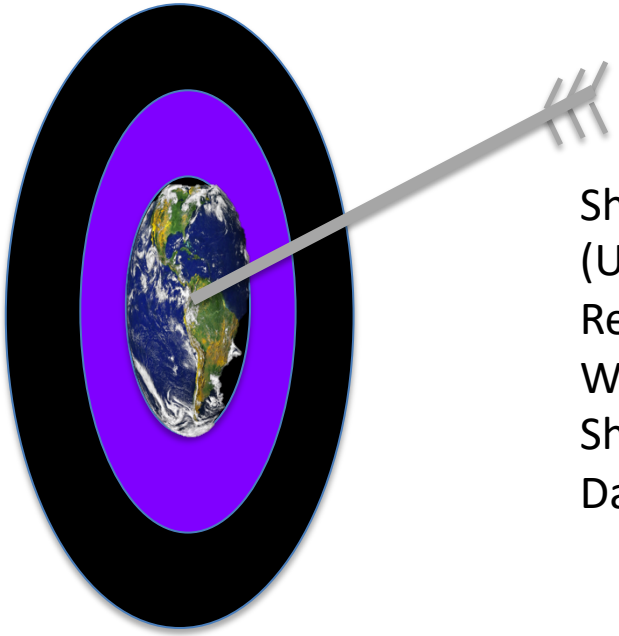
Developing an integrated climatology of global aerosol properties from a constellation of LEO and GEO satellite observations.

Robert C. Levy (NASA-GSFC/613)



Shana Mattoo (SSAI/GSFC), Pawan Gupta (USRA/Marshall), Yingxi Shi (USRA/GSFC), Lorraine Remer (UMBC), Zhaohui Zhang (Adnet/GSFC), Jennifer Wei (GSFC/610.2), Robert Holz (SSEC/UWisconsin), Shobha Kondragunta (NOAA/NESDIS/STAR), Arlindo DaSilva (NASA/GSFC/610.1)

One reason why we care

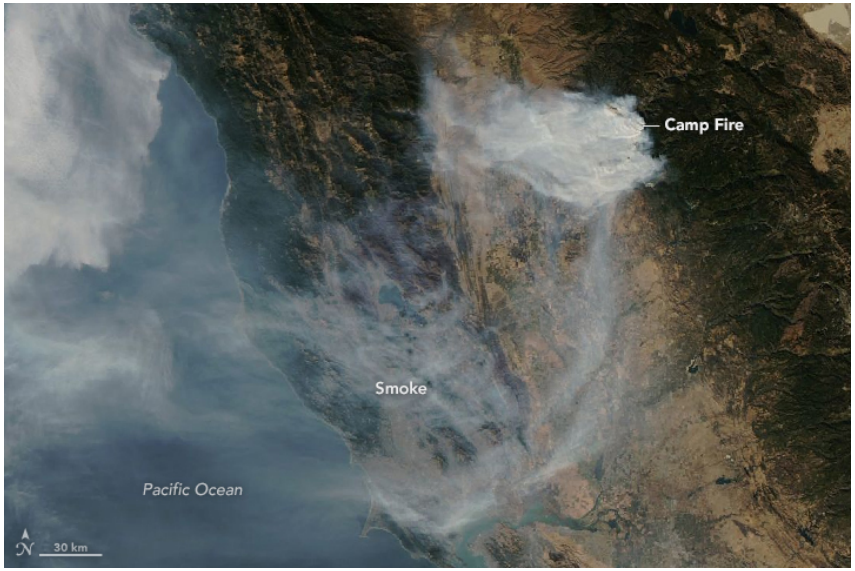
https://earthobservatory.nasa.gov/blogs/earthmatters/2018/11/14/satellites-and-ground-sensors-observe-smoke-blanketing-california

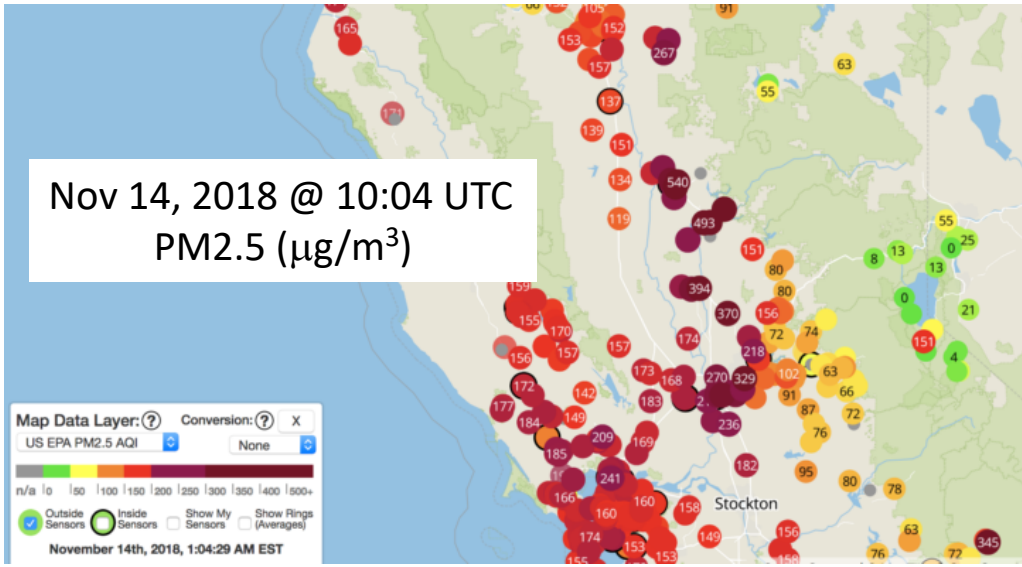
NASA earth observatory

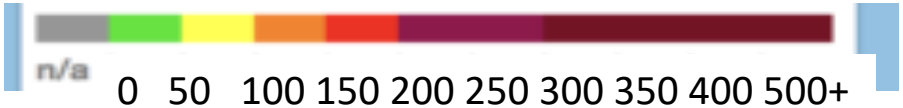
Earth Matters

Satellites and Ground Sensors Observe Smoke Blanketing California

November 14th, 2018 by Adam Voiland



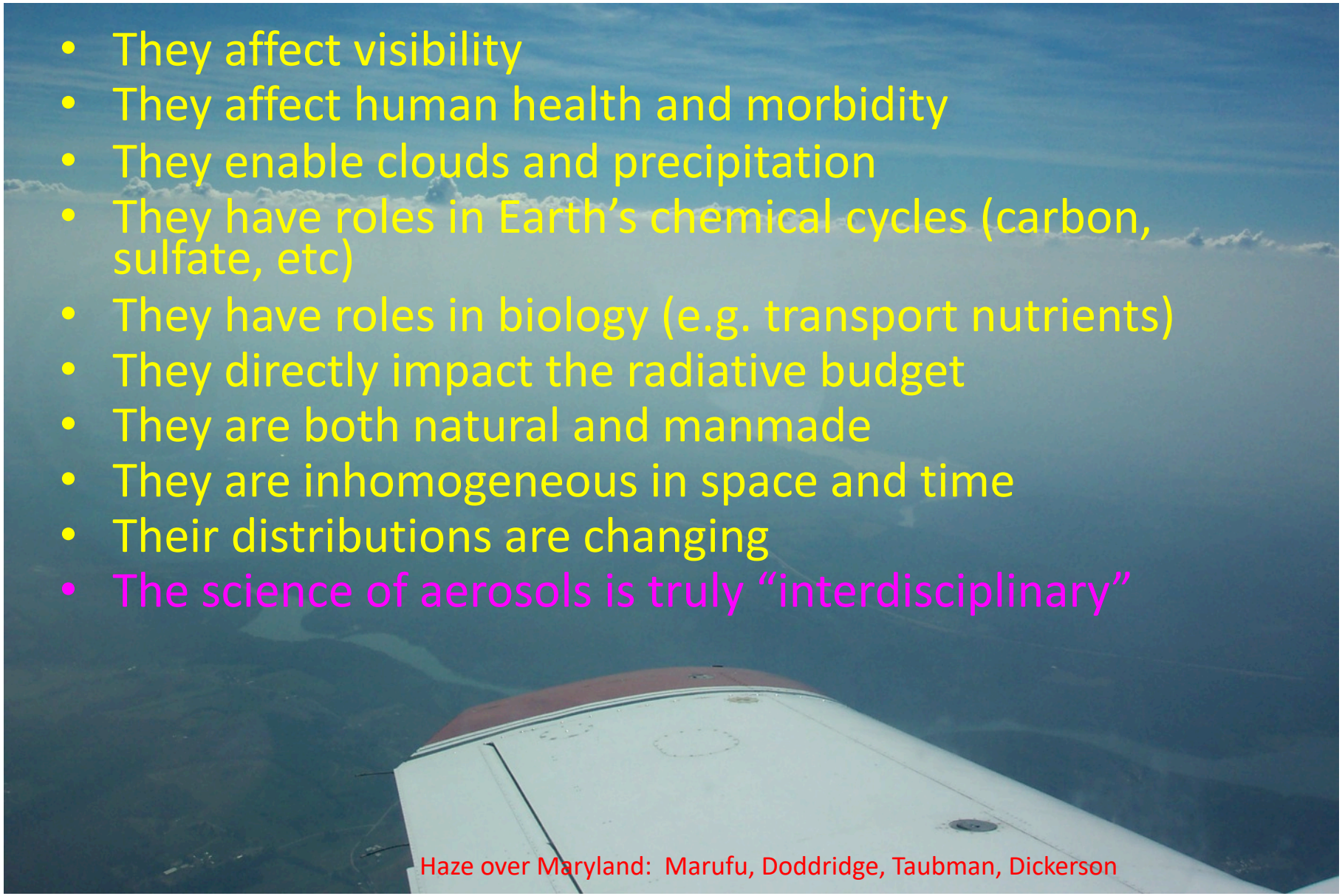




Pawan Gupta (USRA), Robert Levy (NASA),
Prakash Doraiswamy (RTI), Olga Pikelnaya (UCLA)

Aerosols (why do we care?)

- They affect visibility
- They affect human health and morbidity
- They enable clouds and precipitation
- They have roles in Earth's chemical cycles (carbon, sulfate, etc)
- They have roles in biology (e.g. transport nutrients)
- They directly impact the radiative budget
- They are both natural and manmade
- They are inhomogeneous in space and time
- Their distributions are changing
- The science of aerosols is truly "interdisciplinary"



Haze over Maryland: Marufu, Doddridge, Taubman, Dickerson

I joined Goddard team in late 1998

- Charles (Validation & Fires)
- *Vanderlei (Clouds & Absorption)
- Rong-Rong (image Processing)
- *Rich (Case studies)
- Shana (programmer)
- Yoram (vision)
- Marcia (visiting faculty)
- *Lorraine (Ocean alg:Aerosol models
- Rob (filling in cracks)
- Allen (Land algorithm)

*Currently affiliated with UMBC

A global team for a global algorithm

(I grew up near Maryland)

Global Climate Observing System (GCOS) requirements for **aerosol** climate data record (CDR)

Target Requirements

Variable/ Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability
Aerosol optical depth	5-10km	N/A	4h	Max (0.03; 10%)	0.01
Single-scattering albedo	5-10km	N/A	4h	0.03	0.01
Aerosol-layer height	5-10km	N/A	4h	1km	0.5km
Aerosol-extinction coefficient profile	200-500km	<1km near tropopause, ~2km in middle stratosphere	weekly	10%	20 %

Stability means ”drift per decade less than X” .

Also requires: multi-decade (e.g. 30+ year data record)

Let us focus on Aerosol Optical Depth = AOD

Aerosol optical depth: AOD

The optical depth expresses the quantity of light removed from a beam by scattering or absorption

$$\tau = \tau_{aerosol} + \tau_{molecular} + \tau_{gas} + \tau_{cloud} + \tau_{etc}.$$

$$\tau_{aerosol} = AOD$$

Sample AOD values:
0.02 - very clean isolated areas.
0.08 – background over ocean
0.2 – fairly clean
0.6 –polluted
1.5 – heavy smoke/dust event
>3.0 – Sun's disk obscured!

AOD is "spectral": varies with wavelength

Angstrom Exponent (AE: slope of AOD in visible)
<1.0 = "coarse" sized aerosol
>2.0 = "fine" sized aerosol.

Global Climate Observing System (GCOS) requirements for **Aerosol Optical Depth (AOD)** climate data record (CDR):

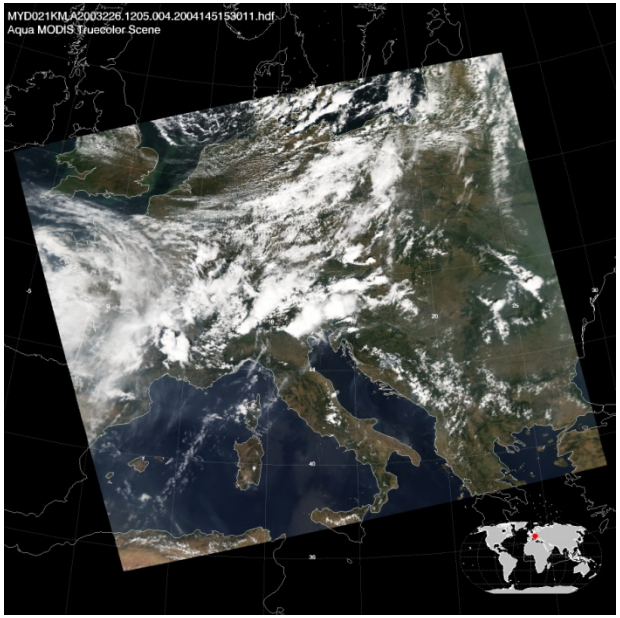
Target metric	Target
Horizontal Resolution	5-10 km, globally
Accuracy	MAX(0.03 or 10%)
Stability / bias	<0.01 / decade
Time Length	30+ years
Temporal Resolution	4 h

These are requirements for “climate” monitoring

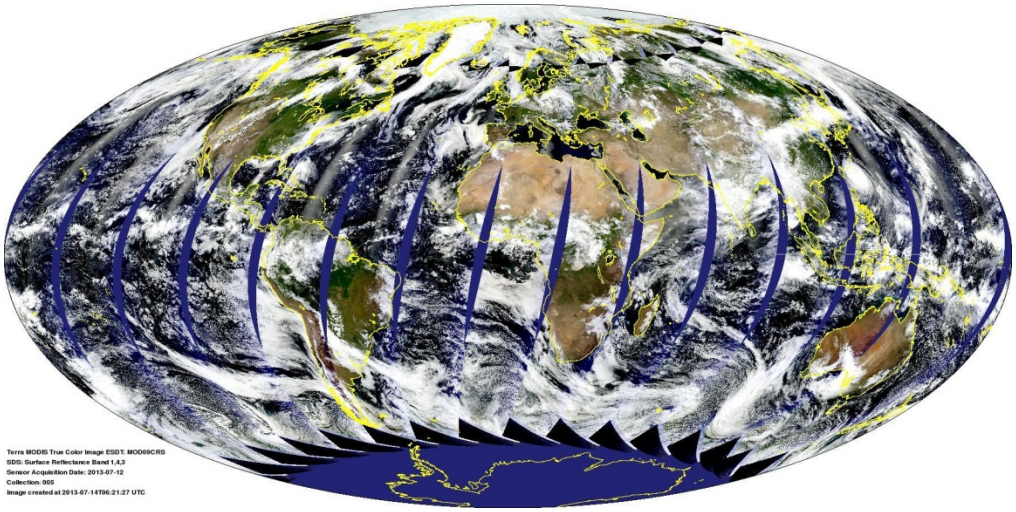
Maybe different requirements for other applications

(air quality, ocean fertilization, weather forecasting...)

The MODIS sensor



MODIS Aqua granule RGB composite for August 14th, 2003, 12:05 UTC



MODIS Terra daytime RGB composite for July 12th, 2013

Images available online at http://modis-atmos.gsfc.nasa.gov

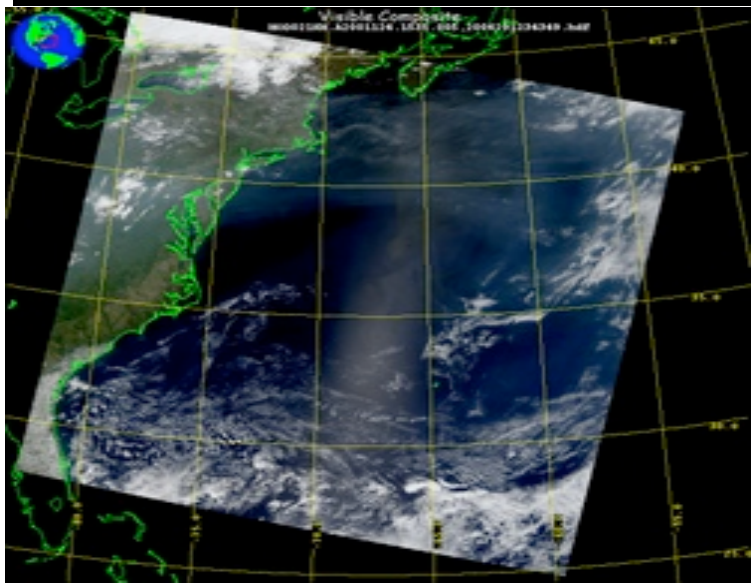
- 36 spectral bands from visible to thermal IR
- Spatial resolutions (level 1b) 250 m to 1 km at nadir
- Swath width 2,300 km, giving near-global daily coverage
- Flying on polar-orbiting platforms: Terra since 2000, Aqua since 2002.

Aerosol retrieval from MODIS?

What MODIS observes

Attributed to aerosol (AOD)

May 4, 2001; 13:25 UTC
Level 1 "reflectance"



?

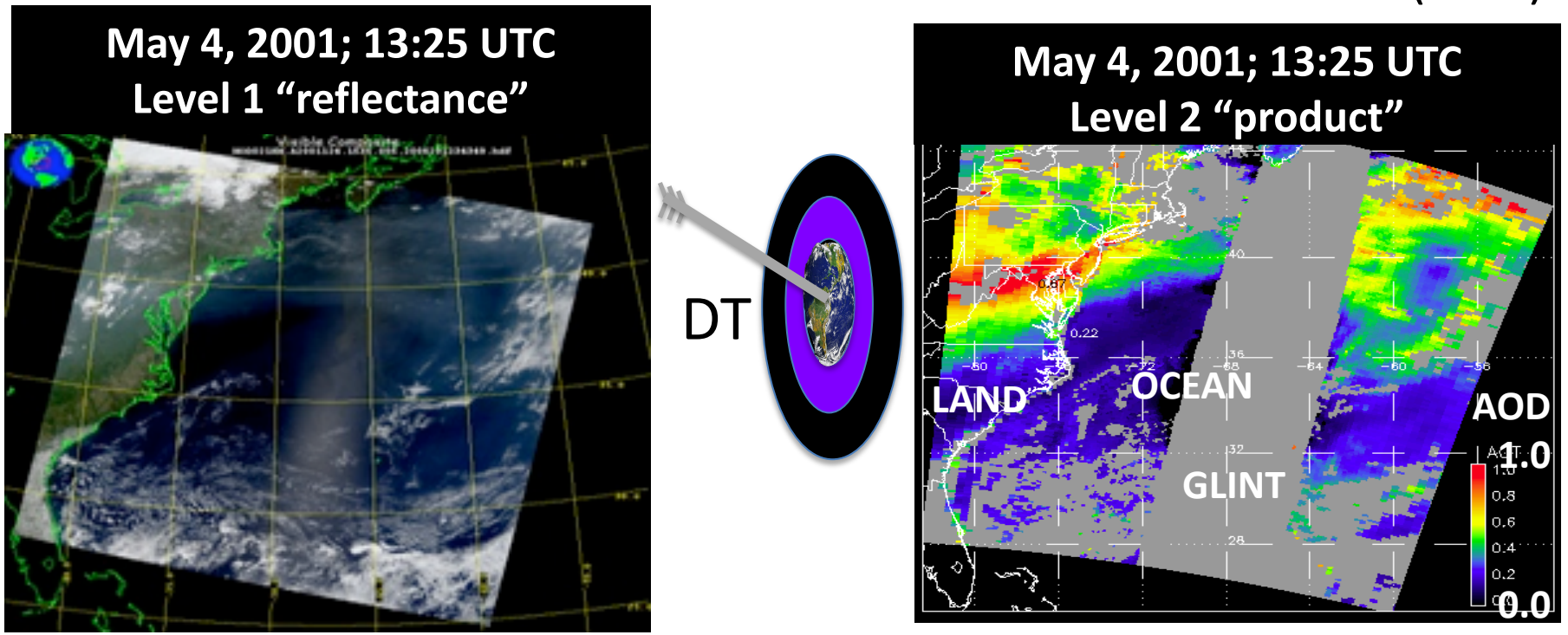
There are many different "algorithms" to retrieve aerosol from MODIS

1. Dark Target ("DT" ocean and land; Levy, Mattoo, Munchak, Remer, Tanré, Kaufman)
2. Deep Blue ("DB" desert and beyond; Hsu, Bettenhousen, Sayer,..)
3. MAIAC (coupled with land surface everywhere; Lyapustin, Wang, Korkin,…)
4. Ocean color/atmospheric correction (McClain, Ahmad, …)
5. Etc (neural net, model assimilation, statistical, …)
6. Your own algorithm (many groups around the world)

Dark-Target: A "Single View" aerosol algorithm (originally developed for MODIS – Terra/Aqua)

What a sensor observes

Attributed to aerosol (AOD)



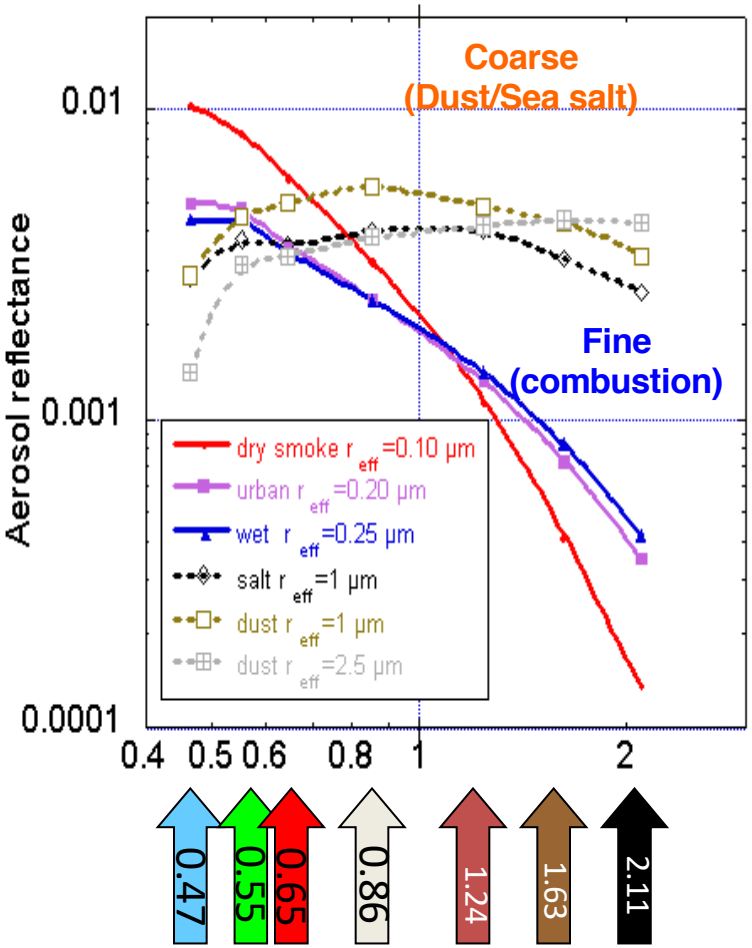
"Established 1997" by Kaufman, Tanré, Remer, etc)

"Modified 2005, 2010, 2013, 2015" by Remer, Levy, Gupta, etc

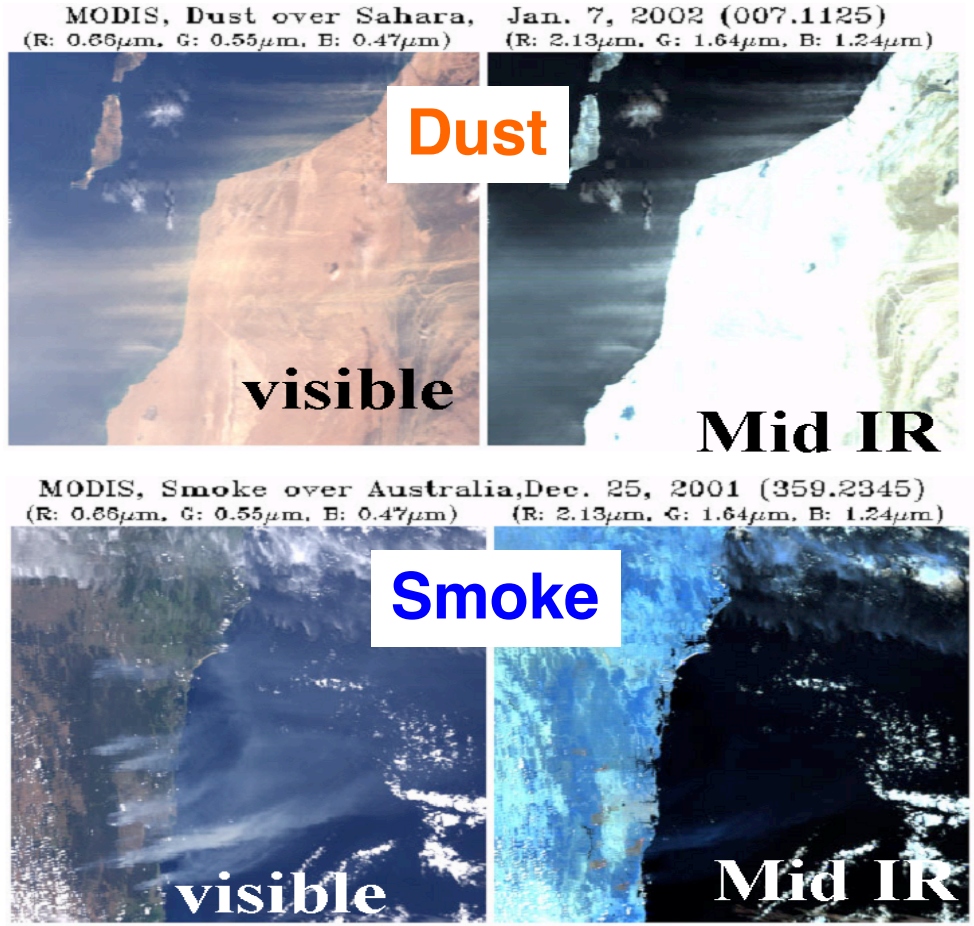
Separate logic over land and ocean

Retrieve: AOD at 0.55 μm, spectral AOD (AE), cloud-cleared reflectances, diagnostics, quality assurance

AOD is “spectrally” (wavelength) dependent (which is correlated to aerosol size)



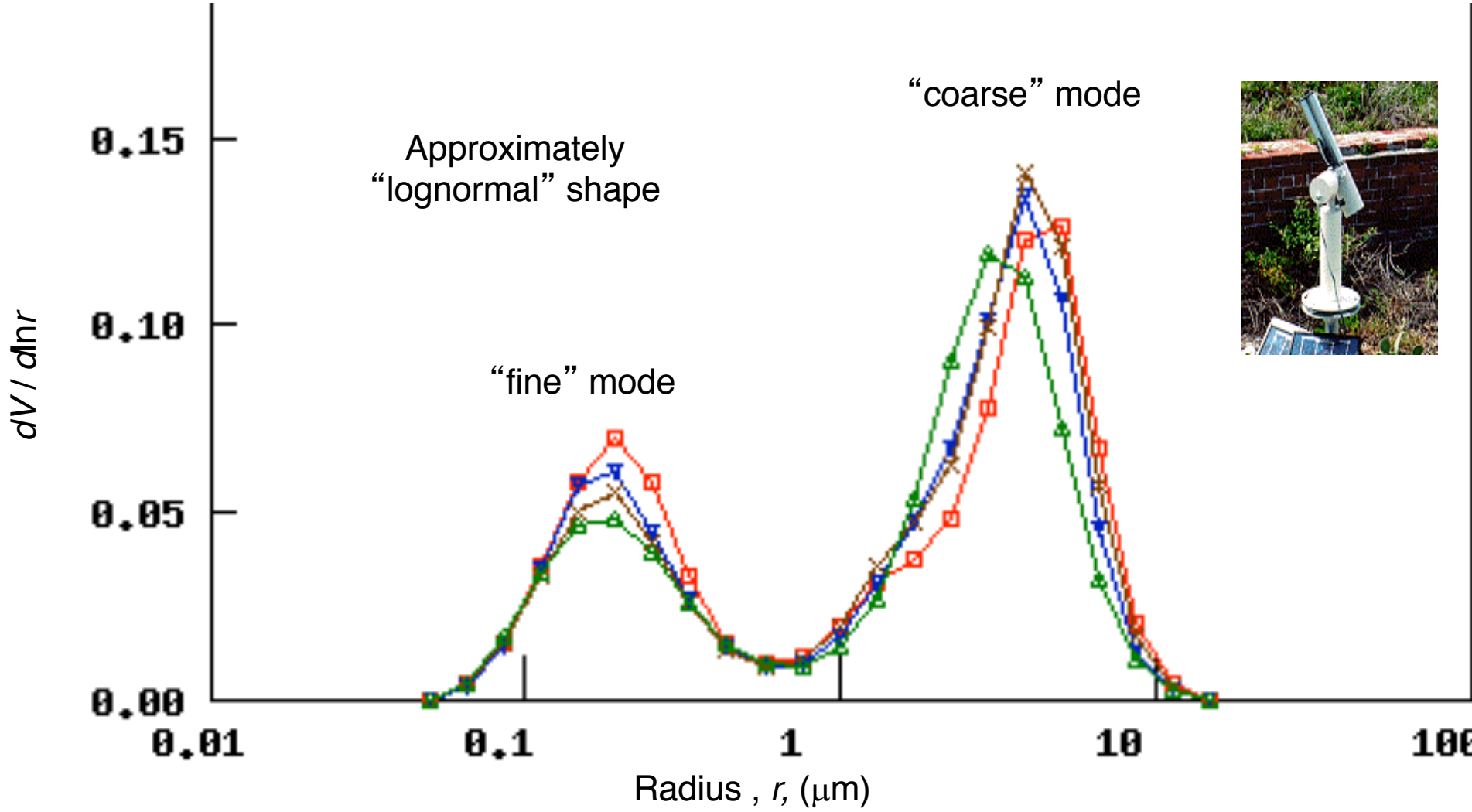
MODIS “Channels”
Used for DT aerosol



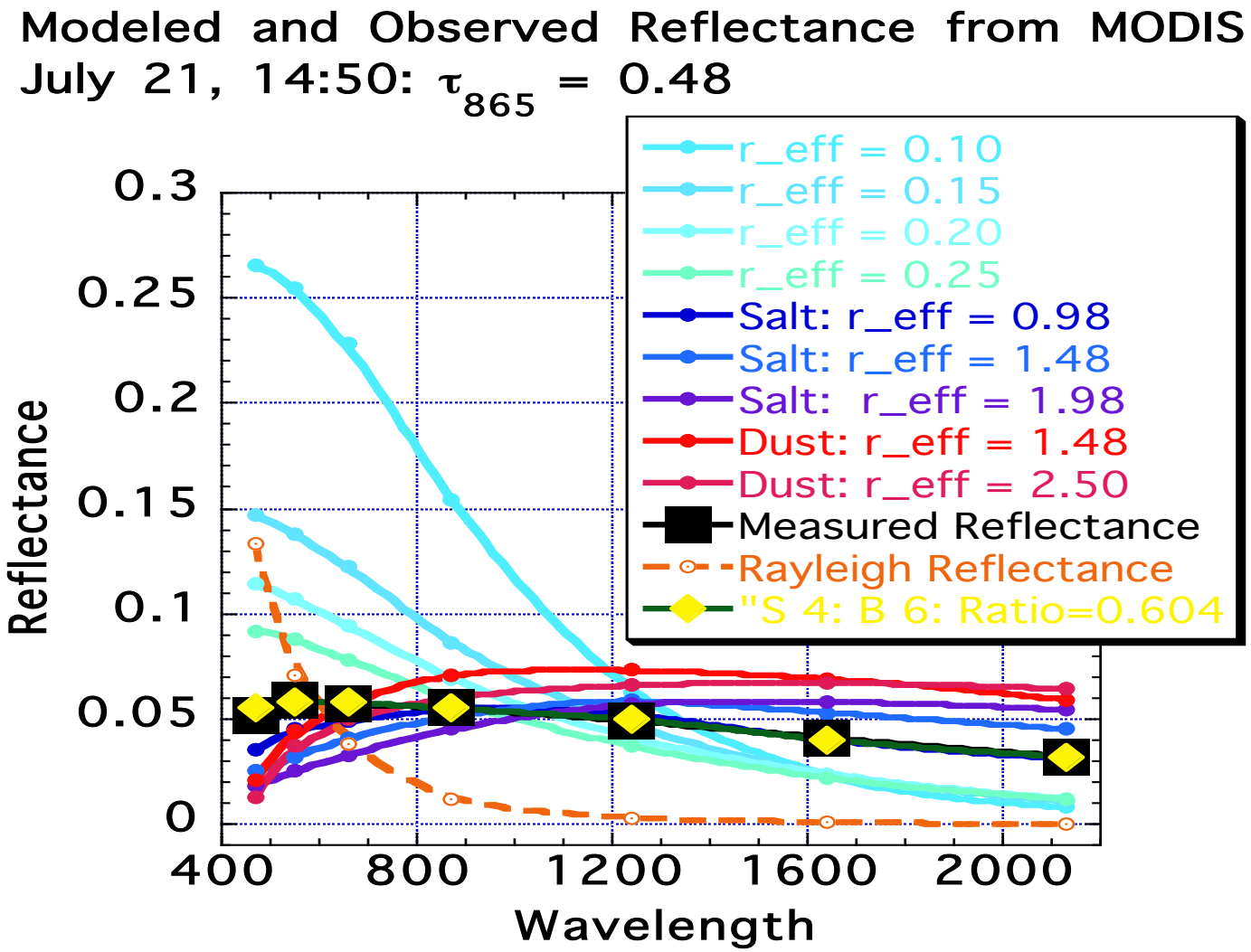
“Big” particles (e.g. Dust) reflect in IR
“Small” particles (smoke/pollution) do not.

Y. Kaufman, D. Tanré

Assumes: Ambient Size Distribution is approximately bi-lognormal (e.g., from AERONET)

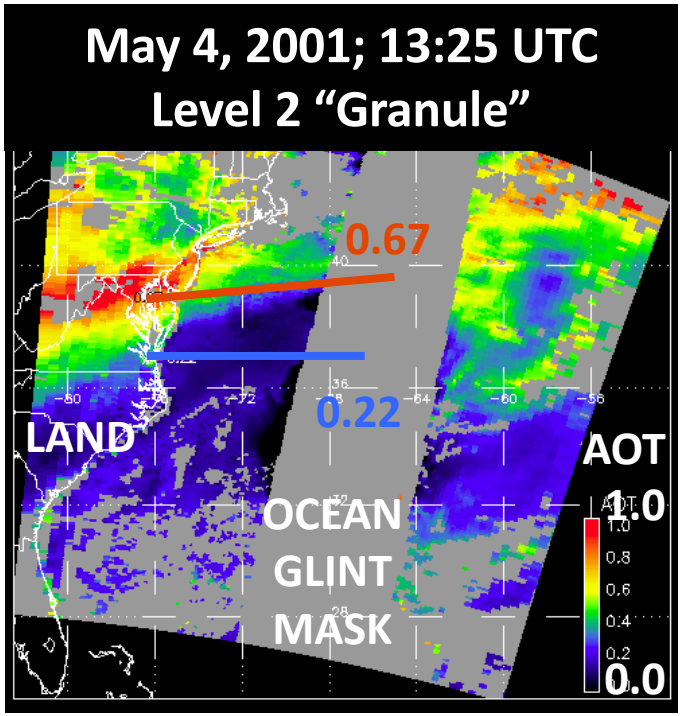


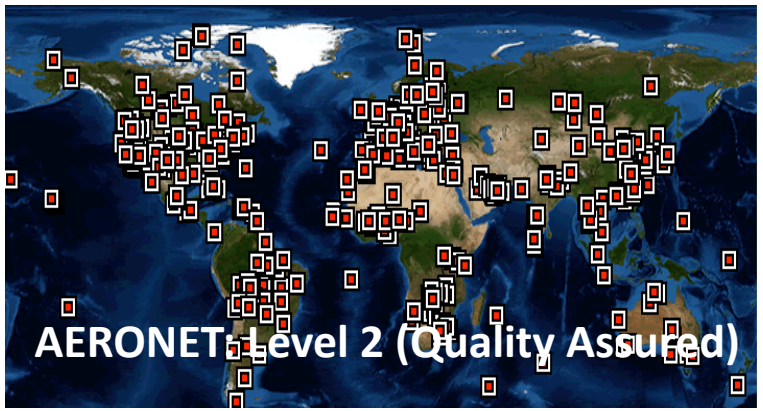
MODIS Ocean Aerosol Retrieval



Remote Sensing of Spectral Aerosol Properties: A Classroom Experience
(Levy and Pinker, BAMS, 2007)

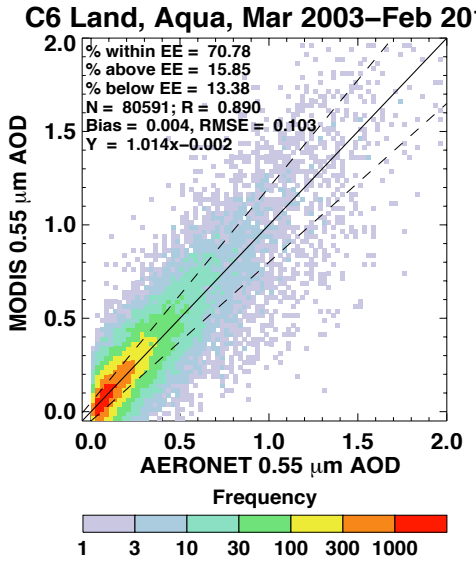
Validation for MODIS product (Level 2)

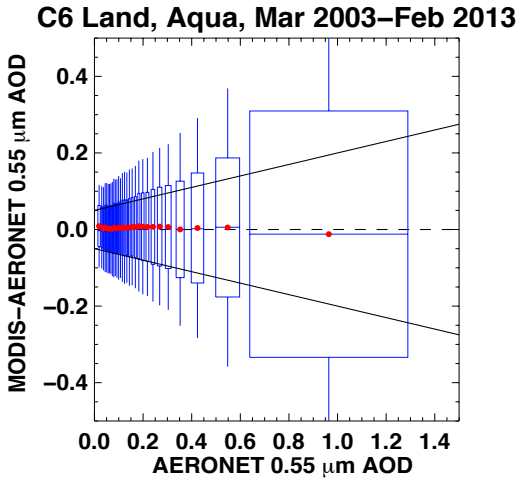




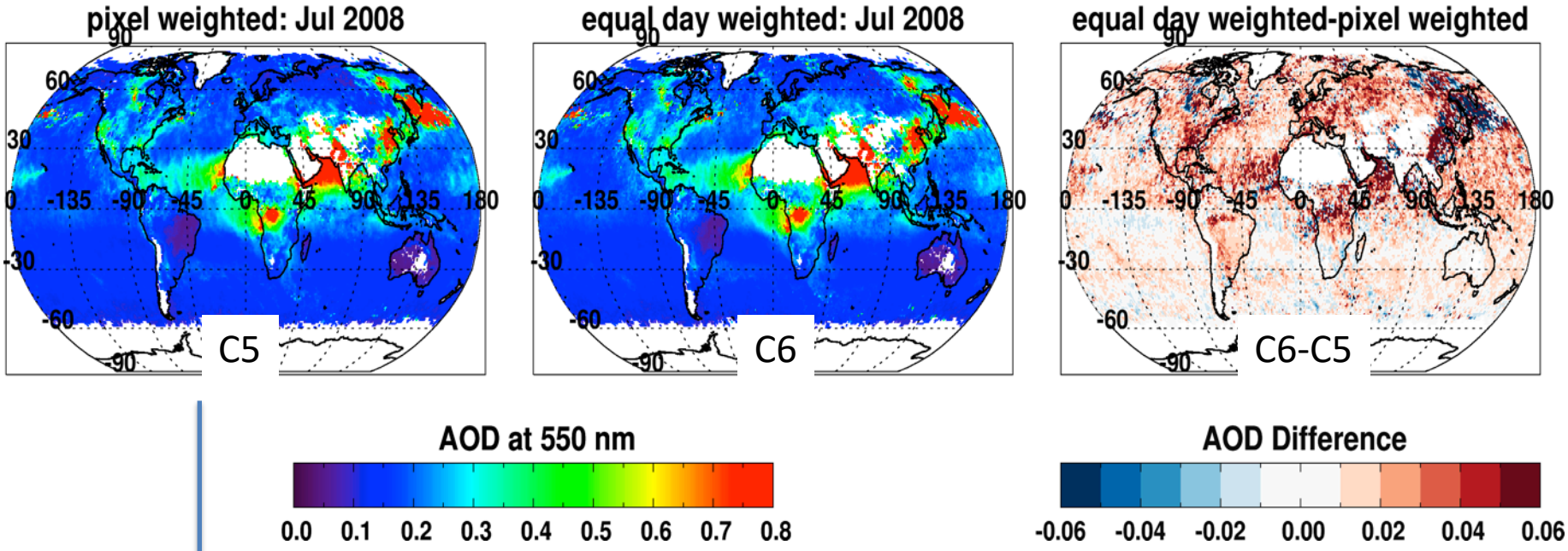
- A **Collection** uses consistent calibration and retrieval algorithms (over entire mission)

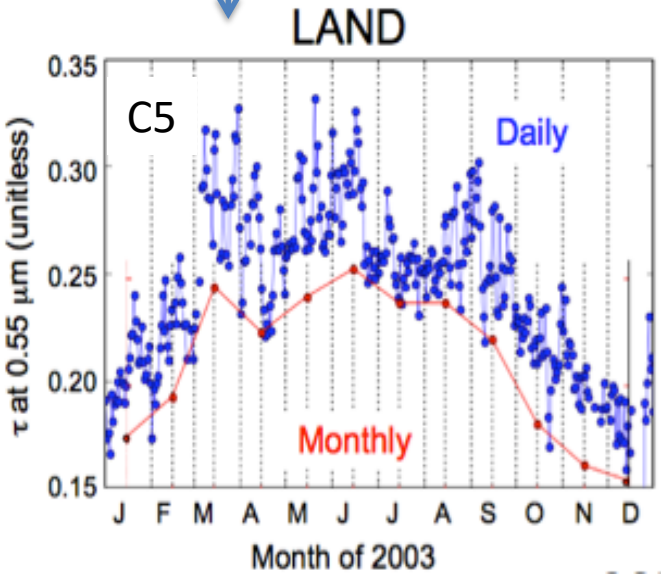
- Compare both land and ocean products to AERONET, separately
- C6.1 Validation for Level 2, 66% are within "Expected Error" (EE)
  - Land: $\pm(0.15\tau + 0.05)$
  - Ocean: $\pm(0.10\tau + 0.04)$
  - Ocean AE: ± 0.4





Level 3 is gridded aggregations of L2

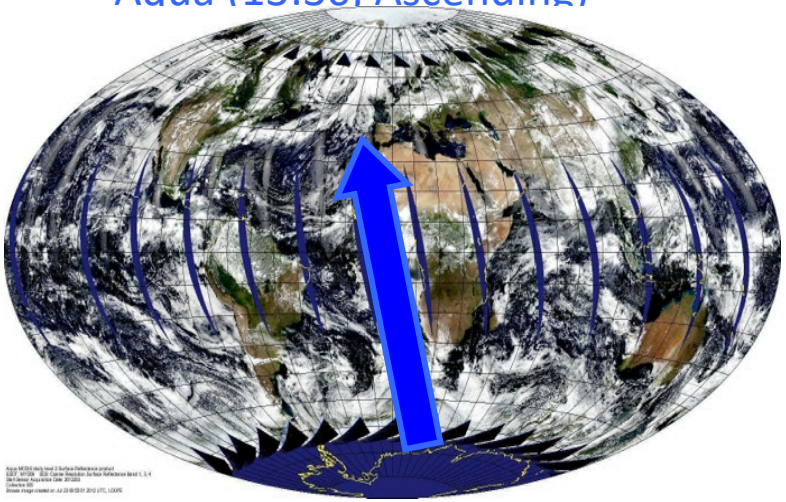




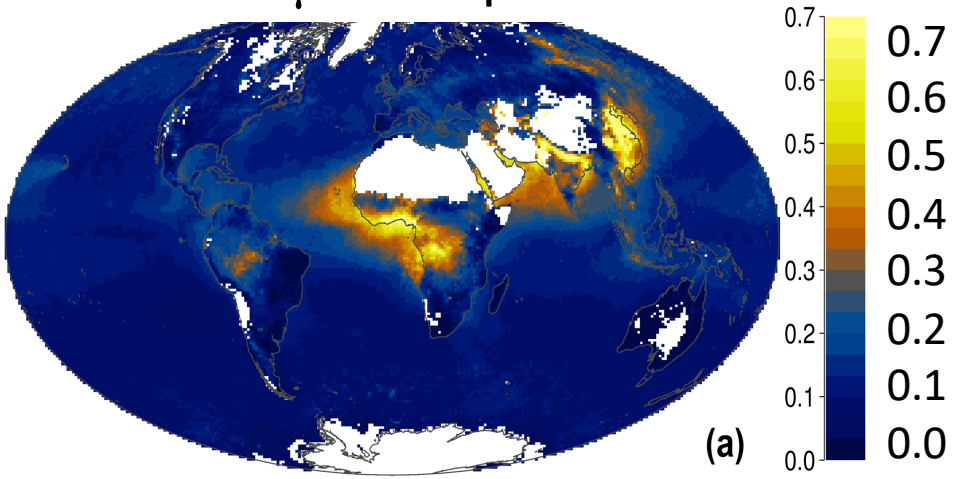
- C6 monthly is "equal day" weighted.
  - Requires 5 pixels in a day,
  - Requires at least 3 pixels in a month
- Not all products can be "aggregated" (e.g. AE)
- MODIS is MOD08_D3 (daily) and _M3 (monthly)

MODIS-Terra vs MODIS-Aqua (Twins!)

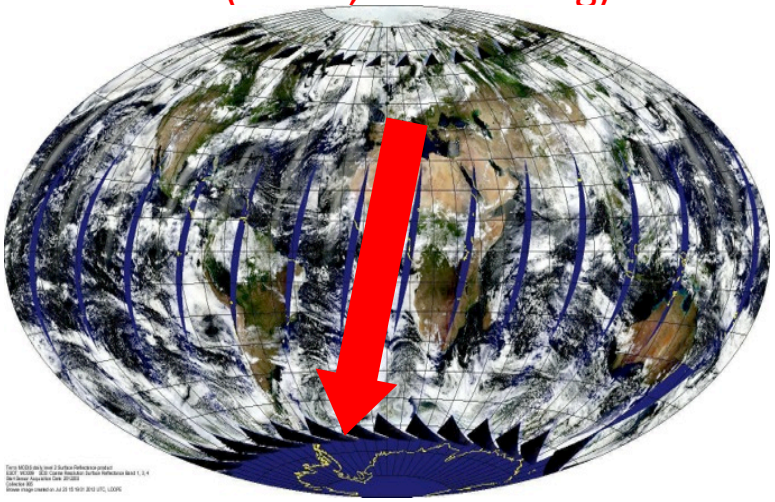
Aqua (13:30, Ascending)



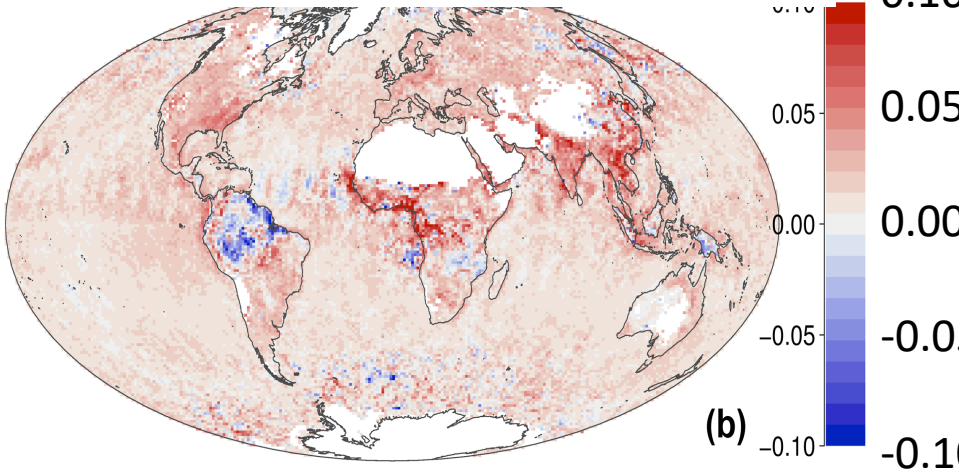
AOD 0.55 μm: Aqua 2008



Terra (10:30, Descending)

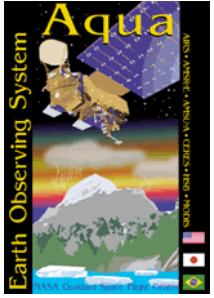


AOD 0.55 μm: Terra - Aqua 2008



Levy, R. C., et al.: Exploring systematic offsets between aerosol products from the two MODIS sensors, *Atmos. Meas. Tech., 11*, 4073-4092, 2018.

MODIS versus GCOS (AOD)



Target metric	Target	Current with MODIS
Horizontal Resolution	5-10 km, globally	10 km over ice-free and cloud-free scenes (No desert for DT)
Accuracy	MAX(0.03 or 10%)	±(0.04+10%): Ocean ±(0.05+15%): Land
Stability / bias	<0.01 / decade	Nearly stable trends, but offsets still
Time Length	30+ years	20 years and counting
Temporal Resolution	4 h	2+ / day (Terra + Aqua)

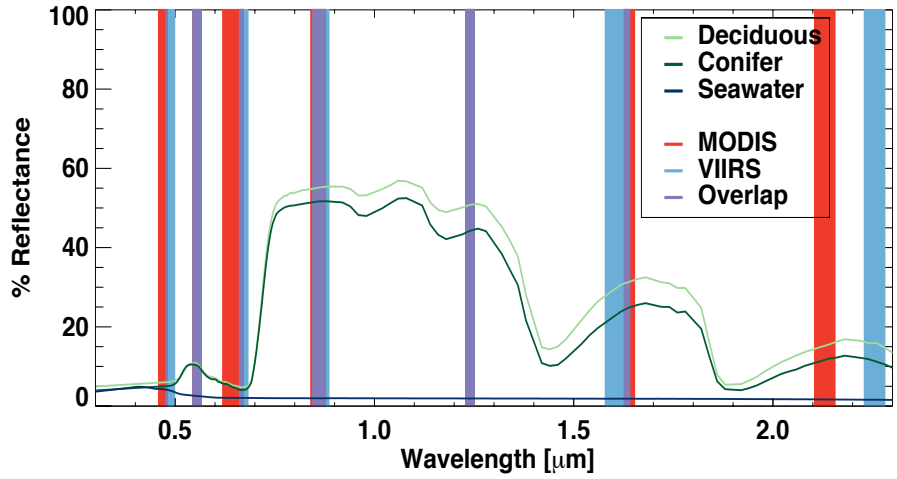
Key: Black = almost there, Blue = on the way, Red = not close or unknown

- Terra (18+) and Aqua (16+) have both have well-exceeded their planned missions.
- With luck, they will last until 2022.
  - **But for climate, we won't get to 30+ years**

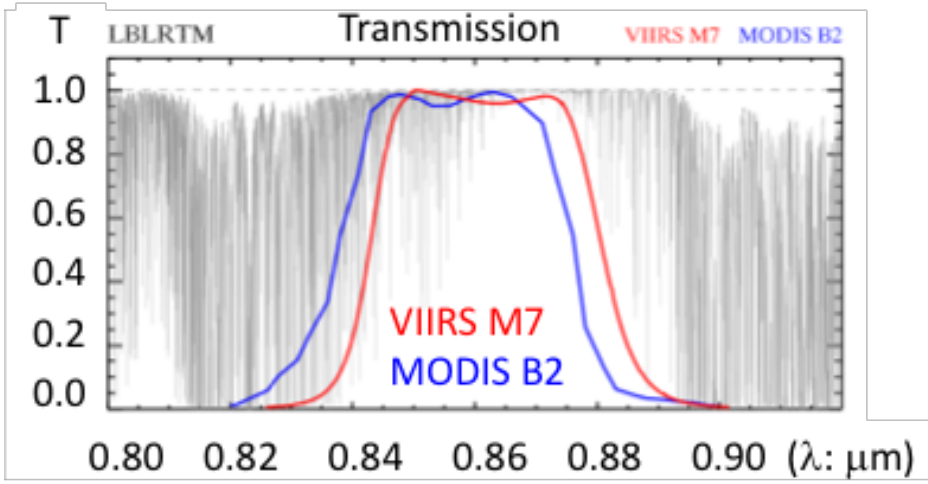
For “continuity” we can port the algorithms (Example: DT from MODIS→VIIRS)

- Deal with differences in wavelengths (gas corrections/Rayleigh, etc)

Wavelength bands & surface spectra



Example: 0.86 μm channel over “clear” sky

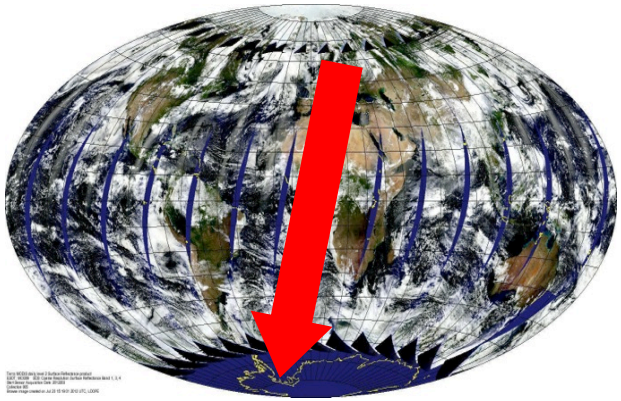


- Deal with differences in resolution, etc.
- Retrieve on new sensors (compared with retrieval on MODIS):

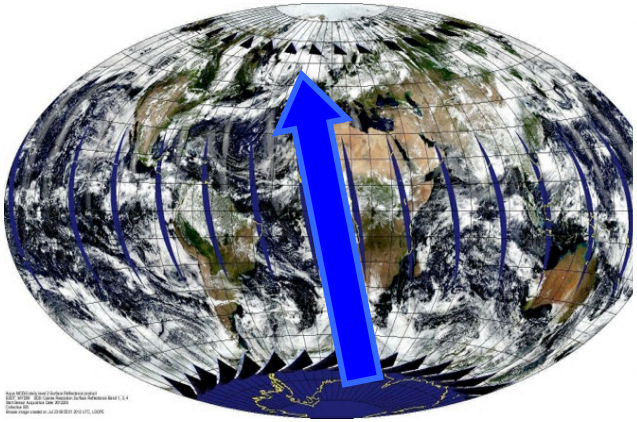
Visible-Infrared Imager Radiometer Suite
aboard Suomi-NPP, JPSS-1/NOAA-20, and future JPSS-2, 3, 4

MODIS-Terra vs MODIS-Aqua vs SNPP-VIIRS

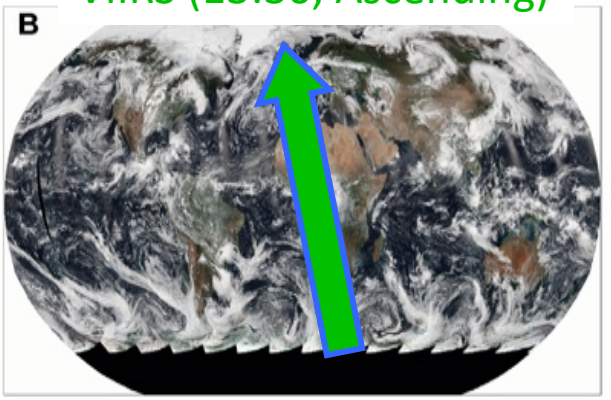
Terra (10:30, Descending)

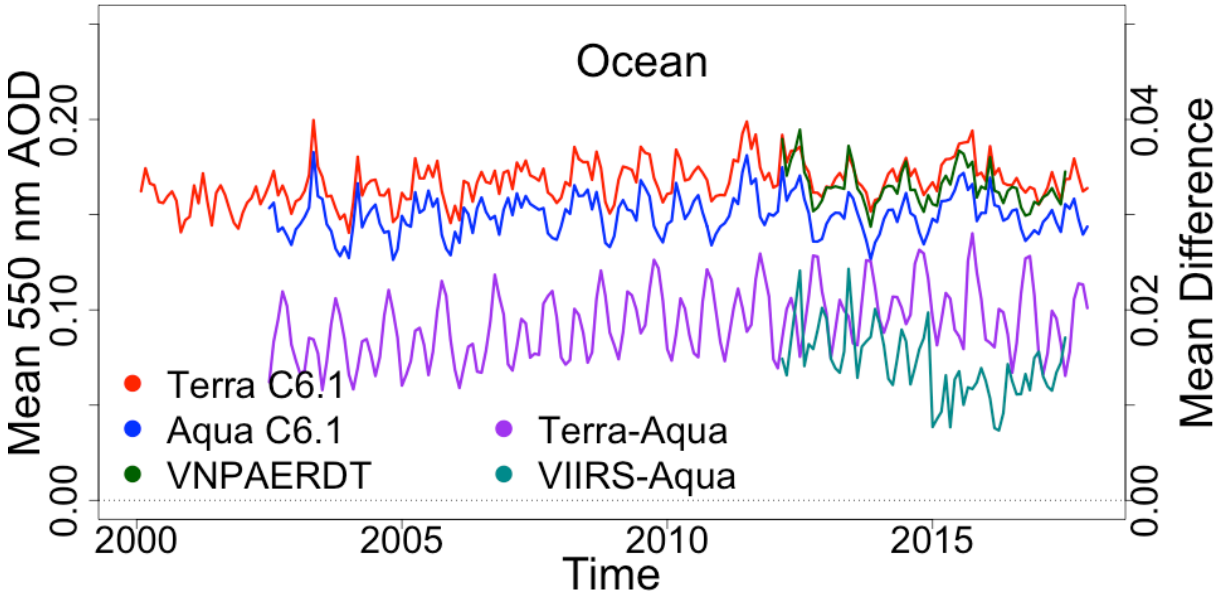


Aqua (13:30, Ascending)



VIIRS (13:30, Ascending)

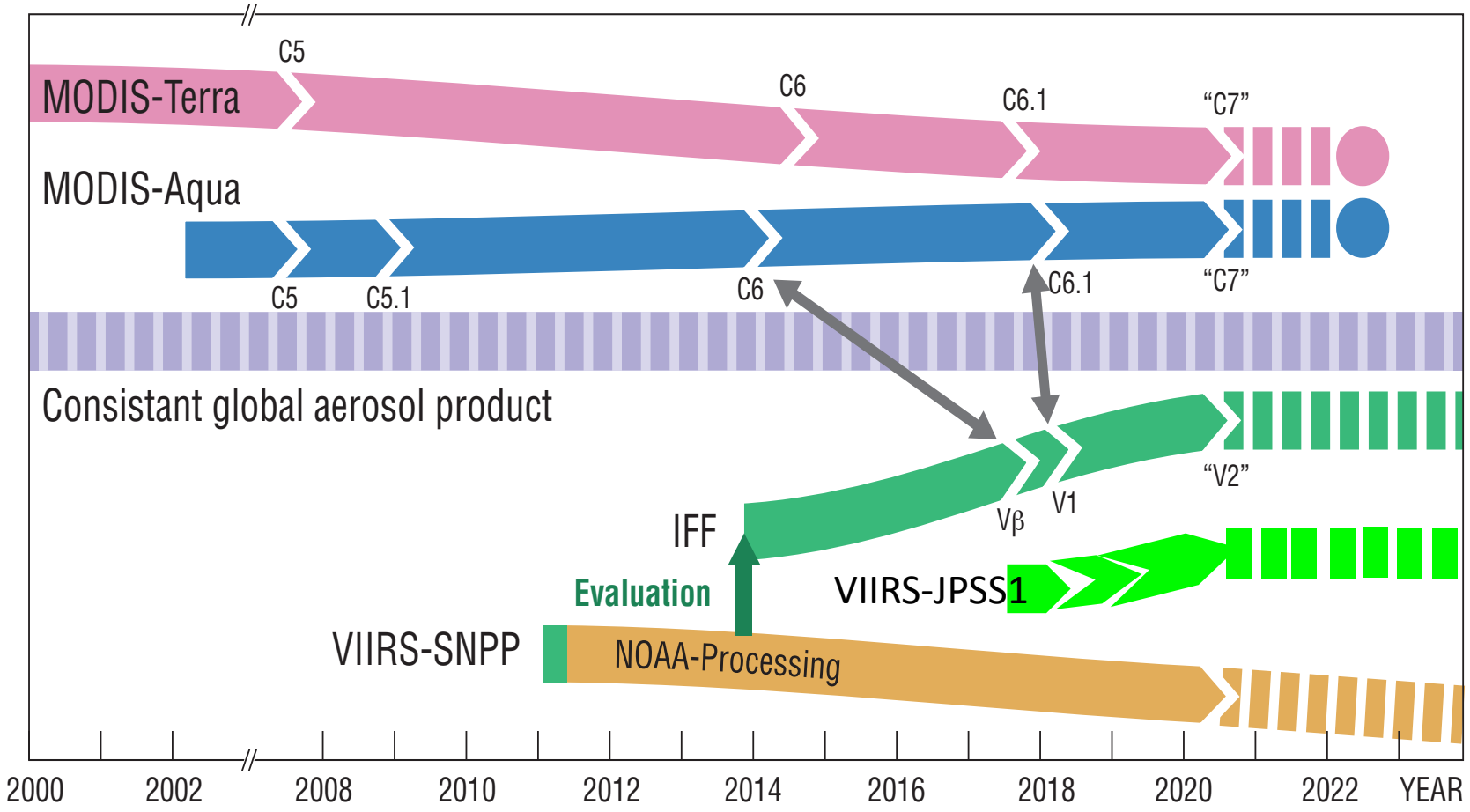




- Offsets remain.
- Why different seasonal cycles of differences?

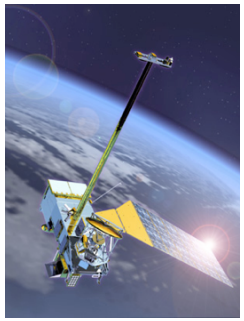
- Calibration?
- Sampling?
- Cloud detection?
- Cloud diurnal cycle?

Towards consistent global aerosol on LEO



VIIRS on SNPP (and beyond) should include all updates (e.g. 6.1) for MODIS.

LEO versus GCOS (for AOD)



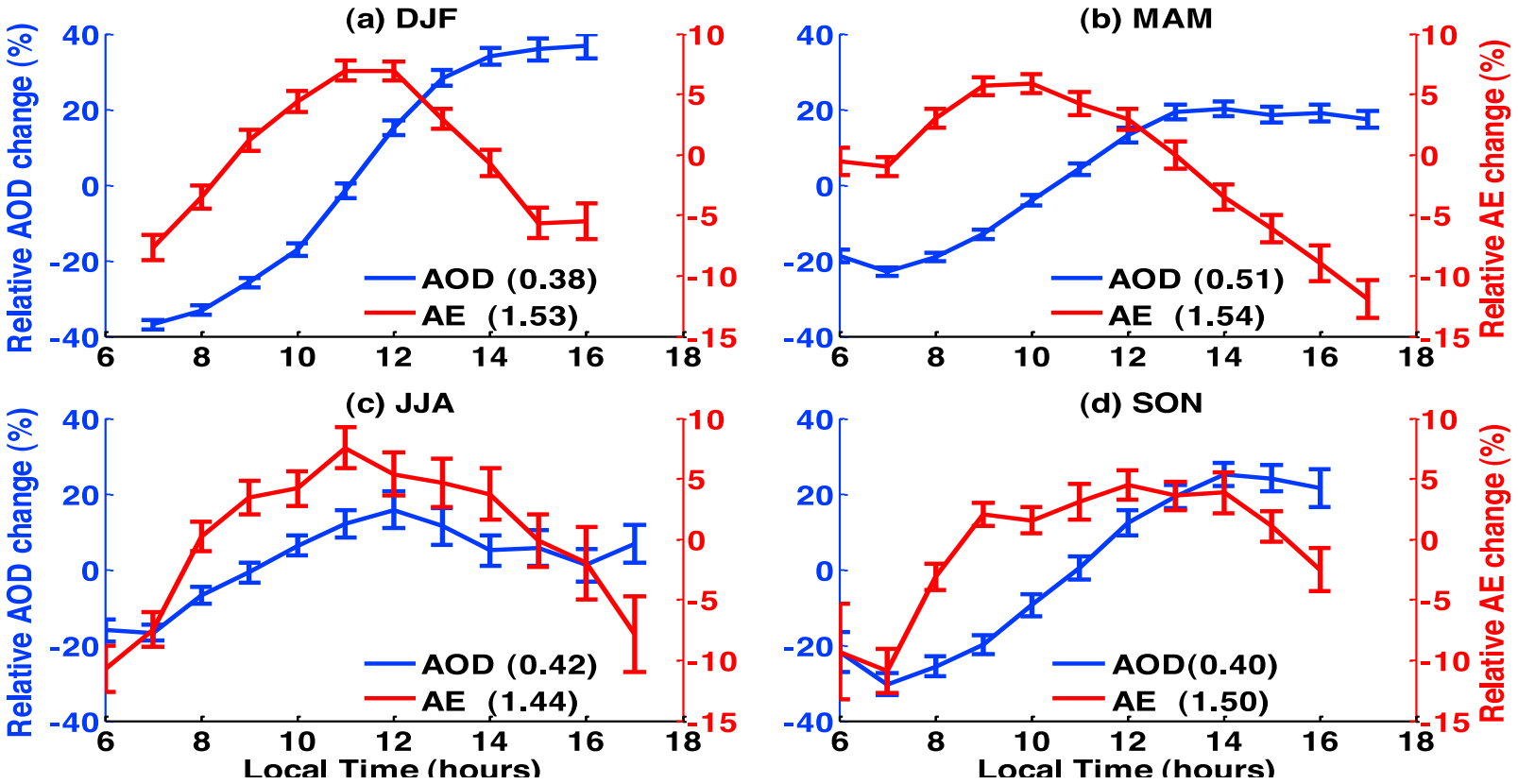
Target metric	Target	Current with MODIS
Horizontal Resolution	5-10 km, globally	≤10 km over ice-free and cloud-free scenes
Accuracy	MAX(0.03 or 10%)	±(0.04+10%): Ocean ±(0.05+15%): Land
Stability / bias	<0.01 / decade	Nearly stable trends, but offsets still
Time Length	30+ years	Can do with MODIS + VIIRS
Temporal Resolution	4 h	2+ / day (Terra + Aqua/VIIRS)

What's still missing?

Temporal variability!

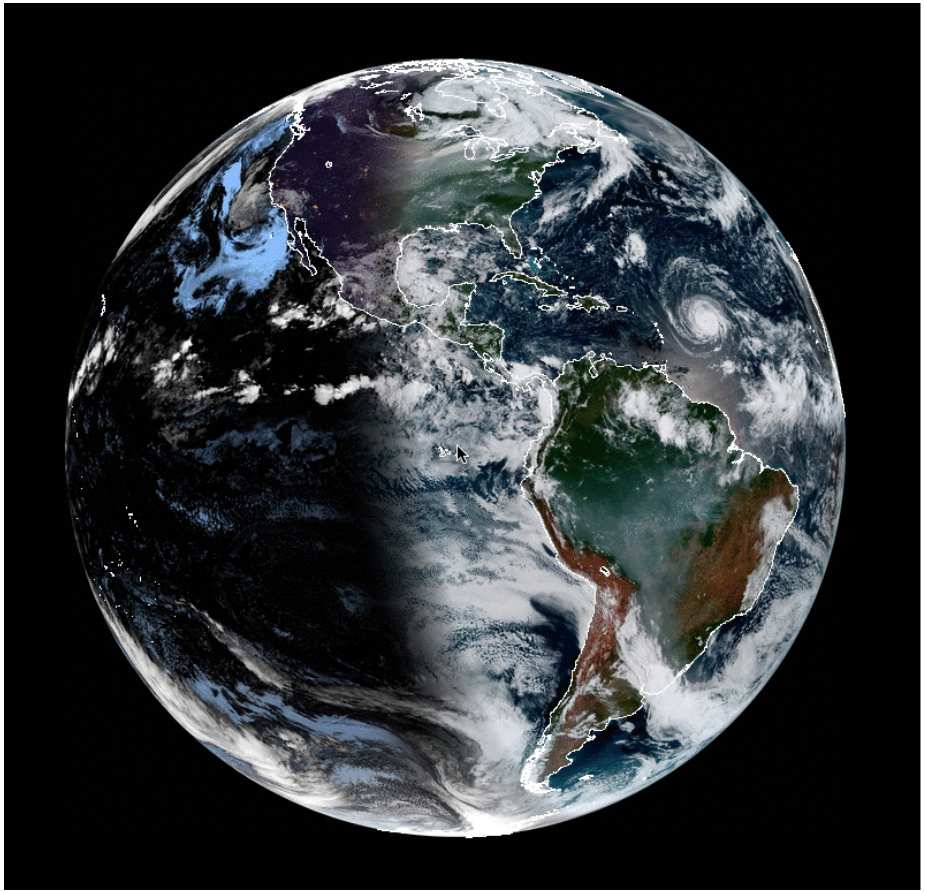
Breaking the Temporal Barrier!

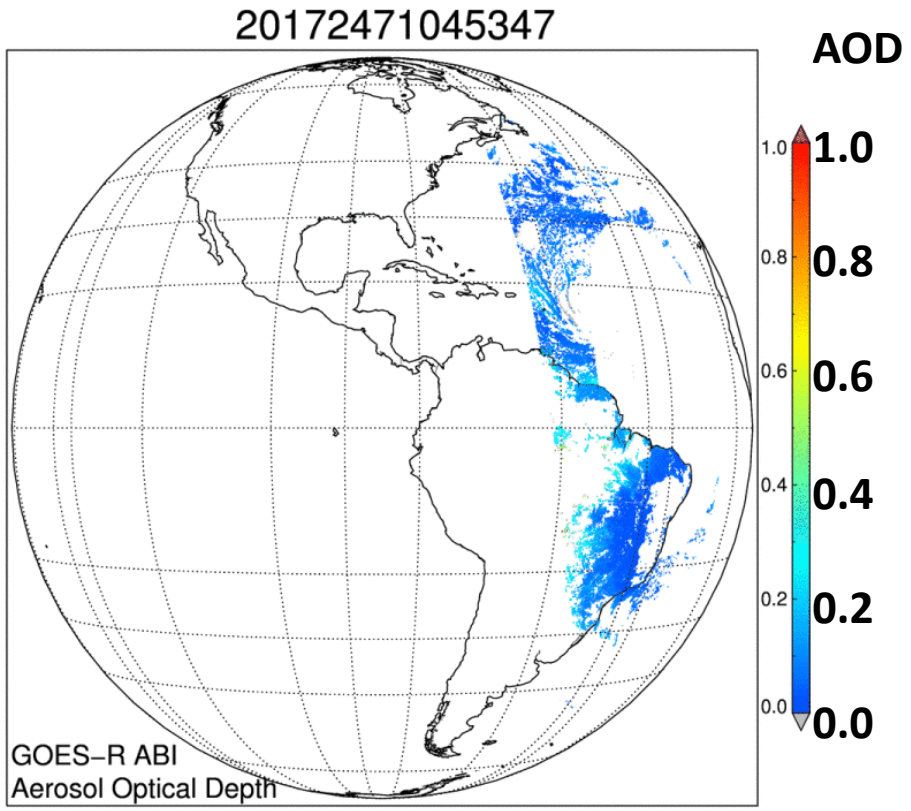
% deviation in hourly AOD and AE relative to the daily means in Mexico City.



From: Zhang, Y., Yu, H., Eck, T. F., et al, (2012). Aerosol daytime variations over North and South America derived from multiyear AERONET measurements, *J. Geophysical Research*.

RGB and AOD from ABI for Sep 4, 2017
Canada/Washington fires and smoke mega-event





ABI = Advanced Baseline Imager
AHI = Advanced Himawari Imager

Port DT algorithm to GEO!

Spectral/Spatial: AHI / ABI ≈ MODIS / VIIRS

	MODIS	VIIRS	AHI	ABI
Blue	0.47/0.5	0.49/0.75	0.47/1.0	0.47/1.0
Green	0.55/0.5	0.55/0.75	0.51/1.0	
Red	0.66/0.25	0.67/0.75	0.64/0.5	0.64/0.5
NIR	0.86/0.25	0.86/0.75	0.86/1.0	0.86/1.0
NIR	1.24/0.5	1.24/0.75		
Cirrus	1.38/0.5	1.38/0.75		1.38/2.0
SWIR	1.61/0.5	1.61/0.75	1.61/2.0	1.61/1.0
SWIR	2.11/0.5	2.25/0.75	2.25/2.0	2.25/2.0

Some details need to be worked out (e.g. lack of "cirrus" band on AHI);

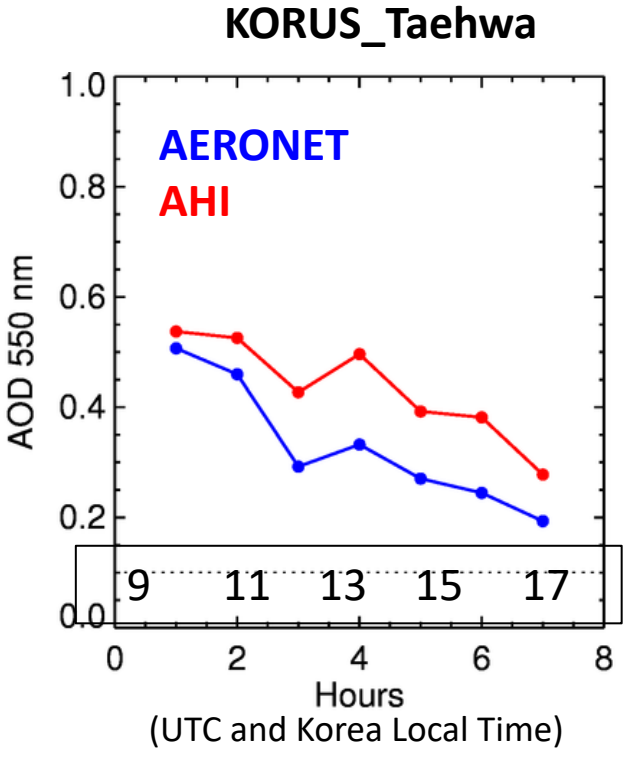
Green band: MODIS/VIIRS @ 0.55 μm, AHI @ 0.51 μm, ABI @ none

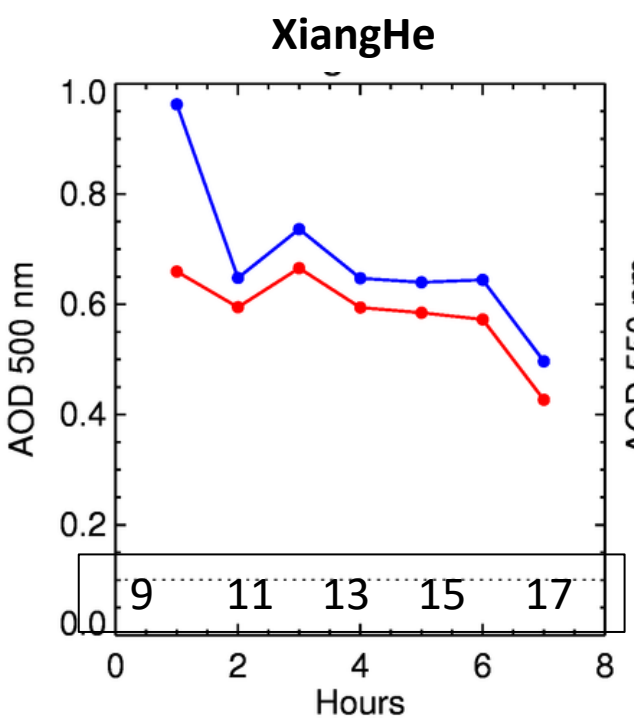
In the end, we will report AOD at 0.55 μm for everyone!

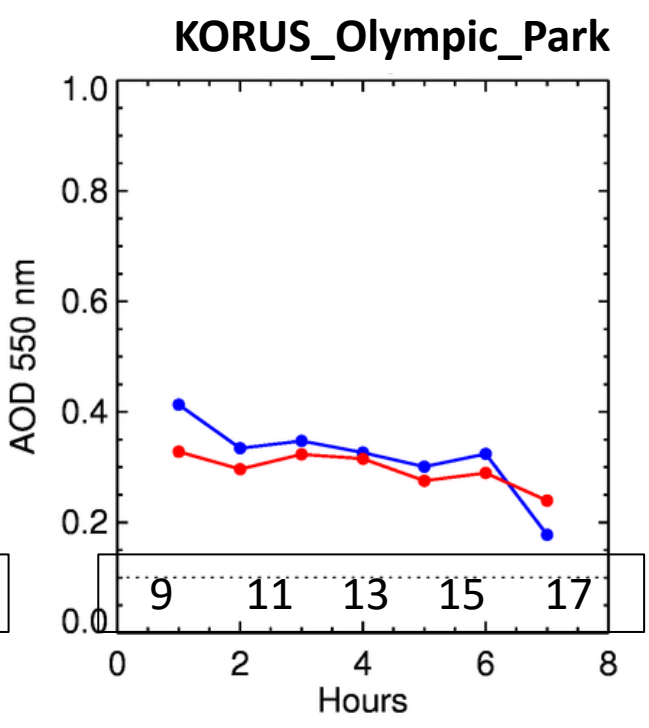
Same products as MODIS, including spectral AOD, cloud-cleared reflectance, etc

Diurnal Cycle of AODs from AHI (from KORUS-AQ, 2016)

-→ GEO does have sensitivity to Diurnal Cycle!!



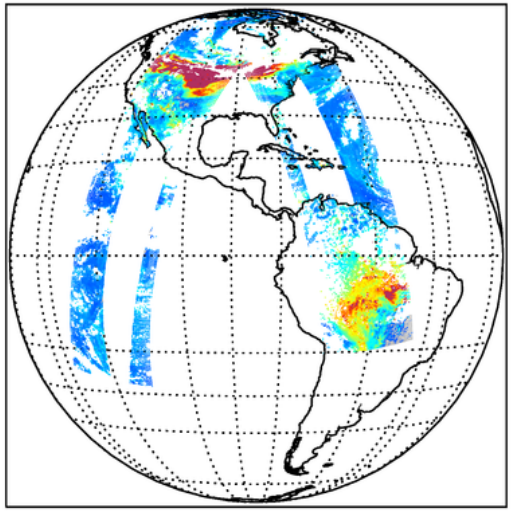




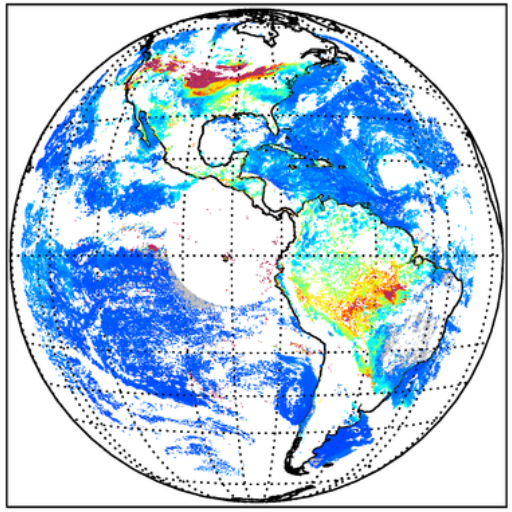
Pawan Gupta

GEO vs LEO : Sep 7, 2017
(±30 minutes of MODIS orbits)

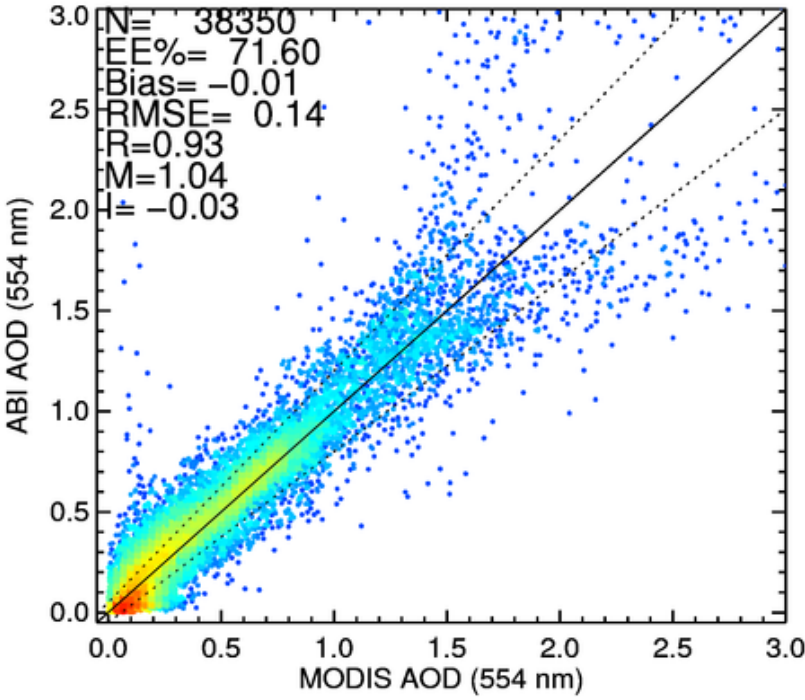
Terra and Aqua
MODIS.20172471800



GOES-16
ABI.20172471800



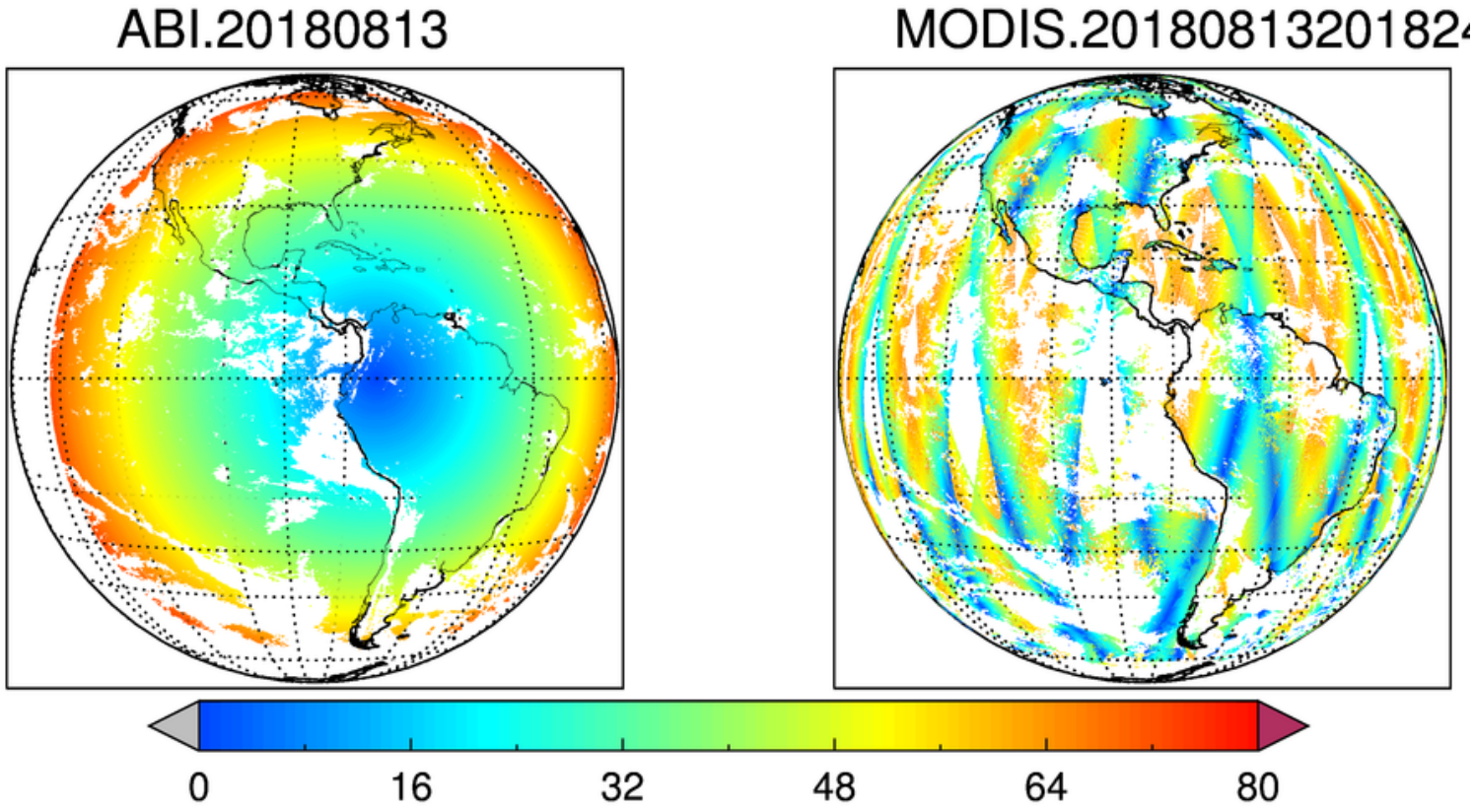
ABI versus MODIS



Overall, not too bad

But are there systematic biases?

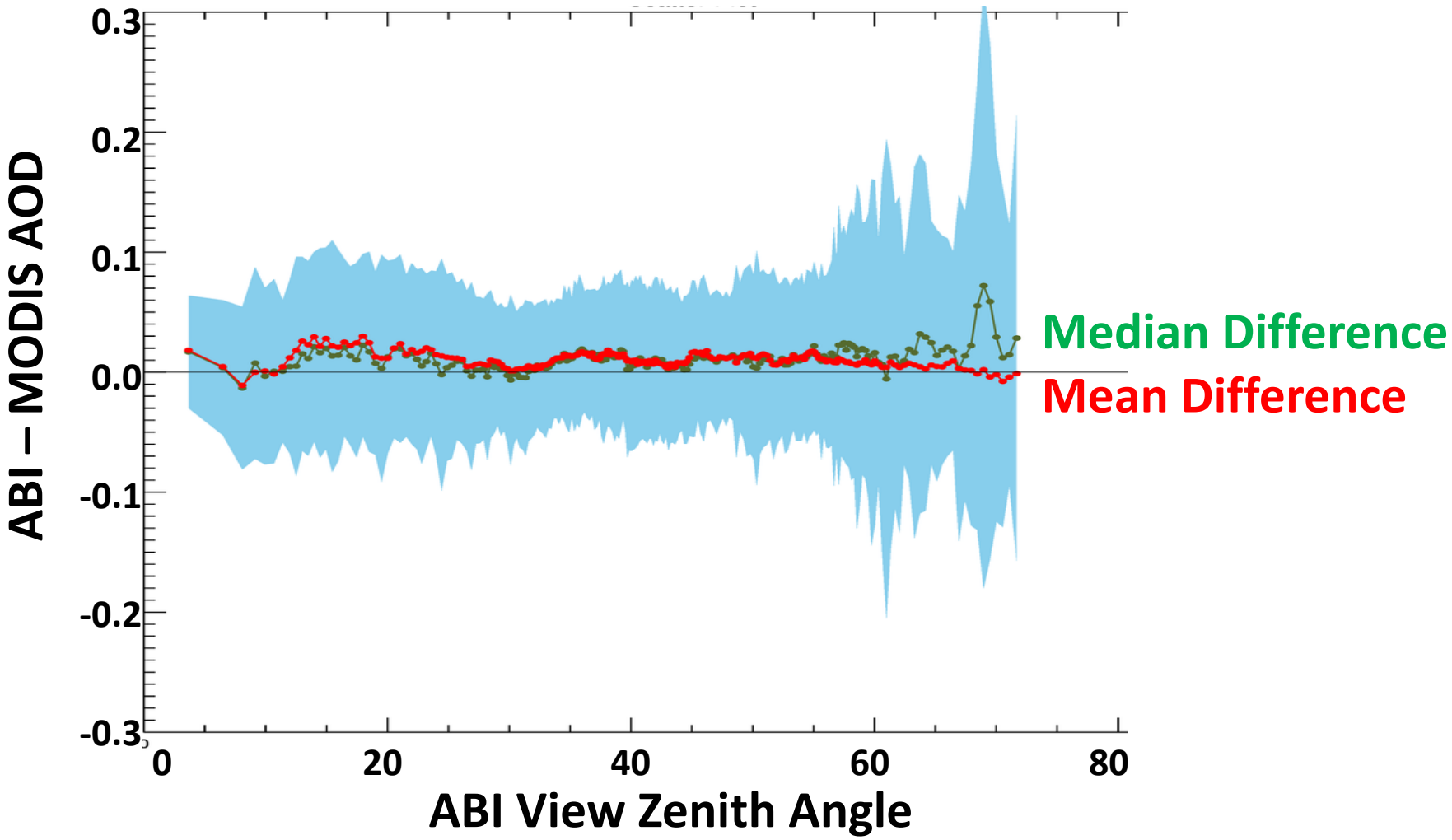
GEO vs LEO: Aug 13, 2018
Sensor View Zenith angle



- GEO Sensor view distribution for all disk images
- LEO sensor view distribution varies along orbit

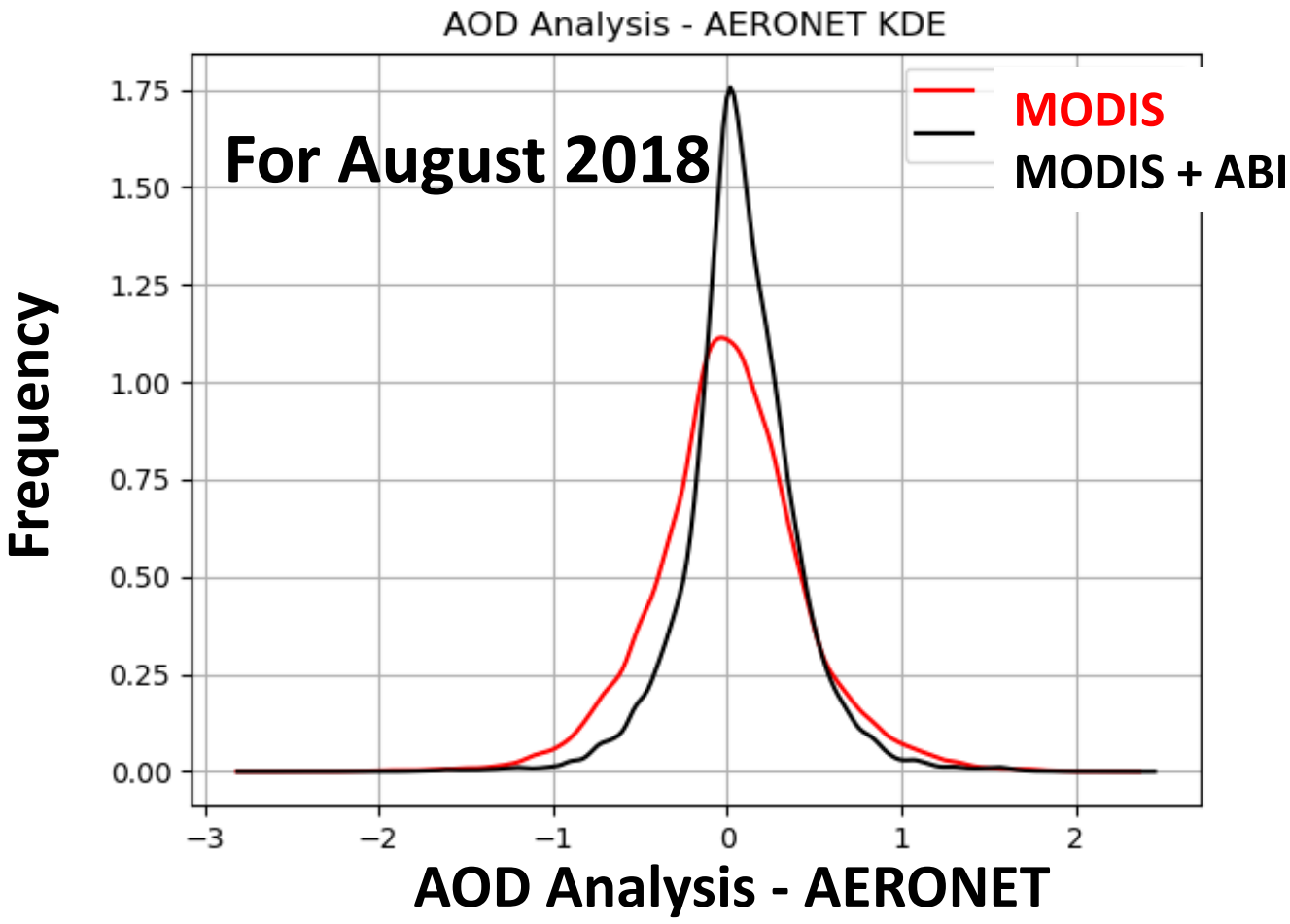
- **We hope to not see consistent biases.**

GEO vs LEO: Aug 13, 2018 Sensor View Angle



- Overall, not too bad, except for when ABI view angle > 65°
- We will have to work on this.

ABI Impact on GEOS-model data assimilation



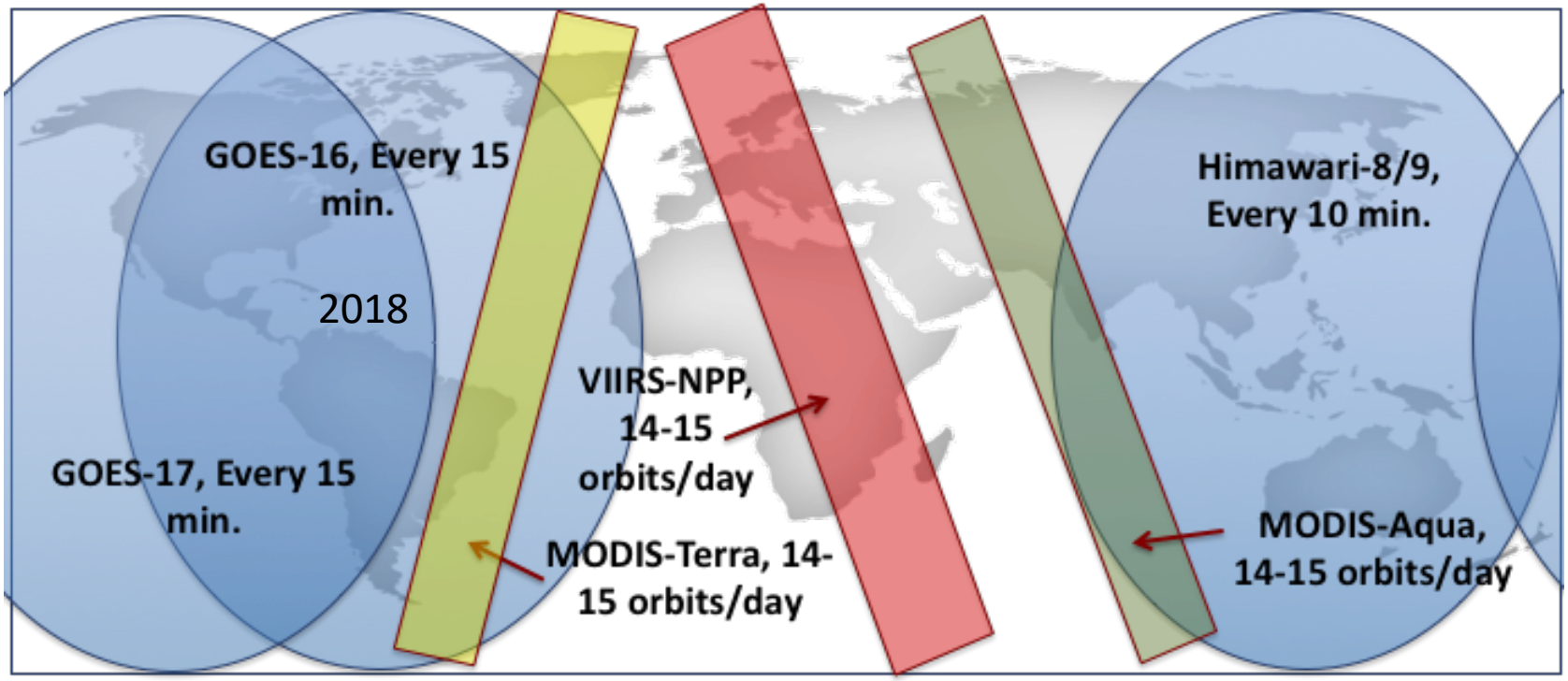
Arlindo da Silva / Patricia Castellanos (NASA / GMAO)

Global/Regional/Temporal synergy with

A consistent DT algorithm?

Statistics of UTC (compare with model)

Statistics of LST (understand local diurnal cycle)

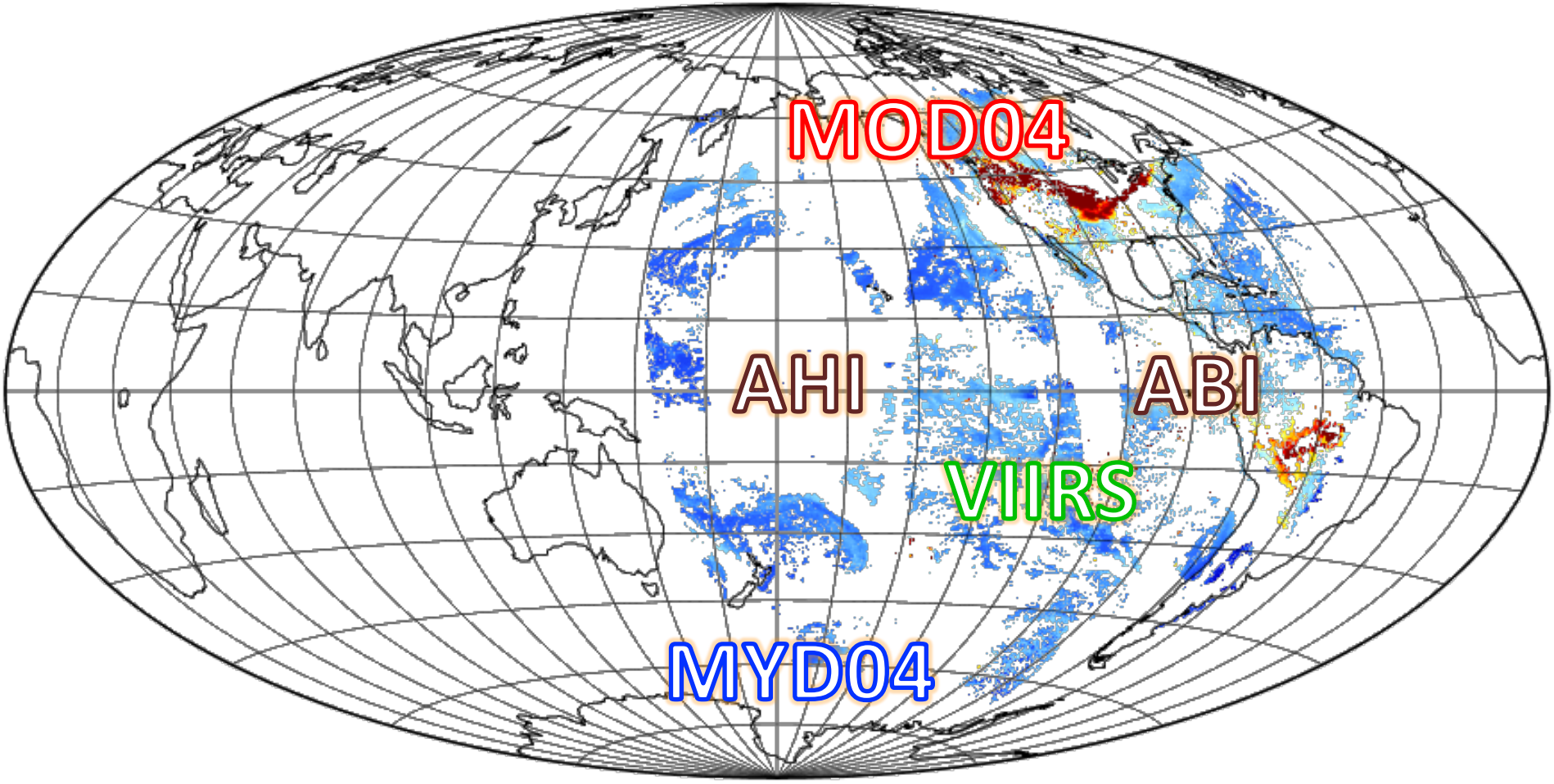


Subject of a recently funded NASA – MEaSUREs project

(with Co–Is = Robert Holz, Jennifer Wei, Shobha Kondragunta, Lorraine Remer, Pawan Gupta)

MAKE DATA USEFUL

AOD from LEO + GEO within ±30 mins
Sept 7, 2017 @ 2030 UTC



AOT at 0.55 micron for both ocean (Average) and land (corrected) with all quality data (Quality flag = 0, 1, 2,...

-0.1 0.1 0.3 0.4 0.6 0.8

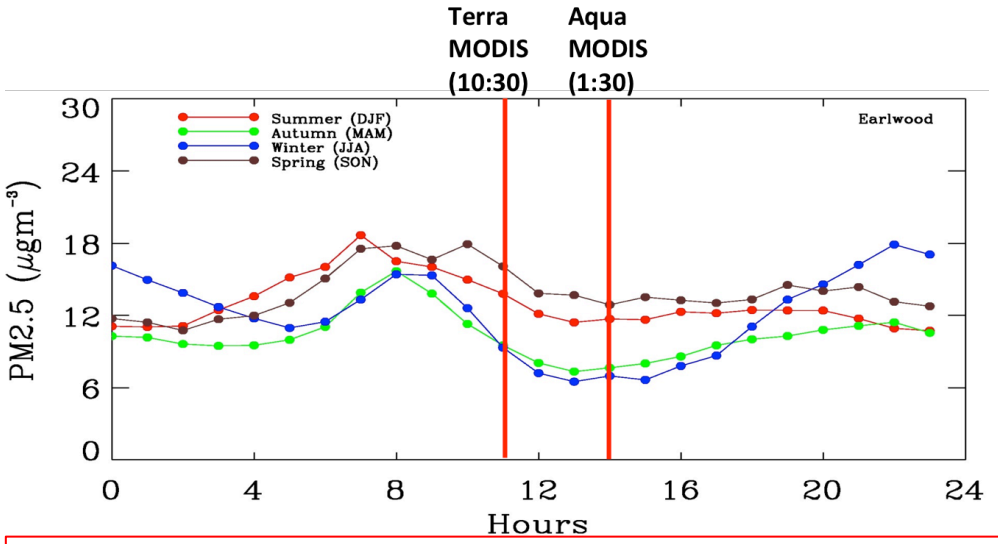
Data Min = -0.1, Max = 5.0, Mean = 0.2

BIG PROBLEM!
How to re-process 5+ years of GEO?

- GEO data are huge! Native-resolution full disc is >GB. We want to reprocess entire time series.
- AHI-8 = 5+ years, ABI-16 = 2+ years, ABI-17, etc.
- Need to modernize DT algorithm, parallelize, access to data, “the Cloud”, etc.
- Outputs must be small, usable, archived and searchable. (“Useful!”)
- Subject of a NASA-MEaSUREs project. (NASA + NOAA + U-Wisc + UMBC).

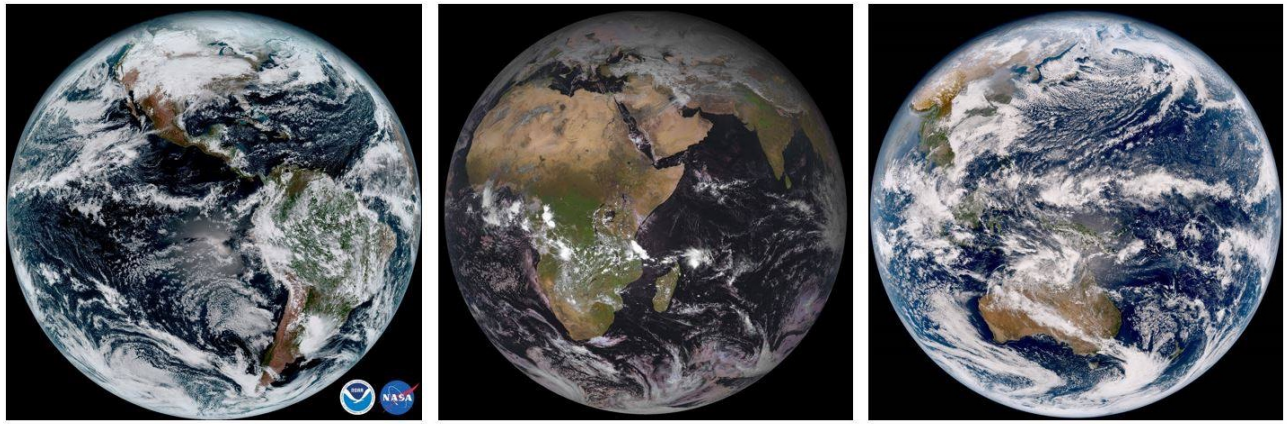
GEO + LEO

- ✓ Aerosol measurements for LEO have long history , validation and use for AQ and climate applications.
- ✓ Aerosol measurements from Geo orbit is a step forward in breaking the temporal barrier.
- ✓ GEO constrains multiple LEO sensors, .and LEO constrains multiple GEO. Synergy!
- ✓ For the global climate record, consistent and long-term aerosol retrieval is a key challenge.
- ✓ GEO can tell us about AM versus PM in historical record



Polar orbiting satellites only provides 1-2 observations per day, which limits the application for looking at diurnal cycle of aerosol

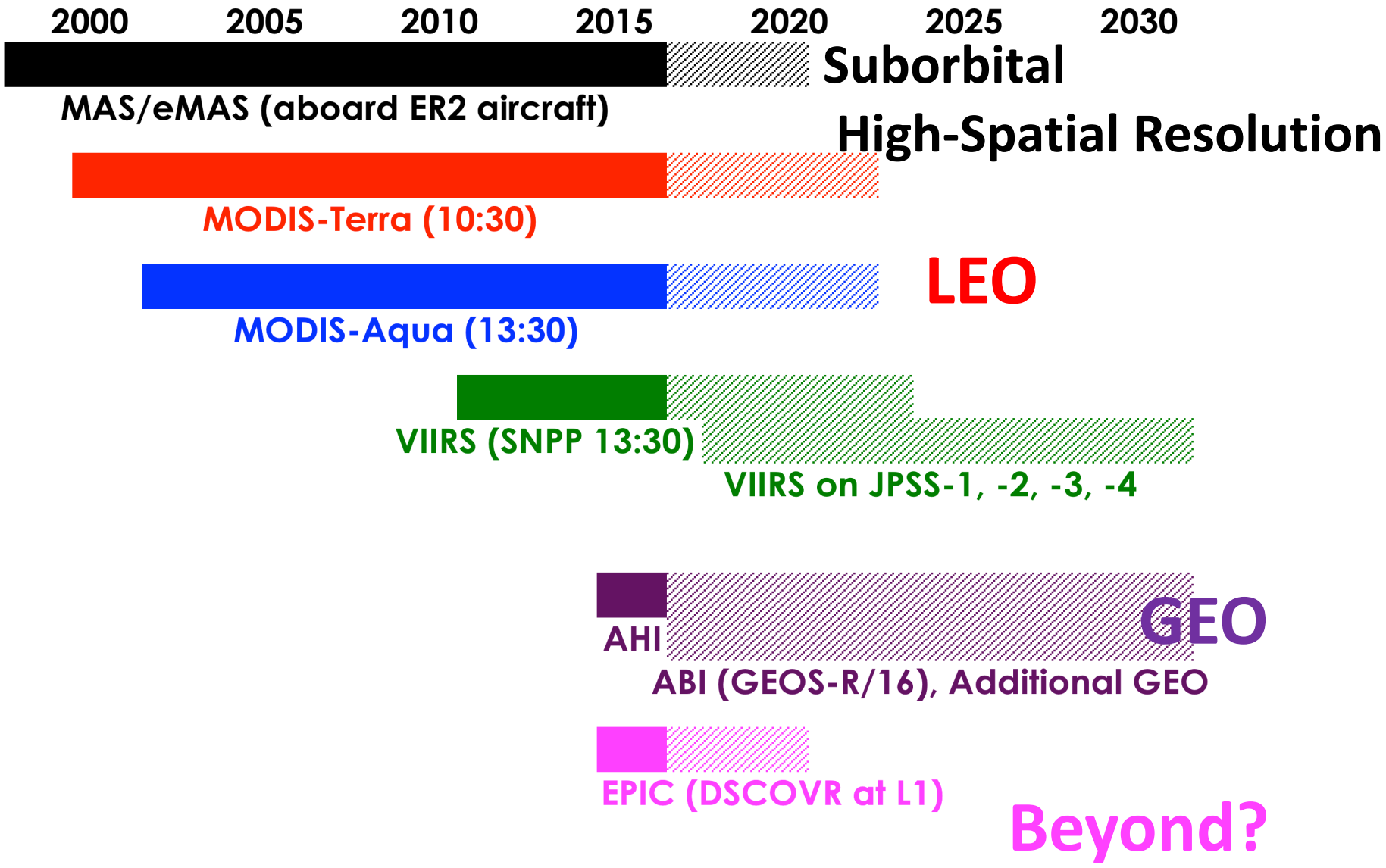
GEO: Breaking the Temporal Barrier



GOES-16 METEOSAT-8 HIMAWARI-9

The beginning of a new era in satellite remote sensing of aerosol

Towards synergy of aerosol observations



Conclusion: Long and wide aerosol climatology

- **AOD is an Essential Climate Variable**, can be retrieved with the Dark-Target algorithm, from any sensor that has sufficient observations of multi-spectral (VIS/NIR/SWIR) reflectance.
- Validation shows that **DT on MODIS nearly meets 2 out of 5 requirements of a Climate Data Record**: Spatial resolution and accuracy.
- **MODIS C6.1** is improvement over C6 due to new urban retrieval, and upstream corrections that reduce relative drifting of Terra versus Aqua.
- C6.1 on MODIS still shows **unexplained 10-15% global offset** between Terra and Aqua. With continued updates in calibration/stability of sensor observations, we may meet **3rd CDR requirement of consistency.**
- **DT is ported to VIIRS**, and the products are almost consistent enough to continue time series to beyond 30 years, meeting **4th CDR requirement**.
- With DT retrieval on **GEO sensors**, and more coming online, we are getting closer to meeting **5th CDR requirement** of temporal resolution.

https://darktarget.gsfc.nasa.gov/