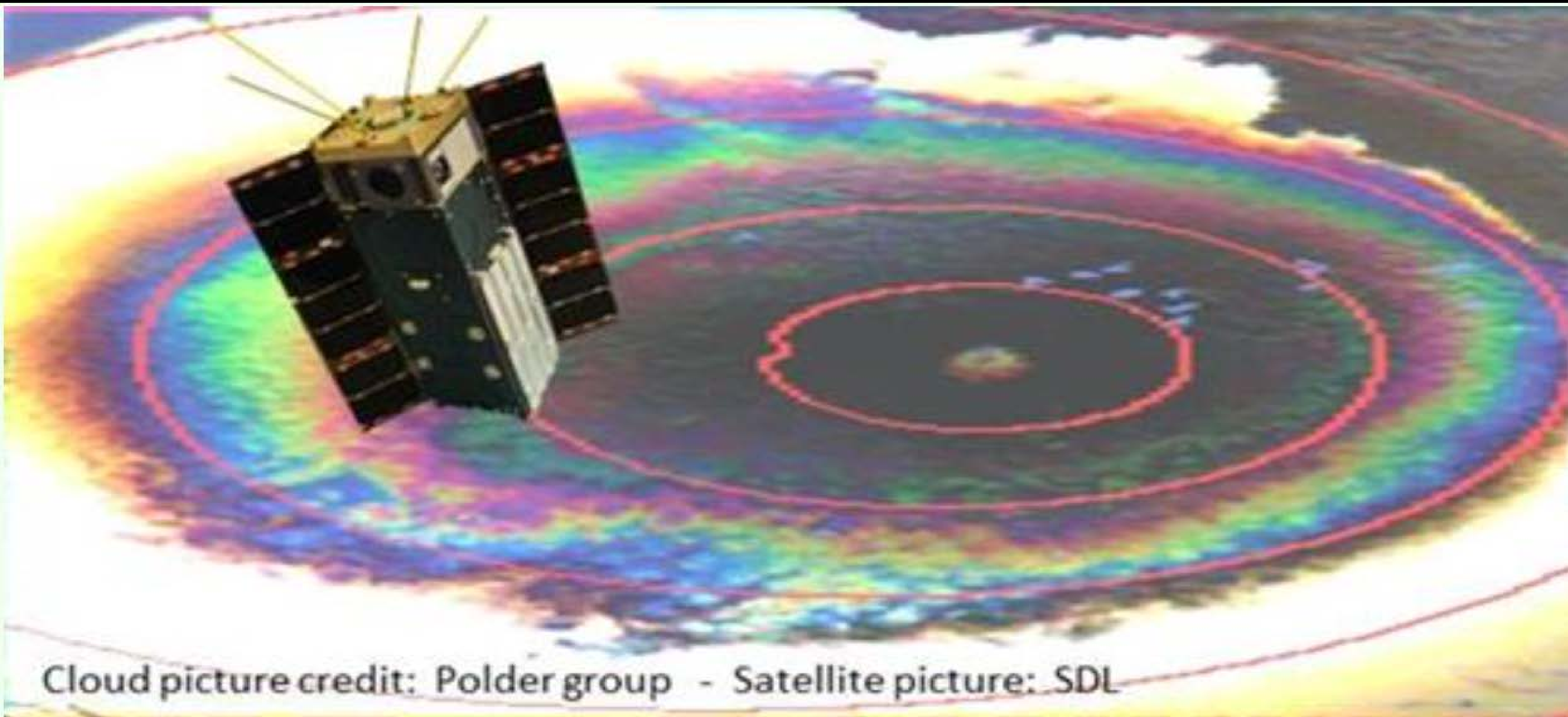
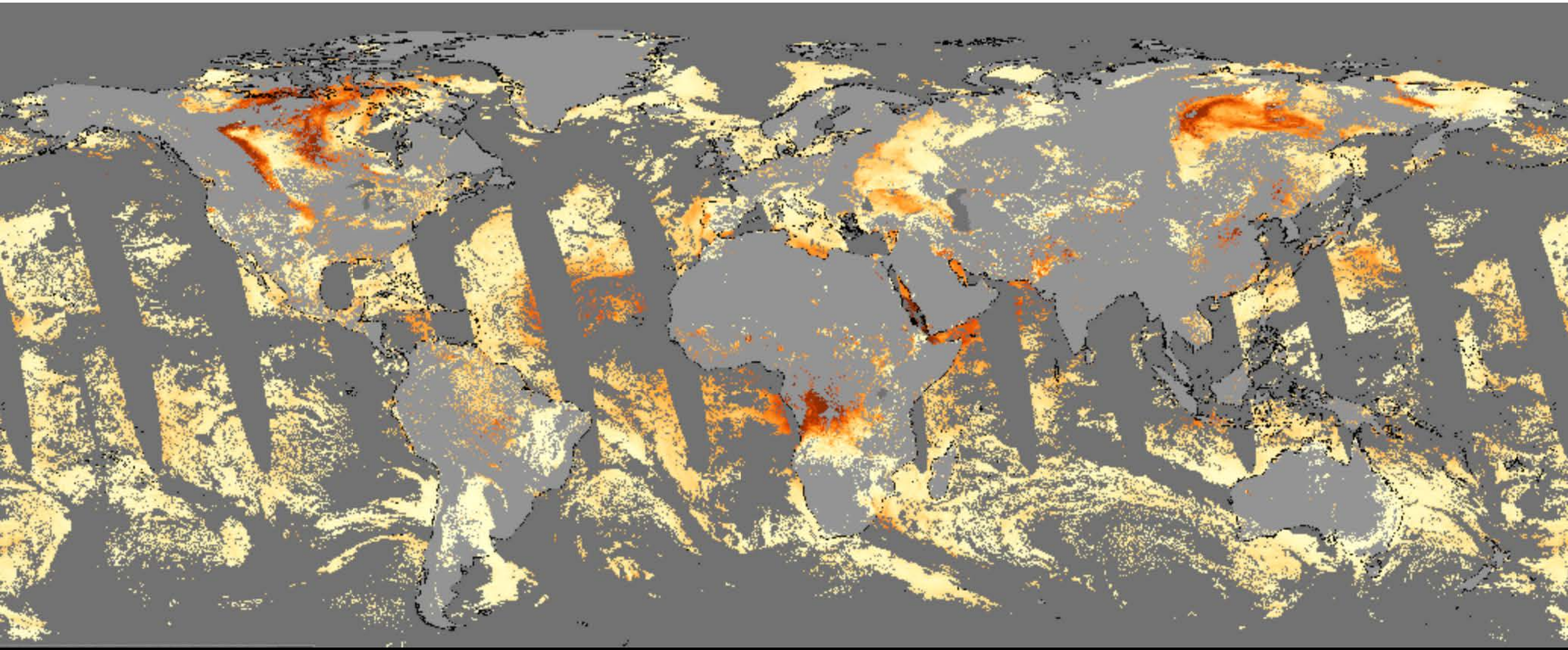
Aerosol Remote Sensing and Atmospheric Correction Beyond VIIRS: What will Expanded Wavelengths, Hyperspectral, Multi-angle, and Polarization Bring to the Table

Lorraine A. Remer
JCET-UMBC



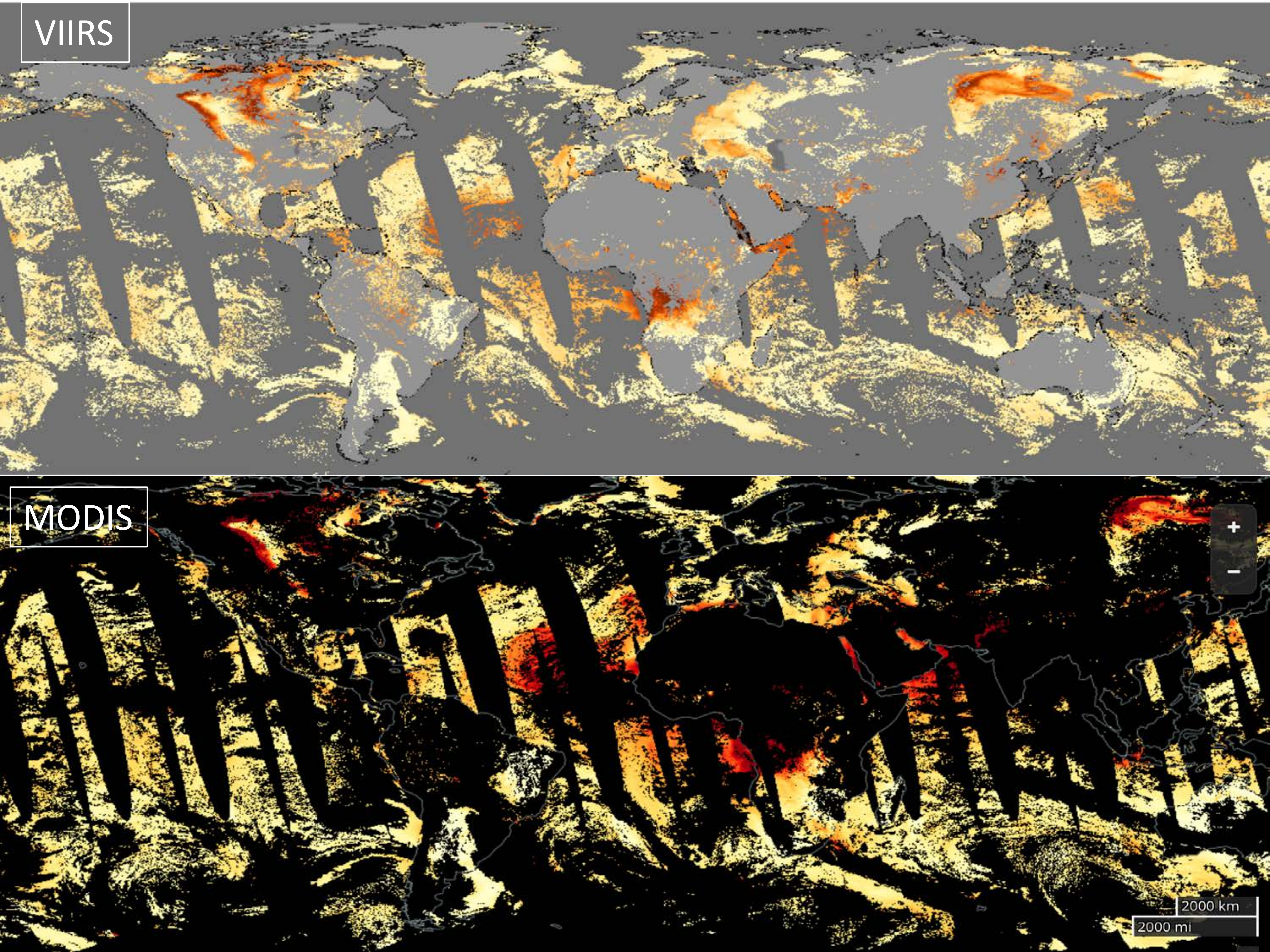
Global Aerosol Optical Depth at 550 nm from VIIRS (IDPS)
13 August 2017



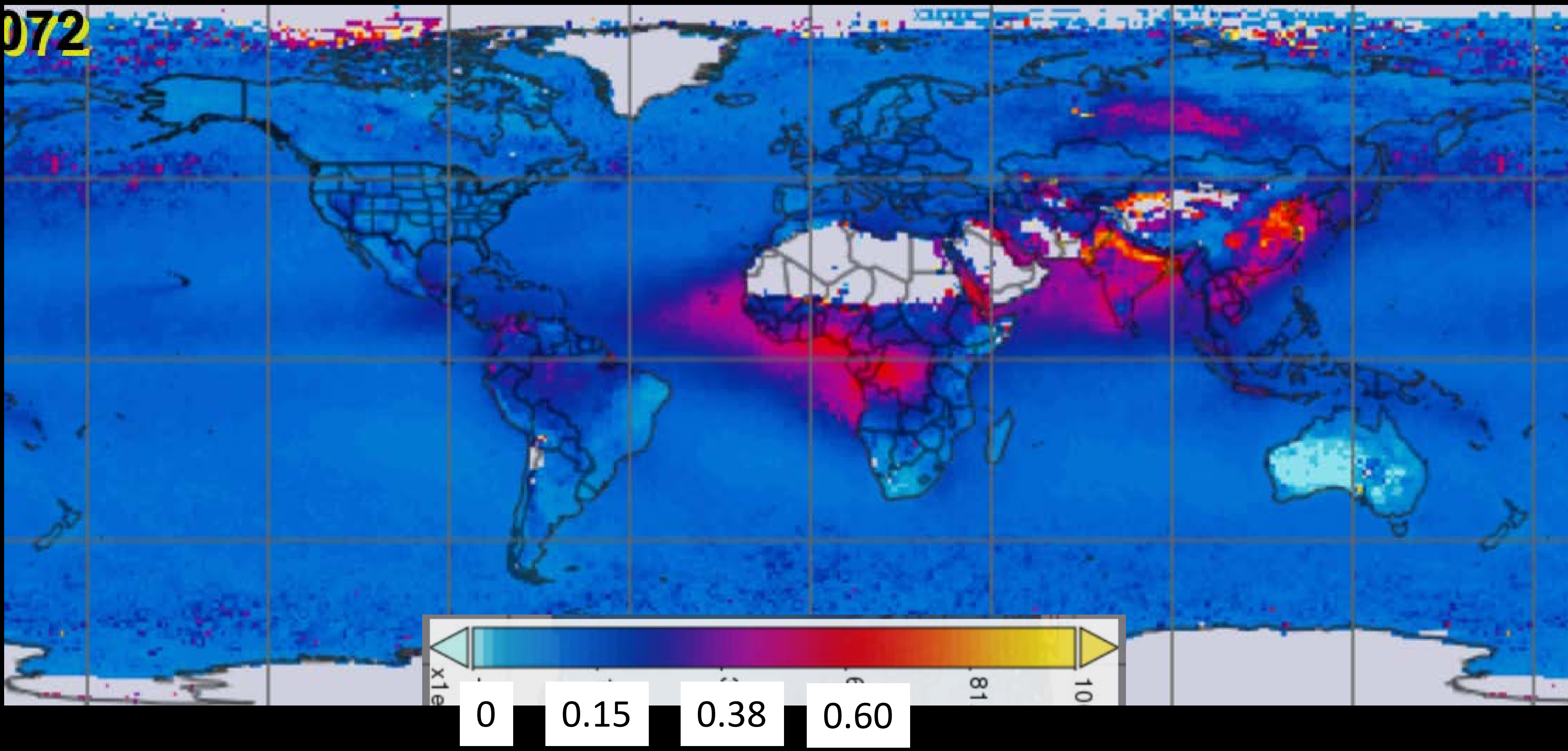
NOAA Global View

Global Aerosol Optical Depth at 550 nm from Aqua MODIS (DT)
13 August 2017

NASA World View


VIIRS
MODIS
2000 km
2000 mi

Global Aerosol Optical Depth at 550 nm from Aqua MODIS (DT)
2016 Annual Mean



NASA Giovanni

$$\underbrace{L(\tau^*, \mu_o, \mu, \varphi)}_{\text{Radiance measured at satellite}} = \underbrace{L_o(\tau^*, \mu_o, \mu, \varphi)}_{\text{Radiance from atmosphere}} + \underbrace{\frac{RE_oT_t(\tau^*, \mu)}{1-RS}}_{\text{Radiance from surface}}$$

μ_o = cos(solar zenith angle)
μ = cos(sensor zenith angle
φ = relative azimuth
τ^* = aerosol optical thickness

R = surface reflectance
E_o = extraterrestrial irradiance
T_t = total transmission
S = spherical albedo

$$\underbrace{L(\tau^*, \mu_o, \mu, \varphi)}_{\text{Radiance measured at satellite}} = \underbrace{L_o(\tau^*, \mu_o, \mu, \varphi)}_{\text{Radiance from atmosphere}} + \underbrace{\frac{RE_oT_t(\tau^*, \mu)}{1 - RS}}_{\text{Radiance from surface}}$$

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μ = cos(sensor zenith angle

φ = relative azimuth

$\boxed{\tau^* = \text{aerosol optical thickness}}$

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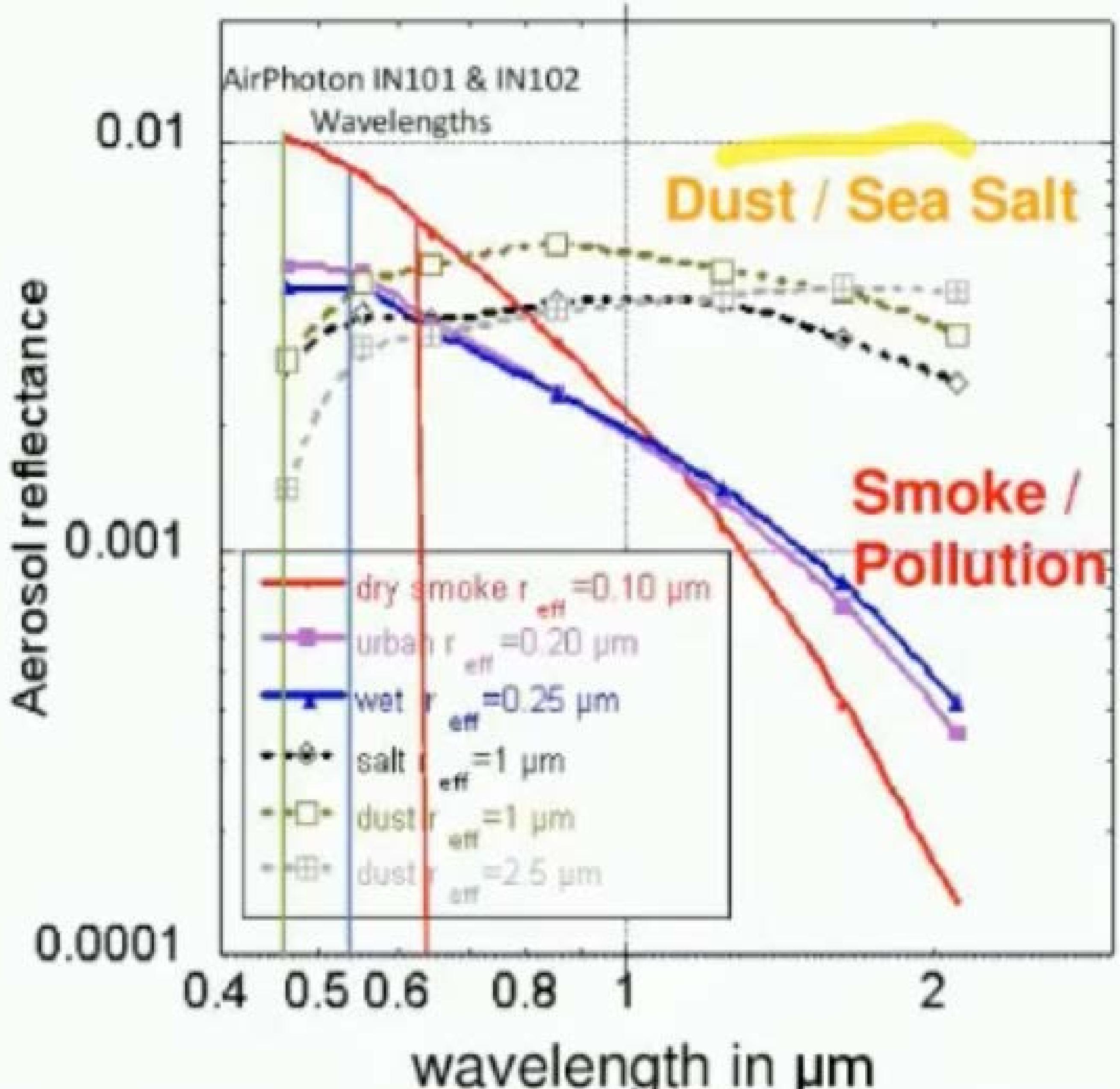
S = spherical albedo

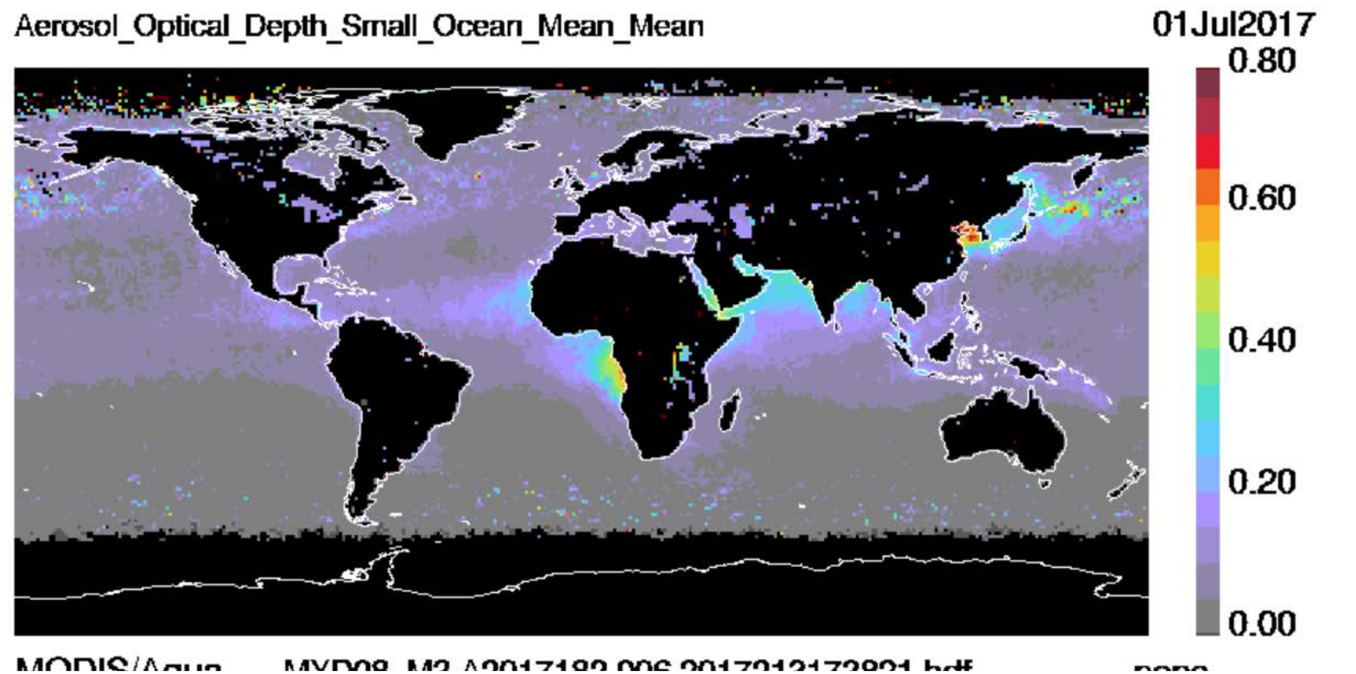
This is a single channel Dark Target retrieval.
(one wavelength at a time)

Requires assumptions of particle size and refractive index, as well as surface reflectance

Returns 1 piece of information: τ^*

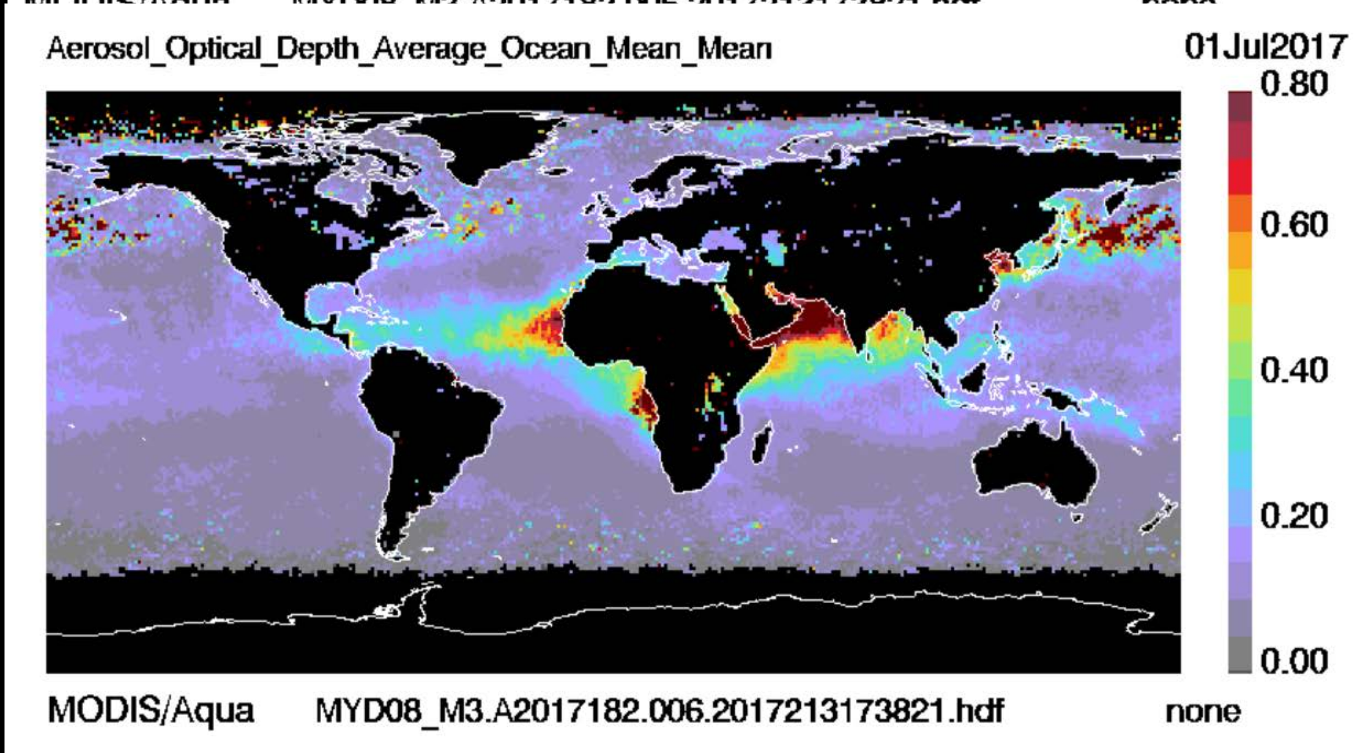


AirPhoton IN101 & IN102
Wavelengths
Dust / Sea Salt
Smoke /
Pollution
Aerosol reflectance
0.01
0.001
0.0001
0.4
0.5
0.6
0.8
1
2
wavelength in µm
dry smoke r eff =0.10 µm
urban r eff =0.20 µm
wet r eff =0.25 µm
salt r eff =1 µm
dust r eff =1 µm
dust r eff =2.5 µm



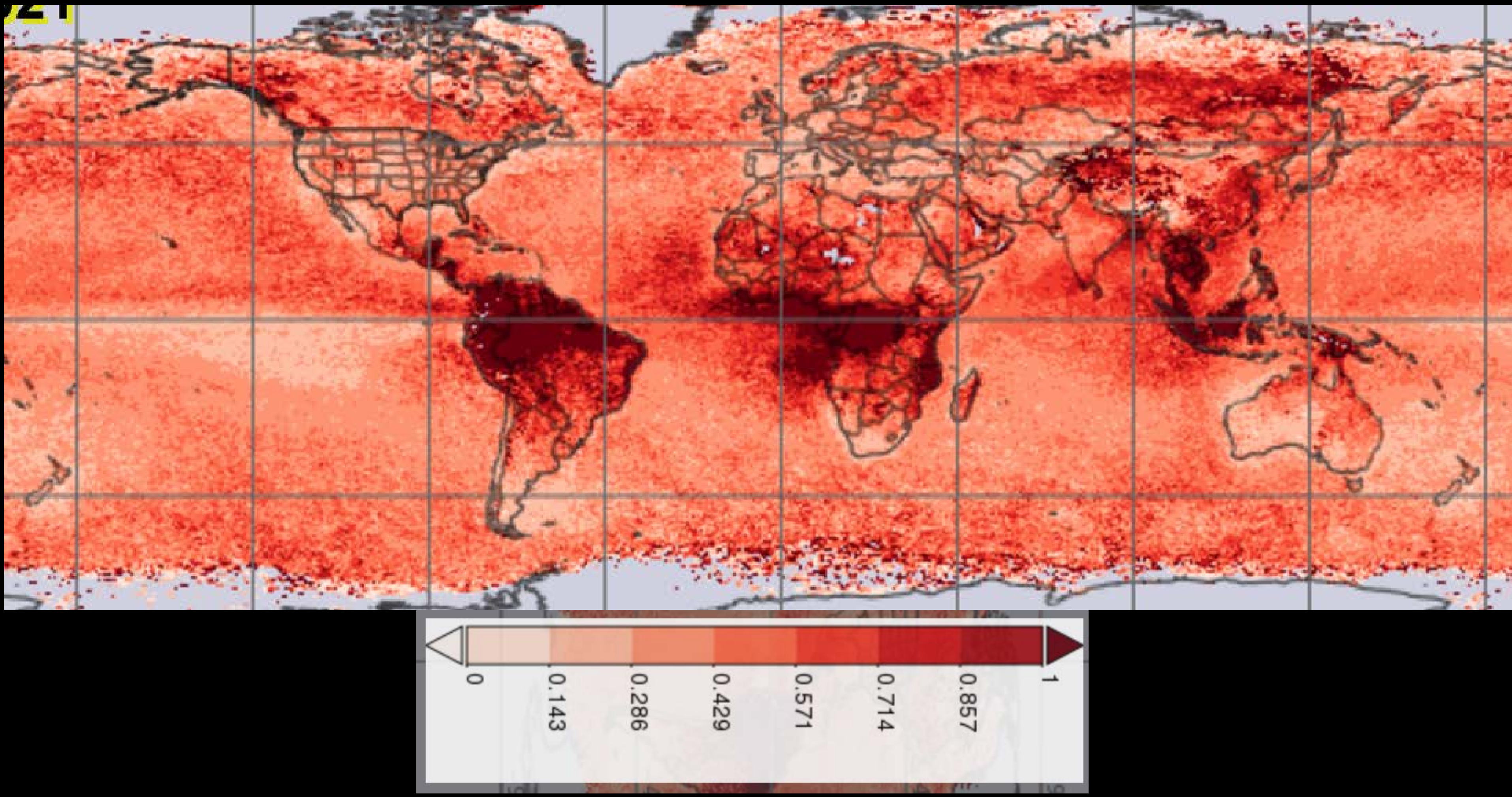
AOD 550 nm
Aqua MODIS
Monthly mean
July 2017

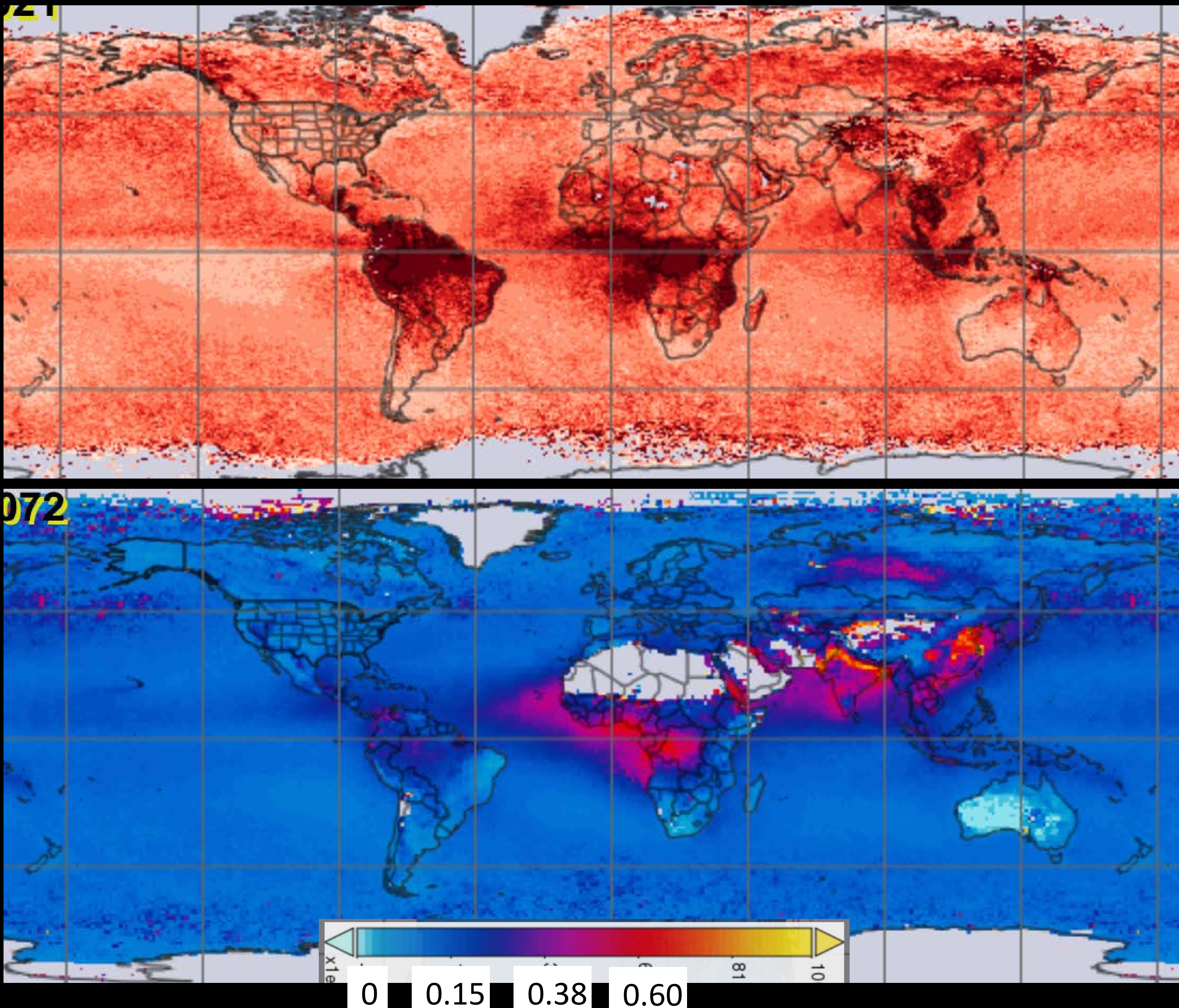
Fine mode only



Total AOD

Global Aerosol Optical Depth at 483 nm from Aura OMI
2016 Annual Mean




072
0
0.15
0.38
0.60

Radiative transfer in the near UV

$$\underbrace{L^{*}(\Omega,\mu,\mu_0,\varphi,p_0)}_{\boxed{\text{Radiance measured at satellite}}} = \underbrace{L^{0}(\Omega,\mu,\mu_0,\varphi,p_0)}_{\boxed{\text{Radiance from atmosphere}}} + \underbrace{\frac{RT_t(\Omega,\mu,\mu_0,p_0)}{1-RS(\Omega,p_0)}}_{\boxed{\text{Radiance from surface}}}$$

Ω = ozone content

p_o = surface pressure

Note: no dependence on aerosol in the equation

Radiative transfer in the near UV

$$L^{*}(\Omega,\mu,\mu_0,\varphi,p_0) = L^{0}(\Omega,\mu,\mu_0,\varphi,p_0) + \frac{RT_t(\Omega,\mu,\mu_0,p_0)}{1-RS(\Omega,p_0)}$$

$$R_{\lambda_0} = \frac{L^{*}_{\lambda_0} - L^{0}_{\lambda_0}}{T_{t\_\lambda_0} + S_{\lambda_0}(L^{*}_{\lambda_0} - L^{0}_{\lambda_0})}$$

Reflectance of the lower surface in one wavelength.

If no aerosol, and ozone absorption is minimal (330-390 nm), then just Rayleigh scattering.

Radiative transfer in the near UV

L^0, T_t and S are obtained from Rayleigh scattering calculations

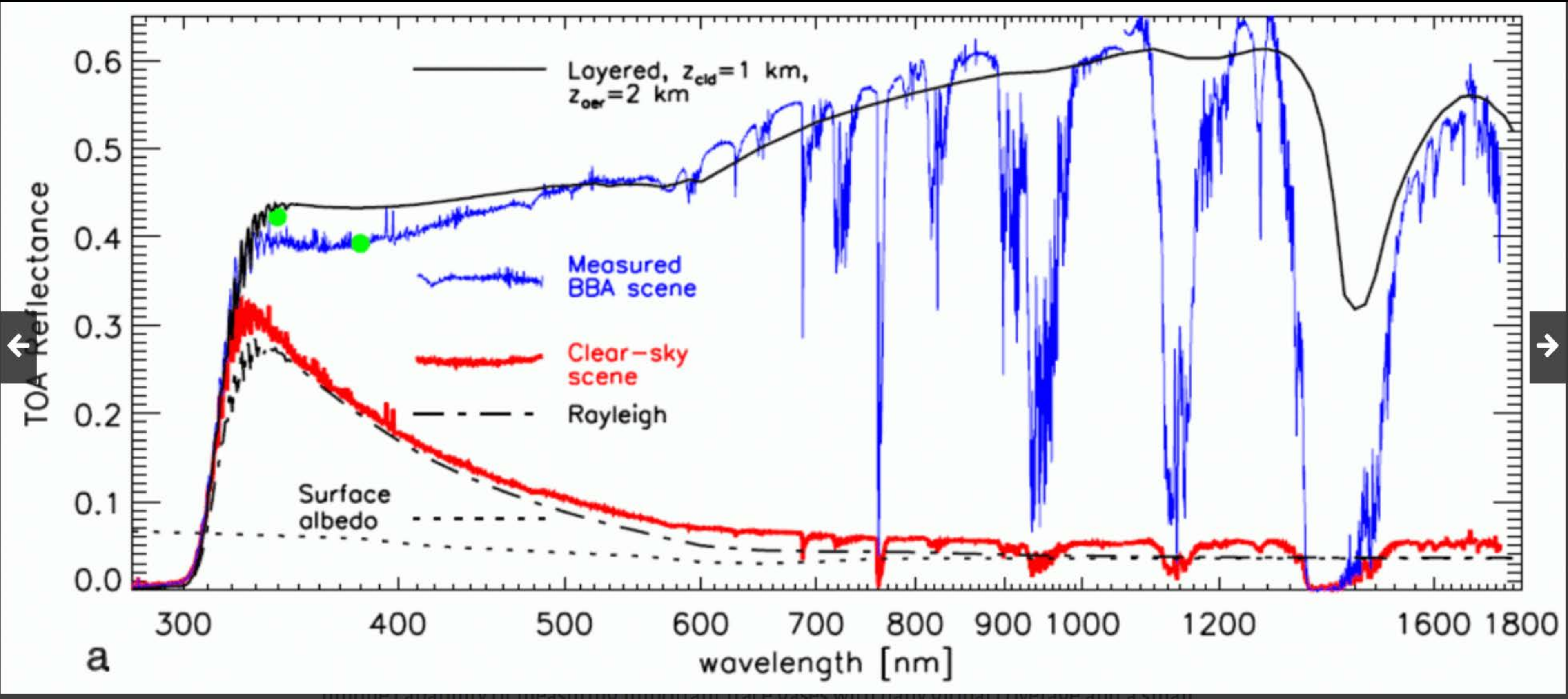
$$R_{\lambda_0} = \frac{L^*_{\lambda_0} - L^0_{\lambda_0}}{T_{t\_\lambda_0} + S_{\lambda_0}(L^*_{\lambda_0} - L^0_{\lambda_0})}$$

Assume lower surface reflectance has NO spectral dependence.

Calculate R at two wavelengths.

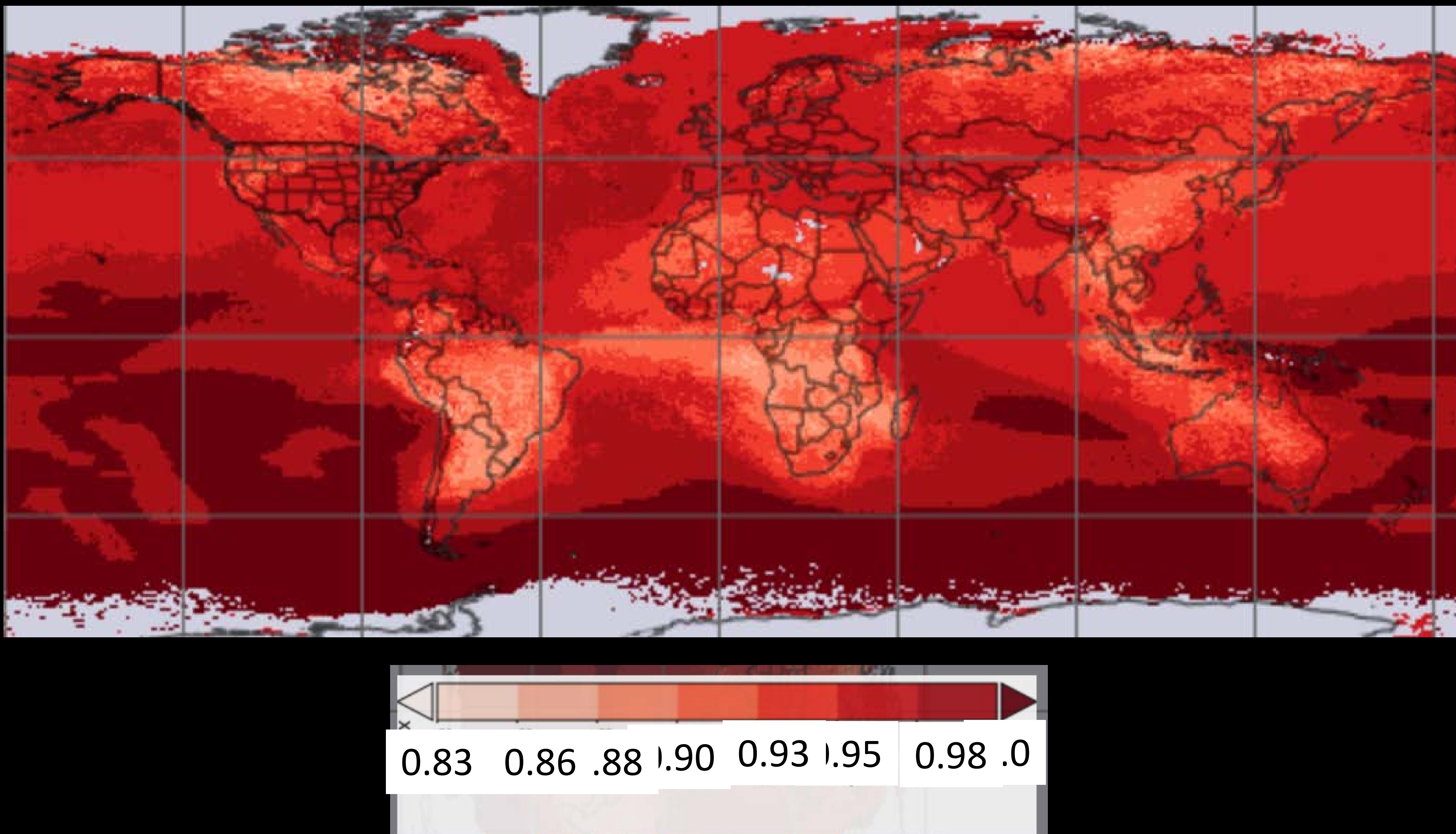
All spectral dependence should match Rayleigh expectations. If not then**, AEROSOL**.

Another SCIAMACHY scene of smoke over broken clouds over ocean



Measurements deviate from Rayleigh-only expectations,
In **magnitude** and in **spectral dependence**.

Global Aerosol Single Scattering albedo at 483 nm from Aura OMI
2016 Annual Mean



One additional problem with the UV approach…

In the UV, deviation from Rayleigh depends on the height of the aerosol.

2 pieces of information/ 3 important parameters:

- Loading (AOD)
- Absorption (SSA)
- Height (h)

The dark target VNIR-SWIR approach…

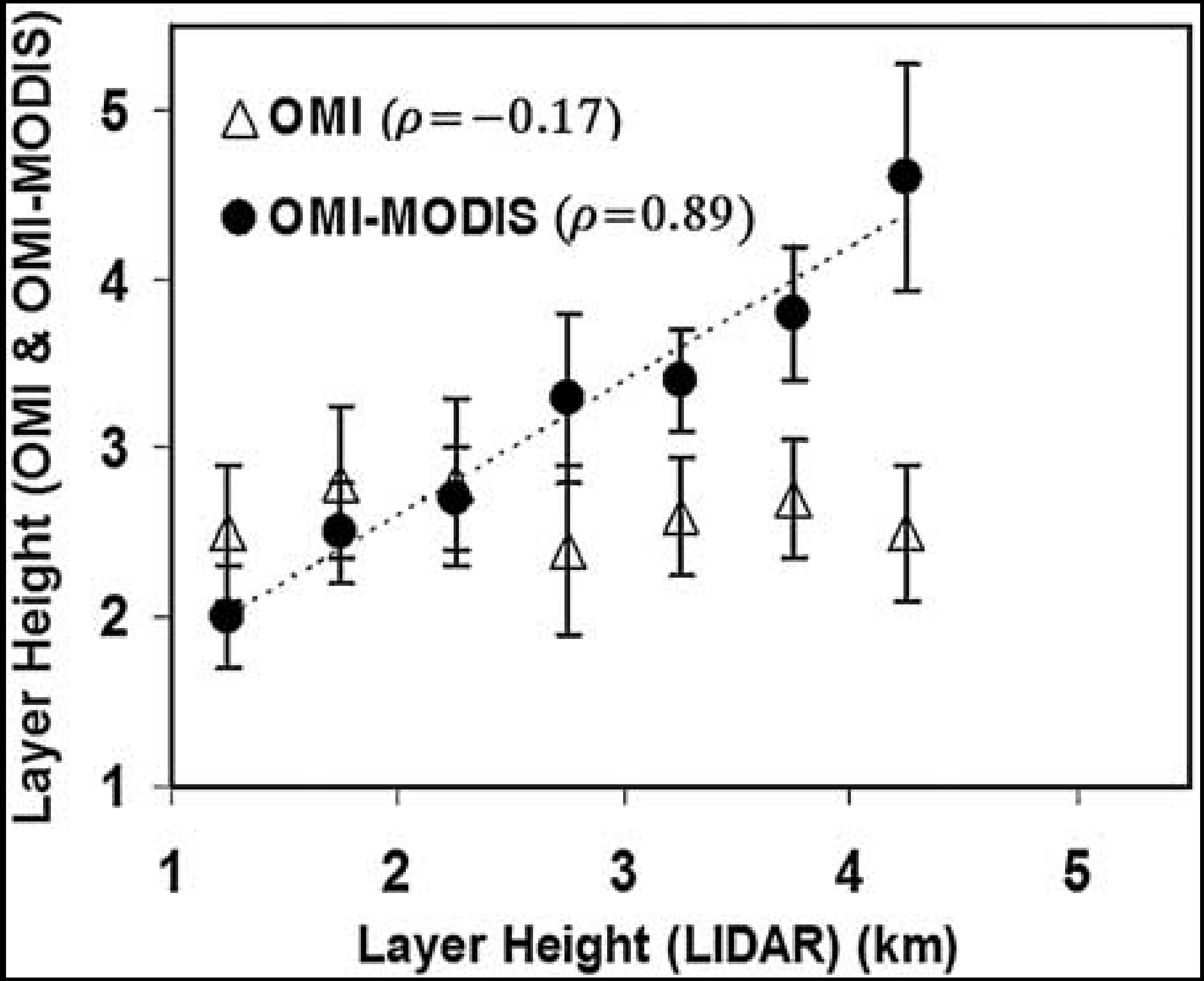
- Quantify the deviation from background radiance
- Spectral dependence gives size.

The UV approach…

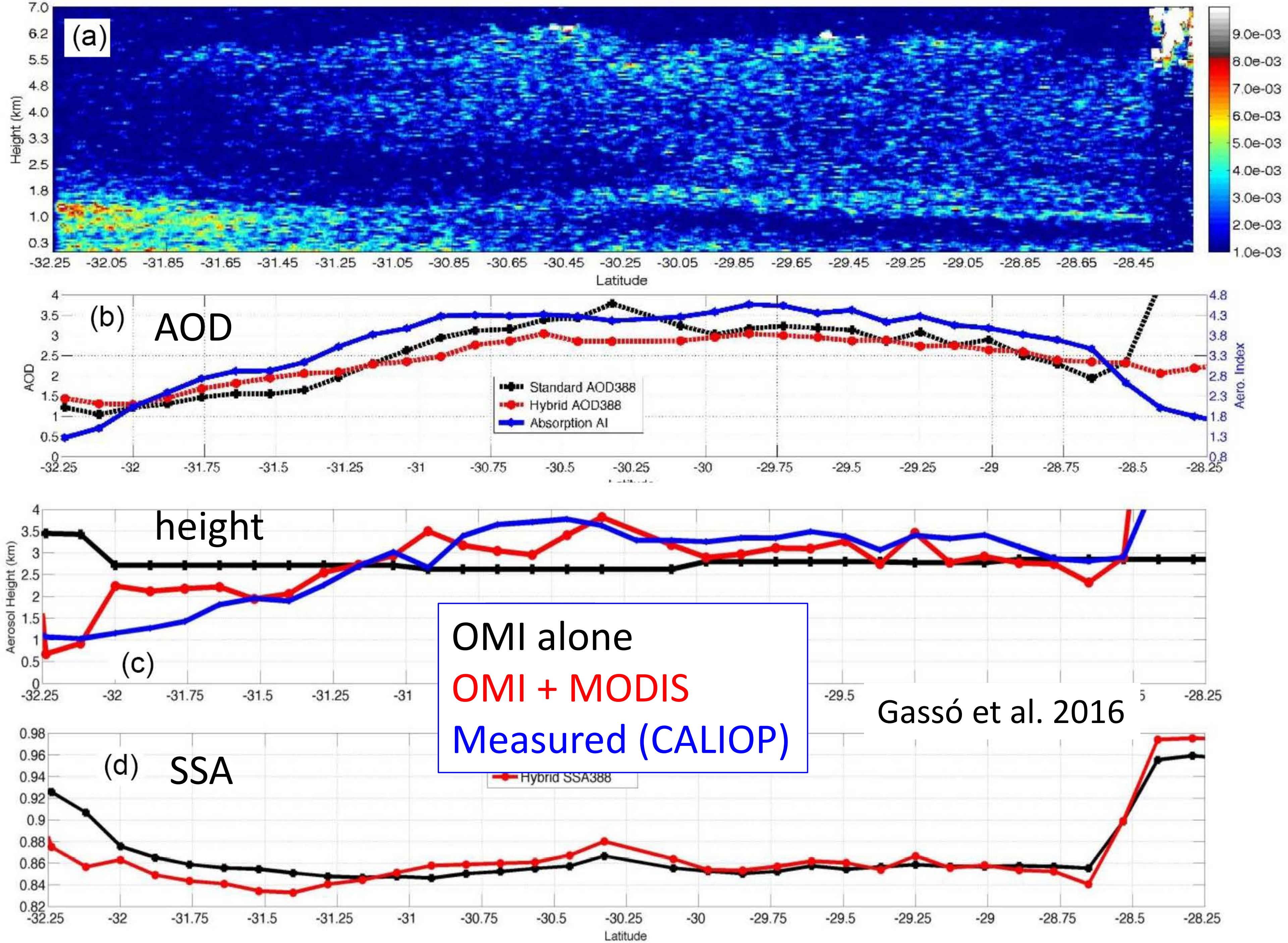
- Quantify the deviation from Rayeigh scattering
- Spectral dependence gives absorption

Combining approaches (MODIS + OMI) we should be able to retrieve **all 3 parameters: AOD, SSA and h**

Retrieval of aerosol height (combined L2 products, not radiances)

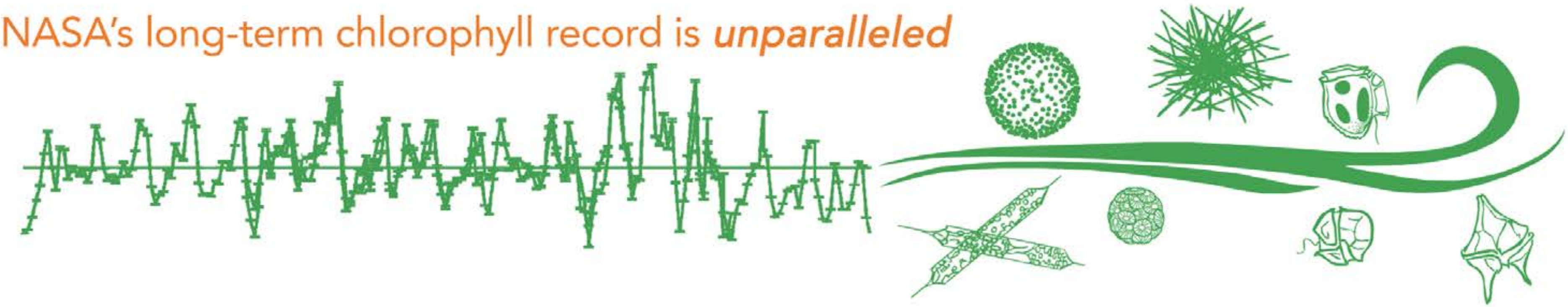


Satheesh, Torres, Remer et al., JGR, 2009


(a)
Height (km)
Latitude
(b)
AOD
Standard AOD388
Hybrid AOD388
Absorption AI
Aero. Index
height
Aerosol Height (km)
(c)
OMI alone
OMI + MODIS
Measured (CALIOP)
Gassó et al. 2016
(d)
SSA
Hybrid SSA388
Latitude

Plankton, Aerosol Cloud ocean Ecosystems
NASA mission for 2022

NASA's long-term chlorophyll record is ***unparalleled***



PACE will show ***all chlorophyll is not created equal***

Primary instrument : Ocean Color Instrument (OCI)

OCI Specifics:

- Single detector, rotating telescope scanner (like SeaWiFS)
- 20-degree tilt to avoid sun glint
- Monthly lunar calibration of all science detectors
- Ground sample distance ~ 1 square kilometer at nadir

- 5 nanometer (nm) resolution from 350 to 890 nm
- Plus short-wave infrared (SWIR) bands centered on 940, 1240, 1380, 1640, 2130 & 2250 nm

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1 km

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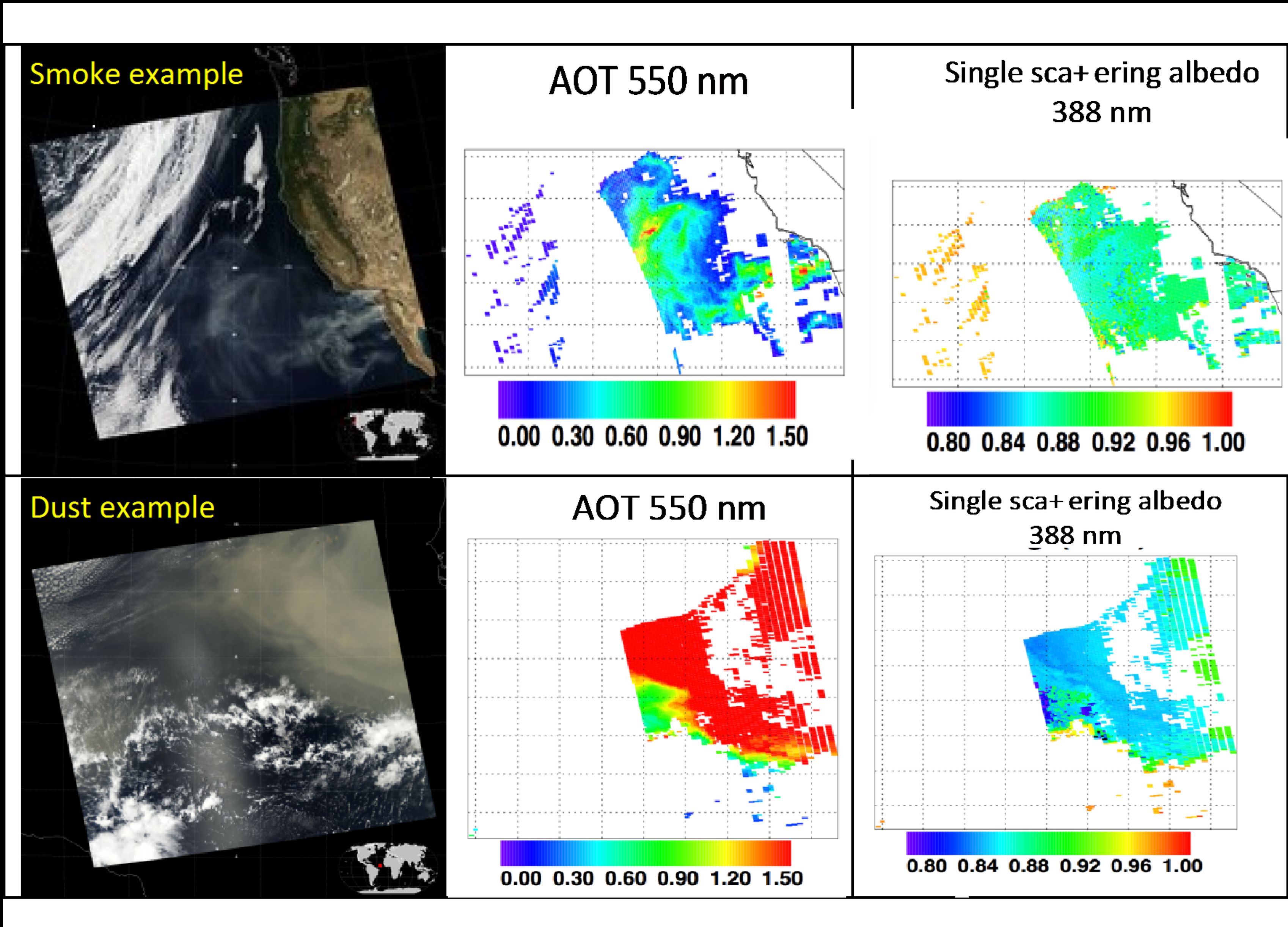

Mattoo and Remer (in progress)

Expected for PACE from OCI

Spectral AOD, SSA and height over oceans (when AOD_550 is sufficiently high ~0.30)

Land not yet explored.

In forward processing, at 3 to 10 km, Across the OCI swath (2-day coverage)

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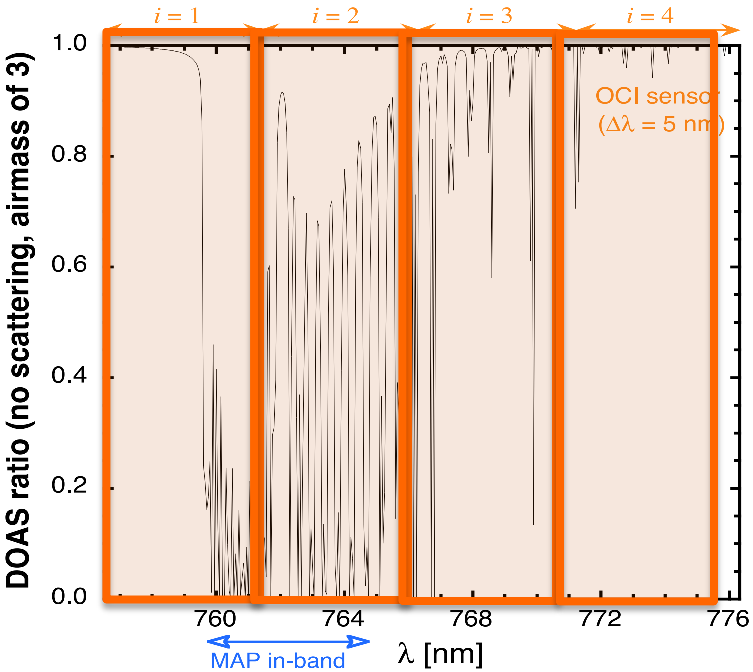


Using Oxygen A-band to retrieve aerosol height

DOAS = differential optical absorption spectroscopy

O_2 : both the amount and cross-section of the gas are accurately known.

DOAS then tells us about the height of the scattering layer (0-2 km vs. 3-5 km)

Davis, Kalashnikova, in progress

Plankton, Aerosol Cloud ocean Ecosystems
NASA mission for 2022

Primary instrument: OCI for ocean color,

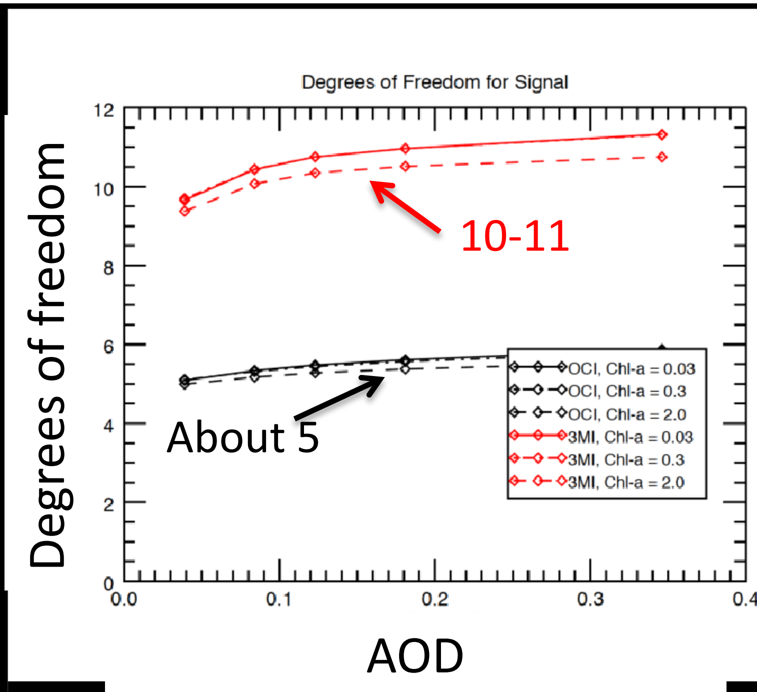
but also **an excellent aerosol instrument**:

- Everything for aerosol that MODIS and VIIRS offers
- Except the thermal channels for cloud mask
- Plus, UV channels at 1 km
- And Oxygen A-band at 5 nm

New opportunities for aerosol absorption and height

Secondary instrument: Multi-angle imaging polarimeter

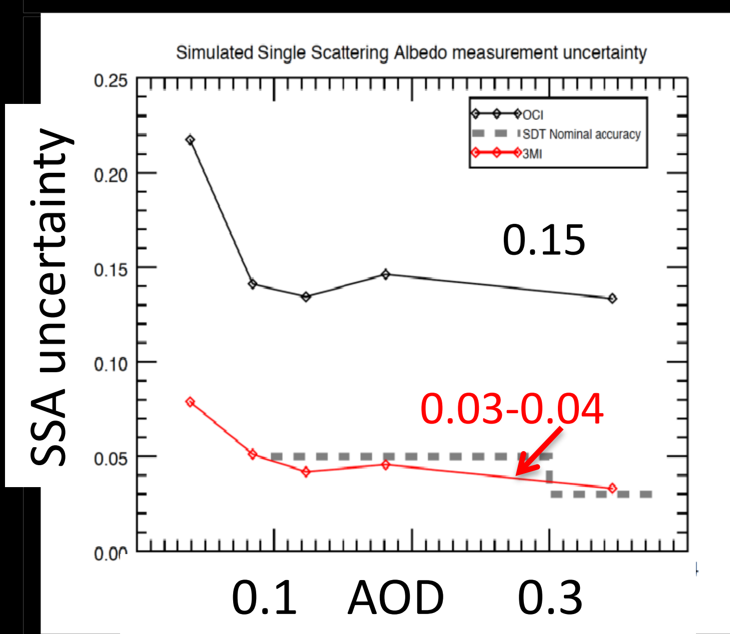
From K. Knobelspiesse

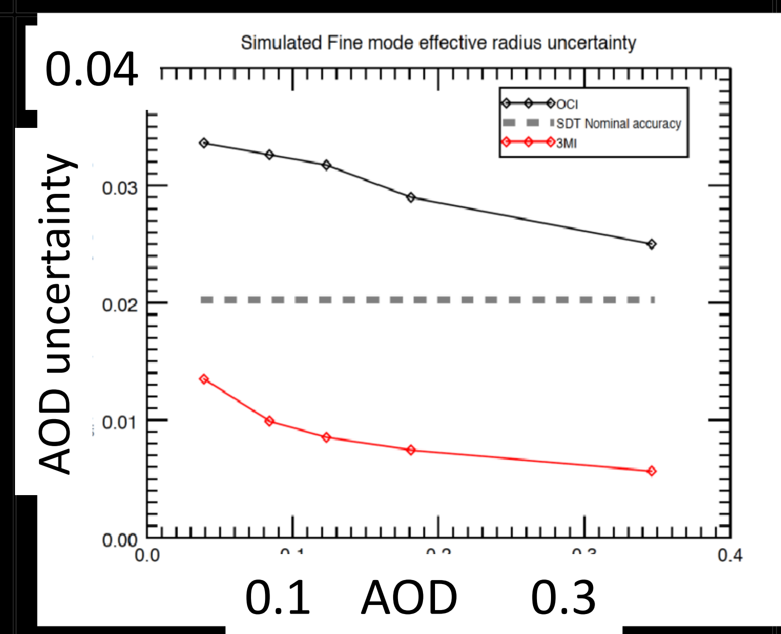


Theoretical calculations

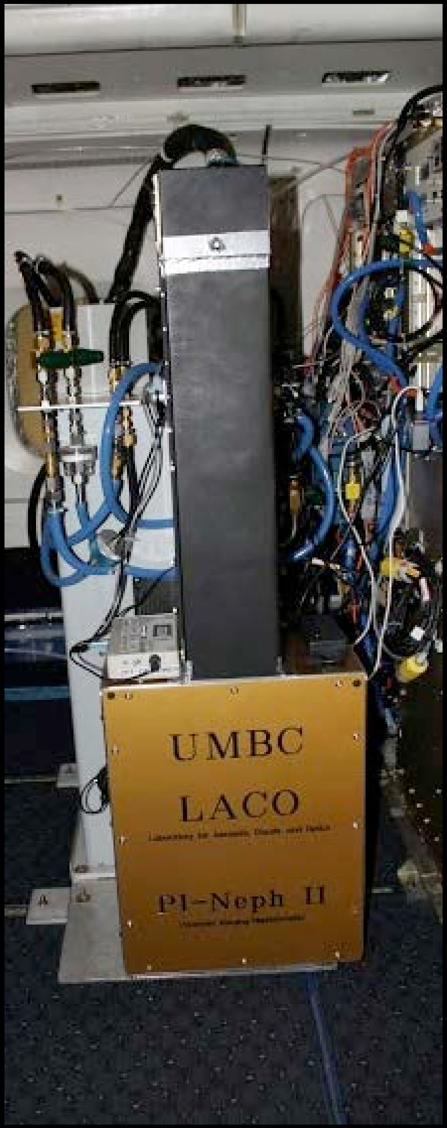
OCI (single angle radiometer) in black

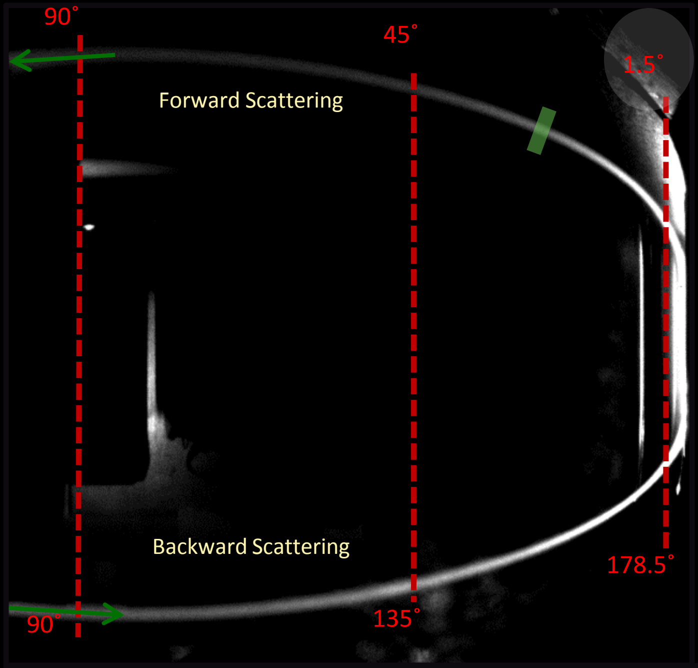
3MI (multiangle polarimeter) in red

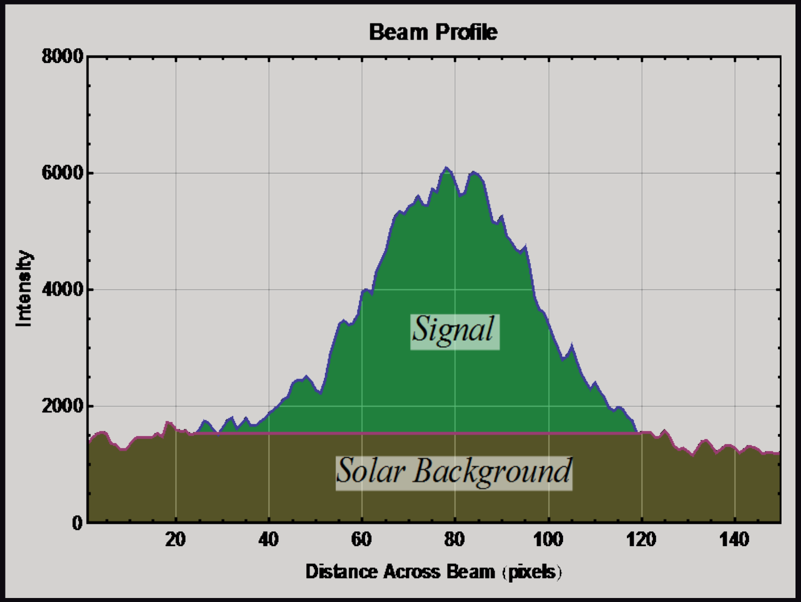




UMBC PI-Neph

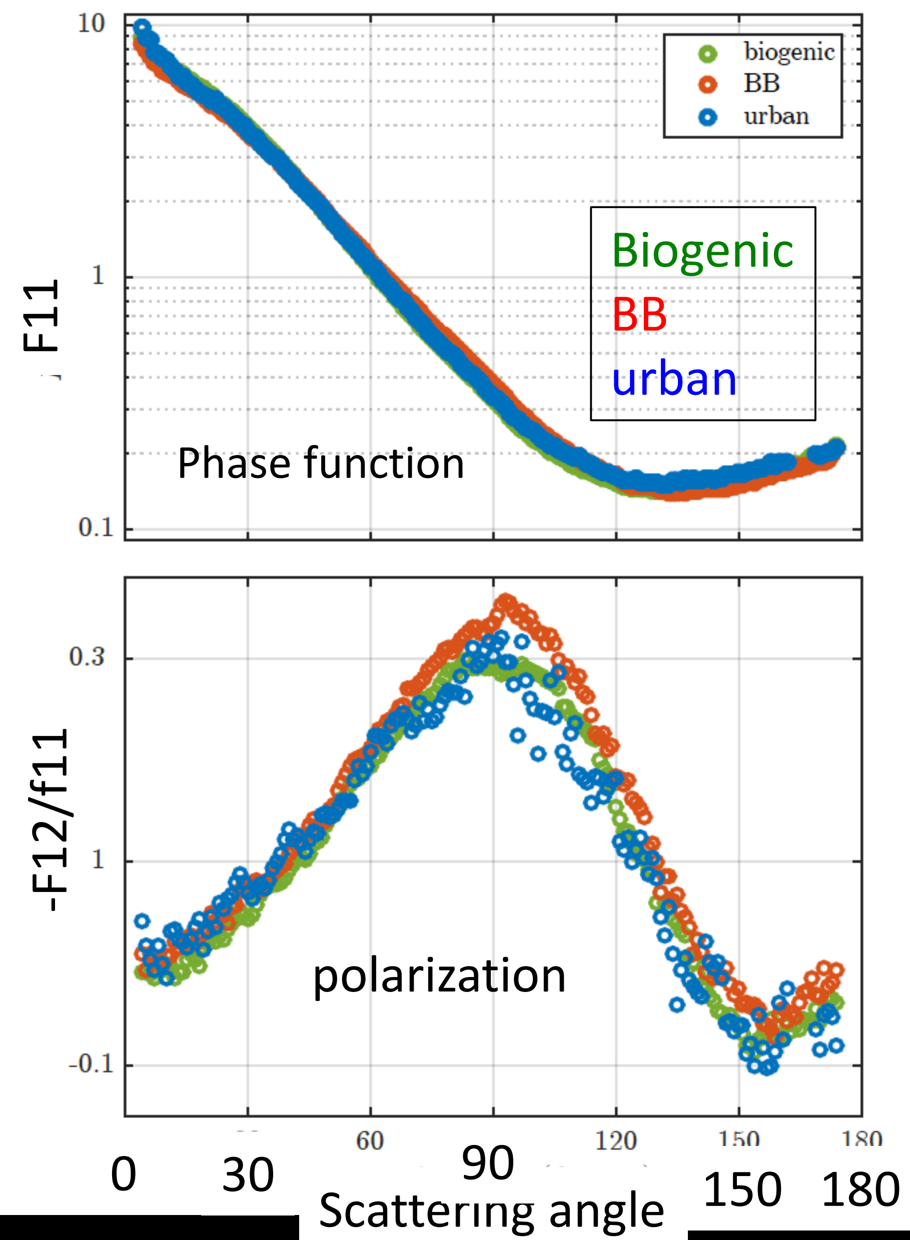




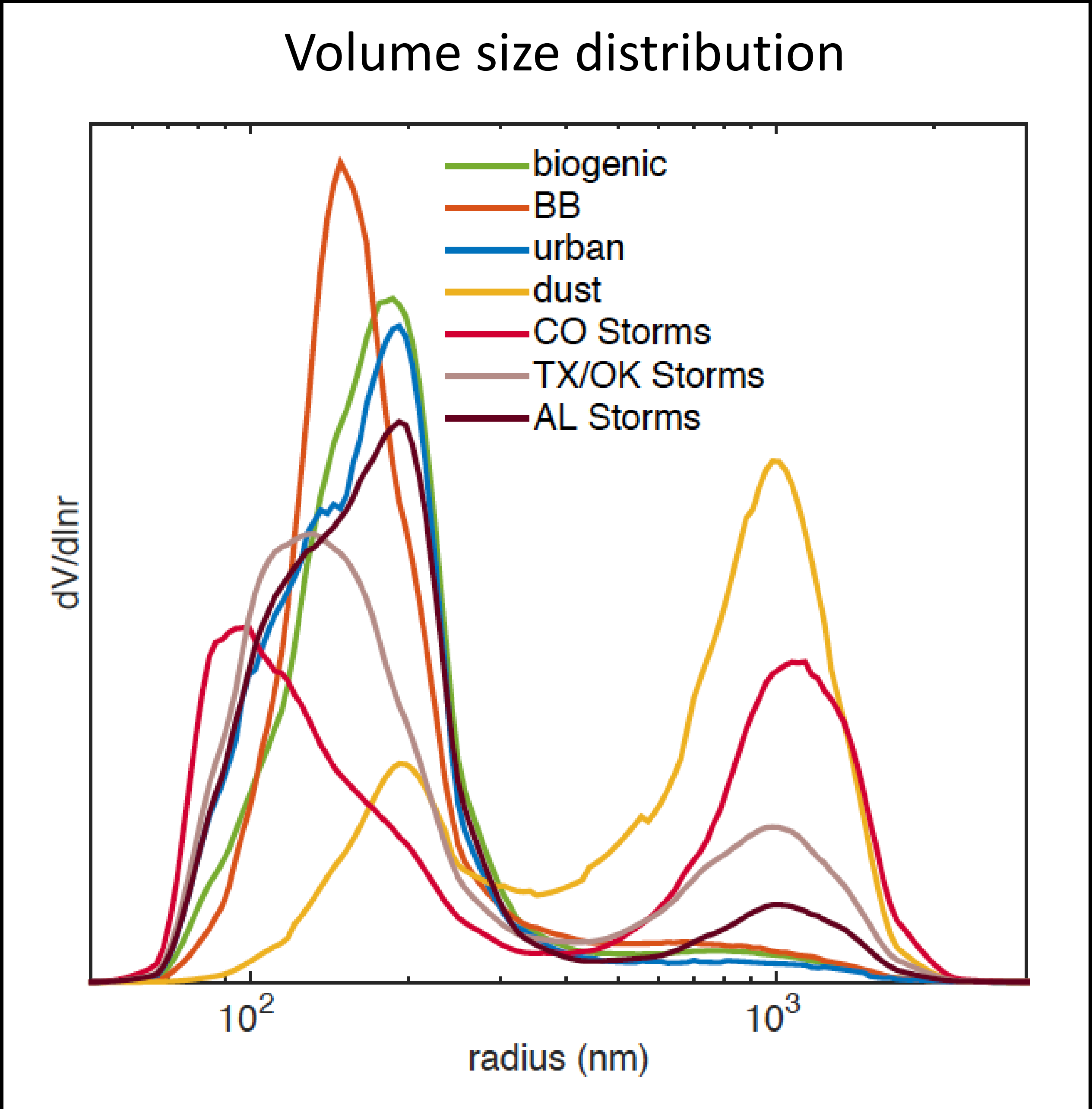


Espinosa, Dolgos and the UMBC team

UMBC PI-Neph measurements of 3 different fine mode aerosols from SEAC4RS



Espinosa et al., 2017

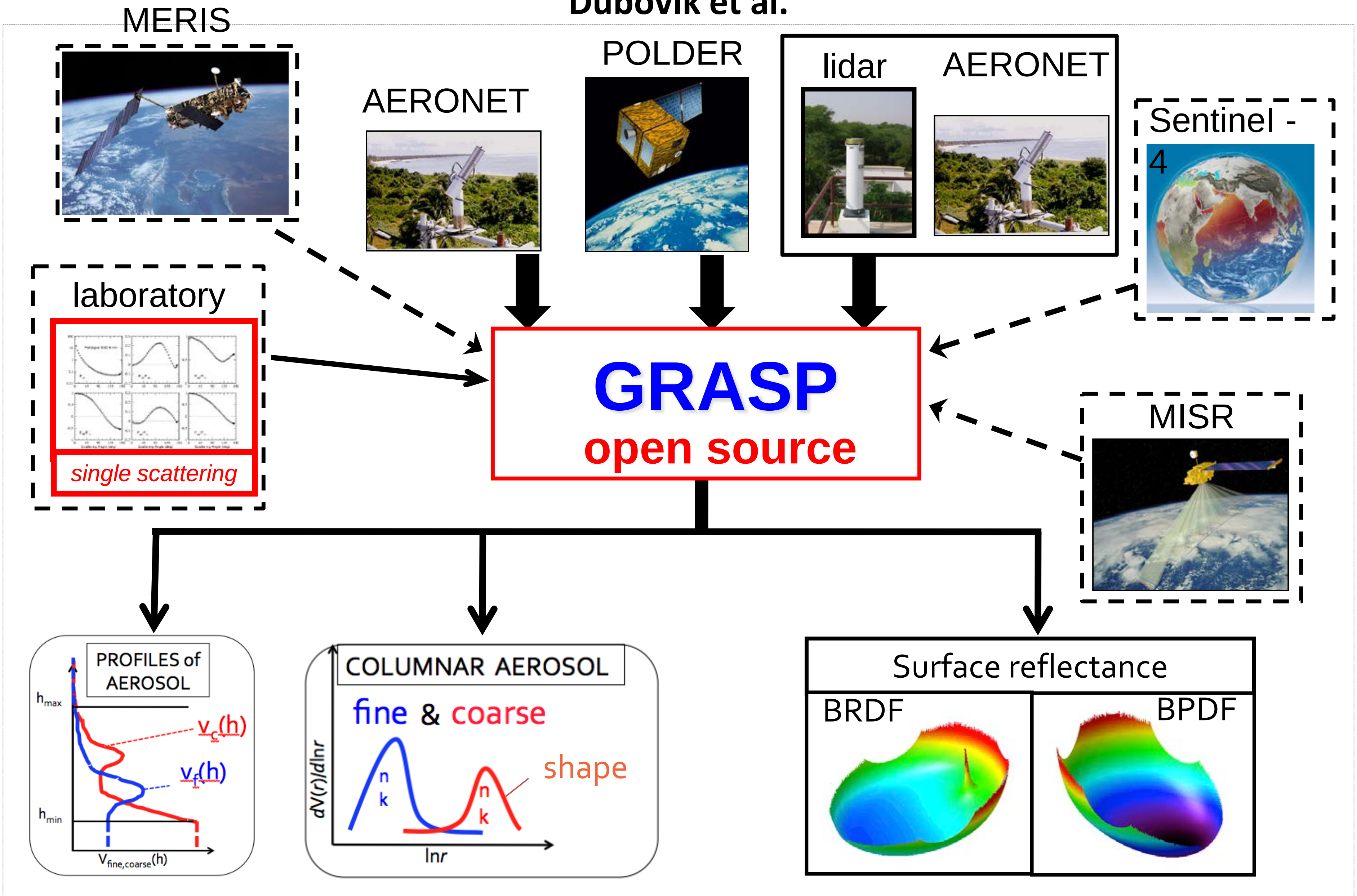


GRASP retrieval applied to PI-Neph measurements

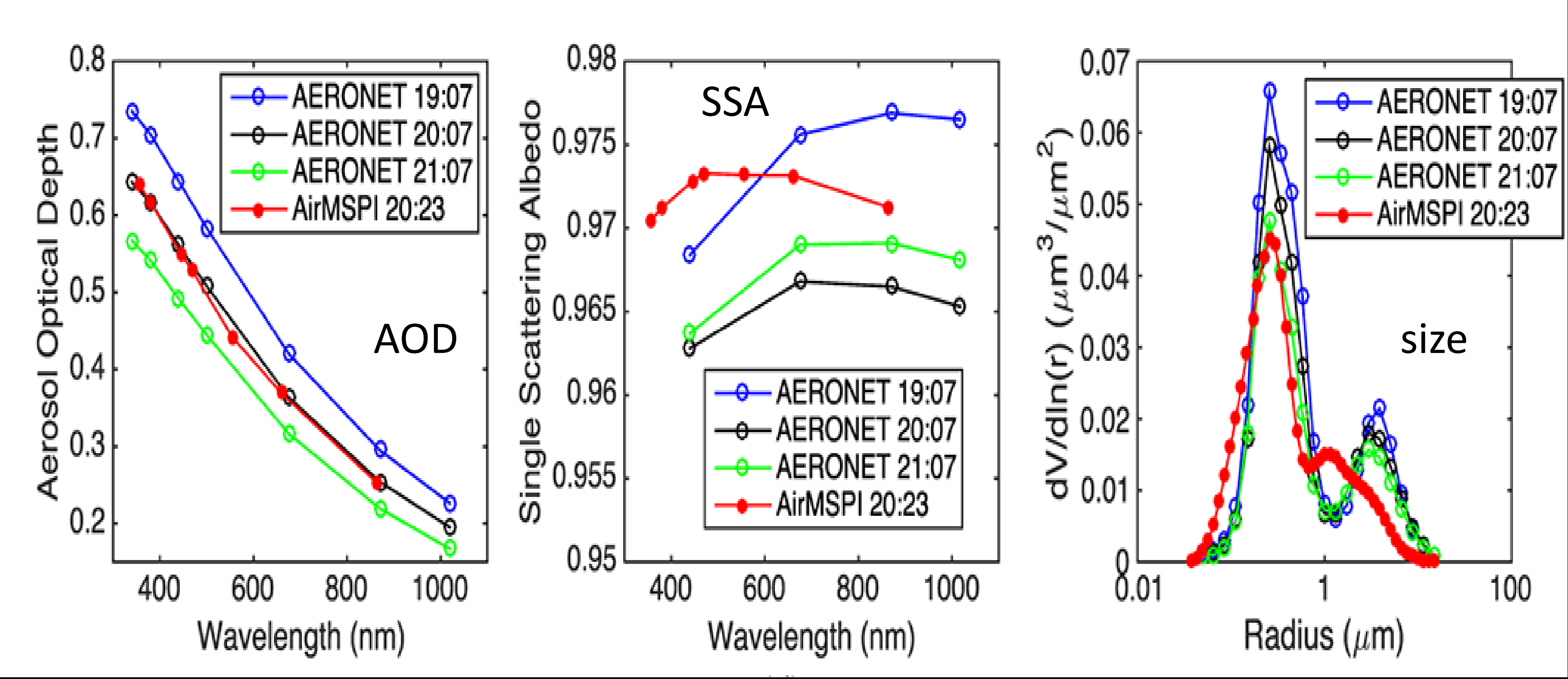
Espinosa et al. (to be submitted)

GRASP: Generalized Retrieval of Aerosol and Surface Properties

Dubovik et al.



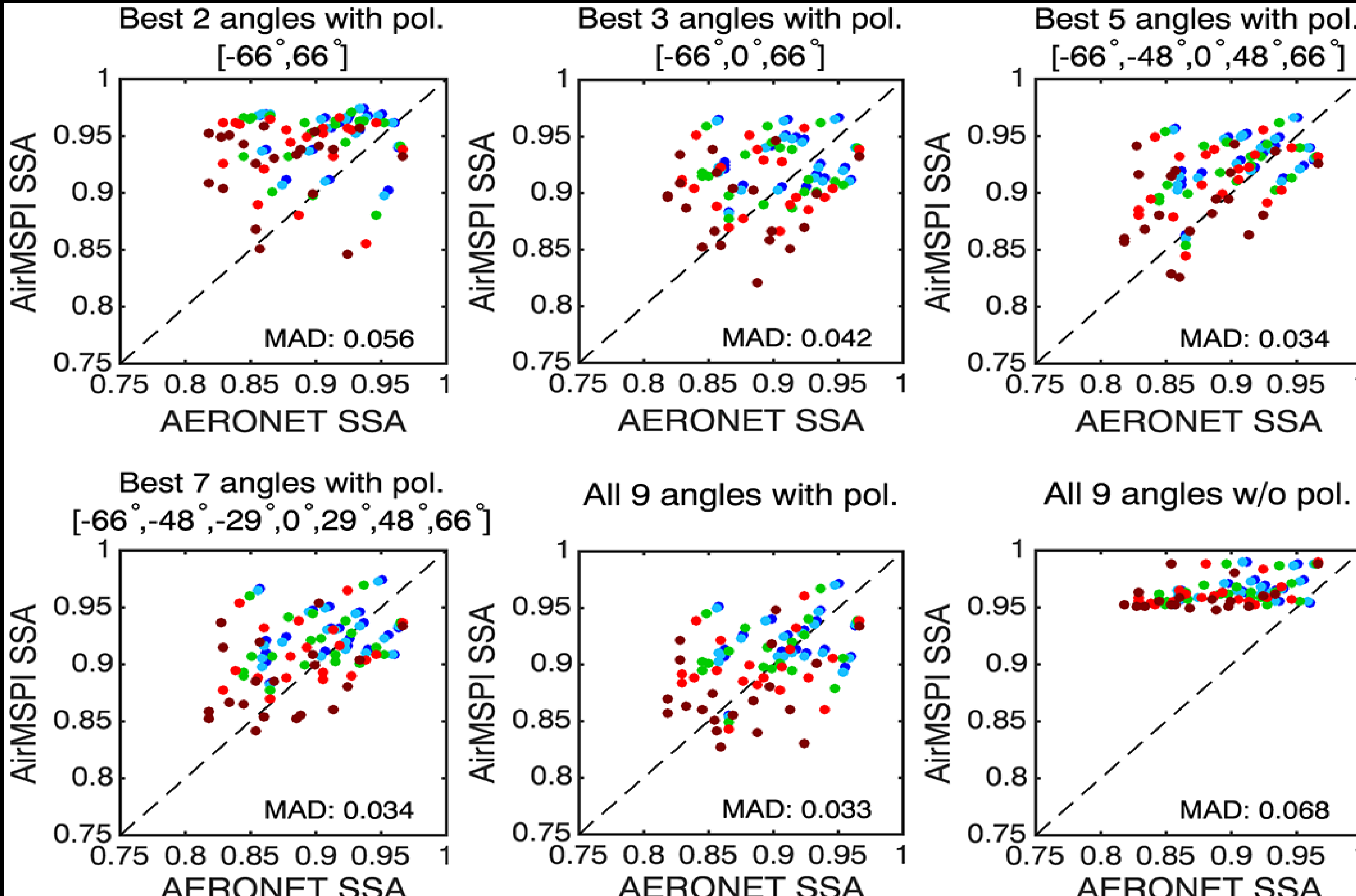
Aerosol retrievals from airborne multi-angle polarimeter (AirMSPI)



AirMSPI on NASA ER-2 over Fresno CA (in red)

Near-time AERONET retrievals at Fresno station (other colors)

Xu et al. (2017)


Best 2 angles with pol.
[-66°,66°]
MAD: 0.056
Best 3 angles with pol.
[-66°,0°,66°]
MAD: 0.042
Best 5 angles with pol.
[-66°,-48°,0°,48°,66°]
MAD: 0.034
Best 7 angles with pol.
[-66°,-48°,-29°,0°,29°,48°,66°]
MAD: 0.034
All 9 angles with pol.
MAD: 0.033
All 9 angles w/o pol.
MAD: 0.068
AirMSPI SSA
AERONET SSA
0.75
0.8
0.85
0.9
0.95
1

Xu et al. 2017

Where are we heading?

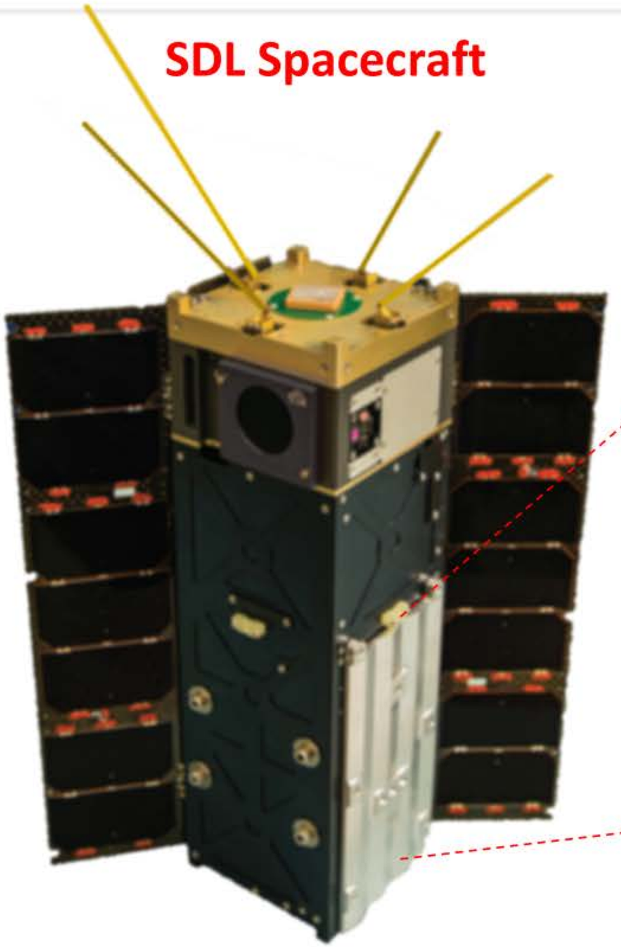
Towards broader aerosol-relevant spectra;
Finer spectral resolution;
Finer spatial resolution for UV;
Multi-angle polarimeters;
Retrievals of more aerosol properties;
With better accuracy;
Expanding retrievals to over clouds and difficult surfaces;
Simultaneous retrievals of aerosol + surface;
Advanced retrieval algorithms that can handle all this information

How will we get there?

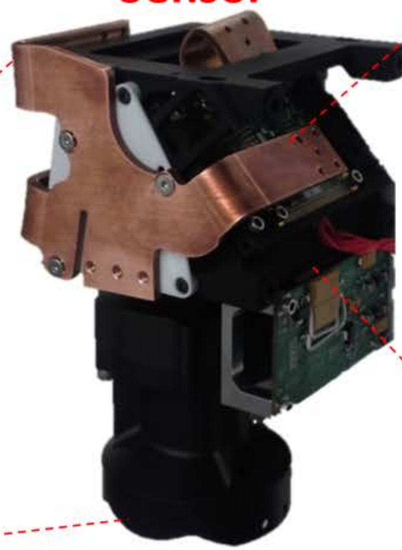
- PACE OCI: 2022, but in political limbo
- PACE polarimeter: even less assured
- MetOP 3MI: 2018 and continuing
- MAIA: an instrument without a launch date
- HARP Cubesat: early 2018

Photos of Actual Instrument & Spacecraft

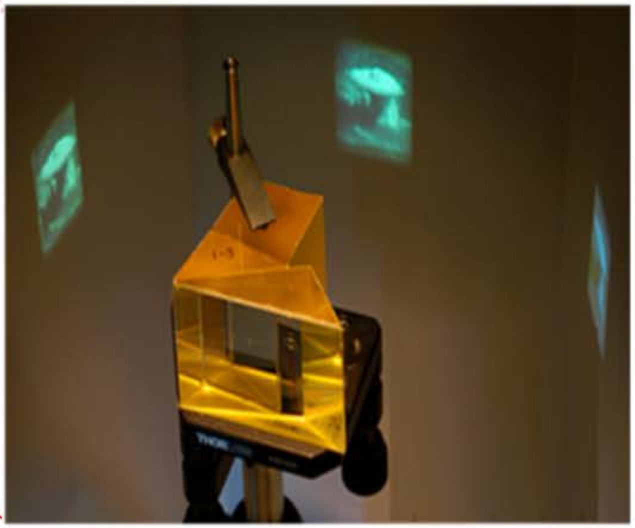
SDL Spacecraft



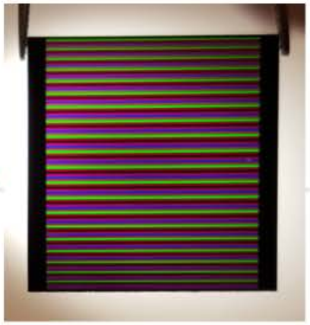
UMBC
Sensor



HARP Prism



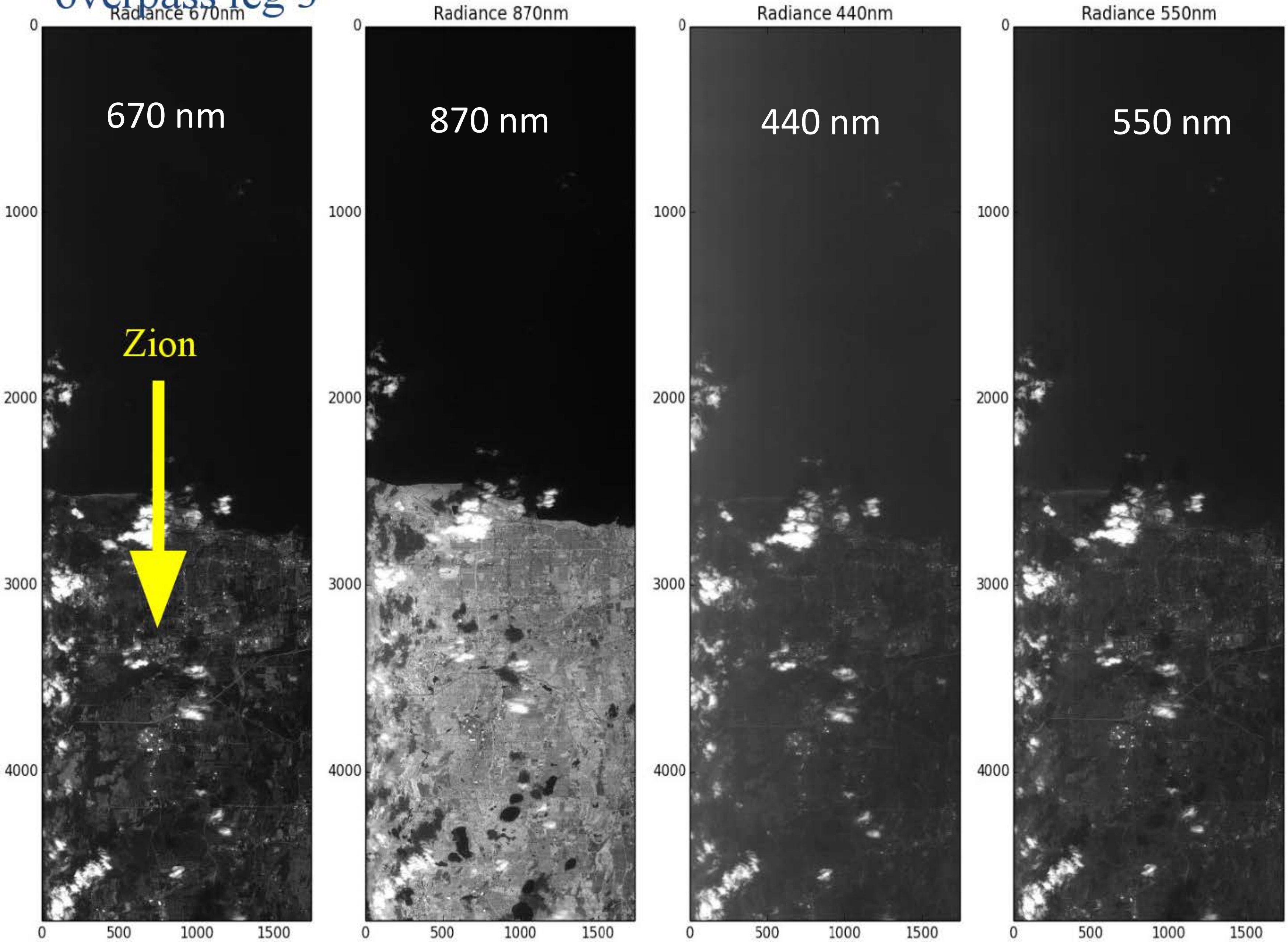
HARP
Stripe
Filter



UMBC
Martins et al.

HARP

Preliminary Results from LMOS, 12 June 2017 – AirHARP Zion overpass leg 3



Example of Multiangle observation