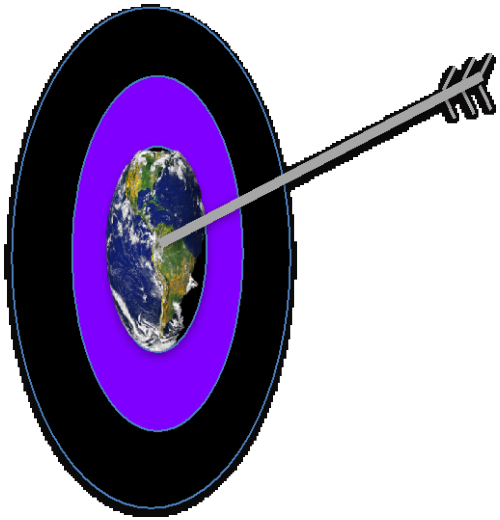


Developing an integrated climatology of global aerosol properties from a constellation of LEO and GEO satellite observations

Robert C. Levy (NASA-GSFC)

At GSFC Building #33:

Shana Mattoo, Virginia Sawyer, Rich Kleidman (SSAI)

Yingxi Shi (USRA), Yaping Zhou (MSU)

Lorraine Remer (UMBC)

Now at NASA – Marshall

Pawan Gupta, Falguni Patadia (USRA)

Outside of #33:

Folks at Atmos-SIPS (U. Wisconsin)

Folks at MODAPS (GSFC)

Global Climate Observing System

GCOS Aerosol CDR* Requirements

CDR = Climate Data Record

For Aerosol Optical Depth (AOD):

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

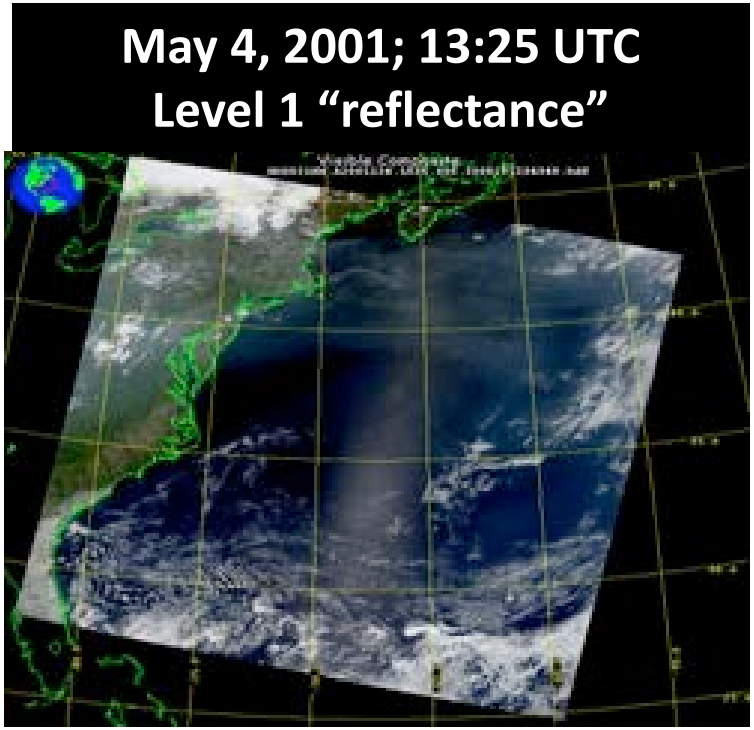
Maybe different requirements for other applications

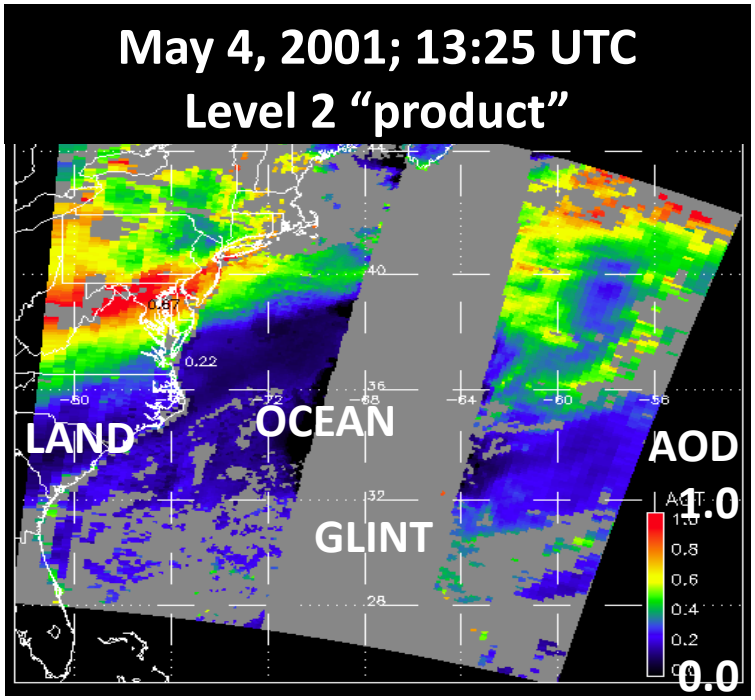
(air quality, ocean fertilization, weather forecasting...)

Dark-Target (DT): A "Single View" aerosol algorithm developed for MODIS (Terra and Aqua)

What a sensor observes

Attributed to aerosol (AOD)





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

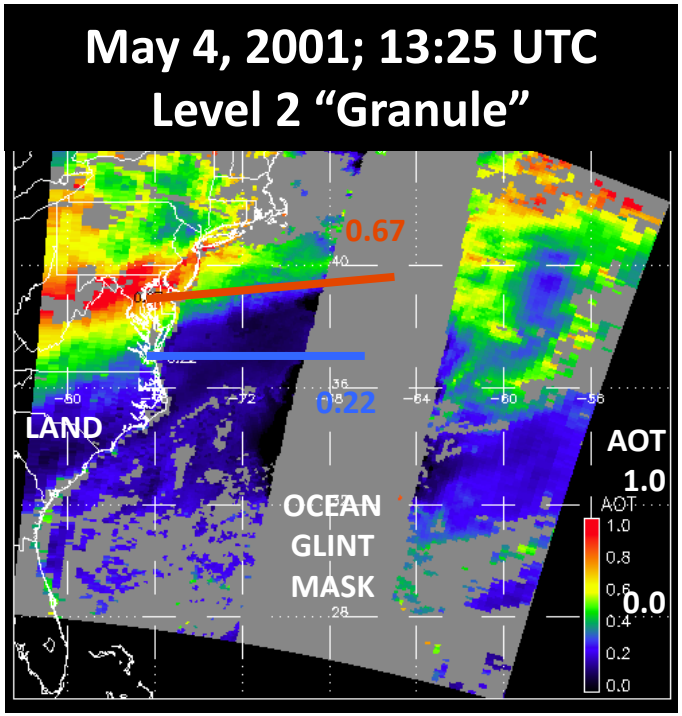
"Modified 2005, 2010, 2013, 2015" by Remer, Levy, Gupta, etc

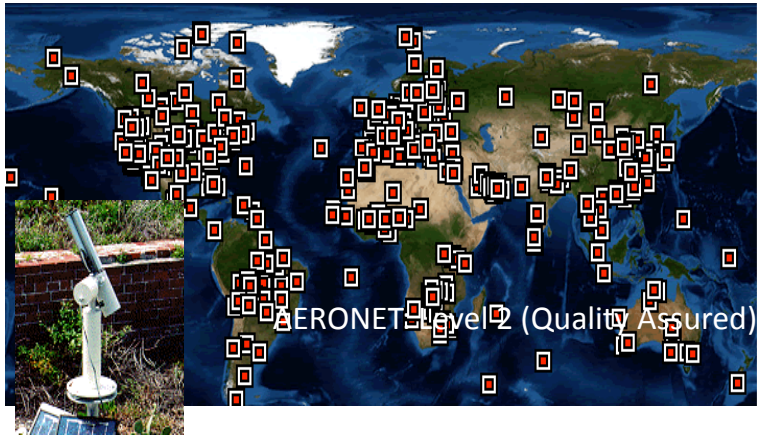
Separate logic over land and ocean

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

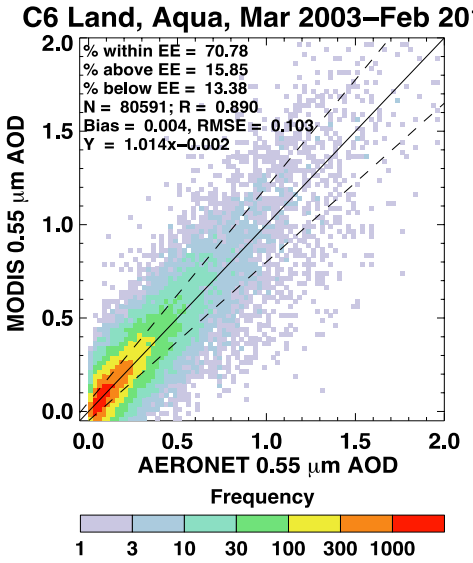
So where are we?

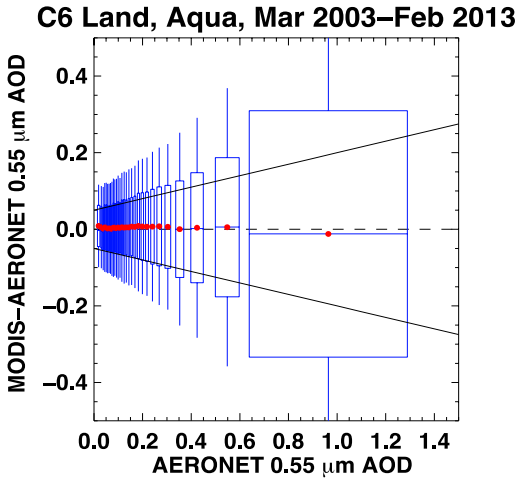
MODIS C6 product (ended 2017)





- Compare both land and ocean products to AERONET, separately
- Validation: 66% are within
  - "Expected Error" (EE) defined as
    - Land: $\pm(0.15\tau + 0.05)$
    - Ocean: $\pm(0.10\tau + 0.04)$

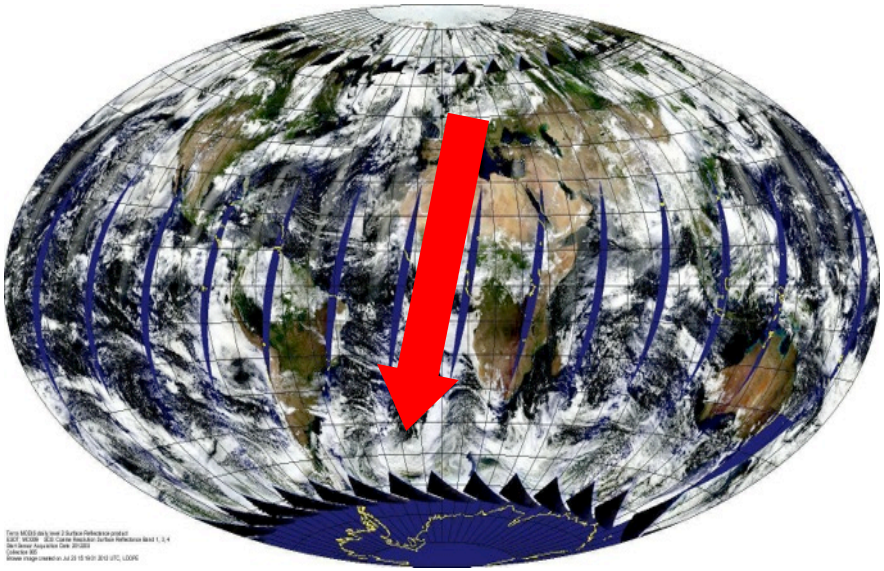




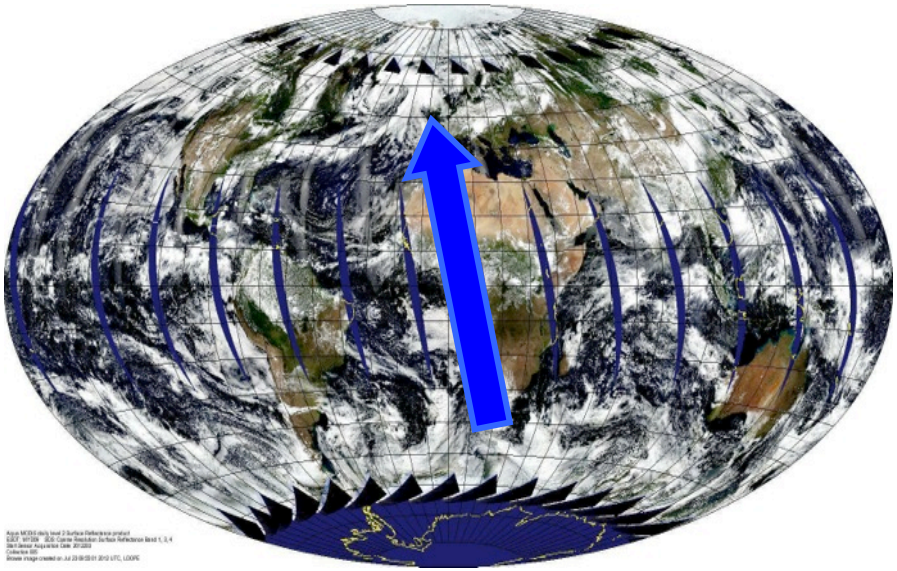
- getting close to CDR accuracy requirements!

MODIS-Terra vs MODIS-Aqua

Terra (10:30, Descending)



Aqua (13:30, Ascending)



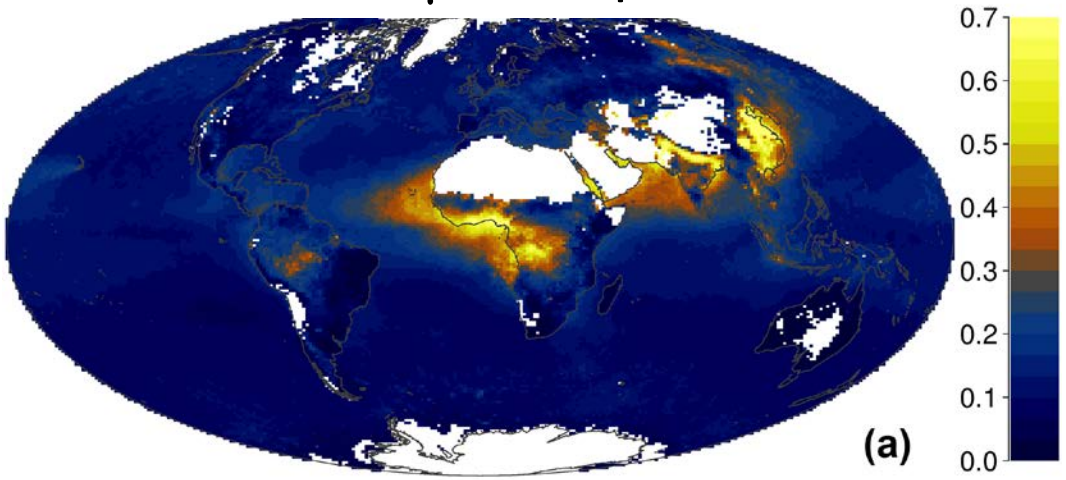
The two MODIS instruments are **TWINS!**

Do they observe the world in the same way?

Levy, R. C., et al.: Exploring systematic offsets between aerosol products from the two MODIS sensors, Atmos. Meas. Tech., 11, 4073-4092, https://doi.org/10.5194/amt-11-4073-2018, 2018.

Aggregations of 2008 AOD shows offsets

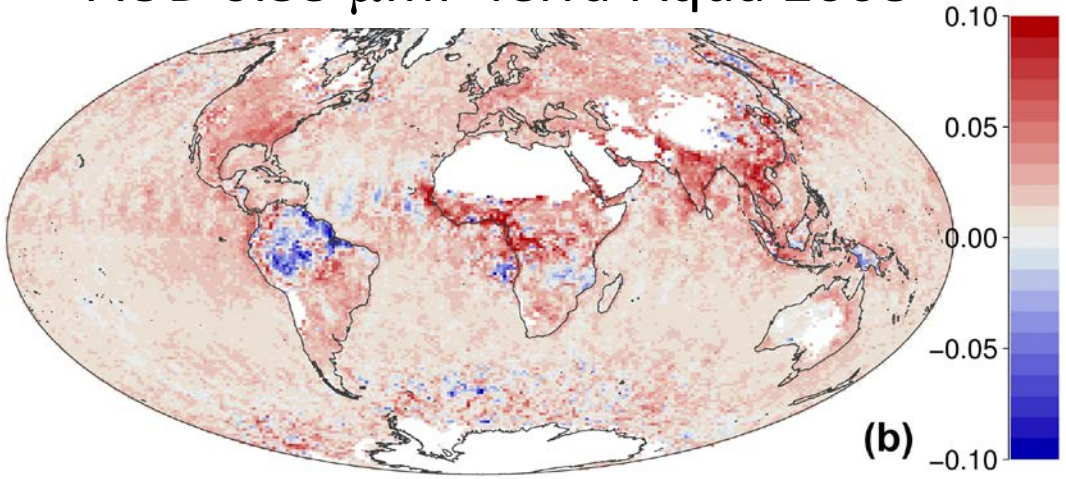
AOD 0.55 μm: Aqua 2008



Higher AODs; Dust, pollution

Lower AODs; open ocean, remote land

AOD 0.55 μm: Terra-Aqua 2008



Positive offset nearly everywhere!

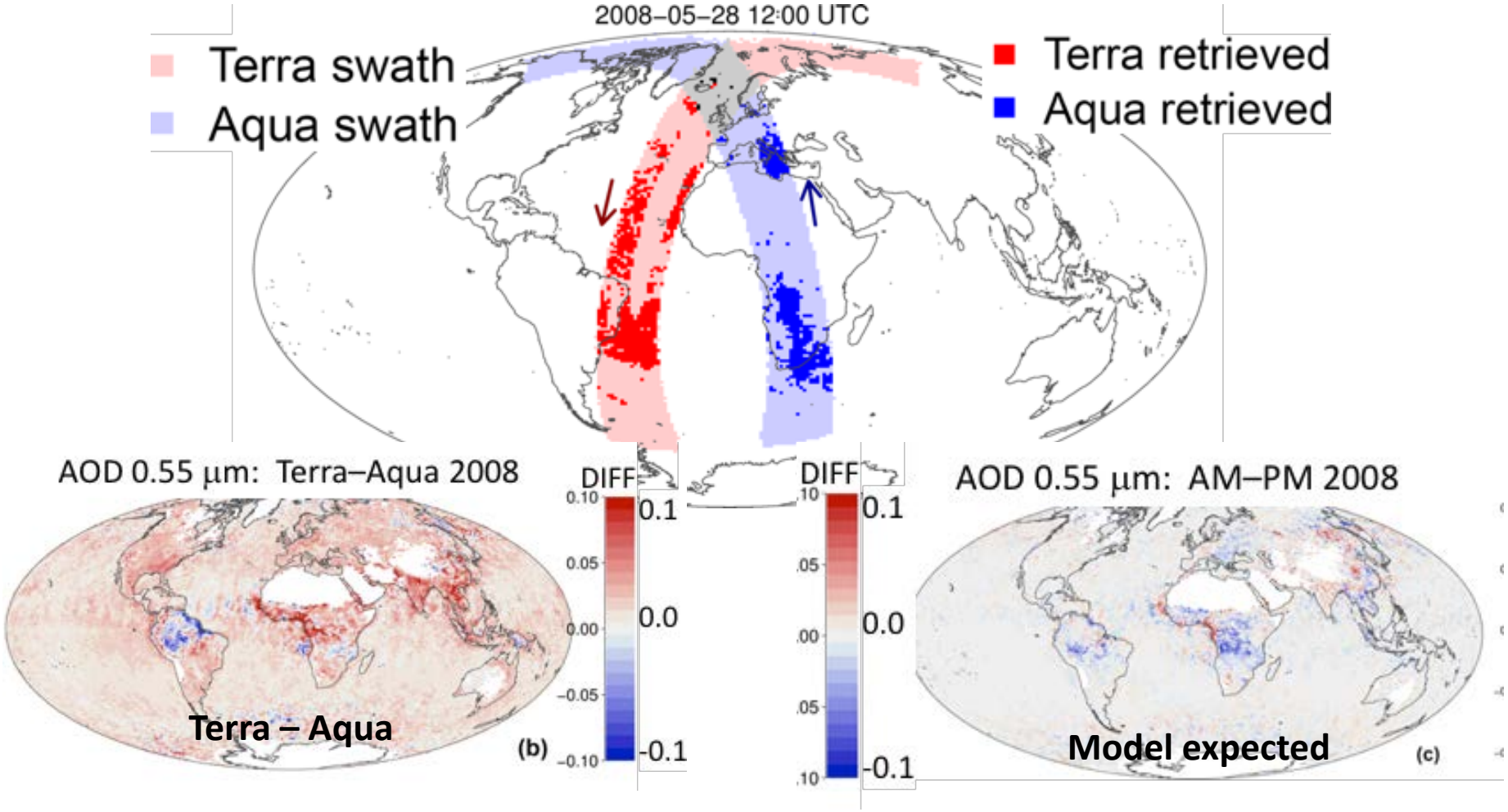
Terra also larger offset compared to AERONET

Angstrom Exponent (AE) also shows offsets

C6: “model” did not explain AOD offset

MERRA-2 (replay) sampled at 12:00 UTC on May 25, 2008

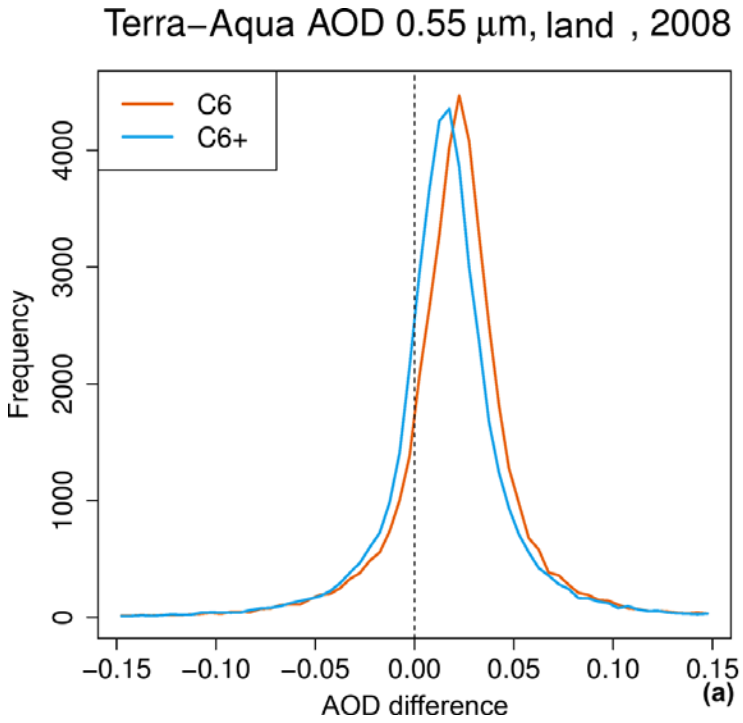
Overpasses within ±30 minutes

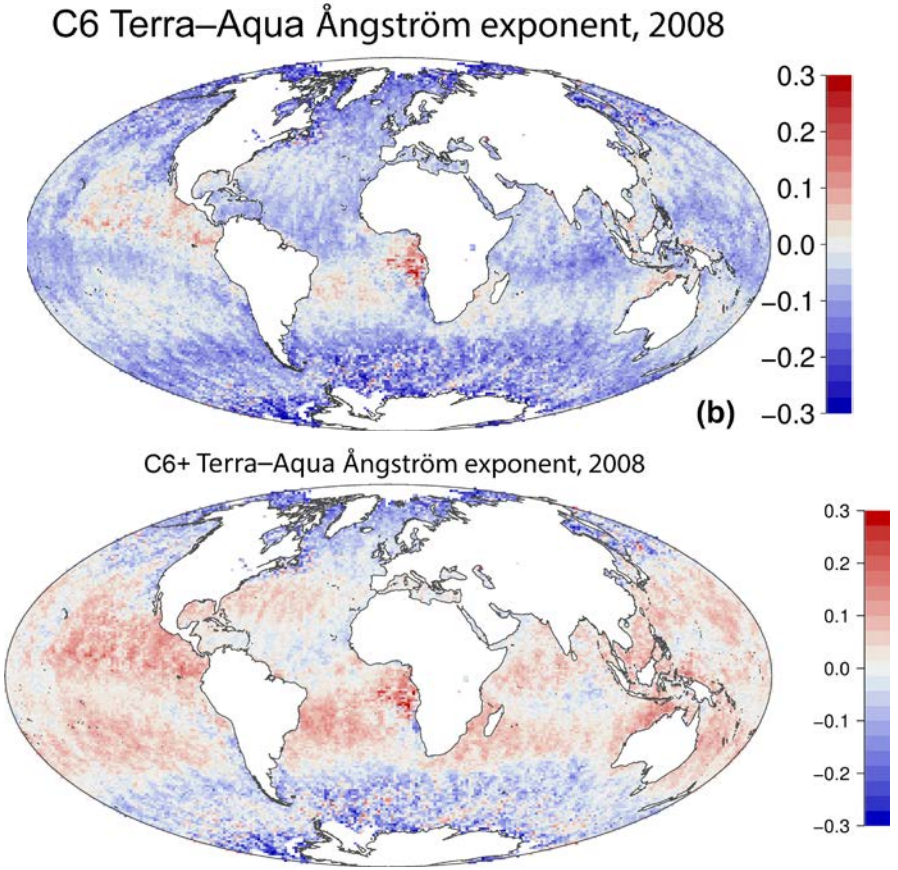


Some similarities in ”smoke” regions

Additional calibration “C6+” helped (a bit)

- Over land, AOD offset is reduced (by 0.005)
- Over ocean, negligible change in AOD offset

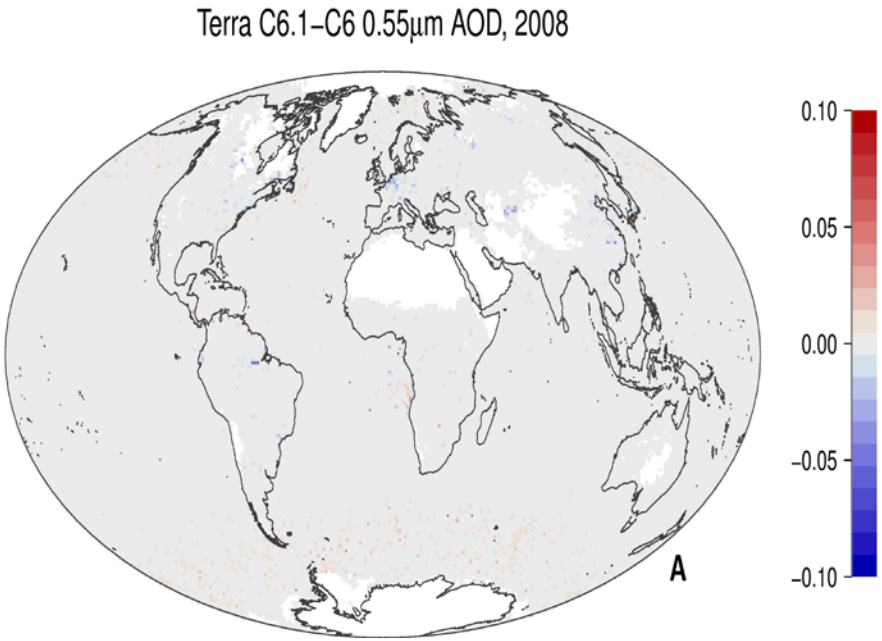




- For AE, C6+ reduces negative offset

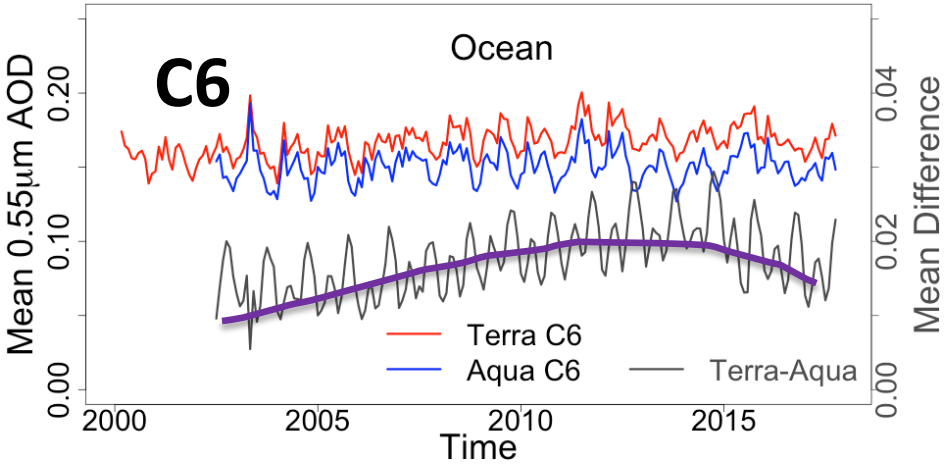
What about Collection 6.1 ? Processing began October 2017

- C6.1 was primarily focused on mitigating thermal infrared drifts and impact on cloud masking
- For DT algorithm, C6.1 included:
  - Correction for bias over urban surfaces
  - Improvement of under-water sediment screening
  - ”reaction” to changes in upstream MxD35 cloud mask
  - Some bug fixes related to diagnostics
- DT 6.1 – 6.0: Changes on a global scale? = **Nada!!!**

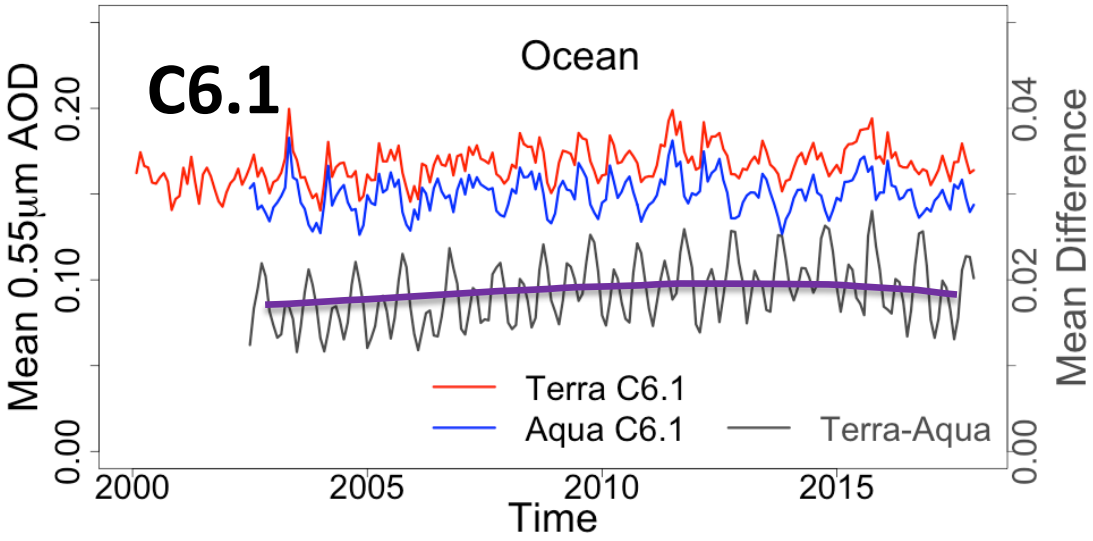


(modis-atmosphere.gsfc.nasa.gov/documentation/collection-61)

C6.1 reduces the global T – A drift!



VS



What about Future MODIS?

("Maintenance Mode")

- Our MODIS work is now under Senior Review since late 2017.
- Meaning we are funded for "maintenance" only. Under this umbrella we are/will:
  - do a comprehensive validation of C6.1.
  - If there is new upstream calibration, we will test if removes Terra-Aqua offset
  - Continue working with users
  - Extract DT algorithm from historic 'MODIS Toolkits' so can be run independently of MODAPS
- TBD whether new 'versions' (e.g. C6.2) or 'collections' (e.g. C7).

Global Climate Observing System

GCOS Aerosol CDR* Requirements

CDR = Climate Data Record

Aerosol Optical Depth (AOD) from MODIS 6.1:

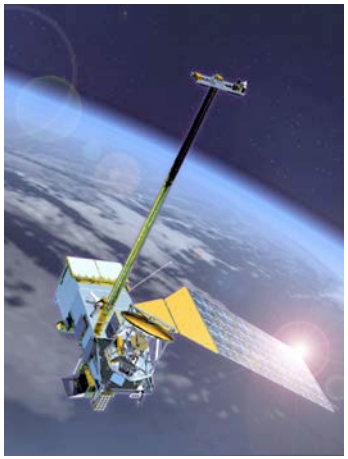
Target metric	Target	Current with MODIS
Horizontal Resolution	5-10 km, globally	10 km over ice-free and cloud-free scenes (No desert for DT)
Accuracy	MAX(0.03 or 10%)	±(0.04+10%): Ocean ±(0.05+15%): Land
Stability / bias	<0.01 / decade	Nearly stable trends, but offsets still
Time Length	30+ years	20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

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

How do we get closer?

Beyond **MODIS**

- Terra (18) and Aqua (16) have both have well-exceeded their planned 5-7 year mission lifetimes.
- With luck, they will last until 2022.
- But for climate, we need to continue the MODIS record to 30+ years



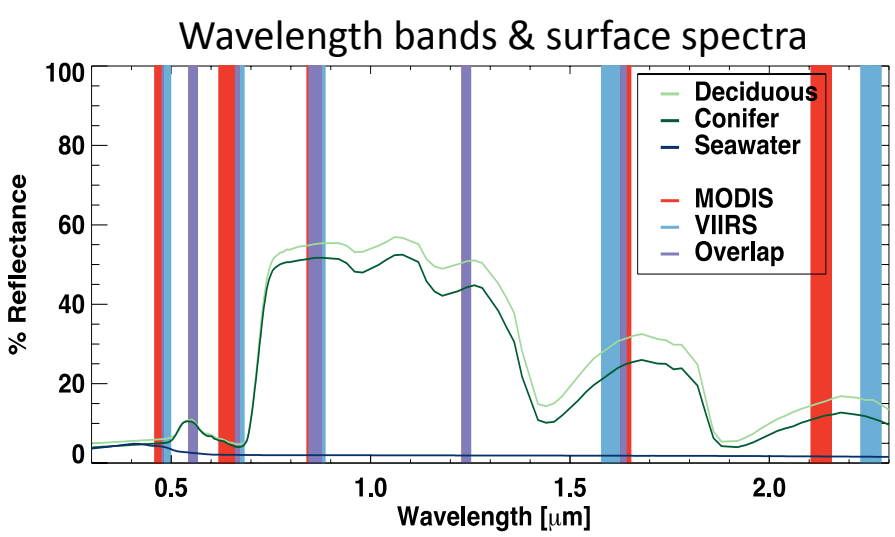
VIIRS!

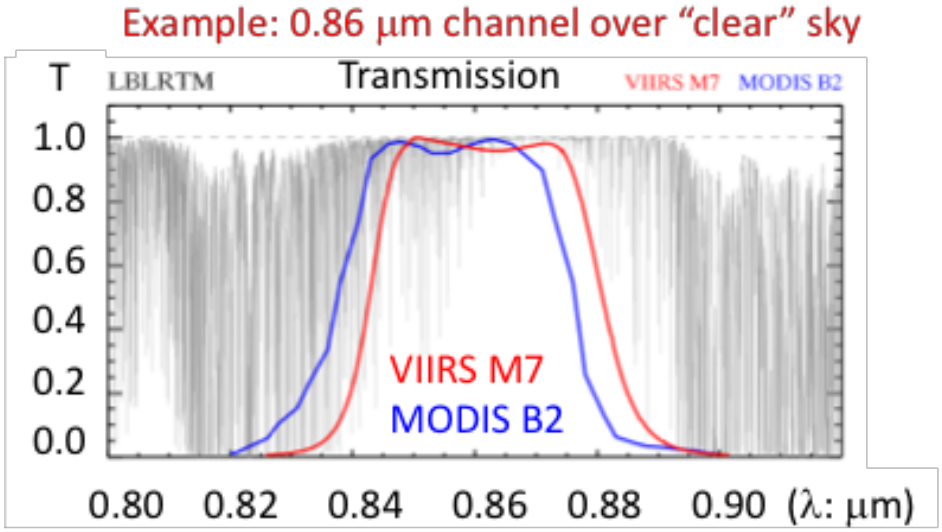
Visible-Infrared Imager Radiometer Suite aboard Suomi-NPP (and future JPSS)

- Both DT and DB algorithms are ported

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

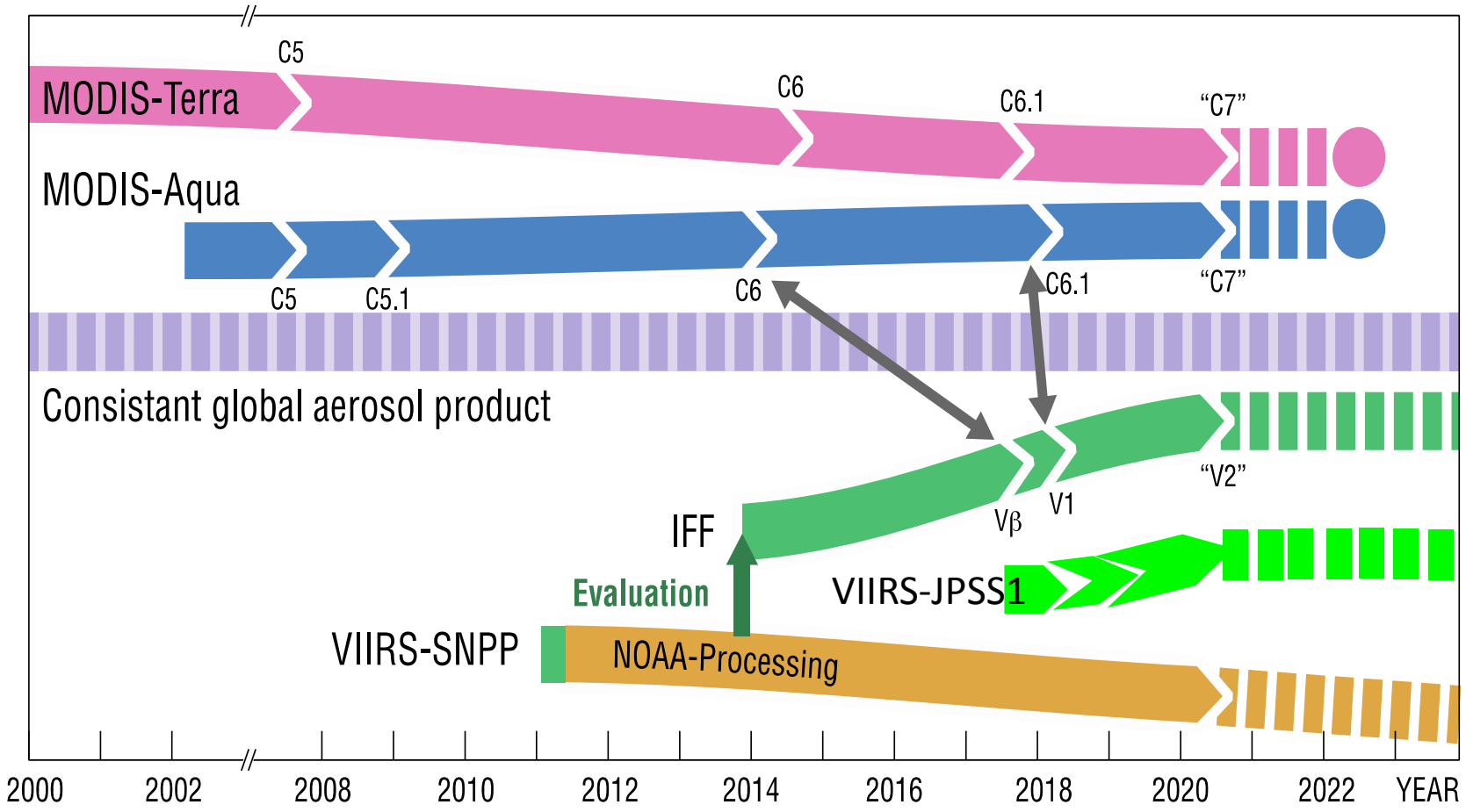
- Deal with differences in wavelengths (gas corrections/Rayleigh, etc)





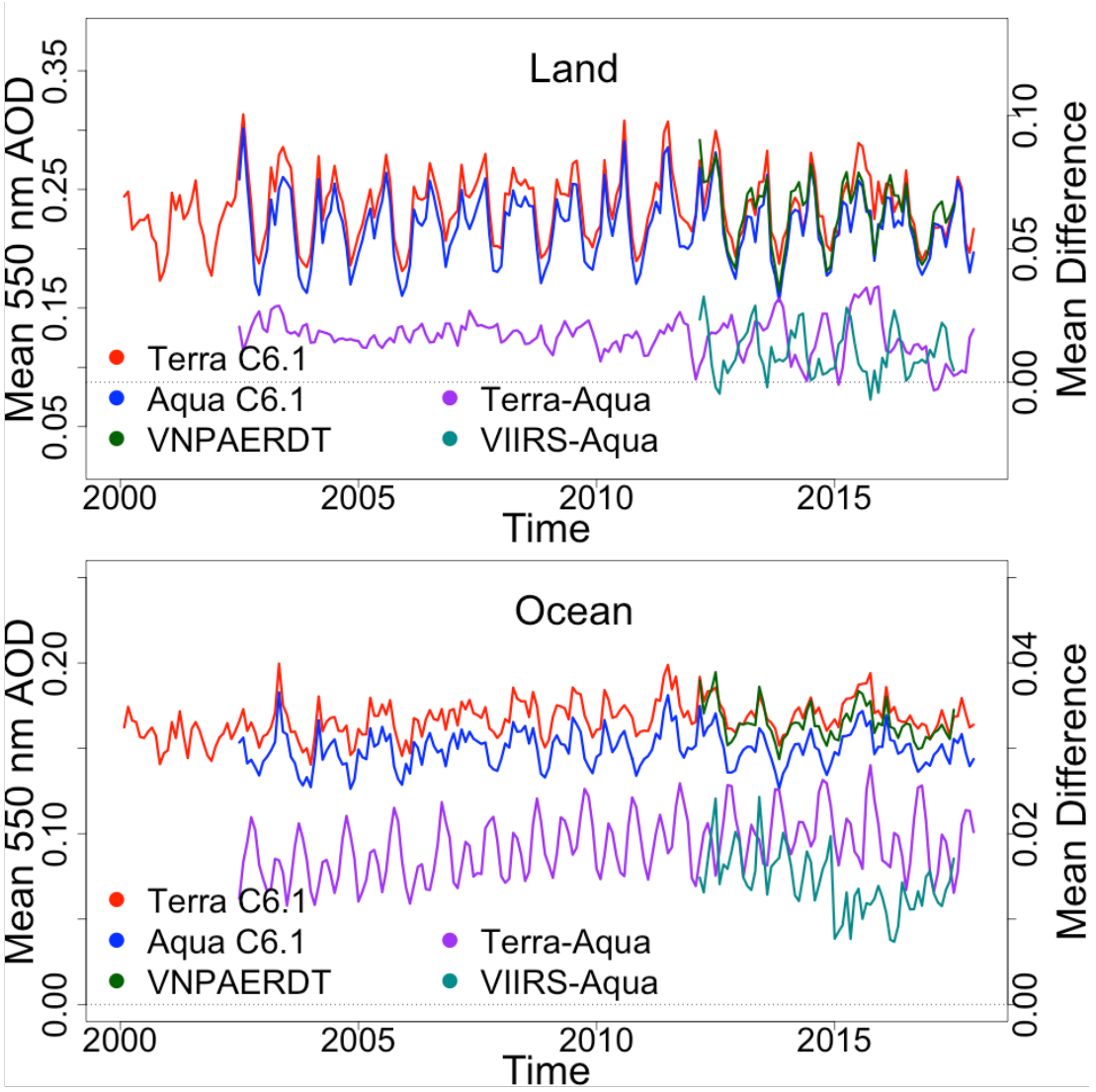
- Deal with differences in resolution, etc.
- Retrieve on new sensors (compared with retrieval on MODIS):

Towards consistent global aerosol on LEO



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

MODIS-T vs MODIS-A vs VIIRS-SNP



VIIRS-SNPP has small offset compared to MODIS-Aqua but less than Terra

Also noting seasonal cycles are different (**VIIRS vs Aqua** compared to **Terra vs Aqua**)

VIIRS-SNPP Dark Target schedule/status

- We currently have no funding for this work.
  But leveraging MODIS maintenance and other projects.

- Previous testing of of VIIRS DT have used Wisconsin's Intermediate File Format (IFF).
- **Current delivered version uses NASA's Level 1B (verified)**
- This "Version 2.0.1" will assume:
  - NASA L1B (calibration),
  - upstream Level 2 (MODIS-VIIRS Continuity cloud mask - MVCCM),
  - Ancillary data = same as MODIS
- Products (AOD at 0.55 μm, FMW, AE, QA-Confidence, input reflectances, etc.) are identical to MODIS.
- Plan for re-processing the entire mission (2011-present)
- If there is revised upstream calibration, we can test it.

- Uncertain about what to do with Level 3 (L3), but we just learned at VIIRS Science team this week, that L3 will be supported.

NASA VIIRS vs MODIS (DT)

Parameter	MxD04	AERDT_L2_VIIRS_SNPP
Mission length	Terra (2000-) 10:30 LST Aqua (2002-) 13:30 LST	SNPP (2012-) 13:30 LST JPSS1 (2017-) 13:30 LST
Pixel / Product size (km) nadir (Level 2)	0.5 km → 10 km	0.75 km → 6 km
Granule size (pixels)	5 minute (203x135)	6 minute (404x400)
File Format	HDF4	NetCDF4
Upstream cloud mask	MODIS Cloud mask = MxD35	MODIS-VIIRS Continuity Cloud Mask (MVCM)
Production	LAADS (at GSFC)	SIPS (at U Wisconsin)
Level 3	LAADS (files=MxD08)	SIPS (files = TBD, $$$?)
Public Archive	LAADS (at GSFC)	?????* Pending $$$

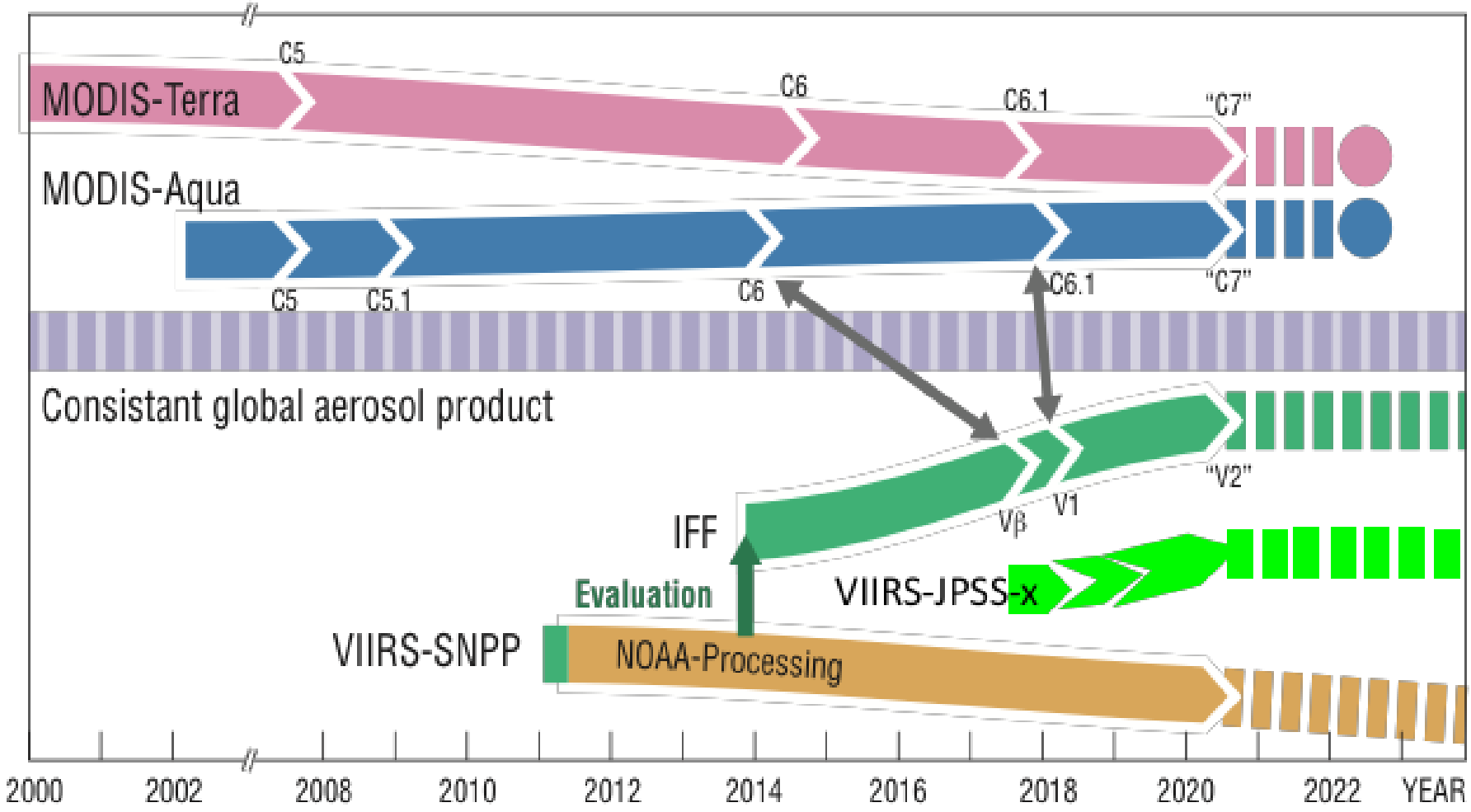
Compared to GCOS requirements

For Aerosol Optical Depth

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	Can do with MODIS + VIIRS
Temporal Resolution	4 h	2+ / day (Terra + Aqua/VIIRS)

- JPSS-1 launched (November 2017), and is in SAME ORBIT as S-NPP!
- JPSS-2, 3 and 4 to launch between 2022, 2026 and 2031.

Towards consistent global aerosol using DT



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

What's missing?
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*.

4 Sept 2017: Alberta/BC, Canada fires observed by ABI (GOES-R before moving to GOES-16/East)

1st loop: RGB
2nd loop: RGB + AOD

But also look at fires in South America!

(NOAA beta products)

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

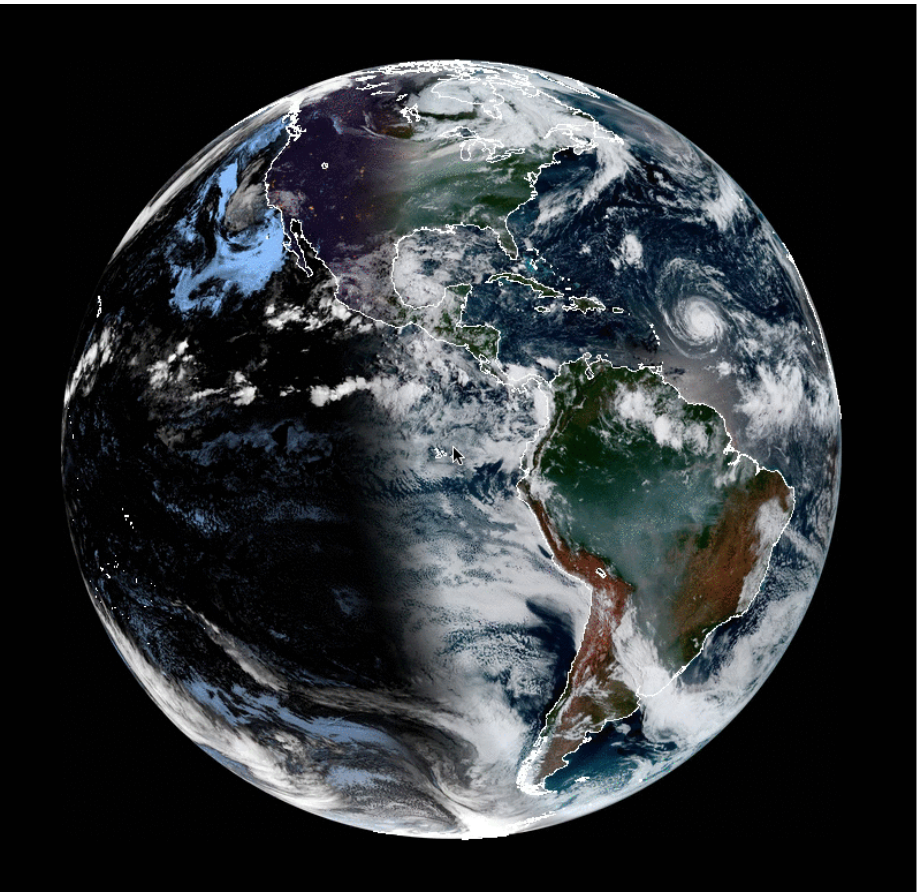
Some details need to be worked out (e.g. lack of "cirrus" band on AHI);

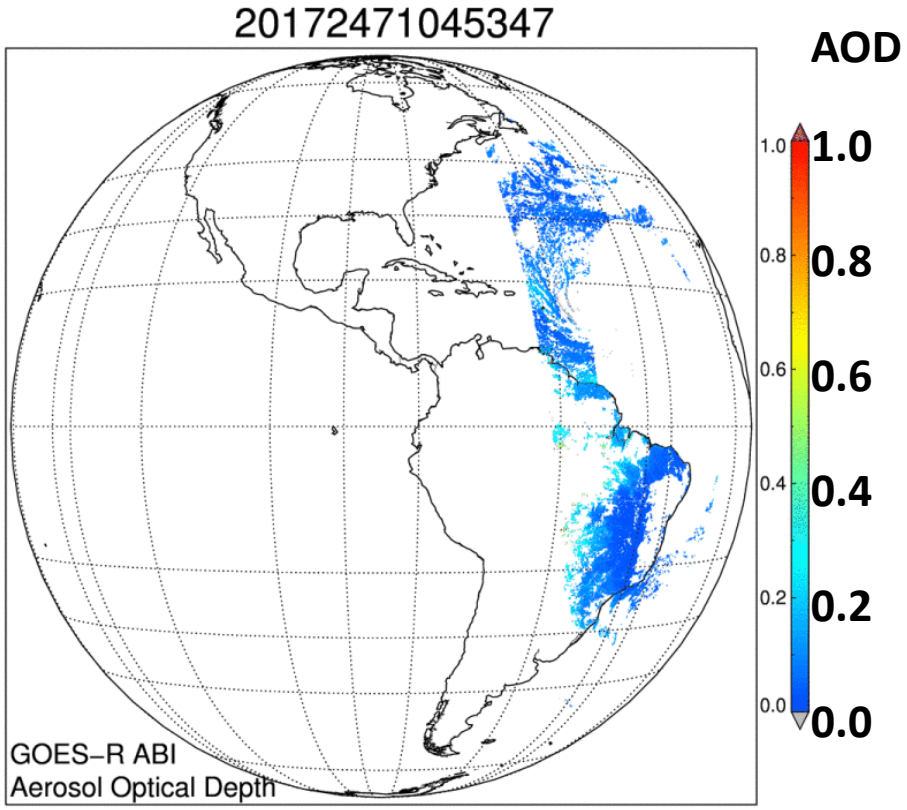
Green band: MODIS/VIIRS @ 0.55 μm, AHI @ 0.51 μm, ABI @ none

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

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

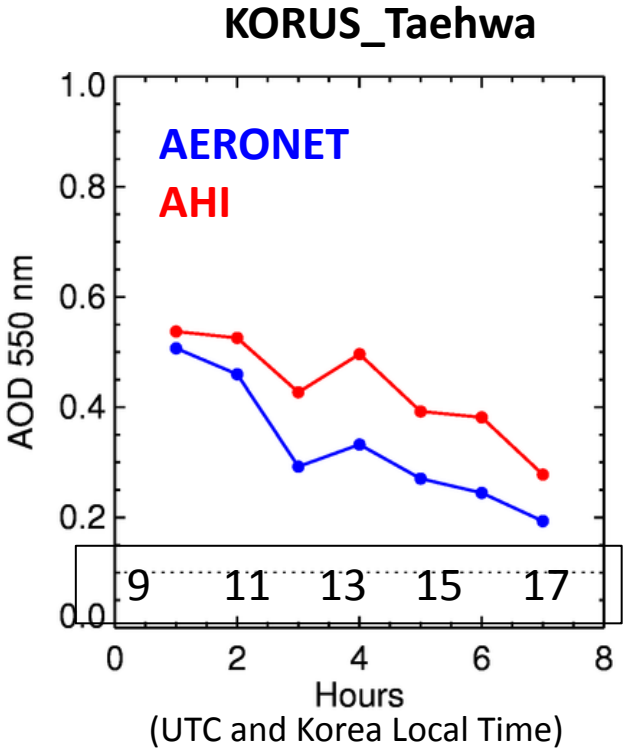
DT: RGB and AOD from ABI for Sep 4, 2017
B.C. Canadian Fires and smoke transport

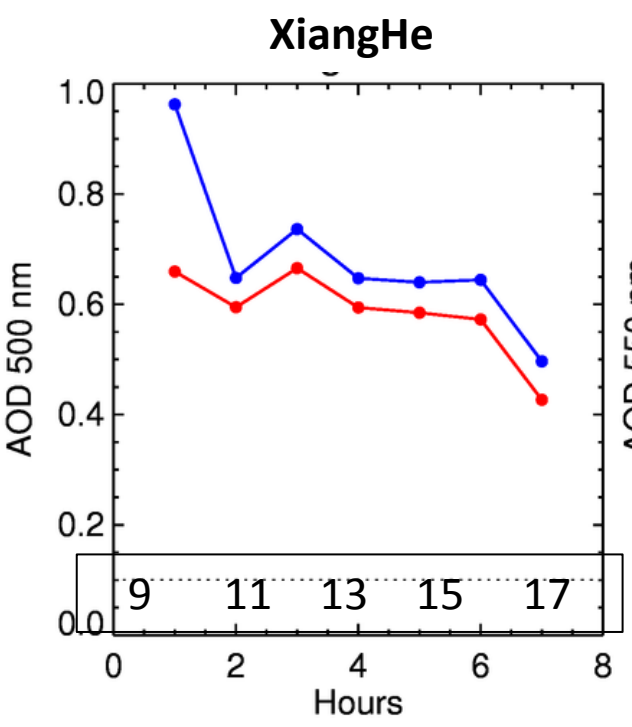


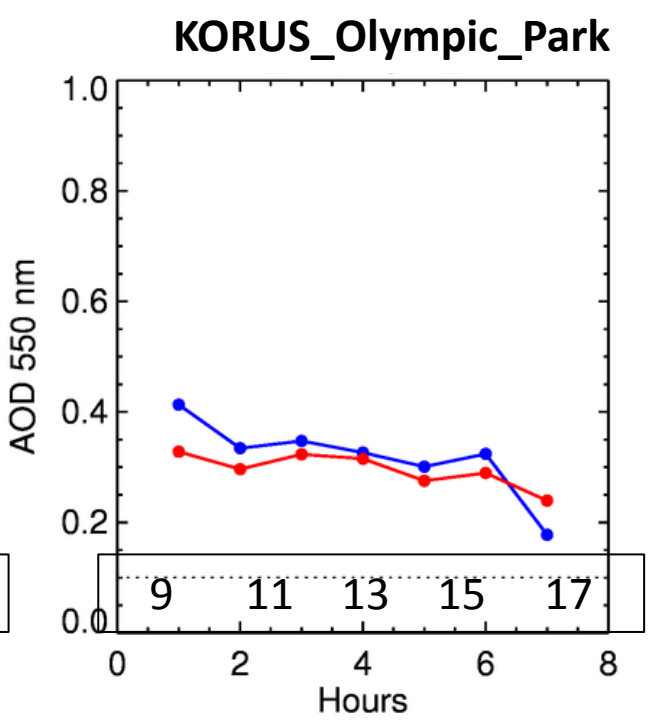


Diurnal Cycle of AODs from AHI (from KORUS-AQ, 2016)

-→ GEO does have sensitivity to Diurnal Cycle!!





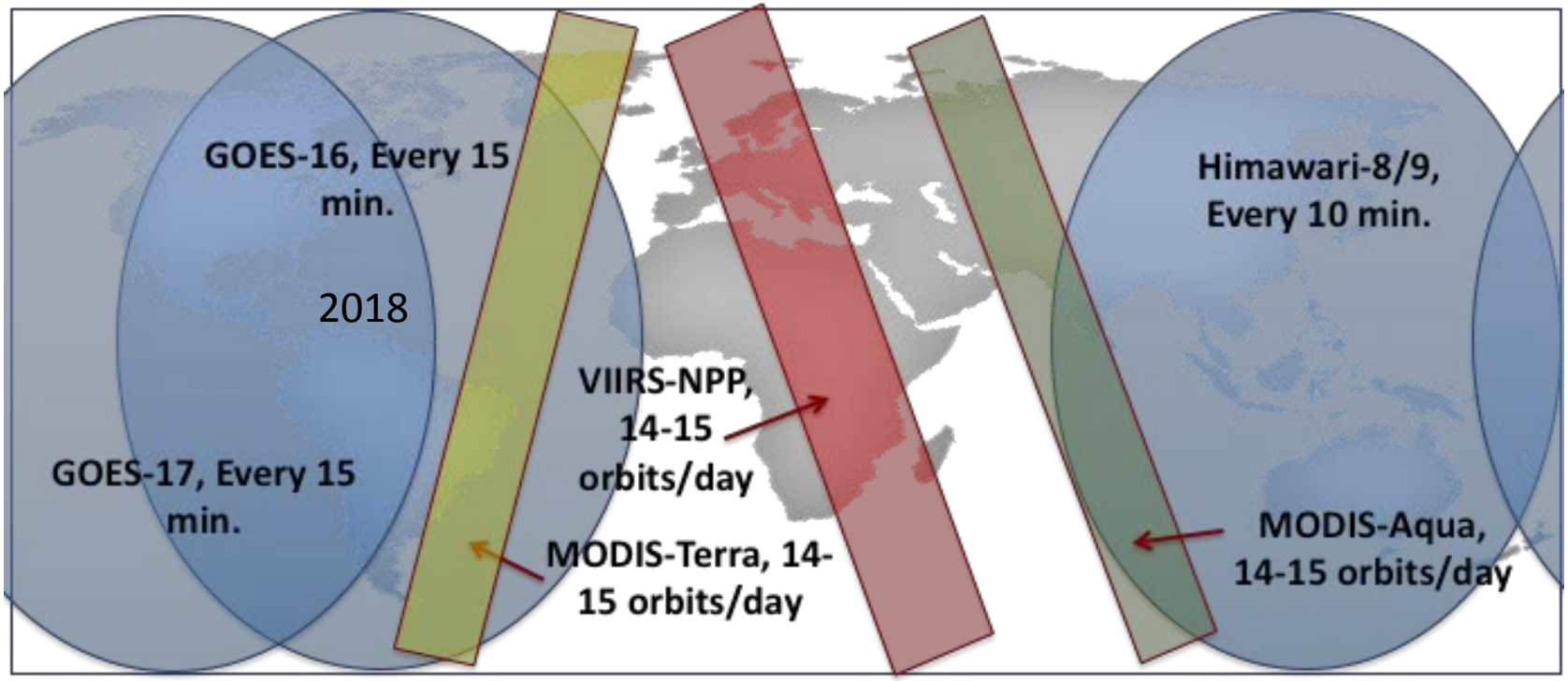


Global/Regional/Temporal synergy with

A consistent DT algorithm?

Statistics of UTC (compare with model)

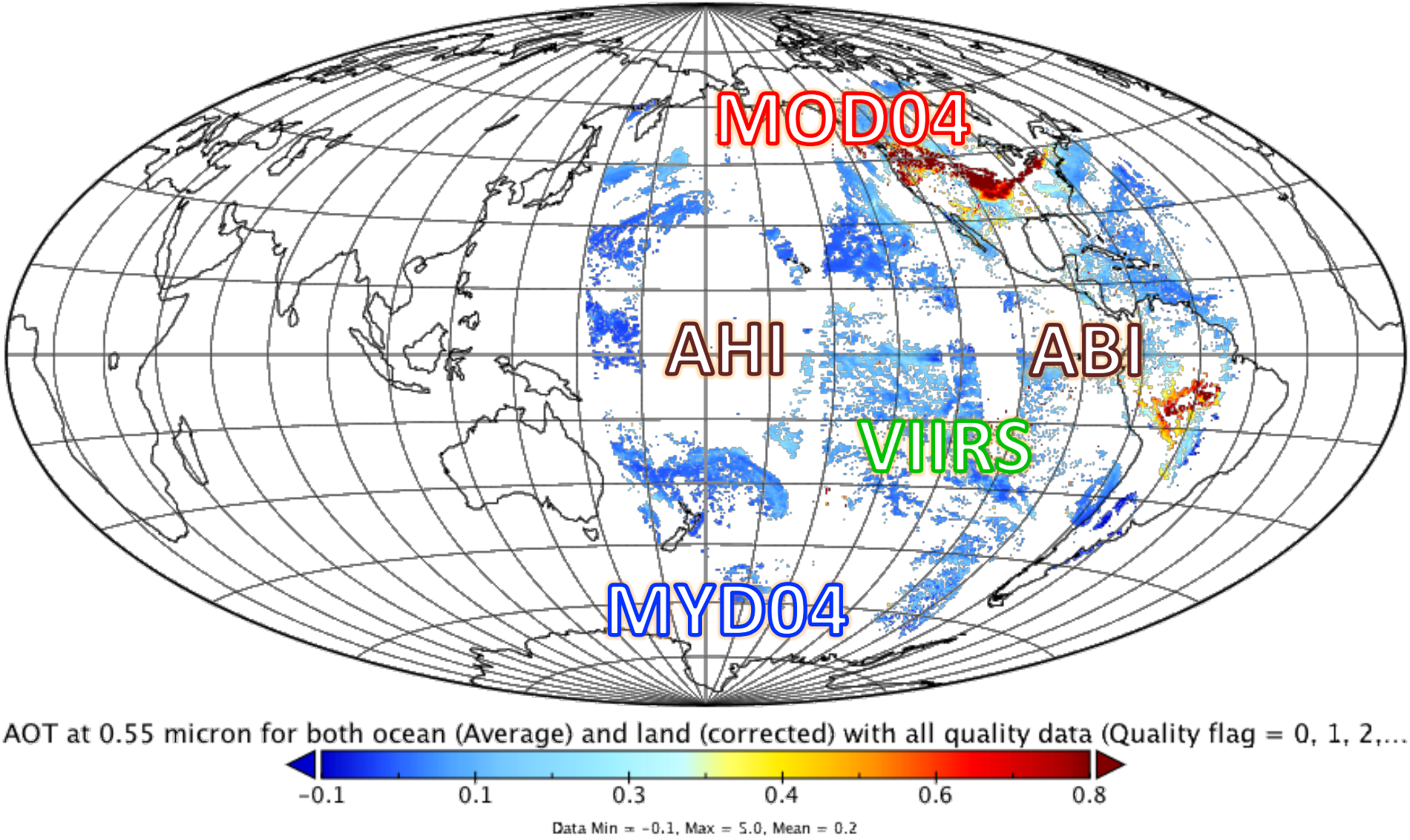
Statistics of LST (understand local diurnal cycle)



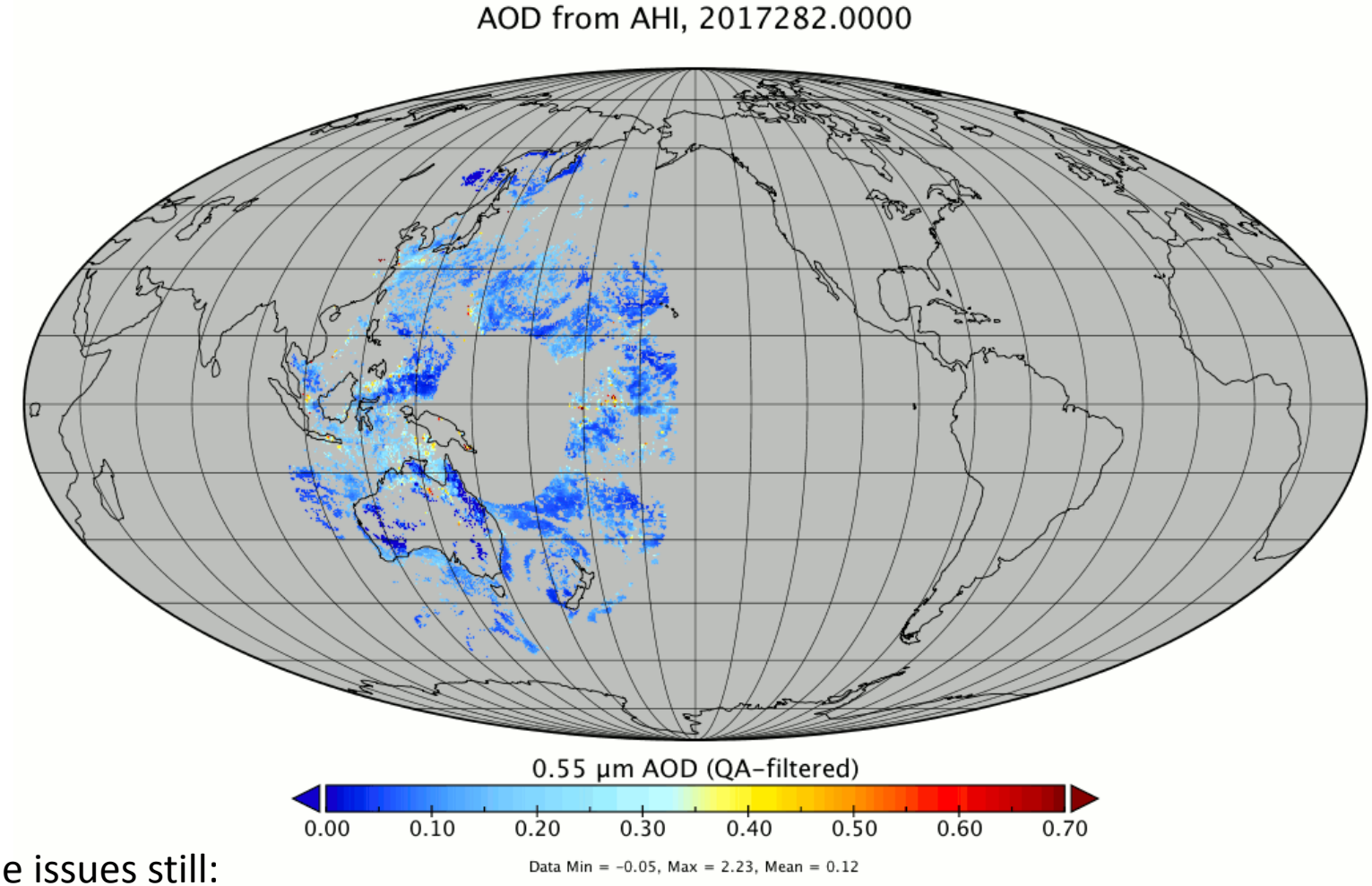
Subject of a recently funded NASA – MEaSUREs project

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

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



AOD from GEO (ABI+AHI): Oct 9-11 2017

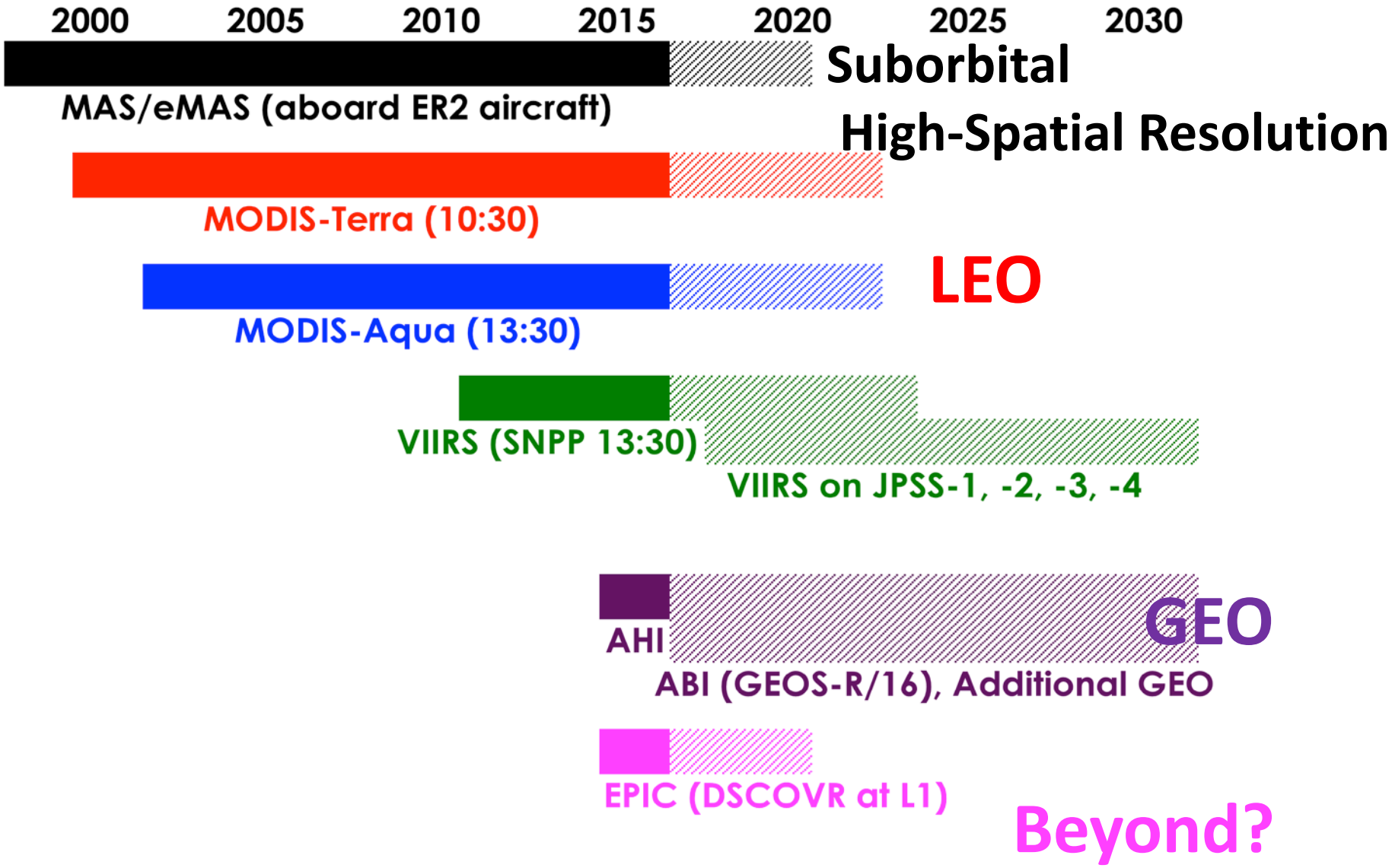


Some issues still:

- High solar and view zenith angles show lower AOD (better spherical corrections?).
- Cloud contamination indicated by “red monsters”
- Not sure why some time stamps are not being processed.
- Calibration uncertainties are still large (maybe as much as 5%!)

But really, really interesting! Potential to learn about Terra vs Aqua (AM vs PM)?

Towards synergy of aerosol observations



Global Climate Observing System

GCOS Aerosol CDR* Requirements

CDR = Climate Data Record

For Aerosol Optical Depth (AOD) from LEO + GEO!

Target metric	Target	with LEO + GEO
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
Time Length	30+ years	30+ years (MODIS + VIIRS on JPSSx)
Stability / bias	<0.01 / decade	Not there yet, but possible?
Temporal Resolution	4 h	**20+/day (daylight only) where GEo**

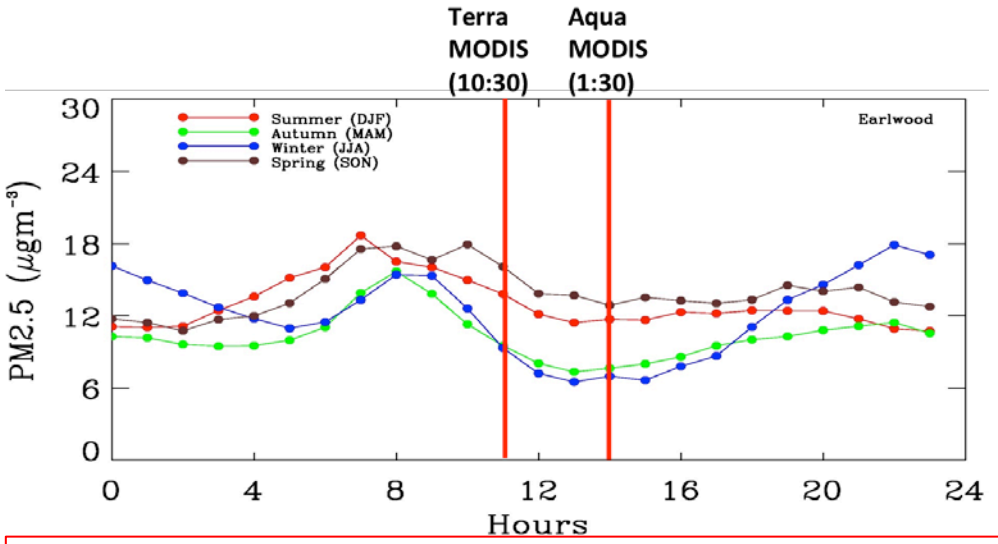
Key: Black = almost there, Blue = on the way, Red = not close or unknown

By 2021 there will be more GEO sensors (Europe, China, etc)

Now we need to work on improving algorithm, coverage to ice surfaces.

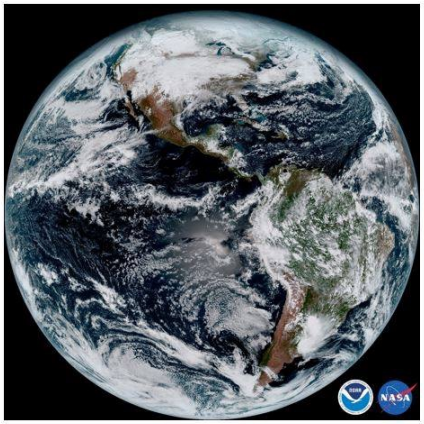
Summary

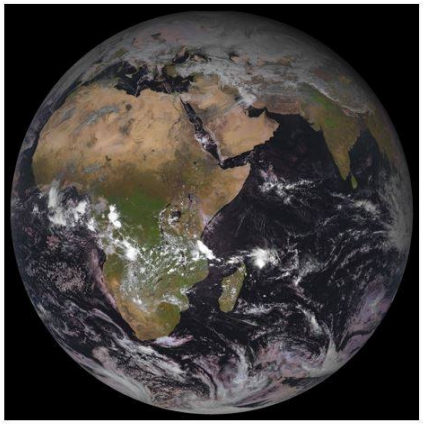
- ✓ Aerosol measurements for LEO have long history , validation and use for AQ and climate applications.
- ✓ Aerosol measurements from GEO orbit is a step forward in breaking the temporal barrier.
- ✓ GEO constrains multiple LEO sensors, .and LEO constrains multiple GEO. Synergy!
- ✓ For the global climate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



Polar orbiting satellites only provides 1-2 observations per day

GEO: Breaking the Temporal Barrier


GOES-16


METEOSAT-8


HIMAWARI-9

a new era in satellite remote sensing of aerosol SYNERGY!

Caveats: But we still got work to do!

- Calibration
- Funky geometry (GEO different than LEO)
- Canceling biases in LEO may not occur in GEO (scattering phase functions versus observing geometry)
- GEO data are huge! (2.75 GB native disk imagery), so reprocessing with consistent algorithms needs thought, CPUs and storage
- How to make data useful? (archive, searchable)
- I expect that assimilation may be key.
- New algorithms, that make use of time-dependence and multi-observation synergy

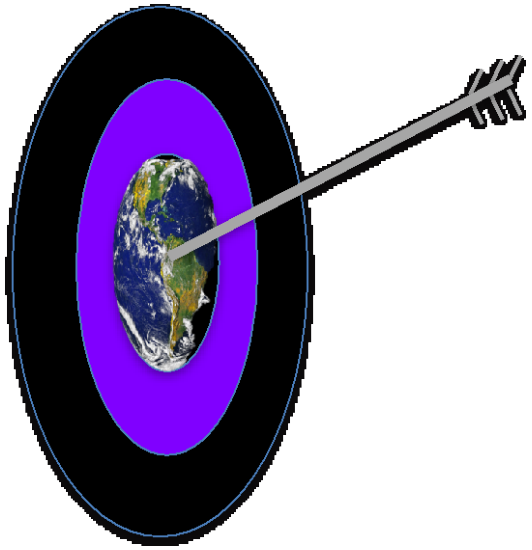
Conclusion I: Long and wide aerosol climatology

- **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.

Conclusion II: Long and wide aerosol climatology

- Many folks are currently using or proposing to use DT products from MODIS and/or VIIRS, however, our team is funded only for **MODIS "maintenance".**
- For now, we **are leveraging GEO funding** to continue delivery of 1st version of VIIRS DT algorithm and products. (We hope this can change!)
- We are grateful for the Wisconsin SIPS to continue supporting our efforts.
- There are still **significant improvements that are possible** for DT algorithm and products.

THANK YOU!



Please see Virginia Sawyer's poster

Some recent publications

1. Levy, R.C., Mattoo, S., Sawyer, V., Shi, Y., Colarco, P.R., Lyapustin, A.I., Wang, Y., Remer, L.A. 2018. Exploring systematic offsets between aerosol products from the two MODIS sensors, *Atmospheric Measurement Techniques Discussions*: 1-37
2. Gupta, P., Remer, L.A., Levy, R.C., Mattoo, S. 2018**.** Validation of MODIS 3 km land aerosol optical depth from NASA's EOS Terra and Aqua missions, *Atmospheric Measurement Techniques*, *11*(5): 3145-3159
3. Patadia, F., Levy, R., Mattoo, S. 2018. Correcting for trace gas absorption when retrieving aerosol optical depth from satellite observations of reflected shortwave radiation, *Atmospheric Measurement Techniques Discussions*, *2018*: 1—45
4. Shi, Y. R., Levy, R. C., Eck, T. F., Fisher, B., Mattoo, S., Remer, L. A., Slutsker, I., and Zhang, J.: Characterizing the 2015 Indonesia Fire Event Using Modified MODIS Aerosol Retrievals, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-468,[in review, 2018.
5. Wang, Y., J. Wang, R. C. Levy, X. Xu, and J. S. Reid. 2017. "MODIS Retrieval of Aerosol Optical Depth over Turbid Coastal Water." Remote Sensing, 9 (6): 595 [10.3390/rs9060595]