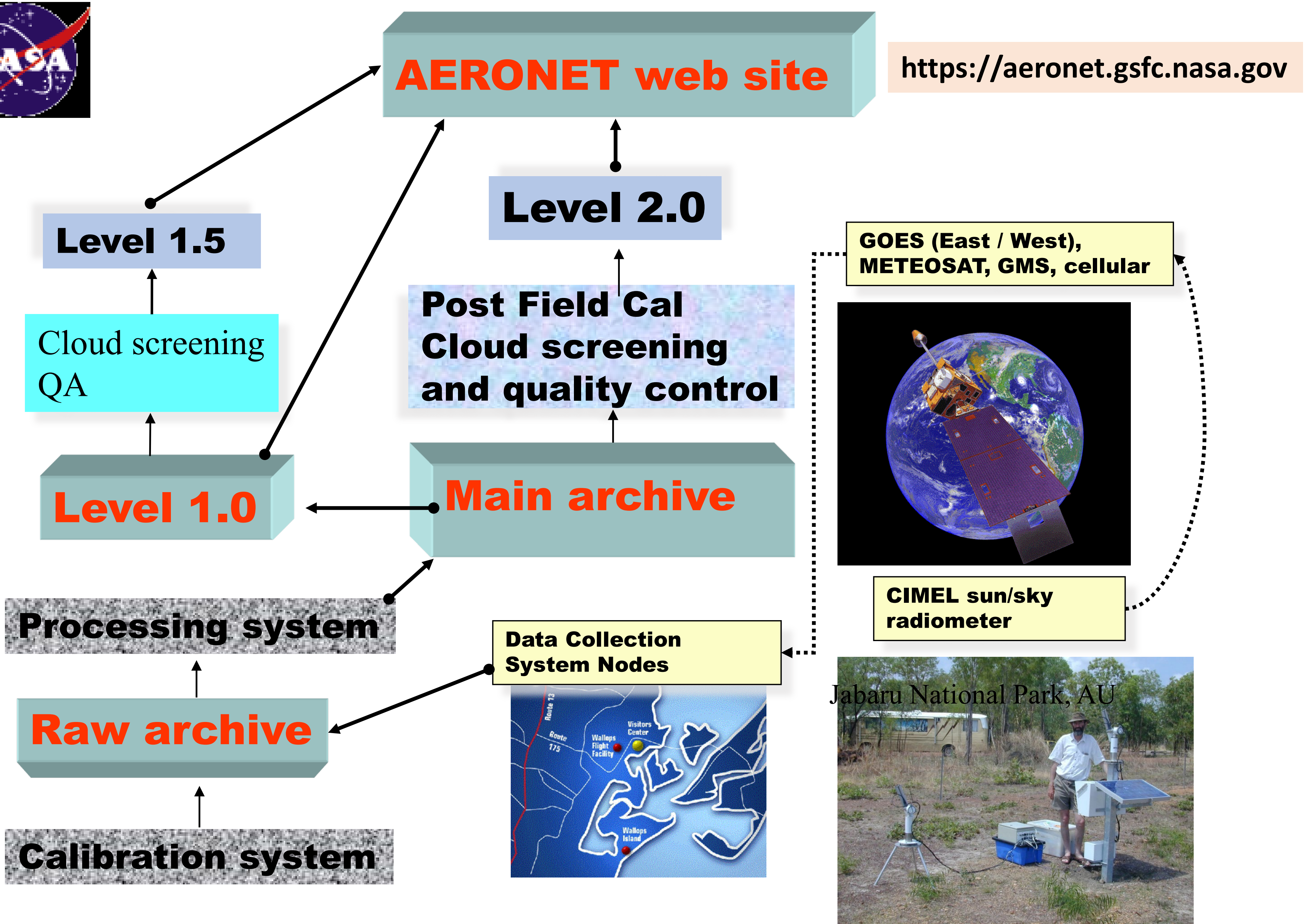
The AERONET program is a federation of ground-based remote sensing aerosol networks established by NASA and LOA-PHOTONS (CNRS) and has been expanded by collaborators from international agencies, institutes, universities, individual scientists and partners.

AERONET provides a long-term, continuous public database of aerosol optical, microphysical, and radiative properties for aerosol research and characterization, validation of satellite measurements, and synergism with other databases.

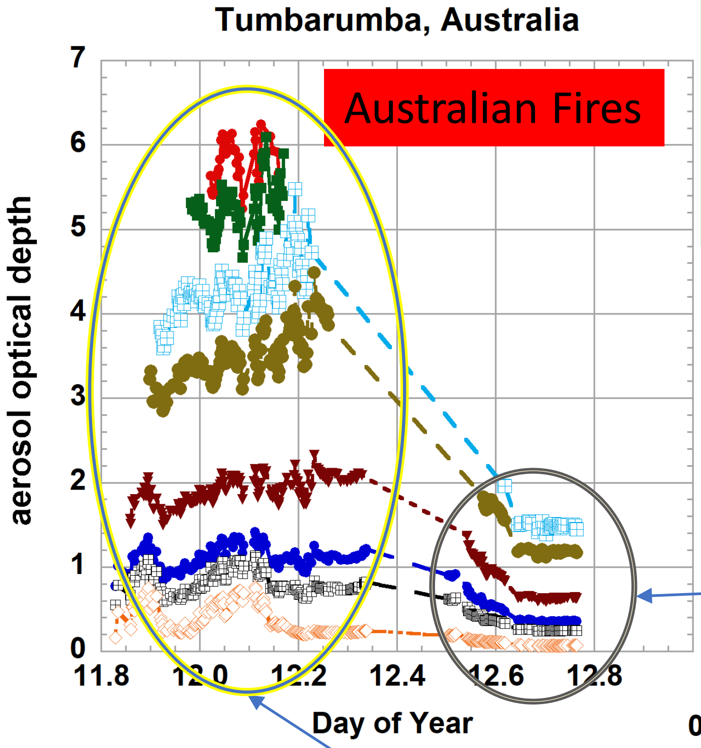
- >7000 citations
- >500 sites
- Over 90 countries
- https://aeronet.gsfc.nasa.gov

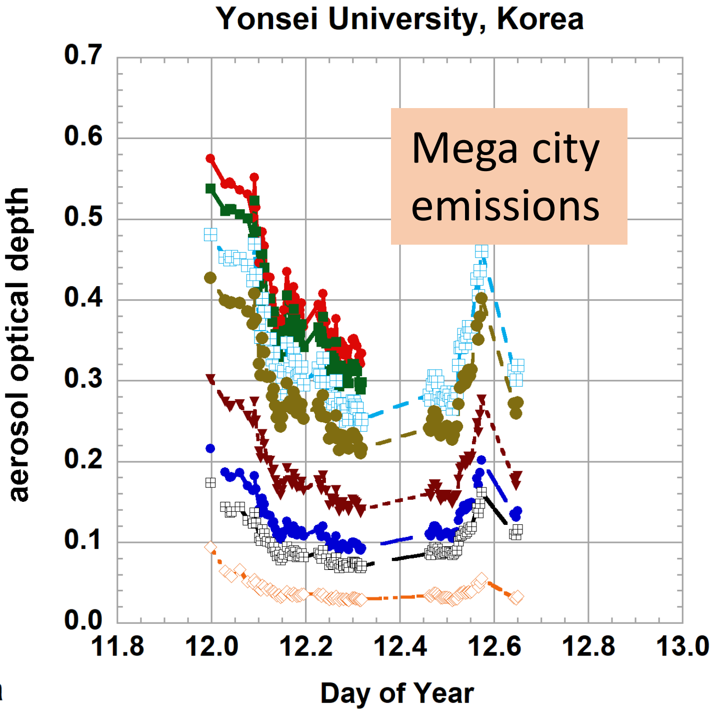
*Federated Network of sun and sky scanning spectral radiometers
*Public Domain Database
*Characterization of Aerosol optical, radiative and microphysical properties
*Atmospheric Correction of airborne and Satellite Remotely Sensed Data
*Validation of satellite and modeled aerosol products and Water leaving Radiances
*Assimilation of modeled aerosol forecasts

The latest AERONET Site: Bahia Blanca, AR


AERONET web site
https://aeronet.gsfc.nasa.gov
Level 1.5
Level 2.0
Cloud screening
QA
Post Field Cal
Cloud screening
and quality control
GOES (East / West),
METEOSAT, GMS, cellular
Level 1.0
Main archive
CIMEL sun/sky
radiometer
Processing system
Data Collection
System Nodes
Raw archive
Calibration system
Route 13
Route 175
Wallops Flight Facility
Visitors Center
Wallops Island
Jabaru National Park, AU

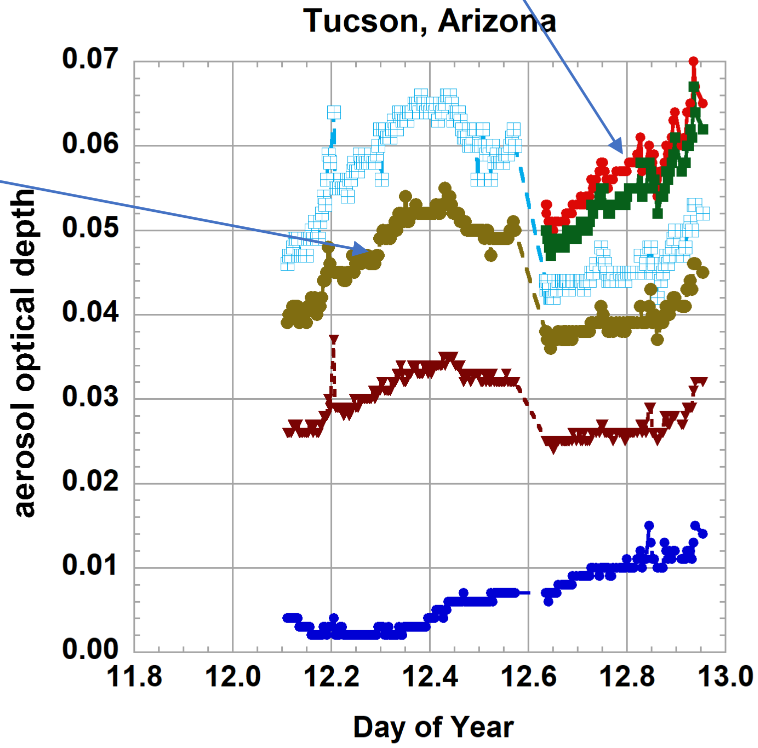
Three magnitudes of **Solar** and **Lunar** Aerosol Optical Depth 12 Jan 2020



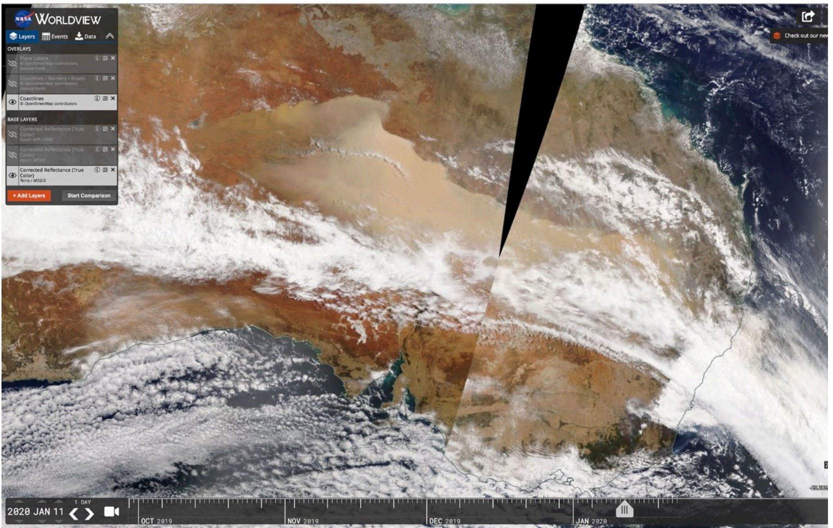


Lunar AOD, (E_o)

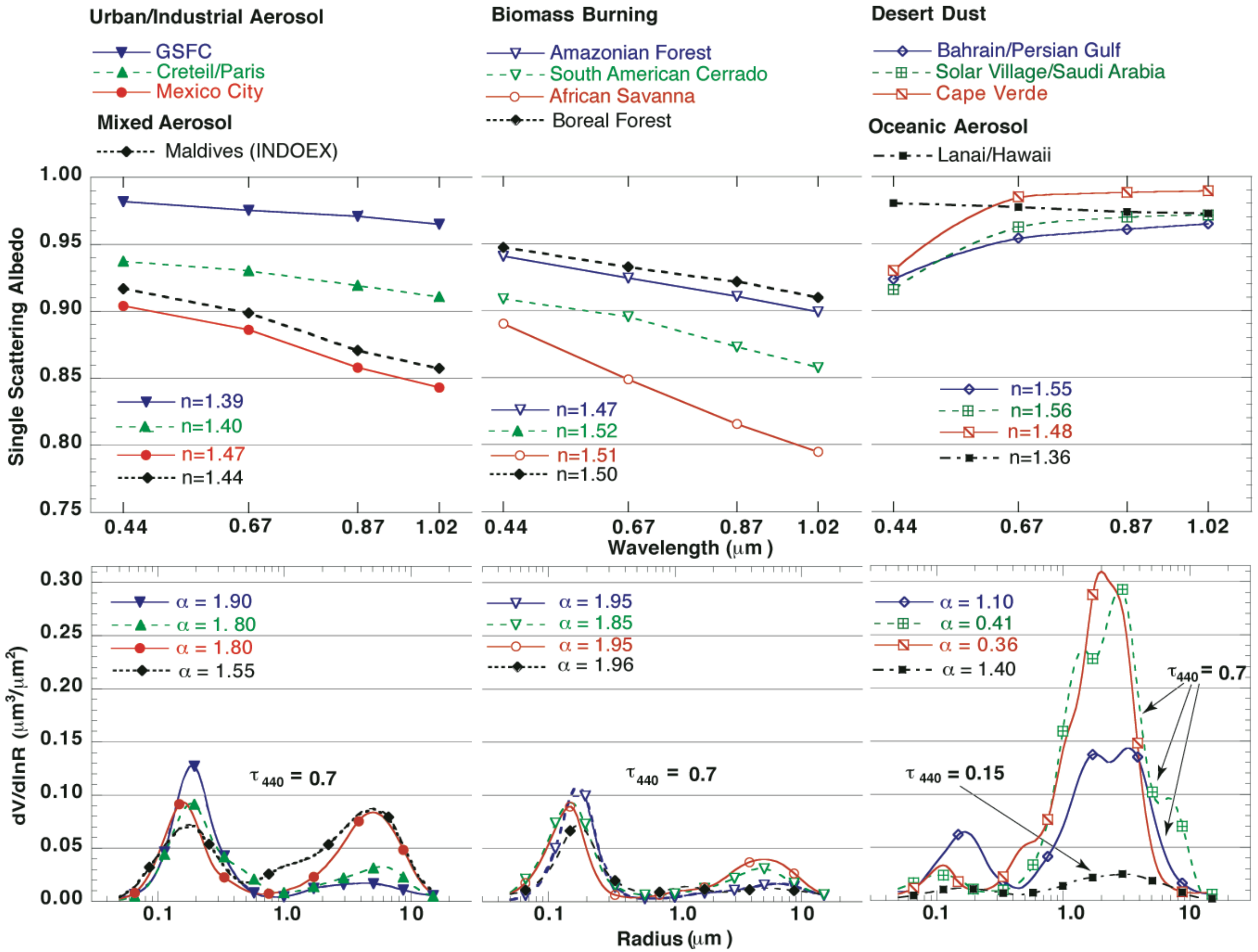
Solar AOD,



Snowbirds



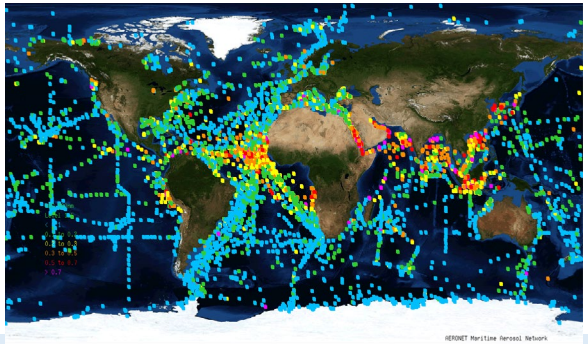
AERONET Milestones: Dubovik & King 2000; Dubovik et al., 2002



Maritime Aerosol Network as a Component of AERONET

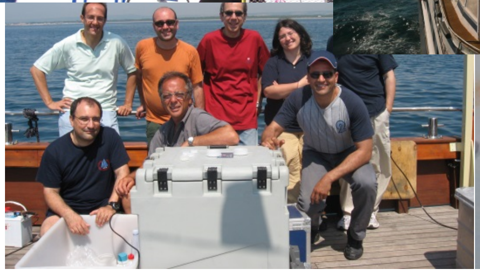
- MAN represents an important strategic sampling initiative and ship-borne data acquisition complements island-based AERONET measurements
- In the last several years data acquisition was extended to the areas that previously had very little or no coverage at all
- Data are easily accessible in the web-based public data archive and will stimulate research and international collaboration in various scientific areas

Maritime Aerosol Network global coverage from October 2006 to January 2020



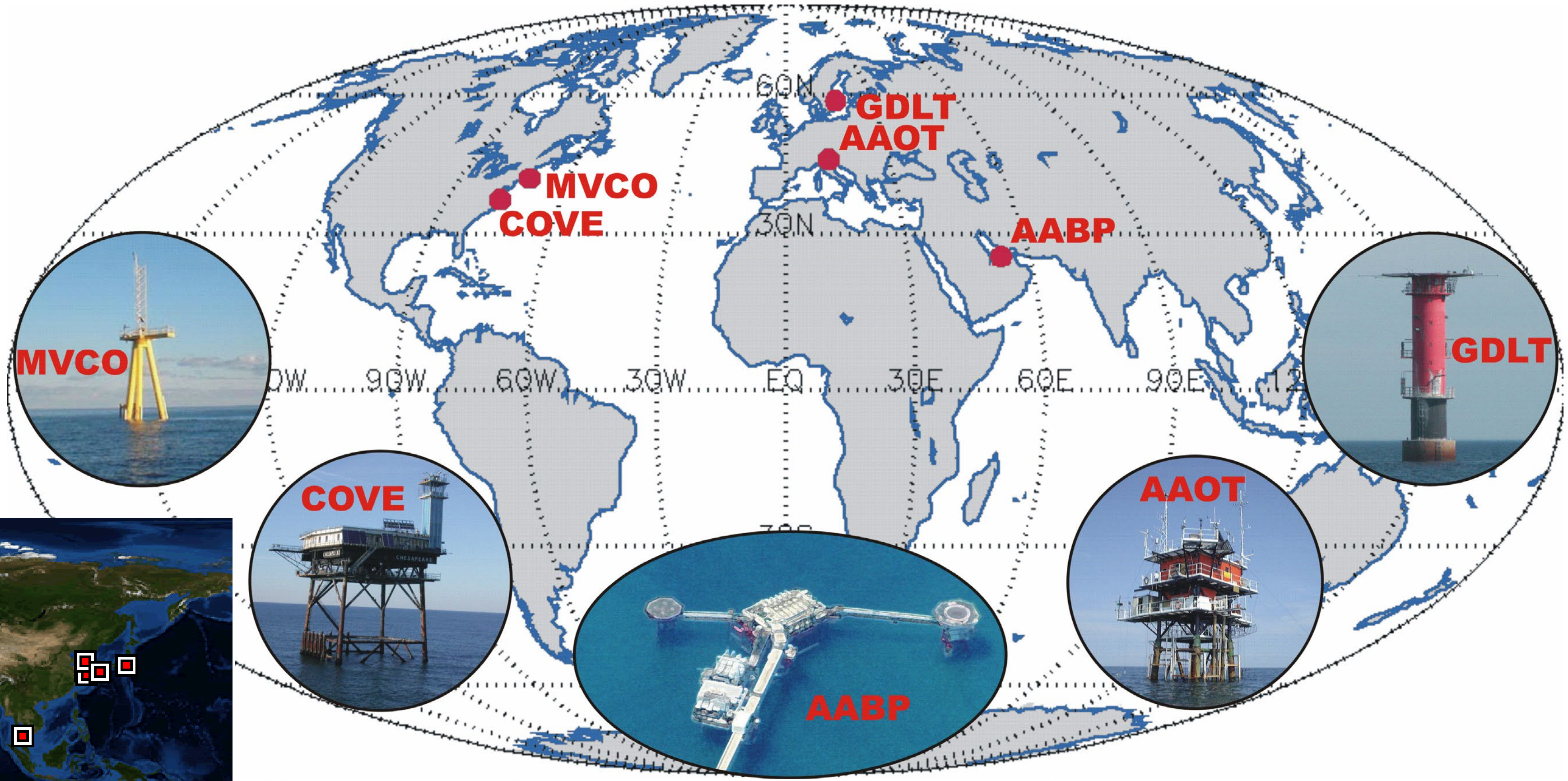
Cruise tracks and daily averages of aerosol optical depth at 500 nm (squares are colored with respect to AOD values, i.e. blue – AOD<0.10 green – 0.1≤AOD<0.2 yellow – 0.2≤AOD<0.3 orange – 0.3≤AOD<0.5 red – 0.5≤AOD<0.7 purple – AOD≥0.7)

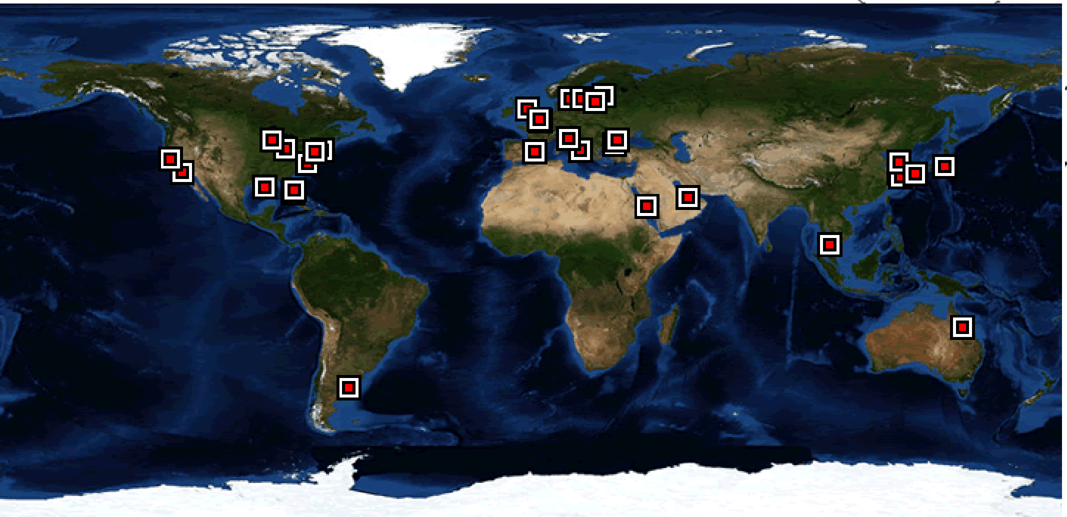
Smirnov, A., B. N. Holben, I. Slutsker, D. M. Giles, C. R. McClain, T. F. Eck, S. M. Sakerin, A. Macke, P. Croot, G. Zibordi, P. K. Quinn, J. Sciare, S. Kinne, M. Harvey, T. J. Smyth, S. Piketh, T. Zielinski, A. Proshutinsky, J. I. Goes, N. B. Nelson, P. Larouche, V. F. Radionov, P. Goloub, K. Krishna Moorthy, R. Matarrese, E. J. Robertson, and F. Jourdin, Maritime Aerosol Network as a component of Aerosol Robotic Network, J. Geophys. Res., 114, D06204, doi:10.1029/2008JD011257, 2009.



G. Zibordi/JRC & S. Hooker/GSFC

AERONET – Ocean Color (AERONET-OC): an integrated network, part of the Aerosol Robotic Network (AERONET), supporting ocean color validation with highly consistent time-series of standardized $L_{WN}(\lambda)$.





Ann. Geophys., 25, 1235–1252, 2007
www.ann-geophys.net/25/1235/2007/

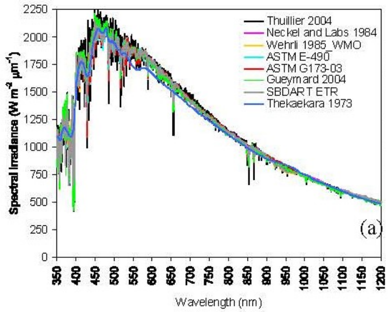
Annales Geophysicae

Reference solar irradiance spectra and consequences of their disparities in remote sensing of the ocean colour

P. Shanmugam and Y. H. Ahn

Ocean Satellite Research Group, Korea Ocean Research and Development Institute, Ansan P.O. Box 29, Seoul 425-600, Korea

Received: 5 February 2007 – Revised: 26 March 2007 – Accepted: 31 May 2007 – Published: 29 June 2007



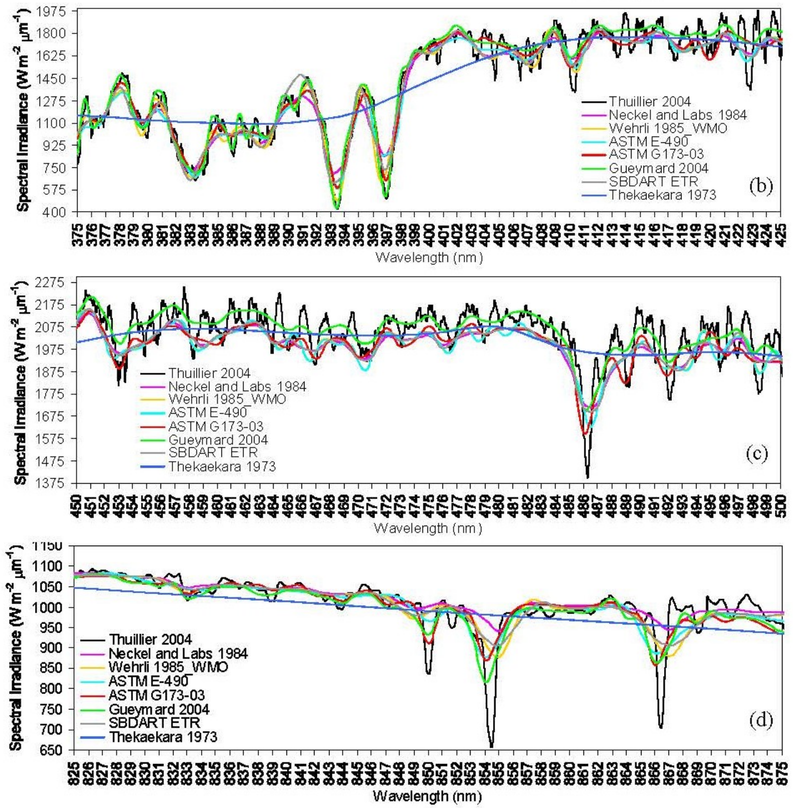


Fig. 3. (a) The spectral irradiance of the eight reference spectra in the UV to NIR (from 350–1200 nm) domains, (b–d) their magnified portions in the ultraviolet-blue-green and NIR, and (e) the peak-normalized irradiance values (at 451 nm) in the 350–1200 nm range.

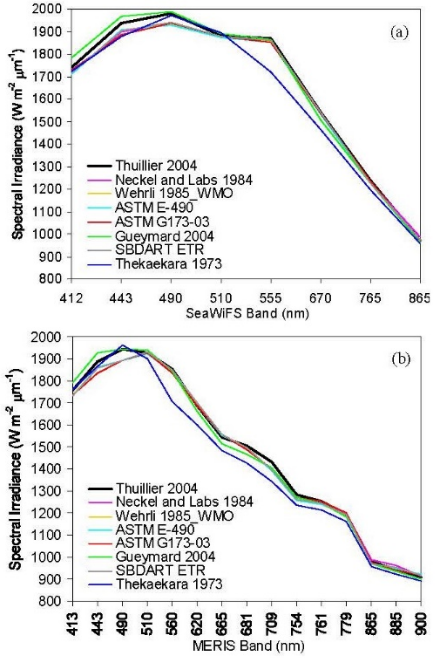


Fig. 4. The in-band irradiances for SeaWiFS (a) and MERIS (b).

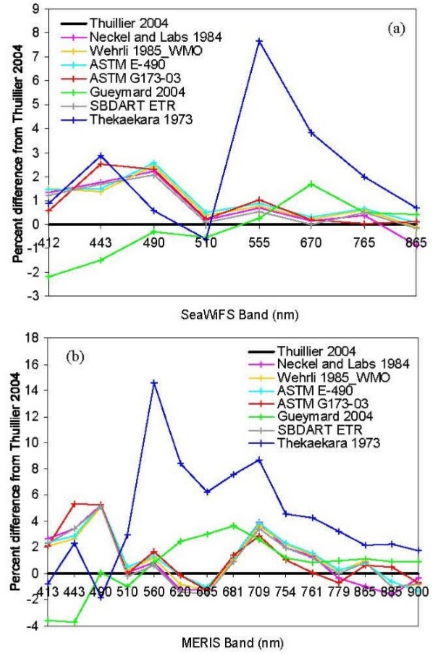


Fig. 5. The percent differences between the Thuillier 2004 and other spectra in SeaWiFS and MERIS channels.

Ann. Geophys., 25, 1235–1252, 2007

Table 1. Background of the applied solar irradiance spectra in various remote sensing applications.

Solar Irradiance Spectrum	Solar constant	Spectral range (nm)	Step size / Increment (nm)	Satellite Sensor	References
Thekaekara 1973	1352.5	115–400 000	5 (VIS), 10 (NIR), >10 (others)	MSS	Dozier and Frew (1981)
Neckel and Labs 1984	1365	380–1250	1	IRS-P3 MOS, SeaWiFS,	Suemnich (1998); Barnes and Zalewski (2003)
Wehrli 1985_WMO	1367	199.5–10 075	1–2 (VIS, NIR), <2 (others)	MODIS, Hyperion, SEVIRI, GOES	Doelling et al. (2004)
ASTM E-490	1366.1	119.5–1 000 000	1 (VIS), 1–2 (VIS-MIR), <20 (others)	IKONOS	Taylor (2005)
ASTM G173-03	1366.1	280–4000	0.5 (UV), 1 (VIS-NIR), >5 (others)	–	–
SBDART ETR		250–4000	0.5–1	–	Ricchiazzi et al. (1998)
Gueymard 2004	1366.1	0.5–1 000 000	0.5 (UV), 1 (VIS, NIR), >1 (others)	–	This study
Thuillier 2001 and 2003	1366.7	200–2397	0.3-1 (UV), 0.1–1 (VIS and NIR)	SeaWiFS, MODIS, MERIS, GLI	Delwart (2001); Nieke and Fukushima (2001); Barnes and Zalewski (2003); Brown et al. (2004)
Thuillier 2004	$1366.7^L/1367.7^H$	0.5–2397	0.05 (UV), 0.05–0.1 (VIS and NIR)	GOCI	This study

* UV – Ultraviolet, VIS – Visible, NIR – Near infrared, MIR – Middle infrared, L – value for low-activity sun, H – value for high-activity sun.

Spectrums used by AERONET 1993-2020

- **V1**; 1993-2004: Four mysterious numbers possibly from Neckel and Labs
- **V2**; 2004-2018: ASTM E-490
- **V3**; 2018-Present: NRL SSI2 (Coddington et al., 2016)
- **New**; Under consideration: TSIS-1 SIM

AERONET parameters and Band Passes (nm) affected by Solar Spectrum

- Single Scattering Albedo
  - 380(2), **440(10)**, 500(10), **675(10), 870(10), 1020(10)**, 1640(25)
- Column integrated water
  - **940(10)**
- Normalized water leaving radiances
  - 400, **412.5, 442.5, 490, 510, 560**, 620, 665, **667**, 709
- Lunar based Aerosol Optical Depth
  - 440, 500, 675, 870, 1020, 1640

Effect of Solar flux on inversions by AERONET's aerosol retrieval algorithm-SSA

Normalized sky radiances (NSR) constitute input to retrieval code:

$$NSR = \frac{\pi * I_{meas.}}{E_0}$$

Solar flux determines the magnitude of NSR which affects the accuracy of retrieved single scattering albedo.

AERONET Single Scattering Albedo

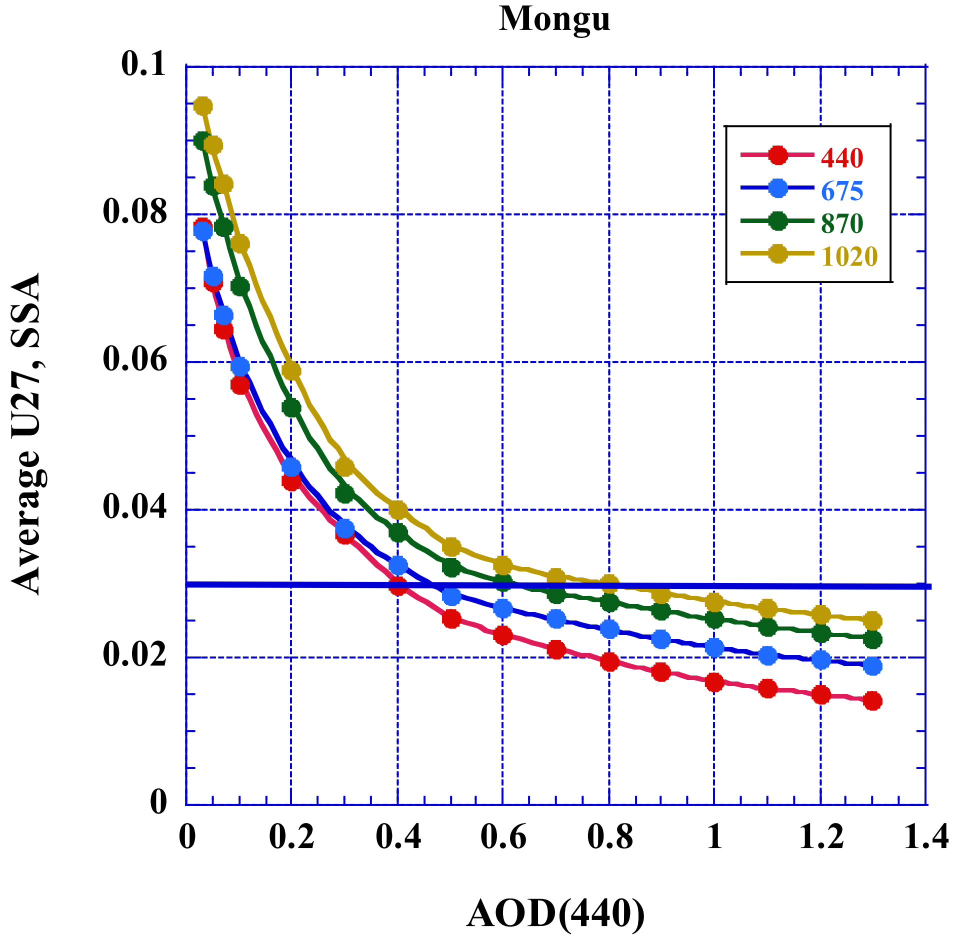
- AERONET's Climate parameter
- $\omega_o = \tau_{sct} / (\tau_{abs} + \tau_{sct})$
- $\omega_o = 0$, radiation completely absorbed
- $\omega_o = 1$, radiation completely scattered
- Typical range 0.85 to 0.99; biomass burning aerosols to seasalt
- Spectrally dependent

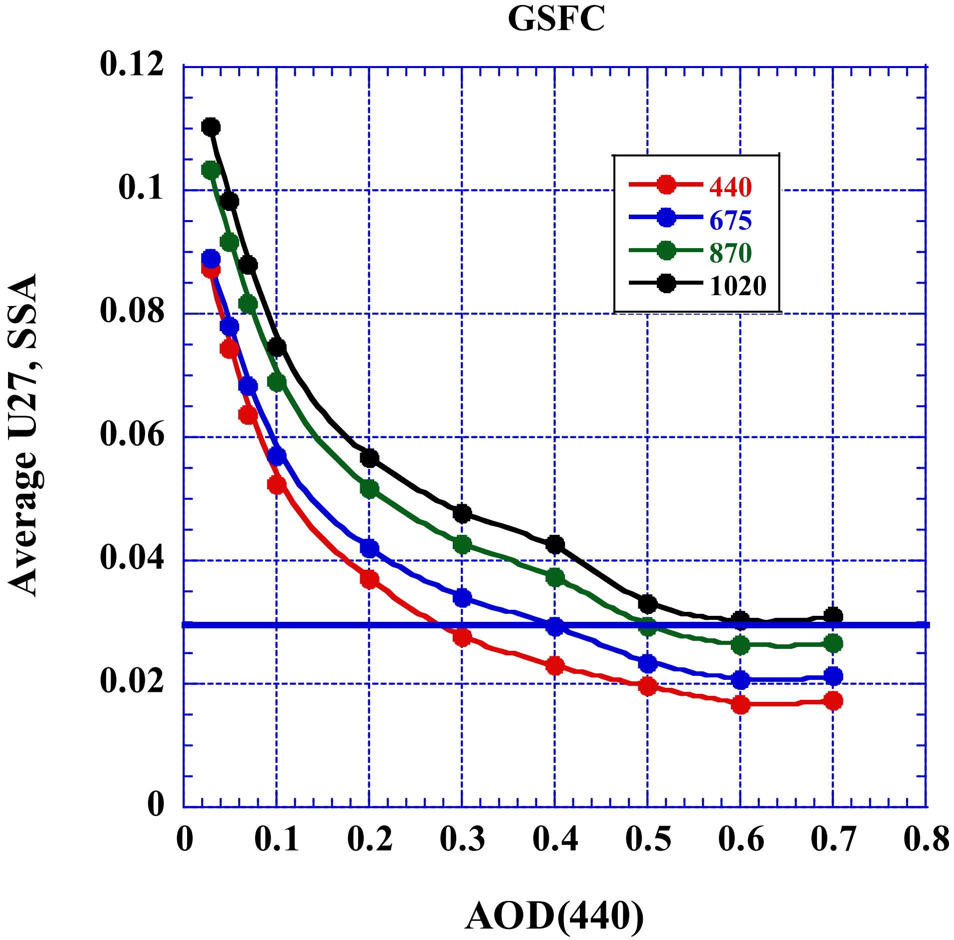
Uncertainty Proxy

Sensitivity to 1 sigma Input Uncertainty

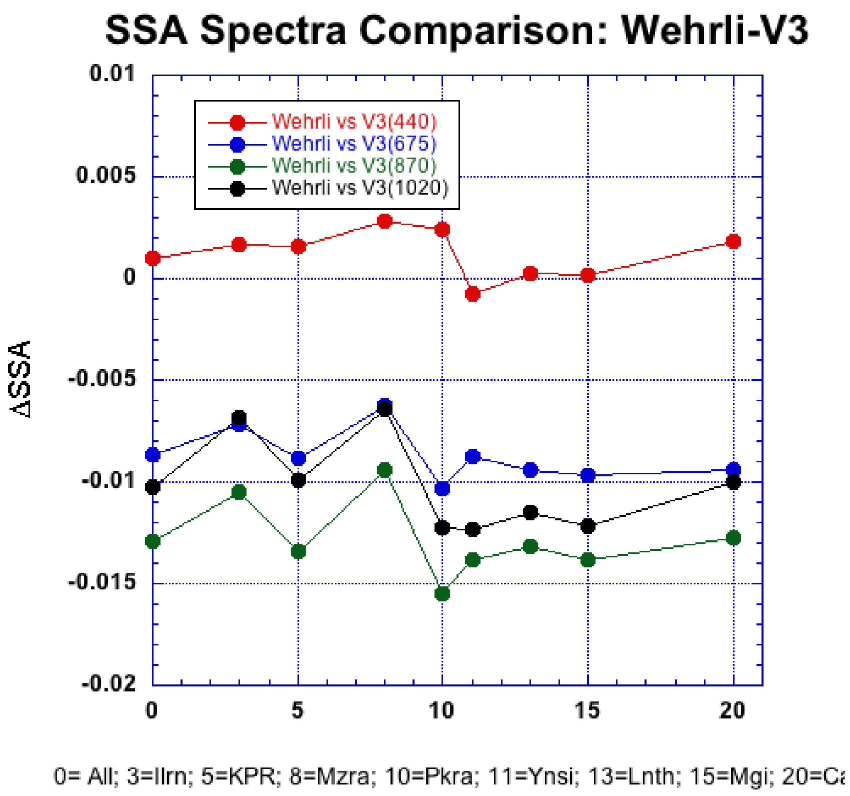
AOD: ± 0.01, BRDF: ± 5.%, Rad. & Irrad: ±5.%

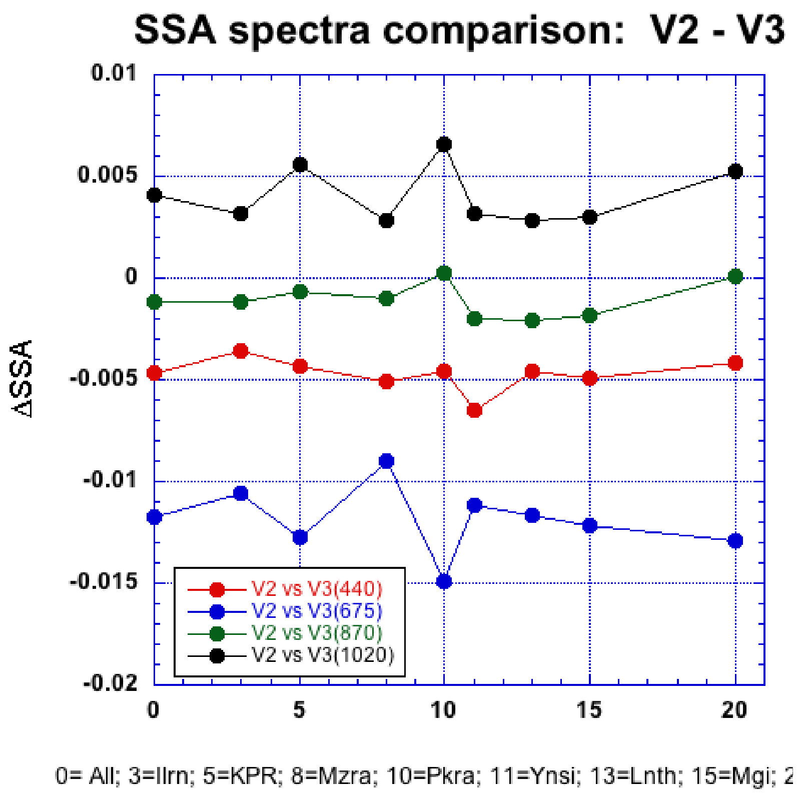
27 inversions: Mean, Stdv, Max, Min

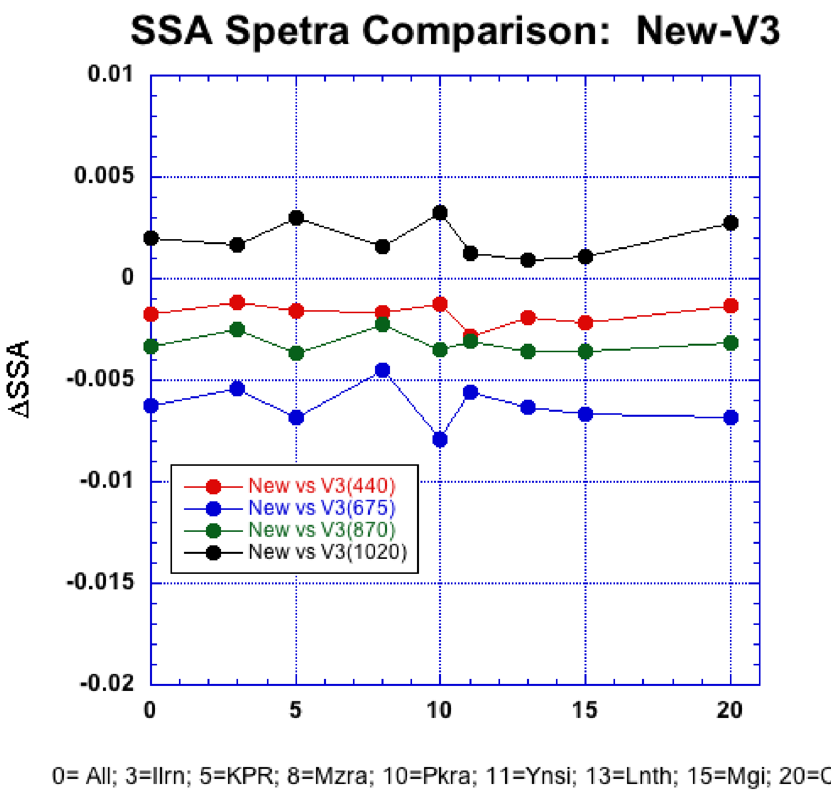




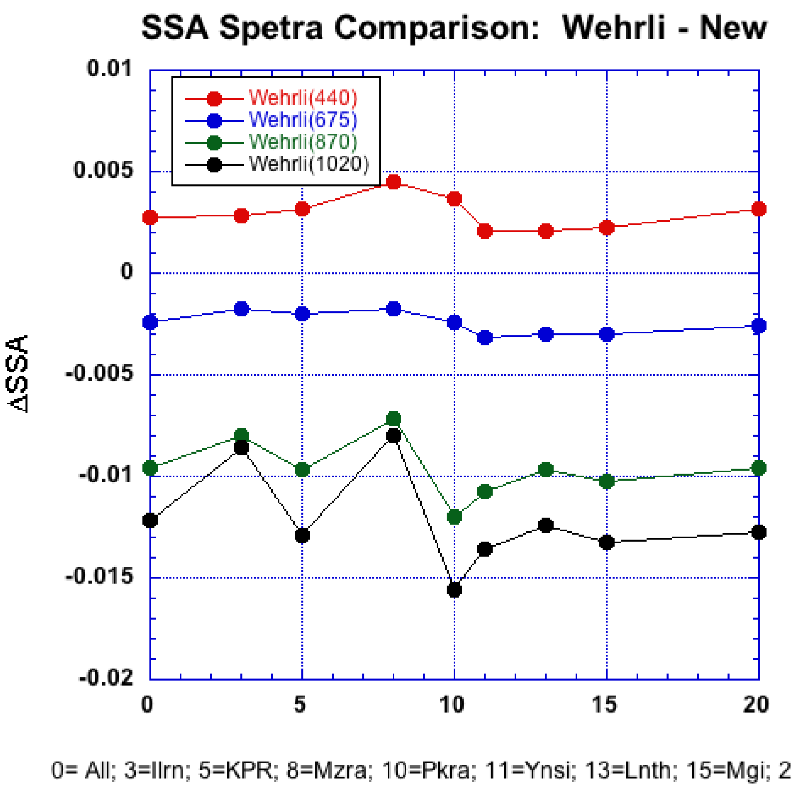
Difference of station mean SSA: Spectra Comparison To AERONET's V3-Coddington et al., 2016

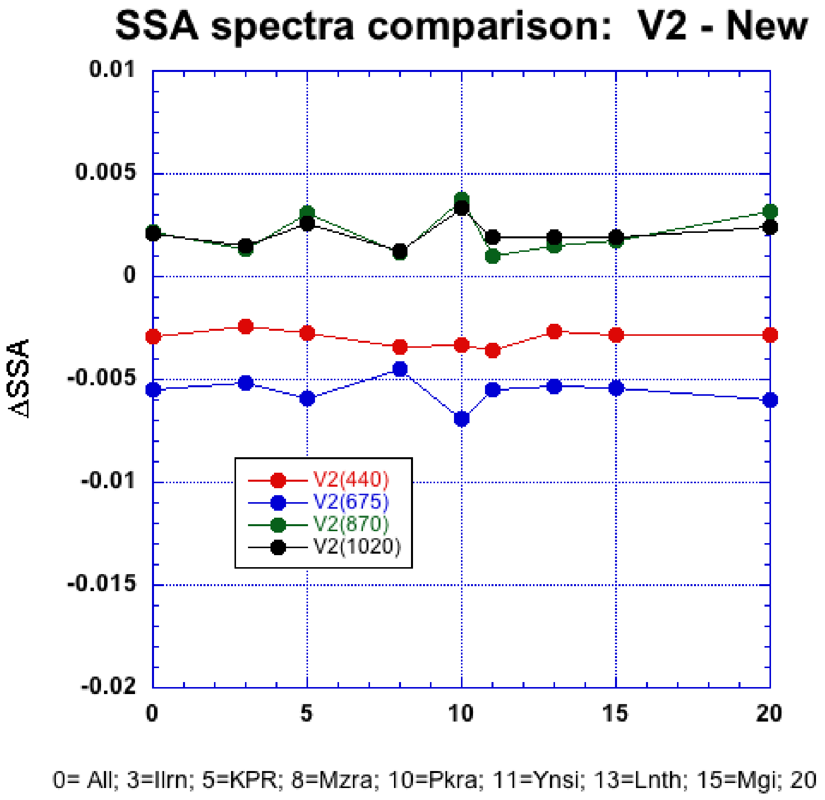


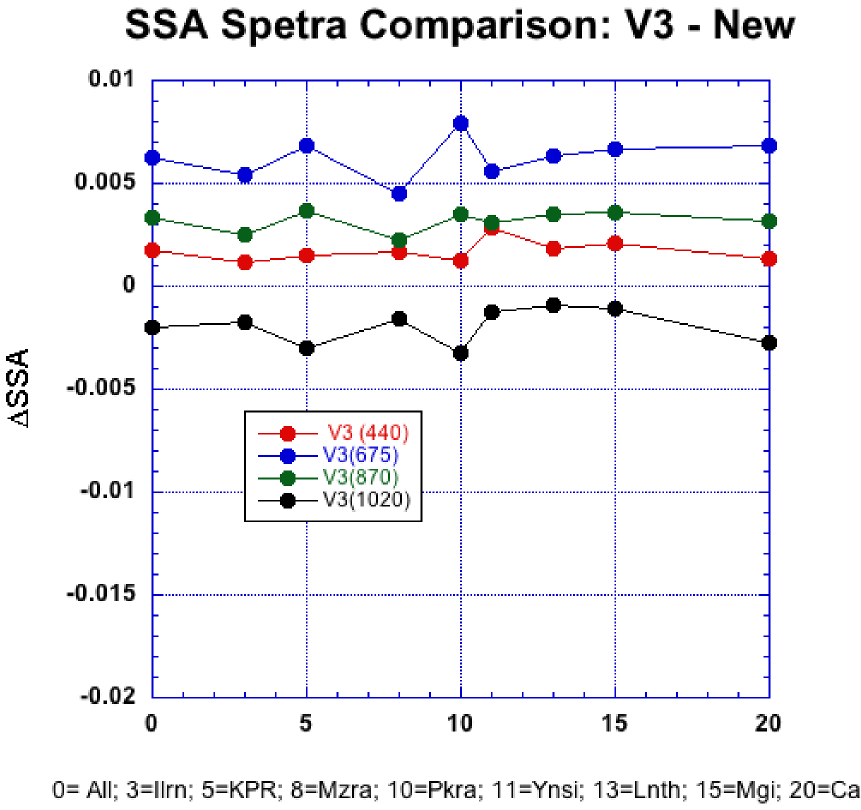




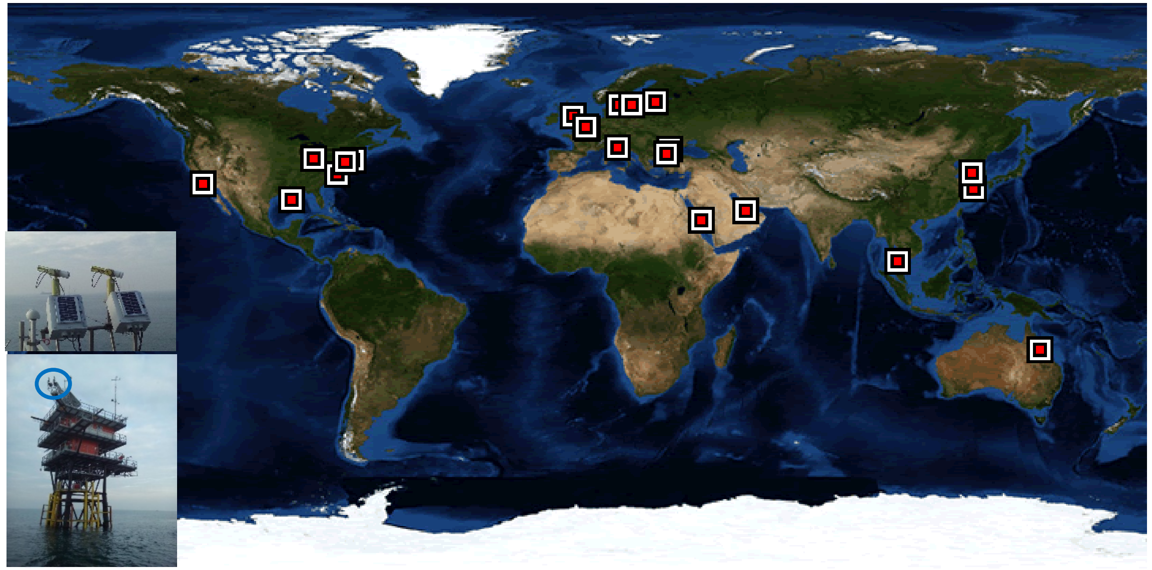
Difference of Station mean SSA: Spectra Comparison To TSIS-1 SIM

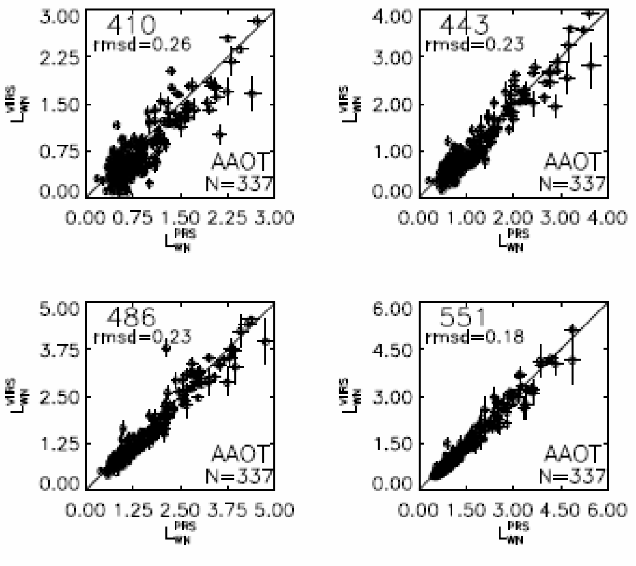






Operational support to ocean color missions





AERONET-OC: sites and data application

- Validate water leaving radiance from Satellite ocean color missions
  - OLCI (Sentinel-3)
  - VIIRS on Suomi NPP
  - VIIRS on NOAA-20
  - PACE
- Autonomous radiometric measurements from offshore platforms
- Collaboration: NASA & Joint Research Centre of the European Commission
- Public Domain Database from 28 globally distributed sites in different Marine regions

E_0's role in AERONET-Ocean Color retrievals of L_{WN}

- $E_0(\lambda)$ affects the determination of corrections applied for the in-water non-isotrophic radiance distribution (i.e., bidirectional effects) affecting the Normalized Water-Leaving Radiance $L_{WN}(\lambda)$
- The correction of $L_{WN}(\lambda)$ for BRDF effects requires an estimate of chlorophyll-*a* concentration (responsible for BRDF together with illumination and measurement geometry). This is obtained through an iterative process implying
  - The quantification of chlorophyll-*a* concentration from regional bio-optical algorithms based on remote sensing reflectance [i.e., $L_{WN}(\lambda)/E_0(\lambda)$] ratios at 490 and 560 nm: $[L_{WN}(490)/E_0(490)]$ / $[L_{WN}(560)/E_0(560)]$
  - The determination of BRDF correction factors from pre-computed look-up tables and their application to $L_{WN}(\lambda)$
  - Successive iterations to convergence

L_{WN}: Spectrum comparison relative to V3 (current) in Percent

Spectra\Lwn	412	442.5	490	560	667
New	0.12	0.14	0.18	0.24	0.14
V2	0.37	0.43	0.57	0.74	0.43
Wehrli	0.36	0.43	0.57	0.74	0.43

Above water radiometry

CE-318 (L_T : Sea-viewing)

$$L_W(\phi,\theta,\lambda) = L_T(\phi,\theta,\lambda) - \rho(\phi,\theta,\theta_0,W)L_i(\phi,\theta',\lambda)$$

$$(\phi = \phi_0 + 90^0; \theta = 40^0\ \theta' = 140^0)$$

$$L_{WN}(\lambda) = L_W(\lambda)\left(D^2 t_d(\lambda)\cos\theta_0\right)^{-1} C_{f/Q}(\lambda,\theta,\phi,\theta_0,\tau_a,Chla,W)$$

$C_{f/Q}$ indicates BRDF correction as a function of: wavelength, viewing and illumination geometry, aerosol optical depth, chlorophyll-a concentration and wind speed)

Uncertainty source	L_{WN}**(%)**		
	443	**551**	**667**
Absolute calibration	2.7	2.7	2.7
Sensitivity change	0.2	0.2	0.2
Corrections	2.0	2.9	1.9
t_d	1.5	1.5	1.5
ρ	1.5	0.6	2.5
Environmental perturbations	2.1	2.1	6.4
Quadrature sum	**4.5**	**4.7**	**7.8**

Uncertainties quantified for mid-latitude marine regions characterized by moderate sediment concentrations

CE-318 (L_i : Sky-viewing)

G.Zibordi, B.Holben, I.Slutsker, D.Giles, D.D'Alimonte, F.Mélin, J.-F. Berthon, D. Vandemark, H.Feng, G.Schuster, B.Fabbri, S.Kaitala, J.Seppälä. AERONET-OC: a network for the validation of Ocean Color primary radiometric products. *Journal of Atmospheric and Oceanic Technology*, 26, 1634-1651, 2009.

Joint Research Centre

Conclusions

- Spectrum induced uncertainties in AERONET products are well within the overall uncertainty estimated for those parameters
- The absolute uncertainty of the spectrum introduces a small bias in some AERONET products (SSA, Lwn, lunar AOD, Column integrated water vapor)
- The magnitude and sign of those biases are not clearly known
- The RS community should identify and use a common reference spectrum
- AERONET and the RS community should identify the spectral resolution
- Virtually every satellite product that is affected by aerosols and every global aerosol model will use AEROENT data—the spectrum does matter.

More Conclusions and thoughts

- AERONET applies one solar spectrum to a nearly three decade record
- Great confusion on a reference spectrum
- Naming??

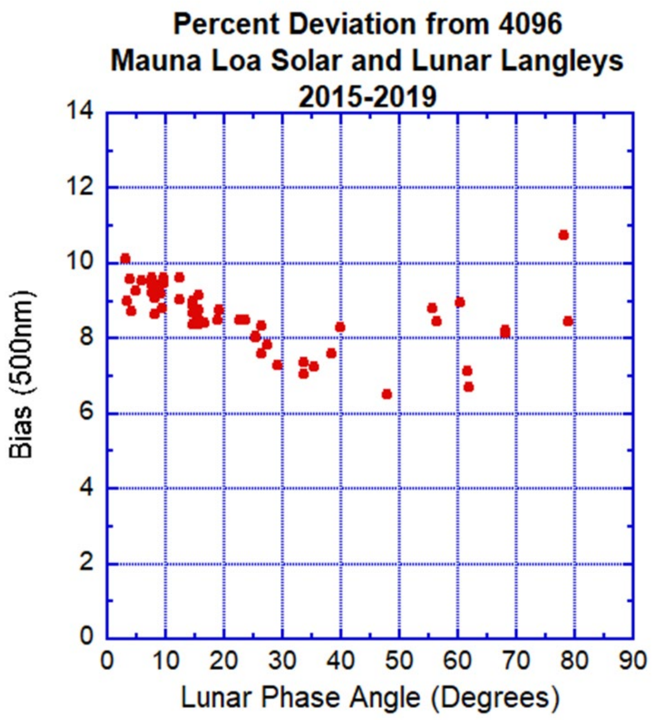
Lunar Measurement Dependence on Extraterrestrial Spectrums

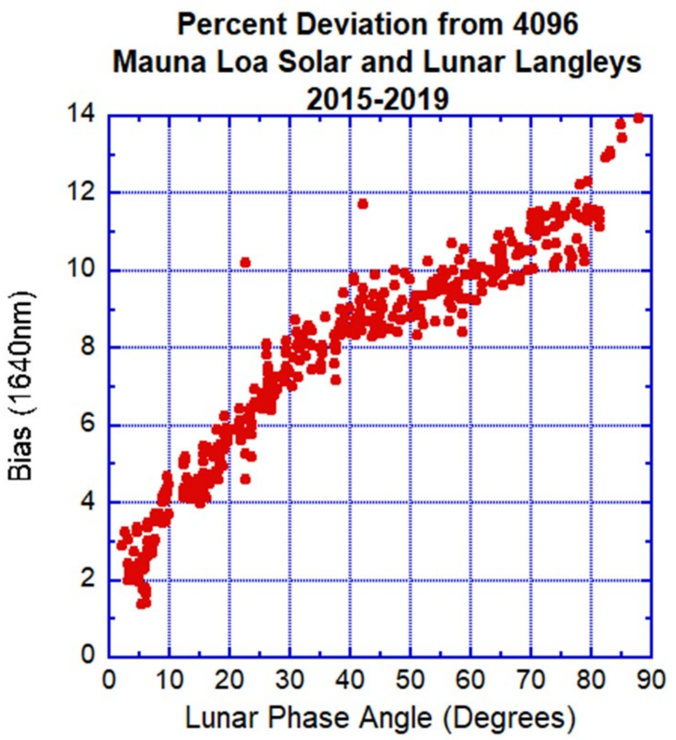
Extraterrestrial solar (E_0^S) and lunar (E_0^L) irradiances and optical air mass (m) are time dependent (t):

$$ln\frac{V^S(t)}{E_0^S(t)} = -T_{const} \cdot m^S(t) - lnC^S \qquad \text{(Sun)}$$

$$ln\frac{V^L(t)}{E_0^L(t)} = -T_{const} \cdot m^L(t) - lnC^L \qquad \text{(Moon)}$$

- E_0^S is adjusted by the Earth-Sun distance factor as Earth moves between aphelion to perihelion (LASP/NRL; Coddington et al., 2016).
- E_0^L changes with the Moon phase and Earth-Moon and Moon-Sun distances (USGS ROLO; Kieffer and Stone, 2005) using solar spectrum of Wehrli (1986).



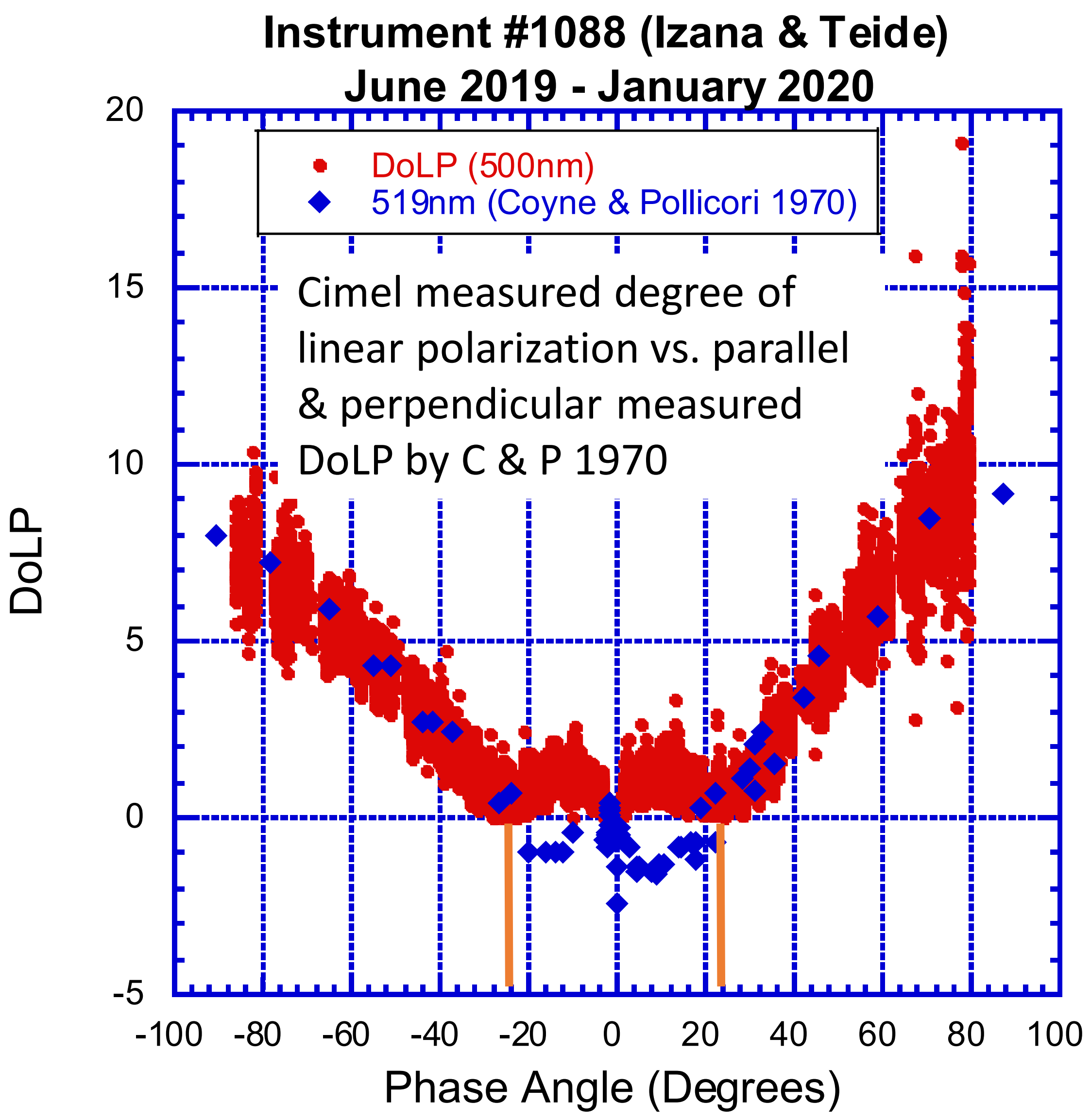


The deviation of C^S and C^Lratio from 4096 determines the lunar bias (δ) by using coincident solar and lunar Langley measurements at Mauna Loa, Hawaii.

$$C^L = \frac{C^S}{4096 \cdot (1 + \delta)}$$

Lunar Measurement Dependence on Extraterrestrial Spectrums

- Solar irradiance spectrum from Coddington et al., 2016 (up to 2% spectrally)
- Lunar irradiance spectrum retrieved by ROLO from Kieffer and Stone, 2005 (up to 3%)
- Instrument nighttime signal instability or dark current (up to 0.5%)
- Unaccounted uncertainty, such as underestimation (up to 2%-7% spectrally); for example, degree of linear polarization (DoLP)



Polarization does not depend on spectrums